Implementing IPv6 Applications

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Intro

We will explain how to implement IPv6 applications

- We assume knowledge of writing IPv4 applications

We also look at porting IPv4 applications to IPv6

We look at writing/porting applications written in C and the POSIX/BSD IPv6 socket API

We do the same for Perl

We consider common application porting issues

We look at standards and recommendations

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Enabling application for IPv6

- Most IPv4 applications can be IPv6 enabled
  - Appropriate abstraction layers used
- Providing ‘Dual stack’ IPv4 and IPv6 is best
  - Run-time (preferable) or compile-time network mode (v6 and/or v4)
- All widely used languages are IPv6-enabled
  - E.g. C/C++, Java, Python, Perl
  - Some languages make it particularly easy
    - E.g Java
- Benefiting from IPv6 is a little more difficult
  - Though most functionality is the similar to IPv4
  - Add special functionality for IPv6 features
- IPv4 and IPv6 APIs have largely converged


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Heterogeneous Environments

Precautions for Dual Stack

Avoid any explicit use of IP addresses

- Normally do Call by Name

Ensure that calls to network utilities are concentrated in one subroutine

Ensure that libraries and utilities used support both stacks

Do not request functions that would not exist in both stacks

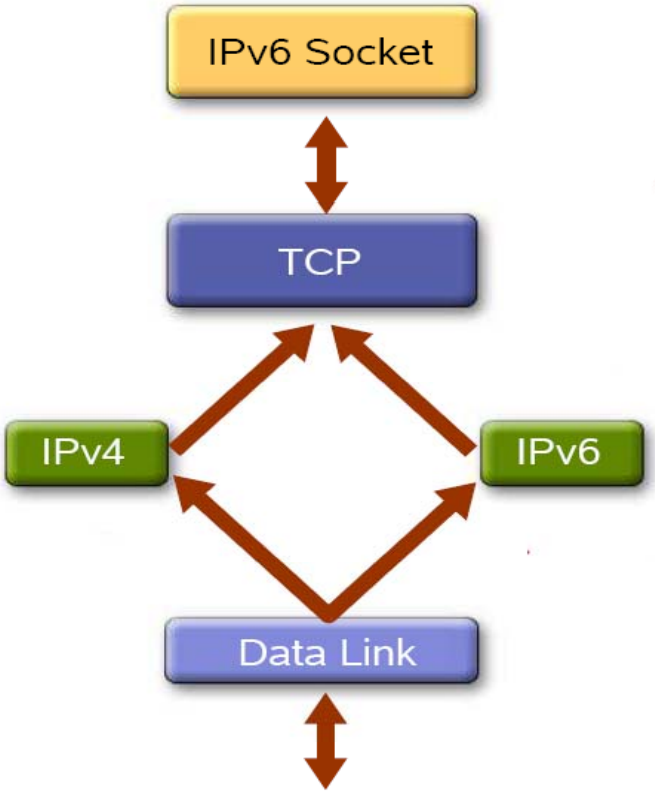
- E.g. IPsec, MIP, Neighbour Discovery may vary

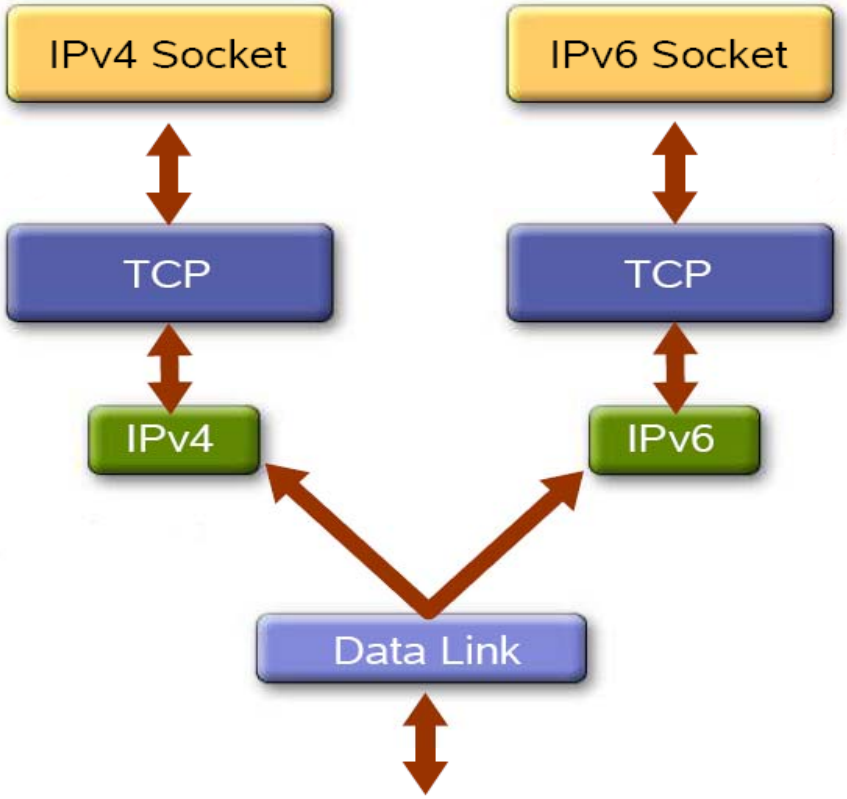
Dual stack configurations

Both IPv4 and IPv6 stacks will be available during the transition period

Dual network stack machine will allow to provide a service both for IPv4 and IPv6

2 different implementations of network stack





Source : Rino Nucara, GARR, EuChinaGRID IPv6 Tutorial

Heterogeneous IPv4/IPv6 Environments

May require dual-stack client/server, accessible by both stacks

- Often used, for example, with Web services and with SIP signalling

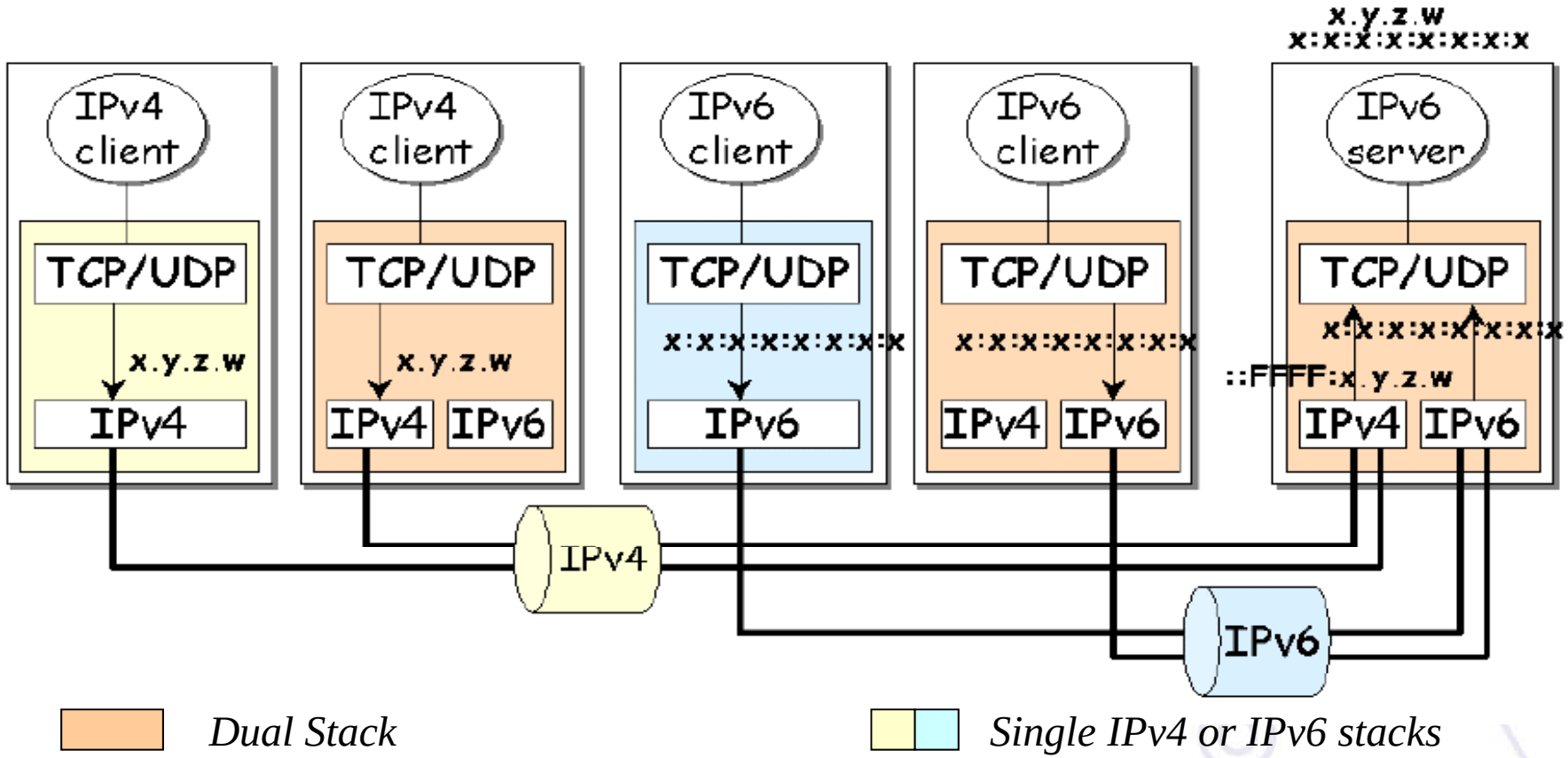
May require transition gateway

- As for example with IPv4 telephones accessing other IPv6 ones

May be complex, as when encrypted IPv4 messages are passed into the IPv6 networks with packet header encrypted, or certificate cryptographically bound to IP4 address

Mapping IPv4 address in IPv6

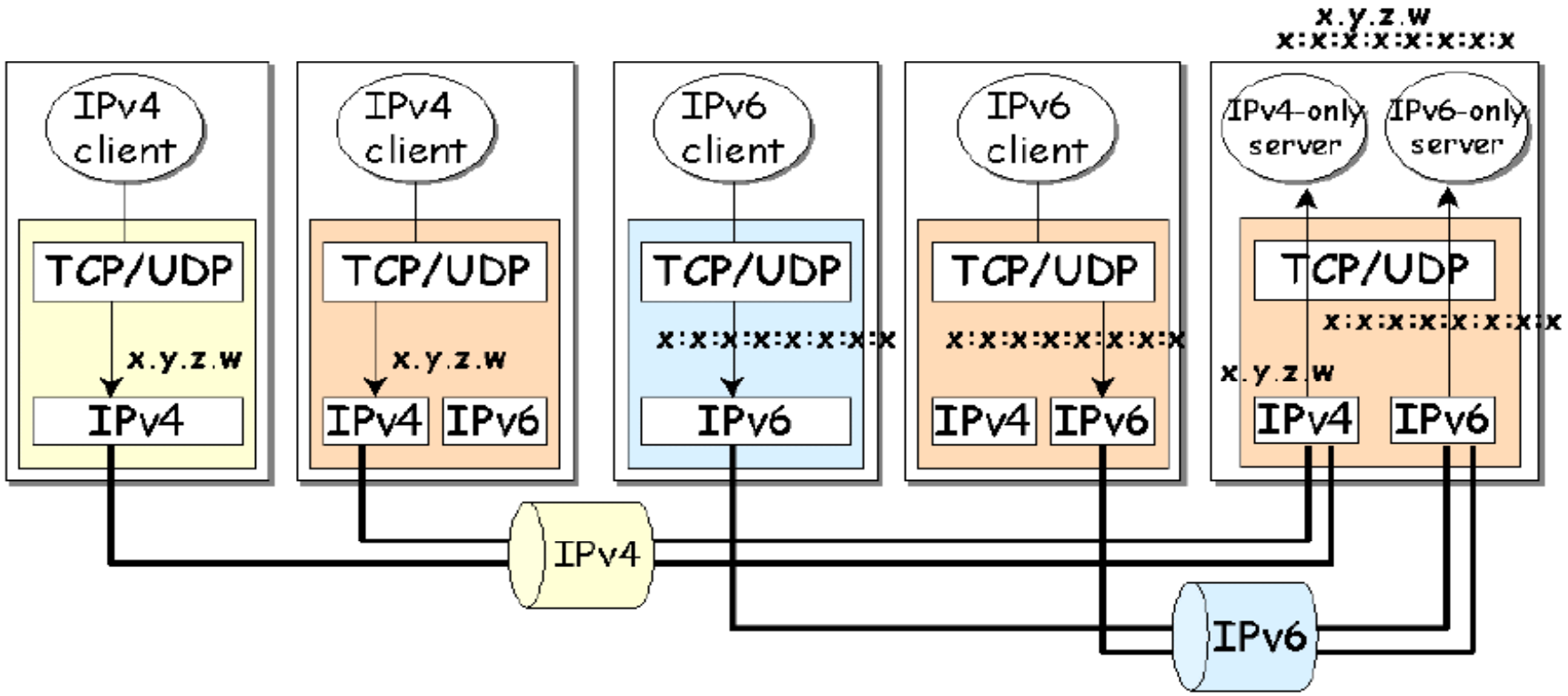
IPv6/IPv4 Clients connecting to an IPv6 server at dual stack node → 1 socket



Source : Programming guidelines on transition to IPv6 T. P de Miguel, E. M. Castro

IPv4-only and IPv6-only

IPv6/IPv4 Clients connecting to an IPv4-only server and IPv6 only server at dual stack node → 2 sockets



Source : Programming guidelines on transition to IPv6 T. P de Miguel, E. M. Castro

New Applications

Simplified by writing apps using a high-level language

- E.g. JAVA seamlessly supports dual stack

Design the application in a protocol independent fashion

Ensure both protocols will be simultaneously operable

Legacy Applications

If most parts are written in say Java, and small parts in say C, try to rewrite C part to be in Java or at least make sure that I/O is concentrated in certain regions

Re-architect code so that it provides

- Appropriate network abstraction layer

Adjust I/f to code to fit dual-stack specs

- Or do all networking via a utility which is IPv6-enabled
- VIC, RAT using RTP are good example

Porting

- The hardest part is often parsing of config files and internal handling of addresses, not the socket code itself
- You may need to write code that works with both old API and new. May end up with lots of ifdefs using old or new as appropriate. Might be good to put this code at a low level and create wrappers around it
- It's not uncommon that large applications have some duplication of network code. When porting it might be a good idea to fix this

Other Issues

Renumbering & Mobility routinely result in changing IP Addresses

- Use Names and Resolve, Don't Cache

Multi-homed Servers

- More Common with IPv6
- Try All Addresses Returned

Using New IPv6 Functionality

IPv6 literal addresses in URL's

From RFC 2732

Literal IPv6 Address Format in URL's Syntax To use a literal IPv6 address in a URL, the literal address should be enclosed in "[" and "]" characters. For example the following literal IPv6 addresses:

FEDC:BA98:7654:3210:FEDC:BA98:7654:3210

3ffe:2a00:100:7031::1

::192.9.5.5

2010:836B:4179::836B:4179

would be represented as in the following example URLs:

http://[FEDC:BA98:7654:3210:FEDC:BA98:7654:3210]:80/index.html

http://[3ffe:2a00:100:7031::1]

http://[::192.9.5.5]/ipng

http://[2010:836B:4179::836B:4179]

Effects on higher layers

Affects anything that reads/writes/stores/passes IP addresses
- Most IETF protocols have been updated for IPv6 compliance

Bigger IP header must be taken into account when computing max payload sizes

Packet lifetime no longer limited by IP layer (it never was, anyway!)

Address scoping for multicast

New DNS record type: AAAA

DNS lookups may give several v4 and/or v6 addresses
- **Applications may need to deal with multiple addresses**

Advanced mobility
- Mobile IPv6, Network Mobility (NEMO)

Miscellaneous issues 1

- For IPv6 UDP checksum is mandatory since there is no checksum in IP header
  - Problematic for applications that can cope with bit errors (e.g. video streaming?). Might be better to have a bit error than losing packet
  - UDP-Lite RFC 3828 is a solution
- connect() might try for like 30s if no response
  - When trying all addresses from getaddrinfo() we may not want to have 30s timeout for each

Miscellaneous issues 2

- URL format for literal IPv6 addresses (RFC 2732)
  - http://[2001:db8:dead:beef::cafe]:80/
- Entering IP addresses more difficult
  - Especially on a numeric/phone keypad
- Better to pass names than addresses in protocols, referrals etc. They can look up addresses in DNS and use what they need
  - If a dual-stack node can't pass fqdn in protocol (referrals, sdp etc), it should be able to pass both IPv4 and IPv6 addresses
  - Important that other clients can distinguish between IPv4 and IPv6 belonging to same host, or being two different hosts

Miscellaneous issues 3

- Hosts will typically have several addresses
  - Dual-stack hosts both IPv4 and IPv6
  - May have multiple IPv6 addresses
    - Multihomed or global prefix + ULA for internal
    - Renumbering
- Addresses may change over time
  - Privacy addresses, e.g. every 24 hours
  - When renumbering

Conclusion

Many existing applications are available in IPv6

Porting applications to IPv6 is straightforward

- Provided certain guidelines are followed

Heterogeneous environments provide the most challenges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C IPv6 API

Basic IPv6 socket programming

- Will go through API within RFC 3493 (Basic Socket Interface Extensions for IPv6) and give recommendations on how to use it
- The Advanced API is specified in RFC 3542
- There is also POSIX, or The Single UNIX Specification, Version 3 at http://www.unix.org/version3/online.html
- RFC and POSIX are roughly the same with some minor differences. Useful to look at both

Socket API Changes

- Name to Address Translation Functions
- Address Conversion Functions
- Address Data Structures
- Wildcard Addresses
- Constant Additions
- Core Sockets Functions
- Socket Options
- New Macros

Important definitions

- PF_INET6, AF_INET6 (PF_INET, AF_INET for IPv4)
- struct in6_addr {
- uint8_t s6_addr[16]; /* IPv6 address */
- };
- struct sockaddr_in6 {
- sa_family_t sin6_family; /* AF_INET6 */
- in_port_t sin6_port; /* transport layer port # */
- uint32_t sin6_flowinfo; /* IPv6 flow information */
- struct in6_addr sin6_addr; /* IPv6 address */
- uint32_t sin6_scope_id; /* set of interfaces for a scope */
- };
  - sin6_flowinfo not used (yet)
  - Will discuss sin6_scope_id later
  - BSD has sin6_len as member too (also sin_len in sockaddr_in)
- struct sockaddr_storage {
- sa_family_t ss_family; /* address family */
- char ss_pad... /* padding to make it large enough */
- };
  - Used when we need a struct to store any type of sockaddr
  - I.e., we can use it in declarations and cast if necessary
  - For generic sockaddr pointer, use struct *sockaddr

Core Socket Functions

Core APIs

- Use IPv6 Family and Address Structures
- socket() Uses PF_INET6

Functions that pass addresses

- bind()
- connect()
- sendmsg()
- sendto()

Functions that return addresses

- accept()
- recvfrom()
- recvmsg()
- getpeername()
- getsockname()

All the above function definitions are unchanged due to use of struct sockaddr and address length

Name to Address Translation

getaddrinfo()

- Pass in nodename and/or servicename string
  - Can Be Address and/or Port
- Optional Hints for Family, Type and Protocol
  - Flags – AI_PASSIVE, AI_CANNONNAME, AI_NUMERICHOST, AI_NUMERICSERV, AI_V4MAPPED, AI_ALL, AI_ADDRCONFIG
- Pointer to Linked List of addrinfo structures Returned
  - Multiple Addresses to Choose From

freeaddrinfo()

```
int getaddrinfo(
    IN const char FAR * nodename,
    IN const char FAR * servname,
    IN const struct addrinfo FAR * hints,
    OUT struct addrinfo FAR * FAR * res
    );
```

```
struct addrinfo {
    int ai_flags;
    int ai_family;
    int ai_socktype;
    int ai_protocol;
    size_t ai_addrlen;
    char *ai_canonname;
    struct sockaddr *ai_addr;
    struct addrinfo *ai_next;
    };
```

Address to Name Translation

getnameinfo()

- Pass in address (v4 or v6) and port
  - Size Indicated by *salen* argument
  - Also Size for Name and Service buffers (NI_MAXHOST, NI_MAXSERV)
- Flags
  - NI_NOFQDN
  - NI_NUMERICHOST
  - NI_NAMEREQD
  - NI_NUMERICSERV
  - NI_DGRAM

```
int getnameinfo(
    IN const struct sockaddr FAR * sa,
    IN socklen_t salen,
    OUT char FAR * host,
    IN size_t hostlen,
    OUT char FAR * serv,
    IN size_t servlen,
    IN int flags
    );
```

Simple old IPv4 TCP client

```
/* borrowed from http://www.ipv6.or.kr/summit2003/presentation/II-2.pdf */

struct hostent *hp;
int i, s;
struct sockaddr_in sin;
s = socket(AF_INET, SOCK_STREAM, IPPROTO_TCP);
hp = gethostbyname("www.kame.net");
for (i = 0; hp->h_addr_list[i]; i++) { /* not so common to loop through all */
        memset(&sin, 0, sizeof(sin));
        sin.sin_family = AF_INET;
        sin.sin_len = sizeof(sin); /* only on BSD */
        sin.sin_port = htons(80);
        memcpy(&sin.sin_addr, hp->h_addr_list[i],
        hp->h_length);
        if (connect(s, &sin, sizeof(sin)) < 0)
                continue;
        break;
}
```

Simple IPv4/IPv6 TCP client

```
/* borrowed from http://www.ipv6.or.kr/summit2003/presentation/II-2.pdf */
struct addrinfo hints, *res, *res0;
int error, s;
memset(&hints, 0, sizeof(hints));
hints.ai_family = AF_UNSPEC;
hints.ai_socktype = SOCK_STREAM;
error = getaddrinfo("www.kame.net", "http", &hints, &res0);
if (error)
        errx(1, "%s", gai_strerror(error));
/* res0 holds addrinfo chain */
s = -1;
for (res = res0; res; res = res->ai_next) {
        s = socket(res->ai_family, res->ai_socktype, res->ai_protocol);
        if (s < 0)
                continue;
        error = connect(s, res->ai_addr, res->ai_addrlen);
        if (error) {
                close(s);
                s = -1;
                continue;
        }
        break;
}
freeaddrinfo(res0);
if (s < 0)
        die();
```

Converting sockaddr to string

- /* from http://www.ipv6.or.kr/summit2003/presentation/II-2.pdf */

- char hbuf[NI_MAXHOST], pbuf[NI_MAXSERV];

- /* convert to names where possible, like www.kame.net/http */
- if (getnameinfo(sa, sa->sa_len, hbuf, sizeof(hbuf), pbuf, sizeof(pbuf), 0) != 0)
- errx(1, “an error occured");

- /* or a numeric address/service port, like 127.0.0.1/80 */
- if (getnameinfo(sa, sa->sa_len, hbuf, sizeof(hbuf), pbuf, sizeof(pbuf), NI_NUMERICHOST|NI_NUMERICSERV) != 0)
- errx(1, “an error occured");

Simple old IPv4 TCP server

- /* from http://www.ipv6.or.kr/summit2003/presentation/II-2.pdf */

```
int s;
struct sockaddr_in sin;
s = socket(AF_INET, SOCK_STREAM, IPPROTO_TCP);
memset(&sin, 0, sizeof(sin));
sin.sin_family = AF_INET;
sin.sin_len = sizeof(sin); /* only on BSD */
sin.sin_port = htons(80);
if (bind(s, &sin, sizeof(sin))>= 0)
        exit(1);
listen(s, 5);
```

Simple IPv4/IPv6 TCP server (1/2)

```
/* from http://www.ipv6.or.kr/summit2003/presentation/II-2.pdf */

struct addrinfo hints, *res, *res0;
int s, i, on = 1;
memset(&hints, 0, sizeof(hints));
hints.ai_family = AF_UNSPEC;
hints.ai_socktype = SOCK_STREAM;
hints.ai_flags = AI_PASSIVE;
error = getaddrinfo(NULL, "http", &hints, &res0);
if (error) {
        fprintf(stderr, "%s", gai_strerror(error));
        exit(1);
}
/* res0 has chain of wildcard addrs */
```

Simple IPv4/IPv6 TCP server (2/2)

```
/* borrowed from http://www.ipv6.or.kr/summit2003/presentation/II-2.pdf */
i = 0;
for (res = res0; res; res = res->ai_next) {
        s = socket(res->ai_family, res->ai_socktype, res->ai_protocol);
        if (s < 0)
                continue;
#ifdef IPV6_V6ONLY
        if (res->ai_family == AF_INET6 && setsockopt(s, IPPROTO_IPV6, IPV6_V6ONLY, &on,
sizeof(on)) < 0) {
                close(s);
                continue;
        }
#endif
        if (bind(s, res->ai_addr, res->ai_addrlen) >= 0) {
                close(s);
                continue;
        }
        listen(s, 5);
        socktable[i] = s;
        sockfamily[i++] = res->ai_family;
}
freeaddrinfo(res0);
if (i == 0)
        errx(1, "no bind() successful");
/* select()/poll() across socktable[] */
```

Server issues

- Note that we typically end up with two sockets, one for v4 and one for v6
  - So need select or poll
- We also note the address family of each socket
  - Useful for some applications (e.g. {get,set}sockopt)
- Many operating systems support sending or receiving IPv4 on an IPv6 socket
  - One then only needs a single socket for receiving both
  - IPv4 address written as “::ffff:a.b.c.d”
- In the example we try to use IPV6_V6ONLY to disable this
- One will typically bind to v6 socket first, then v4 socket. Linux by default uses mapped addresses, so v4 addresses are embedded within v6, and as a consequence doesn’t allow a subsequent bind to addresses covered by an existing bind. But note that I haven’t tested this lately.
- Since bind() behaviour is not well-defined, we only treat it as error if all binds fail

One socket server example (1/2)

- With support for mapped addresses you can use a single IPv6 socket
- Also single v4 or v6 socket if you only need to support one family or take family as an argument on startup
- /* from http://www.ipv6.or.kr/summit2003/presentation/II-2.pdf */
- int af = AF_INET6; /* or AF_INET */
- struct addrinfo hints, *res;
- int s, i, on = 1;
- memset(&hints, 0, sizeof(hints));
- hints.ai_family = af;
- hints.ai_socktype = SOCK_STREAM;
- hints.ai_flags = AI_PASSIVE;
- error = getaddrinfo(NULL, "http", &hints, &res);
- if (error)
- 	exit(1);
- if (res->ai_next) {
- 	fprintf(stderr, "multiple addr");
- 	exit(1);
- }
- /* res has chain of wildcard addrs */

One socket server example (2/2)

```
/* borrowed from http://www.ipv6.or.kr/summit2003/presentation/II-2.pdf */
s = socket(res->ai_family, res->ai_socktype,
res->ai_protocol);
if (s < 0)
        exit(1);
#ifdef IPV6_V6ONLY
/* on here for v6 only, set off for mapped addresses if applicable */
if (res->ai_family == AF_INET6 && setsockopt(s, IPPROTO_IPV6, IPV6_V6ONLY,
&on, sizeof(on)) < 0) {
        close(s);
        continue;
}
#endif
if (bind(s, res->ai_addr, res->ai_addrlen) < 0)
        exit(1);
listen(s, 5);
freeaddrinfo(res);
```

Scope ID

- When using link local addresses a host with multiple interfaces need to know which interface the address is for
- This is what sockaddr_in6's sin6_scope_id is for
- getaddrinfo() can automatically fill this in when called with e.g. "www.kame.net%eth0" or "fe80::1234:5678%eth0"
- This notation is standardized, but the naming of interfaces are not

Address family independent code wherever possible

- Not separate code for v4 and v6
- Try to use sockaddr_in/sockaddr_in6 rather than in_addr/in6_addr
- We then have address family together with the address
- There is struct sockaddr_storage that is large enough for v6 (and sockaddr_un) that can be used for memory allocation and can be typecast to sockaddr_in etc if necessary
- For pointers we can use struct sockaddr *

Specific things to look for

Storing IP address in 4 bytes of an array.

Use of explicit dotted decimal format in UI.

Obsolete / New:

- AF_INET replaced by AF_INET6
- SOCKADDR_IN replaced by SOCKADDR_STORAGE
- IPPROTO_IP replaced by IPPROTO_IPV6
- IP_MULTICAST_LOOP replaced by SIO_MULTIPOINT_LOOPBACK
- Gethostbyname() replaced by getaddrinfo()
- Gethostbyaddr() replaced by getnameinfo()

Porting Steps -Summary

Use IPv4/IPv6 Protocol/Address Family

Fix Address Structures

- in6_addr
- sockaddr_in6
- sockaddr_storage to allocate storage

Fix Wildcard Address Use

- in6addr_any, IN6ADDR_ANY_INIT
- in6addr_loopback, IN6ADDR_LOOPBACK_INIT

Use IPv6 Socket Options

- IPPROTO_IPV6, Options as Needed

Use getaddrinfo()

- For Address Resolution


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Perl IPv6 API

IPv6 API of Perl5

- **relying on the IPv6 support of underlying operating system**
- **you can write Perl applications with direct access to sockets**
- **new IPv6 API for DNS name resolution is important for seamless operation**
- **With simple API creating `sockaddr_in6` might be tedious**
- **There are two modules for Basic IPv6 API**
  - **Socket6**
  - **IO::Socket::INET6**

Perl implementation of new IPv6 DNS + socket packing API

- Socket6 module **- available via CPAN**
- **implemented functions:**
- **`getaddrinfo()` - see usage later**
- **`gethostbyname2 HOSTNAME, FAMILY` - family specific gethostbyname**
- **`getnameinfo` NAME, [FLAGS] - see usage later**
- **`getipnodebyname HOST, [FAMILY, FLAGS]` - list of five elements - usage not recommended**
- **`getipnodebyaddr FAMILY, ADDRESS` - list of five elements - usage not recommended**
- **`gai_strerror ERROR_NUMBER` - returns a string of the error number**
- **`inet_pton FAMILY, TEXT_ADRESS` - text->binary conversion**
- **`inet_ntop FAMILY, BINARY_ADDRESS` - binary-> text conversion**

Perl implementation of new IPv6 DNS + socket packing API/2

- **`pack sockaddr in6 PORT, ADDR` - creating sockaddr_in6 structure**
- **`pack_sockaddr_in6_all PORT, FLOWINFO, ADDR, SCOPEID` - complete implementation of the above**
- **`unpack sockaddr in6 NAME` - unpacking sockaddr_in6 to a 2 element list**
- **`unpack_sockaddr_in6_all NAME` - unpacking sockaddr_in6 to a 4 element list**
- **`in6addr_any` - 16-octet wildcard address.**
- **`in6addr_loopback` - 16-octet loopback address**

Simple getaddrinfo() example

```
use Getopt::Std;
use Socket;
use Socket6;
use strict;

my $inet6 = defined(eval 'PF_INET6');

my %opt;
getopts(($inet6 ? 'chpsn46' : 'chpsn4'), \%opt);
if ($opt{'h'}){
    print STDERR ("Usage: $0 [-h | [-c] [-n] [-p] [-s] [-4" .
                  ($inet6 && "|-6") . "] [host [serv]]]\n" .
                  "-h   : help\n" .
                  "-c   : AI_CANONNAME flag\n" .
                  "-n   : AI_NUMERICHOST flag\n" .
                  "-p   : AI_PASSIVE flag\n" .
                  "-s   : NI_WITHSCOPEID flag\n" .
                  ($inet6 ? "-4|-6: PF_INET | PF_INET6" : "-4   : PF_INET") .
                  "\n");
    exit(4);
}
my $host = shift(@ARGV) if (@ARGV);
my $serv = shift(@ARGV) if (@ARGV);
die("Too many arguments\n") if (@ARGV);
die("Either -4 or -6, not both should be specified\n") if ($opt{'4'} && $opt{'6'});
```

Simple getaddrinfo() example/2

```
my $af = PF_UNSPEC;
$af = PF_INET if ($opt{'4'});
$af = PF_INET6 if ($inet6 && $opt{'6'});

my $flags = 0;
$flags |= AI_PASSIVE if ($opt{'p'});
$flags |= AI_NUMERICHOST if ($opt{'n'});
$flags |= AI_CANONNAME if ($opt{'c'});

my $nflags = NI_NUMERICHOST | NI_NUMERICSERV;
$nflags |= NI_WITHSCOPEID if ($opt{'s'});

my $socktype = SOCK_STREAM;
my $protocol = 0;

my @tmp = getaddrinfo($host, $serv, $af, $socktype, $protocol, $flags);
while (my($family,$socktype,$protocol,$sin,$canonname) = splice(@tmp, $[, 5)){
    my($addr, $port) = getnameinfo($sin, $nflags);
    print("family=$family, socktype=$socktype, protocol=$protocol, addr=$addr, port=$port");
    print(" canonname=$canonname") if ($opt{'c'});
    print("\n");
}
```

Object oriented Perl socket API

- **using basic socket API - sometimes complicated**
- **`IO::Socket::INET` makes creating socket easier - inherits all functions from `IO::Socket + IO::Handle`**
- `IO::Socket::INET6` **- generalisation of IO:Socket:INET to be protocol neutral - available from CPAN**
- **new methods:**
  - `sockdomain()` - Returns the domain of the socket - AF_INET or AF_INET6 or else
  - `sockflow ()` - Return the flow information part of the sockaddr structure
  - `sockscope ()` - Return the scope identification part of the sockaddr structure
  - `peerflow ()` - Return the flow information part of the sockaddr structure for the socket on the peer host
  - `peerscope ()` - Return the scope identification part of the sockaddr structure for the socket on the peer host

IO::Socket::INET6 examples

- **Trying to connect to peer trying all address/families until reach**

```
$sock = IO::Socket::INET6->new(PeerAddr => 'ipv6.niif.hu',
                               PeerPort => 'http(80)',
                               Multihomed => 1 ,
                               Proto    => 'tcp');
```

- **Connecting via IPv4 only - backward compatibility with `IO::Socket::INET`**

```
$sock = IO::Socket::INET6->new(PeerAddr => 'ipv6.niif.hu',
                               PeerPort => 'http(80)',
                               Domain => AF_INET ,
                               Multihomed => 1 ,
                               Proto    => 'tcp');
```

IO::Socket::INET6 examples /2

- **using literal ipv6 address**
- `$sock = IO::Socket::INET6->new(PeerAddr => '[::1]:25');`
- **setting up a listening socket**

```
$sock = IO::Socket::INET6->new(Listen    => 5,
                               LocalAddr => 'localhost',
                               LocalPort => 9000,
                               Proto     => 'tcp');
```


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Further reading

Further reading

- RFCs
  - RFC 3493: Basic Socket Interface Extensions for IPv6 (obsoletes RFC 2553)
    - see getaddrinfo for an example of client/server programming in an IPv4/IPv6 independent manner using some of the RFC 3493 extensions
  - RFC 3542: Advanced Sockets Application Program Interface (API) for IPv6 (obsoletes RFC 2292)
  - RFC 4038: Application Aspects of IPv6 Transition

Further Reading /2

- Links
  - Address-family independent socket programming for IPv6
    http://www.ipv6.or.kr/summit2003/presentation/II-2.pdf
  - Porting applications to IPv6 HowTo
    http://gsyc.escet.urjc.es/~eva/IPv6-web/ipv6.html
  - Porting Applications to IPv6: Simple and Easy - By Viagenie - http://www.viagenie.qc.ca/en/ipv6/presentations/IPv6%20porting%20appl_v1.pdf
  - Guidelines for IP version independence in GGF specifications
    http://www.ggf.org/documents/GWD-I-E/GFD-I.040.pdf
  - IPv6 Forum Programming and Porting links
    http://www.ipv6forum.org/modules.php?op=modload&name=Web_Links&file=index&req=viewlink&cid=56
  - FreeBSD Developers' Handbook Chapter on IPv6 Internals - http://www.freebsd.org/doc/en/books/developers-handbook/ipv6.html

Further Reading /3

- Links
  - Freshmeat IPv6 Development Projects - http://freshmeat.net/search/?q=IPv6
  - FutureSoft IPv6 - a portable implementation of the next generation Internet Protocol Version 6, complying with the relevant RFCs and Internet drafts - http://www.futsoft.com/ipv6.htm
  - IPv6 Linux Development Tools from Deepspace.net - http://www.deepspace6.net/sections/sources.html
  - Libpnet6 - an advanced networking library with full IPv6 support - http://pnet6.sourceforge.net/
  - USAGI Project - Linux IPv6 Development Project
    http://www.linux-ipv6.org/
- Books
  - IPv6 Network Programming by Jun-ichiro itojun Hagino
  - UNIX Network Programming (latest version) by W. Richard Stevens
  - IPv6 : Theory, Protocol, and Practice, 2nd Edition by Pete Loshin
  - IPv6 Network Administration, O'Reilly


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Questions