Networking from the Bottom Up: IPv6

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What We Will Cover

- A bit of the History and Goals of IPv6
- IPv6 Protocol Code
- Neighbor Discovery
- Router Discovery
- ICMPv6
- IPSec

What We Will *Not* Cover

- Routing
- TCPv6
- UDPv6
- SCTP (See Randall Stewart's excellent tutorial.)

What Problem Are You Trying To Solve?

- Running out of addresses
- Efficiency
- Manageability
- Security

Protocol Historical Context

- Early 90s move to classless inter domain routing (CIDR)
- 1990: RFC 1287 Future Internet Architecture
- 1992: RFC 1335 Discusses exhaustion issue
- 1995: First IPv6 RFCs
- 1998: First acceptable IPv6 RFCs (2460 et al)

Code History

- Originally three open source implementations of IPv6
  - Naval Research Lab (US)
  - INRIA (France)
  - Kame (Japan)
- Kame Project Wins out over the other two
- All work originally done in the BSD community
- Largest and riskiest kernel sub system developed outside of the BSD projects
- Kame Project ends active development in 2007
- Code fully taken over by the relevant OS projects

IPv6 Differences

- Addresses
- MTU
- Header Processing
- Scoping
- Multicast
- Autoconfiguration

Addresses

- The most obvious and talked about change
- 128 bits for the host address
- IPv4 didn't have enough for everyone alive
- IPv6 has enough for every atom in the universe

MTU

- Maximum Transfer Unit
- IP is a hop by hop, packet switched protocol
- Fragmentation was seen as a problem
- Having an end to end MTU improves performance

Header Processing

- The IPv4 header is messy
  - Two 4 bit fields
  - One 3 bit field
  - One 13 bit field
  - Options
- Make the header as simple as possible
- Have the packet look like a linked list

Scoping

- A novel way of asking the local/remote question
- An attempt to replace subnetting within organizations
- Too complicated for many uses

Multicast

- More efficient than broadcast
- Available in most common data-link protocols
- Used heaving in auto configuration

Autoconfiguration

- Trying to solve the Dentist's Office
- Does anyone still create isolated networks?
- Introduces new problems

Neighbor Discovery

- Replacement for ARP
- Partial replacement for DHCP
- Removal of a layering violation

Router Discovery

- Lessens the burden of administrators
- Partial replacement for DHCP

Sockets API

- A by-product of some of the changes
- Overcome problems with socket addressing

Directories and Files

- Majority of the code resides in sys/netinet6
- Two files present in sys/netinet
  - icmp6.h
  - ip6.h

Memory for Packets

- Packets need to be stored for reception and transmission
- The basic packet memory stuctures are the `mbuf` and `cluster`
- `mbuf` structures have several types and purposes
- Clusters hold only data
- History dictates that `mbuf`s are named `m`
- In the kernel we will see many pointers to `mbuf`s

Types of mbufs

- Wholly contained
- Packet Header
- Using a cluster

Welcome to SMP

- FreeBSD is a multi-threaded, re-entrant kernel
- Only way to scale on multicore and multi-processor systems
- Kernel is full of cooperating tasks
- Inter process synchronization is *required*

Kernel Synchronization Primitives

- Spin Locks
- Mutexes
- Reader/Writer Locks
- Shared/Exclusive Locks
- Drivers use mostly spin locks or mutexes
  - See locking(9) for more information

IPv6 Specific Data Structures

- Addresses
- Packet Header
- Extension Headers
  - Examined at the endpoint.
- Hop by Hop Options
  - Examined at each intermediate hop

Address Structures

```
struct sockaddr_in6 {
        uint8_t         sin6_len;       /* length of this struct */
        sa_family_t     sin6_family;    /* AF_INET6 */
        in_port_t       sin6_port;      /* Transport layer port # */
        uint32_t        sin6_flowinfo;  /* IP6 flow information */
        struct in6_addr sin6_addr;      /* IP6 address */
        uint32_t        sin6_scope_id;  /* scope zone index */
};

struct in6_addr {
        union {
                uint8_t         __u6_addr8[16];
                uint16_t        __u6_addr16[8];
                uint32_t        __u6_addr32[4];
        } __u6_addr;                    /* 128-bit IP6 address */
};
```

IPv4 Header

```
struct ip {
#if BYTE_ORDER == LITTLE_ENDIAN
        u_int   ip_hl:4,                /* header length */
                ip_v:4;                 /* version */
#endif
#if BYTE_ORDER == BIG_ENDIAN
        u_int   ip_v:4,                 /* version */
                ip_hl:4;                /* header length */
#endif
        u_char  ip_tos;                 /* type of service */
        u_short ip_len;                 /* total length */
        u_short ip_id;                  /* identification */
        u_short ip_off;                 /* fragment offset field */
#define IP_RF 0x8000                    /* reserved fragment flag */
#define IP_DF 0x4000                    /* dont fragment flag */
#define IP_MF 0x2000                    /* more fragments flag */
#define IP_OFFMASK 0x1fff               /* mask for fragmenting bits */
        u_char  ip_ttl;                 /* time to live */
        u_char  ip_p;                   /* protocol */
        u_short ip_sum;                 /* checksum */
        struct  in_addr ip_src,ip_dst;  /* source and dest address */
} __packed __aligned(4);
```

IPv6 Header

```
struct ip6_hdr {
        union {
                struct ip6_hdrctl {
                        u_int32_t ip6_un1_flow; /* 20 bits of flow-ID */
                        u_int16_t ip6_un1_plen; /* payload length */
                        u_int8_t  ip6_un1_nxt;  /* next header */
                        u_int8_t  ip6_un1_hlim; /* hop limit */
                } ip6_un1;
                u_int8_t ip6_un2_vfc;   /* 4 bits version, top 4 bits class */
        } ip6_ctlun;
        struct in6_addr ip6_src;        /* source address */
        struct in6_addr ip6_dst;        /* destination address */
} __packed;
```

Extension Header Structure

```
struct  ip6_ext {
        u_int8_t ip6e_nxt;
        u_int8_t ip6e_len;
} __packed;

/* Fragment header */
struct ip6_frag {
        u_int8_t  ip6f_nxt;          /* next header */
        u_int8_t  ip6f_reserved;     /* reserved field */
        u_int16_t ip6f_offlg;        /* offset, reserved, and flag */
        u_int32_t ip6f_ident;        /* identification */
} __packed;
```

Hop by Hop Options

Next: 0	Next: 51 Length: 1	Next: 50 Length: 4	Next: 6 Length: 6	Data
IPv6	Hop by Hop	AH	ESP	TCP

Hop by Hop Options Structure

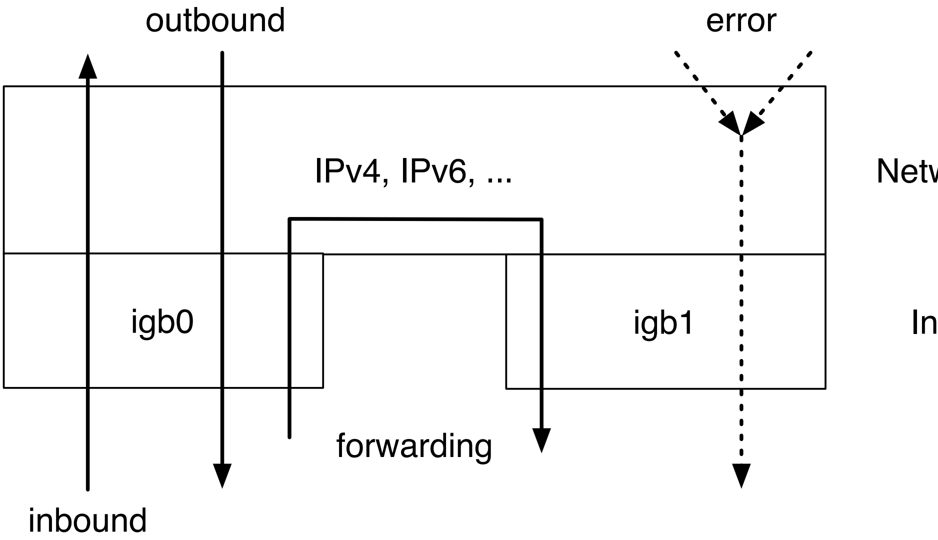
```
struct ip6_hbh {
        u_int8_t ip6h_nxt;      /* next header */
        u_int8_t ip6h_len;      /* length in units of 8 octets */
        /* followed by options */
} __packed;

/* Jumbo Payload Option */
struct ip6_opt_jumbo {
        u_int8_t ip6oj_type;
        u_int8_t ip6oj_len;
        u_int8_t ip6oj_jumbo_len[4];
} __packed;
```

The Four Paths

- Packets traverse four possible paths in the network code
- Inbound (for this host)
- Outbound (from this host)
- Forwarding (between two interfaces on this host)
- Error

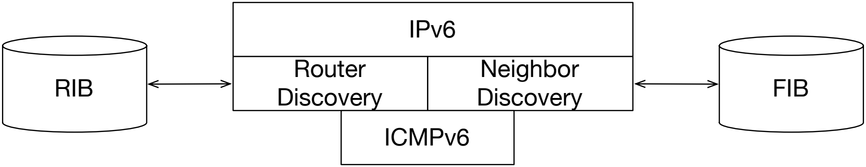
Four Paths Through The Stack



Packet Reception (Outline)

- Initial Reception
- Handle Scoping
- Hop by Hop Options
- Forwarding Decision
- More Packet Unwrapping

IPv6 Routing and Forwarding



Packet Transmission

- Extension Headers
- IPSec Handling
- Length Calculation
- Jumbo Payload
- Pick a Source Address
- Routing Lookup

Packet Transmission (Con't)

- Traffic Class
- Hop Limit
- IPSec Re-injection
- Select a Route
- Outbound Scope Check
- Multicast Handling
- Path MTU

Packet Transmission (Con't)

- Hop by Hop
- Checksumming
- Fragmentation
- Transmit
- Cleanup

ICMPv6

- Now used for more than errors
- An integral part of auto-configuration
- Handles Neighbor and Router Discovery (see next slides)

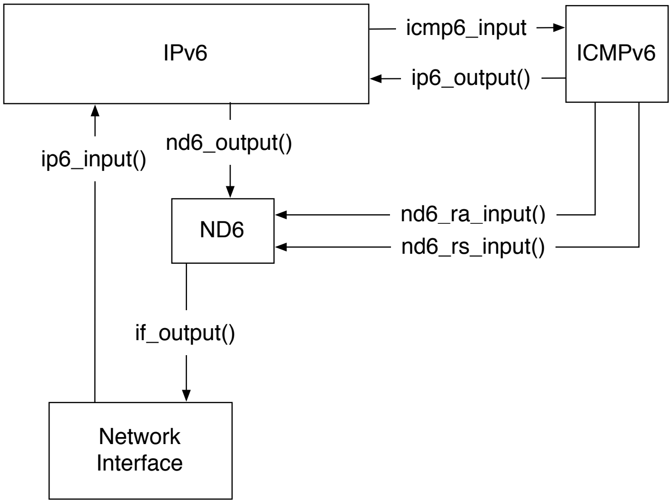
ICMPv6 Packet Reception

- `icmp6_input`
- Preamble
- Get a usable structure
- Calculate the Checksum
- The Massive Switch
- Echo Request (ping)
- Neighbor and Router

The ARP Replacement

- Translate an IPv6 address into a hardware address
- Piggy backed on top of ICMPv6
- Can take the place of DHCP

IPv6 Module Relationships



Neighbor Lookup

- `nd6_output`
- Initial error checks
- Find a cached entry
- Create a new entry
- Send a neighbor solicitation
- Queue the packet
- Transmit the packet

Neighbor Solicitation Transmission

- `nd6_ns_output`
- Preamble
- Multicast Check
- Fill in the solicitation packet
- Duplicate Address Detection
- Call ip6_output (again)

Solicitation Input

- `nd6_ns_input`
- On link check
- Option Processing
- Proxy check
- Tentative

Advertisement Output

- `nd6_na_output`
- Setup
- Create Packet
- Scope Selection
- Target Link Layer Address
- Checksums
- Call ip6_output

Advertisement Input

- `nd6_na_input`
- Preamble
- Flag extraction
- Multicast checks
- Options processing
- Cache lookup
- Entry update
- Address change
- Transmit held packets

Discovering Routers

- Separate from Neighbor Discovery
- Replaces manual configuration as well as DHCP
- Supposed to ease large deployments
- Has security and other implications

Router Advertisement

- `nd6_ra_input`
- Security Check
- Options processing
- Setup default router structure
- Handle prefix information
- MTU advertisement
- Source Link Layer Address

Router Solicitation

- Accepted by *only* by routers
- Used by hosts to find routers
- Handled in user-space by rtsold(8)
- Uses ICMPv6 messages to find nearby routers

Autoconfiguration Wrap Up

- Neighbor Discovery replaces ARP
- Router Discovery replaces configuration files
- ICMPv6 Used Throughout
- Most messages are multicast to known groups

IPSec

- The collection of protocols for IP Security
- Exist for IPv6 and IPv4
- Tunnel Architecture
- Authenticate and Encrypt Packets
- Keyeing is non-trivial
- Can be computationally expensive
- Code is in sys/netipsec

The Protocol Switch

- A table of protoocols and functions
- One for each protocol
- Not specific to IPv6
- `inet6sw`

Initial Reception

- `ipsec6_common_input`
- Pull up the whole packet
- Check the packet
- `ipsec_common_input`

Transformations

- Another set of structures with functions
- One per protocol
  - xform_ah.[ch], xform_esp.[ch]
- Implement a callback API
- Can easily offload to specialized hardware

Transformation Structures

```
struct xformsw {
        u_short xf_type;                /* xform ID */
#define XF_IP4          1       /* IP inside IP */
#define XF_AH           2       /* AH */
#define XF_ESP          3       /* ESP */
#define XF_TCPSIGNATURE 5       /* TCP MD5 Signature option, RFC 2358 */
#define XF_IPCOMP       6       /* IPCOMP */
        u_short xf_flags;
#define XFT_AUTH        0x0001
#define XFT_CONF        0x0100
#define XFT_COMP        0x1000
        char    *xf_name;                       /* human-readable name */
        int     (*xf_init)(struct secasvar*, struct xformsw*);  /* setup */
        int     (*xf_zeroize)(struct secasvar*);                /* cleanup */
        int     (*xf_input)(struct mbuf*, struct secasvar*,     /* input */
                        int, int);
        int     (*xf_output)(struct mbuf*,                      /* output */
                        struct ipsecrequest *, struct mbuf **, int, int);
        struct xformsw *xf_next;                /* list of registered xforms */
};

static struct xformsw ah_xformsw = {
        XF_AH,          XFT_AUTH,       "IPsec AH",
        ah_init,        ah_zeroize,     ah_input,       ah_output,
};
```

Authentication

- Verifies that the sender is who they say they are
- Required before adding or using Encryption

AH Reception

- `ah_input`
- Packet Verification
- Allocate Cryptographic Structures
- Check the `mtag`
- Setup the cryptographic structure
- Callback

AH Callback

- `ah_input_cb`
- Cleanup after the crypto operation
- Preamble
- Re-acquire embedded state
- Error checks
- Authenitcation approved
- Send to correct upper layer

IPv6 IPSec Procesing Continued

- `ipsec6_common_input_cb`
- Called once all IPsec work is done
- Preamble
- Various Sanity Checks
- Header Fixup
- enc0 processing
- Protocol Handoff

Encryption

- Hides the contents of the packet from all but the key holder
- Required for a secure tunnel
- Should always be used with authenticatoin
- Shares much boiler plate with AH

ESP Reception

- `esp_input`
- Preamble
- Pull the packet up
- Sequence check
- Crypto Check
- Get Cryptographic Descriptor
- Fill in descriptors
- Dispatch the operation

ESP Callback

- `esp_input_cb`
- Preamble
- Retrieving data from the descriptor
- Error checks
- Flag mbuf and update the replay sequence
- Strip the header
- See IPv6 IPSec Processing Continued (above)

Security Section Wrap Up

- IPSec works with both IPv4 and IPv6
- AH for Authentication
- ESP for Encryption
- Heavy use of `mtag`s
- Callbacks used to interact with hardware
- Transformations contain the protocol functions

Questions?