Part C

1)

```
mininet@mininet-vm:~/pox$ ./pox.py --verbose py openflow.of_01 --port=6633 openflow.discovery forwarding.l2_learning host_tracker
POX 0.7.0 (gar) / Copyright 2011-2020 James McCauley, et al.
INFO:host_tracker:host_tracker ready
DEBUG:core:POX 0.7.0 (gar) going up...
DEBUG:core:Running on CPython (3.6.9/Jan 26 2021 15:33:00)
DEBUG:core:Platform is Linux-4.15.0-112-generic-x86_64-with-Ubuntu-18.04-bionic
WARNING:version:Support for Python 3 is experimental.
INFO:core:POX 0.7.0 (gar) is up.
DEBUG:openflow.of_01:Listening on 0.0.0.0:6633
Ready.
POX> INFO:openflow.of_01:[00-00-00-00-00-07 2] connected
DEBUG:openflow.discovery:Installing flow for 00-00-00-00-00-07
DEBUG:forwarding.l2_learning:Connection [00-00-00-00-00-07 2]
INFO:openflow.of_01:[00-00-00-00-00-04 3] connected
DEBUG:openflow.discovery:Installing flow for 00-00-00-00-00-04
DEBUG:forwarding.l2_learning:Connection [00-00-00-00-00-04 3]
INFO:openflow.of_01:[00-00-00-00-00-05 8] connected
DEBUG:openflow.discovery:Installing flow for 00-00-00-00-00-05
DEBUG:forwarding.l2_learning:Connection [00-00-00-00-00-05 8]
INFO:openflow.of_01:[00-00-00-00-00-02 7] connected
DEBUG:openflow.discovery:Installing flow for 00-00-00-00-00-02
DEBUG:forwarding.l2_learning:Connection [00-00-00-00-00-02 7]
INFO:openflow.of_01:[00-00-00-00-00-06 4] connected
DEBUG:openflow.discovery:Installing flow for 00-00-00-00-00-06
DEBUG:forwarding.l2_learning:Connection [00-00-00-00-00-06 4]
INFO:openflow.of_01:[00-00-00-00-00-01 5] connected
DEBUG:openflow.discovery:Installing flow for 00-00-00-00-00-01
DEBUG:forwarding.l2_learning:Connection [00-00-00-00-00-01 5]
INFO:openflow.of_01:[00-00-00-00-00-03 6] connected
DEBUG:openflow.discovery:Installing flow for 00-00-00-00-00-03
DEBUG:forwarding.l2_learning:Connection [00-00-00-00-00-03 6]
INFO:openflow.discovery:link detected: 00-00-00-00-00-05.2 -> 00-00-00-00-00-07.3
INFO:openflow.discovery:link detected: 00-00-00-00-00-05.1 -> 00-00-00-00-00-06.3
INFO:openflow.discovery:link detected: 00-00-00-00-00-05.3 -> 00-00-00-00-00-01.2
INFO:openflow.discovery:link detected: 00-00-00-00-00-01.1 -> 00-00-00-00-00-02.3
INFO:openflow.discovery:link detected: 00-00-00-00-00-06.3 -> 00-00-00-00-00-05.1
INFO:openflow.discovery:link detected: 00-00-00-00-00-01.2 -> 00-00-00-00-00-05.3
INFO:openflow.discovery:link detected: 00-00-00-00-00-02.2 -> 00-00-00-00-00-04.3
INFO:openflow.discovery:link detected: 00-00-00-00-00-02.3 -> 00-00-00-00-00-01.1
INFO:openflow.discovery:link detected: 00-00-00-00-00-02.1 -> 00-00-00-00-00-03.3
INFO:openflow.discovery:link detected: 00-00-00-00-00-03.3 -> 00-00-00-00-00-02.1
INFO:openflow.discovery:link detected: 00-00-00-00-00-04.3 -> 00-00-00-00-00-02.2
INFO:openflow.discovery:link detected: 00-00-00-00-00-07.3 -> 00-00-00-00-00-05.2
DEBUG:openflow.of_01:1 connection aborted
INFO:host_tracker:Learned 3 1 00:00:00:00:00:01
INFO:host_tracker:Learned 3 1 00:00:00:00:00:01 got IP 10.0.0.1
INFO:host_tracker:Learned 6 1 00:00:00:00:00:05
INFO:host_tracker:Learned 6 1 00:00:00:00:00:05 got IP 10.0.0.5
DEBUG:forwarding.l2_learning:installing flow for 00:00:00:00:00:05.1 -> 00:00:00:00:00:01.3
DEBUG:forwarding.l2_learning:installing flow for 00:00:00:00:00:05.1 -> 00:00:00:00:00:01.3
DEBUG:forwarding.l2_learning:installing flow for 00:00:00:00:00:05.2 -> 00:00:00:00:00:01.1
DEBUG:forwarding.l2_learning:installing flow for 00:00:00:00:00:05.3 -> 00:00:00:00:00:01.1
DEBUG:forwarding.l2_learning:installing flow for 00:00:00:00:00:05.3 -> 00:00:00:00:00:01.1
DEBUG:forwarding.l2_learning:installing flow for 00:00:00:00:00:01.1 -> 00:00:00:00:00:05.3
DEBUG:forwarding.l2_learning:installing flow for 00:00:00:00:00:01.1 -> 00:00:00:00:00:05.3
DEBUG:forwarding.l2_learning:installing flow for 00:00:00:00:00:01.1 -> 00:00:00:00:00:05.2
DEBUG:forwarding.l2_learning:installing flow for 00:00:00:00:00:01.3 -> 00:00:00:00:00:05.1
DEBUG:forwarding.l2_learning:installing flow for 00:00:00:00:00:01.3 -> 00:00:00:00:00:05.1
POX>
```

The output including the line “Ready” and all lines above is the startup information, which displays the version, platform, and the default port 6633 it’s listening on. Then, the following lines indicate connections between the controller and switches are initialized (xx-xx-xx-xx-xx-xx is the address while another number is the connection number) and initial flows are installed to each of those connections. Next, “openflow.discovery” can now determine the existing links between switches from the flows installed above. After that, “host_tracker” tracks the hosts in the network and assigns them IP addresses. At last, flows are installed to enable communication between hosts h1 and h5.

2)

```
mininet> h1 ping h5
PING 10.0.0.5 (10.0.0.5) 56(84) bytes of data.
64 bytes from 10.0.0.5: icmp_seq=1 ttl=64 time=13.9 ms
64 bytes from 10.0.0.5: icmp_seq=2 ttl=64 time=0.052 ms
64 bytes from 10.0.0.5: icmp_seq=3 ttl=64 time=0.058 ms
64 bytes from 10.0.0.5: icmp_seq=4 ttl=64 time=0.043 ms
64 bytes from 10.0.0.5: icmp_seq=5 ttl=64 time=0.057 ms
```

We can observe the RTT of the first ping is longer than the subsequent ones. The reason is that the network has to do two additional steps for the first packet. One is to resolve the mac address of destination IP and cache it for the subsequent pings. Another one is to setup a new flow for the new traffic pattern. This is done by the controller.

3)

Before the ping:

```
mininet@mininet-vm:~/cs456-a3/part-C$ sudo ovs-ofctl dump-flows s1
 cookie=0x0, duration=178.991s, table=0, n_packets=70, n_bytes=2870, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=178.948s, table=0, n_packets=0, n_bytes=0, priority=32769,arp,dl_dst=02:00:00:00:be:ef actions=CONTROLLER:65535
mininet@mininet-vm:~/cs456-a3/part-C$ sudo ovs-ofctl dump-flows s2
 cookie=0x0, duration=215.407s, table=0, n_packets=126, n_bytes=5166, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=215.370s, table=0, n_packets=0, n_bytes=0, priority=32769,arp,dl_dst=02:00:00:00:be:ef actions=CONTROLLER:65535
mininet@mininet-vm:~/cs456-a3/part-C$ sudo ovs-ofctl dump-flows s3
 cookie=0x0, duration=216.779s, table=0, n_packets=43, n_bytes=1763, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=216.735s, table=0, n_packets=0, n_bytes=0, priority=32769,arp,dl_dst=02:00:00:00:be:ef actions=CONTROLLER:65535
mininet@mininet-vm:~/cs456-a3/part-C$ sudo ovs-ofctl dump-flows s4
 cookie=0x0, duration=218.046s, table=0, n_packets=43, n_bytes=1763, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=218.005s, table=0, n_packets=0, n_bytes=0, priority=32769,arp,dl_dst=02:00:00:00:be:ef actions=CONTROLLER:65535
mininet@mininet-vm:~/cs456-a3/part-C$ sudo ovs-ofctl dump-flows s5
 cookie=0x0, duration=219.712s, table=0, n_packets=129, n_bytes=5289, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=219.684s, table=0, n_packets=0, n_bytes=0, priority=32769,arp,dl_dst=02:00:00:00:be:ef actions=CONTROLLER:65535
mininet@mininet-vm:~/cs456-a3/part-C$ sudo ovs-ofctl dump-flows s6
 cookie=0x0, duration=221.100s, table=0, n_packets=42, n_bytes=1722, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=221.057s, table=0, n_packets=0, n_bytes=0, priority=32769,arp,dl_dst=02:00:00:00:be:ef actions=CONTROLLER:65535
mininet@mininet-vm:~/cs456-a3/part-C$ sudo ovs-ofctl dump-flows s7
 cookie=0x0, duration=222.414s, table=0, n_packets=44, n_bytes=1804, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=222.373s, table=0, n_packets=0, n_bytes=0, priority=32769,arp,dl_dst=02:00:00:00:be:ef actions=CONTROLLER:65535
```

After the ping:

```
mininet@mininet-vm:~/cs456-a3/part-C$ sudo ovs-ofctl dump-flows s1
 cookie=0x0, duration=43.985s, table=0, n_packets=8, n_bytes=672, hard_timeout=1800, priority=65001,dl_src=00:00:00:00:00:05,dl_dst=00:00:00:00:00:01 actions=output:"s1-eth1"
 cookie=0x0, duration=43.979s, table=0, n_packets=7, n_bytes=630, hard_timeout=1800, priority=65001,dl_src=00:00:00:00:00:01,dl_dst=00:00:00:00:00:05 actions=output:"s1-eth2"
 cookie=0x0, duration=337.129s, table=0, n_packets=131, n_bytes=5371, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=337.086s, table=0, n_packets=0, n_bytes=0, priority=32769,arp,dl_dst=02:00:00:00:be:ef actions=CONTROLLER:65535
mininet@mininet-vm:~/cs456-a3/part-C$ sudo ovs-ofctl dump-flows s2
 cookie=0x0, duration=46.203s, table=0, n_packets=8, n_bytes=672, hard_timeout=1800, priority=65001,dl_src=00:00:00:00:00:05,dl_dst=00:00:00:00:00:01 actions=output:"s2-eth1"
 cookie=0x0, duration=46.199s, table=0, n_packets=7, n_bytes=630, hard_timeout=1800, priority=65001,dl_src=00:00:00:00:00:01,dl_dst=00:00:00:00:00:05 actions=output:"s2-eth3"
 cookie=0x0, duration=339.339s, table=0, n_packets=199, n_bytes=8159, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=339.302s, table=0, n_packets=0, n_bytes=0, priority=32769,arp,dl_dst=02:00:00:00:be:ef actions=CONTROLLER:65535
mininet@mininet-vm:~/cs456-a3/part-C$ sudo ovs-ofctl dump-flows s3
 cookie=0x0, duration=47.823s, table=0, n_packets=8, n_bytes=672, hard_timeout=1800, priority=65001,dl_src=00:00:00:00:00:05,dl_dst=00:00:00:00:00:01 actions=output:"s3-eth1"
 cookie=0x0, duration=47.822s, table=0, n_packets=7, n_bytes=630, hard_timeout=1800, priority=65001,dl_src=00:00:00:00:00:01,dl_dst=00:00:00:00:00:05 actions=output:"s3-eth3"
 cookie=0x0, duration=340.966s, table=0, n_packets=67, n_bytes=2747, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=340.922s, table=0, n_packets=0, n_bytes=0, priority=32769,arp,dl_dst=02:00:00:00:be:ef actions=CONTROLLER:65535
mininet@mininet-vm:~/cs456-a3/part-C$ sudo ovs-ofctl dump-flows s4
 cookie=0x0, duration=342.600s, table=0, n_packets=67, n_bytes=2747, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=342.559s, table=0, n_packets=0, n_bytes=0, priority=32769,arp,dl_dst=02:00:00:00:be:ef actions=CONTROLLER:65535
mininet@mininet-vm:~/cs456-a3/part-C$ sudo ovs-ofctl dump-flows s5
 cookie=0x0, duration=50.930s, table=0, n_packets=8, n_bytes=672, hard_timeout=1800, priority=65001,dl_src=00:00:00:00:00:05,dl_dst=00:00:00:00:00:01 actions=output:"s5-eth3"
 cookie=0x0, duration=50.922s, table=0, n_packets=7, n_bytes=630, hard_timeout=1800, priority=65001,dl_src=00:00:00:00:00:01,dl_dst=00:00:00:00:00:05 actions=output:"s5-eth1"
 cookie=0x0, duration=344.106s, table=0, n_packets=201, n_bytes=8241, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=344.078s, table=0, n_packets=0, n_bytes=0, priority=32769,arp,dl_dst=02:00:00:00:be:ef actions=CONTROLLER:65535
mininet@mininet-vm:~/cs456-a3/part-C$ sudo ovs-ofctl dump-flows s6
 cookie=0x0, duration=52.894s, table=0, n_packets=8, n_bytes=672, hard_timeout=1800, priority=65001,dl_src=00:00:00:00:00:05,dl_dst=00:00:00:00:00:01 actions=output:"s6-eth3"
 cookie=0x0, duration=52.884s, table=0, n_packets=7, n_bytes=630, hard_timeout=1800, priority=65001,dl_src=00:00:00:00:00:01,dl_dst=00:00:00:00:00:05 actions=output:"s6-eth1"
 cookie=0x0, duration=346.036s, table=0, n_packets=66, n_bytes=2706, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=345.993s, table=0, n_packets=0, n_bytes=0, priority=32769,arp,dl_dst=02:00:00:00:be:ef actions=CONTROLLER:65535
mininet@mininet-vm:~/cs456-a3/part-C$ sudo ovs-ofctl dump-flows s7
 cookie=0x0, duration=347.410s, table=0, n_packets=69, n_bytes=2829, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=347.369s, table=0, n_packets=0, n_bytes=0, priority=32769,arp,dl_dst=02:00:00:00:be:ef actions=CONTROLLER:65535
```

The initial flow rules are for network discovery and basic packet handling. Specifically, the first rule for each switch helps controller to discover links between switches. The second one handles the requests that resolving the mac address of destination IP.

It can be observed that only those switches in the path from h1 to h5 have newly installed flow rules. The reason is that other switches do not participate in forwarding the ping packets. These newly installed flow rules make it possible to forward packets between the hosts involved without the controller.

From the output, we notice that the OVS rules here use MAC addresses to make forwarding decisions (i.e., match). But, in part A, we used IP addresses and in_ports to match. Thus, this controller implements a Layer-2 switching, that is, MAC-based packet-forwarding.