# book6

A collaborative IPv6 book.

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# book6: A Collaborative IPv6 Book.

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# Introduction and Foreword



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## Foreword

This book is written and maintained by a team of volunteers, who are all actively involved as users or providers of IPv6 services. It is their hope that the book will be useful and up to date as IPv6 usage in the Internet continues to grow.

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## How to use this book

This book is, and we hope always will be, a work in progress. It is intended for people who plan, deploy, maintain and operate computer networks using Internet Protocol version 6 (IPv6). It is being written and updated by exactly such people. IPv6 is a mature protocol but every day we gain more experience, products are updated, and quite often the underlying technical standards are updated too. Therefore, this book will likewise be constantly updated. It's issued under an open source license. You are welcome to make a printed copy at your own expense, but be aware that the book will evolve constantly.

The list of contents should act as an on-line guide to the topics covered. Most readers will probably not read from cover to cover. Design your own path through the book.

There is also an index.

A little tip if you are reading this on GitHub: For some reason, GitHub doesn't support automatically opening a link in a new browser tab or window, so clicking on links will always take you away from the current page. To avoid this, with most browsers you can use CTRL+click (on Windows and Linux) or CMD+click (on MacOS) to open a new tab.

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## How a user sees IPv6

The answer should be: *they don't*. In an ideal world, users would never need to be aware of the lower layers of the protocol stack, and they certainly should never have to see a hexadecimal number, or even be aware that they are using IPv6. The goal of a network designer or operator should be to make this true.

However, it's unlikely that this will always succeed. It's likely that if a user ever does see something specific to IPv6, it's probably at the worst possible time: when there is a fault or a system configuration issue. That is exactly when the user is either reading on-line help information, or in contact with a help desk. It is therefore recommended to review any documentation you provide to users or to help desk staff to make sure that when IPv6 is mentioned, the information is complete, correct and up to date. It's also important that configuration tools are designed to avoid or minimize any need for users to enter IPv6 addresses by hand.

P.S. In case you're wondering whether you can in fact use IPv6 right now, try https://ipv6test.google.com/. GitHub, where this book is hosted, supports IPv6 for many things, but not everything.

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## How an application programmer sees IPv6

In a very theoretical world, an application programmer could rely on a DNS lookup to return the best (and only) address of a remote host, and could then pass that address directly to the network socket interface without further ado. Unfortunately the real world is not that simple. Even without considering the version number, there are several types of IP address, and a DNS lookup may return a variety of addresses. In most cases, applications will use the function `getaddrinfo()` ("get address information") to obtain a list of valid addresses, typically containing both IPv6 and IPv4 addresses. Which is the best one to use, and should the program try more than one?

We do not go into this subject in detail, because this book is not aimed primarily at application programmers. However, operators need to be aware that the default behavior of most applications is simply to use the *first* address returned by `getaddrinfo()`. Some applications (such as web browsers) may use a smarter approach known as "happy eyeballs" (RFC 8305) by means of a heuristic to detect which address gives the fastest response. However, operators need to understand the various address types in order to configure systems optimally, including the `getaddrinfo()` precedence table (RFC 6724) in every host.

When developing IPv6 enabled applications, keep in mind that IPv6 addresses are longer and look different than IPv4 addresses. This may sound obvious, but the past has shown that these are two of the most common problems, especially when you store IPv6 addresses in a database or have an existing input field in your application that is too small. Also, regular expressions for validating IP addresses are different. As you will learn later in this book there are different types of IPv6 addresses and several ways to write them. Make sure your application only accepts the correct type of addresses and is also not too strict by only accepting one format. Users want to use copy-and-paste or automation and the input format of an IP address may not always be what your application expects. Always remember: "Be conservative in what you do, be liberal in what you accept from others". And it's probably always a good idea not to reinvent the wheel but use library functions that your programming language of choice provides, e.g. the `ipaddress` module for Python. And please don't hard-code IP addresses of any kind in your code. Always make them configurable and if possible use FQDNs (DNS names) instead of IP addresses.

Address types are discussed further in 2. Addresses. Address *selection* is discussed here. How applications relate to a mixture of IPv4 and IPv6 addresses is also discussed in 3. Dual stack scenarios.

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## How a network operations center sees IPv6

This is really the topic of this entire book. In the long term, we expect that "running an IPv6 network" will be synonymous with "running a network". IPv6 should not be viewed as an add-on, but as the primary network protocol. How it coexists and interacts with IPv4 is the subject of Chapter 3. This section gives an overview of how IPv6 looks when viewed from the NOC, and the rest of the book covers the details.

IPv6 is, at its roots, not fundamentally different from IPv4 - just different in almost every detail. So the *nature* of NOC design and operation is not changed by IPv6, but existing operations and management tools need to be updated. For example, any configuration databases, whether home-grown or purchased, must be able to handle IPv6. For operators, there are many new details to learn. Also, supporting IPv4 and IPv6 simultaneously is obviously more complicated than supporting only one protocol.

Enterprise networks, carrier networks, and data center networks each have their own requirements and challenges, with differing geographical spreads, availability requirements, etc. Various chapters of this book tackle different aspects of NOC operations: 5. Network Design, 6. Management and Operations, 9. Troubleshooting. The 7. Case Studies will also be relevant to NOCs.

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## How to keep up to date

The intention is for this book to be kept up to date by its user community. However, for the very latest information on IPv6 operational best practices and protocol details, readers may wish to track the discussions in the relevant IETF working groups, in particular IPv6 Operations (v6ops) and IPv6 Maintenance (6man). These groups are open to all, although following the discussion can be quite time-consuming.

The final results of these working groups are published as Internet Request for Comments documents (RFCs), freely available from the RFC Editor. *Warning:* obsolete RFCs are never modified or deleted. It is essential to look at the current status of an RFC before trusting it. For example, the current status of the 2017 version of the main IPv6 standard is shown at this info page.

This book intends to cite the latest version of all the RFCs it mentions, but it never hurts to check the info page.

Also see the Further Reading chapter for more explanation about RFCs and for other resources.

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## How to contribute

If you find an error or a gap in this book, or a recommendation that you disagree with on the basis of practical experience, you are most welcome either to raise an issue, or even better to draft updated or new text. We are maintaining this book using GitHub - see the book6 repository.

You can raise issues through the book's issue tracker. General discussions also take place here on GitHub.

To become an active contributor check the conditions and instructions. Then submit GitHub PRs. Your contributions will be reviewed by an editorial team.

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## Acknowledgments

Currently the editorial committee includes Nick Buraglio and Brian Carpenter.

Contributors via GitHub may be identified at Contributors.

Other direct and indirect contributors, either of text or very helpful comments (mainly via email), include:

- Tim Chown
- Gert Doering
- David Farmer
- John Klensin
- Gábor Lencse
- Jyrki Soini

(with apologies to those forgotten)

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## Why version 6

This section is mainly historical. Cutting a long story short, IPv6 was designed in the early 1990s because people knew that IPv4 was destined to run out of addresses. But why is the version number 6?

Some people ask why IPv4 went to version 6, leaping the next number. This was *not* related to the programmer's superstition where odd numbers should be beta releases. Maybe we should start by asking why IPv4 was version 4. Stated simply, that was because versions 0 through 3 were assigned in 1977 and 1978 during the evolution from ARPANET to TCP/IP. So version 4 was the next number available for use in the final design RFC 791. A rather more subtle explanation is given by the late Danny Cohen, one of the pioneers involved, at 38 minutes and 26 seconds into the video A Brief Prehistory of Voice over IP.

So why not IPv5? The answer is quite simple. The number 5 in the version field of the IP header was already assigned for what was called the Internet Stream Protocol, or ST. It's a bit confusing, but ST, ST-2 and ST-2+ [RFC1819] were designed and proposed as protocols for applications like voice and video that demand quality of service. As IP datagrams are delivered on a “best effort” basis, the ST proposals were more like ATM networks, using stateful relationships, queuing and much more. Each ST flow would hold connection state and dynamic controls to ensure quality of service. As we can see in RFC 1190, the ST header is completely different from IPv4, except for the very first field where is the version number 5:

```
 0                   1                   2                   3
   0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
  |  ST=5 | Ver=2 | Pri |T| Bits  |           TotalBytes          |
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
  |              HID              |         HeaderChecksum        |
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+

  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
  |                                                               |
  +-                          Timestamp                          -+
  |                                                               |
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

As ST would be incompatible with IP, the next version number was assigned to identify its packets. Ever since then, the number 5 was reserved for ST in the IP version field (layer 3) and protocol number (layer 4) field. The idea is that routers could differentiate packets or that IPv4 packets could carry encapsulated ST packets, where the number 5 would show up as an upper layer protocol. Since RFC 762 we can see number 5 assigned in "protocol numbers":

```
                 ASSIGNED INTERNET PROTOCOL NUMBERS
```

```
In the Internet Protocol (IP) [44] there is a field to identify the
the next level protocol.  This field is 8 bits in size.  This field
is called Protocol in the IP header.

Assigned Internet Protocol Numbers

   Decimal    Octal      Protocol Numbers                  References
   -------    -----      ----------------                  ----------
        0        0        Reserved
        1        1        raw internet datagrams                  [44]
        2        2        TCP-3                                   [36]
        3        3        Gateway-to-Gateway                      [49]
        4        4        Gateway Monitoring Message              [41]
        5        5        ST                                      [45]
        6        6        TCP-4                                   [46]
```

ST protocols never left an experimental phase, but for live experiments on the early Internet, its own version number was needed. While (as far as we know) there is no ST in use anywhere in the Internet today, its version number is still assigned, so it would not make sense for the **next generation IP** to carry that number, so it was "skipped". The number 6 would only appear a few years later in an "Assigned numbers" update [RFC1700], then named as "Simple Internet Protocol" (SIP). This acronym has been recycled for the Session Initiation Protocol.

```
Assigned Internet Version Numbers

Decimal   Keyword    Version                            References
-------   -------    -------                            ----------
   0                 Reserved                                [JBP]
  1-3                Unassigned                              [JBP]
   4        IP       Internet Protocol                 [RFC791,JBP]
   5        ST       ST Datagram Mode                 [RFC1190,JWF]
   6        SIP      Simple Internet Protocol                [RH6]
   7        TP/IX    TP/IX: The Next Internet                [RXU]
   8        PIP      The P Internet Protocol                 [PXF]
   9        TUBA     TUBA                                    [RXC]
10-14                Unassigned                              [JBP]
  15                 Reserved                                [JBP]
```

Note that IANA had assigned numbers 6 through 9 for the then "competitors" of what became IPv6. Number 7 was chosen for TP/IX [RFC1475], as its designer expected ST version 2 would use number 6, which did not happen. But unexpectedly, a different "IPv7" proposal was announced during the Internet Society's INET conference in Kobe, Japan, in June 1992, by IAB members. There was no consensus among IETF engineers at that time about the new protocol, and some IAB members proposed using ISO/OSI's CLNP - designating it as IPv7 without a formal IANA assignment. This caused some discomfort in the Internet community and became known in technical circles as the “Kobe incident”. Numbers 8 and 9 were used by proposals that came to be merged into IPv6's ultimate design. As the lowest number available after 4, and already used by the same author's SIP, number 6 was kept for the first official specification in RFC 1883. Therefore, do not expect IP versions 7 or 8 in the future, nor even 9 that also belongs to an April fool's day joke [RFC1606].

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# IPv6 Basic Technology

The main standard for IPv6 is STD 86, currently defined by RFC 8200. Many other relevant RFCs are cited in IPv6 node requirements (BCP 220), although this is always slightly behind the latest RFCs. Quotes from relevant RFCs are included in this chapter.

Some generic terms that should be used precisely are given in Section 2 of STD 86. In particular:

- Node: a device that implements IPv6
- Router: a node that forwards IPv6 packets not explicitly addressed to itself
- Host: any node that is not a router

To avoid confusion, note that a router may receive and send its own packets, and run IPv6 applications, just as a host does.

The rest of this chapter covers various basic aspects of IPv6. Some topics are very closely linked, especially address resolution and auto-configuration, so the reader is advised to read in sequence.



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## Packet Format

IPv6 packets are transmitted independently of each other even if they belong to the same application session, so they are sometimes referred to as *datagrams*. The basic datagram header is as follows. (The diagram is 32 bits wide and big-endian.)

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

`(Followed immediately by one or more "next headers" including the upper layer payload.)`

Some notes on these fixed fields:

- Version: is always 6
- Traffic class: six bits of differentiated services code point (DSCP) followed by two ECN bits. See Traffic class and flow label.
- Flow label: 20 bits. Should be a pseudo-random value unique to a given traffic flow. See Traffic class and flow label.
- Payload length: Length of the rest of the packet following this IPv6 header, counted in bytes.
- Next header: an integer defining the type of the following header.
- Hop limit: counts down at each routing hop. The packet is discarded when it hits zero.

- Addresses: 128 bits; see below.

The "next headers" are an important aspect of the design. After the fixed header just defined, there are one or more additional headers chained together. The best description is probably in the standard itself, so we only give a summary here. Every header format has a known length, and includes a "next header" field identifying the next header (d'oh). The last header in a packet is usually a TCP or UDP header containing the actual payload. The last header naturally has a "next header" field, but it contains the magic number 59, which means "no next header", and terminates the chain.

(The standard seems to allow a packet which has 59 as the initial "Next header" and therefore no extension headers and no payload. There is no reason to lose sleep over this.)

The earlier headers have functions including:

- Hop-by-hop options, for packet-level options that should be examined by every node on the path.
- Fragment header, when a packet has been fragmented (which happens only at the source, if the raw packet exceeds the known MTU of the transmission path, which is at least the IPv6 minimum MTU of 1280 bytes).
- Destination options, for packet-level options only useful at the destination node.
- Routing header, if non-standard routing is required.
- Encapsulating security payload, if IPsec is in use.

An interesting feature of IPv6 is that extension header types are numbered out of the same space as IP protocol numbers. It isn't a coincidence that the next header type for UDP is 17, the same as IPPROTO_UDP; it's by design. The latest set of valid extension header types is always available from IANA.

Extension headers and options are described in more detail in the section Extension headers and options. It's also worth noting that Wireshark knows all about IPv6 header formats.

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## Addresses

A 128 bit address is big enough that, assuming the adoption of wise allocation policies, IPv6 will never run out of addresses. However, the reason for choosing 128 rather than 64 was not just that: it was also to allow for some intrinsic structure to addresses, as described below. On the other hand, a *fundamental* property of IPv6 unicast routing is that it is based on all 128 bits, regardless of any internal structure. In other words, a unicast routing prefix is anywhere between 1 and 128 bits long. There is more about routing below.

The IPv6 addressing architecture is defined by RFC 4291, which has not been fundamentally revised since 2006, although there are a number of RFCs that partially update it.

### Notation

We'll first introduce the notation for writing down IPv6 addresses, and then use that notation to explain the main features.

The only feasible way to write down 128 bit addresses is in hexadecimal. There's no doubt this is less convenient than the decimal notation used for IPv4, but that's unavoidable. Despite what you may see in older RFCs, the recommendation by RFC5952 today is to use lower-case letters for hexadecimal. Thus a basic example of the notation is:

`2001:0db8:ef01:2345:6789:abcd:ef01:2345`

In that example, there are 8 groups of 4 hexadecimal digits, to specify all 128 bits in 16 bit chunks. In conventional hexadecimal notation, that would be `0x20010db8ef0123456789abcdef012345`. The colons (':') are there to help the reader.

In each chunk of 16 bits, leading zeros are dropped, so we write:

`2001:db8:ef01:45:6789:abcd:ef01:2345`

**not**:

`2001:0db8:ef01:0045:6789:abcd:ef01:2345`

There is often a run of zero bytes in an IPv6 address. One such run can be replaced by a double colon ('::') so that we write:

`2001:db8::6789:abcd:ef01:2345`

**not**:

`2001:db8:0:0:6789:abcd:ef01:2345`

The idea is that IPv6 addresses should be cut-and-pasted in almost all cases. If you ever do have to enter one manually, a great deal of care is needed. Note that not all implementations will strictly follow RFC9592, and older documentation often uses uppercase hexadecimal.

The choice of ':' as the separator is annoying in one particular aspect - where a colon has another meaning and works as a separator between address and port. This is quite common in (Web) URLs, that's why IPv6 addresses in URLs are in square brackets like this:

```
https://[2001:db8:4006:80b::200e]:443
```

### Easy addresses

The unspecified IPv6 address is simply zero, represented as `::`.

The loopback IPv6 address is 1, represented as `::1`. Note that IPv6 only has one loopback address whereas IPv4 has `127.0.0.0/8` reserved for loopback addressing.

### Routeable unicast addresses

This is the most familiar case. A unicast address is split into a routing prefix followed by an interface identifier (IID). The normal case is a 64 bit prefix that identifies a subnet, followed by a 64 bit IID. Thus:

```
 ----- prefix ----  IID
 |               |  |  |
 2001:db8:4006:80b::cafe
```

However, that's a bad example because 'cafe' might be guessable. For privacy reasons, a pseudo-random IID is strongly recommended:

```
 ----- prefix ---- ------- IID -------
 |               | |                  |
 2001:db8:4006:80b:a1b3:6d7a:3f65:dd13
```

This replaces a deprecated mechanism of forming the IID based on IEEE MAC addresses. Many legacy products still use that mechanism.

In this example, we used a 64 bit prefix based on the `2001:db8::/32` prefix, which is reserved for documentation use, but at present all prefixes allocated to the Regional Internet Registries start with a 2. Often such addresses are referred to as GUAs (globally reachable unique addresses). The background to prefix assignment policies by the registries is covered by BCP 157.

(Incidentally, `2001:db8::/32` is the full notation for a 32-bit prefix, but sometimes it is written informally as `2001:db8/32`, leaving the reader to insert the missing '::'.)

GUAs are often described as belonging administratively to one of two classes, PI or PA. Provider Independent (PI) address prefixes are those that have been assigned directly to an end-user site by one of the address registries. Provider Assigned (PA) address prefixes are those that have been assigned to an end-user site by one of its Internet Service Providers. PI prefixes are valid even if the site changes to a different service provider; PA prefixes vanish if the site drops the ISP concerned, and some ISPs change a site's PA prefix from time to time without warning. The benefit of PA addresses is that all of a given ISP's customer prefixes can be aggregated into a single BGP-4 announcement, thus greatly reducing growth in the Internet's global routing tables. By contrast, each new PI prefix adds to the global routing tables. For this reason, it is unacceptable for millions of sites to use PI prefixes.

Another type of routeable unicast address exists, known as Unique Local Addresses (ULA). The benefits of these are:

1. They are self-allocated by a particular network for its own internal use.
2. They are all under a /48 prefix that includes a locally assigned *pseudo-random* 40 bit part.
3. They **MUST NOT** be routed over the open Internet, so remain private.

An example:

```
----- prefix --- ------- IID -------
|              | |                 |
fd63:45eb:dc14:1:a1b3:6d7a:3f65:dd13
```

The 'fd' prefix is enough to identify a ULA. In this example,

- `fd63:45eb:dc14::/48` is the so-called ULA prefix.
- The locally generated pseudo-random part is `0x6345ebdc14`.
- `fd63:45eb:dc14:1::/64` is the subnet prefix.

Occasionally people use the prefix `fd00::/48` (zero instead of the pseudo-random bits) but this is not recommended. If two such networks are merged, things will break.

It is slightly confusing that both GUAs and ULAs are architecturally defined as having 'global scope', but ULAs are forbidden *by rule* to be routed globally.

In the preceding examples, the prefix boundary is shown after bit 63 (counting from zero), so the subnet prefix is `2001:db8:4006:80b/64` or `fd63:45eb:dc14:1/64`. This is the normal setting in IPv6: subnets have 64 bit prefixes and 64 bit IIDs. Automatic address configuration depends on this fixed boundary. Links that don't use automatic address configuration are not bound by the /64 rule, but a lot of software and configurations rely on it.

An important characteristic of routeable IPv6 unicast addresses is that they are assigned to interfaces (not whole nodes) and each interface may have several addresses at the same time. For example, a host in an enterprise network could in theory have all of the following simultaneously:

- A fixed GUA with a DNS entry for it to act as a web server
- A temporary GUA with a random IID for it to act as a client for remote web access [RFC8981]
- A fixed ULA used for transactions within the enterprise
- A second fixed GUA under a different prefix, with a DNS entry, for backup

You may see multiple temporary GUA addresses with random IID when you have some long-running TCP sessions, e.g. ssh, and your system created new addresses while the session(s) were up and running.

However, making the last two settings (GUA plus ULA, or two GUA prefixes) work smoothly can be challenging and is discussed in 6. Multi-prefix operation.

### Anycast addresses

Syntactically, anycast addresses are identical to unicast addresses, so any GUA or ULA may be treated as anycast. A special case is that on a link with prefix P, the address P::/128 (i.e. with the IID set to zero) is the subnet-router anycast address. Here is an example:

```
 ----- prefix ----
 |               |
 2001:db8:4006:80b::
```

### Link local addresses

These look like:

```
prefix ------- IID -------
 |    ||                 |
 fe80::a1b3:6d7a:3f65:dd13
```

The `fe80::/64` prefix is enough to identify a link local address.

Link local addresses (LLAs) do what it says on the can: they are *never* forwarded by a router (but they will be forwarded by a Layer 2 switch). They are essential during the startup phase for address allocation and they are essential for reaching a first-hop router.

LLAs are specific to a given interface, and a host with multiple Layer 2 interfaces will have a different address on each one. There's a special notation for this, e.g.:

```
prefix ------- IID ------- zone
 |    ||                 | |  |
 fe80::a1b3:6d7a:3f65:dd13%eth0

or

 fe80::a1b3:6d7a:3f65:dd13%7
```

The first of these would be seen on, say, a Linux host and the second on a Windows host; the character(s) after the '%' sign are the Layer 2 interface's locally defined identifier. Unfortunately, that makes two 'identifiers' in one address. Technically, the second one can be referred to as the 'Zone ID' according to RFC 4007.

### Embedded IPv4 addresses

It's possible to embed an IPv4 address in an IPv6 address in some circumstances. Here we'll just give the notation - the usage is discussed in Chapter 3.

An IPv4-mapped IPv6 address is a way to represent an IPv4 address as if it was an IPv6 address, e.g.

```
96 bit
prefix -- IPv4 ---
|    | |         |
::ffff:192.0.2.123
```

That is, the prefix at full length would be `0:0:0:0:0:ffff::/96`.

(Note that `::ffff::/96` would be ambiguous. Only one '::' is allowed.)

In particular, this form of address can be used to make the IPv6 socket interface handle an IPv4 address (see RFC 4038).

### Multicast addresses

IPv6 multicast address are all under the `ff00::/8` prefix, i.e. they start with 0xff. The next 8 bits have special meanings, so 112 bits are left to specify a particular multicast group. The special meanings are well explained in Section 2.7 of RFC 4291, so this is not repeated here. Some multicast addresses are predefined; for example `ff02::1` is the link-local "all nodes" address that every IPv6 node must listen to, and `ff02::2` is the link-local "all routers" address that every IPv6 router must listen to.

All the officially assigned multicast addresses may found at IANA.

### Literal addresses in web browsers

Browsers can recognize a literal IPv6 address instead of a host name, but the address must be enclosed in square brackets, e.g.:

```
https://[2001:db8:4006:80b:a1b3:6d7a:3f65:dd13]
```

Of course, literal addresses should only be used for diagnostic or testing purposes, and will normally be cut-and-pasted rather than being typed in by hand.

### Some addresses are special

Special-purpose IPv6 addresses and their registry are described in RFC 6890.

You may have noticed that many examples above use the prefix `2001:db8::/32`. That prefix is reserved for documentation and should never appear on the real Internet.

#### Obsolete address types

- A mapping of some OSI addresses into IPv6 addresses, and of arbitrary OSI addresses into IPv6 destination options, was made obsolete by RFC 4048.
- A format known as "Top Level Aggregator (TLA)" was made obsolete by RFC 3587.
- A format known as "site-local" addresses was made obsolete by RFC 3879.
- A format known as "IPv4-Compatible IPv6" addresses was made obsolete by RFC 4291.
- Address prefixes previously allocated for special use are mentioned in the unicast address registry.

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## Layer 2 functions

Every IPv6 packet has to be wrapped in a Layer 2 packet (or frame) for physical transmission on the "wire", which of course is more likely to be an optical fibre or a radio link in many cases. This statement needs two immediate qualifications:

1. For hardware media with very small frame sizes, an IPv6 packet may need to be split between several Layer 2 packets. This is *not* fragmementation as far as IPv6 is concerned, because it is handled as a Layer 2 function (sometimes called an "adaptation layer"), whether hardware or software.
2. For IPv6-in-IPv4 tunnels, it is IPv4 that serves as Layer 2; see 3. Tunnels.

There is a considerable difference between the mapping of IPv6 onto Ethernet-like links (including WiFi) and the mapping onto various forms of wireless mesh networks. An Ethernet-like link (including many point-to-point links) is one that send or receives one complete frame at a time with a raw size of at least 1500 bytes and a 48 bit IEEE MAC address at Layer 2. It must provide or emulate classical Ethernet multicasting. The IPv6 mapping then follows RFC 2464 from 1998, except for some updates to multicast address details in RFC 6085 and to the interface identifier in RFC 8064. IPv6 has its own Ethertype field (0x86dd), so that IPv6 and IPv4 packets can be distinguished at driver level. Documents similar to RFC 2464 exist for several other hardware media and are often known as "IPv6-over-foo" documents.

Interestingly, there is *no* IPv6-over-WiFi document; IPv6 relies on WiFi completely emulating Ethernet, including multicast. This has consequences for the scaleability of IPv6 over WiFi which are discussed in RFC 9119.

A consequence of the Ethernet legacy frame size of 1500 bytes is that the Internet-wide required minimum transmission unit size (MTU) for IPv6 is set at **1280 bytes** (reduced from 1500 to allow for possible encapsulation overhead). Therefore, *any* IPv6-over-foo mechanism **MUST** provide at least this MTU, and this applies to every adaptation layer.

IPv6 can be transmitted over PPP (Point-to-Point Protocol) links [RFC5072, RFC 5172]. Similarly, it can be transmitted using GRE (Generic Routing Encapsulation, RFC 7676).

IPv6 can also be transmitted over MPLS infrastructure [RFC4029]. Further details can be found in [3. Tunnels].

Mapping IPv6 to mesh networks, which have no native support for multicast and no simple model of a shared link like Ethernet, is rather different. RFC 9119 is relevant here too, and RFC 8376 provides general background on the challenges involved. Operational experience is limited today and best practices are not yet established.

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## Address resolution

When an IPv6 node "A" becomes aware of the IPv6 address of another node "B", and requires to send a packet to B, it must first determine whether B is directly connected to one of the same links as A. If not, it will need to send the packet to a router (see Routing). This is known as "on-link determination". The simplest case is when the address of B is a link local address as described in Addresses. In that case, it is necessarily on-link. In cases where B has a routeable address, A can determine whether it is on-link by consulting information received from Router Advertisement (RA) messages. This process is well described in RFC 4861, so is not repeated here.

When A has determined that B's address is on-link, and in the process determined which interface that link is connected to, it starts address resolution, also known as neighbor discovery (ND). It multicasts a Neighbor Solicitation message via that interface to the relevant link local multicast address, which is known as the solicited-node multicast address. This is defined in RFC 4291, but explained in RFC 4861. Neighbor Solicitation is a specific form of ICMPv6 message; ICMPv6 is defined in RFC 8200. Since this is a link local multicast, such messages never escape the local link.

All IPv6 nodes **MUST** monitor multicasts sent to the solicited-node multicast address. When B receives the Neighbor Solicitation from A, it replies with a Neighbor Advertisement ICMPv6 message, sent unicast to A's link local address. A will then decode that message to obtain B's Layer 2 address (typically an IEEE MAC address), and will record the information in its Neighbor Cache for future use. At that point, A has all the information it needs to send packets to B.

These are the essentials of address resolution; readers who want more detail should consult RFC 4861.

This mechanism works well on a small scale, and it was designed with full knowledge of the "ARP storms" experienced on large bridged Ethernets running IPv4. However, it can cause significant multicast overloads on large bridged WiFi networks, and is made worse by the need for duplicate address detection (DAD) described in the next section. Multicast is badly supported by large WiFi networks, as discussed in RFC 9119 and in Section 4.2.1 of RFC 5757. As an absolute minimum, the WiFi infrastructure switches in a large network need to support *MLD snooping* as explained in RFC 4541. "MLD" means "Multicast Listener Discovery" and is the mechanism used by IPv6 routers to identify which nodes require to receive packets sent to a given multicast address. Version 2 of MLD is specified by RFC 3810. Of course, all IPv6 nodes must join the `ff02::1` multicast group, as well as the relevant solicited-node multicast group, so MLD snooping does not avoid the scaling problem, but at least it suppresses multicasts on WiFi segments that do not need them.

Some optimizations have been defined, such as Gratuitous Neighbor Discovery

[RFC9131], but further standards work is needed in this area.

Operational issues with neighbor discovery and wireless multicast have been analyzed in the past (RFC 6583, RFC 6636, RFC 9119), but it remains the case that very large WiFi networks (such as the IETF builds several times a year for its plenary meetings) are subject to significant multicast overloads. In practice, this causes the WiFi switches to arbitrarily throttle the rate of multicasting, so neighbor discovery proceeds very slowly. It is **strongly** recommended to limit the size of wireless subnets as much as practicable.

A summary of the issues and complications of neighbor discovery on wireless networks in general (not just WiFi) can be found in this draft.

Considerable work has been done to alleviate these problems in the case of Low-Power Wireless Personal Area Networks (6LoWPANs, using the IEEE 802.15.4 standard). Relevant RFCs include RFC 6775, RFC 8505, RFC 8928 and RFC 8929. These improvements might be applied more generally in future.

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## Auto-configuration

One design goal for IPv6 was that it could be used "out of the box" in an isolated network (referred to in the early 1990s as a "dentist's office" network). Today, of course, this is a less likely scenario if taken literally, but all the same, isolated network segments do indeed arise. For this scenario, IPv6 has an elegant solution: when an IPv6 node first detects an active network interface, it will automatically configure a link local address on that interface, such as `fe80::a1b3:6d7a:3f65:dd13`. The interface identifier is a pseudo-random 64-bit number, normally fixed for a given interface. (In legacy implementations, it may be derived from the interface's IEEE MAC address, but this method is now deprecated.)

Link local addresses are usable only for operations on the same link. The most common case is for traffic between a host and its first-hop router. Another likely case is traffic between a host and local printer. There is nothing to stop them being used for any other type of traffic between local nodes, but they are useless *off* the given link and should definitely never appear in DNS.

Further details are given in RFC 4862. Also, we have skipped an important issue that will be discussed later: duplicate address detection.

When a node has configured a link local address, it then continues a process known as SLAAC (pronounced 'slack') -- StateLess Address AutoConfiguration -- in order to configure at least one routeable address [RFC4862]. Naturally, this can only happen on a link with an IPv6 router connected to it. If there is no such router, only link local IPv6 operation is possible. The first step, therefore, is router discovery. IPv6 routers supporting SLAAC **MUST** listen to the link local all-routers multicast address, defined as `ff02::2`. The new node will send a Router Solicitation ICMPv6 message to that address. Each SLAAC router will respond with a Router Advertisement (RA) ICMPv6 message to the new node at its link local address. (RA messages are also sent periodically to `ff02::1`, the link local all-nodes multicast address. This is important to refresh information in all nodes.)

RA messages are quite complex and are defined in detail in RFC 4861. They contain one Prefix Information Option (PIO) for each routeable IPv6 prefix that they can handle. A PIO naturally contains the prefix itself (theoretically of any length; in practice normally 64 bits), some lifetime information, and two flag bits known as L and A. L=1 signifies that the prefix is indeed supported on the link concerned -- this is needed for on-link determination as mentioned in the previous section. A=1 signifies that the prefix may indeed be used for stateless address auto-configuration. A PIO with A=L=0 signifies only that the router can act as the first hop router for the prefix concerned [RFC8028]. For auto-configuration, when a node receives a typical RA/PIO with A=L=1, it configures an address for itself, and also records the fact the the announced prefix is on-link. For example, if the prefix announced in the PIO is `2001:db8:4006:80b::/64`, and the pre-defined interface identifier for the interface concerned is `a1b3:6d7a:3f65:dd13`, the node will configure the interface's new address as `2001:db8:4006:80b:a1b3:6d7a:3f65:dd13`.

As mentioned in 2. Addresses, the interface identifier should be pseudo-random to enhance privacy, except in the case of public servers (thus a certain large company uses identifiers like `face:b00c:0:25de`). For practical reasons, stable identifiers are often preferred [RFC8064] but privacy is better protected by temporary identifiers [RFC8981].

An important step in configuring either a link local address or a routeable address is *Duplicate Address Detection* (DAD). Before a new address is safe to use, the node first sends out a Neighbor Solicitation for this address, as described in the previous section. If it receives a Neighbor Advertisement in reply, there's a duplicate, and the new address must be abandoned. The Neighbor Solicitations sent for DAD add to the multicast scaling issues mentioned above.

It's worth underlining a couple of IPv6 features here:

1. Several subnet prefixes can be active on the same physical link. Therefore, a host may receive several different PIO messages and configure several routeable addresses per interface. Also, for example when using temporary addresses [RFC8981], a host may have several simultaneous addresses *under the same prefix*. This is not an error; it's normal IPv6 behavior.

2. Both GUA and ULA addresses (see 2. Addresses) are routeable, even though the ULA is only routeable within an administrative boundary. Having both a GUA and a ULA simultaneously is also normal IPv6 behavior.

All IPv6 nodes **MUST** support SLAAC as described above, in case they find themselves on a network where it is the only method of acquiring addresses. However, some network operators prefer to manage addressing using DHCPv6, as discussed in the next section. There is a global flag for this in the RA message format known as the M bit (see RFC 4861 for details). If M=1, DHCPv6 is in use for address assignment. However, PIOs are still needed to allow on-link determination, and link-local addresses are still needed.

*More details*: This section and the previous one have summarized a complex topic. Apart from the basic specifications RFC 4861 and RFC 4862, many other RFCs exist on this topic, including for example:

- Enhanced Duplicate Address Detection, RFC 7527
- IPv6 Subnet Model: The Relationship between Links and Subnet Prefixes, RFC 5942

The numerous options allowed in RA messages, and the other ICMPv6 messages used for address resolution and SLAAC, are documented in IANA's IPv6 Neighbor Discovery Option Formats registry.

A simple network can operate with SLAAC as the only way to configure host IPv6 connections. DNS parameters can be configured using RA options (Recursive DNS Server Option and DNS Search List Option) [RFC8106].

However, as noted in the previous section, the dependency of neighbor discovery and SLAAC on link-layer multicast does not scale well, particularly on wireless networks. Also, the ability of SLAAC to assign multiple addresses per host, especially dynamic temporary addresses [RFC8981], can create scaling problems for routers.

When preferred by an operator, managed configuration, especially for large networks, can be achieved using DHCPv6, as described in the next section.

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## Managed configuration

Host addresses and other IPv6 parameters can be configured using the Dynamic Host Configuration Protocol for IPv6 (DHCPv6). The players in DHCPv6 are the client (the host to be configured), the server (providing configuration data), and optionally DHCPv6 relay agents connecting a host indirectly to the main server.

People sometimes wonder why both this and SLAAC exist. The reason is partly historical (DHCP for IPv4 was new and not widely deployed when IPv6 was designed). In addition, the concept of SLAAC (previous section) was intended to avoid any need for a separate configuration protocol in simple networks. The result is that even in a complicated network, Neighbor Discovery and Router Advertisement messages remain necessary, even if DHCPv6 is deployed.

The Android operating system does not support DHCPv6. This means that a network that requires to support Android hosts must provide SLAAC as well as DHCPv6. In an enterprise environment, that might lead an operator to run a separate (WiFi) network that supports SLAAC, isolated from other corporate networks managed using DHCPv6. Alternatively, they may simply not provide IPv6 support for Android users. Cellular mobile service providers do support SLAAC over a point-to-point 3GPP link from the network to the mobile device. Public networks as in coffee-shops and hotels, if they support IPv6 at all, do so via SLAAC. So the domain of applicability for DHCPv6 is mainly enterprise networks. They tend to prefer managed addresses because of security compliance requirements.

DHCPv6 is defined by RFC 8415. It is conceptually similar to DHCP for IPv4, but different in detail. When it is in use, each host must contain a DHCPv6 client and either a DHCPv6 server or a DHCPv6 relay must be available on the subnet. DHCPv6 can provide assigned IPv6 addresses and other parameters, and new options can be defined. (All registered DHCP parameters can be found on the IANA site.) DHCPv6 messages are transmitted over UDP/IPv6 using ports 546 and 547.

A notable feature of DHCPv6 is that it can be used *between routers* to assign prefixes dynamically. For example, if a new segment is switched on and its router doesn't have an IPv6 prefix, an infrastructure router "above" it in the topology can assign it one (e.g. a /64 prefix), using the `OPTION_IA_PD` and `OPTION_IAPREFIX` DHCPv6 options (previously defined by RFC3633, but now covered by Section 6.3 of RFC8415. This process is known as DHCPv6-PD (for "prefix delegation").

However, the 3GPP specifications for IPv6 usage over cellular mobile systems make both DHCPv6 and DHCPv6-PD optional [RFC7066], and experience shows that many common 3GPP implementations do not support them. Thus mobile devices can only rely on RA-based address and prefix mechanisms.

DHCPv6 message types include:

- SOLICIT (discover DHCPv6 servers)
- ADVERTISE (response to SOLICIT)
- REQUEST (client request for configuration data)
- REPLY (server sends configuration data)
- RELEASE (client releases resources)
- RECONFIGURE (server changes configuration data)

DHCPv6 options include:

- Client Identifier Option
- Server Identifier Option
- Identity Association for Non-temporary Addresses Option
- Identity Association for Temporary Addresses Option
- IA Address Option
- Authentication Option
- Server Unicast Option
- Status Code Option
- DNS Recursive Name Server Option
- Domain Search List Option
- Identity Association for Prefix Delegation Option
- IA Prefix Option

Readers who want more details should consult RFC 8415 directly. Be warned, this is a very complex RFC of about 150 pages. Also, the full lists of defined messages and options may be found at IANA, with citations of the relevant RFCs.

A missing DHCPv6 option is information about default routers; this is only available via RAs, as described in the previous sections. No consensus has been reached in the IETF to also supply this information via DHCPv6. In fact, DHCPv6 is designed to supplement router advertisement information and is not intended to work on a subnet that has no router. Therefore DHCPv6 assigned addresses effectively have prefix length /128, and clients need to combine that information with RA information to communicate with other on-link hosts.

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## DNS

We assume that the reader has a good general understanding of the Domain Name System (DNS). Many aspects of the DNS are unaffected by IPv6, because it was designed on very general principles.

A specific Resource Record type is defined to embed IPv6 addresses: the AAAA Record [RFC3596]. This simply provides a 128 bit IPv6 address in the same way that an A record provides an IPv4 address. (AAAA is normally pronounced "Quad-A".)

Similarly, reverse lookup is enabled by the `IP6.ARPA` domain. This is done using 4-byte nibbles respresented as hexadecimal characters, so the address `2001:db8:4006:80b:a1b3:6d7a:3f65:dd13` will appear as `3.1.d.d.5.6.f.3.a.7.d.6.3.b.1.a.b.0.8.0.6.0.0.4.8.b.d.0.1.0.0.2.IP6.ARPA`. Clearly, these entries are for computers, not for humans.

A corollary of defining the AAAA record is that DNS lookups that *indirectly* cause an A record lookup must also cause a AAAA lookup. This concerns NS, SRV and MX lookups.

This change also affects API calls that involve the DNS. The old `gethostbyname()` and `gethostbyaddr()` calls are **OBSOLETE** and should no longer be used. They are replaced by `getaddrinfo()` and `getnameinfo()`, which handle IPv6 as well as IPv4. In particular, `getaddrinfo()` provides the programmer with a list of both IPv6 and IPv4 addresses, and it is the programmer's job to decide which one to use. The order in which addresses are presented to the programmer is determined by a local configuration table on the host, in a way described by RFC 6724. Unfortunately the standard DHCPv6 mechanism for remote configuration of this table [RFC7078] is not widely used. Operators need to be aware of this complexity when attempting to cause users to favor IPv6 over IPv4 (or the converse).

Apart from this, in an ideal world DNS for IPv6 should not cause extra operational issues. However, in practice, there are some matters of concern:

- As noted in 2. Managed configuration, the DNS server for a subnet must be announced by a Router Advertisement even if DHCPv6 is in use.
- DNS IPv6 Transport Operational Guidelines are documented in BCP 91.
- Considerations for Reverse DNS in IPv6 for Internet Service Providers are documented in RFC 8501.
- It is not unknown for some sites to register IPv4-mapped IPv6 addresses, e.g. `::ffff:198.51.100.99`, with AAAA records. While this seems to work in most cases, it is inappropriate if the host in question has a valid IPv6 address, and pointless otherwise.
- Certain IPv6 address types should **never** be visible in global DNS: ULAs (starting with `fdxx:` or even `fcxx:`) or link-local (starting with `fe80::`).

Beware that automated mechanisms like Active Directory might add ULAs to global DNS by default. Of course, it is OK to include ULAs in *local* DNS if a split DNS configuration is used.

*Note:* Some AAAA records for ULA addresses do exist in the DNS, and are not a security risk, but they may cause unexpected failures from a user's standpoint.

Some statistics on AAAA records and reachability may be found at Dan Wing's site.

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## Routing

This section is a short introduction to a complex topic. IPv6 packets are routed individually and statelessly, like any datagram protocol. Consecutive packets may follow different routes, may be lost on the way, may arrive out of order, and transit times are variable. In practice, operators attempt to minimize these effects but upper layer protocols cannot rely on this. In some cases, quality of service mechanisms such as differentiated services [2. Traffic class and flow label] may help, but packet delivery remains statistical.

IPv6 routing in general operates by longest-match, i.e. each router forwards each packet to another router known to handle an address prefix that is the longest one (up to 128 bits) that matches the packet's destination address [BCP198]. Routers use various routing protocols among themselves to distribute information about which prefixes they handle. Common routing protocols are:

*For site and enterprise networks:*

- OSPFv3 [RFC5340] is most common.
- IS-IS [RFC5308, RFC 7775].
- RIPng [RFC2080, RFC 2081] is defined but seems to be little used.

*Small enterprise and home networks*

- The Babel Routing Protocol [RFC8966].

*Inside carrier (ISP) networks or very large enterprise networks:*

- IBGP (internal use of BGP-4) optimized by route reflection [RFC4456].
- IS-IS [RFC5308, RFC 7775]
- OSPFv3 [RFC5340].

*Between carrier (ISP) networks (inter-domain routing):*

- Border Gateway Protocol 4 (BGP-4) in its multiprotocol form [RFC2545, RFC 4271, RFC 4760]. Autonomous System numbers work the same way for IPv6 and IPv4.

*For emerging mesh networks:*

- RPL (IPv6 Routing Protocol for Low-Power and Lossy Networks) [RFC6550, RFC 9008, RFC 9010].
- The Babel Routing Protocol [RFC8966].

IPv6 routers can be placed in various categories, each of which requires different features to be active. These categories may overlap:

- Customer Edge (CE) routers (enterprise): These are routers that connect an enterprise network to one or more ISPs [RFC7084, RFC 8585, RFC 9096].

- Enterprise routers: Internal routers within a large enterprise network.
- Subnet routers: Internal routers that support one or more links connecting end hosts (typically Ethernet or WiFi). Such a router will be the last-hop router for incoming traffic and the first-hop router for outgoing traffic. It must also provide Router Advertisement services for the end hosts, and either SLAAC or DHCPv6 or both [See 2. Address resolution etc.].
- Customer Edge (CE) routers (domestic): These are cheap routers connecting home or small office networks to an ISP. They typically act as subnet routers too, but are unlikely to provide the full set of enterprise CE router services. They need little or no configuration for basic operation.
- Provider Edge routers. These are routers within ISP networks that directly connect to CE routers.
- Transit routers within ISPs.
- Inter-domain routers connecting ISPs to peer ISPs and/or Internet Exchange Points.

A general comment is that IPv6 prefixes being longer than IPv4 prefixes (up to 64 bits instead of, say, 24 bits), one might expect routing tables to require much more memory space. While this is true, IPv6 was designed for classless route aggregation from the beginning, which generally permits there to be fewer IPv6 prefixes, mitigating the table size issue. (Nevertheless, the BGP-4 table for IPv6 continues to grow, as discussed in this CCR paper.) Interested readers can find exhaustive data on BGP-4 table sizes at Geoff Huston's site. For a deep dive on BGP-4 itself, with much focus on IPv6, see the e-book by Iljitsch van Beijnum: Internet Routing with BGP (2022).

As explained in 3. Dual stack scenarios, IPv6 routing generally works independently of IPv4 routing, which was indeed a fundamental design choice. However, if necessary, encapsulated IPv4 traffic can be carried over an IPv6-only path. To enable this, multiprotocol BGP-4 has provisions to advertise IPv4 reachability over an IPv6-only path [RFC8950].

Finally, IPv6 allows routing headers, interpreted by intermediate nodes along a packet's path. These are briefly explained in Extension headers and options.

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## Transport protocols

Applications can readily be updated to work in dual stack mode, because the transport layer is affected very little by IPv6. Therefore, IPv6 supports all the common transport protocols:

- UDP. There is no separate specification for UDP over IPv6; RFC 768 still applies! However, the UDP checksum is mandatory for IPv6 (since the IPv6 header itself has no checksum), except as allowed by RFC 6936.
- UDP-lite [RFC3828] also supports IPv6. There is interesting background on UDP and UDP-lite in RFC 8304.
- TCP. IPv6 support is fully integrated in the latest TCP standard [STD7].
- RTP fully supports IPv6 [RFC3550].
- QUIC fully supports IPv6 [RFC9000].
- SCTP fully supports IPv6 [RFC4960].
- MPTCP fully supports IPv6 [RFC8684].

Also, the secure transports TLS, DTLS and SSL all work normally with IPv6. So does SIP (Session Initiation Protocol [RFC3261]), which does not require NAT traversal support (STUN) in the case of IPv6.

All quality of service and congestion control considerations should be approximately the same for IPv4 and IPv6. This is why RFC 2474 defined differentiated services identically for both versions of IP, and the same applies to ECN (Explicit Congestion Notification [RFC3168]).

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### Extension headers and options

As explained in 2. Packet Format, every IPv6 packet may include one or more extension headers before the transport layer payload (UDP, TCP, etc.). For the precise rules of how extension headers and options are encoded, see STD 86. The current set of standardized extension headers is listed at IANA. Here are some notes on the most common ones:

- Hop-by-Hop (HBH) options, for packet-level options that should be examined by every node on the path. The defined options are listed, with references, at IANA. Option 0x05 "Router Alert" is perhaps the most interesting; it is intended to warn every router on the path that the packet may need special handling. Unfortunately, experience shows that this extension header can be problematic, and that many routers do not in fact process it. Indeed, RFC 8200 states that "it is now expected that nodes along a packet's delivery path only examine and process the Hop-by-Hop Options header if explicitly configured to do so."

  Router Alert types have their own registry at IANA.

- Fragment header, when a packet has been fragmented (which happens only at the source, if the raw packet exceeds the known MTU of the transmission path, which is at least the IPv6 minimum MTU of 1280 bytes). IPv6 fragmentation is significantly different from IPv4 fragmentation, which may occur anywhere along the path. The technical details are described in STD 86. Of course, fragmentation interacts with PMTUD (Path Maximum Transmission Unit Determination) so the lazy solution is to never exceed the 1280 byte limit. For PMTUD, see STD 87, RFC 8899, and (for horror stories) RFC 7690. Also see "IP Fragmentation Considered Fragile" for operational recommendations [BCP230].

- Destination options, for packet-level options only useful at the destination node. These are also listed at IANA.

- Routing header, if non-standard routing is required. There are various routing header types. An important current one is the Segment Routing Header (type 4, RFC 8754). A router that acts as an intermediate destination and therefore processes routing headers is known as an 'intermediate node' in STD 86.

- Encapsulating security payload, if IPsec is in use. This is the defined mechanism for IPv6 security at layer 3. This is probably the most widely used IPv6 extension header.

Both hop-by-hop and destination options include flag bits in the option type for nodes that may not understand the option, telling the node whether to simply ignore the unknown option, or whether to drop the whole packet and possibly send an ICMP response.

There is a recognized operational problem with IPv6 extension headers: while they work well within a limited domain with consistent administration and security rules, they are not reliably transmitted across the open Internet, presumably due to firewall and router filtering rules. RFC 7872 reported on the situation in 2015, and there is ongoing work to update similar measurements. The operational implications are described in RFC 9098 and filtering recommendations are in RFC 9288.

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## Traffic class and flow label

The Traffic Class in every IPv6 packet is a byte also known as the Differentiated Services field. It is treated in every respect exactly like the same field in every IPv4 packet (originally named the TOS octet in RFC 791). It contains six bits of differentiated services code point followed by two ECN (Explicit Congestion Notification) bits. RFC 8100 gives a good overview of current differentiated service interconnection practices for ISPs. RFC 5127, RFC 4594, RFC 5865, RFC 8622 and RFC 8837 also describe current practice.

ECN is intended for use by transport protocols to support congestion control.

The Flow Label is a 20 bit field in every IPv6 packet, although as its name indicates, it is only relevant to sustained traffic flows. The sender of a packet should fill it with a pseudo-random non-zero value unique to a given traffic flow, such as a given TCP connection. It can then be used downstream in support of load balancing. By definition, the 20 bits have no semantics, although some deployments are known to have broken this guideline, which would interfere with load balancing. See IPv6 Flow Label Specification, Using the IPv6 Flow Label for Equal Cost Multipath Routing and Link Aggregation in Tunnels and Using the IPv6 Flow Label for Load Balancing in Server Farms.

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## Source and Destination address selection

As described in [2. Addresses], a host will have more than one IPv6 address per interface. Because of the presence of multiple addresses in the same address family, there must be a process for selecting the source and destination address pair for general use. This address selection is described in RFC 6724 and further, more complex topics and scenarios can be found in the [6. Multi-prefix operation] section. Address selection is complicated by the flexibility that is afforded by the multi-addressing nature of IPv6, and the ability for a given host and applications ability to further define behavior. Server applications are the best example of an application prescriptively defining a specific address with which to source traffic. In the case that an application specifies a specific address, then the process generally stops there for that particular traffic, the host is not required to further evaluate and the traffic in question is sourced from the address specified by the given application.

In cases where there is no specificity by a given application, the operating system will evaluate the available addresses of both IPv4 and IPv6 address families and sort them according to a set of rules, returning the top address from its evaluated list based on the pair of source address and destination addresses, often shortened to "SA/DA" for documentation and brevity. The sorting is done in order, and ceases once a match is made. Address pairs for given traffic is evaluated in the following order:

1. Prefer same address contacted
2. Prefer appropriate address scope
3. Avoid deprecated addresses
4. Prefer home addresses
5. Prefer outgoing interface
6. Prefer matching address label
7. Prefer privacy addresses
8. Use longest matching prefix

The default sorting behavior is generally defined by the following table:

```
Prefix                          Prec   Label
::1/128                         50     0
::/0                            40     1
::ffff:0.0.0.0/96               35     4
2002::/16                       30     2
2001::/32                        5     5
fc00::/7                         3    13
::/96                            1     3
fec0::/16                        1    11
3ffe::/16                        1    12
```

### Destination address selection

Destination address selection is somewhat complex, and it should be understood that it is configurable and may be somewhat inconsistent based on the implementation of a given IPv6 network stack and the age of the operating system. At the time of this writing there are still operating systems that employ aspects of or full implementations of RFC 3484, which was obsoleted by RFC 6724 in 2012. To fully understand address selection, one can reference the file */etc/gai.conf* in a modern Linux system as it has the most succinct example of the rules governing the process.

### Changing address selection policy

In the vast majority of use cases, the default policy table is unchanged and consistent. However, on platforms such as Linux and Microsoft Windows, it is possible to adjust this table to create desired behavior, up to and including creating address pairings, adjusted preferences, and unique traffic SA/DA characteristics.

A site using DHCPv6 options 84 and 85 can change the default settings for address selection via RFC 7078, but unfortunately this is not widely implemented. In principle this can also be achieved by system commands in each host (e.g. *netsh interface ipv6 add prefixpolicy* in Windows and *ip addrlabel add prefix* in Linux) but this is rarely done. The result is that hosts generally apply the default policy for their operating system release, even when a different policy would work better.

### ULA considerations

In default situations where both IPv4 and ULA are present, IPv4 will be the preferred protocol. This is often counter to general understanding of how IPv6 behavior works in a dual stacked environment and can be observed in the aforementioned *gai.conf* file with the following line:

```
Prefix                              Prec   Label
...
::ffff:0.0.0.0/96                   35     4
```

This is the IPv6 conversion of IPv4 address space. Because this block of addresses has a higher preference value than ULA addressing, it will be preferred by default by the operating system and application due to its preference value.

draft-ietf-v6ops-ula described in detail many of the considerations for use of ULA, specifically in a dual stacked environment. It should be noted that in an IPv6-only environment, the address selection process is generally problem free, leveraging the above process.

### Labels

Not to be confused with flow labels, address labels are a powerful and often overlooked tool in the selection process. Address labels allow for prefix or address pairings thus forcing traffic pairs to act in consistent or desirable ways that may differ from default for technical, security, or policy reasons. Taking a basic Linux system and creating an address pair with matching labels will cause the system to act on the labels and generate traffic between the SA/DA pairs as determined by the operator.

Using a vanilla linux system the following changes can be made using the ip command `{ip addrlabel add prefix <PREFIX> label <LABEL>}` easily creating a working SA/DA pair.

For example:

```
sudo ip addrlabel add prefix fd68:1e02:dc1a:9:ba27:ebff:fe84:781c/128 label 97
sudo ip addrlabel add prefix 2001:db8:4009:81c::200e/128 label 97
```

Yields:

```
user@v6host:~$ sudo ip addrlabel list
prefix 2001:db8:4009:81c::200e/128 label 97
prefix fd68:1e02:dc1a:9:ba27:ebff:fe84:781c/128 label 97
prefix ::1/128 label 0
prefix ::/96 label 3
prefix ::ffff:0.0.0.0/96 label 4
prefix 2001::/32 label 6
prefix 2001:10::/28 label 7
prefix 3ffe::/16 label 12
prefix 2002::/16 label 2
prefix fec0::/10 label 11
prefix fc00::/7 label 5
prefix ::/0 label 1
```

### Source address selection

In practice, source address selection is difficult to configure outside of link local, GUA, and ULA default preferences, and varies by host and application implementations. It is possible to create address pairings using the IPv6 address label mechanisms, however.

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## Coexistence with Legacy IPv4

The notion of a utopian IPv6-only world is a noble goal. However, as with any tectonic change, it happens slowly, and differing elements exist simultaneously. As such, expectations should be set that in many cases coexistence with legacy IPv4 is the norm, and while it should be considered a transitional state, it may exist for extended or indefinite periods of time. Since 2012, the IETF has therefore required all new or updated Internet Protocol implementations to support IPv6 [BCP177].

Reasoning for coexistence will vary and is typically only locally relevant to a given environment. It may be due to the requirement for legacy hardware with no IPv6 support that requires capital expenditure beyond the budget of an organization, such as a specialized piece of operational technology, or it may be due to lagging compliance regulations that have not tracked current technology standards. It may simply be the conclusion from a cost/benefit analysis. Regardless, the reasonings are less important than the details necessary to support a dual-stacked environment.

Before describing the specific techniques for IPv6/IPv4 coexistence -- dual stacks, tunnels, and translators -- it is useful to answer a basic question that newcomers sometimes have: *Why isn't IPv6 backwards compatible with IPv4?* The answer is quite simple: this is a mathematical impossibility. IPv4 contains no provision for any address length other than 32 bits. Stretching the address length by only one bit, let alone by 32 or more bits, would completely break all existing IPv4 implementations. Therefore, **backwards compatibility at the IP packet level was impossible, so was not a design goal.**

Given that fundamental incompatibility, the designers of IPv6 decided to meet a number of requirements that IPv4 could never satisfy. As a result, the IP packet header was redesigned in the light of experience. This has no impact except on the low-level code that actually processes a raw packet.

Another basic decision was to develop a co-existence model from the start, since it was clear that a quick transition to a new version of IP was unthinkable. In short, a *dual stack* originally meant that hosts and routers were able to handle both IPv4 and IPv6 at the same time. Recently, this simple view of dual stacks has been complicated by the introduction of "IPv4 as a service", as discussed below. *Tunnels* means that IPv6 hosts can talk to each other over an IPv4 network, by encapsulating their packets, and vice versa. *Translation* means that, in a limited way, an IPv6 host can talk to an IPv4 host via a translation mechanism. The following sections discuss those three methods of co-existence in more detail. Later sections list some mechanisms that are no longer recommended, and the main differences between IPv4 and IPv6.

We first give two quite general references for this complex topic:

1. Although a few years old, RFC 6180 gives useful guidelines for deploying various IPv6 transition mechanisms.

2. A common tactic today for operators wishing to simplify their infrastructure is to provide IPv4 as a *service* over the top of an underlying IPv6 layer. Various ways to achieve this are described in RFC 9313.

As networks migrate away from IPv4 and into an IPv6-only environment, they will undoubtedly discover unexpected hurdles consisting of half-completed protocol stacks, lack of capabilities, and unexposed configuration knobs. These will almost certainly be discovered in the periphery of the network. Elements such as power controllers, optical multiplexing platforms, mechanical control systems, and other speciality hardware tend to possess a very long mean time to replacement, and a slow to modernize firmware offering. Operational technologies and SCADA systems are also very slow to update and may also live in the network for many years, if not decades. In domestic networks, old network appliances may persist for many years. With that acknowledgment, it should be expected that there will exist one or more enclaves that differ in their network addressing schema.

To summarize the coexistence scenarios, we have:

- IPv4 only enclaves:

  Areas where IPv6 simply is not possible or desirable for compliance, technological, policy, budgetary, or other strategic reasons may operate as an IPv4-only or Legacy IP enclave. This may be the result of migration happening around the enclave, or it may be an intentionally created segment for housing legacy services, devices, or application stacks. It is important to accept that there may be long-lived enclaves where legacy IPv4 is a hard requirement. This fact should inform policy, however, but in an ideal situation will not necessarily define it.

- IPv4-IPv6 dual stack "on the wire"
  - Supporting "ships in the night" protocols
    - Consistent policy
    - Monitoring and measurement
    - Multi-topology within the Internet
  - Widely deployed but requires dual management

- IPv6 only infrastructure networks
  - Native access to IPV6 resources
  - Requiring access to IPv4-only resources via IPv4 as a service
  - Reduced management complexity
  - Still presents a dual stack to the upper layer API

In the long term, it is conceivable that all useful resources on the Internet will be accessible by IPv6, in which case IPv4 as a service could be discontinued, leaving IPv4-only enclaves to fend for themselves. However, there is no time scale for when this might occur.

This chapter is about IPv6/IPv4 coexistence, because IPv6-only enclaves can only be part of the whole Internet if they support at least one coexistence mechanism. Theoretically, such an enclave could be connected to the Internet by an application layer gateway, but we do not describe this further. An IPv6 network where there is no coexistence mechanism whatsoever is out of scope.



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## Dual stack scenarios

We must distinguish the original model of dual stack deployment from the new concept of presenting a dual stack to the upper layer protocols while providing IPv4 as a *service* over an IPv6 infrastructure.

### Original dual stack model

Dual-Stack was originally described (along with basic tunneling) in RFC 4213. In 2020, it appeared to be the most widely deployed IPv6 solution (about 50%, see the statistics reported in ETSI-IP6-WhitePaper).

In a classical dual stack deployment, packets on the link are either native IPv6 or native IPv4. All routers support IPv6 and IPv4 simultaneously, with separate routing tables: this is known as "ships in the night".

```
Ships that pass in the night, and speak [to] each other in passing,
only a signal shown, and a distant voice in the darkness
  --  Henry Wadsworth Longfellow, 1863
```

Today, the core of the Internet - all the major international transit providers and all major Internet Exchange Points - support dual stack routing. So do many local ISPs.

Also, all hosts in a dual stack network should support IPv6 and IPv4 simultaneously, with IPv6 preferred. Such a deployment can tolerate the presence of legacy IPv4-only hosts and applications, and can reach external IPv4-only services, with no special arrangements. An essential part of this model is that applications using the network see a version of the socket API that intrinsically supports both IPv4 and IPv6. Thus, [RFC3542] introduced a dual-stack API, including the important `getaddrinfo()` ("get address information") function, which has since been adopted by both POSIX and Windows operating systems.

RFC 8305 explains the "Happy Eyeballs" technique for applications seeking to optimize dual-stack performance.

With Dual-Stack, IPv6 can be introduced together with other network upgrades and many parts of network management and Information Technology (IT) systems can still work in IPv4. As a matter of fact, IPv4 reachability can be provided for a long time and most Internet Service Providers (ISPs) are leveraging Carrier-Grade NAT (CGN, RFC 6888) to extend the life of IPv4. However, large ISPs have discovered the scaling limits and operational costs of CGN.

A gap in this classical dual stack approach is that it does not allow an IPv6-only client to communicate with an IPv4-only server. IPv6-only devices do exist, e.g. Thread devices, and more are to be expected in future. This situation requires a translation mechanism, such as NAT64 + DNS64 (see [Translation and IPv4 as a service]), which will allow IPv6 only devices, on a dual stack network, to access IPv4 hosts. Typically, dual stack clients on the same network will also use NAT64 (instead of RFC 1918 addresses and NAT44) to access IPv4 only hosts, but they are using NAT either way. See this helpful blog article.

A specific issue is that SIP (Session Initiation Protocol for IP telephony) will not work without provision for IPv6/IPv4 coexistence [RFC6157].

Although Dual-Stack provides advantages in the initial phase of deployment, it has some disadvantages in the long run, like the duplication of network resources and states. It also requires more IPv4 addresses, thus increasing both Capital Expenses (CAPEX) and Operating Expenses (OPEX). To be clear, a network (whether a home network or an office network) can today work very smoothly with every host having both an IPv4 address and an IPv6 address, and using whichever works best for a particular application.

### IPv6-Mostly Networks

With the standardization of RFC 8925 ("IPv6-Only Preferred Option for DHCPv4") there now exists a supportable, standard mechanism for gracefully migrating off of legacy IP while preserving access for systems and network stacks that either do not support IPv6 or only support classical dual-stack. (Such systems do not automatically support the 464XLAT technique described below, or are otherwise unable to operate without legacy IPv4 for application or internal operating system requirements). What IPv6-mostly provides is a low risk mode of converting legacy IPv4 or existing dual stack networks to IPv6-only in a very measured manner. By leveraging the IPv6-only-preferred option for legacy IPv4 (DHCP option 108) an operator is able to signal via a network protocol that is likely already in use (DHCP for IPv4) that the network is able to support IPv6-only mechanisms if the host is capable of utilizing them. Conversely, if a device does not implement and understand DHCP option 108, they happily move on with a dual-stack IPv4/IPv6 experience, again, with no user intervention.

This methodology holds several advantages, notably the simplification of network segments and protocol deployment. This deployment model allows for the host stacks to "operate at their highest level of evolution" insomuch that they are able to, and based on the signal from the DHCP server, disable their legacy IP stack for the duration of time communicated in the DHCP transaction. This "timed disablement" methodology also allows for measured testing, should there be a need to test disabling legacy IPv4 for a short period of time, and guarantee that it will be re-enabled. Additionally, this allows for an operator to slowly migrate off of legacy IPv4 at the pace of the evolution of the operating systems within their operational domain and allows for the coexistence of a wide variety of hosts on a given network segment: IPv4-only hosts, IPv6-only hosts, and dual-stacked hosts. As operating systems add support for DHCP option 108, reliance on legacy IPv4 naturally becomes smaller and smaller until it can eventually be disabled or is diminished enough that it can be removed.

One operational glitch has been observed in this scenario. If a host that supports

DHCP option 108 has any kind of misconfiguration that prevents IPv6 from working properly, it can enter a state where it disables IPv4 but has no IPv6 connectivity either. For example, if a host's intrinsic firewall is configured to block incoming ICMPv6 and IPv6 packets, yet the host respects option 108, it will fail to connect to either version of IP when it encounters an IPv6-mostly network. This misconfiguration has been observed in laptop computers with a mandatory corporate security configuration, when they roam to an IPv6-mostly network outside the corporate network.

Apart from this problem, controlled and deliberate migration via IPv6-mostly allows the operating system to decide how much or how little it can support without needing input from the user, making the network fit the capabilities of the host, thus lowering the risk of incompatibility (and lowering the rate of problem reports). Like most existing IPv6-only networks, IPv6-mostly will nevertheless require packet and DNS translation services (discussed later) as well as knowledge of the IPv6 prefix used for translation (ditto). With these features suppported, hosts on an IPv6-mostly network will have a full suite of capabilities.

There is a great deployment report on IPv6-mostly at a large conference.

### The need for IPv4 as a service

Globally unique IPv4 addresses are now scarce and have significant commercial value. Indeed, even if private IPv4 addresses are used with CGN, global IPv4 addresses for the CGN systems must be paid for by somebody.

For this reason, when IPv6 usage exceeds a certain threshold, it may be advantageous to start a transition to the next phase and move to a more advanced IPv6 deployment, also referred to as IPv6-only. To be clear, that does not mean removing access to IPv4-only resources. Some method of access to IPv4 resources must be retained, as the primary network infrastructure is switched from a dual stack. In effect the *application layer* in a host will still see a dual stack environment, even if the packets on the link are no longer a mixture of native IPv6 and native IPv4.

Such solutions are known as "IPv4 as a Service" (IPv4aaS) and can be used to ensure IPv4 support and coexistence when starting the IPv6-only transition for the infrastructure. This can be a complex decision. As mentioned in RFC 9386, IPv6-only is generally associated with a scope, e.g. IPv6-only overlay or IPv6-only underlay.

"IPv6-only overlay" denotes that the overlay tunnel between the end points of a network domain is based only on IPv6. IPv6-only overlay in a fixed network means that IPv4 is encapsulated in IPv6 (or translated) at least between the interfaces of the Provider Edge (PE) nodes and Customer Edge (CE) node (or the Broadband Network Gateway (BNG)). As further mentioned in Tunnels, tunneling provides a way to use an existing IPv4 infrastructure to carry IPv6 traffic. There are also translation options described in Translation and IPv4 as a service. This approach with IPv6-only overlay helps to maintain compatibility with the existing base of IPv4, but it is not a long-term solution

"IPv6-only underlay" relates to the specific domain, such as IPv6-only access network or IPv6-only backbone network, and means that IPv6 is the network protocol for all traffic delivery. Both the control and data planes are IPv6-based. For example, IPv6-only underlay in fixed network means that the underlay network protocol is only IPv6 between any Provider Edge (PE) nodes.

To ensure IPv4 support, the concept of IPv4aaS is introduced and means that IPv4 connection is provided by means of a coexistence mechanism, therefore there is a combination of encapsulation/translation + IPv6-only underlay + decapsulation/translation. IPv4aaS offers Dual-Stack service to users and allows an ISP to run IPv6-only in the network, typically the access network. Some network operators already started this process, as in the case of T-Mobile US, Reliance Jio and EE.

RFC 9313 compares the merits of the most common IPv6 transition solutions, i.e. 464XLAT [RFC6877], DS-lite [RFC6333], Lightweight 4over6 (lw4o6) [RFC7596], MAP-E [RFC7597], and MAP-T [RFC7599].

A framework for carriers is proposed in a current draft [draft-ietf-v6ops-framework-md-ipv6only-underlay]. Customer edge routers need to support RFC 8585. The reader will notice that the solutions most commonly adopted today, such as this one, exploit both the use of tunnels (IPv4 carried over IPv6) and translation (IPv4 re-encoded as IPv6). The following two sections separate out these two techniques. [3. Translation] also gives more detail on IPv4aaS.

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## Tunnels

At its simplest, two IPv6 hosts or networks can be joined together via IPv4 with a tunnel, i.e. an arrangement whereby a device at each end acts as a tunnel end-point. Typically such a tunnel connects two IPv6 routers, using a very simple IPv6-in-IPv4 encapsulation described in RFC 4213, with IP Protocol number 41 to tell IPv4 that the payload is IPv6. Conversely, IPv4-in-IPv6 tunnels are also possible, with IPv6 Next Header value 4 to tell IPv6 that the payload is IPv4. This would allow an operator to interconnect two IPv4 islands across an IPv6 backbone. (Naturally, IPv6-in-IPv6 tunnels are also possible, if needed.)

However, such simple encapsulation is rarely needed today, with direct IPv6 transit being widely available from major ISPs. Tunnels are used in other co-existence scenarios, some of which we will now describe.

Early solutions assumed that an ISP's infrastructure was primarily IPv4; RFC 6264 is no longer up to date, but it provided background on how IPv6-in-IPv4 tunnels would be used in such cases. Today, the picture is reversed, and the emphasis is on ISP infrastructure which is primarily IPv6.

DS-Lite (Dual-Stack Lite Broadband Deployments Following IPv4 Exhaustion) [RFC6333] uses an IPv4-in-IPv6 tunnel between the the ISP's carrier-grade NAT (CGN) and the customer's Customer Edge (CE) router. The customer is given a private IPv4 prefix [RFC1918] and the CGN translates IPv4 traffic to and from a public IPv4 address. Thus, the infrastructure between the CGN and the CE router can be pure IPv6.

IPv6 can be tunneled using GRE (Generic Routing Encapsulation, RFC 7676).

IPv6 can be tunneled over MPLS [RFC4029]; for example, see "Connecting IPv6 Islands over IPv4 MPLS Using IPv6 Provider Edge Routers (6PE)" [RFC4798]. A common solution is to connect IPv6 networks over IPv4 MPLS via IPv6 Provider Edge routers (6PE) [RFC4798]. RFC 7439 provided a gap analysis for IPv6-only MPLS networks. RFC 7552 closed many of those gaps. Interested readers can study a 125 page NANOG tutorial.

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## Translation and IPv4 as a service

When an operator wants to reduce infrastructure costs by running a single protocol, IPv6, instead of a dual stack, the strategic approach is to minimize IPv4 presence in the network. Unfortunately, some resources are available only on IPv4 and some client applications may *require* IPv4. Hence, a pure IPv6-only environment is unrealistic for the foreseeable future. In some situations, tunneling (as described above) is sufficient, but typically translation between IPv6 and IPv4 is unavoidable. Especially, when providing IPv4 as a Service (IPv4aaS), a typical scenario will:

1. Let IPv6 native traffic flow directly between the client and the server.
2. Translate the traffic of local IPv6 clients to remote IPv4-only servers, using a centralized NAT64 device.
3. Encapsulate literal IPv4 address requests into IPv6 on the client then decapsulate and translate it on the centralized NAT to access the IPv4 server.

Because of this, it is essentially impossible to separate the discussion of translation techniques from the discussion of IPv4 as a service.

### Terminology

- SIIT (Stateless IP/ICMP Translation Algorithm). This is also known simply as "IP/ICMP Translation Algorithm" [RFC7915, RFC 6144]. It translates IPv4 packets to IPv6 format and the opposite. Note that translation is limited to basic functionality, and does not translate any IPv4 options or any IPv6 extension headers except the Fragment Header. Technically the mechanism is stateless (i.e., it relies on no stored information) but in practice it is used as part of stateful mechanisms.

- NAT64 refers to address translation between IPv6 clients and IPv4 servers, using the SIIT mechanism.

  - RFC 6146 defines *stateful* NAT64, which (like IPv4 NAT) includes port translation and supports two-way transport sessions.
  - DNS64 [RFC6147] supports DNS extensions for clients of stateful NAT64.
  - PREF64 refers to the IPv6 prefix used "outside" the NAT64 translator. RFC 8781 and RFC 8880 are mechanisms by which a host can learn the PREF64 in use.

- 464XLAT (Combination of Stateful and Stateless Translation) [RFC6877] is SIIT plus address translation *from* IPv4 clients to IPv6 transport and *back to* IPv4 servers. This is used for IPv4 traffic to cross an IPv6-only network.

  - CLAT is the client side translator in 464XLAT. It implements stateless NAT46 (SIIT) translation.

  - PLAT is the provider side translator in 464XLAT. It is nothing else than a stateful NAT64 gateway.
  - This is the only well-defined model for NAT464 translation.

- The final two items have nothing to do with IPv6/IPv4 co-existence but are included here for completeness:

  - NPTv6 (IPv6-to-IPv6 Network Prefix Translation) is an *experimental* technique [RFC6296] whose applicability is debated.

  - NAT66 is not defined by the IETF and, given the vast supply of IPv6 addresses, is not generally considered useful enough to overcome its disadvantages, which it shares with classical IPv4 NAT [RFC5902]. Like IPv4 NAT, it may be implemented with support of port translation (i.e., NAPT66), but as there is no shortage of IPv6 addresses, port translation is unnecessary.

### Further details of IPv4 as a service

Point 2 listed above evidently needs stateful NAT64 [RFC6146].

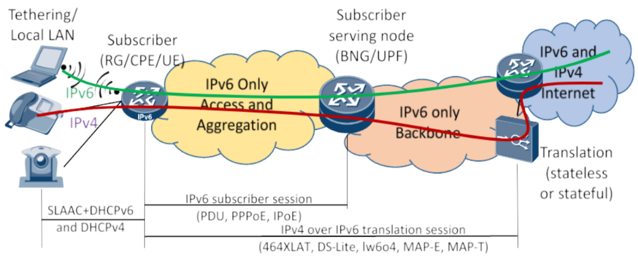
Additionally, the client could be triggered to start a cross-protocol connection. For this, the client should be told that the server is available on the IPv6 Internet. DNS64 [RFC6147] can do this on the ISP side. It can synthesize an IPv6 address from an IPv4 address, by adding a particular static prefix. When the client asks for `www.example.net` (which only has an A record in the global DNS), DNS64 will synthesize and return an AAAA record. Deployment of DNS64 involves complications and is not necessary in the presence of IPv4-as-a-service.

Point 3 above may be implemented (in addition to points 1 and 2) by various technologies:

- 464XLAT (Combination of Stateful and Stateless Translation) [RFC6877]
- DS-Lite (Dual-Stack Lite) [RFC6333]
- lw4o6 (Lightweight 4over6) [RFC7596]
- MAP E (Mapping of Address and Port with Encapsulation) [RFC7597]
- MAP T (Mapping of Address and Port using Translation) [RFC7599].

RFC 9313 has a good overview and comparison of these technologies.

The following figure illustrates such a scenario.




- 464XLAT is the widely preferred translation technology now because it has a natural synergy with NAT64 (which is highly desirable by itself) and because it is the only solution supported on mobile devices. The centralized NAT64 engine is called PLAT, and is the same [RFC6146] as for ordinary NAT64. The client side is called CLAT, and is typically a stateless NAT46 translation [RFC7915]. A good analysis of deployment considerations is in RFC 8683, from which an operator might conclude *not* to implement DNS64, since IPv4 clients can simply use the normal DNS A records and the IPv4 service as if it was native.
- DS-Lite was the most popular technology for a considerable period of time.
- Lw6o4 has not gained significant market adoption.
- Technically, MAP-E and MAP-T are stateless with significant related advantages: no need for logs, possible to implement on routers. But MAP needs a rather big IPv4 address space to be reserved for all clients (even when disconnected) and MAP is not available by default on the majority of Mobile OSes. As a result, MAP has a small market share.

### IPv4 as a service for mobile devices

The diagram above covers IPv4aaS for a network. A special case is IPv4aaS for a mobile device, especially when the device has only been provided with a single /64 prefix, as is the case in most 3GPP deployments. In this case, 464XLAT is the only available solution, and as described in Section 6.3 of RFC 6877, the

CLAT will use a specific address from that /64 prefix.

### Further details of NPTv6

Network Prefix Translation (NPTv6) [RFC6296] is a special technology available only in IPv6. It exchanges prefixes between "inside" (private network) and "outside" (public network) of the translation engine and modifies the IID. The IID is changed so as preserve the transport layer checksum despite the prefix change. Hence, it is transparent for all transport layer protocols. In principle it would, for example, allow a site using ULA addresses [2. Addresses] to communicate with global IPv6 addresses, but with some of the disadvantages of classical IPv4 NAT, sometimes referred to as 1:1 NAT, and not to be confused with masquerading address translation. The principal difference between NPTv6 and classical NAT is that it permits connection initiation in both directions. However, it is not fully transparent for applications that embed IP addresses at high layers (so-called "referrals"). Hence, it cannot be considered end-to-end transparent.

A particular difficulty is that SIP (Session Initiation Protocol for IP telephony) will not work behind NPTv6 without the support of a proxy mechanism [RFC6314].

As stated above, NPTv6 is outlined in RFC 6296; however, although there is significant commercial support, it should be noted that the RFC is experimental as of the time of this writing, so it is not considered standards track.

It goes without saying that NPTv6 is *never* justified by a shortage of IPv6 addresses. Nevertheless, while there is controversy about breaking end-to-end address transparency in IPv6, there are valid use cases for such architectures, and breaking the end-to-end model is more of an unfortunate side effect than a feature of such tools. Some details on the "breakage" caused by NPTv6, and a comparison with classical NAT, are given in Section 5 of RFC 6296.

In large scale deployments of wide area architectures, NPTv6 does enable some compelling use cases which enable diversity in security platforms such as stateful unified threat management devices (UTMs). These are positioned in geographically and topologically diverse locations, but require flexibility of *external* layer 3 addressing to support flow identification. Using NPTv6 to perform re-mapping of addressing allows inspection engines to maintain the flow symmetry that is required for stateful deep packet inspection engines to operate, as asymmetry will cause them to mark all flows as incomplete. It is in this model that it can be GUA to GUA, and this is a valid, supportable, and definitely production deployed architecture.

In smaller deployments, NPTv6 can be leveraged to create stable addressing inside a network that may be too small for PI address space, but too large to operate without service provider diversity. In this model, such as an SD-WAN deployment, a GUA or ULA prefix may be deployed, delegated by a home office, other IT governance body, or a local administrator, and mapped to one or more PA prefixes provided by lower cost commercial internet services. This allows for internal addressing to be stable, while providing a more robust connectivity model, and the ability to more quickly switch providers if required by leveraging dynamic addressing externally mapped to stable addressing internally. This model more closely aligns with the current IPv4 architectures pervasively deployed nearly everywhere with stable internal IPv4 addressing masqueraded to one or more PA addresses provided by an upstream ISP.

#### Further details on NAT66

NAT66 is currently a non-standards based mechanism for statefully translating one or more IPv6 addresses to one or more other IPv6 addresses. When port translation is also provided (as is very common for IPv4 NAT), the term NAPT66 may also be used.

It goes without saying that NAT66 is *never* justified by a general shortage of IPv6 addresses. Like NPTv6, NAT66 should be used only when necessary or required. Moreover, is is also very important to understand that the intent of these tools is to translate, hence the names. They may play a part in compliance requirements, but they are - at their core - translation tools and not security mechanisms. Address translation is often deployed alongside stateful packet filtering, but the two are, in actuality, exclusive toolkits. That is to say, they are not tied to each other, and should be considered distinct - address translation is not a security tool.

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## Obsolete techniques

As IPv6 has matured and people have gained operational experience, various co-existence and transition techniques have either been shown to be unsatisfactory or have simply been overtaken by events. This section simply lists such techniques, with minimal explanation. Readers are advised to ignore these techniques for new deployments, and to consider removing them from existing deployments.

Tunneling IPv6 over IPv4, or the converse, remains fundamental to co-existence, although various specific tunnel mechanisms are listed below as obsolete.

Note that three such mechanisms (6to4, Teredo and ISATAP) have left behind them some operational security risks related to IPv4 protocol type 41, as described in Plight at the End of the Tunnel - Legacy IPv6 Transition Mechanisms in the Wild, preprint here.

- Transmission of IPv6 over IPv4 Domains without Explicit Tunnels [RFC2529]. As far as is known, this was never deployed in practice.
- IPv6 Tunnel Broker [RFC3053].
- Connection of IPv6 Domains via IPv4 Clouds ("6to4") [RFC3056] [RFC3068]. The problems with this are documented in RFC 6343 and it was largely deprecated by RFC 7526.
- Teredo: Tunneling IPv6 over UDP through Network Address Translations (NATs) [RFC4380].
- SOCKS-based IPv6/IPv4 Gateway [RFC3089].
- ISATAP [RFC5214].
- 6rd [RFC5569].
- An Incremental Carrier-Grade NAT (CGN) for IPv6 Transition [RFC6264].
- 6a44 [RFC6751].

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## IPv6 primary differences from IPv4

This book intentionally describes IPv6 as the "new normal" IP protocol, but this section mentions the main ways that it differs from IPv4, using terminology from 2. IPv6 Basic Technology.

IPv6 is very similar for transit routing, but has some considerable differences on the first hop for hosts as well as for routers that do more than pure routing.

The primary differences are:

- The first difference is desirable and expected: IPv6 has a four times bigger address size (128 bits against 32 bits).

  SLAAC is more used on IPv6 than DHCPv6. A SLAAC subnet prefix is 64 bits for historical reasons that are fixed in many standards. 2^64 hosts are of course not possible in one subnet, but the address space is reserved even for a smartphone. Hence, it is disputable what is the effective IPv6 address space. It is bigger than 2^64 bits but the 64 IID bits are utilized for privacy and security, not for addressing *per se*.

- NAT44 is a common solution in IPv4 networking.

  NAT66 is discouraged by IETF and not specified as a standard. IPv6 end-to-end connectivity is considered a big value.

- IPv4 has only one address per interface (without special hacks).

  Many IPv6 addresses on every interface are the norm. It is not just different address types (LLA, ULA, and GUA) but additionally many instances of GUA and ULA for security or virtualization reasons. The popular ChromOS has seven IPv6 addresses as the minimum. Additionally, the number of IPv6 addresses per interface could almost double in the case of link renumbering.

- IPv4 has only centralized DHCPv4 address acquisition.

  IPv6 has additionally distributed address acquisition by SLAAC which is widely adopted. SLAAC considerably changes the logic of the link operation. (The problems caused by broadcast IPv4 ARP are replaced by the problems caused by multicast IPv6 Neighbor Solicitation!)

- IPv4 has a complex (many fields) and theoretically variable header that is practically fixed because options are not widely used.

  IPv6 has a simple and fixed header. Additionally, IPv6 could have extension headers that permit unlimited protocol extensibility at the data plane. Many extension headers are already used in limited domains. Just like IPv4 options, deployment of new IPv6 extensions headers and options across the open Internet is problematic.

- IPv4 fragmentation is in the basic header and permitted in transit.

IPv6 fragmentation uses an extension header and is prohibited in transit.

- IPv4 address resolution on the link by ARP protocol is at layer 2 (for the IEEE 802 media it is an IEEE 802 frame). IPv6 address resolution on the link by ND protocol is at layer 3 (IPv6 packet over LLA or other IP addresses).
- Multicast is not needed for IPv4 itself.

  Multicast is mandatory for the IPv6 link operation. Many ND functions are using multicast. That may create advantages (for Ethernet) and disadvantages (for many types of wireless).

The list above is not comprehensive, but the other differences are probably smaller.

An obvious question is: With all these differences, what is the difference in performance between IPv6 and IPv4? There is no simple answer to this question. Since the IPv6 packet header is 20 bytes larger than for IPv4, the raw payload throughput of a link carrying full sized IPv6 packets is slightly less than for IPv4 (about 1.3% less for 1500 byte packets). However, many other factors come into play and measurements often show better end-to-end performance for IPv6. For example, in most countries Google statistics show lower latency (transit time) for IPv6. The safest summary is that there is no significant performance difference.

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## Security

Security has ever-growing importance in general and the IP protocol has been a big area for security research and development. The majority of IPv4 practices remain applicable to IPv6. Exceptions exist for aspects of the first hop and for extension headers that are significantly different in IPv6. Distributed address acquisition (SLAAC, 2. Auto-configuration) creates its own additional security challenges. Multiple addresses per host improve privacy, but not without complications. Extension headers give IPv6 great flexibility and extensibility that may be abused, leading to additional security precautions.

Initially, it was expected that end-to-end cryptography (encryption and authentication) would be a mandatory part of IPv6 (IPsec, RFC 4301 and SEND, RFC 3971). This proved unrealistic, so cryptography has been accepted as optional at the networking layer, exactly as it is for IPv4. At the same time, cryptography has become widespread at the transport or application layers.

IPv6 aims at restoring end-to-end connectivity to the networking layer. Therefore, IPv6 security in no way relies on the presence of network address translation. IPv6 has no standardized NAT66 and even network prefix translation (NPTv6, RFC 6296) is little used. NAT or NPTv6 provide at best weak security protection at the network boundary, so this is not seen as a defect. The normal approach to boundary security for IPv6 is a firewall; most firewall products support IPv6 as well as IPv4. Topology hiding is addressed in a later section of this chapter.

Today, the "Zero-trust" approach in security tends to move the stress from perimeter protection to the authentication and encryption for all traffic (including internal for any perimeter). If this approach succeeds, some enterprises may choose to reduce the role of firewalls in future. IPv6 is well positioned for this change.

A good design and policy rule to follow is that in a dual-stacked deployment, which is by and large the largest percentage of IPv6 deployments, security policy for IPv4 and IPv6 should match in order to ensure consistency of operational and user experience. In an IPv6-only deployment, implementation of policy should be derived from overall network security policy, taking into account protocol specifications that may require adjustments from legacy IP (i.e. differences in ICMP handling between IPv4 and IPv6).

There is a good overview of IPv6 security in RFC 9099. This is a good repository of references to many documents on various IPv6 security aspects.



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## Layer 2 considerations

IPv6 is comparatively flexible at the link layer. Flexibility typically comes with complexity, which can drive security challenges.

Initially, there was a belief that cryptographic SEcure Neighbor Discovery (SEND, RFC 3971) would resolve the majority of neighbor discovery risks. Unfortunately, SEND was not accepted by the market. Hence, the security problems discussed in RFC 3756 section 4.1 are still active:

- A malicious node could answer to Duplicate Address Discovery (DAD) for any request of a legitimate node, amounting to a denial of service attack;
- A malicious node could poison the neighbor cache of another node (especially the router) to intercept traffic directed to another node (man-in-the-middle attack); it is possible for neighbor solicitation and neighbor advertisement in many different cases.

There is no big difference here from IPv4 ARP spoofing. Of course, the danger only exists if a bad actor succeeds in implanting a malicious node. Where this is felt to be a significant risk, the strongest protection method is host isolation on a separate link with a separate dedicated /64 prefix. IPv6 has enough address space to follow this strategy. All subscribers (including mobile) already have at least one /64 prefix. A /56 prefix is considered as the minimum for ordinary domestic subscribers with the possibility for /48 for even a small business. The latter would theoretically allow 65,535 hosts each to have their own /64.

An alternative method of protection is Source Address Validation Improvement (SAVI) - see RFC 6620 which is based on the full Neighbor Discovery (ND) exchange monitoring by the switch to dynamically install filters. Like SEND, it is not a very popular solution.

Cellular mobile links (3GPP etc.) are always a point-to-point tunnel. Hence, it was possible to greatly simplify the ND protocol (address resolution and DAD are unnecessary) to avoid complexity and the majority of security threats – see RFC 7849.

It is of the same importance as for IPv4 to restrict who could claim the default router and DHCP server functionality because it is the best way to organize man-in-the-middle attacks. Hence, RA-Guard RFC 6105 and DHCPv6-Shield RFC 7610 are defined. Unfortunately, there is a possibility to hide the purpose of a packet by prepending the transport layer with extension headers (especially dangerous fragmentation). Hence, RFC 7113 and RFC 7112 are additionally needed for protection against rogue Router or DHCP.

There is a new security attack vector related to IPv6 specifically. SLAAC address acquisition is distributed, so the router may not know all addresses configured on the link even if all ND exchange is monitored by the router. Hence, the router needs to request address resolution after the first packet of a new session is received from an external source. At the same time, the IPv6 link address space is huge (2ˆ64) by default. Hence, it is potentially possible to force the router (even from an external network) for address resolution a huge number of times. It is an effective DoS attack that has simple protection measures. RFC 6583 discusses how to rate-limit the number of address resolution requests or minimize subnet size.

ND heavily relies on multicast which may create problems in the wireless environment. See 2. Address resolution and Multicast efficiency. ND DoS activity may be effective for that reason but the attacker should be local to the link. Hence, perimeter security may help. The multicast storm is less of a problem in a wireline environment because of MLD snooping typically implemented on the link (RFC 4541).

IPv6 has a new feature that improves privacy. It is normal for an IPv6 host to have many IP addresses for the same interface, often with unpredictable (pseudo-random) IID values. Some IP addresses may be used temporarily (RFC 8981) which creates a challenge for intermediate Internet nodes to trace suspicious user activity, for the same reason that it protects privacy.

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## Filtering

Filtering is a big part of safe Internet connection. IPv6 filtering in general may be easy because of the hierarchical address plan. However, each filter almost always consumes four times more resources in products. This may affect scalability or performance, if equipment is underspecified.

The majority of practices do not change with IPv6 adoption:

- BCP 38 recommends carriers to filter traffic based on *source* addresses on ingress from the client to prevent address spoofing. Source addresses in the range delegated to this client are allowed; other sources addresses should be filtered (except for the case mentioned in [6. Multi-prefix operation]). Operators that do not implement BCP38 are condoning address spoofing.
- "Martian" addresses should be filtered on the perimeter according to RFC 6890. In the case of IPv6, this refers to the IANA IPv6 Special-Purpose Address Registry.
- Filtering on BGP Peering and RPKI do not change for IPv6.
- The router's control plane protection [RFC6192] is universal for IPv6 or IPv4.
- Remote Triggered Black Hole is the same for IPv4 and IPv6, excapt that the prefix for IPv6 100::/64 has been defined separately.
- All IGP protocols should filter announcements for the local link according to RFC 5082. In the case of IPv6, this means that announcements are allowed only from link-local addresses.
- DNSSEC is recommended, independent of A or AAAA requests.

Some filters are specific to IPv6.

The biggest difference is related to the typical prefix size (/64). Filtering anything longer than this is useless, because of the unpredictable temporary addresses that a host may generate. Moreover, if there is a desire to filter one subscriber it may be apprpriate to filter even shorter prefixes, such as a /56. It is recommended to filter /64 initially and then monitor the situation; if the problem persists, then filter /60, then /56. /48 is the maximum that may belong to an ordinary subscriber, so it cannot make sense to filter shorter prefixes than that to block a single subscriber.

The address plan design of an organization may be different, including /128 addresses with DHCPv6 configuration, but it is never possible to know this from the outside. If the organization employs SLAAC then again /64 is the minimum that makes sense to filter.

The addresses of different scopes should be filtered at respective borders:

- LLA should be not forwarded outside of the link according to IPv6 Addressing Architecture,
- ULA should be filtered at organization borders according to RFC 4193,
- Multicast addresses have 5 defined scopes (Interface, Link, Admin, Site,

and Organization) according to IPv6 Addressing Architecture that should be filtered at respective borders. For the lowest scopes, the perimeter is evident and typically hard-coded into nodes. For the scopes with flexible borders (like Admin, Site, Organization) it needs a special configuration.

PMTUD operation is more important in IPv6 because fragmentation is prohibited in transit. Hence, ICMP filtering may do more harm in IPv6. It is discussed in Recommendations for ICMPv6 filtering what should be dropped or permitted.

Security devices and destination nodes should check that the first fragment should have all headers (including the transport layer) and fragments should not have an overlap according to RFC 8200.

Filtering recommendations for packets with extension headers is oriented for the transit case where excessive filtering is common. This RFC motivates what particular EHs to permit, drop, reject (with ICMP), rate-limit, or ignore. It is important to mention that these additional actions are recommended in addition to the basic rule of RFC 7045 to allow by default the transmission of all extension headers in transit.

Limiting ND messages on the link is discussed in Address resolution.

There is a risk for IPv4-only networks caused by IPv6 preference programmed into hosts. The activation of IPv6 by a malicious node could create security problems. Security Implications of IPv6 on IPv4 Networks discusses what is important to block in this scenario. These are primarily different tunneling protocols that might help to bypass perimeter security, and rogue DHCP or Router code for a man-in-the-middle attack.

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## Topology obfuscation

There are various operational contexts in which an operator needs to obfuscate or otherwise hide a network's topology, equipment, and hosts from outsiders. Since IPv6 promotes end-to-end addressing, the question arises of how to achieve topology hiding or obfuscation in the absence of network address translation (NAT).

One important context for this is networks that must conform to standards such as Payment Card Industry Data Security Standard Requirements (PCI-DSS), issued by the PCI Security Standards Council. (This standard can be downloaded free of charge, but beware that you must agree to a license in order to do so.) PCI-DSS requires an enterprise that stores certain types of customer data to do so on servers that are effectively isolated from the Internet and undiscoverable from outside the enterprise. Yet these systems might also be offering Web services to clients anywhere in the Internet. A common solution to this dilemma for IPv4 has two parts:

1. A "demilitarized zone" (DMZ) between the Internet and the core of the enterprise network.
2. When a server in the core communicates with a client elsewhere in the Internet, the requirement to hide the server is commonly satisfied by IPv4 NAT between the server and the DMZ.

It goes without saying that such traffic will flow through a firewall (which PCI-DSS refers to as a Network Security Device or NSD). The question is how should such a system obscure the server's regular IPv6 address as effectively as NAT obscures its IPv4 address. Note that PCI-DSS (version 4, March 2022) does not require NAT, although it is mentioned as a solution for IPv4. For IPv6, it suggests using temporary addresses [RFC8981] for outgoing sessions (although it cites an obsoleted RFC). Placing system components behind proxy servers is also suggested, and it seems probable that large installations will do this anyway to support load balancing [RFC7098]. Proxy servers and load balancers will intrinsically hide the core topology from attackers.

Other aspects of topology hiding were discussed in RFC 4864, but that document is significantly out of date.

Another common architectural scenario entails dis-aggregating a GUA allocation, typically an RIR provided address block, and announcing only the part of the assignment requiring public access, leaving the prefix requiring obfuscation unannounced within the global DFZ. This model allows for a similar level of topology obscurement without the added configuration complexity and potentially inconsistent behavior of ULA or address translation. It should be noted, however, that while this design model does reduce complexity at the host and network layer, it may add minor routing complexity at the border and incur risk of unintentionally leaking the GUA prefix that has been earmarked for local-only use. In the latter case, use of a "belt and suspenders" implementation of creating route policy in addition to access control lists preventing prefix use is frequently employed.

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## Network Design

A first very general remark is that since IPv6 is a datagram protocol, whose routing relies on longest matching of address prefixes, the highest level of design decisions are identical to those for IPv4.

There is one constraint that does not apply to IPv6: there is effectively no theoretical limit to the number of hosts per subnet. (Mathematically, there is a limit of about 18.1018 nodes on a /64 subnet, but this is of no practical concern.) However, most network designers will never place hundreds or thousands of hosts on a single subnet, for performance reasons.

A network designer does, however, have more flexibility with IPv6. If an enterprise has a /48 prefix, 16 bits are available to identify more than 65 thousand individual subnets, a luxury for most IPv4 network designers.

Setting these details aside, there is no reason why an IPv6 network will have a different macroscopic design than an IPv4 network. The detailed approach will vary.

- If the intention is a "retrofit" where IPv6 support is added to an existing IPv4 network, major topology will not change, but items such as border routers, firewalls, interior routers, and DMZs will need to be upgraded accordingly. Clearly, a specific choice of IPv6/IPv4 coexistence mechanism must be made, and applied consistently. In the past, most networks have chosen the original dual-stack approach [3. Dual stack scenarios] but designers should now also consider 3. Translation and IPv4 as a service. A priority will be adding comprehensive IPv6 support to the NOC and all its systems, before deployment to users. An equal priority will be training of all NOC and support personnel: they need to be IPv6 evangelists.
- If the intention is a "greenfield" deployment with no existing IPv4 network, the main topology will be conventional, but a specific choice of mechanism for IPv4 as a service must be made [3. Translation and IPv4 as a service]. The NOC must be designed from the start based on IPv6, with the ability to manage IPv4 as a service.
- A specific difference between a retrofit design and a greenfield design is that an existing IPv4 network almost inevitably has subnets limited to 256 or fewer hosts, often as few as 64. Since the normal subnet prefix in IPv6 is a /64, there is no such limitation in a greenfield deployment of IPv6. However, for practical reasons such as the rate of link-local multicasts, very large subnets should be avoided. As noted elswehere [2. Address resolution] this applies particularly to wireless networks.

This chapter continues with a discussion of address planning, inevitably combined with subnet design.

Address Planning

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## Address Planning

As you would expect, in IPv6 networks all nodes may have globally unique addresses. All networks will be given at least a /64 global prefix to operate. As for carriers, they should deliver a longer prefix to subscribers, so that they can have multiple /64 subnets within their organizations or home environments. Even a home customer can have a public network prefix to be split into smaller networks, which is a paradigm shift from “hiding behind NAT" on a few public IPv4 addresses (or even inside `100.64.0.0/10` [RFC6598]).

In IPv6 networks, it is often necessary to manage received prefixes, even if it is done automatically by a CE router. Likewise, network operators receive large address blocks from the RIRs and must plan their address distribution in order to handle address blocks assigned to customers or their own infrastructure.

For instance, we can start with a network operator. Consider a carrier called “ISP” that received the prefix `2001:db8::/32`. It is necessary to separate address blocks asigned for home customers, corporate customers and for ISP's own infrastructure. First, let's see what space is available for planning:

```
 Global ID -Subnets- -- Interface IDs --
| 32 bits | 32 bits |   64 bits         |
 2001:0db8:0000:0000:0000:0000:0000:0000
```

The first 32 bits will remain unchanged, of course, and the last 64 bits will always belong to the ending subnet nodes. It leaves us the 32 bits between them to work with. Keep in mind that there is no concern about exhaustion of IPv6 addresses(or prefixes), seeing that this single assignment for an autonomous system (ISP) gives the equivalent of the entire IPv4 Internet address space to work with. And this is not about unique addresses, but /64 network prefixes! As am analogy, a /64 prefix would be the equivalent of leasing a public IPv4 address to a single network or subscriber. In this way, in IPv6 planning we can favor organization and clearer management instead of saving as many addresses as possible. On IPv6 networks it makes no sense to count unique addresses; instead, we consider the number of available /64 prefixes. Think of a /64 prefix as a standard unit that fits all network sizes.

Remember that our 32-bit subnet space embodies 4 billion /64 networks, so there is room for good planning and management as there will be no address shortage on any reasonable timescale. A good addressing plan should always have room for future expansion and favor network aggregation and management. (Of course, even IPv6 address space is not infinite, but the policies applied by the various Regional Address Registries will avoid any risk of exhaustion.) For this reason, in the following example, we will use the technique known as **leftmost**, to guarantee a more balanced distribution on all available space. Back to the example, consider our 32 bits where we can use the first 4 (one "nibble" or hexadecimal character) to assign sixteen regions, as 0 to F, resulting on a /36 per region. A region may be a data center, geographical area or a branching network. A. Region A - Main Datacenter B. Region B - City south C. Region B - City north So the first layer of our address plan may look like this:

```
2001:0db8:0000::/36 - Reserved
2001:0db8:1000::/36 - Reserved
2001:0db8:2000::/36 - Reserved
2001:0db8:3000::/36 - Reserved
2001:0db8:4000::/36 - Reserved
2001:0db8:5000::/36 - Reserved
2001:0db8:6000::/36 - Reserved
2001:0db8:7000::/36 - Reserved
2001:0db8:8000::/36 - Reserved
2001:0db8:9000::/36 - Reserved
2001:0db8:A000::/36 - Region A
2001:0db8:B000::/36 - Region B
2001:0db8:C000::/36 - Region C
2001:0db8:D000::/36 - Reserved
2001:0db8:E000::/36 - Reserved
2001:0db8:F000::/36 - Reserved
```

(Note: We are using uppercase characters to distinguish the locally assigned prefixes; this breaks the usual recommendation to use lowercase.)

Each region have functional divisions that may earn one or more address blocks. Each division could be for instance:

1. Internal infrastructure
2. Domestic clients
3. Corporate clients Using the same logic you can split a region's /36 into 16 /40 prefixes, so it is easier to manage. Keep in mind that it is possible to assign more prefixes for each one if necessary. Now let's see the address plan for **Region A** where we have 16 /40 prefixes:

```
2001:0db8:A000::/40 - Corporate clients ---|
2001:0db8:A100::/40 - Corporate clients    |---> 1024 x /48 prefixes
2001:0db8:A200::/40 - Corporate clients    |
2001:0db8:A300::/40 - Corporate clients ---|
2001:0db8:A400::/40 - Internal infrastructure ---> 256 x /48 prefixes for infrastructure
2001:0db8:A500::/40 - Reserved
2001:0db8:A600::/40 - Reserved ---> 768 x /48 prefixes for expansion
2001:0db8:A700::/40 - Reserved
2001:0db8:A800::/40 - Domestic clients ---|
2001:0db8:A900::/40 - Domestic clients    | 2048 x /48 prefixes
2001:0db8:AA00::/40 - Domestic clients    | or
2001:0db8:AB00::/40 - Domestic clients    | 2001:db8:A800::/37
2001:0db8:AC00::/40 - Domestic clients    | or
2001:0db8:AD00::/40 - Domestic clients    | 2048 x 256 x /56 prefixes
2001:0db8:AE00::/40 - Domestic clients    |
```

```
2001:0db8:AF00::/40 - Domestic clients ---|
```

As shown above, we have a good measure for corporate and home customers, plus a room for expansion, added by a generous /40 just for internal infrastructure. Of course, this can be changed according to needs on each case. For example, increase the number of prefixes for corporate clients, or take some space in infrastructure reserved part, which is very large. Even add another entire /36 block for the same region. If you do the math, the numbers are always very loose so that we can always give preference to address organization, aggregation and good management.

### Client delegations

It is recommended to delegate at least a /48 block to clients. Best practice says that corporate clients always receive at least a /48 prefix and domestic clients receive at least a /56 prefix. Mobile access clients may receive a single /64 (but more would be better, to allow IPv6 "hot spots"). See below with 2 prefixes from Region A's /40 block: a /48 assigned to a corporate customer and a /56 to a domestic customer:

1. `2001:0db8:A3CC:0000::/48` The least four Zeros shows 16 bits given within a /48 prefix, available to address 2^16=65536 /64 subnets.
2. `2001:0db8:ABDD:DD00::/56` The least two Zeros represent 8 bits given within a /56 prefix available to address 2^8=256 /64 subnets.

See that a single corporate client is up to a virtually unlimited address space and a domestic subscriber may have 256 subnets on a home network. Once a client leases an address block it has to split it for given subnets inside the network. Let's take that same home customer with the `2001:0db8:ABDD:DD00::/56` prefix and see what we can do:

```
2001:0db8:ABDD:DD00::/64 ---> Main home subnet
2001:0db8:ABDD:DD01::/64 ---> Wifi subnet
2001:0db8:ABDD:DD02::/64 ---> Wifi Guest subnet
2001:0db8:ABDD:DD(...)::/64 ---> Reserved
2001:0db8:ABDD:DDFE::/64 ---> IoT subnet
2001:0db8:ABDD:DDFF::/64 ---> VoIP subnet
```

ISP customers typically lease address blocks through **DHCPv6 prefix delegation** [RFC8415]. Instead of acquiring only one Internet facing address, the customer premises router requests an entire GUA block. Once it has it, the smaller /64 blocks are typically handled as a prefix pool, where each is assigned to a internal subnet.

### Other sources of information

Daryll Swer has written an excellent blog that covers subnet and addressing design (also available from APNIC).

Although quite old, the following book may be helpful: IPv6 Address Planning by Tom Coffeen.

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# Management and Operations

*This chapter is at an early stage and is expected to grow dynamically over time.*

Management and operations is a complex topic not just for IPv6, but for information technology in general. Because there are many types of networks consisting of a myriad of components, naturally operations and management will vary based on the use cases, environments, policies, and budgets of any given network ecosystem. To understand how to manage a given resource, it is imperative that there exist an understanding of that resource, and how it is to be used. Most networks can be broadly categorized into one of a small number of general types: Carrier, Personal, Enterprise, Mobile, and Data Center. There are obviously more subtle categories, but in order to maintain an element of completeness, these five categories will encompass the broad spectrum of networks in use today.

Because most networks are comprised of similar elements and that the core function of a network is to connect endpoints and to deliver data, it is expected that there is overlap of operational requirements and solutions in these categories.

*Carrier*

This category includes local Internet Service Providers serving a single market, national or international carriers, and a handful of backbone or international carriers who offer transit services to other carriers. Internet Exchange Points may also be considered as a special type of transit carrier. Carriers in general do not offer services direct to end users, except that they must all play a part in DNS infrastructure.

*Personal*

This refers primarily to domestic networks, which are often quite simple today (no internal routing) but are expected to become more complex as more and more smart devices are deployed in the home. Needless to say, they should be highly automated and should not rely on human expertise for operations.

*Enterprise*

This covers a wide range of networks which may have very different characteristics. At the simple end, a small office network may be little different from a domestic network, and is often referred to as SOHO (small office, home office). A small to medium enterprise network may be more complex, with internal routing and perhaps several nearby physical locations. A large enterprise network could span anywhere from a small town up to several continents. Some large enterprise networks may equal or exceed a carrier network in complexity. Enterprises of all sizes are likely to offer services to other enterprises or to the public, so will be much more concerned by transport and application layer issues than most carriers.

*Data Center*

Large data centers, either embedded in enterprise networks, or specialized enterprises in themsleves, have a unique set of networking and performance requirements.

*Other*

We do not claim that the above list is complete. For example, a fast growing category is *Building Services Networks* for the automation of the infrastructure of large buildings. It is expected that *Vehicular Networks* will be widely deployed. Other forms of industrial networks also have to be provided for. These networks (often bundled together as "Internet of Things") may not be of concern to typical network operations centers, but they will strongly influence future technical development of IPv6.

This chapter starts by describing how various management and operations tools apply to IPv6, and then continues by discussing some specific topics where IPv6 presents its own challenges. The emphasis is on carrier, enterprise and data center scenarios.



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## Address and Prefix Management

Three main cases can be distinguished:

1. Unmanaged networks will generally use stateless address autoconfiguration (SLAAC, RFC 4862) within the subnet prefix(es) assigned to them by a service provider. This is in contrast to IPv4 practice, where DHCP is automatically configured in most unmanaged networks.

2. Provider networks will generally configure prefixes and addresses on network elements, including customer gateways, according to a predefined plan as discussed in [5. Address Planning]. DHCPv6 Prefix Delegation `OPTION_IA_PD` may be used to assign prefixes to routers, even if DHCPv6 is not used for address assignment [2. Managed configuration].

3. Managed enterprise networks will prepare an addressing and subnet plan that meets their specific requirements. To take a very simple example, an enterprise given a /48 prefix by its ISP might assign a /56 to each branch office and then assign /64 subnets as needed within each branch. The decision must then be taken whether to deploy SLAAC throughout the network, or to use DHCPv6 `OPTION_IA_NA`for address assignment [2. Managed configuration]. This choice has implications for both troubleshooting and security incident management.

When a help-desk call or a security alert concerns a specific IPv6 address, the responder needs to know which computer and which user are involved. In some security cases, this may have financial implications and may need to meet a forensic evidentiary standard. Therefore, ascertaining the correspondence between the address, the device, and the user is a hard requirement for many enterprises.

In the case of SLAAC, the correspondence between IPv6 addresses and the MAC addresses of connected devices is embedded in the neighbor discovery caches of other devices on the same link, including the subnet router. This is volatile information, especially if IPv6 temporary addresses [RFC8981] or variable MAC addresses [draft-ietf-madinas-mac-address-randomization] are in use. A supplementary mechanism is needed to extract and log this information at a suitable frequency. An alternative would be to continuously monitor neighbor discovery traffic and extract and log the same information. It has also been observed that monitoring DAD (duplicate address detection) traffic will work, as described in this blog. All these solutions have unpleasant scaling properties for a large enterprise.

In the case of DHCPv6, the IPv6-MAC address correspondence is embedded in the DHCP server configuration. In the simplest approach, MAC addresses are pre-registered and neither temporary IPv6 addresses nor variable MAC addresses are supported. However, this exposes the network to attack, since it is trivial to forge a MAC address with most modern equipment.

With either SLAAC or DHCPv6, the user of an unknown MAC addresses can be authenticated by IEEE 802.1X access control, and this would provide a robust link between the MAC address in use and the human user whose credentials were used for authentication.

An additional factor is that one widely used host operating system, Android, does not currently support host address assignment via DHCPv6. One solution to this, for a dual stack deployment, is to accept that affected devices will only use IPv4. Another is to have a separate WiFi BSS for "bring your own" devices (BYOD) where SLAAC is available, but this network will be treated as suspect and will be effectively outside the corporate firewall. A third solution is to offer no service at all for such devices, which will have to connect to a public cellular system instead.

A network operator must make a conscious choice between SLAAC and DHCPv6, in conjunction with their choice of IPAM (IP Address Management) solution if applicable. An important question is whether tools exist to meet the help desk and security needs described above *for the specific vendor equipment and software in use.*

This book does not recommend specific products. However, it is to be noted that an open source solution does exist that supports DHCPv6-based address management including dynamic DNS.

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## Remote configuration

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## Benchmarking and monitoring

Tody, IPv6 monitoring is often forgotten, ignored or done from the wrong vantage point.

Some examples from experience:

- Large corporate network with no IPv6 monitoring, because the part of the network where the monitoring system was located had no IPv6.
- Web services with AAAA records [2. DNS] and proper configuration; monitoring said that everything okay, but users could not access the web services via IPv6 from the Internet. Someone forgot a firewall rule, and the monitoring system was on the inside of the network.
- Mail (SMTP) server with AAAA records. However, IPv6 was disabled (or blocked by a firewall) for whatever reason, but nobody removed the AAAA records. Wasn't noticed internally, i.e. they did not monitor via IPv6.

There is no fundamental difference between monitoring services for IPv4 or IPv6; it just has to be done for all services and, if they are dual-stacked, for both protocols.

In case of the mail server example above, there were probably three different teams involved and they either didn't talk to each other or had an inadequate process implemented and no automation.

Related to this, implementing IPv6 also gives an operator the chance to clean up operational documentation, ops infrastructure and NOC processes. It may also be an oportunity to implement more automation.

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## Routing operation

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## Multi-prefix operation

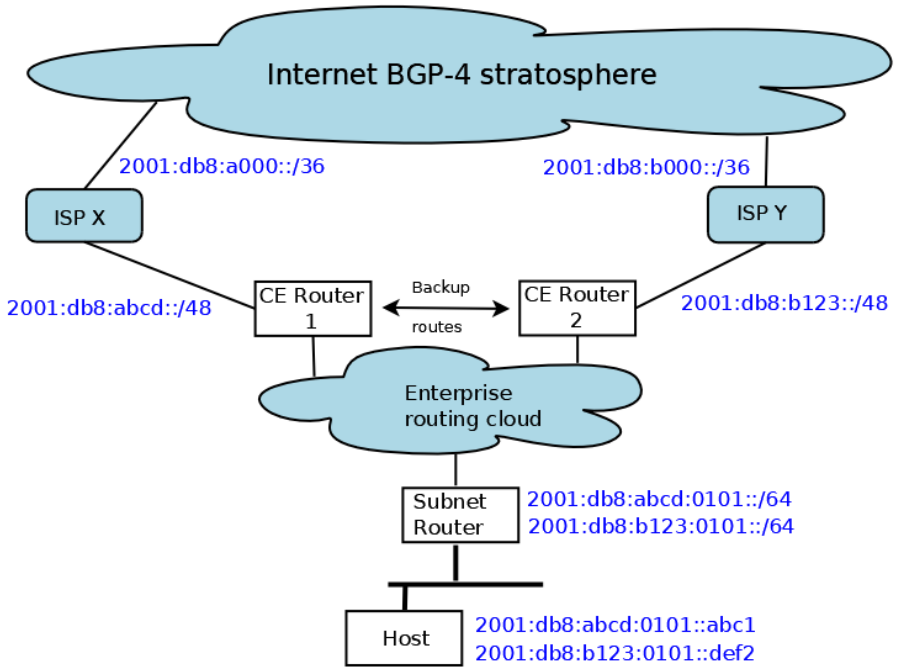
As mentioned in 2. Addresses, an IPv6 node may have multiple addresses. A trivial example is a home PC with both an Ethernet and a WiFi interface both connected to the same local segment. As a minimum, it will have two link-local addresses (one for each interface) and two GUA (global unicast addresses), all assigned automatically by SLAAC. In practice, this situation presents no problems: the link-local addresses will not be used for external traffic, and the two GUAs will both be assigned under the home network's IPv6 prefix assigned by its ISP. It is of little importance which of the GUAs a particular outgoing application session uses, because routing is the same for either of them. If the PC is using temporary IPv6 addresses for privacy [RFC8981], they too will be under the same prefix and will present no routing problem.

Similarly, an enterprise network with a single IPv6 prefix (typically a /48) does not have any routing problems as a result of enterprise hosts using multiple GUAs under subnet prefixes derived from that prefix. (An enterprise might have other reasons, such as logging and auditing, for wishing to avoid multiple addresses per host; such an enterprise is likely to use DHCPv6 for address configuration, rather than SLAAC.) However, a problem arises if a network operator wishes to connect to two (or more) different ISPs, each providing its own prefix. Such prefixes are known as PA (provider-assigned or sometimes provider-aggregatable) because they can be summarized into a single BGP-4 route announcement for the ISP as a whole.

Here is an illustrative example. Suppose provider X has obtained the prefix `2001:db8:a000::/36` from its regional registry, and provider Y has obtained `2001:db8:b000::/36`. Suppose our enterprise has then been assigned `2001:db8:abcd::/48` from X, and `2001:db8:b123::/48` from Y. These prefixes will then flow down to the subnets within the enterprise. We will assume that a particular subnet has been given the prefixes `2001:db8:abcd:0101::/64` and `2001:db8:b123:0101::/64`. Therefore, hosts on that subnet will acquire at least two GUAs, one under each of those prefixes. A particular host, for example, might end up with the addresses `2001:db8:abcd:0101::abc1` and `2001:db8:b123:0101::def2`.

(To make the example more legible, we have not used randomized IID values.)

The following diagram shows the example:




If, for some reason, there is more than one subnet router on the subnet, the host can be informed which one to use as suggested in RFC 8028.

For this to work as intended, it is necessary to configure routing so that traffic from `2001:db8:abcd:0101::abc1` exits the site towards ISP X, and traffic from `2001:db8:b123:0101::def2` exits towards ISP Y. Suitable source routing rules in the subnet router and the rest of the enterprise routing cloud will do it. Such source routing rules typically have to be set up as routing policies, including the relevant source prefixes, configured on each router by a proprietary mechanism.

But what happens if the link to ISP X goes down? Presumably the reason for having two ISP connections is precisely for backup.

We can configure low priority (high metric) routes between the two exit routers, such that when one ISP link is down, traffic is redirected to the other. However, this may fail if the backup ISP applies ingress filtering [BCP84], so the enterprise needs to arrange for its ISPs to accept mutual backup traffic.

If these steps (source routing *and* backup routes *and* filtering exceptions) are not taken, a failure of one of the two ISP connections will cause the failure of all user sessions using addresses under that ISP's PA prefix.

Even with backup routes in place, there may be a problem if user client sessions originating *within* the enterprise use IPv6 source addresses under a failing PA prefix. This will happen unless the host is somehow caused to deprecate such source addresses, so that the algorithm of RFC 6724 will not select them.

An additional technique that has been suggested is for a site to deploy *conditional* router advertisements [RFC8475].

This whole topic is discussed in more depth in RFC 8678.

The need for complex configuration and the resulting failure modes explain why many enterprises have not opted for multi-prefix PA-based multihoming. Instead, they have paid to obtain provider-independent (PI) IPv6 prefixes, typically /48 in length, from an Internet registry. However, this is expected to be problematic in the long term, since every such enterprise adds to the size of the Internet-wide BGP-4 routing table. This may be viable for a few thousand enterprises, but not for millions, i.e. not for small businesses or even home offices that might benefit from multihoming.

At the time of writing, the most practical solution for multihoming with multiple providers of IPv6 service (known as MHMP) remains under discussion in the IETF.

Another use case for multiple prefixes is an enterprise (or home) that in addition to its PA or PI prefix, which is routable anywhere on the Internet, also decides to use a Unique Local Address (ULA) prefix for strictly internal communication. Although unfamiliar to most operators, this is conceptually simple and creates a class of traffic that *by definition* cannot escape the site, which has obvious privacy and security attractions. Services that should only be accessed internally could be configured with ULAs *only* and those addresses may be entered in local split-horizon DNS (Section 4 of [RFC6950]). At the time of writing, there is an operational problem in this scenario: host computers configured with default settings from RFC 6724 will not prefer ULAs over IPv4 addresses [draft-ietf-v6ops-ula]. A site using DHCPv6 can change the default settings via RFC 7078, but unfortunately this is not widely implemented.

A partial work-around for this problem is for a host to have two AAAA records in DNS, e.g. `www.example.com` for its GUA and `w3.example.com` for its ULA, the latter only being present in local split-horizon DNS.

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## Multihoming

Multihoming means configuring a site in such a way that it is connected via more than one link to the Internet, preferably via different ISPs, usually to provide redundancy in case of failures. The phrase "multihoming with multiple providers" (MHMP) is sometimes used. The previous section describes the problems in achieving MHMP using multiple address prefixes. This section discusses practical techniques for site multihoming.

Domestic or very small office installations are out of scope for this topic. They are rarely connected permanently to more than one ISP, and therefore cannot expect smooth failover. They might have an alternative connection (e.g., a wireless hot spot instead of a terrestrial connection) but the changeover would amount to a network restart and would likely be manual.

Note that the term "multihoming" is sometimes used to describe a configuration *inside* a site network where a node is connected to more than one internal router to provide redundancy. That complicates site routing, and is not the topic here.

In 2003, the IETF established goals for site multihoming [RFC3582]. In summary, the main goals were: redundancy, load sharing, performance, policy control, simplicity, and transport session survivability. Without describing all the efforts made since then, it is clear that a solution that satisfies all these goals simultaneously has been difficult to find. A more recent overview can be found in RFC 7157.

### Large sites

Today, the most practical approach for a large site, or for a large enterprise network distributed over multiple physical sites, is to obtain a provider-independent (PI) prefix from the appropriate Internet address registry, which will typically be a /48 prefix such as `2001:db8:face::/48`. Then all hosts in the enterprise network that require Internet access will be assigned IPv6 addresses within that prefix. They might also be assigned Unique Local Addresses (ULAs) for internal use, or IPv4 addresses, or both. The enterprise will then select at least two ISPs to provide redundant connectivity to the Internet, and arrange for both of them to advertise a BGP-4 route to that prefix.

A /48 prefix provides the theoretical capacity for more than 65 thousand subnets. However, extremely large enterprises can obtain prefixes shorter than /48 from one of the address registries, if they provide an adequate technical justification.

Internal routing must be arranged to direct traffic as required, using routing metrics that favor one ISP or another, or spread the load, as desired. When the egress to a particular ISP fails, backup routes to an alternative egress router will take over. An additional advantage to the enterprise is that address renumbering will never be required, since the /48 prefix is tied to the enterprise, not to one of their ISPs.

This method is tried and tested. However, there are two reasons why it cannot be extended indefinitely to cover smaller enterprises or even domestic users. Firstly, it is significantly more costly than a single provider-assigned (PA) prefix, and requires some level of operational management by skilled technicians. Secondly, the wide area BGP-4 routing system is widely considered unable to cope with the millions of PI prefixes that would ensue if a majority of small and medium enterprises adopted this solution. In November 2023, the global BGP-4 system carried about 200,000 IPv6 routes. There are estimated to be 32 million small businesses in the USA alone, and 200 million in the world. If every small business suddenly had its own PI prefix, the Internet would stop working.

**Small or medium sites**

Except for some thousands of large enterprises, a viable solution for multihoming of small or medium enterprises must be based on PA addresses, if it is to be used by millions of sites. However, as shown in the previous section, operating with more than one PA prefix at the same time is currently impractical, especially if transport session survivability is required.

The IETF has made various attempts to solve this problem, including the SHIM6 protocol [RFC5533] and the Multiple Provisioning Domain Architecture [RFC7556]. Such methods have not been successfully deployed. Other options, such as centralizing redundant connections for a large corporate network at a single site, or deploying application layer proxies to decouple internal and external addressing, remain out of reach for small or medium enterprises.

If we abandon the goal of transport session survivability, so that applications will have to recover from broken transport connections after a multihoming failover, the problem is simplified. It should be noted that essentially all mass market client applications already handle such disconnects, which are commonplace when mobile or portable devices move from place to place. This leads to one possible approach to multihoming for small sites, which is essentially to do nothing except connect the site to two (or more) ISPs and assign two (or more) PA prefixes, and leave client applications to find a working path by trial and error. This is essentially a generalization of the Happy Eyeballs approach [RFC8305], but it will lead to help desk calls in the case of applications that are not sufficiently resilient. It is clearly not sufficient for a large site, especially if it operates servers as well as client hosts.

An approach that should avoid some of these help desk calls, but is not currently favored by the IETF, is to used dynamic network prefix translation, known as NPTv6 [RFC6296], [3. Translation and IPv4 as a service]. In this model, a translator is placed at the site exit router towards each ISP. Outgoing and incoming packets are translated to and from appropriate PA addresses. The routeable prefix part of each address is changed, and possibly some bits in the IID, in a way that avoids transport checksum errors. This translation is stateless and reversible, so causes much less difficulty than traditional NAT; no port translation is needed.

To simplify the translation processs, internal hosts (both clients and servers) would be assigned Unique Local Addresses (ULAs) [RFC4193] that would rarely change. However, servers will be announced to the outside world via DNS using their translated PA addresses.

This method is known to have been successfully tested, although not recommended by the IETF. It should be noted, however, that NPTv6 does not share all the disadvantages of IPv4 NAT. As discussed in RFC 6296,

- NPTv6 does not need to translate port numbers, and it is checksum-neutral, so the transport layer is effectively unaffected.
- Translation is stateless, so matters such as asymmetric routing, load sharing, and router fail-over are not affected.
- Filtering of unwanted traffic requires an adequate firewall, but this is true for any serious IPv6 (or IPv4) deployment.
- Topology hiding, which is sometimes cited as an argument for NAT, is discussed in [4. Topology obfuscation]. NPTv6 does indeed largely obfuscate local topology. For example (again following RFC 6296), a host whose actual address is `fd01:0203:0405:0001::1234` might appear on the Internet as `2001:db8:0001:d550::1234`. An attacker that does not know the site's ULA prefix (`fd01:0203:0405::/48`) cannot reverse the translation and deduce the actual subnet prefix.

Of course, NPTv6 retains some of the disadvantages of NAT: all of the problems that directly follow from having different IP addresses at the two ends of a connection. Section 5 of RFC 6296 discusses this. Any site running NPTv6 must either deal with these problems, or avoid any affected applications. In particular, SIP (Session Initiation Protocol for IP telephony) will not work without the support of a proxy mechanism [RFC6314] as well as provision for IPv6/IPv4 coexistence [RFC6157]. This limits the applicability of NPTv6.

#### Transport layer solutions

Another possible approach to site multihoming is to treat it as a transport layer problem. If a transport protocol is agile enough to use multiple paths (i.e., multiple source/destination address pairs), failures at the network layer can be hidden. Multipath TCP (MPTCP, [RFC8684]) is defined but not widely available. A multipath version of QUIC is under discussion, as is a versatile API for the transport layer that would support multipath solutions. Discussion continues in the IETF.

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### Energy consumption

There is no firm evidence whether IPv6 has net energy consumption greater or less than IPv4 for the same application layer traffic load. There are factors that might work in favour of IPv6, such as a larger minimum PDU size or less energy spent on network address translation, and factors that might work against it, such as the transmission time for longer packet headers or greater use of link-local multicast. Equally, there is no evidence whether different co-existence strategies (e.g., native dual stack versus IPv4-as-a-service) have significantly different energy costs.

BCP 202 makes specific recommendations on reducing the energy consumption of IPv6 Router Advertisements.

It is worth noting that in the area of constrained IPv6 nodes with very limited battery power and transmission capacity [RFC8376], considerable attention has been paid to energy consumption, including compression mechanisms such as Generic Framework for Static Context Header Compression and Fragmentation (SCHC) [RFC8724].

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### Basic Windows commands

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# Case Studies

This chapter will contain a variety of short case studies, based on real experience, for a range of network types. It will never be complete, as every network is slightly different, and it will evolve as time goes on.

A good set of existing case studies from ARIN members can be found in the ARIN blog.

Here is a Malaysian case study via APNIC.

Here is a deployment case at a large conference.

This is an **open invitation** to contribute a case study for this chapter. If you have deployed an IPv6 network, please write a short section with emphasis on what major choices you made, what worked well, and what problems you encountered. Even a summary in one paragraph would be helpful. Large and small enterprise networks, and large or small carrier networks, are all of interest. It isn't necessary to identify the particular network, if you prefer to keep that private.

If you have already published such a description, just a pointer will be fine.

How to contribute

CERN and the LHC

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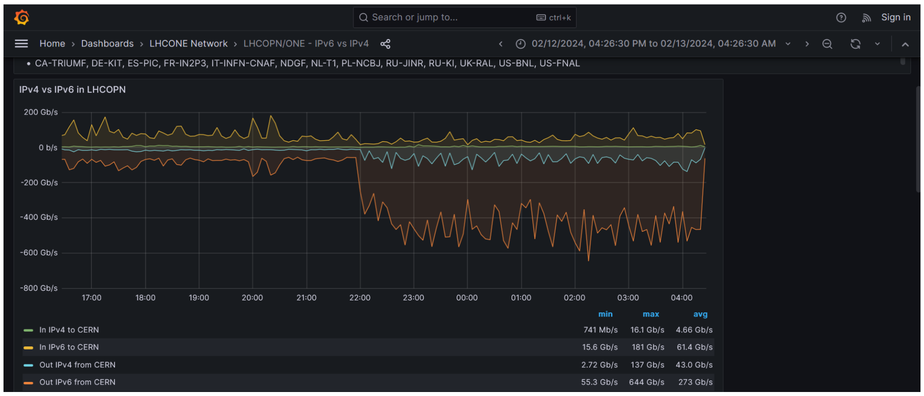
## CERN and the LHC

The CERN laboratory and the Worldwide LHC Computing Grid (WLCG) are large users of IPv6 for massive data transfers. Some recent statistics are shown here:




(Image from the February 2024 data challenge at CERN.)

The CERN site itself operates a classical IPv4 and IPv6 dual stack, and uses DHCPv6 for IPv6 address assignment.

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## Deployment Status



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### Status

When speaking of IPv6, a question immediately comes up: "How many people do use IPv6 on the Internet?". Answering this question is fundamental to get an immediate understanding of the real adoption of IPv6. A recent overview is presented in RFC 9386.

A count of IPv6 users is monitored by various organizations. For example, both Facebook and Google provide statistics on the users that access their services over IPv6. A very informative blog was posted in 2023 by Cloudflare, showing that humans use IPv6 a lot more than bots, which seem to prefer IPv4. At the end of 2023, Google and Cloudflare roughly agreed on 46% adoption by worldwide users.

Akamai provides data measuring the number of hits to their content delivery platform. For example, they showed 72% adoption in India in early 2024.

APNIC quantifies the use of IPv6 by means of a script that runs on Internet browsers.

Some statistics on DNS records and reachability for top web sites may be found at Dan Wing's site. These data suggest 29% IPv6 penetration by July 2023.

At the time of writing, there are large discrepancies between data from these and other sources. In fact there is no well-defined metric for "how many IPv6 users exist" or "how much IPv6 traffic exists". To take one example, Google estimates the fraction of Google "hits" that use IPv6, yet Google is very little used in China so these data cannot represent the true world-wide situation. Estimates posted to the IETF by Geoff Huston in July 2023 suggest that Google observes a 7% adoption rate in China, while the APNIC measurement reports 30%.

We show here the APNIC presentation of results, as it comes from a Regional Internet Registry (RIR) to show the number of the Internet IPv6 users compared with the total Internet population (in million, see next table).

| | Sep 2018 | Sep 2019 | Sep 2020 | Sep 2021 | Sep 2022 | CAGR |
|---|---|---|---|---|---|---|
| IPv6 | 563.55 | 707.49 | 1,107.15 | 1,170.63 | 1,392.48 | 25.38% |
| World | 3,475.41 | 4,211.31 | 4,245.40 | 4,246.68 | 4,316.33 | 5.57% |
| Ratio | 16.22% | 16.80% | 26.08% | 27.57% | 32.26% | |

A third of the Internet population apparently employs IPv6. It is also interesting to look at the growth curve. The main indicator here is the Compound Annual Growth Rate (CAGR), which shows a two-digit growth across the 5-year period 2018-2022.

There is a caveat, though, we may want to consider. The method used by APNIC cannot be fully employed in China, due to local policy filtering traffic from abroad. An independent Chinese research reports 713 million measured IPv6 customers as of September 2022, against the 220 million reported by APNIC. If we add the difference between the two statistics to the global count, we end up with a Ratio of 43.68% in September 2022, not that far from the "psychological" threshold of 50%.

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## Deployment by carriers

All the organizations providing or using Internet connectivity services have an associated Autonous System Number (ASN). APNIC provides statistics on the evolution of IPv6 support across the ASNs in the world, as observed in the Internet routing tables.

| Advertised ASNs | Jan 2018 | Jan 2019 | Jan 2020 | Jan 2021 | Jan 2022 | CAGR |
|---|---|---|---|---|---|---|
| IPv6-capable ASNs | 14,500 | 16,470 | 18,650 | 21,400 | 28,140 | 18% |
| Total ASNs | 59,700 | 63,100 | 66,800 | 70,400 | 72,800 | 5% |
| Ratio | 24.3% | 26.1% | 27.9% | 30.4% | 38.7% | |

The percentage of IPv6-capable ASNs is growing over the years, which is a good sign. On the other hand, the table does not distinguish the degree of adoption across the different industries, that is whether the ASNs are associated to a carrier, a service provider or an entreprise. To zoom in at that level, it is necessary to look at more detailed statistics such as those provided by Akamai or APNIC.

Not unsurprisingly, the vast majority of carriers worldwide already support IPv6. Yet, differences exist. As a general rule, the carriers active in those countries with higher IPv6 adoption also show higher levels of IPv6 utilization. For example, based on the Akamai statistics, IPv6 adoption in the United States is 51%. Carriers such as AT&T, Comcast, T-Mobile and Verizon all exceed 70% of IPv6 use in their networks. In Europe, both Belgium and Germany reach 50% of IPv6 traffic. Proximus, Telenet, DT, Telefonica Germany, Versatel and Vodafone Germany range from 50% to 70%. India shows 51% IPv6 adoption. Carriers there also have a high IPv6 rate. Bharti, Reliance Jio and Vodafone India find themselves between 60% and 70%.

Whilst it cannot be gneralized, in countries with lower IPv6 adoption the local carriers also tend to be slower in enabling IPv6. For example, European countries such as Spain, Italy and Poland show respectively 4.5%, 7% and 13.5% adoption. Based on APNIC data, exluding the exceptions of Telefonica de España (26%), Vodafone Italy (21%), Wind/3 Italy (22%) and Orange Poland (23%), all the other carries sit quite below the threshold of 20% adoption.

Differences also apply between wired and wireless carriers. The latter are often more advanced with IPv6. In several cases [RFC9386], the reason for them to move to IPv6 depended on the lack of public IPv4 addresses. Those carriers have decided to develop strategic plans to enable IPv6-only underlay services, for example through the adoption of translation mechanisms such as 464XLAT (Reliance Jio, T-Mobile), guaranteeing legacy IPv4-as-a-Service support. Notable examples of early IPv6 adoption in the wired domain are Comcast in the US and Sky in the UK.

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### Deployment in the home

It is hard to estimate what fraction of home users have IPv6 connectivity on a given date. The Google statistics are interesting, because they clearly show weekend peaks in IPv6 access (up to 43% in April 2023), suggesting a quite high level of home and/or mobile IPv6 connectivity.

Some, but not all, devices on the market for home (or small office) use support both IPv6 and IPv4. However, older devices only have IPv4. For this reason, a typical home network today runs a dual stack. Also, a typical network does not include multiple subnets; the only router present is at the same time the subnet router and the CE router. Assuming the ISP supports IPv6, regardless whether it provides native IPv4 or IPv4 as a service, the router provides a dual stack service on the LAN. The LAN itself is typically WiFi, possibly bridged to Ethernet. (Even if the CE router does *not* support IPv6 at all, link-local IPv6 should work.)

As a result, things are fairly simple. Devices such as PCs and printers can communicate with each other using whatever works -- IPv4, link-local IPv6, or global IPv6. (For example: a Windows 10 PC installed in 2019 communicates with a Canon inkjet printer installed in 2022, using link-local IPv6, needing no manual configuration.) Connections to the Internet will be preferentially established using IPv6 for services that have a AAAA address in the DNS, or IPv4 otherwise. Such connections may be optimized by the Happy Eyeballs technique [RFC8305]. Most home users will remain largely ignorant of all this.

The situation becomes more complicated when various home automation devices are considered, especially if it becomes desirable to split the home network into separate subnets. Such networks need to be essentially self-configuring and self-managing, as do "Internet of Things" networks. These complex topics are out of scope for this book.

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## Deployment in the enterprise

Measuring the adoption of IPv6 in the enterprise domain is not straightforward. Since it is hard to look at it from the network "inside", one of the few currently available approaches is to check the IPv6 readiness from outside the enterprise's network. NIST provides a method to infer whether US enterprises support IPv6 by checking its external services, such as the availability of Domain Name System (DNS) AAAA records, an IPv6-based mail service, or the support of IPv6 on their website. The same method can be applied to Chinese and Indian enterprises.

DNS has a good support in all cases: more than 50% of the enterprises in the three economies considered have AAAA records, a sign that IPv6 support is generally available. The same cannot be said of the other services that have much lower adoption. [RFC9386] provides other statistics about more specific industry domains.

What are the factors hindering the adoption of IPv6 in the enterprise? Appendix B of [RFC9386] reports the result of a poll issued by the Industry Network Technology Council (INTC) to check the need for IPv6 training by some medium and large US enterprises.

The poll shows that lack of IPv6 knowledge is one of the main issues. This reflects into the need for training, in particular in the areas of IPv6 security and IPv6 troubleshooting. Apart from training, enterprises feel that IPv6 security is of operational concern as well as the conversion of the applications they use in their daily activity to IPv6.

### Addressing in the enterprise

How organizations craft their addressing schemes will be varied and will likely be determined by a number of factors. The largest factor that will influence the procurement or otherwise obtaining of address resources will be organizational size. The size of a given organization often (but not always) dictates the criticality of networking resources which includes both physical assets (routers, switches, security appliances) as well as human resources, and the level of skill available either by direct employment or by contracted assistance. Also included in these resources is the logical elements required for a presence on the global internet in the manner of addressing. Larger or more mature organizations may already posses network resources such as Autonomous System Numbers (ASNs), legacy IP resources, and possibly existing provider independent (PI) IPv6 space. First, it is important to make the distinction of address space types. There are really three different types of address allocations possible, provider independent, provider allocated, and unique local addressing [2. Addresses].

Organizations will need to understand the differences as it will be both dictated by resource availability and will inform routing policy and future deployment changes.

### Provider Independent address space

Provider Independent (PI) address space consists of address resources obtained directly from a regional internet registry (RIR). These address resources are allocated to a requesting entity after a formal request process that entails a light justification process and an annual fee collection. The addressing is allocated to the requesting entity and, within the scope of the global internet best practices, can be used however the assigned entity sees fit.

For PI address space based deployments, organizations will need to contract external consultancy or have in-house expertise in obtaining address space from a regional internet registry (RIR) that will be determined by the locality of their organization. Further, obtaining PI address space from an RIR means coordinating with their ISP(s) to route the PI space based on some routing policy with upstream provider(s). If an organization is not staffed to or does not have the experience or knowledge on the processes of obtaining address space and routing it globally (i.e. within the internet default free zone (DFZ)), it will be required to contract such tasks. In house or contracted IT support should understand the intricacies of routing policy of said PI address space in the appropriate routing registries, maintaining best practice filtering (MANRS), populating and maintaining internet route registry (IRR) data, implementing Resource Public Key Infrastructure (RPKI), and have at least a rudimentary understanding of what operating in the DFZ means. In general, maintaining PI address space offers the most flexibility and stability due to the portable nature of the resources, and although it does have a higher startup cost both operationally and financially, is the preferable method for medium to large enterprises.

### Provider Assigned address space

Provider Assigned (PA) address space consists of address space that is assigned to a specific upstream provider and sub-delegated to a customer.

If receiving PA from an upstream provider, designs such as multihoming is a more involved process that will involve coordination with the upstream transit provider that owns the IP resources. (See [6. Multi-prefix operation] for some discussion of multihoming.) Additionally, renumbering is functionally required if said provider is exchanged for another unless NAT is employed as a translation tool. Obtaining additional address space may require more effort and expense, or may not be possible.

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## Troubleshooting

If you know what should be written here, please write it! How to contribute.

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## Advanced Troubleshooting

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## Tools

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## Further Reading

There are massive amounts of information about IPv6 "out there" on the Internet. Readers should be aware that not all of it is reliable. Very often, it is out of date, because IPv6 was originally designed in the 1990s and the Internet as a whole has evolved a lot since then, and IPv6 has been updated in consequence.

The definitive source of IPv6 standards, best current practices, and other technical information is the *latest* RFCs (Requests for Comments) from the IETF. RFCs are freely available from the RFC Editor.

*Warning:* obsolete RFCs are never modified or deleted. It is essential to look at the current status of an RFC before trusting it. For example, the current status of the 2017 version of the main IPv6 standard is shown at this info page. If an RFC is marked as "Obsoleted by" it should be ignored - look instead at the newer RFC that replaces it. Thus, any reference to RFC 2460 should be treated as a reference to RFC 8200.

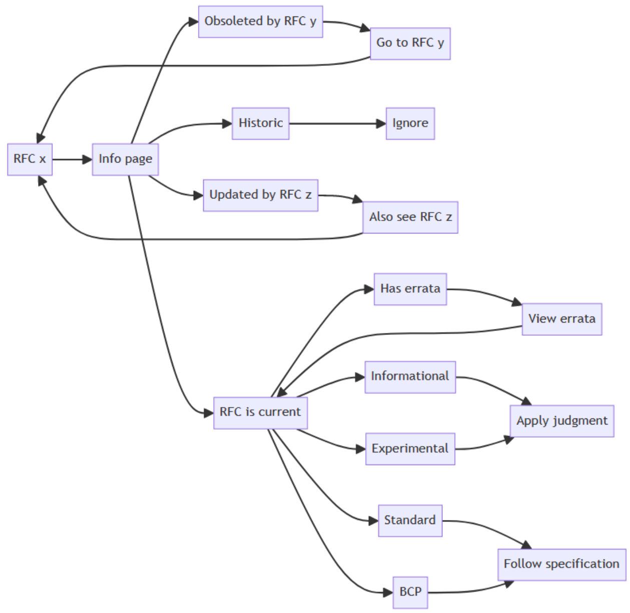
Even if not obsoleted, an RFC may be "Updated by" one or more newer RFCs. You need to look at those in addition.

If an RFC is marked as "Proposed Standard", "Draft Standard", "Internet Standard" or "Best Current Practice (BCP)" it is the result of rough consensus in the IETF and is a definitive specification. However, that doesn't override "Obsoleted by" or "Updated by".

If it's marked "Informational", "Experimental", or "Historic", those words mean exactly what they say. Some of these RFCs don't even come from the IETF; they may come from the IAB (Internet Architecture Board), the IRTF (Internet Research Task Force) or elswehere.

Any RFC may be marked as having *errata*, the Latin word for errors. Check them! Often they are trivial, but sometimes they are important.

Here's an attempt to explain this with a diagram:

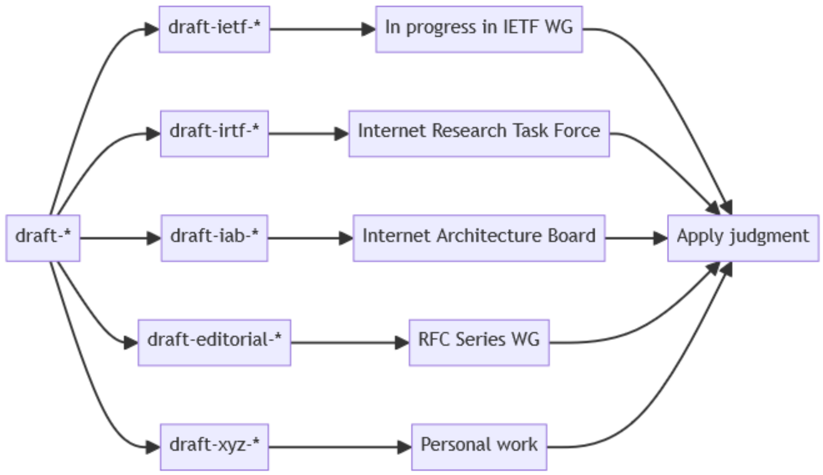



An important RFC is the latest version of IPv6 Node Requirements, which cites numerous other RFCs. However, at the time of this writing, there are already at least 12 more recent IPv6 RFCs from the IETF since the last update of the node requirements. The documents of the main IETF working groups concerned with IPv6 are listed at the 6MAN and V6OPS web pages. Beware of the fact that these pages list unapproved drafts and obsolete RFCs as well as current RFCs.

In a few cases in this book, we refer to unapproved drafts (usually known as Internet-Drafts or I-Ds). Officially, it is inappropriate to use I-Ds as reference material. While sometimes very useful and up-to-date, such drafts do not have the same status as RFCs and should not be relied on as stable documents [draft-wkumari-not-a-draft]. They have not been thoroughly reviewed, they may be wrong, and there is a high probability that they will never be published as an RFC. A draft whose file name starts "draft-ietf-" has been adopted by an IETF working group, so it has passed a preliminary review, but it is still a draft, it may still be wrong, and may never become an RFC.

Drafts whose names do *not* start "draft-ietf-" are named according to an agreed convention, but they have almostly certainly not been adopted by an IETF working group and should be read with caution. The definitive source of information about I-Ds is the IETF data tracker.

All I-Ds are open to comment and contain contact information. Feel free to email their authors or the relevant mailing list. This diagram gives an overview:




There are also numerous books, book chapters, and other documents about IPv6. However, any source that is more than one or two years old is likely to be out of date in some aspects, and discuss obsolete deployment options. Here are some starting points:

- Inessential IPv6. This project overlaps in intent with book6 so we will attempt to coordinate.
- The JANET technical guide to IPv6 (2021)
- The APNIC IPv6 Fundamentals Course
- Olivier Bonaventure's Computer Networking : Principles, Protocols and Practice (2019)
- ISOC's IPv6 Security for IPv4 Engineers (2019)
- ISOC's IPv6 Security FAQ (2019)
- Graziani, Rick. IPv6 Fundamentals: A Straightforward Approach to Understanding IPv6 (2nd edition), Cisco Press, ISBN 978-1587144776 (2017). A very good book, but 5 years' worth of progress has happened since then!
- Great IPv6 blogging from Iljitsch van Beijnum
- van Beijnum, Iljitsch. Internet Routing with BGP (2022). This contains a lot about IPv6 inter-domain routing.
- more TBD

RFC bibliography

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## RFC bibliography

This section is a machine-generated list of all current RFCs that mention IPv6 or DHCPv6 in their title or come from the major IPv6 working groups. Obsolete RFCs are not included. There are subsections for Standards, BCPs, Informational and Experimental RFCs. Be *cautious* about old Informational or Experimental RFCs - they may be misleading as well as out of date.

RFCbib6 run at 2024-08-14 15:40:55 UTC+1200 (487 RFCs found)

### Standards Track (262 RFCs)

- RFC 2080: RIPng for IPv6
- RFC 2428: FTP Extensions for IPv6 and NATs
- RFC 2464: Transmission of IPv6 Packets over Ethernet Networks
- RFC 2467: Transmission of IPv6 Packets over FDDI Networks
- RFC 2470: Transmission of IPv6 Packets over Token Ring Networks
- RFC 2473: Generic Packet Tunneling in IPv6 Specification
- RFC 2474: Definition of the Differentiated Services Field (DS Field) in the IPv4 and IPv6 Headers
- RFC 2491: IPv6 over Non-Broadcast Multiple Access (NBMA) networks
- RFC 2492: IPv6 over ATM Networks
- RFC 2497: Transmission of IPv6 Packets over ARCnet Networks
- RFC 2526: Reserved IPv6 Subnet Anycast Addresses
- RFC 2529: Transmission of IPv6 over IPv4 Domains without Explicit Tunnels
- RFC 2545: Use of BGP-4 Multiprotocol Extensions for IPv6 Inter-Domain Routing
- RFC 2590: Transmission of IPv6 Packets over Frame Relay Networks Specification
- RFC 2675: IPv6 Jumbograms
- RFC 2710: Multicast Listener Discovery (MLD) for IPv6
- RFC 2711: IPv6 Router Alert Option
- RFC 2894: Router Renumbering for IPv6
- RFC 3056: Connection of IPv6 Domains via IPv4 Clouds
- RFC 3111: Service Location Protocol Modifications for IPv6
- RFC 3122: Extensions to IPv6 Neighbor Discovery for Inverse Discovery Specification
- RFC 3146: Transmission of IPv6 Packets over IEEE 1394 Networks
- RFC 3162: RADIUS and IPv6
- RFC 3175: Aggregation of RSVP for IPv4 and IPv6 Reservations
- RFC 3226: DNSSEC and IPv6 A6 aware server/resolver message size requirements
- RFC 3306: Unicast-Prefix-based IPv6 Multicast Addresses
- RFC 3307: Allocation Guidelines for IPv6 Multicast Addresses
- RFC 3319: Dynamic Host Configuration Protocol (DHCPv6) Options for Session Initiation Protocol (SIP) Servers

- RFC 3595: Textual Conventions for IPv6 Flow Label
- RFC 3596 (STD 88): DNS Extensions to Support IP Version 6
- RFC 3646: DNS Configuration options for Dynamic Host Configuration Protocol for IPv6 (DHCPv6)
- RFC 3776: Using IPsec to Protect Mobile IPv6 Signaling Between Mobile Nodes and Home Agents
- RFC 3810: Multicast Listener Discovery Version 2 (MLDv2) for IPv6
- RFC 3898: Network Information Service (NIS) Configuration Options for Dynamic Host Configuration Protocol for IPv6 (DHCPv6)
- RFC 3956: Embedding the Rendezvous Point (RP) Address in an IPv6 Multicast Address
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- RFC 4295: Mobile IPv6 Management Information Base
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- RFC 4338: Transmission of IPv6, IPv4, and Address Resolution Protocol (ARP) Packets over Fibre Channel
- RFC 4380: Teredo: Tunneling IPv6 over UDP through Network Address Translations (NATs)
- RFC 4429: Optimistic Duplicate Address Detection (DAD) for IPv6
- RFC 4443 (STD 89): Internet Control Message Protocol (ICMPv6) for the Internet Protocol Version 6 (IPv6) Specification
- RFC 4449: Securing Mobile IPv6 Route Optimization Using a Static Shared Key
- RFC 4489: A Method for Generating Link-Scoped IPv6 Multicast Addresses
- RFC 4580: Dynamic Host Configuration Protocol for IPv6 (DHCPv6) Relay Agent Subscriber-ID Option
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- RFC 4659: BGP-MPLS IP Virtual Private Network (VPN) Extension for IPv6 VPN
- RFC 4668: RADIUS Authentication Client MIB for IPv6
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- RFC 5555: Mobile IPv6 Support for Dual Stack Hosts and Routers
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- RFC 6515: IPv4 and IPv6 Infrastructure Addresses in BGP Updates for Multicast VPN
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- RFC 5855 (BCP 155): Nameservers for IPv4 and IPv6 Reverse Zones
- RFC 6177 (BCP 157): IPv6 Address Assignment to End Sites
- RFC 6540 (BCP 177): IPv6 Support Required for All IP-Capable Nodes
- RFC 6853 (BCP 180): DHCPv6 Redundancy Deployment Considerations
- RFC 7227 (BCP 187): Guidelines for Creating New DHCPv6 Options
- RFC 7526 (BCP 196): Deprecating the Anycast Prefix for 6to4 Relay Routers
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- RFC 7934 (BCP 204): Host Address Availability Recommendations
- RFC 8180 (BCP 210): Minimal IPv6 over the TSCH Mode of IEEE 802.15.4e (6TiSCH) Configuration
- RFC 8421 (BCP 217): Guidelines for Multihomed and IPv4/IPv6 Dual-Stack Interactive Connectivity Establishment (ICE)
- RFC 8504 (BCP 220): IPv6 Node Requirements
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- RFC 1881: IPv6 Address Allocation Management
- RFC 1887: An Architecture for IPv6 Unicast Address Allocation
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- RFC 2185: Routing Aspects of IPv6 Transition
- RFC 2375: IPv6 Multicast Address Assignments
- RFC 2928: Initial IPv6 Sub-TLA ID Assignments
- RFC 3053: IPv6 Tunnel Broker
- RFC 3089: A SOCKS-based IPv6/IPv4 Gateway Mechanism
- RFC 3142: An IPv6-to-IPv4 Transport Relay Translator
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- RFC 5014: IPv6 Socket API for Source Address Selection
- RFC 5118: Session Initiation Protocol (SIP) Torture Test Messages for Internet Protocol Version 6 (IPv6)
- RFC 5149: Service Selection for Mobile IPv6
- RFC 5180: IPv6 Benchmarking Methodology for Network Interconnect Devices
- RFC 5181: IPv6 Deployment Scenarios in 802.16 Networks
- RFC 5220: Problem Statement for Default Address Selection in Multi-Prefix Environments: Operational Issues of RFC 3484 Default Rules
- RFC 5221: Requirements for Address Selection Mechanisms
- RFC 5270: Mobile IPv6 Fast Handovers over IEEE 802.16e Networks
- RFC 5271: Mobile IPv6 Fast Handovers for 3G CDMA Networks
- RFC 5375: IPv6 Unicast Address Assignment Considerations
- RFC 5419: Why the Authentication Data Suboption is Needed for Mobile IPv6 (MIPv6)
- RFC 5569: IPv6 Rapid Deployment on IPv4 Infrastructures (6rd)
- RFC 5570: Common Architecture Label IPv6 Security Option (CALIPSO)
- RFC 5637: Authentication, Authorization, and Accounting (AAA) Goals for Mobile IPv6
- RFC 5757: Multicast Mobility in Mobile IP Version 6 (MIPv6): Problem Statement and Brief Survey
- RFC 5902: IAB Thoughts on IPv6 Network Address Translation
- RFC 5963: IPv6 Deployment in Internet Exchange Points (IXPs)
- RFC 6018: IPv4 and IPv6 Greynets
- RFC 6092: Recommended Simple Security Capabilities in Customer Premises Equipment (CPE) for Providing Residential IPv6 Internet Service
- RFC 6097: Local Mobility Anchor (LMA) Discovery for Proxy Mobile IPv6
- RFC 6104: Rogue IPv6 Router Advertisement Problem Statement
- RFC 6105: IPv6 Router Advertisement Guard
- RFC 6127: IPv4 Run-Out and IPv4-IPv6 Co-Existence Scenarios
- RFC 6144: Framework for IPv4/IPv6 Translation
- RFC 6169: Security Concerns with IP Tunneling
- RFC 6180: Guidelines for Using IPv6 Transition Mechanisms during IPv6 Deployment
- RFC 6214: Adaptation of RFC 1149 for IPv6
- RFC 6219: The China Education and Research Network (CERNET) IVI Translation Design and Deployment for the IPv4/IPv6 Coexistence and Transition
- RFC 6224: Base Deployment for Multicast Listener Support in Proxy Mobile IPv6 (PMIPv6) Domains

- RFC 6264: An Incremental Carrier-Grade NAT (CGN) for IPv6 Transition
- RFC 6279: Proxy Mobile IPv6 (PMIPv6) Localized Routing Problem Statement
- RFC 6294: Survey of Proposed Use Cases for the IPv6 Flow Label
- RFC 6324: Routing Loop Attack Using IPv6 Automatic Tunnels: Problem Statement and Proposed Mitigations
- RFC 6342: Mobile Networks Considerations for IPv6 Deployment
- RFC 6343: Advisory Guidelines for 6to4 Deployment
- RFC 6436: Rationale for Update to the IPv6 Flow Label Specification
- RFC 6459: IPv6 in 3rd Generation Partnership Project (3GPP) Evolved Packet System (EPS)
- RFC 6547: RFC 3627 to Historic Status
- RFC 6568: Design and Application Spaces for IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs)
- RFC 6583: Operational Neighbor Discovery Problems
- RFC 6586: Experiences from an IPv6-Only Network
- RFC 6589: Considerations for Transitioning Content to IPv6
- RFC 6606: Problem Statement and Requirements for IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) Routing
- RFC 6612: Interactions between Proxy Mobile IPv6 (PMIPv6) and Mobile IPv6 (MIPv6): Scenarios and Related Issues
- RFC 6629: Considerations on the Application of the Level 3 Multihoming Shim Protocol for IPv6 (Shim6)
- RFC 6653: DHCPv6 Prefix Delegation in Long-Term Evolution (LTE) Networks
- RFC 6654: Gateway-Initiated IPv6 Rapid Deployment on IPv4 Infrastructures (GI 6rd)
- RFC 6666: A Discard Prefix for IPv6
- RFC 6782: Wireline Incremental IPv6
- RFC 6866: Problem Statement for Renumbering IPv6 Hosts with Static Addresses in Enterprise Networks
- RFC 6877: 464XLAT: Combination of Stateful and Stateless Translation
- RFC 6879: IPv6 Enterprise Network Renumbering Scenarios, Considerations, and Methods
- RFC 6883: IPv6 Guidance for Internet Content Providers and Application Service Providers
- RFC 6948: Some Measurements on World IPv6 Day from an End-User Perspective
- RFC 6964: Operational Guidance for IPv6 Deployment in IPv4 Sites Using the Intra-Site Automatic Tunnel Addressing Protocol (ISATAP)
- RFC 6992: Routing for IPv4-Embedded IPv6 Packets
- RFC 7010: IPv6 Site Renumbering Gap Analysis
- RFC 7031: DHCPv6 Failover Requirements
- RFC 7040: Public IPv4-over-IPv6 Access Network
- RFC 7059: A Comparison of IPv6-over-IPv4 Tunnel Mechanisms
- RFC 7066: IPv6 for Third Generation Partnership Project (3GPP) Cellular

Hosts

- RFC 7084: Basic Requirements for IPv6 Customer Edge Routers
- RFC 7098: Using the IPv6 Flow Label for Load Balancing in Server Farms
- RFC 7113: Implementation Advice for IPv6 Router Advertisement Guard (RA-Guard)
- RFC 7123: Security Implications of IPv6 on IPv4 Networks
- RFC 7157: IPv6 Multihoming without Network Address Translation
- RFC 7269: NAT64 Deployment Options and Experience
- RFC 7278: Extending an IPv6 /64 Prefix from a Third Generation Partnership Project (3GPP) Mobile Interface to a LAN Link
- RFC 7368: IPv6 Home Networking Architecture Principles
- RFC 7381: Enterprise IPv6 Deployment Guidelines
- RFC 7404: Using Only Link-Local Addressing inside an IPv6 Network
- RFC 7421: Analysis of the 64-bit Boundary in IPv6 Addressing
- RFC 7439: Gap Analysis for Operating IPv6-Only MPLS Networks
- RFC 7445: Analysis of Failure Cases in IPv6 Roaming Scenarios
- RFC 7511: Scenic Routing for IPv6
- RFC 7561: Mapping Quality of Service (QoS) Procedures of Proxy Mobile IPv6 (PMIPv6) and WLAN
- RFC 7690: Close Encounters of the ICMP Type 2 Kind (Near Misses with ICMPv6 Packet Too Big (PTB))
- RFC 7707: Network Reconnaissance in IPv6 Networks
- RFC 7721: Security and Privacy Considerations for IPv6 Address Generation Mechanisms
- RFC 7739: Security Implications of Predictable Fragment Identification Values
- RFC 7755: SIIT-DC: Stateless IP/ICMP Translation for IPv6 Data Center Environments
- RFC 7756: Stateless IP/ICMP Translation for IPv6 Internet Data Center Environments (SIIT-DC): Dual Translation Mode
- RFC 7824: Privacy Considerations for DHCPv6
- RFC 7849: An IPv6 Profile for 3GPP Mobile Devices
- RFC 7872: Observations on the Dropping of Packets with IPv6 Extension Headers in the Real World
- RFC 7943: A Method for Generating Semantically Opaque Interface Identifiers (IIDs) with the Dynamic Host Configuration Protocol for IPv6 (DHCPv6)
- RFC 7973: Assignment of an Ethertype for IPv6 with Low-Power Wireless Personal Area Network (LoWPAN) Encapsulation
- RFC 8021: Generation of IPv6 Atomic Fragments Considered Harmful
- RFC 8043: Source-Address-Dependent Routing and Source Address Selection for IPv6 Hosts: Overview of the Problem Space
- RFC 8065: Privacy Considerations for IPv6 Adaptation-Layer Mechanisms
- RFC 8096: The IPv6-Specific MIB Modules Are Obsolete
- RFC 8136: Additional Transition Functionality for IPv6
- RFC 8219: Benchmarking Methodology for IPv6 Transition Technologies

- RFC 8273: Unique IPv6 Prefix per Host
- RFC 8354: Use Cases for IPv6 Source Packet Routing in Networking (SPRING)
- RFC 8369: Internationalizing IPv6 Using 128-Bit Unicode
- RFC 8468: IPv4, IPv6, and IPv4-IPv6 Coexistence: Updates for the IP Performance Metrics (IPPM) Framework
- RFC 8475: Using Conditional Router Advertisements for Enterprise Multihoming
- RFC 8501: Reverse DNS in IPv6 for Internet Service Providers
- RFC 8585: Requirements for IPv6 Customer Edge Routers to Support IPv4-as-a-Service
- RFC 8678: Enterprise Multihoming using Provider-Assigned IPv6 Addresses without Network Prefix Translation: Requirements and Solutions
- RFC 8683: Additional Deployment Guidelines for NAT64/464XLAT in Operator and Enterprise Networks
- RFC 8978: Reaction of IPv6 Stateless Address Autoconfiguration (SLAAC) to Flash-Renumbering Events
- RFC 8992: Autonomic IPv6 Edge Prefix Management in Large-Scale Networks
- RFC 9030: An Architecture for IPv6 over the Time-Slotted Channel Hopping Mode of IEEE 802.15.4 (6TiSCH)
- RFC 9098: Operational Implications of IPv6 Packets with Extension Headers
- RFC 9099: Operational Security Considerations for IPv6 Networks
- RFC 9288: Recommendations on the Filtering of IPv6 Packets Containing IPv6 Extension Headers at Transit Routers
- RFC 9313: Pros and Cons of IPv6 Transition Technologies for IPv4-as-a-Service (IPv4aaS)
- RFC 9365: IPv6 Wireless Access in Vehicular Environments (IPWAVE): Problem Statement and Use Cases
- RFC 9386: IPv6 Deployment Status
- RFC 9433: Segment Routing over IPv6 for the Mobile User Plane
- RFC 9453: Applicability and Use Cases for IPv6 over Networks of Resource-constrained Nodes (6lo)

**Experimental (23 RFCs)**

- RFC 4620: IPv6 Node Information Queries
- RFC 5514: IPv6 over Social Networks
- RFC 5572: IPv6 Tunnel Broker with the Tunnel Setup Protocol (TSP)
- RFC 5726: Mobile IPv6 Location Privacy Solutions
- RFC 5739: IPv6 Configuration in Internet Key Exchange Protocol Version 2 (IKEv2)
- RFC 6058: Transient Binding for Proxy Mobile IPv6
- RFC 6296: IPv6-to-IPv6 Network Prefix Translation
- RFC 6618: Mobile IPv6 Security Framework Using Transport Layer Secu-

rity for Communication between the Mobile Node and Home Agent

- RFC 6743: ICMP Locator Update Message for the Identifier-Locator Network Protocol for IPv6 (ILNPv6)
- RFC 6744: IPv6 Nonce Destination Option for the Identifier-Locator Network Protocol for IPv6 (ILNPv6)
- RFC 6751: Native IPv6 behind IPv4-to-IPv4 NAT Customer Premises Equipment (6a44)
- RFC 7028: Multicast Mobility Routing Optimizations for Proxy Mobile IPv6
- RFC 7109: Flow Bindings Initiated by Home Agents for Mobile IPv6
- RFC 7161: Proxy Mobile IPv6 (PMIPv6) Multicast Handover Optimization by the Subscription Information Acquisition through the LMA (SIAL)
- RFC 7287: Mobile Multicast Sender Support in Proxy Mobile IPv6 (PMIPv6) Domains
- RFC 7411: Multicast Listener Extensions for Mobile IPv6 (MIPv6) and Proxy Mobile IPv6 (PMIPv6) Fast Handovers
- RFC 7417: Extensions to Generic Aggregate RSVP for IPv4 and IPv6 Reservations over Pre-Congestion Notification (PCN) Domains
- RFC 7600: IPv4 Residual Deployment via IPv6 - A Stateless Solution (4rd)
- RFC 7837: IPv6 Destination Option for Congestion Exposure (ConEx)
- RFC 8135: Complex Addressing in IPv6
- RFC 8885: Proxy Mobile IPv6 Extensions for Distributed Mobility Management
- RFC 9229: IPv4 Routes with an IPv6 Next Hop in the Babel Routing Protocol
- RFC 9268: IPv6 Minimum Path MTU Hop-by-Hop Option

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# Chapter Template

This chapter shows how to write a new chapter. It is intentionally listed in the contents of the book itself, and is intended to be a living chapter of a living book. You should also check CONTRIBUTING and LICENSE before contributing.

The second section in this chapter shows how to write a new section.

We use the GitHub dialect of Markdown. There is some information about this in the Markdown Usage section below, including how to include diagrams.

A chapter lives in its own directory, e.g. this chapter lives in the directory `99. Chapter Template`. Of course, the spaces are part of the directory name and the name is case-sensitive. The introduction to the chapter (like this file) is a markdown file with the same name again, e.g. `99. Chapter Template.md`.

The first line in this file is:

```
# Chapter Template
```

so that makes three repetitions of `Chapter Template`.

Start with the general intro for a chapter. Tell the reader what the chapter is all about. Then give a list of the sections. It would be possible to embed the sections right here, but maintenance by multiple authors will be easier with a separate file per section. So write the introductory text and then add a list of sections that you intend to write. For example, after the introduction, put:

```
## First Section
## Section Template
## Last Section
```

Please keep the section names short. They are also used as filenames. The text of the section `Section Template` will be in a file called `Section Template.md`.

Please do not add text inside or after the list of sections. That will confuse everybody.

Important: Markdown can't handle file names with spaces in them. When creating links, we have to replace spaces with %20, or avoid spaces in the file names. So here is the template for the list of sections after inserting links:

```
## [First Section](First%20Section.md)
## [Section Template](Section%20Template.md)
## [Last Section](Last%20Section.md)
```

That's a bit complicated, and since file names are case-sensitive, errors are easy to make. Therefore, there exists a Python program called makeBook, which can be run occasionally to create such links automatically, and reconcile differences between the actual chapter contents and the main Contents page.

It does some other things as well, to help authors:

1. If it finds a chapter in the main contents, but there is no corresponding chapter directory, it creates the latter with appropriate template files that the author(s) can edit. So adding `25. Interesting Stuff` at the obvious place in Contents.md would work.

2. If it finds a section in a chapter introduction, but there is no corresponding Markdown file, it creates such a file. The author only has to add the content.

3. If it finds a Markdown file in the chapter directory, but it's not in the chapter contents, it adds it to the list of contents.

4. It automatically inserts links at the bottom of each section pointing to the previous and next sections (if they exist) and back to the chapter introduction.

5. It expands certain references, as explained in Markdown Usage.

makeBook has to be run on the main Github branch from time to time. At this writing, there is limited practical experience with this - patience, please. If it goes wrong, there is nothing that can't be fixed manually. The main rule is: don't mess with the automatically generated links.

So, to repeat: add a new ## item to the chapter introduction, and makeBook will create the necessary .md file. Add a new .md file to the chapter directory, and makeBook will add it to the chapter contents.

*Pro tip:* Adding a new chapter, renaming or deleting a section or chapter, or moving a section from one chapter to another, etc., are not automated at present and may require a good deal of manual work. For that, see the special instructions.

First Section

Section Template

Markdown Usage

Last Section

**Back to main Contents**

## First Section

Section text goes here

**Next Top**

### Section Template

The section text goes here, all in Markdown. Don't try to insert or correct the following links by hand; the makeBook program will do that later.

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## Markdown Usage

The basics of using the GitHub dialect of markdown are here. As a general rule, please use the simpler constructs and avoid fancy formatting.

And don't forget, a separate .md file for each new section in any chapter of the book.

For some markdown editing tools, flowed text with no line breaks is a nuisance. Preferably, wrap the text at ~72 characters. makeBook will do this whenever it needs to write a file back, using the `mdformat` tool.

Web references can be done in basic markdown form, i.e.:

```
[text](URL)               to refer to any valid URL
```

but a feature adapted from kramdown is also available, e.g.

```
{{RFC8200}}               to refer to an RFC
{{BCP198}}                to refer to an IETF Best Current Practice
{{STD86}}                 to refer to an IETF Internet Standard
{{I-D.ietf-v6ops-xxx}}    to refer to an Internet Draft
{{draft-ietf-v6ops-xxx}}  the same!
{{Last Section}}          to refer to a section in the present chapter
{{2. Addresses}}          to refer to a section in another chapter  (the single space is r
```

Such references will be fixed up by the next run of makeBook, since they are unknown to GitHub's built-in markdown. There is some checking of the RFCs, draft names, etc. (but only when makeBook has web access).

*Note 1:* References will be surrounded by square brackets thus: [RFC8200]. If you want them without square brackets for grammatical reasons, such as using RFC 8200 as a noun, use *three* curly brackets:

```
{{{RFC8200}}}
{{{2. Addresses}}}
```

*Note 2:* If you string several references together, e.g.,

```
{{RFC4291}}{{RFC8200}}
```

they will be shown in a single pair of square brackets with commas: [RFC4291, RFC 8200].

Diagrams can be ASCII art when applicable, using `~~~` before and after, e.g.:

```
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |Version| Traffic Class |           Flow Label                  |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |         Payload Length        |  Next Header  |   Hop Limit   |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                             etc.                              |
```

More complex diagrams may be included using PNG generated by a separate drawing tool such as *mermaid* or *dia*, with the PNG file also stored here on GitHub, e.g.:

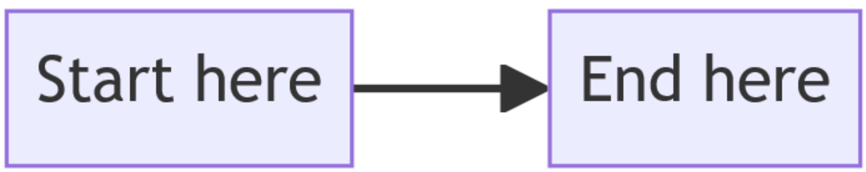
Source of *mermaid* diagram:

````
```mermaid
flowchart LR
    S[Start here] --> E[End here]
```
````

Embedded in markdown as a PNG file generated by *mermaid.live*:

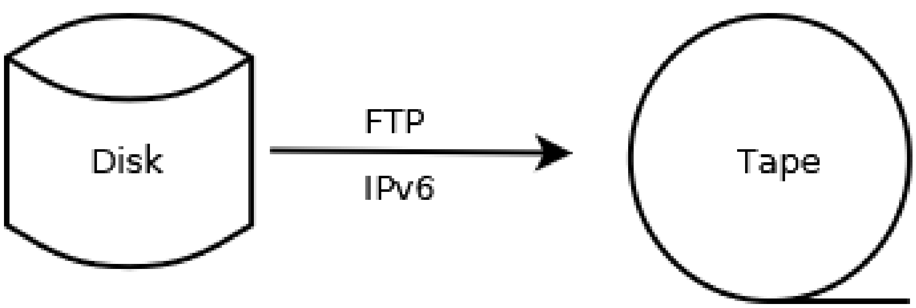
`<img src="./example1.png" width=250 alt="Start here, end here">`

Displayed thus:




Example generated with *dia*:

`<img src="./diag.png" alt="Disk feeding tape">`




Please add alternate text to help people with visual difficulties.

*Note 3:* Direct use of *mermaid* in markdown source is not recommended, as it causes difficulty when generating a PDF version of book6.

*Note 4:* Earlier versions of this section recommended SVG format. This has been removed since SVG causes difficulty when generating a PDF version of book6.

Existing diagrams in JPG format can be inserted in the same way.

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## Last Section

Section text goes here

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## book6 Main Index

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This index was created automatically, so it's dumb. It is not case-sensitive. It has links to each section that mentions each keyword. If you think any keywords are missing, please raise an issue (use link on GitHub toolbar).

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## book6 Citation Index

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RFC1918 ¶ ¶

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