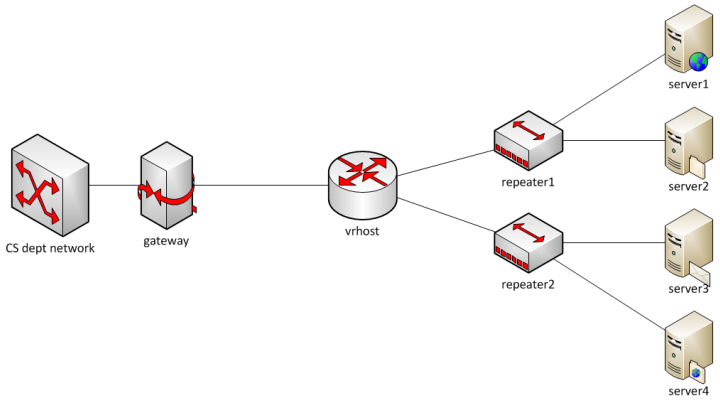
Build Your Own Router

In this project you will implement a functional IP router that is able to route real traffic. You will be given an incomplete router to start with. What you need to do is to implement the Address Resolution Protocol (ARP), the basic IP forwarding, and ICMP ping. A correctly implemented router should be able to forward traffic for any IP applications, including downloading files between your web browser and a web server via your router.

Overview



This is the network topology, and *vrhost* is the router that you will work on.
Each topology has its own unique IP addresses and Ethernet addresses. Make sure to use only the topology assigned to you. The *vrhost* connects the CS department network to two internal subnets, each of which has two web servers in it. The goal of this project is to implement essential functionality in the router so that you can access those web servers from the CS Department network to download files.

Note: This topology is only accessible from within the CS department. You need to run your router software and tests on lectura.

In this assignment we provide you the skeleton code for a Simple Router (sr), that can connect to vrhost and launch itself, but doesn't implement any packet processing or forwarding, which will be filled in by you.

Test Driving the Router Stub Code

Download the stub code tarball from D2L and untar it

```
tar xvf stub_sr.tar
```

This will generate a ***stub_sr*** directory. This is your working directory.

Your assignment email has an attachment, top#.tar, where top# is the topology number, such as 301.

Save this tarball in stub_sr and untar it:

```
tar xvf top#.tar
```

It must be done in the stub_sr folder.

Compile the code: `make`

Run the router: `./sr -t top#`

You should see something like this, which means sr now runs on vrhost:

```
Using VNS sr stub code revised 2010-01-21 (rev 0.23)
Loading routing table
---------------------------------------------
Destination  Gateway             Mask                Iface
0.0.0.0             172.29.9.169 0.0.0.0             eth0
172.29.9.160        0.0.0.0      255.255.255.248     eth1
172.29.9.176        0.0.0.0      255.255.255.248     eth2
---------------------------------------------
Client bzhang connecting to Server 171.67.71.18:3250
Requesting topology 313
Virtual Network Lab, connection open
/home/vnl/topo/313.sh: line 250: kill: (3251) - No such process
successfully authenticated as bzhang
Router interfaces:
eth0
  hardware address 52:5e:35:95:7d:4a
  ip address 172.29.9.168
  mask 255.255.255.254
eth1
  hardware address 62:24:78:cc:7b:99
  ip address 172.29.9.166
  mask 255.255.255.248
eth2
  hardware address d2:41:af:c3:48:67
  ip address 172.29.9.182
  mask 255.255.255.248
<-- Ready to process packets -->
```

On a separate terminal, ping any one of the servers in your topology.

```
ping server_ip_address
```

You can get the server IP address from the topology picture in your email, or the file vnltopo*.iplist in stub_sr folder.

On the router terminal, you should see output like:

```
*** -> Received packet of length 42
*** -> Received packet of length 42
*** -> Received packet of length 42
```

This is sr reporting that it has received a packet. Since it doesn't have any packet processing capability yet, all these packets are dropped.

Since the packets are dropped, on the ping terminal, you should see messages like

```
From 192.168.56.24 icmp_seq=1 Destination Host Unreachable
From 192.168.56.24 icmp_seq=2 Destination Host Unreachable
From 192.168.56.24 icmp_seq=3 Destination Host Unreachable
```

Use ctrl-c (^c) to terminate sr and ping.

Important functions and data structures

First Two Functions

The two most important methods for developers to get familiar with are:

in `sr_router.c`

```
void sr_handlepacket(struct sr_instance* sr,
        uint8_t * packet /* lent */,
        unsigned int len,
        char* interface /* lent */)
```

This method is invoked each time a packet is received. The `*sr` pointer allows access to this router's interfaces and routing/forwarding table. The `*packet` points to the buffer containing the incoming packet. It includes the Ethernet header (but without Ethernet preamble and CRC) and everything else above Ethernet. The length of the packet and the name of the receiving interface are also passed into the method as well.

in `sr_vns_comm.c`

```
int sr_send_packet(struct sr_instance* sr /* borrowed */,
                   uint8_t* buf /* borrowed */ ,
                   unsigned int len,
                   const char* iface /* borrowed */)
```

This method allows you to send out an Ethernet packet (`"buf"`) of certain length (`"len"`), via the outgoing interface `"iface"`. Remember that the packet buffer needs to start with an Ethernet header.

In the stub code, sr_handlepacket( ) does nothing but printing a message on stdout. Your job is to implement the rest of this method so that we can access the router and servers.

Important Data Structures

The context of the router is housed in `struct sr_instance` defined in file `sr_router.h`. It has two pieces of important information: the router's routing table (`*routing_table`) and a list of its three interfaces (`*if_list`).

Interface:
Each interface (`sr_if.c, sr_if.h`) contains its hardware address (i.e., Ehternet address), IP address, mask, and its interface name (e.g., eth0, eth1, eth2). At the start time, `sr` receives this information for your topology and populates the interface list for your code to use. You may find sr_get_interface( ) and sr_print_if( ) useful. Note that IP addresses are stored in *network order*, so you don't need htonl( ) when copying an address from the interface list to a packet header.

Routing Table:
The routing table (`sr_rt.c, sr_rt.h`) in this project is read from a file "`rtable`" at start time. A table has multiple rows/entries and look like this:

```
0.0.0.0         172.24.74.17   0.0.0.0             eth0
172.24.74.64    0.0.0.0        255.255.255.248     eth1
172.24.74.80    0.0.0.0        255.255.255.248     eth2
```

The four fields, from left to right, are
`dest, gw(i.e., nexthop), mask, and interface.` See `struct sr_rt` in `sr_rt.h`.

Table Lookup:
The "dest" and "mask" together define the *destination network*. If a packet's destination address is within the destination network, i.e.,

dest & mask == dest-address & mask

Then this table entry *matches* this packet.

If there're more than one matching entry for a packet, only the longest prefix match should be used in packet forwarding. In other words, the matching entry whose mask is the largest number should be used.

You can see that the first entry in the table above will match any destination address, but its mask is the smallest possible. This entry is called the *default route*, meaning that it will be used only if there is no other matching entry.

IP Packet Forwarding
The matching entry tells where a packet should be forwarded to: the nexthop (gw) node at the outgoing interface. For example, the first entry in the table says packets should be

forwarded to 172.24.74.17 via interface eth0, i.e., towards the CS department network.

The next two entries in the table have 0.0.0.0 in the gw field. That means the nexthop node is the final destination of the packet. Therefore the destination address in the IP header should be used as the nexthop, and the packet should forwarded to it.

When a packet is forwarded, its IP header should keep the original destination address unchanged since that represents the final destination of the packet. Its Ethernet header, however, should use the nexthop's Ethernet address in the destination field, and the outgoing interface's Ethernet address in the source field. This allows the packet to be received by the nexthop node.

How do you get the nexthop's Ethernet address given the routing table only records its IP? By running the address resolution protocol (ARP), you can learn a node's Ethernet address given its IP address.

Dealing with Packet Headers

In this project the router needs to process various protocol headers. The packet formats are summarized here: Ethernet, ARP, IP, and ICMP. You only need to process a small number of essential fields, not all the protocols details. The Peterson & Davie book has more explanations of the protocols, and there are plenty of material online if you need further information.

The stub code provides data structures in sr_protocols.h for IP, ARP, and Ethernet headers. The Linux system also defines data structures for various protocols in /usr/include/net and /usr/include/netinet.

Starting with a pointer to a packet (uint8_t *), you can cast it to an Ethernet header pointer (struct sr_ethernet_hdr *) in order to access Ethernet fields. Then move the pointer pass the Ethernet header and cast it again to a pointer to ARP header or IP header, and process them accordingly. This is how you access different protocol headers in a packet.

When you read and/or print header fields, be careful about the byte order problem (big-endian vs. little-endian).

Implementing required functionality

ARP

The very first packet that will arrive at the router is most likely an ARP request. The EtherType field in the Ethernet header denotes it's an ARP packet, and the field in the ARP header tells it's a request or reply message.

An ARP request carries an IP address in the header and asks for the corresponding

Ethernet address. Your router needs to check whether the IP address is one of the router's, and if it is, the router should send an ARP reply containing the Ethernet address. Often times your router also needs to know the Ethernet addresses of other nodes. It should compose its own ARP request, send it out, receive the ARP reply, and process it. While the router is waiting for ARP reply, there may be more packets arrive. The router should buffer these packets while waiting, and send them all after getting the ARP reply.

You can create your ARP packet from scratch, or reuse the received ARP packet and change the value of the fields. Either way works, but you need to make sure that the values of all the fields are correct; otherwise other nodes will not be able to understand the packet.

To avoid sending ARP request for every packet, the router should implement an *ARP cache*:

- once it learns the Ethernet address for a given IP address, it saves the result and reuses it next time when sending packets to the same IP.
- The cache should be discarded after 10s. You don't need to implement it using a signal or timer. You can record the time (gettimeofday()) when the result is saved, and every time before using the cached result, check whether 10s has passed. If yes, remove the cached result and send an ARP request.

IP

If the incoming packet is an IP packet (based on EtherType), the router needs to carry out the following steps:

1. If the destination IP is one of the router's,
    a. If the packet is an ICMP echo request, the router should respond with an ICMP echo reply. (See ICMP below).
    b. Otherwise discard the packet, i.e., return from the function without any further processing.
2. Decrement TTL by 1.
    a. If the result is 0, discard the packet.
    b. Otherwise, calculate header checksum and save the result to the checksum field.
3. Use the IP destination address to look up the routing table, find the matching entry to be used for packet forwarding.
4. Send the packet to the nexthop on the interface from the matching entry
    a. Obtain nexthop's Ethernet address from ARP cache, or ARP request if it's not in the cache.

The Peterson & Davie book has IP header checksum algorithm and sample code that you can use. A great way to test if your checksum function works is to run it on an arriving packet. If you get the same checksum that is already contained in the packet, then your function is working. Remember to zero out the checksum field before feeding the packet to the checksum calculation. If the checksum is wrong, tcpdump/wireshark will point it out when displaying the packet.

ICMP

In order to be able to ping your router, it needs to support ICMP echo request/reply. You can tell it's an ICMP packet by the "protocol" field in IP header, and whether it's an echo request by "Type" in ICMP header.

When the router receives an ICMP echo request destined to the router itself, it should change the Type to echo reply, update the checksum (which covers the entire ICMP message starting from the Type field), and send it back to the original sender. Keep the rest of the ICMP part unchanged. Note that you also need to take care of the IP and Ethernet header.

Inspecting network traffic with tcpdump/wireshark

Probably the most important network debugging tool is a packet sniffer, e.g., `tcpdump` and `wireshark` (which has GUI and much easier to use). A packet sniffer captures packets from the wire and displays their contents. As you work on the `sr` router, you will very often want to see what is exactly transmitted on the wire. This is done by logging network traffic to a file and then displaying them using `tcpdump or wireshark`.

First, tell your router to log packets to a file in the so-called pcap format:

```
./sr -t top# -l logfile
```

As the router runs, it will record all the packets that it receives and sends in the file named "`logfile`." After stopping the router, you can use tcpdump to display the contents of the logfile:

```
tcpdump -r logfile -e -vvv –xx
```

The `-r` switch tells tcpdump to read "logfile", `-e` tells tcpdump to print the headers of the packets, not just the payload, `-vvv` makes the output very verbose, and `-xx` displays the content in hex, including the link-level (Ethernet) header.

NOTE: in order to use tcpdump in lectura, you need to make a copy of /usr/sbin/tcpdump in your local directory and execute this local copy. Or you can download the log file to local machine and use wireshark to read it.

Learn to read the hexadecimal output from tcpdump. It shows you the packet content including the Ethernet header and IP header, which will be very helpful in debugging. For example, you can see how a correctly formatted ARP request (coming from other nodes) looks like, and check which bytes of your ARP request/reply packet may have problems.

Testing

A correctly implemented router is expected to pass the following tests:

1. Ping all the interfaces of the router results in 0% loss and delay < 10ms.
2. Ping all server interfaces results in 0% loss and delay < 10ms.
3. Examine the traffic log to verify correct ARP behavior, including the use of ARP cache and the timeout of ARP cache.
4. Successful retrieval of a web page:
   wget http://server_IP:16280
5. Successful retrieval of a large web object:
   wget http://server_IP:16280/64MB.bin

Optionally you can use a web browser to access the web pages hosted on the servers. Lectura has a text-based browser, "lynx", that you can use. To use a browser on your own machine, you need to set up a SOCKS proxy so that the traffic will go through lectura:

- On your local machine, run an ssh tunnel for SOCKS proxy:
  - *ssh -D 1080 lectura.cs.arizona.edu*
- Configure your browser to use the proxy. On Firefox, open the network preferences, choose manual proxy, SOCKS, localhost, port 1080.
- Access `http://server_IP:16280`

Troubleshooting of the topology

Normally you shouldn't need to use any of the following commands. But just in case, they're listed here for your information.

You can view the status of your topology nodes: (replace 87 with your topology number)

```
./vnltopo87.sh gateway status
./vnltopo87.sh vrhost status
./vnltopo87.sh server1 status
./vnltopo87.sh server2 status
```

If your topology does not work correctly, you can attempt to reset it: (replace 87 with your topology id), or notify the instructor/TA.

```
./vnltopo87.sh gateway run
./vnltopo87.sh server1 run
./vnltopo87.sh server2 run
```

Grading

The project will be graded on lectura using a different topology.

DO NOT hardcode anything about your topology (e.g., IP address, Ethernet address) in your code.

Your code must be written in C and use the stub code.

You can work by yourself or in a group of two students.

Grading is based on functionality, i.e., what works and what doesn't, **not the source code**.

Submission

Only one submission per group.

1. Rename your working directory by the topology number top#. For example, if you're assigned topology 78, you should name your working directory as 78.

2. Make sure this directory has all the source files and the Makefile. Include a README.txt file listing the names and emails of group members, and anything you want us to know about your router. Especially if your router only works partially, you would want to explain what works and what not in README.txt to help the instructor/TA determine partial credit.

3. Create a tarball

```
cd top#
make clean
cd ..
tar -zcf top#.tgz top#
```

4. Upload top#.tgz to D2L.

Deadline

Monday Oct 10, 2022, at 11:59pm.