

# Past, Present, and Future of (our) Networking Labs

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## 1. Prequel

In the late 1990, with the rising relevance of the Internet, instructors of computer networking courses realized a need for hands-on education on IP protocols. At the time, exposure to actual network environments were mostly absent in undergraduate or graduate networking courses. In fact, most universities and colleges did not offer undergraduate networking courses until the mid-1990s. Key concepts such as the dynamics of routing algorithms were taught purely at an abstract algorithmic level. Practical aspects of computer networking were typically addressed in programming assignments.

Since 1994, a didactic method for learning about networking protocols from observations of *tcpdump* traces existed with W. Richard Stephens' "TCP Illustrated. Volume I." Some instructors, e.g., Prof. Shiv Panwar at Polytechnic University, developed lab courses using this approach, but labs for computer networking courses had not entered the mainstream of networking education.

In the NSF project "Internet Engineering Curriculum<sup>1</sup>," Evi Nemeth and CAIDA led efforts in 1999-2002 to assist instructors with designing and updating networking courses by setting up repositories with teaching materials and by holding workshops. One initiative of this project, spearheaded by Kevin Thompson of MCI Worldcom, sought to disseminate used backbone routers for the establishment of Internet teaching labs<sup>2</sup> (ITLs) at 25 universities. The ITLs were modeled after the VINTLab,<sup>3</sup> a hands-on teaching lab that Jörg Liebeherr had set up with donated Cisco 7000 routers from MCI Worldcom and Cisco Systems.

At an ITL workshop in 2001, Magda El Zarki from UC Irvine presented a modular design for a network teaching lab, where workstations, referred to as "racks," are equipped with four PCs and four 2500 class Cisco routers.<sup>4</sup> The modular design allowed the number of racks to be scaled to the course enrollment. Taking an open lab approach, where students complete experiments without supervision, the lab reduced the need for TA or lab supervisors. Following the workshop, Jörg Liebeherr and Magda El Zarki collaborated on developing a sequence of 10 labs on various aspects of TCP/IP networking. The labs were targeted at undergraduate students or beginning graduate students. The lab equipment was presented at the 2002 ACM Sigcomm Education Workshop (see Appendix). In 2004, the lab instructions were published by Addison-Wesley under the title "Mastering Internet Lab: An Internet Lab Manual" sequence. Figure 1 shows the equipment of a rack for the labs, and Figure 2 lists the topics of the 10 developed labs.

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<sup>1</sup> <https://www.caida.org/projects/iec/about/>

<sup>2</sup> <https://www.caida.org/projects/itl/press/index.xml>

<sup>3</sup> <https://web.archive.org/web/20000819161223/http://www.cs.virginia.edu/vintlab/index.html>

<sup>4</sup> [https://www.caida.org/workshops/itl/0106/materials/ITL\\_Workshop.ppt](https://www.caida.org/workshops/itl/0106/materials/ITL_Workshop.ppt)

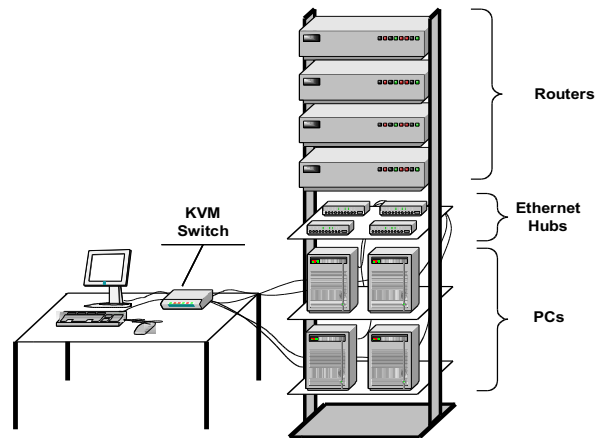


Figure 1. Internet Lab Equipment Rack

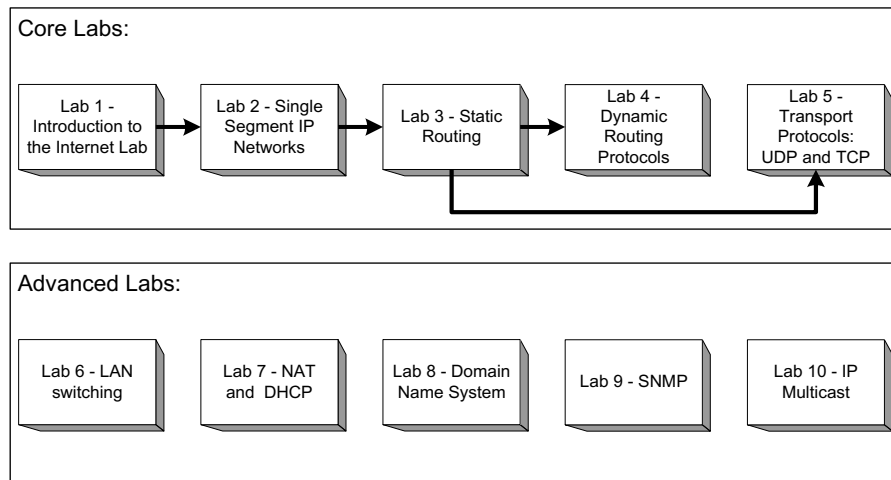


Figure 2. Labs of the Internet Lab (2002).

## 2. Design Philosophy of the 2002 Labs

In addition to the open lab approach, the labs were designed with the following objectives:

- Use science labs as model:** The organization of the labs follow the model of introductory labs in the sciences, where guided observations and measurements guide students to new insight and understanding of the subject. For the network labs, the object of study is network traffic and network protocols. Instead of scales and voltage meters, students work with tools for traffic generation and capture, e.g., *Wireshark* and *iperf*.
- Emphasize learning over skills:** A non-goal of the labs is to replicate the content of certification courses of equipment vendors (these already existed in the 1990s) or other training programs that cover details of router configuration and troubleshooting. Students are exposed to just enough knowledge of router and Linux configuration to complete the lab exercises.
- Keep it real:** The labs do not use simulators, emulators, or web-based configuration tools, as they present layers of abstractions between students and the equipment they operate. Students should get a sense of having complete control of the lab equipment.

- **No coding:** Programming assignments have been used successfully in networking education for studying protocol design, client-server interactions, and basic protocol mechanisms. The focus of the Internet lab on network experimentation offers an alternative perspective to study network protocols.

The lab was adopted by several universities and colleges (a report from the publisher listed about 45 US institutions as having adopted the lab manual). Some universities used the labs as a starting point for the creation of their own teaching materials.

### 3. Pros and Cons for Updating the Labs

After 15 years, there is no denying that the Internet lab manual has become outdated. Floppy disks, which were used to save data in the labs, have been long ago replaced by USB flash drives. Linux configuration commands and files have changed significantly. New protocols have become established (e.g., IPv6) or behave differently than what is assumed in the lab manual (e.g., ARP, TCP congestion control).

In 2017, Parviz Kermani from UMass suggested to revise the labs and include new trends in networking such as SDN. In discussions between us (the authors of this whitepaper) we weighed pros and cons of such an endeavor.

#### Cons:

- Introductory networking courses now cover TCP/IP protocols extensively, some even including exercises with *Wireshark* and SDN.
- Physical labs (as shown in Figure 1) can be replaced more cost-efficiently with virtual platforms. In 2015, Magda El Zarki transitioned the lab sequence shown in Figure 2 to virtual labs based on GNS3.<sup>5</sup>
- There exists an entire ecosystem of (mostly virtual) networking labs, covering not only routing and switching, but also security, wireless, and mobility. Numerous sites and videos explain every conceivable aspect of hands-on networking.
- Industry trends now emphasize scalability and virtualization of networks, which is not well suited for the limited equipment of the Internet lab.

#### Pros:

- Students' interest in the lab courses taught by the authors has remained high, and feedback from students continues to be overwhelmingly positive. Many students appreciate learning about practical aspects of networking and find it a valuable asset when entering the job market.
- While Internet protocols and deployments have changed, the principles of TCP/IP networking have not.
- Advanced networking topics, e.g., virtual network functions, assume familiarity with fundamental concepts in networking. Studying classical TCP/IP protocols provides a good foundation that enables students to move on to more advanced and novel concepts.

The most convincing arguments in favor of updating the labs emerged from the “science lab” approach discussed in Sec. 2. Introductory lab courses in chemistry, biology, and physics have changed only little over the years. Experiments that explore interference diffraction of light, osmosis, or thermodynamics remain fundamental in the presence of new advances in

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<sup>5</sup> <https://www.gns3.com/>

nanomaterials, microbiology, or polymers. With virtually all communication networks using TCP/IP protocols or being compatible with them, the case can be made that basic knowledge of TCP/IP networking is foundational.

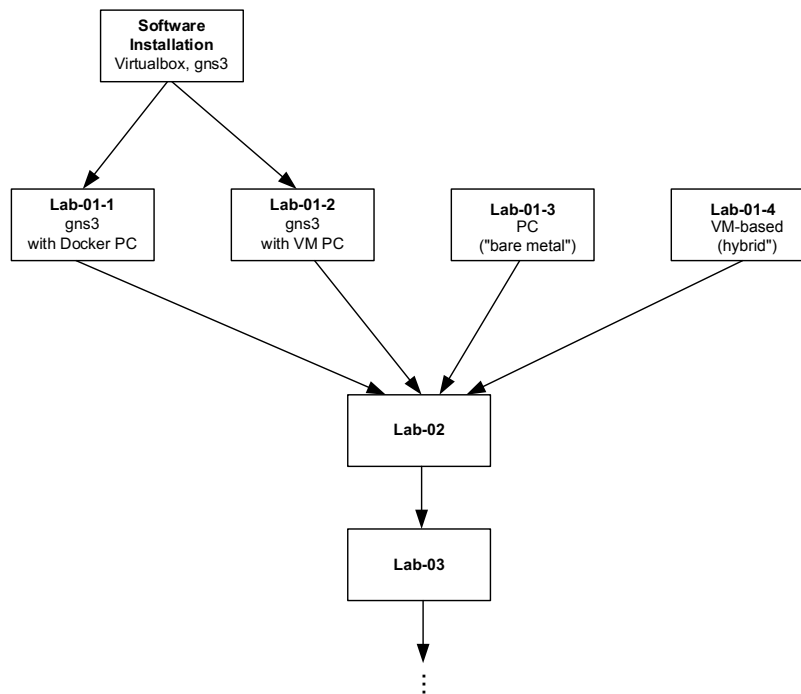


Figure 3. Roadmap for the new Internet Lab.

A second “science lab” argument derives from our observation that the vast majority of hands-on labs on TCP/IP networking, particularly, instructional videos, have a vocational emphasis. Instructions often focus on the “How-to” without exploring the “What-if”. For example, commands for configuring an IP address are mundane, but we can use them to explore what happens when two interfaces on a subnet have the same IP address. Or, consider static configurations of routing tables, where we can use configuration commands (the “How-to”) to check what happens when we set up routing loops. Our hope is that long after students have forgotten the details of configuration commands, they will remember the discoveries and observations from the networking labs.

#### 4. Virtual or Physical Labs, or Both?

There are many opinions and preferences on offering a networking lab as a physical lab, where students work with actual routers and switches, or as a virtual lab, that uses network emulation or simulation. Whatever the preferences, the decision between virtual and physical labs is often not up to the instructor, but determined by economics, or, in these days, by public health considerations.

Physical labs arguably offer a more immersive experience to the subject at hand. With our desire to “keep it real” (see Sec. 2), we want to continue offering labs with actual hardware. On the other hand, virtual labs are less costly and scale better to large classes. We believe that both types of labs will coexist for the foreseeable future. Instead of creating two versions of the Internet lab, we set out to create a single set of lab instructions that can be used for both a physical and a virtual setup. The physical lab continues to use equipment as shown in Figure 1, and the virtual lab is based on GNS3.

The organization of the new labs follows the roadmap shown in Figure 3. In Lab 1, we address all issues where physical and virtual labs differ. (Note in the figure that there are two variants each for the physical and the virtual version of Lab 1.) For example, when connecting two PCs in the physical lab by an Ethernet switch, we explain how to locate the Ethernet ports on the PCs and the switch, and how to connect them with an unshielded twisted pair cable. In the virtual labs, the instructions are about drawing a line between icons (see Figure 4). Starting with Lab 2, there is only a single version for each lab that applies to physical and virtual labs.

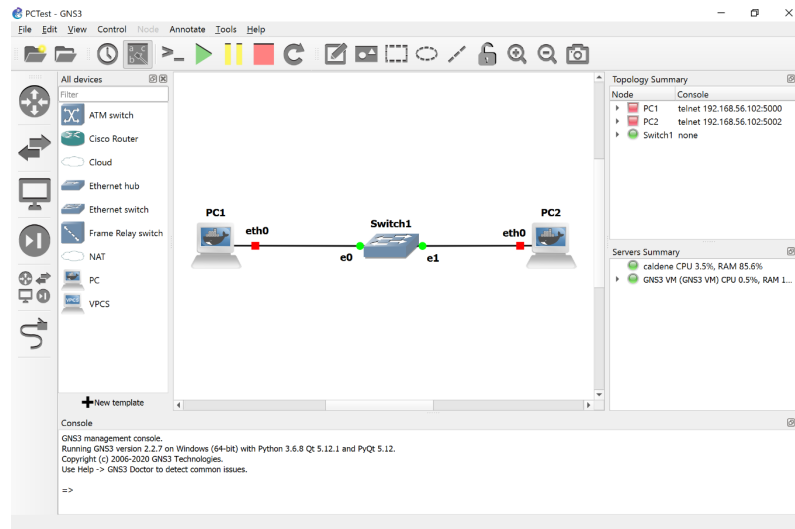


Figure 4. Connecting two PCs by an Ethernet switch in GNS3.

## 5. How about SDN?

When considering additional topics to be covered in the Internet Lab, SDN immediately comes to mind. Since many years, the Mininet emulation tool<sup>6</sup> has been used successfully for research and education on SDN technology. Creating a hands-on lab (or set of labs) in our setting views SDN as an extension of Layer-2/Layer-3 routing and switching. In the virtual labs, SDN switches are realized by Linux systems that are configured with an Open vSwitch.<sup>7</sup> The same can be done in the physical labs by re-purposing the PCs of a rack, however, it reduces the number of available PCs that can act as hosts. Commercial SDN enabled switches generally have a large number of ports, and, because of this, are quite costly. An interesting alternative is presented by the Zodiac switch from Northbound Networks,<sup>8</sup> which offers a 4-port SDN Open vSwitch for less than US\$ 100. However, availability of these switches is limited. Given the potential of SDN technology, it is interesting that education and training is stymied by low-cost SDN switches for use in education and training. Ironically, the situation mirrors the lack of low-cost commercial routers that we found when we started the Internet lab 20 years ago.

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<sup>6</sup> <http://mininet.org/>

<sup>7</sup> <https://www.openvswitch.org/>

<sup>8</sup> <https://northboundnetworks.com/>

# Internet Lab

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## Motivation Topics

- Goals:**
- Build a networking lab that is practical for large classes
  - Design open lab sessions to reduce the need for teaching assistants

- **Lab 1: Introduction to the Internet Lab**  
Introduction to Linux operation system, basics of tcpdump and ethereal
- **Lab 2: Single Segment IP Networks**

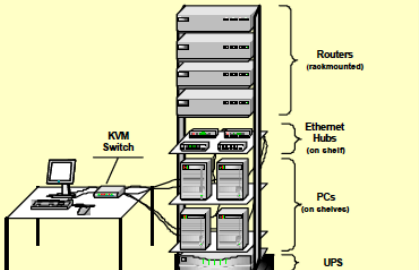
### "The Rack"

- One rack per 15-20 students
- Cost per rack is US\$ 7,000-15,000
- Racks are placed in a publicly accessible area (e.g., a computer room)

**Equipment:**

- 19" equipment rack
- 4 Cisco Routers
- 4 Ethernet Hubs
- 4 hosts
- Cables and connectors
- UPS
- 1 Monitor, 1 keyboard, 1 mouse, 1 KVM switch

\*Complete equipment list available from <http://www.tcspg-lab.net>

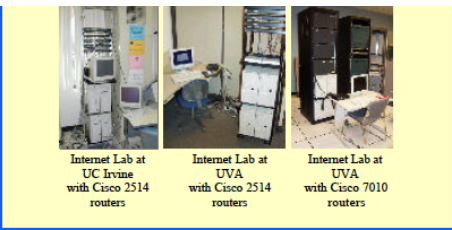


### Lab exercises

- Emphasis understanding of network protocols
- No emphasis on administrative skills
- Use science labs as model: Interpretations of measurements and observations lead to insights
- Each lab has three phases: (1) Prelab exercises, (2) Lab experiments, (3) Lab report
- Students have complete control of the equipment (incl. setting up cables, configuration)

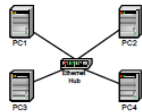
- Setting up hostnames and IP networking, configuring network interfaces, netstat command, experiments with ARP
- **Lab 3: Multiple Segment IP Networks and Static Routing**  
Setting up a computer as a router, static routing, update routing table via ICMP redirect, subnet masks
- **Lab 4: Dynamic Routing Protocols (RIP and OSPF)**  
Routing updates, convergence of routing protocols after topology changes under RIP and OSPF, split-horizon and triggered updates with RIP
- **Lab 5 - LAN Switching**  
Learning bridges, IEEE 802.1d spanning tree algorithm, mixed switching and routing
- **Lab 6: Transport Layer Protocols: UDP and TCP**  
UDP and TCP throughput, start and CP error

- Main tool: Ethereal**
- Network protocol analyzer with GUI
  - Freely available



- **Lab 7: IP Multicast**  
IGMP, PIM Dense Mode, PIM Sparse Mode
- **Lab 8 - NAT, DHCP**  
Network address translation, private networks, IP masquerading, IP address assignment with DHCP, DHCP relay agents
- **Lab 9: DNS**  
DNS resolver, DNS name server, DNS queries, hierarchical DNS servers

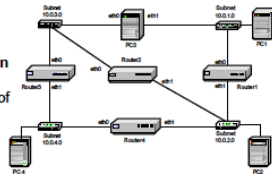
### Examples



**From Lab 2: Duplicate IP addresses**  
Observe what happens if two hosts on a network have the same IP address

- **Lab 10: Network Management**  
Accessing a MIB, SNMP traps, network configuration with SNMP
- **Lab 11: Firewall and Network Security (in preparation)**

**From Lab 4: Count-to-infinity Problem in RIP**  
Observe slow convergence of Routing Information Protocol (RIP) after changes to the network topology



### Conclusions

- Internet Lab is an attempt to reduce the overhead involved in teaching a lab course in computer networking
- Intended for advanced undergraduate students or beginning graduate students