The SEED Internet Emulator and Its Applications in Cybersecurity Education

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ABSTRACT
In cybersecurity courses, it is quite challenging to do hands-on activities that involve many components of the Internet, such as bringing down the Internet, attacking a blockchain, etc. To solve this problem, we have developed an open-source Internet Emulator, which is a Python library, consisting of the classes for each essential element of the Internet, including autonomous system, network, host, router, BGP router, Internet exchange, etc. It also includes the classes for a variety of services, including Web server, DNS, Botnet, Darknet, Blockchain, and more are being developed. Using these classes, users can construct a mini-Internet to emulate the real-world Internet. Although it is small, it has all the essential elements of the real Internet. The construction is compiled into Docker container files, and the emulation is executed by Docker on a single machine, or on multiple cloud machines.

With this Internet Emulator, we can develop a variety of hands-on activities for cybersecurity courses, including BGP prefix hijacking, attacks on smart contract, using Darknet to achieve anonymity, launching Botnet and ransomware attacks, etc. While the emulator was initially developed for cybersecurity courses, it can also be used for network courses, for students to learn how the Internet technologies work, such as routing, BGP, IP Anycast, and DNS. Many other interesting network technologies can also be deployed on the emulator, such as content delivery network and software-defined network. This is an open-source project: https://github.com/seed-emulator.

KEYWORDS
Internet emulation, cybersecurity education, networking

1 INTRODUCTION
How to design lab activities that involve a large number of computers has been a challenging problem in cybersecurity education. There are two typical solutions to this problem. A common approach is to use a dedicated infrastructure, such as cyber ranges, consisting of many physical machines or virtual machines. NSF has funded some of such infrastructures, such as the DETER project [4]. Many companies and organization also offer cyber range as a service. These infrastructures, although useful for education, are quite expensive to build and maintain. Based on a report [7], a cyber range costs $336K to $576K for the first year, and $70K to $100K for each consecutive year. Not many institutes can build their own cyber ranges, much less individual instructors.

Another approach is to use a simulator/emulator to simulate/emu- late the behaviors of a large network and its nodes. Existing works include Common Open Research Emulator (CORE) [5], NS-3 [3], GNS-3 [2], Greybox [12], NetSim (commercial) [15], OPNET (commercial) [18], etc. These simulators/emulators can run on a single or a small number of computers, making them much more affordable than the infrastructure approach. This is a much more promising approach. We envision that a well-developed Internet emulator, specifically designed for cybersecurity, will significantly help improve the hands-on learning in cybersecurity.

Internet emulation consists of two main challenges: the building part (how to build the emulator) and the emulation part (how to conduct the emulation). Most of the existing work focuses on the emulation part. This includes CORE [5] (Greybox [12] is based on CORE) and GNS-3 [2]. They focus primarily on emulating different types of networks (hardware). While this is necessary for research and product testing, it is not essential for cybersecurity education, as most of the cyber attacks are at the higher layers, which are not specific to network hardware; they are related to protocols, services, and applications.

For cybersecurity education, being able to emulate generic network hardware will be sufficient to cover most scenarios. This can be done using the matured Docker and container technologies [14]. Using these technologies, we can use docker containers to emulate hosts and routers, while using virtual networks to emulate the networks. These are the building blocks of the Internet. Moreover, we can install additional software (such as routing software) inside the containers, so the emulated nodes can communicate with one another. This is the approach taken by Mini-Internet [13].

With the emulation challenge being solved by Docker, the primary challenge left for building an Internet emulator becomes the building part, i.e., how to build an emulation. This involves building the image for each individual container, including specifying how the image should be built, providing all the needed files for the image, configuring the operating system and software running inside the image, and connecting the container to networks. Constructing docker images manually is not viable even for a small-size Internet emulator. It is better to use tools to generate the emulation files.

The main contribution of our work, also the main difference separating our work from the other work, is how we construct the emulation files. We have developed an open-source Python library, consisting of the classes for each essential element of the Internet, including autonomous system, network, host, router, BGP router, Internet exchange, etc. It also includes the classes for a variety of services, including Web server, DNS, Botnet, Darknet, and Blockchain. Using these classes, users can construct an Internet emulator using Python programs. The construction is then compiled into container files for Docker to run on a single machine or on multiple machines from the cloud.
2 OVERVIEW OF THE DESIGN

In this section, we provide a brief overview of the design. Detailed discussions of each element in our system are provided in separate sections.

2.1 The Programming Approach

Among the existing emulators (not necessarily in the field of networking), three approaches are typically used to compose an emulation.

- GUI approach: use a graphic tool.
- Configuration file: describe how the emulator should be built in configuration files, and then use programs to convert them to the emulation files.
- Programming: provide libraries and APIs, so users can write programs to directly generate the emulation files.

These approaches have one thing in common: they all ask users to use a specific language to build the emulation. They differ in their language choices: graphic language, configuration language, and programming language. The first two types of languages do not require a programming skill, so they can be used by more people. Behind the scene, they still have to rely on programming to produce the final emulation. The third approach eliminates the “middle man”, asking users to directly write programs.

The first two approaches lower the barrier to use at the cost of expressive power: their expressive power cannot match that of a Turing-complete programming language, which is the case for most general-purpose languages, such as C/C++, Java, JavaScript, and Python. For example, generating 1000 nodes with a slightly different configuration is quite difficult to achieve using the graphic or configuration language, but using programming, it is just a simple loop.

In our early design, we did use the configuration file approach, but as our emulator became more and more complicated, the size of the configuration file became too large to manage. Moreover, every time we needed to make changes to some places, we had to change many different places. We wished that the language we chose could support variables, functions, loops, etc. so the configuration could be more concise and managing large configuration could be easier. Eventually, we realized that what we wished for already exists, and it is called programming language. Users interested in building Internet emulators are very likely those who already have a programming background, so programming language is the best choice for building such an emulator. We picked the Python language due to its wide popularity, easiness to use, and rich set of modules.
The layer idea was inspired by the image/video editing software such as Adobe Photoshop and Premier, where each layer contains parts of the image/video (in our case, part of the emulation).

There are two types of layers, base layers and service layers. The base layers describe the "base" of the topologies, like how routers, servers, and networks are connected, how autonomous systems are peered with each other. The service layers describe the high-level services on the Internet. Examples of services layers are web servers, DNS servers, Ethereum blockchain, and botnet. No layers are tied to any other layers, meaning each layer can be individually manipulated, exported, and re-used in another emulation. One can build an entire DNS infrastructure, complete with root DNS, TLD DNS, and deploy it on any base layer, even with vastly different underlying topologies.

The rendering phase. During the composition phase, layers are composed separately, and no hard-coded dependency or reference between layers is allowed. However, layers that install services, like the DNS layer, need to know what physical node in the emulation to install and configure the service on. In order to archive this, we introduce the virtual node, which is merely a string, a symbolic name. The layers track the changes using the virtual node name. Virtual nodes are not bound to any physical nodes at the base layer. Decoupling services layers from the base layers reduces the dependency of layers, making the services layer more portable. During the rendering phase, all the layers will be merged, and the virtual nodes will be bound (or deployed) to physical nodes.

The compiling phase. When composing the Internet emulator, we do not make any assumption on the underlying emulation technologies. We simply build the Internet; how to run the Internet is not the concern of the composition. That is the compiler’s concern. The compiler is the one that generates the final emulation files.

Separating the concerns of composition and emulation is important for an extensible design. By implementing different compilers, we can generate the emulation files for different technologies. For this project, we have only implemented three compilers, one for Docker on a single computer, one for the cloud computer (also using Docker), and the other one for simply generating the topology diagram. However, if we want to run our emulator on other platforms, such as ns-3, GNS-3, and CORE, we just need to implement a corresponding compiler for them.

2.3 Visualization
For the purpose of education, being able to visualize what is happening on the Internet is important. For example, to launch the BGP prefix hijacking attack, it will be more interesting if students can see visually how this attack changes the packet flows on the Internet. We have develop an independent web-based tool for the visualization of the emulated Internet, as well as providing a way for users to interact with the nodes in the emulator. Users can also record the events occurred on the emulator, and replay them in a slower speed, so they can see exactly what has happened. The tool is presented in Section 5.

3 THE BASE
The Internet is formed by host machines, routers, networks, Internet exchanges, and autonomous systems. The autonomous systems peer with one another using BGP. To build an Internet in an emulation, we need to provide the building blocks corresponding to these entities.

3.1 Internet Exchange
An autonomous system needs to connect to other autonomous systems, so they can exchange network traffic. Without the connection, an AS will be an isolated system. Through the connections, users from one autonomous system can reach the users on another AS. Connecting two autonomous systems is called peering. There are two types of peering, public peering and private peering. Public peering usually occurs inside a public facility called Internet Exchange points (IX). Private peering can also be done inside an IX, but most private peering occur at colocation center, which is a special type of data center.

We emulate both the public and private peering at Internet exchanges. An IX is basically a big high-throughput switch that connects the routers from different ASes. Through this switch, packets from one AS can be handed over to another AS. In the follow example, we create two Internet exchanges, IX-100 and IX-101 (the numbers are the autonomous system number assigned to the IXes). Internally, a network is created for each IX (their network names are automatically set to ix100 and ix101 in our convention).

```plaintext
ix100 = base.createInternetExchange(100)
ix101 = base.createInternetExchange(101)
```

3.2 Stub Autonomous System
An autonomous system (AS) is a collection of connected Internet Protocol (IP) routing prefixes under the control of one or more network operators on behalf of a single administrative entity or domain. As an essential element of the Internet, AS is emulated in our emulator.

When composing the emulator, we can create an autonomous system, and then create hosts, routers, and networks inside it. In the following example, we create an AS with the AS number 150;
we then create a network, a router, and two hosts inside the AS. Hosts and routers need to be attached to networks.

```java
as2 = base.createAutonomousSystem(2)
as2.createNetwork("net0")

# Create 3 internal networks
as2.createNetwork("net1")
as2.createNetwork("net2")

# Create 4 routers
as2.createRouter("r0").joinNetwork("ix100")
.as2.createRouter("r1").joinNetwork("net0")
.as2.createRouter("r2").joinNetwork("net2")
.as2.createRouter("r3").joinNetwork("ix100")

Routers should be attached to multiple networks. In the example above, router0 is attached to the AS’s internal network net0 and a network called ix100. The second one is the name of the switch network inside the Internet exchange IX-100. Therefore, router0 is automatically treated as a BGP router in the emulation, and the corresponding BGP configuration will be conducted on this router.

In the example given above, AS-150 is only connected to one Internet exchange, so it does not provide transit services to others. This is a stub AS. It emulates the end customers, such as universities, organizations, and most companies.

3.3 Transit Autonomous System

Transit AS is another type of AS connecting to multiple ASes, typically at multiple locations. It offers to route packets from one AS to another AS, i.e., it provides transit services to others. In our emulator, creating a transit AS is similar to creating a stub AS. An example is provided in the following.

```java
# Create the autonomous system (asn = 2)
as2 = base.createAutonomousSystem(2)

# Create 3 internal networks
as2.createNetwork("net0")
as2.createNetwork("net1")
as2.createNetwork("net2")

# Create 4 routers
as2.createRouter("r0").joinNetwork("ix100")
.as2.createRouter("r1").joinNetwork("net0")
.as2.createRouter("r2").joinNetwork("net2")
.as2.createRouter("r3").joinNetwork("ix100")

In this emulation, we have created three networks, which are connected using four routers. The network topology is depicted in Figure 3. Although this example only shows a simple linear network topology, as we can see from the example, more complicated topologies can also be created using the provided APIs. This is one of the advantages of using programs to construct an emulation over the other approaches, due to the expressive power of a programming language.

The routers r0, r1, and r3 also connect to an Internet exchange network at IX-100, IX-101, and IX-102, respectively (see the lines marked by ♠). Therefore, these three routers are BGP routers. Internally, they will be peered with one another via the IBGP (Internal BGP) protocol. This is required for these BGP routers to exchange information obtained from their respective external peers.

Inside an autonomous system, the internal routers talk among themselves, exchanging routing information, so routers know where to route packets within the AS. These routers only talk to the routers within the same AS, and they do not talk to the outsider. Examples of IGP includes OSPF, RIP, and IGRP. In our current implementation, we only use the OSPF protocol, but other protocols can also be supported. Therefore, the routers r0 to r3 are configured to run the OSPF internal routing protocol.

3.4 BGP Peering

There are two types of BGP peering: EBGP and IBGP peering. EBGP peering is for BGP routers from different autonomous systems. For the BGP routers in the same autonomous systems to exchange information, they also need to peer with each other and run the BGP protocol to exchange information. The BGP protocol conducted by the BGP routers inside the same AS is called Internal BGP (IBGP).

As we have mentioned earlier, in the emulator, IBGP peering will be automatically set up. All the BGP routers within an AS will peer with one another using IBGP.

For EBGP peering, we need to explicitly specify which ASes peer with each other. In the following example, AS-3 peers with AS-160, AS-161, and AS-162 at IX-103; their peer relationship is provider and customer, with AS-3 being the providers to the others (i.e., the other three ASes are customers of AS-3, and in the real world they need to pay AS-3 for the transit service provided by AS-3).

```java
ebgp.addPrivatePeerings([103, [3], [160, 161, 162]], PeerRelationship.Provider)

In a public Internet exchange, autonomous systems want to peer with many other autonomous systems. Let’s say we have N autonomous systems, and they want to peer with one another. If we use the approach described earlier, each pair of ASes needs to set up a peering relationship. That will be quite complicated. Most
Internet exchanges provide a mechanism to simplify this. They provide a special server called route server. All these N autonomous systems will only need to peer with this route server. When the router server receives a route from a participant over BGP, it redistributes the routes to all other connected participants. The route server function pretty much like multicast: any BGP route sent to the router server will be received by everybody that peers with the route server.

Peering using the route server is supported in the emulator. In the following example, we peer AS-2, AS-3, and AS-4 at IX-100 using the route server approach. One line of code will create the peering among these three ASes.

```
1  ebgp.addRsPeers(100, [2, 3, 4])
```

**Peering relationship and BGP communities.** What routes a BGP router sends to its peer is based on the BGP peering relationship. The emulator supports two common peering relationship: provider-to-customer and peer-to-peer. However, to support other peering relationship, we have implemented the BGP Large communities protocol [17] in the emulator.

This protocol provides a generic solution for BGP routers to decide which routes should be exported to or imported from a peer. With this protocol, each route is marked by labels (community). During route exporting and importing, actions can be applied to these routes based on which communities they belong to. There are many applications of the BGP Large Communities, such as identifying routes by their geographically locations (countries, continent etc.), the business relationships between peers (customers, providers, or peers), and many other aspects. In our current implementation, we only use the BGP Large communities to implement the peering relationship, but more interesting applications can be supported by our design.

**The routing software.** The routing software used in the Emulator is called BIRD, an acronym standing for “BIRD Internet Routing Daemon” [8]. BIRD is open source under the GNU General Public License. It supports a number of standard routing protocols, including the Border Gateway Protocol (BGP), the Routing Information Protocol (RIP), and the Open Shortest Path First protocol (OSPF). We mainly use BGP and OSPF in the Emulator.

### 3.5 Shadow Internet

By default, the SEED Internet emulator is isolated from the outside: machines from outside cannot communicate with those inside the emulator. This is done on purpose. In our design, we do provide support so users from outside can join the emulation by attaching their computers to a network inside the emulation. We also provide the support so packets inside the emulation can be routed out to the real Internet.

When we put them together, the emulator becomes a shadow Internet (see Figure 4). Users from outside who want to visit a computer on the real Internet, such as example.com, will route their example.com-bound packets into the shadow Internet (by changing the routing table on the user’s machine). The packets will eventually exit the emulator, into the real Internet, and eventually reach its final destination. If we want to emulate a real attack against example.com, we can now do it inside the emulator, which to the user, is equivalent to the attack inside the real Internet.

```
1  as152 = base.getAutonomousSystem(152)
2  as152.getNetwork('net0').enableRemoteAccess(oVPN)
```

To allow outside machines to become a part of the emulator, we just need to host a VPN server on a node inside the emulator and export the port, so it is accessible from the outside. In the following example, we will create a VPN server on the net0 network inside AS-152. Once an outside machine VPNs into the network, it essential becomes a host on the net0 network, and can thus access all the other machines inside the emulation via the net0 network.

```
1  as11872 = base.createAutonomousSystem(11872)
2  as11872.createRealWorldRouter('rw').
3      joinNetwork('ix102', '10.102.0.118')
```

Once the above is set up, packets (from inside the emulator) going to Syracuse University’s networks will be routed to this AS, and then be forwarded to the real world (through a NAT server). Returning packets will come back from the outside, enter the emulator at this AS, and be routed to its final destination inside the emulator.

### 3.6 APIs on Host

To support various applications inside the emulator, we need to be able to install more software and file on the hosts, as well as being able to conduct configuration. While this can be done during

![Figure 4: The Shadow Internet](image-url)
the runtime, i.e., when the emulator is running, it can be time-consuming if we have to do these on many hosts. In our design, we provide APIs so these tasks can be done when we construct the emulator. The following example shows some of the useful APIs.

```python
# Get an instance of the host from AS-151
host0 = as151.getHost('host0')

# Install software on the host
host0.addSoftware('telnetd').addSoftware('telnet')

# Import a file to the host
host0.importFile(hostpath="/home/seed/ddos.py", nodepath="/tmp/ddos.py")

# Create a file on the host
host0.setFile(content="some content", path="/tmp/file.txt")

# This command is executed when the container is built
host0.addBuildCommand('useradd -m -s /bin/bash seed
& echo "seed:dees" | chpasswd')

# Append a command to the start script
host0.appendStartCommand('cd /bof && /bof/server &')
```

4 COMPONENTS

Building a good and realistic emulator takes time and efforts, so it will be desirable if the entire or parts of an emulator can be shared and used as building blocks for other emulators. Good emulators/simulators come with this kind of pre-built parts. For example, Matlab’s Simulink has many pre-built components for simulation. We call these pre-built emulator (or its part) component, and they can be added to an emulator. For example, we can build a DNS infrastructure that contains 5 root servers, 30 top-level domain servers, and 100 domain name servers. This DNS infrastructure can be exported as a component. Any Internet emulator that needs a DNS infrastructure can use this component, instead of building one from scratch.

4.1 The Extensible Design

The biggest challenges in supporting components are how to make the components portable and how to connect them to emulators. First, to support portability, we use dynamic binding to bind nodes from the service layer to the base layer. In our layered design, nodes used at the service layer are virtual nodes, not physical ones. Physical nodes (containers) are only in the base layer. When we build each layer, we do not bind them, so each layer can be built, modified, and exported independently. There is no dependency among layers. When the emulator construction is finished, we will render the final emulator. That is when the layers are merged and virtual nodes are bound to the physical nodes at the base layer. See Figure 5.

Second, when a component is exported, we would like to allow users to use the component as a blackbox, without the need to know its internal logic. To support this, all the virtual nodes of a component need to be exposed, so when we connect the component to an emulator, we need to connect the virtual nodes to the physical nodes. We draw our inspiration from the circuit design, where complicated components are enclosed inside a chip, and a chip connects to the rest of the circuit via pins. We use a similar design pattern, packaging each component as a “chip”. Let us use an example to illustrate the design.

4.2 Example 1: DNS Infrastructure

A DNS component (Figure 6) is at the service layer. Its main goal is to set up the DNS infrastructure, including configuring the zone files for each domain hosted in this infrastructure. When we build such a component, we will provide a data sheet to show the purpose of each pin. When users deploy this DNS component inside an emulator, they will specify how each pin is connected to the base layer. For example, they can connect the EDU-1 pin to a randomly selected node inside the autonomous system 1192 in the base layer, while connecting the nsf.gov pin to the node with the IP address 128.150.4.107.

![Figure 5: Making module portable](image5)

![Figure 6: Examples: DNS component](image6)
In the following, we show how we create an DNS infrastructure. The `dns.install(name)` will create a node using name if such a node does not exist. We can install zones on these nodes, and configure their zone files. These nodes are virtual nodes; they are just names, and they do not bind to any existing physical node in the emulator. This makes the component portable.

```python
dns = DomainNameService()

# Create a DNS layer
dns.install('root-a').addZone('.').setMaster()
dns.install('root-b').addZone('.')

dns.install('com-a').addZone('com.').setMaster()
dns.install('com-b').addZone('com.').
dns.install('edu').addZone('edu.')

dns.install('ns-example-com').addZone('example.com.').
dns.install('ns-syr-edu').addZone('syr.edu.').
dns.install('ns-google-com').addZone('google.com.').

# Add records to zones
dns.getZone('example.com.').addRecord('@ A 2.2.2.2')
.addRecord('www A 5.5.5.5')
.addRecord('xyz A 5.5.5.6')
```

The above DNS component can be saved into a file and be plugged into any base. To do that, we bind each of the virtual node in this component to a physical node in the base. After that, all the DNS configuration conducted on the virtual node will be applied to the physical node. The following code shows how the binding is conducted. For example, the virtual node `root-a` is bound to a host in ASN-171 (the emulator will find a suitable host for us). After the binding, this selected host will become a DNS root server.

```python
e1 = eth.install('eth1').startMiner()
e2 = eth.install('eth2').startMiner()
e3 = eth.install('eth3').startMiner()
e4 = eth.install('eth4').startMiner()
e5 = eth.install('eth5')
e6 = eth.install('eth6')

e1.setBootNode(True)
e2.setBootNode(True)

e3.deploySmartContract(contract)
```

4.3 Example 2: Blockchain

We have also implemented an Ethereum-based blockchain component. In the following example, we create 6 nodes, with 4 of them being miners. We also deploy a smart contract from one of the nodes. These nodes are virtual nodes. To deploy this blockchain to an emulator, we just need to bind these virtual nodes to physical nodes.

```python
# Create Ethereum nodes
e1 = eth.install('eth1').startMiner()
e2 = eth.install('eth2').startMiner()
e3 = eth.install('eth3').startMiner()
e4 = eth.install('eth4').startMiner()
e5 = eth.install('eth5')
e6 = eth.install('eth6')

# Set bootnodes on e1 and e2.
# The other nodes can use these bootnodes to find peers.
e1.setBootNode(True)
e2.setBootNode(True)

# Deploy a smartcontract on e3
contract = SmartContract("./Contracts/contract.bin", "./Contracts/contract.abi")
e3.deploySmartContract(contract)
```

One thing that is worthy to mention is that mining is very computational intensive, and can quickly consume 100 percent of the CPU, freezing the entire emulation. To solve this problem, we add a nice value to the miner’s processes, lowering their priority. Therefore, even though they still consume 100 percent of the CPU, they yield to the other processes of the emulation. In the real world, we want the miners to run as fast as we can (so miners can earn more money), but in the emulator, we own all the miners, so it does not matter who “makes” money. Lowering the CPU and memory consumption to allow us to run more miners is more important in the emulation.

4.4 Developing a Library of Components

Apart from the two component examples, we have developed a few more components, including Darknet and Botnet. Many more interesting components can be built for our Internet emulator. We plan to develop a rich library of components. We also envision that others may add the components they build to this open-source and extensible platform. There are three types of components that we would like to build: (1) infrastructure-level service components, (2) simple service components, and (3) base-layer components.

**Infrastructure-level service component.** It emulates an infrastructure on the Internet, and it typically involves a large number of nodes. Examples of this type of components include DNS infrastructure, Blockchain, Botnet, Darknet (Tor), Public-Key Infrastructure, advertisement network (for web tracking), SDN (Software Defined Network), CDN (Content Delivery Network), etc.

**Simple service component.** It involves a single node or a small number of nodes. For example, a domain registration service is used for people to “purchase” domains, we can build a component for it to
emulate domain registrars like GoDaddy.com. We can implement a mail server using the open-source software, so users can send emails to each other inside the emulated network. We can also develop a number of vulnerable websites and servers, and package each of them into a component. These components can be added to an emulator for security-related activities.

*Base layer component.* It involves autonomous systems, Internet exchanges, networks, nodes, and routing. They emulate a portion of the Internet, such as an organization’s network, an Internet backbone (regional or national), and a collection of autonomous systems and their peering relationships. Building a fictitious component at the base layer is not difficult; the challenge is how to build one that accurately emulates its counterpart in the real world. For example, to build a component for the Internet-2 national backbone, we need to know its network topology, where (i.e., at what Internet exchange) it peers with other autonomous systems, how its routes are decided, etc. The more data we can get about this backbone, the more accurately we can emulate it. We plan to collect this type of data using the BGP looking glasses deployed around the world. For missing data, we will use our imaginations.

5 **VISUALIZATION**

We have also designed a web-based tool called Map to visualize the emulated Internet, as well as providing a way for users to interact with the nodes in the emulator. This is an independent tool. It interacts with the emulation via the APIs provided by the docker daemon. This tool is also provided to users in the form as an independent container. When this container starts, the map can be accessed from this URL: http://localhost:8080/map.html.

The architecture of the Map tool is depicted in Figure 7. This is a web application consisting of a front end a backend. The front end is the UI part running inside a browser, while the backend runs on the web server side. The backend retrieves the information about the containers and the network from the Docker daemon (using the APIs provided by Docker), and send them to the front end for visualization.

![The Map Application](image)

**Figure 7: The architecture of the Map tool**

When we compile the emulation into final docker files, we attach meta data to each container, including the node’s name, display name, and description, list of connected networks, and IP addresses. This information can be retrieved by the backend via the Docker daemon, and that is how we can visualize the emulation. A picture of the GUI can be found in Figure 8.

Users can also set filters to visualize network traffic. The syntax of the filter is the same as that in `tcpdump`; actually, the filter is directly fed into the `tcpdump` program running on all nodes. When a node sees the packets that satisfy the filter, it sends an event to the map, which will highlight the node briefly on the map.

Sometimes, a sequence of events happen too fast to see the actual order among them. In this case, we can use the Replay panel (see Figure 9) to record the events and then replay them at a slower pace. The speed of replaying can be adjusted by changing the event interval.

The extensible design. While capturing the events at the packet level may be sufficient for many applications, it may not be able to capture the events at the application level. For example, in Blockchain, when a node has successfully mined a block and added the block to the blockchain, it is an interesting event that is worth visualizing. This event is very difficult to capture at the packet level, even though all the information is included inside packets. It is better to capture the events using the event registration mechanism provided by Ethereum. Therefore, to support application-dependent visualization, our design supports plugins. When a component is developed, a corresponding visualization plug-in can also be developed.

6 **EVALUATION**

We have conducted a comprehensive evaluation on the performance of the emulator. In this paper, we will only show a subset of the evaluation results. Full details of the evaluation, can be found in Zeng’s Master thesis [19].

The performance tests will be conducted in two parts. The first part evaluates the per-unit resource consumption versus the number of hosts, routers, and networks in emulation. The second part evaluates the impact on packet forwarding performance when traveling through emulated nodes.

Performance information like CPU and memory usage will be obtained from the `/proc/stat` and `/proc/meminfo` files. All tests will be conducted without overloading the host system to ensure accurate results. All CPU and memory tests result are obtained by first starting the emulation, waiting for 60 seconds (to allow route propagation), then snapshotting `/proc/stat` and `/proc/meminfo` every one second for the next 100 seconds. Average CPU utilization and memory are then used as the result for each test. In order to make sure the physical memory is fully utilized, the swapness is set to 1. Evaluations were conducted in two different environments.

- On a powerful server: it has two Intel Xeon E5-2660-v2 CPU (40 threads; 20 cores in total), with 128 GB of DDR3 memory.
- On a personal computer: a virtual machine with 2 Intel Xeon Silver 4210 CPU @ 2.00GHz virtual CPUs and 4 GB of DDR4 memory.

6.1 **Number of ASes**

In this test, there is just one BGP router (no other hosts) in each autonomous system. Each Internet exchange houses five autonomous systems, which forms full-mesh peering within the internet exchange, using the Unfiltered relationship, i.e., each AS will peer with the other four. Figures 10 and 11 show the CPU and memory usage when the number of ASes increases from 0 to 1,000.
Figure 8: The visualization tool

Figure 9: Capturing and replaying events

Figure 10: Number of ASes vs. memory consumption

The CPU usage is linear to the number of ASes and it is quite low. Even with 600 ASes, the CPU usage is still under 1% (note: our test machine has 20 cores). Since the host memory is 128 GB, it reaches the physical limit after the number of ASes reaches 700. The host system starts to swap memory pages to the disk. That is when the CPU usage jumps due to the swapping. For the memory consumption, the function used to fit the memory graph is 
\[ y = 0.1782 \times x^2 + 33.06 \times x + 10.57, \]
where \( y \) is the memory consumption in MB.

- The constant part 10.57 represents the memory consumed by the host system even when it is not doing anything.
- The linear part 33.06 \( x \) represents the memory consumption for each added AS due to the addition of new network bridges, BGP routers, etc.
- For the quadratic part 0.1782 \( x^2 \), it is safe to assume that this is the memory consumed by the routing table, because the total number of entries in the routing table does increase quadratically.

6.2 Number of Hosts

This evaluation focuses on the memory consumption of the host nodes running some lightweight services. The number of autonomous systems is fixed to 10, with each AS having one BGP router, one internal network, and \( K \) number of hosts, with \( K \) ranging from 0 to 80 (so the total number of hosts is from 0 to 800). Every host node
will run a nginx web server and also ping a random router in the emulator. Figure 12 shows the results.

![Figure 12: Number of hosts vs. memory consumption](image.png)

From the results, one can see that the memory consumption for host nodes is linear. This result is quite intuitive, because adding new host nodes is merely creating a new container in the emulation that runs some software. In this case, the software running on the host node operates individually (ping and nginx), meaning adding a new instance of the software does not make any difference to the existing instance of the software.

The CPU usage is not plotted, but it is linear to the number of hosts, and it is quite low. Even with 800 hosts, the CPU usage is still below 1.5 percent.

6.3 Number of Internal Routers

This test looks at the unit performance when the number of autonomous systems is small, but each autonomous system has a lot of internal routers and a lot of internal networks. In this test, there are total ten autonomous systems, with five ASes in each Internet exchange. We increase the number of internal routers in each AS from 1 to 90.

![Figure 13: Number of internal routers vs. memory usage](image.png)

Figure 13 shows the results. Two fits were attempted on the test results, one using the results for 0 - 30 routers and the other using the results for 30 - 100 routers. One may observe that the memory consumption starts showing a quadratic-like trend when the number of routers is small. This is because the total number of routes among all routers increases quadratically to the number of routers.

However, when the number of routers become large, the trend starts to become linear. One reason for this is that, as the number of routes from the same autonomous system increases, the number of memory consumed per route will decrease, because the underlying BIRD routing software uses an efficient way to store routes, where routes with the same route attribute will be “combined.” [8].

![Figure 14: Number of routers per AS vs. CPU time](image.png)

Figure 14 shows the relationship between numbers of routers and CPU time. It follows a quadratic trend. Since the IBGP layer configures full-mesh IBGP between all reachable internal routers, the number of IBGP sessions pairs in terms of the number of routers is $n_{pairs} = \frac{(n_{router} \cdot (n_{router} - 1))}{2}$. This leads to the quadratic trend. If we use MPLS (Multiprotocol Label Switching) [16], we no longer need to have full mesh IBGP peerings, and can thus significantly reduce the CPU and memory usage. MPLS is supported in the emulator.

6.4 Network Throughput

We also measure the network performance of the emulator. We use iPerf3 and ping to test the throughput and latency. iPerf3 is a network benchmarking tool that can be used to measure the throughput of the network.

In each autonomous system, we create 10 internal networks to form a linear topology. The client and server are placed at the edge, so there are 10 hops between them. The default TCP congestion control algorithm (cubic) is used on the client and server. The iPerf3 tool is used to test the TCP transmitting (TX) and receiving (RX) speed using a single connection between the client and server. We have created $x$ number of autonomous systems in the emulator, with $x$ ranging from 1 to 20, so we have $x$ number of parallel streams.

Figure 15 shows the relationship between number of parallel streams and the throughput. The relationship appears logarithmic. With each additional new pair of client and server, the throughput increase to some extent, but the increase in throughput drops as the number of streams go up. One may also notice that the speed stopped increasing at around 11 streams at around 13 Gbps. At the same time, when it reaches 13 Gbps, the CPU usage on all cores reaches around 100%. This indicates a hardware performance limit.

In another test, we run ping between the client and server to measure the round-trip time (RTT). We configured ping send one
ICMP echo message every millisecond, with a total of 1,000 ping packets being sent out. Figure 16 shows the RTT and its relationship with the number of parallel streams. Even when it reaches 20 streams (or 200 routers), the RTT is still below 1.5ms. The relationship itself appears linear.

![Figure 15: The transmission and receiving speed](image1.png)

![Figure 16: The Round-trip time (RTT)](image2.png)

The round-trip time in the emulator is much faster than that in the real Internet. This is expected because the networks in the emulator are all virtual. In the future, we will allow users to add delay to the virtual networks, so we can better emulate the real Internet.

6.5 Performance on the VM Setting

The tests conducted so far are carried out on a powerful server. We also envision that many users will choose to run a smaller scale emulator on their personal computers, inside a virtual machine with limited resources. Therefore, we also conducted the tests on a virtual machine with the following hardware:

- 2 virtual CPUs: Intel Xeon Silver 4210 CPU @ 2.00GHz
- 4 GB of DDR4 memory

Using the same test as the one conducted in Section 6.1, we have measured memory consumption and CPU usage versus the number of ASes (one router and one network in each AS). Figure 17 shows the memory consumption. The CPU usage is still quite low (below 1.5% when x reaches 100), so we do not plot the result. We have also measured the network throughput using the same test as the one conducted in Section 6.4. Figure 18 shows the result.

![Figure 17: Memory consumption](image3.png)

![Figure 18: The network throughput](image4.png)

6.6 Insights from the Evaluation

In most tests, the bottleneck is at memory since the emulation node uses only a small amount of CPU compared with the amount of memory they used. Unless one is performing heavy tasks inside the emulator, like running Ethereum miner, they are most likely to hit the physical memory limit before hitting the CPU limit.

7 APPLICATIONS

The Internet emulator can have many applications. Currently, we mainly focus on the applications on cybersecurity education, and use it to develop hands-on labs. In this section, we give a brief overview on some of the labs that have already been developed.

7.1 “Yesterday Once More”

Many interesting attacks and incidents happened to the Internet in the past, and they are very educational. However, as instructors, we are only able to tell them to students as stories, describing what has happened technically, on paper. It will be much better if we can bring students back to the past to experience in person what has happened, and to gain the first-hand knowledge. This kind of
time-travel has been the subject of many sci-fi movies. Now, we can actually do it using our emulator.

We plan to build emulators to recreate those attacks and incidents, so students can see with their own eyes the unfolding of the events. They can observe what has actually happened technically, and they can even interfere and change the course of the events. We strongly believe that such a first-hand experience will significantly enhance students’ understanding. We have so far developed two labs based on the past attacks/incidents, but more are being developed. We give a brief overview of one of the labs.

7.2 Morris Worm Attack Lab

In this application, we create a mini-Internet emulator using 275 containers, consisting of 5 Internet exchanges, 12 stub autonomous systems (AS), with each AS having one internal network with 20 hosts (240 hosts in total). These ASes peer with several transits ASes at the Internet exchanges. See Figure 19. During the construction of the emulator, we installed a vulnerable server on these 240 host containers. The server has a buffer-overflow vulnerability. The construction only involves 86 lines of Python code. Despite having these many machines, the entire emulator can run on a Ubuntu 20.04 virtual machine with 2 cores and 8GB of RAM, so it is possible to run on most students’ personal computers.

![Figure 19: The spreading of the worm: the nodes with the bold black border are compromised nodes, which are also attacking others.](image)

The attack code consists of five steps: (1) find a target machine, (2) launch the buffer-overflow attack on it, (3) store a copy of the attack code on the target machine, (4) execute the attack code on the target machine, (5) go back to the first step and repeat the attack.

We made simplification from the original Morris worm, so the lab can be done in a short period of time. However, the main essence of the worm is preserved, including the attack, self duplication and propagation. The attack part directly uses the code from the buffer-overflow lab (one of the popular SEED labs), so this lab can be used as a follow-up lab, with the buffer-overflow lab focusing on the attack, and this one focusing on the spreading of the worm.

After compromising a target machine, we also run “ping 1.2.3.4” on the target machine. That’s how we can visualize which node is compromised via tcpdump. Figure 19 shows the attack in progress. Here is the reaction from a student after seeing his successful attack: “Seeing it from the entire Internet perspective is remarkable and stunning.”

In our attack code, if we intentionally make the same mistake as what Morris made, an attack machine can get re-infected repeatedly, each time, a new instance on the attack will be created, consuming additional resources. We can observe that once most of the machines are compromised on the emulated Internet, the CPU usage will become 100%. After a while, the host VM will become slow, and eventually become non-responsive. Basically, the worm has melted down the emulated Internet. That was exactly what the Morris Worm has caused to the real Internet in 1988. This lab and its demonstration video can be found on the SEED website [11].

7.3 Other Labs

We list some of the ideas that we are currently investigate. Eventually, we will build a lab for each of these ideas.

- **The BGP & Attack Lab.** The goal of this lab is to help students understand how BGP “glues” the Internet together, and how the Internet is actually connected. Students will need to configure some of the BGP routers to establish some required peering relationship. Students will also launch the BGP prefix hijacking attacks to blackhole a target network. This lab is already published [10].
- **Blockchain and Smart Contract.** Using the blockchain component, we can deploy some vulnerable smart contracts in the emulator, and then ask students to launch attacks against them.
- **Botnet Attack.** We have already implemented a prototype of the botnet component, so we can easily deploy a botnet [6] inside an emulator. We can then design lab activities to help students understand how this type of attacks works, what it is capable of, what techniques it uses to evade detection, etc.
- **Darknet.** We have already implemented a prototype of the Darknet component based on tor [9]. We can deploy it inside an emulator, and design lab activities to help students understand how the Darknet works, and how it achieves sender’s and receiver’s anonymity.
- **Firewalls: we will simulate some realistic networks from a fictitious enterprise, and ask students to deploy firewalls in the emulation, so these networks can be protected. Automated attacks will be built into the emulation to test how good the defense is.

8 RELATED WORK

NS-3 is a discrete-event network simulator, targeted primarily for research and educational use [3]. We tried to use NS-3 as the base for our work, but eventually moved away from it because of a critical issue: to run programs in NS-3, one needs to use NS-3 versions
of the APIs. Since nodes in NS-3 are not real machines, system calls, socket APIs, and everything that has operating system APIs involved needs to be re-written in NS-3’s API to run inside NS-3. NS-3 attempts to solve this issue by providing the Direct Code Execution (DCE) framework, which provides emulated Linux APIs that programs can use. However, NS-3 implementations of the APIs are not complete, meaning most of the programs will not be able to run properly under DCE or require major code changes.

EVE-NG [1] and Graphical Network Simulator-3 (GNS-3) [2] are two network emulators that use virtual machines to do the emulation. These two emulators are very similar: they both use a graphical user interface to build emulations. Since the emulations are done by real virtual machines, they can support any kind of nodes, including commercial router software from vendors like Cisco and Juniper. While they are widely used by professionals, these emulators do not align well with what we want to achieve. One issue is that they both require interacting with a user interface to build emulation. It is impractical to build large size emulation with a user interface. Another issue is that they focus primarily on emulating different types of networks (hardware). While this is necessary for research and product testing, it is not essential for cybersecurity education. Without this part, Internet emulation can become much simplified.

Common Open Research Emulator (CORE) is another network emulation tool [5]. It is also a Python-based emulation framework. Its main focus is on running an emulation rather than building emulations. It also uses containers, but it directly uses Linux namespace to create containers, instead of using Docker. Basically, a significant amount of work implemented in CORE can be easily done using Docker. We have chosen to use Docker instead of CORE as our emulation platform.

Greybox is a single-host Internet simulator for offline exercise and training networks [12]. It allows a single host (physical or VM) to provide the illusion of connectivity to the real Internet: a realistic BGP backbone topology with point-to-point link delays based on the physical distance between the routers’ real-world locations, combined with TopGen’s application services (HTTP, DNS, email, and more). Its underlying emulation platform is based on CORE.

Omur work and Greybox do have many things in common. The major differences between them are summarized in the following: (1) Greybox uses configuration to describe emulations instead of building emulations programmatically. While configurations is an acceptable format for saving the final product of the emulation, it does not offer good portability and reusability. (2) The way Greybox runs services on hosts is that only one node runs actual services for all servers in the emulation. The router nodes merely forward traffic to that one single node. This dramatically reduces the reality of the emulation. (3) Greybox offers limited options for services.

Mini-internet [13] is a project that also targets education. The main goal of the project is to build a large network with multiple autonomous systems and internet exchanges to enable students to understand Internet operations alongside their pitfalls. The project is also built using the container technology. The main differences between our work and mini-internet are summarized in the following: (1) The mini-internet project is a good fit for experimenting with the Internet operations, but it lacks the ability to host other services, which are essential for cybersecurity education. (2) Mini-internet uses configuration to describe emulations, and then use programs to convert the configuration to the container files. Our work builds the emulation using Python programs. In terms of the expressive power, programming languages are much more powerful than configuration languages.

9 SUMMARY AND FUTURE WORK

In cybersecurity courses, it is quite challenging to do hands-on activities that involve many components of the Internet. To solve this problem, we have developed an Internet emulator. This paper explains the design of the SEEDE Internet emulator, and presents the evaluation results. It also demonstrates how this emulator can be used to design hands-on lab activities for Cybersecurity education.

This is still an ongoing project, and we plan to develop more components for the emulator, so a wide spectrum of the Internet services and infrastructures can be included in the emulator. We will also improve the visualization tool and develop more hands-on labs based on the emulator. The source code of this open-source project is available at GitHub: https://github.com/seed-labs/seed-emulator.

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