Enabling P4 Hands-on Training in an Academic Cloud

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Agenda

• Motivation for virtual labs and Academic Cloud
• Academic Cloud
• POD design and lab libraries
• Using the Academic Cloud
• Relevant features
• Concluding remarks
Motivation for Virtual Labs and Academic Cloud

• According to the IEEE and ACM\(^1\), the IT curriculum should emphasize “learning IT core concepts with authentic practice” and “use of professional tools and platforms”
  ➢ “It is not enough to simply attend courses and read books. Hands-on learning is essential…”

• Using physical laboratories has been challenging
  ➢ Difficult to scale
  ➢ Expensive (space, maintenance, staff)
  ➢ Since COVID-19 emerged, the capacity of labs has been further reduced (distance requirements)

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1. Information Technology Curricula 2017, ACM/IEEE Joint Committee. Online: [https://tinyurl.com/4nqqwa5m](https://tinyurl.com/4nqqwa5m).
Motivation for Virtual Labs and Academic Cloud

• A report on what can be done to reach out those who are yet to be engaged in STEM workforce
• 15 focus groups, experts on research computing infrastructure
  ➢ “The present research computing and data ecosystems look impenetrable to many of those not yet engaged…”
  ➢ “Lower barriers to entry, but build up the controls at the same time”
  ➢ “Invest in cyberinfrastructure and community laboratories at the edge, enabling broader and more diverse participation in science and engineering”
  ➢ “Explore investments in research computing and data infrastructure approaches that are easily accessible (such as GUIs, science apps, and field tools)”
Academic Cloud

- The University of South Carolina (USC) (SC), the Network Development Group (NDG) (NC), and Stanly Community College (SCC) (NC) are deploying the Academic Cloud
- A system dedicated to teaching, training, and research
- The Academic Cloud provides remote-access capability to lab equipment via Internet
- It seamlessly pools and shares resources (CPU, memory, storage) from four data centers; resources are allocated to run virtual laboratories
Academic Cloud

- Data center locations: USC (South Carolina), SCC (North Carolina), NDG (IL), and Idaho National Laboratory (ID)

LMS: Learning Management System. LTI: Learning Tools Interoperability
Academic Cloud

- Data center locations: USC (South Carolina), SCC (North Carolina), NDG (IL), and Idaho National Laboratory (ID)

Front-end portals

(a) NC Cyber; (b) SC Cyber; (b) Companion material for a book; (d) General access
Inside a Data Center

- Hosts 1-n store virtual machines (VMs) for virtual labs
- Management server runs vCenter, Management Software (NETLAB+)
- Partnership with Network Development Group (NDG)

1. Network Development Group (NDG). Online: https://netdevgroup.com
## Inside a Data Center

- Example: Stanly Community College

<table>
<thead>
<tr>
<th>Device</th>
<th>Cores</th>
<th>Storage (TBs)</th>
<th>RAM Memory (GB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Server 1 (management SCC)</td>
<td>20</td>
<td>12</td>
<td>264</td>
</tr>
<tr>
<td>Server 2 (hosting vLabs pods)</td>
<td>32</td>
<td>4</td>
<td>768</td>
</tr>
<tr>
<td>Server 3 (hosting vLabs pods)</td>
<td>32</td>
<td>4</td>
<td>768</td>
</tr>
<tr>
<td>Server 4 (hosting vLabs pods)</td>
<td>32</td>
<td>4</td>
<td>768</td>
</tr>
<tr>
<td>Server 5 (hosting vLabs pods)</td>
<td>32</td>
<td>4</td>
<td>768</td>
</tr>
<tr>
<td>Server 6 (hosting vLabs pods)</td>
<td>32</td>
<td>4</td>
<td>768</td>
</tr>
<tr>
<td>Server 7 (hosting vLabs pods)</td>
<td>48</td>
<td>1.92</td>
<td>768</td>
</tr>
<tr>
<td>Server 8 (hosting vLabs pods)</td>
<td>48</td>
<td>1.92</td>
<td>768</td>
</tr>
<tr>
<td>Server 9 (hosting vLabs pods)</td>
<td>48</td>
<td>1.92</td>
<td>768</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>324</strong></td>
<td><strong>37.76</strong></td>
<td><strong>6408</strong></td>
</tr>
</tbody>
</table>
POD Design

- A virtual laboratory experiment requires a **pod** of devices, or simply pod
- Example: perfSONAR library

![POD Design Diagram](image)

<table>
<thead>
<tr>
<th>POD for perfSONAR labs</th>
<th>perfSONAR labs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internet</td>
<td>1. Configuring Administrative Information Using perfSONAR Toolkit GUI</td>
</tr>
<tr>
<td>Border router</td>
<td>2. PerfSONAR Metrics and Tools</td>
</tr>
<tr>
<td>R1</td>
<td>3. Configuring Regular Tests Using perfSONAR GUI</td>
</tr>
<tr>
<td>203.0.113.0/24</td>
<td>5. Configuring Regular Tests Using pScheduler CLI Part II</td>
</tr>
<tr>
<td>R2</td>
<td>6. Bandwidth-delay Product and TCP Buffer Size</td>
</tr>
<tr>
<td>192.168.3.0/24</td>
<td>7. Configuring Regular Tests Using a pSConfig Template</td>
</tr>
<tr>
<td>Client</td>
<td>8. perfSONAR Monitoring and Debugging Dashboard</td>
</tr>
<tr>
<td>Client</td>
<td>9. pSConfig Web Administrator</td>
</tr>
<tr>
<td>perfSONAR1</td>
<td>10. Configuring pScheduler Limits</td>
</tr>
<tr>
<td>perfSONAR2</td>
<td></td>
</tr>
</tbody>
</table>
POD Design

- Details of perfSONAR pod
  - Four networks
  - Three servers
  - One client
  - Three routers
  - Connectivity to the Internet
  - Total of seven heterogeneous VMs
Pod Design

- Details of perfSONAR pod
  - PODs running simultaneously use the same block of IP addresses
  - Lab manuals are uniform
  - There is a master pod in the system
  - Linked clone VMs are created from the master pod VMs
Introduction to P4 Lab Series

Lab experiments
Lab 1: Introduction to Mininet
Lab 2: Introduction to P4 and BMv2
Lab 3: P4 Program Building Blocks
Lab 4: Parser Implementation
Lab 5: Introduction to Match-action Tables (Part 1)
Lab 6: Introduction to Match-action Tables (Part 2)
Lab 7: Populating and Managing Match-action Tables
Lab 8: Checksum Recalculation and Packet Deparsing

Exercises
Exercise 1: Building a Basic Topology
Exercise 2: Compiling and Testing a P4 Program
Exercise 3: Parsing UDP and RTP
Exercise 4: Building a Simplified NAT
Exercise 5: Configuring Tables at Runtime
Exercise 6: Building a Packet Reflector
Lab experiments

Lab 1: Introduction to Mininet
Lab 2: Introduction to P4 and BMv2
Lab 3: P4 Program Building Blocks
Lab 4: Defining and processing custom headers
Lab 5: Monitoring the Switch’s Queue using Standard Metadata
Lab 6: Collecting Queueing Statistics using a Header Stack
Lab 7: Measuring Flow Statistics using Direct and Indirect Counters
Lab 8: Rerouting Traffic using Meters
Lab 9: Storing Arbitrary Data using Registers
Lab 10: Calculating Packets Interarrival Time w/ Hashes and Registers
Lab 11: Generating Notification Messages from the Data Plane
Using the Cloud System

Cyberinfrastructure Lab @ UofSC
Using the Cloud System

Scheduled Lab Reservations

- You have no scheduled lab reservations.
- Select from the Schedule menu above to add reservations.
Using the Cloud System

Introducing P4 programmable data planes with BMv2

- Lab 1: Introduction to Mininet
- Exercise 1: Building a Basic Topology
- Lab 2: Introduction to P4 and BMv2
- Exercise 2: Compiling and Running a P4 Program
- Lab 3: P4 Program Building Blocks
Using the Cloud System
Using the Cloud System

Lab Reservations

<table>
<thead>
<tr>
<th>ID</th>
<th>Date/Time</th>
<th>Description</th>
<th>Pod</th>
</tr>
</thead>
<tbody>
<tr>
<td>162</td>
<td>2022-05-31 11:01</td>
<td>Class: P4 Tofino Training</td>
<td>Tofino_H1_300</td>
</tr>
<tr>
<td></td>
<td>2022-05-31 15:00</td>
<td>Lab: Lab 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 hrs., 48 mins.</td>
<td>Type: Instructor</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>User: Jorge Crichigno</td>
<td></td>
</tr>
</tbody>
</table>

Showing 1 to 1 of 1 items

New Lab Reservation
Using the Cloud System
Using the Cloud System
Using the Cloud System

- Readily available platform
- Topology complexity
  - 6.4 Tbps programmable switch
  - Tofino programmable chip (Intel)
  - Tofino model for debugging (trace execution in the data plane)
  - Servers to send/receive data to/from the switch/other servers
  - Multi-mode fiber
  - QSFP28+ transceivers
  - Open Network Linux (ONL) (control plane)
  - Software Development Environment (SDE) from Intel (control plane)
  - Compiler
  - Sample P4 codes for each lab (data plane)
  - Laboratory experiments with step-by-step directions (thousands of development hours)

- Logistics
  - NDA with Intel, lawyers’ agreement
  - Procurement process
  - Physical hardware, rack space, data center, etc.
  - Software tools, SDE, operating system, etc.
## Cloud Features

<table>
<thead>
<tr>
<th>Feature</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allocation of resources</td>
<td>Pod granularity</td>
</tr>
<tr>
<td>Custom pods</td>
<td>Easy to create custom pods</td>
</tr>
<tr>
<td>Cost</td>
<td>Cost-effective when used extensively</td>
</tr>
<tr>
<td>Presentation layer for pedagogy</td>
<td>Topology is graphically presented to the learner using a regular browser</td>
</tr>
<tr>
<td>Time sharing</td>
<td>The owner controls who can access resources; easy to implement time-sharing policies</td>
</tr>
<tr>
<td>IP addresses</td>
<td>Pods (and learners) can have the same topology and IP addresses (overlapping addresses w/o conflict)</td>
</tr>
<tr>
<td>Functional realism</td>
<td>Virtual labs have the same functionality as real IT hardware in a real deployment, and execute the same code</td>
</tr>
<tr>
<td>Traffic realism</td>
<td>Devices generate/receive real, interactive network traffic to/from the Internet, or to/from other devices within the lab environment</td>
</tr>
</tbody>
</table>
Concluding Remarks

• The Academic Cloud has served over 100,000 learners (dozens of virtual libraries: Linux, virtualization, cybersecurity, etc.)
• Academic institutions (colleges, universities, high-schools), training centers
• Self-pace learners
• Usage example from one institution supporting one academic program (~300 students, January 1, 2020 – December 30, 2020)
Concluding Remarks

• The system has shown to be scalable
  ➢ It has served over 100,000 learners in 2020
• Due to the positive feedback, the system is expanding with more virtual labs
• The team is exploring the viability of connecting the Academic Cloud to FABRIC
• URL: http://ce.sc.edu/cyberinfra/cybertraining.html
Acknowledgement

• This work is supported by the National Science Foundation, award 2118311
## Academic Cloud vs Public Clouds

<table>
<thead>
<tr>
<th>Feature</th>
<th>Academic Cloud</th>
<th>Public Cloud</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allocation of resources</td>
<td>Granular allocation of physical resources (CPUs, NICs, etc.)</td>
<td>Not granular (access to the physical resources requires additional fees)</td>
</tr>
<tr>
<td>Custom pods</td>
<td>Easy to create custom pods</td>
<td>Difficult; hard to design complex topologies</td>
</tr>
<tr>
<td>Cost</td>
<td>Cost-effective when used extensively</td>
<td>Cost-effective for individual / small VMs; costly for large VMs over time</td>
</tr>
<tr>
<td>Presentation layer for pedagogy</td>
<td>Very flexible. Topology is graphically presented to the learner using a regular browser</td>
<td>Not flexible; limited to providers’ interface, e.g., command-line interface</td>
</tr>
<tr>
<td>Time-sharing resource feature</td>
<td>The owner controls who can access resources. Easy to implement time-sharing policies</td>
<td>Cloud provider controls who can access resources (typically, a fee is required per user)</td>
</tr>
<tr>
<td>Integration of physical devices</td>
<td>Easy; physical hardware can be integrated into pods</td>
<td>Difficult; no subscription plan permits integrating customized physical devices</td>
</tr>
<tr>
<td>Flexible use of IP addresses and subnets</td>
<td>Each pod runs in a sandbox. Pods (and learners) have the same topology and IP addresses (overlapping addresses without conflict)</td>
<td>IP addresses are typically unique. The vLabs manuals and companion material are not identical, requiring per-learner adjustment</td>
</tr>
<tr>
<td>Target</td>
<td>Specially built for pedagogy (education, research, and training)</td>
<td>General, used by a large variety of users</td>
</tr>
<tr>
<td>Typical users</td>
<td>From entry-level learners to PhD researchers</td>
<td>More experienced professionals, educators, students</td>
</tr>
</tbody>
</table>