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:[00-00-00-00-00-01 4] connected
DEBUG:openflow.discovery:Installing flow for 00-00-00-00-00-01
DEBUG:forwarding.l2_learning:Connection [00-00-00-00-00-01 4]
INFO:openflow.of_01:[00-00-00-00-00-06 5] connected
DEBUG:openflow.discovery:Installing flow for 00-00-00-00-00-06
DEBUG:forwarding.l2_learning:Connection [00-00-00-00-00-06 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.of_01:[00-00-00-00-00-05 7] connected
DEBUG:openflow.discovery:Installing flow for 00-00-00-00-00-05
DEBUG:forwarding.l2_learning:Connection [00-00-00-00-00-05 7]
INFO:openflow.discovery:link detected: 00-00-00-00-00-01.2 -> 00-00-00-00-00-05.3
INFO:openflow.of_01:[00-00-00-00-00-02 8] connected
DEBUG:openflow.discovery:Installing flow for 00-00-00-00-00-02
DEBUG:forwarding.l2_learning:Connection [00-00-00-00-00-02 8]
INFO:openflow.discovery:link detected: 00-00-00-00-00-04.3 -> 00-00-00-00-00-02.2
INFO:openflow.discovery:link detected: 00-00-00-00-00-01.1 -> 00-00-00-00-00-02.3
INFO:openflow.discovery:link detected: 00-00-00-00-00-05.2 -> 00-00-00-00-00-07.3
INFO:openflow.discovery:link detected: 00-00-00-00-00-05.3 -> 00-00-00-00-00-01.2
INFO:openflow.discovery:link detected: 00-00-00-00-00-05.1 -> 00-00-00-00-00-06.3
INFO:openflow.discovery:link detected: 00-00-00-00-00-06.3 -> 00-00-00-00-00-05.1
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: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
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
POX>
```

Firstly, when controller is initialized, it is listening to the port 6633. Then when tree topology is created and connect it to the controller through port 6633, it identifies the links between switches. When try pinging h5 from h1, it firstly finds the ip address of h1 and h5 and find the switch which is directly connected to h1 or h5. Then it starts to generate the flow rules from h1 to h5. Note that 00-00-00-00-00-0x seems to be the dpid of sx. Then for the line which shows installing flow for ···, it seems that the controller is generating the rules on the path between two directed connected switches.

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=51.8 ms
64 bytes from 10.0.0.5: icmp_seq=2 ttl=64 time=0.040 ms
64 bytes from 10.0.0.5: icmp_seq=3 ttl=64 time=0.040 ms
64 bytes from 10.0.0.5: icmp_seq=4 ttl=64 time=0.041 ms
64 bytes from 10.0.0.5: icmp_seq=5 ttl=64 time=0.044 ms
```

It is obviously that the first ping is much slower than the rest ones. This is because for the first pinging, the controller needs to install flow rules to the switch. For the rest ones, the packet can follow the rules directly without installation.

3)
Before pinging

```
mininet@mininet-vm:~$ sudo ovs-ofctl dump-flows s1
 cookie=0x0, duration=28.922s, table=0, n_packets=14, n_bytes=574, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=28.899s, 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:~$ sudo ovs-ofctl dump-flows s2
 cookie=0x0, duration=31.357s, table=0, n_packets=21, n_bytes=861, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=31.339s, 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:~$ sudo ovs-ofctl dump-flows s3
 cookie=0x0, duration=33.233s, table=0, n_packets=8, n_bytes=328, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=33.212s, 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:~$ sudo ovs-ofctl dump-flows s4
 cookie=0x0, duration=49.252s, table=0, n_packets=11, n_bytes=451, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=49.226s, 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:~$ sudo ovs-ofctl dump-flows s5
 cookie=0x0, duration=51.483s, table=0, n_packets=32, n_bytes=1312, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=51.467s, 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:~$ sudo ovs-ofctl dump-flows s6
 cookie=0x0, duration=53.348s, table=0, n_packets=12, n_bytes=492, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=53.308s, 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:~$ sudo ovs-ofctl dump-flows s7
 cookie=0x0, duration=55.057s, table=0, n_packets=12, n_bytes=492, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=55.057s, table=0, n_packets=0, n_bytes=0, priority=32769,arp,dl_dst=02:00:00:00:be:ef actions=CONTROLLER:65535
```

After pinging

```
mininet@mininet-vm:~$ sudo ovs-ofctl dump-flows s1
 cookie=0x0, duration=11.181s, table=0, n_packets=9, n_bytes=770, 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=11.162s, table=0, n_packets=8, n_bytes=728, 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=13.933s, table=0, n_packets=8, n_bytes=328, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=13.891s, 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:~$ sudo ovs-ofctl dump-flows s2
 cookie=0x0, duration=12.816s, table=0, n_packets=9, n_bytes=770, 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=12.805s, table=0, n_packets=8, n_bytes=728, 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=15.545s, table=0, n_packets=11, n_bytes=451, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=15.528s, 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:~$ sudo ovs-ofctl dump-flows s3
 cookie=0x0, duration=14.409s, table=0, n_packets=9, n_bytes=770, 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=14.405s, table=0, n_packets=8, n_bytes=728, 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=17.155s, table=0, n_packets=5, n_bytes=205, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=17.125s, 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:~$ sudo ovs-ofctl dump-flows s4
 cookie=0x0, duration=18.755s, table=0, n_packets=5, n_bytes=205, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=18.716s, 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:~$ sudo ovs-ofctl dump-flows s5
 cookie=0x0, duration=17.467s, table=0, n_packets=9, n_bytes=770, 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=17.442s, table=0, n_packets=8, n_bytes=728, 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=20.193s, table=0, n_packets=13, n_bytes=533, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=20.172s, 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:~$ sudo ovs-ofctl dump-flows s6
 cookie=0x0, duration=19.127s, table=0, n_packets=9, n_bytes=770, 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=19.084s, table=0, n_packets=8, n_bytes=728, 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=21.860s, table=0, n_packets=6, n_bytes=246, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=21.824s, 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:~$ sudo ovs-ofctl dump-flows s7
 cookie=0x0, duration=24.463s, table=0, n_packets=6, n_bytes=246, priority=65000,dl_dst=01:23:20:00:00:01,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=24.463s, 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:~$
```

For initial rules, it is probably used to connected to the controller through the specified port. Since pinging from h1 to h5 need s1, s2, s3, s5, and s6. Comparing the information before and after pinging, it is obviously that these switches installed two more flow rules which is need when ping. While s4 and s7 are still only containing their initial rules since they are not used in pinging. The difference between the generated rules and the rules defined in part A, the dl_src and dl_dst are the source and destination of the packet though the whole route, thus this implies the controller implements a destination-based forwarding.