

# Teaching Lab-based Computer Networking through the Designing of a Miniature Internet (MINT)

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## Abstract

In this paper, we propose a laboratory-based computer networking course to better teach various networking concepts to undergraduate students. Specifically, we ask students to build the lab network as a miniature Internet (MINT) from the ground up. Each laboratory builds upon the last until the desired infrastructure is in place. Students are then asked to set up common network services, extend/modify some networking mechanisms, and compare the performance of different topologies, hardware and protocols. This paper describes the necessary hardware and an overview of the procedures involved for each laboratory. More detailed information about each lab can be found at [www.cs.utsa.edu/~korkmaz/teaching/mint](http://www.cs.utsa.edu/~korkmaz/teaching/mint). Finally, this paper presents the method of student evaluation in relation to the course's overall objectives.

## 1 Introduction

In recent years, computer networking, specifically the Internet, has become an indispensable part of our every day life. While the public uses the Internet and discusses how it changes our world, we (as academicians and researchers) want to know what is under the hood, how/why it works, how to make it better, and more importantly how to teach it to the next generations for continuous improvements. With this in mind, many books have been written on computer networking and are being taught in both undergraduate and graduate level courses. While students learn various concepts in these traditional courses, they do not have enough hands-on experience with real networks or in-depth understanding of how things work in practice (except for developing network applications based on client/server paradigm). Realizing such shortcomings of traditional networking courses, many universities have been developing complementary lab-based networking courses [5, 4, 1]. Although lab courses are very useful in teaching various networking concepts, they can not cover as much material as in traditional courses due to lack of time and resources. Therefore, one needs to focus on certain aspects of computer networks and accordingly design lab experiments while taking the availability of resources into account. This makes it very difficult to directly take others' lab materials and use them in a networking laboratory course.

In this paper, we present a new undergraduate laboratory course focusing on how to teach various networking concepts by establishing a miniature Internet (MINT)<sup>1</sup> step-by-step in a bottom-up fashion.

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<sup>1</sup>Note that the Internet is one of the largest systems that has ever been implemented as a community effort. It is estimated

This approach allows students not only to gain hands-on experiences and learn details of various concepts but also to see how they fit/work together within the big picture of the Internet. In this course, we specifically focus on the Internet's routing architecture, networking services, network management, and performance analysis. Accordingly, we design several lab experiments that can be classified under five parts. In Section 3, we describe each lab, but more details about each lab can be obtained from [www.cs.utsa.edu/~korkmaz/teaching/mint](http://www.cs.utsa.edu/~korkmaz/teaching/mint).

**Part I: Establishing the routing infrastructure for the MINT:** To achieve this goal in a bottom-up fashion, we consider five labs as follows. First we establish a local area network (LAN) and study various concepts including IP addressing, ARP. In the next experiment, we connect two LANs via a router and study routing related concepts. In the third experiment, we increase the number of routers and study static routing using a multi-router topology. In the fourth experiment, we then use this topology as an autonomous system (AS) to study dynamic intra-domain routing and related concepts such as shortest path computation, distance-vector and link-state protocols (e.g., RIP, OSPF). Finally, in the fifth lab, we connect ASs and study inter-domain routing and related concepts including policy-based path selection, path-vector routing protocol (e.g., BGP). At the end of part one, A working MINT is ready to be used in later parts.

**Part II: Donating the MINT with networking services and applications:** There are several networking services and applications. We consider some of the most commonly used ones (e.g., DNS, DHCP, HTTP, FTP, CDN, Cluster computing) through three labs. Mainly students install related programs at different nodes and experiment with them.

**Part III: Managing the network:** We consider one lab here focusing on how to use SNMP.

**Part IV: Implementing/modifying network and transport layer mechanisms:** We consider three experiments such as changing FIFO queuing with class-based queuing to provide differentiated services at the network layer, changing TCP or UDP to provide a slightly different transport layer service, implementing network layer multicasting.

**Part V: Analyzing the performance of various configurations and protocols:** We revisit previous experiments and analyze the performance of different configurations and protocol (e.g., compare a router with a switch in connecting two LANs, compare the modified TCP with original TCP).

Many other lab experiments (even more advanced ones related to QoS, multimedia, peer-to-peer) can also be conducted using the MINT. However, since we plan to initially offer our lab networking course to undergraduate students, our lab experiments in this paper specifically focus on how things work and perform in practice. For the graduate version of this course, we plan to advance the experiments along with new equipments and ask students not only to learn and evaluate the existing mechanisms but also to design and implement new ones that are being discussed in research community (e.g., implement explicit congestion control).

Before offering the proposed lab course as a regular semester course, we wanted to have a proof-of-concept. For that purpose, we offered the proposed lab course to a few students as an independent study.

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that millions of computers (hosts) are now able to communicate with each other using the Internet. Given this scope and complexity, it is clear that no one can replicate the Internet in a lab environment. On the other hand, even a single computer would be enough to experience some basic principles behind the Internet. As we gather more equipment (computers, hubs, switches, and routers) and carefully interconnect them step-by-step using various routing protocols, networking services and applications, we can establish a MINT in a bottom-up fashion, as done in our lab course. Since many experiments will require the full control of the underlying network resources and protocols, the MINT should be a dedicated network ranging from a single computer to a set of computers/routers that are connected via various networking equipment. In our experiments, we use at most 9 Linux-based PC's, 5 Cisco 2600 series routers, 3 hubs/switch, and several cables.

We met weekly on Mondays for one hour and discussed a new experiment. Students were then asked to read/investigate related topics in detail and to conduct the experiment until the following Thursday. Based on the experiment and collected data/information, students wrote their final reports and turned them in before the next experiment. In a regular semester course, we believe that the same plan can be used (i.e., one hour on Monday and 2 hours on Thursday). We definitely recommend that each lab experiment be conducted under the supervision of the instructor or TA. The number of students can change depending on the availability of resources, but more than 20 students per lab session would be unmanageable.

The rest of this paper is organized as follows. In Section 2 we present some background information about the Internet and discuss the related work. In Section 3 we provide an overview of the course plan and describe our experiments along with the required equipments. In Section 4, we explain our approach to student evaluation. Finally, we conclude this paper and give some directions for future work in Section 5.

## 2 Background and Related Work

The Internet began as a project by the U.S. Department of Defense and a group called the Advanced Research Projects Agency(ARPA). The goal of this project was to decentralize computer resources in order to protect those resources from attack and to limit operating costs. This early computer network, known as ARPAnet, allowed different users to utilize the computing power of more expensive machines while only bearing the cost burden of a smaller more manageable machine. As more people realized the usefulness of computer communication more people developed their own networks. Eventually the individual networks were connected together to form what we refer to as the Internet. It is the collection of different networks inter-connected and operated by different organizations.

Part of the work that ARPA did was develop protocols to facilitate communication within ARPAnet. These protocols defined rules for the communicating computers to follow in order to ensure the receiving computer understood what was being sent. The Internet has grown far beyond ARPAnet and the other initial networks. As the Internet grew more complex, new protocols were needed for routing data throughout the collection of developing networks. The standards developed for the Internet led to its dramatic growth. New services for the Internet could be developed as long as the defined protocols were followed and new protocols were established for the new service.

The evolution of the Internet demonstrates a logical progression in developing computer communication. It evolved through the stages of setting up the network, connecting different networks to form a hierarchy of networks and establishing different services within the network. It is our intention to teach Computer Networking principles by following the progression of these stages. This will give students hands-on experience in various networking concepts and services.

It is recognized that a laboratory for computer networking is a valuable tool for teaching networking concepts. It gives the student a chance to see how various concepts work and what types of behavior a network exhibits. To capitalize on this resource much work has been done in developing networking laboratories. ACM SIGCOMM held a conference to discuss the Computer Network curriculum and workshop ideas on methods and designs of teaching Computer Networks [4]. There are numerous different laboratories that reflect the diversity of the computer networking discipline and vary in focus from a hardware oriented approach to work on specific network layers. A paper published in *IEEE Transactions on Education* describes a laboratory developed at the School of Engineering at the University of New South Wales that demonstrates the transmission of data between computers [2]. The laboratory allows students to interact with hardware to develop their understanding of how data and its representative signals move through a network. Another paper describes a laboratory that focuses on three layers in the network and allows the students to implement the software to support the Data Link Layer [3].

### 3 Lab Experiments

The course will be taught with the objective of establishing a MINT to provide hands-on experience and better understanding of various networking concepts. It is divided into five parts covering different but complementary aspects of computer networks. The five parts are: (1) establishing the routing infrastructure for a MINT, (2) donating this infrastructure with networking services and applications, (3) managing the underlying network(s), (4) implementing or modifying some mechanisms at the network and transport layers, (5) analyzing and comparing the performance of various configurations and protocols studied in previous parts. To be able to progress step-by-step, each part is broken up into several labs each of which can be completed in a week by undergraduate students who have already taken an introductory networking course (e.g., CS 4873 in our department). We now describe the main goals, tasks, and equipment of each lab experiment, while more details about each lab can be obtained from [www.cs.utsa.edu/~korkmaz/teaching/mint](http://www.cs.utsa.edu/~korkmaz/teaching/mint).

**Lab 0: Introduction:** Before starting the actual experiments, it will be useful to provide a general introduction to lab equipments and softwares. In general, students install the Linux operating system and practice with useful utilities for network study in the Linux environment (e.g., vi, ifconfig, netstat, ping, tcpdump). While it is not the intention to teach specific proprietary software we do use Linux as well as CISCO IOS commands throughout this lab course. Since the focus is not on Linux or CISCO routers, the requirements for operating the labs in terms of the software are minimal and, when necessary, the information is provided to the students.

#### 3.1 Establishing the routing infrastructure for the MINT

**Lab 1: Establishing a Local Area Network (LAN):** In Lab 1 the main objective is to set up a Local Area Network similar to the one described in Figure 1. The main concepts involved in this lab are IP addressing and the Address Resolution Protocol (ARP). The required equipments for this lab are

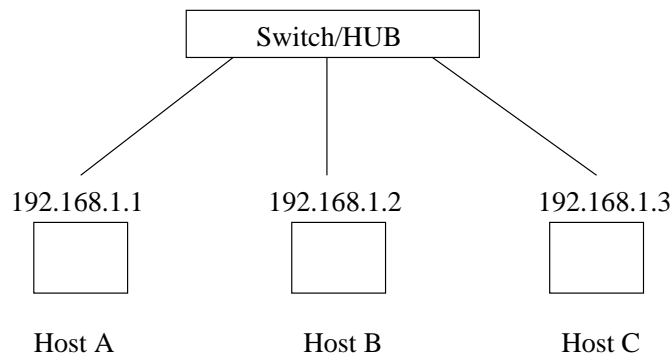


Figure 1: Establishing a LAN for Lab 1.

three PC's equipped with at least one NIC, one HUB or Switch and the necessary cables. Once the physical LAN is set up the hosts need to be configured using the ifconfig command. To verify communication among the machines the ping command is used. Next, the students are asked to manipulate the routing tables at the hosts to understand how machines know where to send packets. Since the ifconfig command places a default route into the routing tables this route must be deleted to 'blindfold' the machine. The ping command is used again to show that communication is no longer available. To re-establish communication the routes are put back into the routing table one host at a time. Communication is once again verified using the ping command.

**Lab 2: Connecting two LANs via a router:** In Lab 2 the main objective is to connect two LANs using a router. The concepts covered in this lab will be IP addressing with multiple networks and default gateways. The equipment used during this lab are those involved in the set-up of two LANs and one router. Students are asked to set up the equipment as in Figure 2. The router configuration

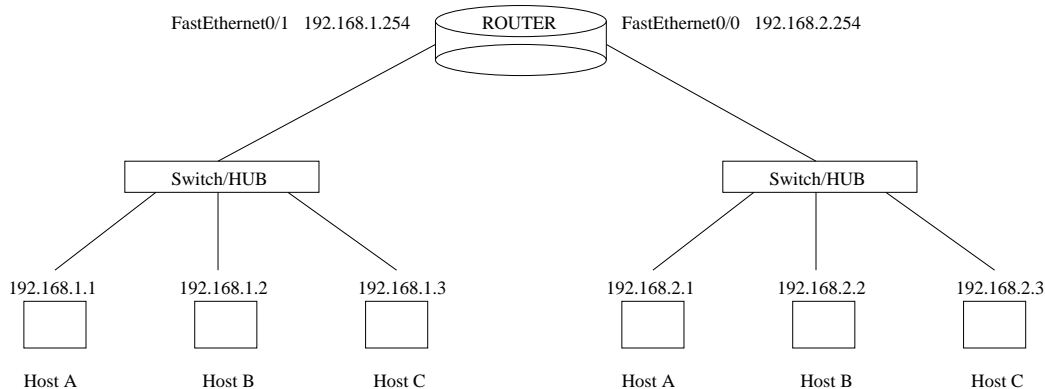


Figure 2: Connecting two LANs via router for Lab 2.

at this point is trivial since the router does not do any 'routing' but is more involved with forwarding packets. We take this opportunity to introduce some router configuration commands as well as using minicom to interface with a router. Once an interface is established password recovery is performed on the router to demonstrate how the router loads configuration settings. With the new password established the configuration of the router can be performed. During configuration the interfaces are set according to Figure 2 and verified once configuration is finished. Since the two LANs are directly connected the routing table at the router will know how to forward the packets once the interfaces are set. Communication is verified using ping from a host on one LAN to a host on another. When communication is verified students are asked to run traceroute to see how the packets move through the router.

**Lab 3: Connecting two LANs using multi-router topology with static routes:** The main objective for Lab 3 is to extend Lab 2 by using multiple routers. The concepts for this lab include IP addressing and basic network routing principles. The equipment used for this lab are the same as Lab 2 with four additional routers. Students connect two LANs using the topology in Figure 3. Once the physical set-up is complete the interfaces are configured according to the diagram. During router configuration attention is paid to the types of interfaces as additional issues are involved with set-up. For example, the serial interfaces require clocking mechanisms to be set correctly. Once the interfaces are working the ping command is used to check for communication between LANs. The failure of communication illustrates the need for routes to be established inside the routing infrastructure. Static routes are used to show how packets can be transported through any reasonable route. Students are asked to run traceroute on two different configurations to demonstrate the implementation of different routes.

**Lab 4: Dynamic routing using Routing Information Protocol (RIP):** The main objective for Lab 4 is to implement dynamic routing using the Routing Information Protocol(RIP) for the established network. The concepts of this lab involve routing principles and how a network communicates routing information within its own network. The equipment required for this lab is the same as in Lab 3. No additional configuration of the router interfaces is required for this lab. The first procedure is to delete the static routes established in the previous lab. This is required so the dynamic routes will be used by the router. RIP is started on each router and the available networks are configured for the

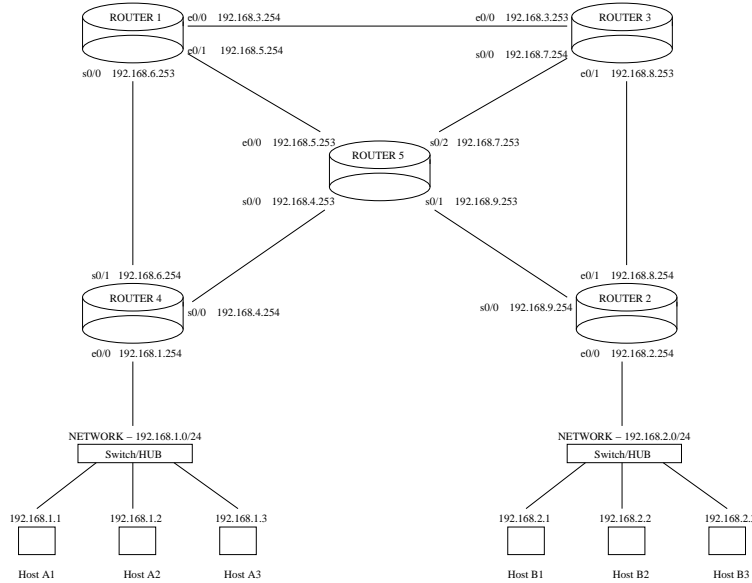


Figure 3: Multi-router topology for Lab 3.

protocol to advertise. After configuring RIP the router's routing table is checked to see the different networks are being added by the neighboring router's advertisements. When all routers have been configured traceroute is used to see how the routers forward the packets through the networks. The next step is to change the metrics on the interfaces to have the routers advertise different information. This is used to show how RIP will dynamically change the routes a packet takes according to network attributes. Traceroute is used to show the new route through the network.

**Lab 5: Dynamic Inter-domain routing using Border Gateway Protocol (BGP):** In Lab 5 the main objective is to set up the Border Gateway Protocol (BGP) to communicate routing information between Autonomous Systems. The concepts covered include interior and exterior routing protocols. The equipment used in this lab is the same as in Lab 4. Autonomous Systems (AS's) are set up according to Figure 4 and routing protocols are started on the appropriate routers. In order to set up the AS's certain router interfaces are disabled to simulate the absence of a network connection. The routers running BGP are set up to advertise networks available within the AS to the BGP neighbors. RIP is used to advertise networks within the AS's so it will need to be reconfigured to advertise appropriately. Once the routing protocols are established the routers connected to the LANs need to have their default routes set to the gateway router for the respective AS. The routing tables are viewed at each router to see how the routing protocols are propagating routes throughout the network. Traceroute is used to demonstrate the paths packets are taking to get to their destinations. This is the last lab in setting up the infrastructure for the MINT.

### 3.2 Donating the MINT with networking services and applications

**Lab 6: Network Services and applications:** The main objective for Lab 6 is to set up different networking services including Domain Name Service(DNS), Dynamic Host Configuration Protocol(DHCP), File Transfer Protocol(FTP) and Hyper-Text Transfer Protocol(HTTP). The major concepts covered in this lab is the use of servers and daemon processes to supply network services. A working MINT is used in this lab to set up the different networking services. Figure 5 shows the set-up of the network for this lab. The first service to be set-up is a DNS. In each LAN students select hosts on which the DNS server and DNS cache will be set up. The djbdns package is used for the servers and caches.

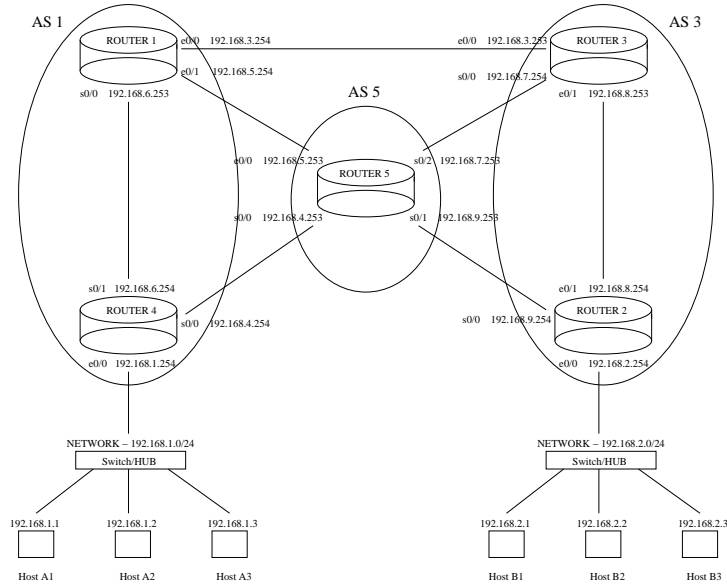


Figure 4: Multi-router topology for Lab 5.

Due to limited hardware and the requirement that the server and the cache be used on different hosts the interface on the host running the server and the cache is aliased. After setting up the aliases the interfaces are configured to the new addresses for these services. The new information is put into the routing table and the server is configured. Configuring the server involves adding the addresses of the hosts and name server to the DNS data file. When the set-up is complete name resolution is tested using the host command. The next service to be set-up is DHCP. The DHCP script is edited using the network's information and range of desired addresses. The script is then copied into the appropriate directory and the service is started. In order to test the service the IP address of an interface of another host in the LAN is removed. That host then runs the dhclient command to contact the DHCP server to be given a new IP address. The command will output the results for the assignment. To set-up a FTP server the students create a non-privileged user account for anonymous use. The FTP script is edited to use the anonymous account and set to run. The script is started and netstat is used to confirm the FTP server is running. Students are asked to test the operation of the server by logging in from another host using the anonymous FTP account. To set up a web server the httpd script is edited and the listening port is specified. The user group settings are also verified not to be set to root. A name is assigned for the server and the document root is set to the appropriate directory where the HTML files are located. The script is started and the server is verified to be running using netstat. The server is tested by connecting to the port on which it is running.

**Lab 7: Content Distribution:** In Lab 7 the main objective is to implement a simple content distribution network. The main concepts for this lab are content distribution and the advantages of distributed resources. This lab uses the model described in Figure 6. Students are asked to review and implement the procedures for setting up DNS and HTTP servers on the appropriate hosts. HTML files are created at www.cdn.com and images are stored at the different locations to give a visual representation of where the content is from. The wget command is used by the hosts in network A and network B to retrieve content from the site www.cdn.com. The HTML file from the www.cdn.com uses a reference to cdn.omega.com to retrieve local copies of a resource, in our case an image. For our implementation of content distribution the interface on the content distribution host is aliased to

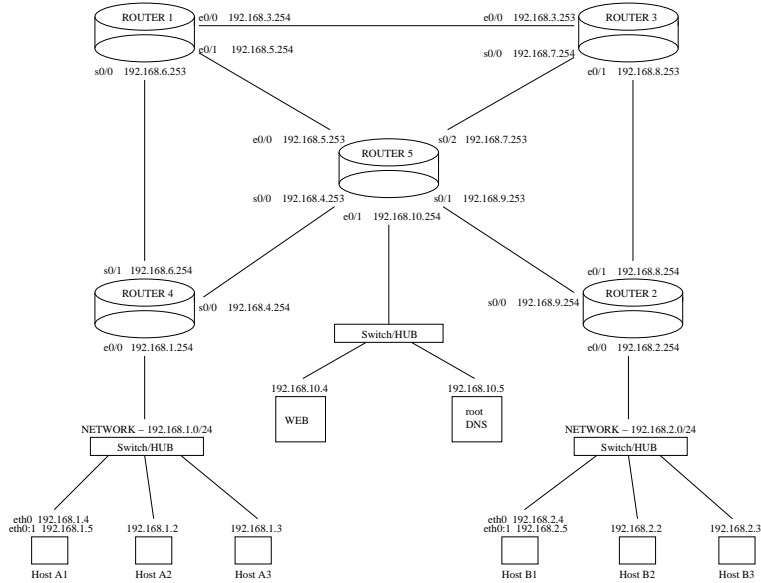


Figure 5: Multi-router topology for Lab 6.

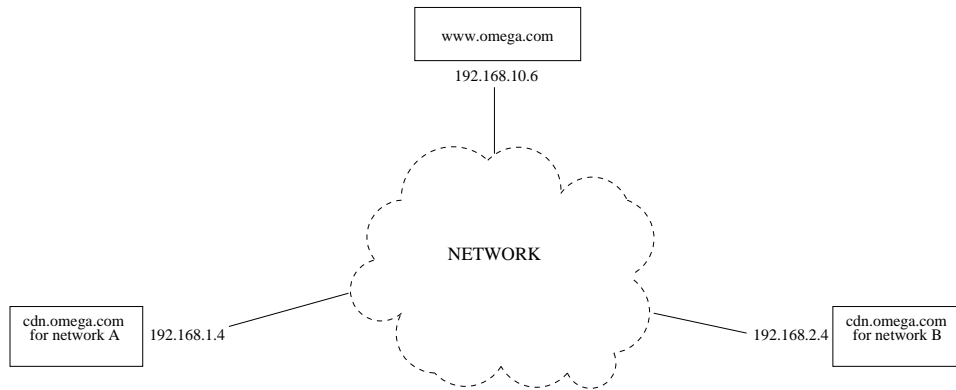


Figure 6: Content distribution network for Lab 7.

recognize the two different networks that will request the resource. When the resource refers to the location `cdn.omega.com` the local copy at each network will be used to display in the browser. The students are then asked to run trace route on the resources to illustrate the usefulness of content distribution.

**Lab 8: Clustering:** In Lab 8 the main objective is to set up a Cluster. The concept involved for this lab is the usefulness of load distribution. This lab requires multiple PCs with a switch capable of supporting them and a router with two available Ethernet interfaces. This lab uses the model described in Figure 7. The first thing the students do in this lab is to reconfigure the linux kernel for network clustering and virtual servers. The package `ipvsadmin` is installed to actually administer the virtual server that will act as the director in our cluster. The director script is then configured to forward requests to the real servers using direct routing in a round robin manner. The server scripts and the director script are started and tested. The testing involves uses host specific HTML files which are accessed by the client. For repeated accesses it can be seen that the director is rotating through the real servers for each request.



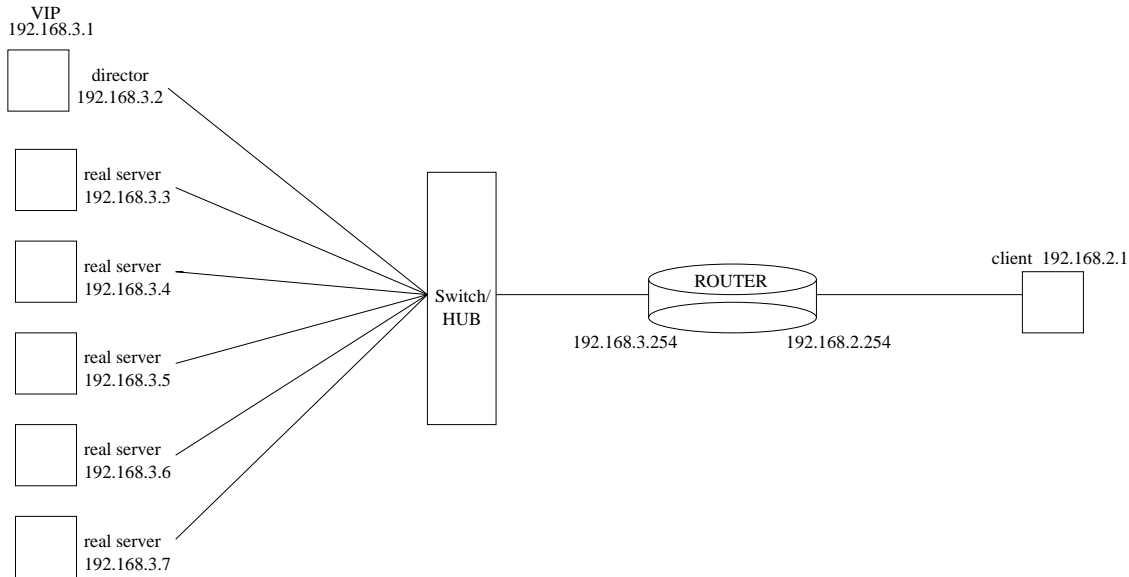


Figure 7: A cluster for Lab 8.

### 3.3 Managing the underlying network

**Lab 9: Simple Network Management Protocol (SNMP):** The main objective for Lab 9 is to use the Simple Network Management Protocol for network management. The concepts covered in this lab include the Management Information Base (MIB) and network event traps. This lab uses the infrastructure developed up to this point. A host is selected to be the network management station and the `net-snmp` package is installed. The `snmpd` script is started on all hosts that will require monitoring. Next, the routers are configured by setting community strings for both queries and management procedures. MIB tree structures are investigated by performing queries on the routers using the `snmpget` and `snmpwalk` commands. Once the students identify the appropriate MIBs they are asked to perform useful management functions such as changing the state of an interface on a router or querying for the number of packets dropped on an interface. Students then set `snmp` traps to be notified when events occur at the routers. The students test the traps by using `snmp` to bring down an interface and verify the `snmp` trap catches and logs the event.

### 3.4 Implementing/modifying network and transport layer mechanisms

**Lab 10: Class-based scheduling at network layer:** The main objective in this lab is to set up packet prioritization. The concepts covered will be packet classification and packet queuing. This lab requires a switch and four PC's; three host PC's and one PC to run as a router. The kernel on the PC/router should have Quality of Service (QoS) support enabled. The PC used as the router should also have two NICs to support the topology given in Figure 8. Instead of FIFO scheduling, we consider packet prioritization based on the value of the packet's type of service field. The first step is to set up QoS support and rebuild the kernel if QoS is not already enabled. The next step is to initialize the queuing discipline for the appropriate interface and attach it to the corresponding device. Once the root queuing discipline is established classes are created for different packet classifications. In order to actually classify incoming packets filters are attached to the classes to identify different attributes such as the type of service. Once the queues and filters are set up packet scheduling is tested. Testing is accomplished by the two hosts on the switch pinging the destination host with different values for their type of service field. A packet capturing application, like `ethereal` or `tcpdump`, is run at the

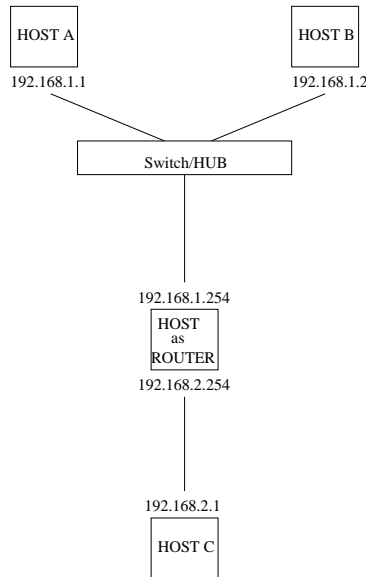


Figure 8: Setup for Lab 10.

destination host to verify the higher priority traffic is being given preferential treatment at the router.

**Lab 11: Modify the congestion control of TCP:** In this lab the main objective is to examine the operation of TCP's congestion control and modify the behavior. The basic concept of this lab will be how a host transmits using TCP in a congested network. There are no hardware requirements for this lab since it only involves modifying the source code for Linux's implementation of TCP's congestion control. The first step is to locate the code that is responsible for congestion control. Once located the students are asked to change the code on one host so that the window size remains the same even when congestion is detected. Regular operation reduces the window size to half to reduce network traffic. Finally, the kernel is recompiled on the host with the new implementation of TCP that ignores a congested network.

### 3.5 Analyzing the performance of various configurations and protocols

**Lab 12: Original TCP versus the above modified one:** In this lab the students are asked to compare the performance between the operation of TCP with congestion control and the operation of TCP as implemented in Lab 12. The main objective is for students to examine how TCP responds to a congested network. The concepts involved in the lab include network congestion and the host responsibilities for communicating over a network. This lab requires three PC's connected to a switch. One PC is designated as the target host and the other two PC's will transfer a file from the target host using FTP. A load is placed on the network to simulate congestion and the file is transferred, first by the host using the normal TCP and then by the host using the modified version. This procedure is performed multiple times to determine average statistics. The students are then asked to summarize the results and draw conclusions about the performance differences and the underlying implications for hosts operating in a network environment.

**Lab 13: Router versus switch:** The main objective of this lab is to examine the performance differences using different hardware. The concept involved in this lab is network behavior differences based on network hardware. The required hardware for the lab is at least two PCs, one router and one switch. First, the performance measurements are taken for the switch. In order to accomplish this

the topology of Figure 9. is used to transfer a file from one network to the other. The time and

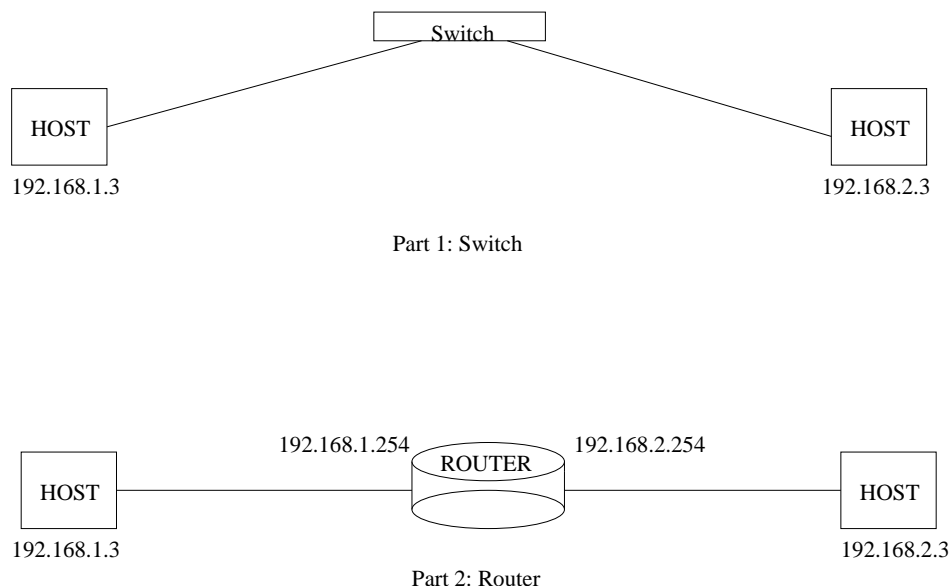


Figure 9: Setup for Lab 14.

throughput measurements are recorded and the switch is exchanged with a router. Once the router is set up measurements for the file transfer using a router are recorded and compared to the previous results. The students are then asked to draw conclusions about their results and give reasons for the differences.

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## 4 Student evaluation

The objectives for the laboratory course are for students to get hands-on experience and to clarify theoretical abstractions. The students will be evaluated weekly by being given questions regarding the current laboratory assignment. These questions will range from being broad and theoretical to specific and technical. The questions are intended to confirm that the concepts are known and well understood. The students will also be evaluated on their participation during the lab time. Since a number of the labs will require groups of students to work toward a common goal the instructor will be responsible for ensuring each student does a fair share of the work. As a final examination the instructor will randomly choose an experiment from all of the lab experiments and the students will be expected to perform the appropriate procedures.

## 5 Conclusions and future work

The use of the Internet as a model to teach students computer networking concepts allows students to observe theoretical concepts in practice. It also gives students some perspective regarding the interaction of various layers of network hardware and software. The clarification of networking abstractions will lead to greater understanding of and appreciation for the complexity of computer networks. A practical laboratory used in conjunction with or as a supplement to traditional lecture should provide the student with a strong foundation for further study.

This laboratory will continue to develop in response to changes in hardware availability and student feedback. It is also proposed that the laboratory be extended to the graduate level by focusing on specific layers or protocols and having the students develop new protocols to either support existing functionality or demonstrate particular behaviors of computer networks.

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