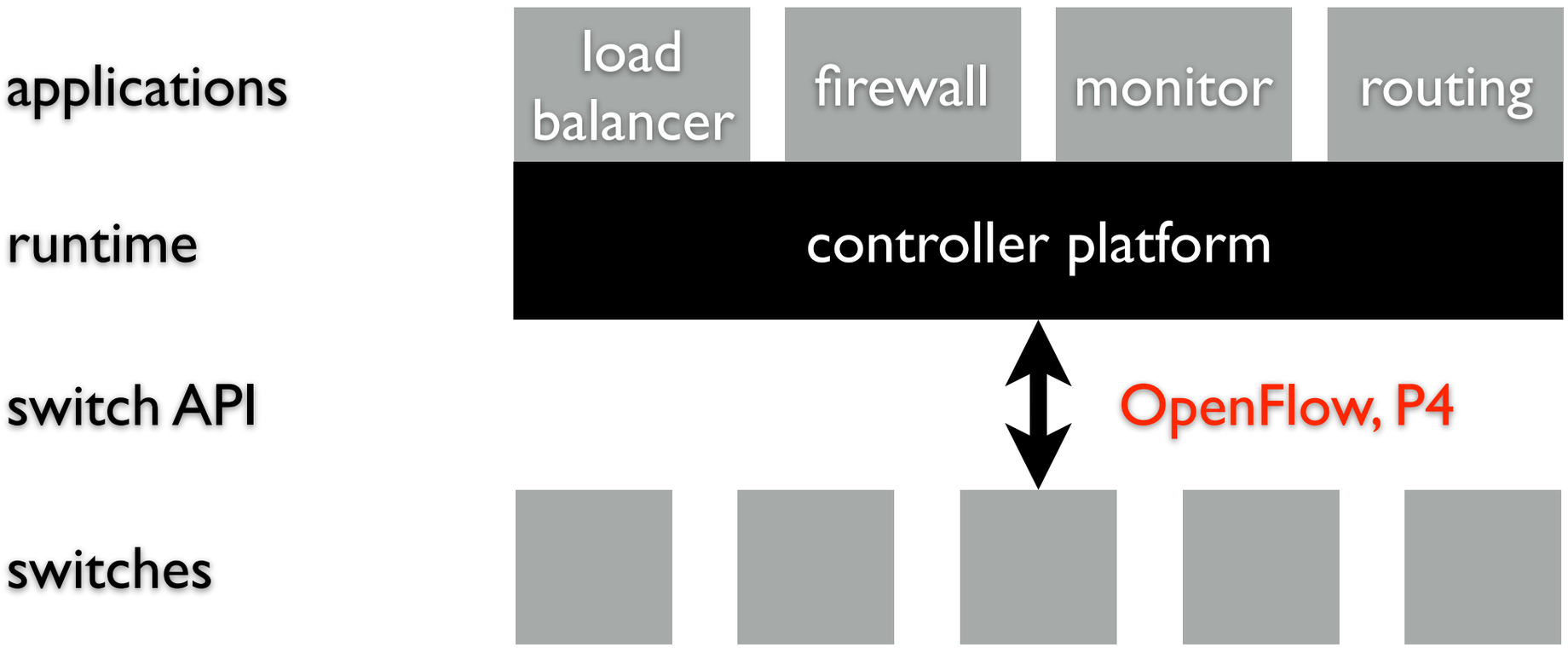
# programming SDN

## 5590: software defined networking

anduo wang, Temple University

T 17:30-20:00


applications
runtime
switch API
switches
load balancer
firewall
monitor
routing
controller platform
OpenFlow, P4

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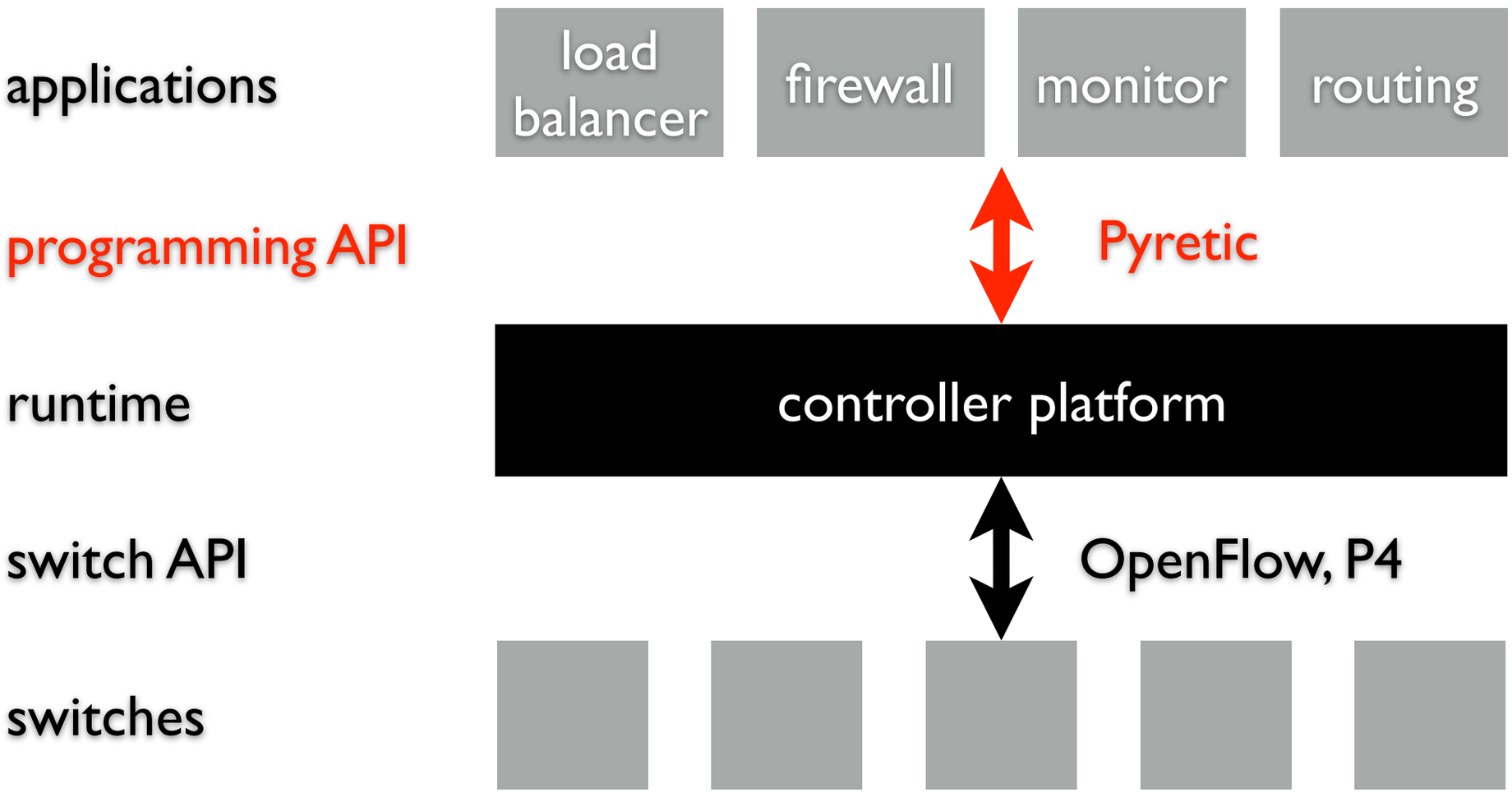
## low-level programming interface

- akin to assembly language: a thin "wrapper" around switch operations

## monolithic applications with intertwined logic

- handlers that respond to events
  - packet arrival
  - topology changes
  - traffic statistics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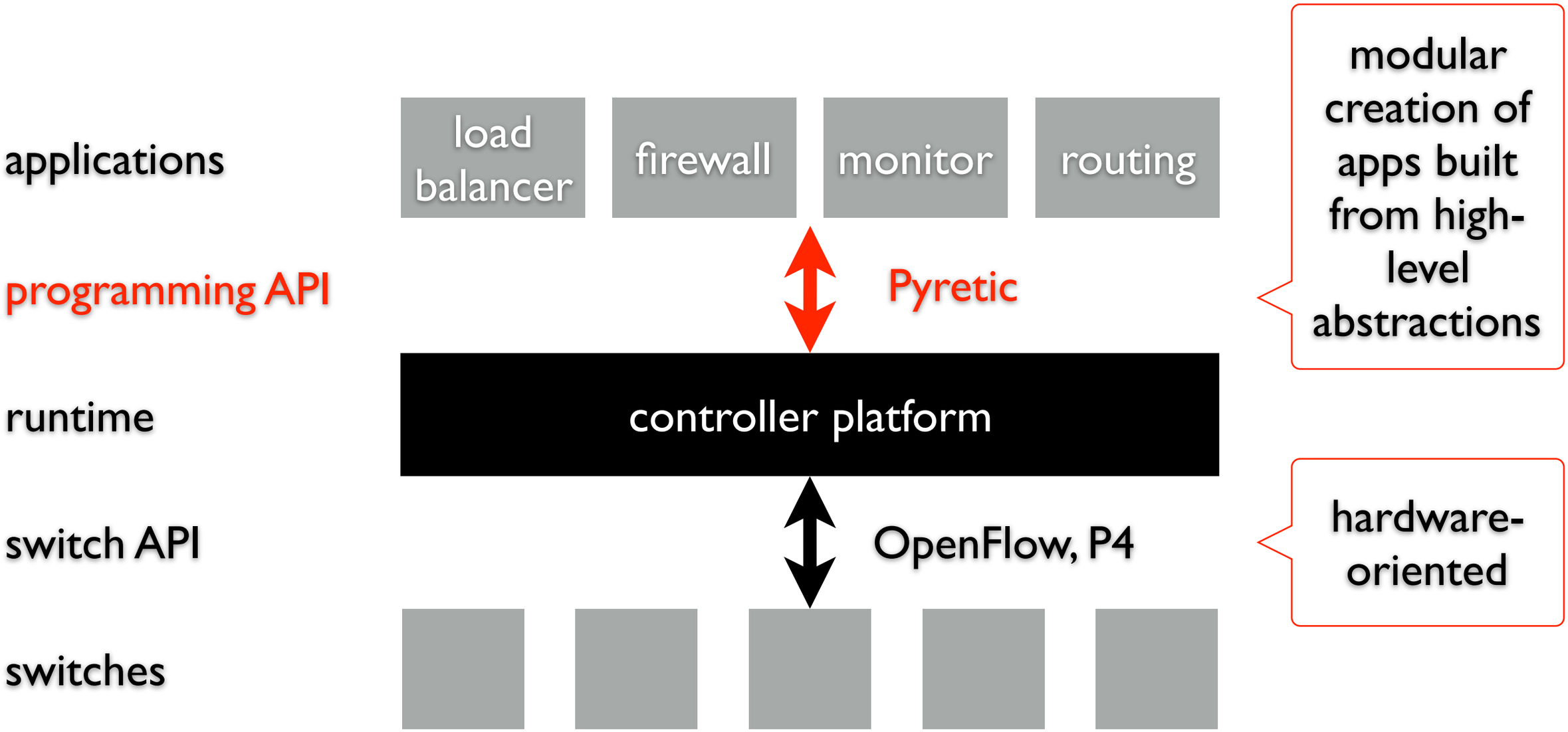
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OpenFlow, P4
switches
modular creation of apps built from high-level abstractions
hardware-oriented

# Pyretic —
# modular programming

# Pyretic language and system

*creating a single application out of multiple, independent, reusable network policies that affect the processing of the "same" traffic*

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# Pyretic language and system

the enabling constructs and mechanisms

- high level abstraction
- composition
- abstract network topology

implementation

- an interpreter that handles each packet at the controller (POX)

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# from OF rules to functions

OF like rules at a switch *s*:

patten (field =value) ➡ action

a function:

takes as input a packet on a particular port on *s*, outputs a multiset of zero or more packets on various outports of *s*

# policy as functions

a function:

takes as input a packet on a particular port on *s*,
outputs a multiset of zero or more packets on

a network-wide policy function:

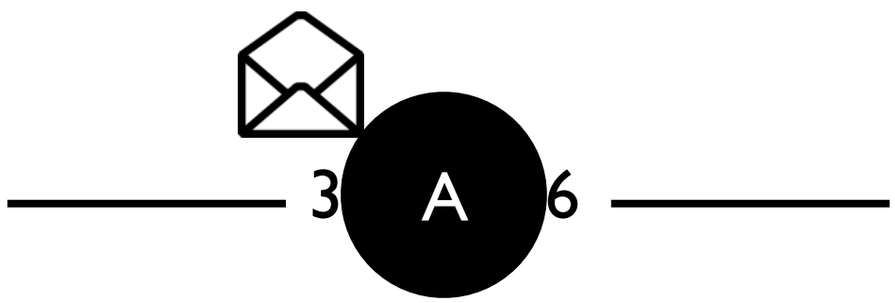
locate packets ➡ located packets

# abstract packet model

the "located packet" model

- a packet ✉ is a

  {switch: A, inport: 3, ...}



# abstract packet model

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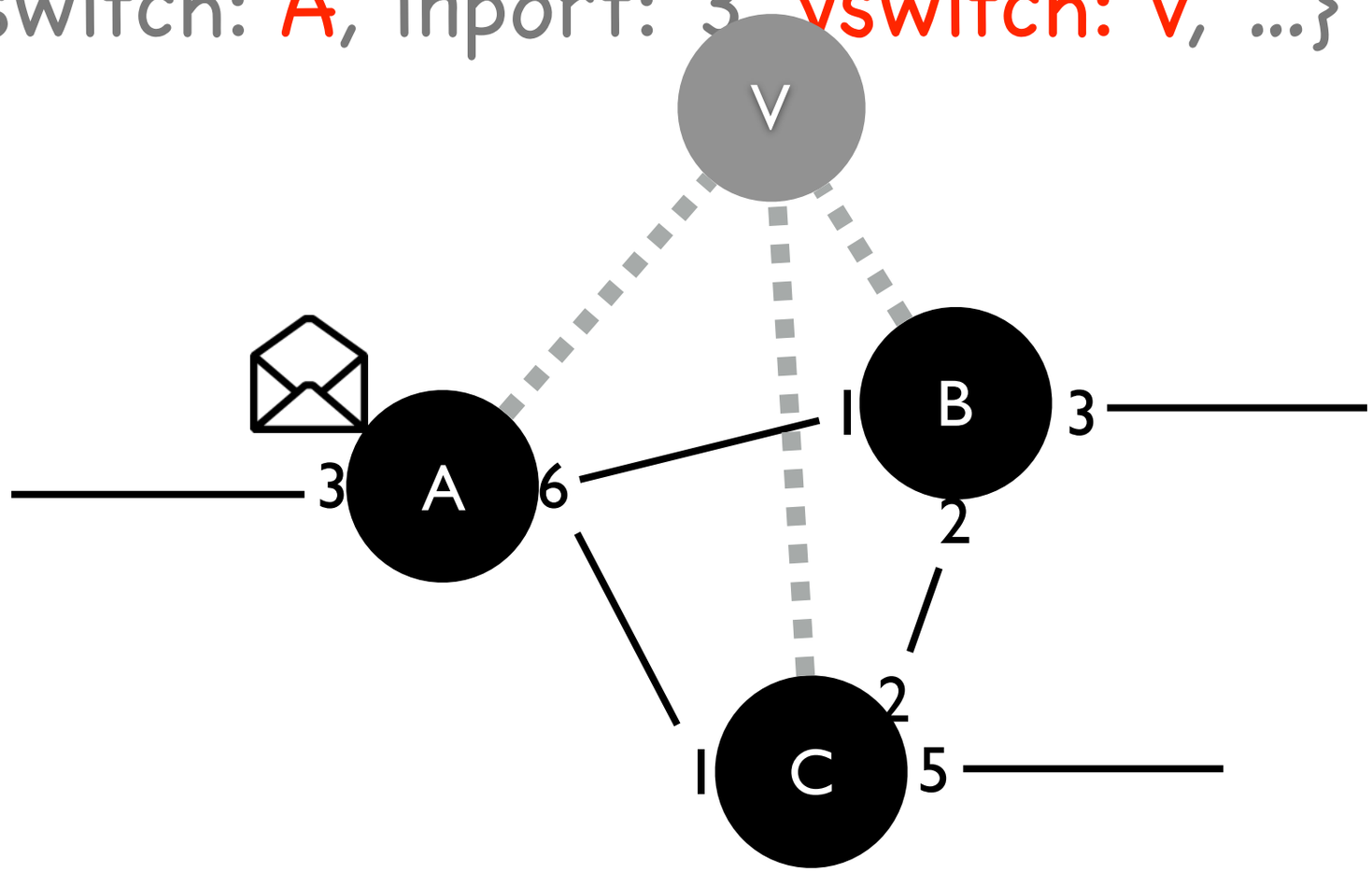
  {switch: A, inport: 3, vswitch: V, ...}



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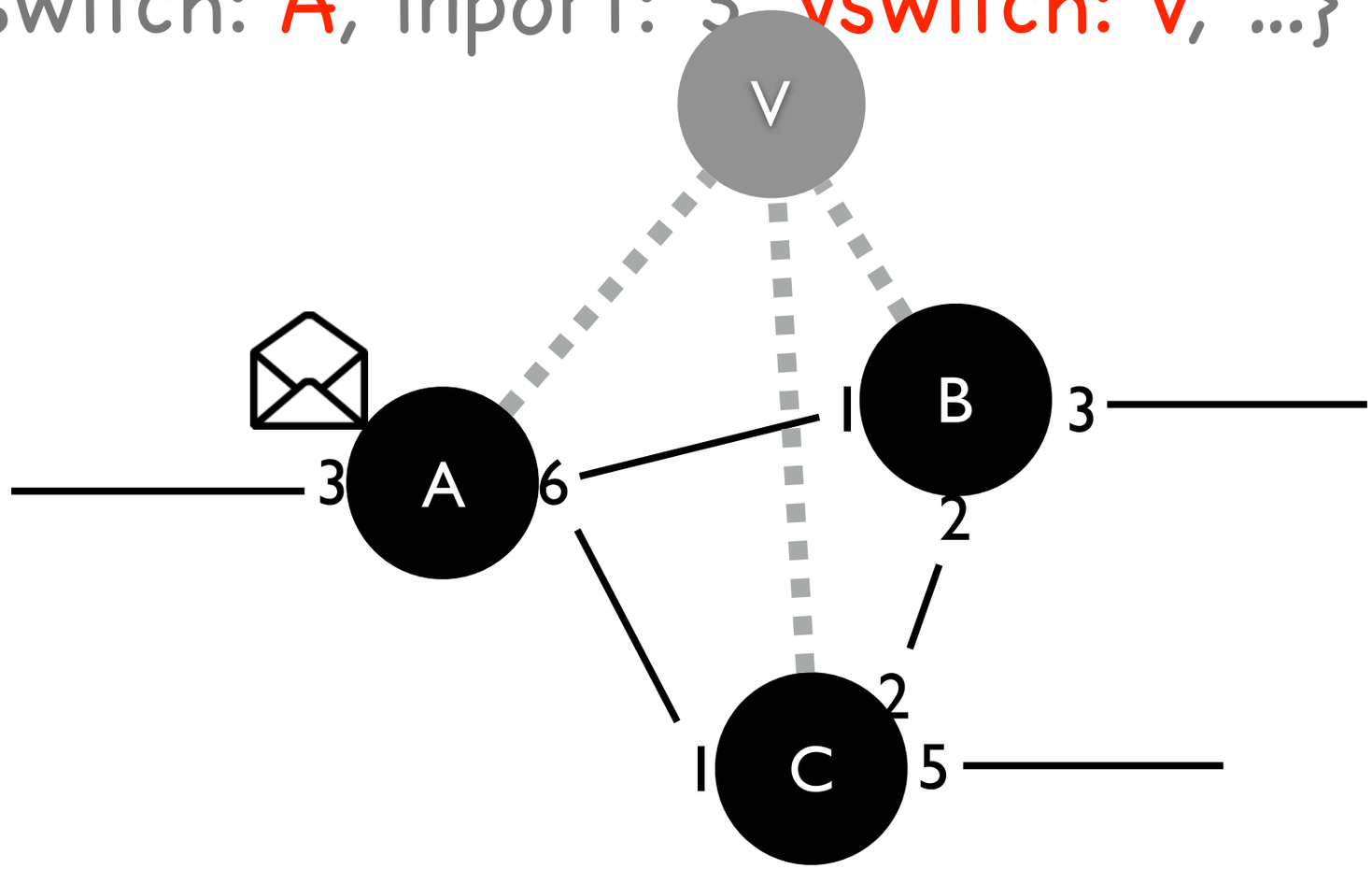

# abstract packet model

## the "located packet" model

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  {switch: [V,A], inport: 3, …}

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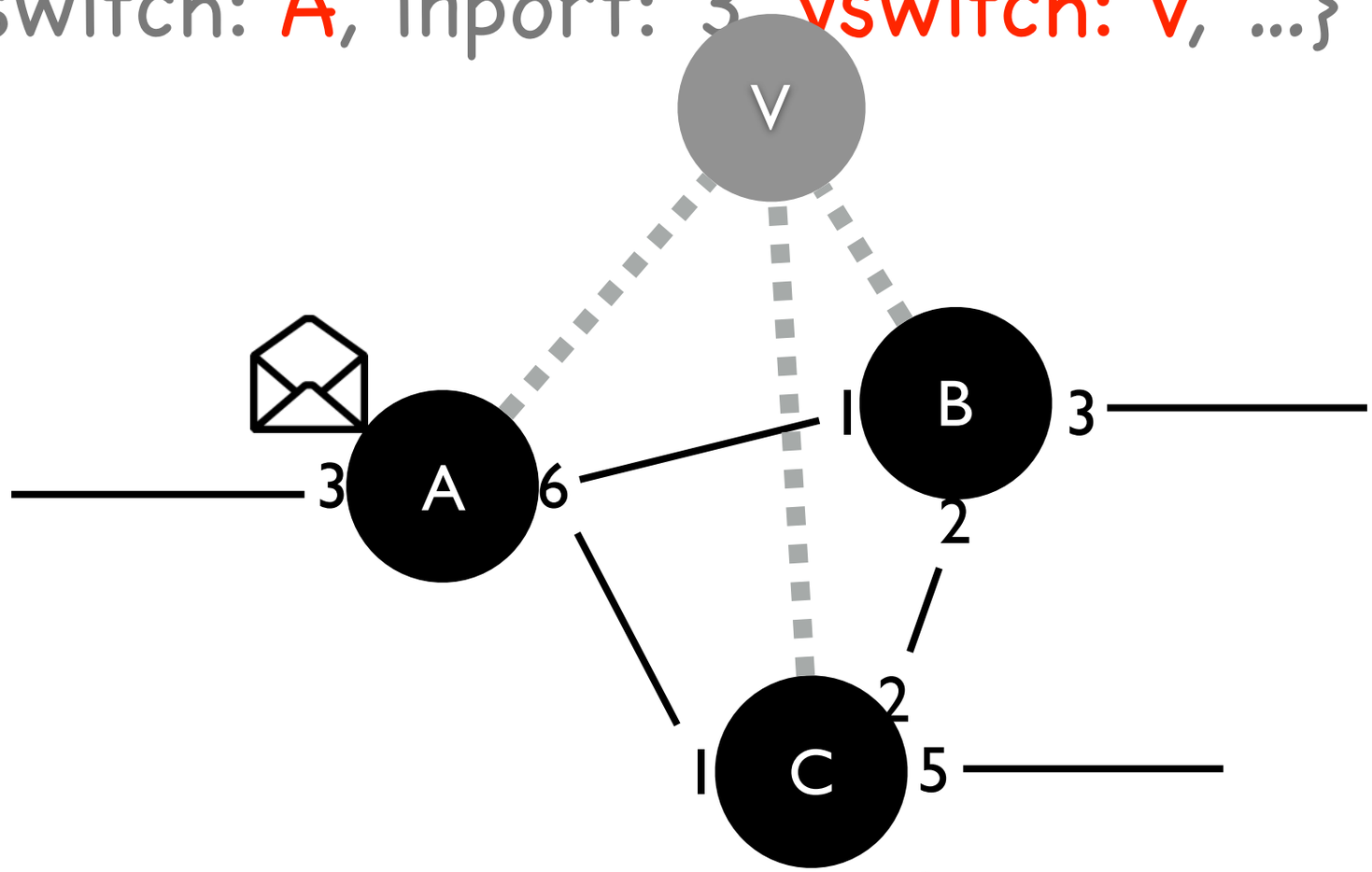


## more: IP addresses, MAC addresses …

# Pyretic policies

## locate packets ➡ located packets

## static policy

- a snapshot of a network's global forwarding behavior
- an abstract function

## dynamic policy

- a series of static policies

# static policy (simplified)

define policy

C ::= A | P[C] | C+C | C»C

# primitive actions

define policy

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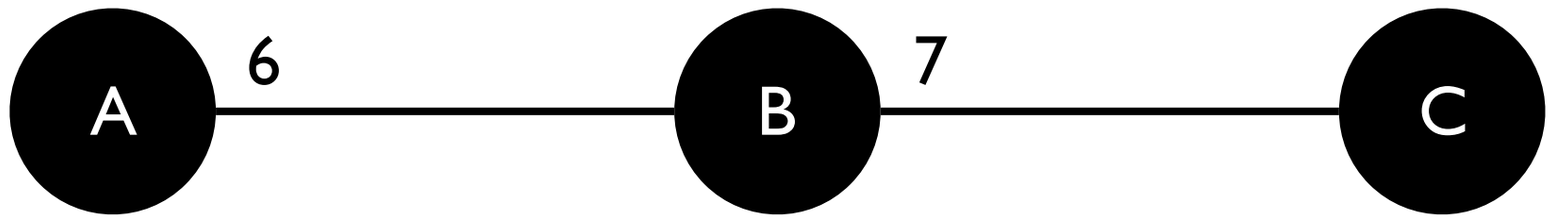
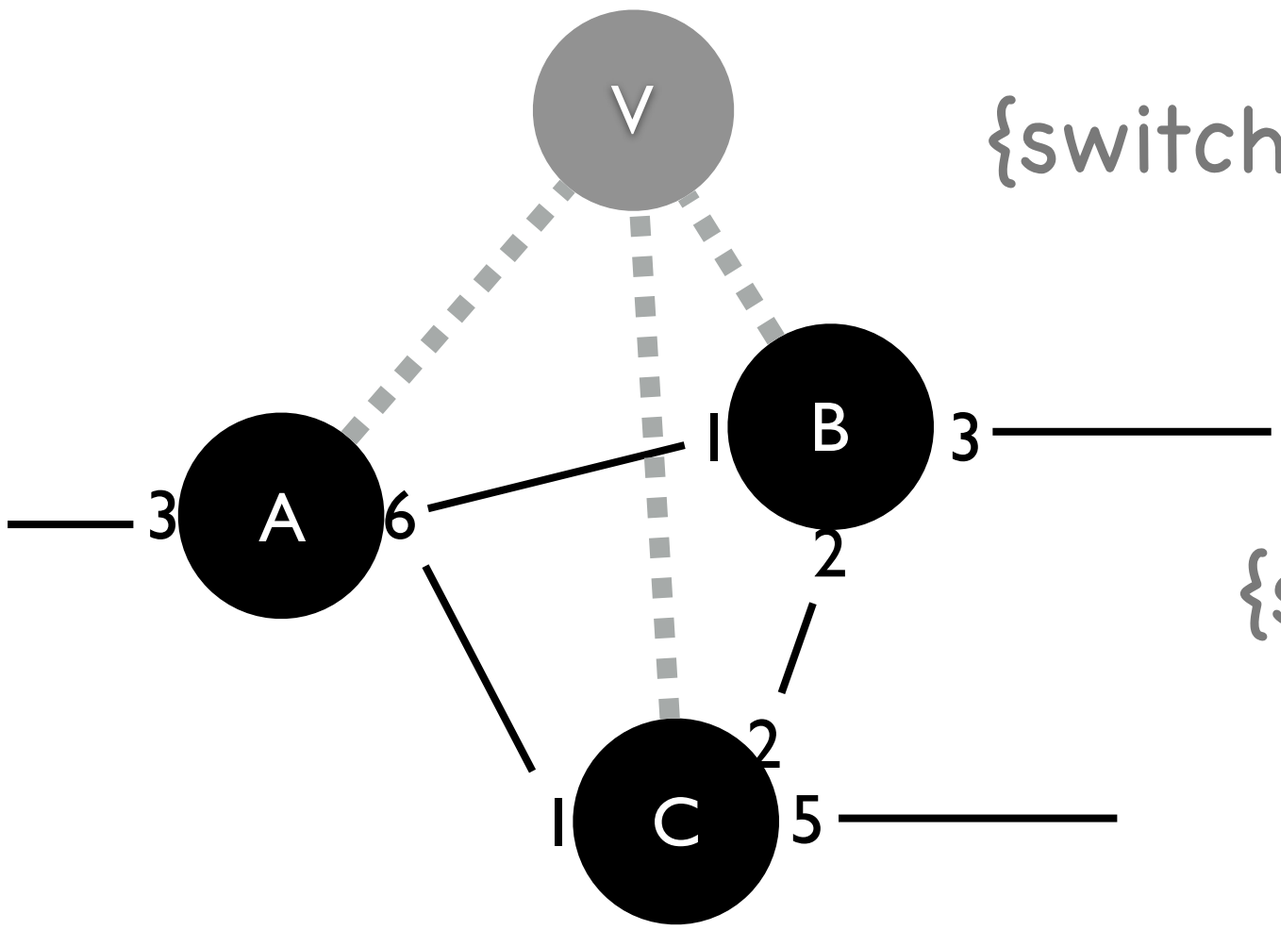



fwd(6)

# primitive actions

define policy

C ::= A | P[C] | C+C | C»C




{switch: A, inport: 3, vswitch: V, ...}

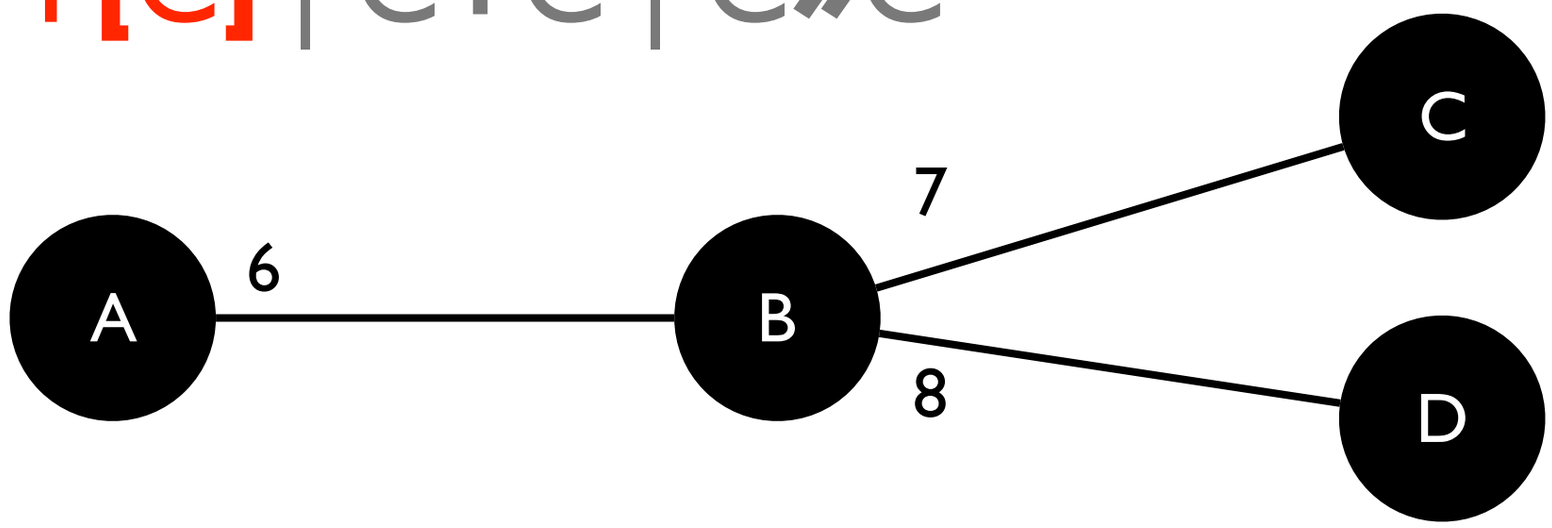
push(h=V)

{switch: [V,A], inport: 3, ...}

# predicates

define policy

C ::= A | P[C] | C+C | C»C




match(switch='B', src='A') [flood]

# sequential composition

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define policy

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# sequential composition

define policy

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define $C_1$»$C_2$ as $C_3$

- $C_3$(packet) =
- $C_1(p_1)$ U … U $C_2(P_n)$ where $\{P_1,\ldots P_n\}$ = $C_1$(packet)

# parallel composition

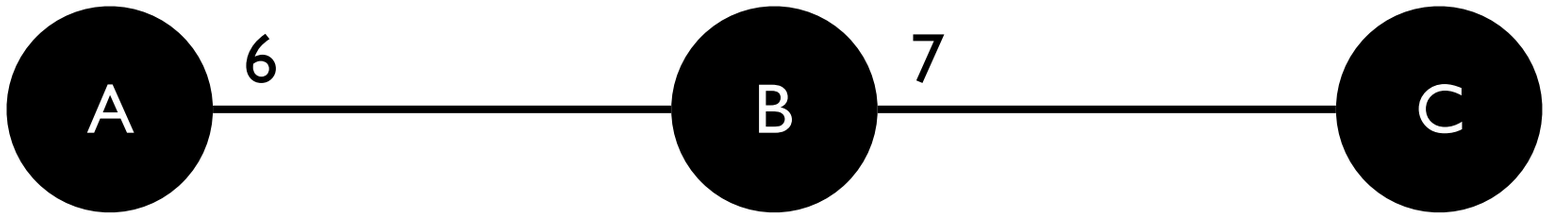
define policy

C ::= A | P[C] | C+C | C»C

define $C_1$+$C_2$ as $C_3$

- $C_3$(packet) = $C_1$(packet) U $C_2$(Packet)

# composite policy example




```
match(switch='A', dstip='C') » fwd(6) +
match(switch='B', dstip='C') » fwd(7)
```

# example sequential composition

| Monitor |
|---|
| srcip=5.6.7.8 → count |

| Route |
|---|
| dstip=10.0.0.1 → fwd(1) |
| dstip=10.0.0.2 → fwd(2) |

| Compiled Prioritized Rule Set for "Monitor ⨟ Route" |
|---|
| srcip=5.6.7.8,dstip=10.0.0.1 → count,fwd(1) |
| srcip=5.6.7.8,dstip=10.0.0.2 → count,fwd(2) |
| srcip=5.6.7.8 → count |
| dstip=10.0.0.1 → fwd(1) |
| dstip=10.0.0.2 → fwd(2) |

# example parallel composition

| Route |
| --- |
| dstip=10.0.0.1 → fwd(1) |
| dstip=10.0.0.2 → fwd(2) |

| Load-balance |
| --- |
| srcip=0*,dstip=1.2.3.4 → dstip=10.0.0.1 |
| srcip=1*,dstip=1.2.3.4 → dstip=10.0.0.2 |

| Compiled Prioritized Rule Set for “Load-balance >> Route” |
| --- |
| srcip=0*,dstip=1.2.3.4 → dstip=10.0.0.1,fwd(1) |
| srcip=1*,dstip=1.2.3.4 → dstip=10.0.0.2,fwd(2) |

# Pyretic — dynamic policy

# query policy

define policy

C ::= A | P[C] | C+C | C»C | Q

Q ::= packets | count

packet, count buckets

- resulting located packets diverted to “buckets” in the controller
- application registers listeners with buckets
- buckets passes entire packets to the listeners

# query policy

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packet, count buckets

- resulting located packets diverted to "buckets" in the controller
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```
match(switch='A', dstip='C') [Q + fwd(6)]
```

# query policy example

- application registers listeners with buckets
- buckets passes entire packets to the listener

```
def printer(pkt):
  print pkt

def dpi():
  Q = packets(None,[])
  Q.when(printer)
  return match(srcip='1.2.3.4')[Q]

def main():
  return dpi() | flood
```

# example: deep packet inspection

- application registers listeners with buckets
- buckets passes entire packets to the listener

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create a query policy, monitoring all traffic

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register `printer` as a listener

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each time a packet arrives at `packet_bucket`, `printer` is called, printing the (passed) packet

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- buckets passes entire packets to the listener

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construct a policy that collects traffic from `1.2.3.4`

# from query to dynamic policy

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## dynamic policy

- changes in response to network changes
- query policies drive changes to other policies

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## dynamic policy

- changes in response to network changes
- query policies drive changes to other policies

## pattern

- query policy A collects network change
- A register dynamic policy B as listener
- upon network change
  - A passes the change (pkt) to B
  - B updates its policy dynamically

# example: round-robin load-balancer

```
class rrlb(DynamicPolicy):

 def __init__(self,s,servers):
  self.switch = s
  self.servers = servers
  ...

  Q = packets(limit=1,group_by=['srcip'])
  Q.register_callback(self.round_robin)
  self.policy = match(dstport=80) >> Q

 def round_robin(self,pkt):
  self.policy = if_(match(srcip=pkt['srcip']),
                    modify(dstip=self.server), self.policy)
  self.client += 1
  self.server = self.servers[self.client % m]


servers = ['2.2.2.8','2.2.2.9']
rrlb_on_switch3 = rrlb(3,servers)
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create a query policy

register round_robin

update server assignment

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create a query policy

register round_robin

update server assignment

3 runs rrlb for two servers

# limitation to Pyretic policies

*programmers must specify policies in terms of the underlying physical topology*

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abstract network topology

*allow a new derived topology to be built on top of an already existing existing underlying network*

# Pyretic —
# abstract topology abstraction

# topology abstraction

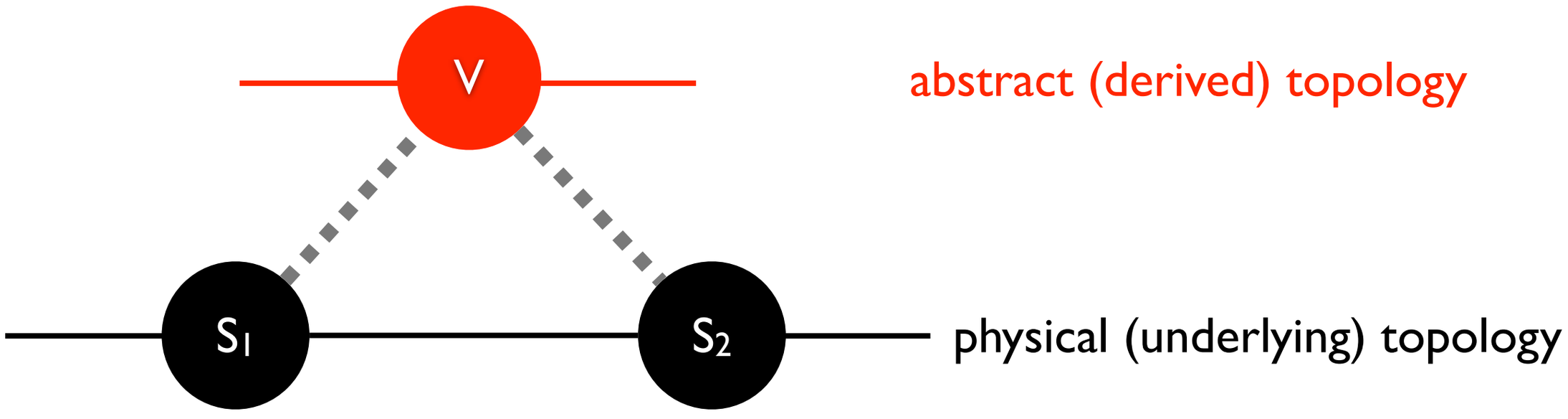
modular programming constrains

- what each module sees and can do

enabled by network objects

- an abstract topology
  - can be a mix of physical and virtual switches
  - can be multiple levels of nesting on top of the one real network
- a policy function applied to this topology

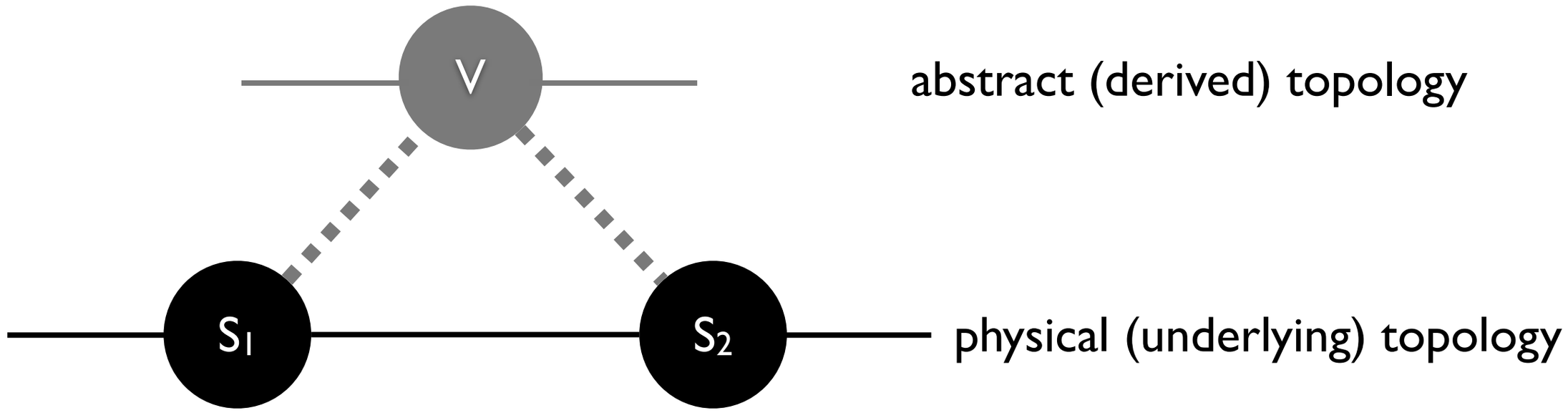
# topology abstraction




## Pyretic network objects

- an abstract topology
- a policy applied to the abstract topology
- a mapping (for derived network)

# topology abstraction




## mapping

- a function to map changes to the underlying topology up to changes on the derived network
- a function to map policies against the derived topology down to equivalent policy expressed only in terms of the underlying topology

# topology abstraction example

## MAC learning

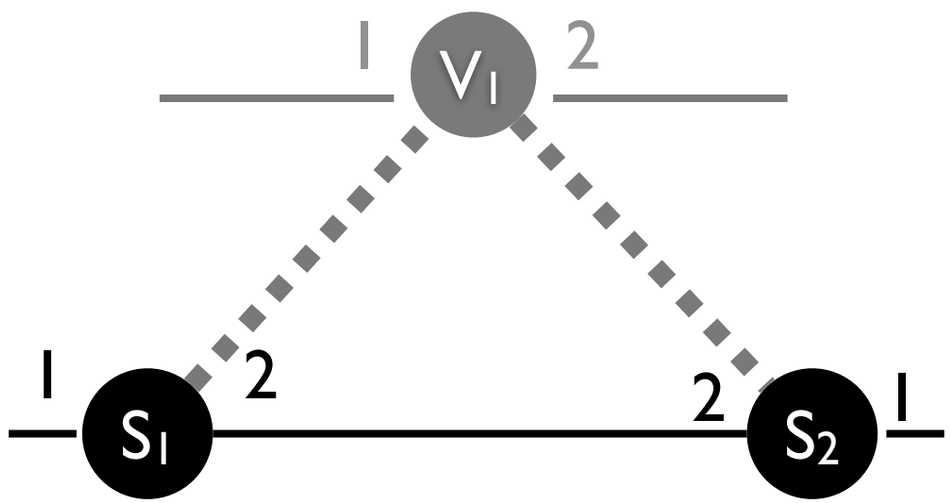
- one big switch, learns where the hosts are located

## switching fabric

- sees the entire physical network
- performs routing from one edge link to another

MAC learning
(derived network)

switching fabric
(underlying network)



# coordinating modules

## MAC learning module

- specifies chosen output port(s)

## switching module

- directs traffic on a path to the (corresponding) egress port(s)

# coordination via abstract packet model

## virtual packet header

- a module can push, pop, and inspect
- MAC learning directs traffic from one input port to an output port
- fabric switching sees a virtual header indicating the corresponding ingress/egress

## runtime performs the mapping

# example: transforming topology

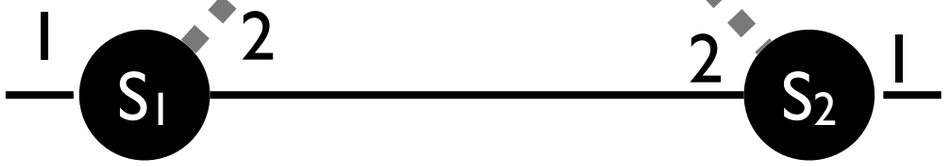
a dictionary (mapping)

- (vswitch, vport) ➡ (switch, port)

derived network underlying network

derived network


underlying network



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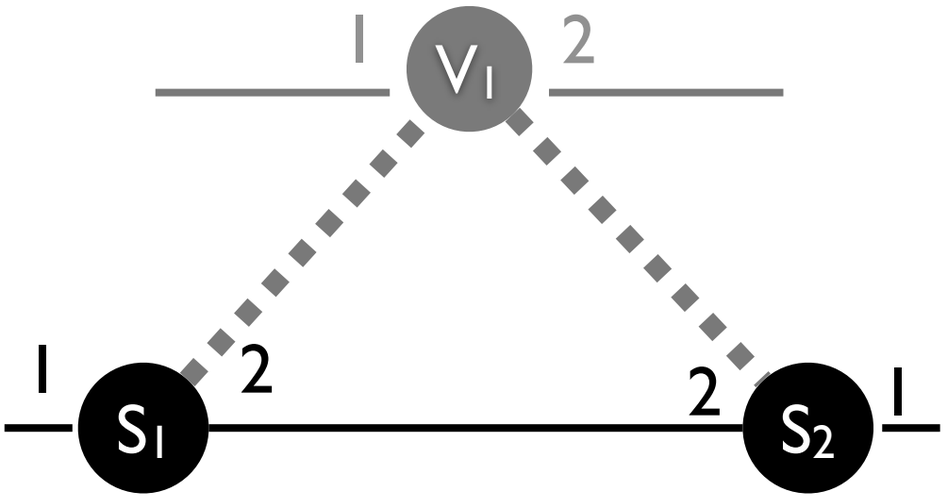


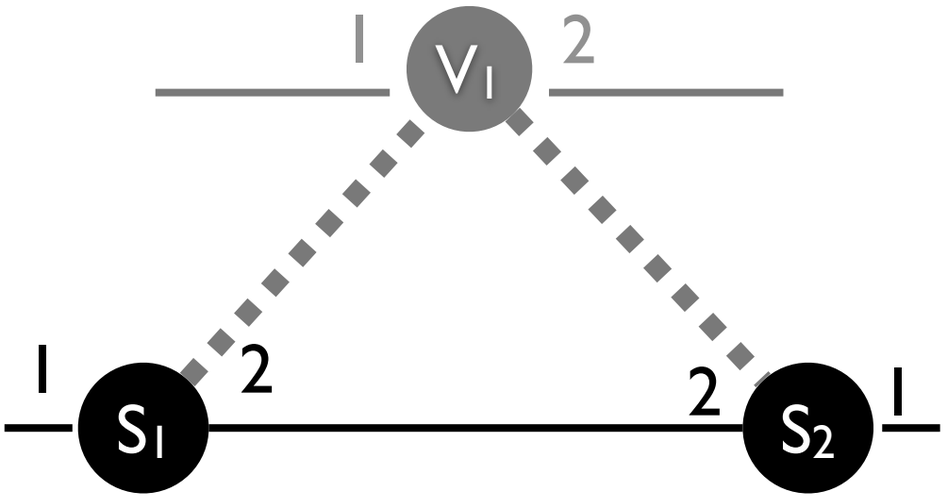

```
def bfs_vmap(topo):
    vswitch = 1
    vport = 1
    for (switch, port) in topo.egress_locations:
        vmap[(vswitch, vport)] = (switch, port)
        vport += 1
    return vmap
```

recall the packet model {switch: A, inport: 3, vswitch: V, ...}

# example: transforming policy

Pyretic generates ingress function

- "lifts" packets from the underlying network up to the derived

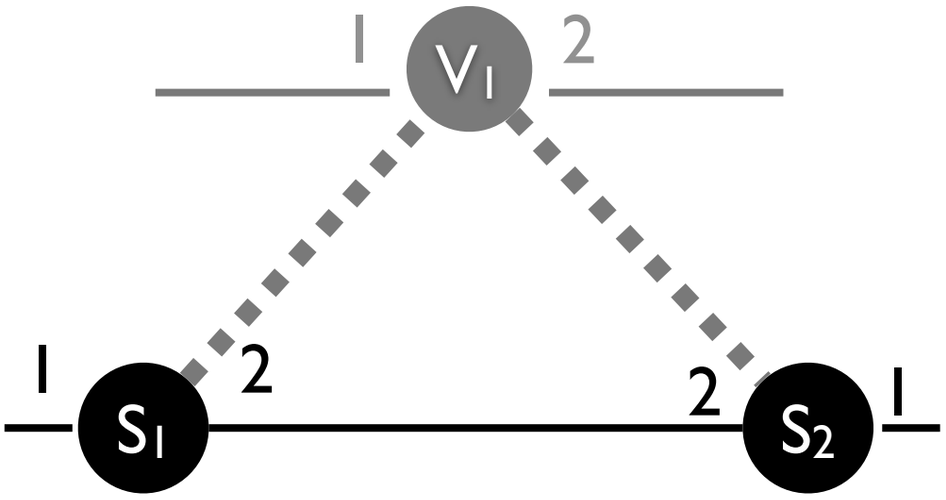



```
ingress_policy =
( match(switch=S1, inport=1)
   [push(vswitch=V, vinport=1)]
| match(switch=S2, inport=1)
   [push(vswitch=V, vinport=2)])
```

# example: transforming policy

Pyretic generates egress function

- "lowers" packets from the derived to the underlying network

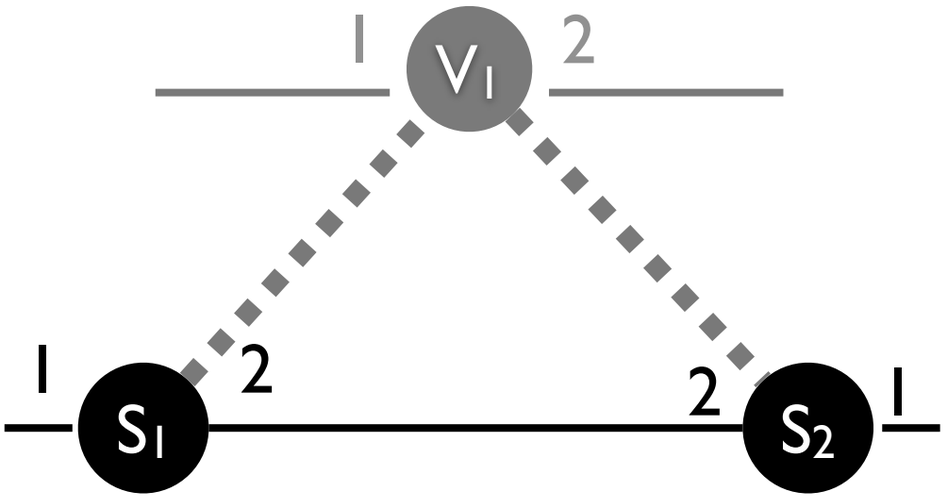



```
egress_policy = match(vswitch=V)
    [if_(match(switch=S1, voutport=1)
      | match(switch=S2, voutport=2),
      pop(vswitch, vinport, voutport),
      passthrough)]
```

# example: transforming policy

## Pyretic generates fabric policy

- forwarding between ports in the derived network via a path in the underlying network




```
fabric_policy = match(vswitch=V)[
 ( match(switch=S1, voutport=1)[fwd(1)]
  |match(switch=S1, voutport=2)[fwd(2)]
  |match(switch=S2, voutport=1)[fwd(2)]
  |match(switch=S2, voutport=2)[fwd(1)])]
```

# virtualizing template

```
def virtualize(ingress_policy,
                   egress_policy,
                   fabric_policy,
                   derived_policy):
    return if_(~match(vswitch=None),
      (ingress_policy >>
       move(switch=vswitch,inport=vinport) >>
       derived_policy >>
       move(vswitch=switch,vinport=inport,voutport=outport)),
     passthrough) >>
fabric_policy >>
egress_policy
```

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fabric_policy >>
egress_policy
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    egress_policy
```
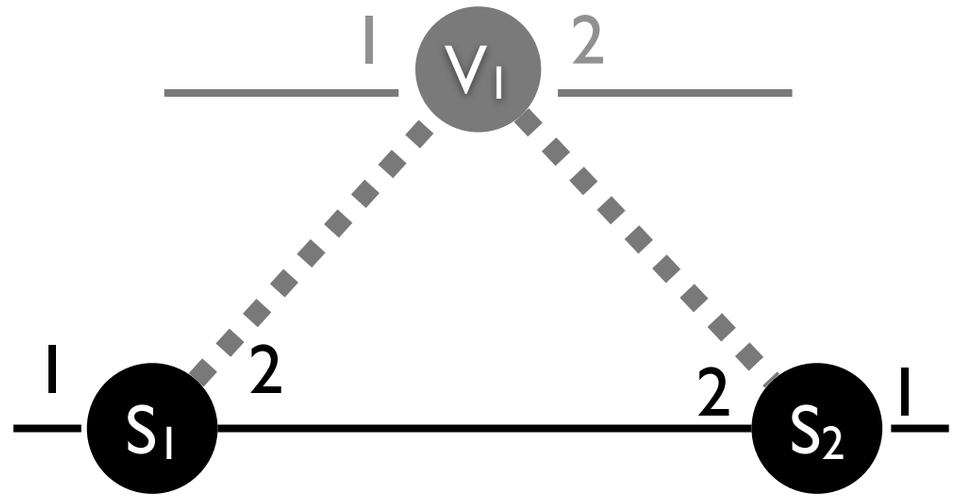
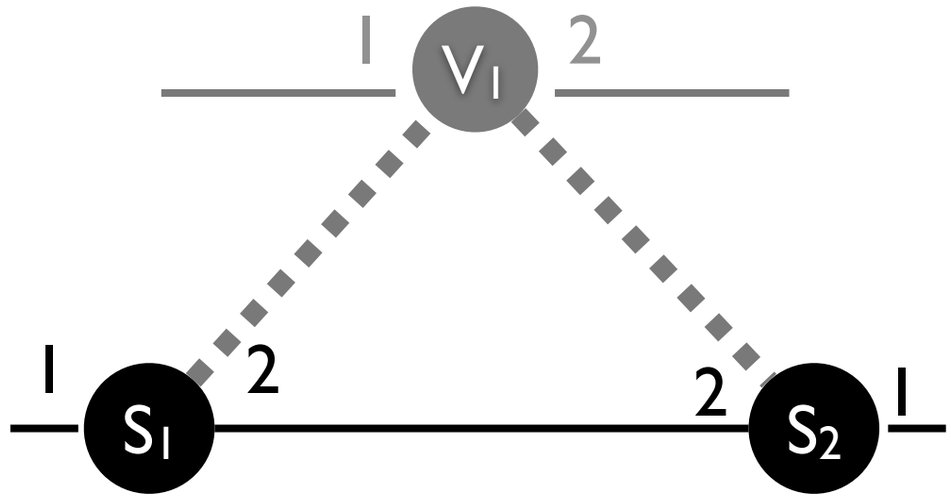

# packet processing




{switch:S1, inport:1, … }

```
ingress_policy >>

move(switch=vswitch,inport=vinport)>>

derived_policy (flood) >>

move(vswitch=switch,vinport=inport,vouptport=outport) >>

passthrough

fabric_policy >>

egress_policy
```

# packet processing




{switch:S1, inport:1, … }

ingress_policy >>

{switch:S1, inport:1, vswitch:V, vinport:1, … }

move(switch=vswitch,inport=vinport)>>

derived_policy (flood) >>

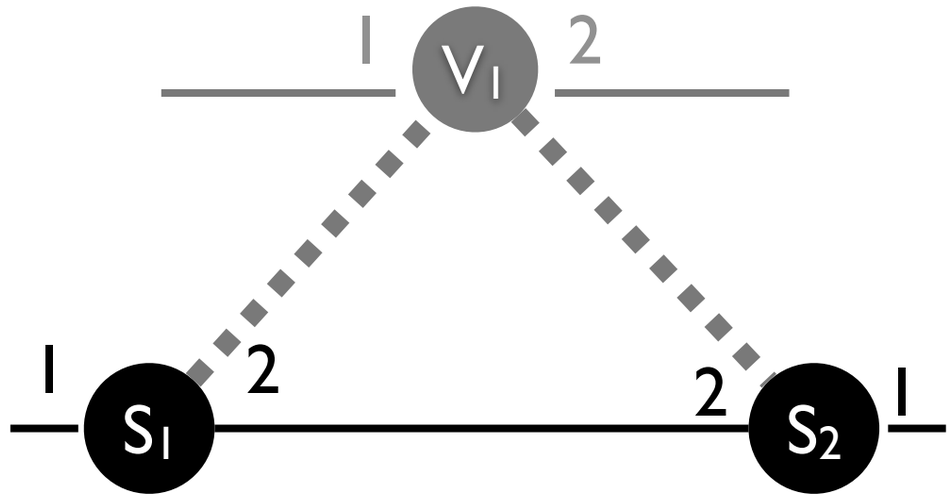
move(vswitch=switch,vinport=inport,vouptport=outport) >>

passthrough

fabric_policy >>

egress_policy

# packet processing




{switch:S1, inport:1, … }

ingress_policy >>

{switch:S1, inport:1, vswitch:V, vinport:1, … }

move( switch=vswitch,inport=vinport )>>

{switch:[V, S1], inport:[1, 1]}

derived_policy (flood) >>

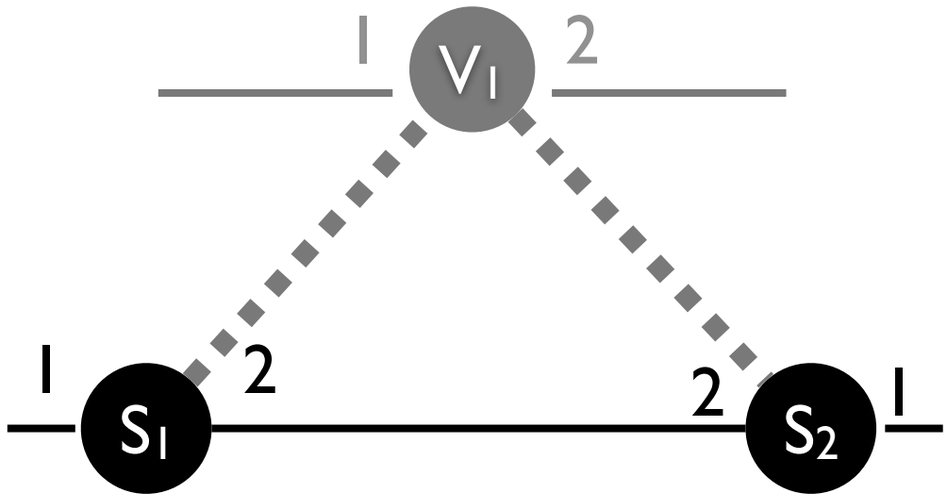
move( vswitch=switch,vinport=inport,vouptport=outport ) >>

passthrough

fabric_policy >>

egress_policy

# packet processing




{switch:S1, inport:1, … }

ingress_policy >>

{switch:S1, inport:1, vswitch:V, vinport:1, … }

move( switch=vswitch,inport=vinport )>>

{switch:[V, S1], inport:[1, 1]}

derived_policy (flood) >>

{switch:[V, S1], inport:[1, 1], outport:2, …}

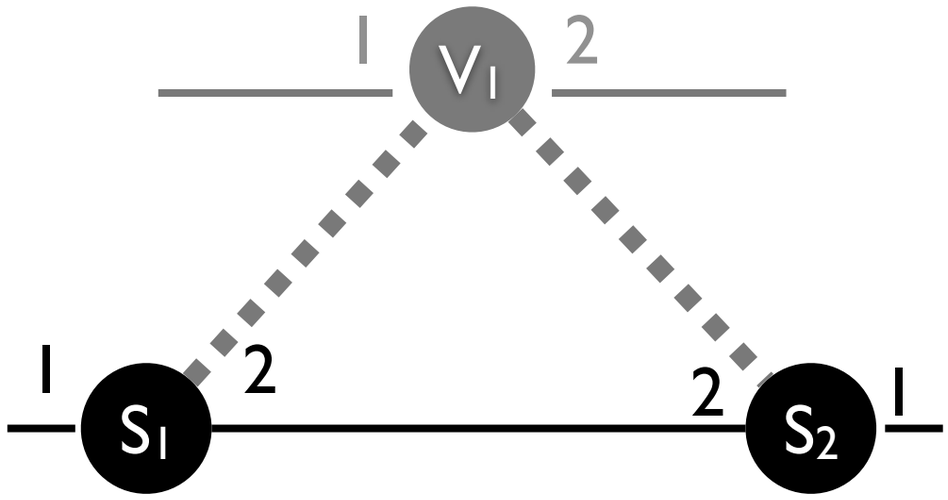
move( vswitch=switch,vinport=inport,vouptport=outport ) >>

passthrough

fabric_policy >>

egress_policy

# packet processing

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{switch:[V, S1], inport:[1, 1]}

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{switch:[V, S1], inport:[1, 1], outport:2, …}

move( vswitch=switch,vinport=inport,vouptport=outport ) >>

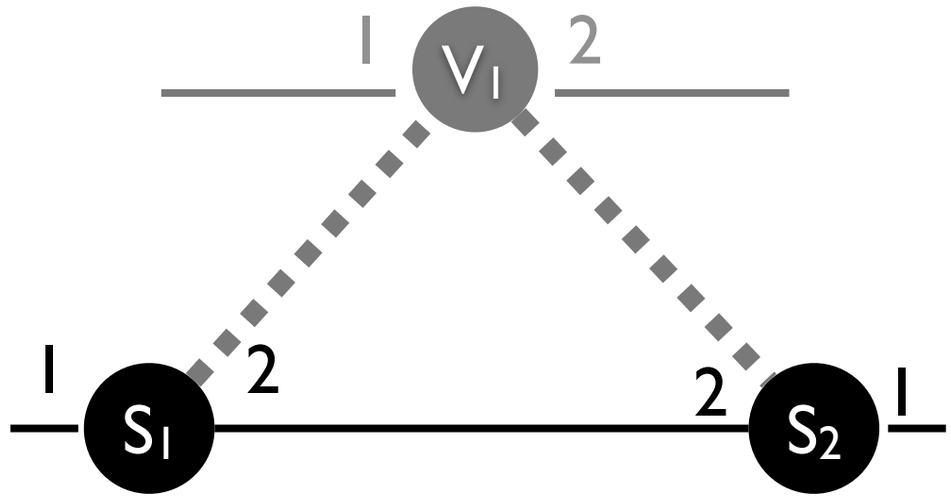
{switch:S1, inport:1, vswitch:V, vinport:1, voutport:2 }

fabric_policy >>

egress_policy

passthrough

# packet processing

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move( switch=vswitch,inport=vinport )>>

{switch:[V, S1], inport:[1, 1]}

derived_policy (flood) >>

{switch:[V, S1], inport:[1, 1], outport:2, …}

move( vswitch=switch,vinport=inport,vouptport=outport ) >>

{switch:S1, inport:1, vswitch:V, vinport:1, voutport:2 }

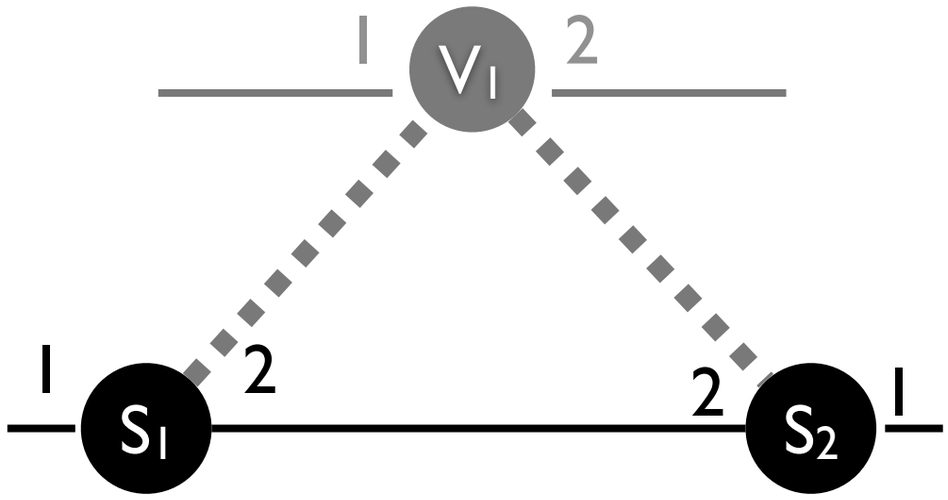
fabric_policy >>

{switch:S1, outport:2,vswitch:V, vinport:1, voutport:2 }

egress_policy

passthrough

# packet processing

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ingress_policy >>

{switch:S1, inport:1, vswitch:V, vinport:1, … }

move( switch=vswitch,inport=vinport )>>

{switch:[V, S1], inport:[1, 1]}

derived_policy (flood) >>

{switch:[V, S1], inport:[1, 1], outport:2, …}

move( vswitch=switch,vinport=inport,vouptport=outport ) >>

{switch:S1, inport:1, vswitch:V, vinport:1, voutport:2 }

fabric_policy >>

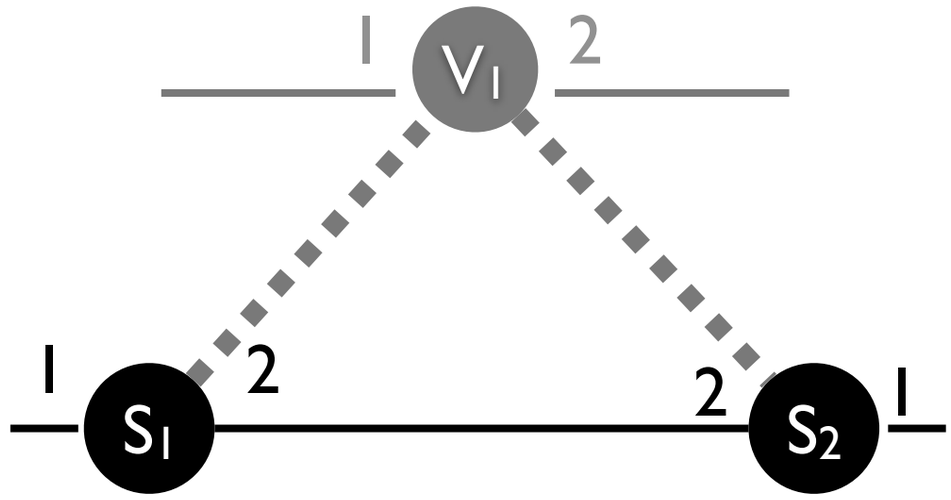
{switch:S1, outport:2,vswitch:V, vinport:1, voutport:2 }

egress_policy

{switch:S1, outport:2,vswitch:V, vinport:1, voutport:2 }

passthrough

# packet processing




{switch:S1, inport:1, … }

ingress_policy >>

{switch:S1, inport:1, vswitch:V, vinport:1, … }

move( switch=vswitch,inport=vinport )>>

{switch:[V, S1], inport:[1, 1]}

derived_policy (flood) >>

{switch:[V, S1], inport:[1, 1], outport:2, …}

move( vswitch=switch,vinport=inport,vouptport=outport ) >>

{switch:S1, inport:1, vswitch:V, vinport:1, voutport:2 }

passthrough

fabric_policy >>

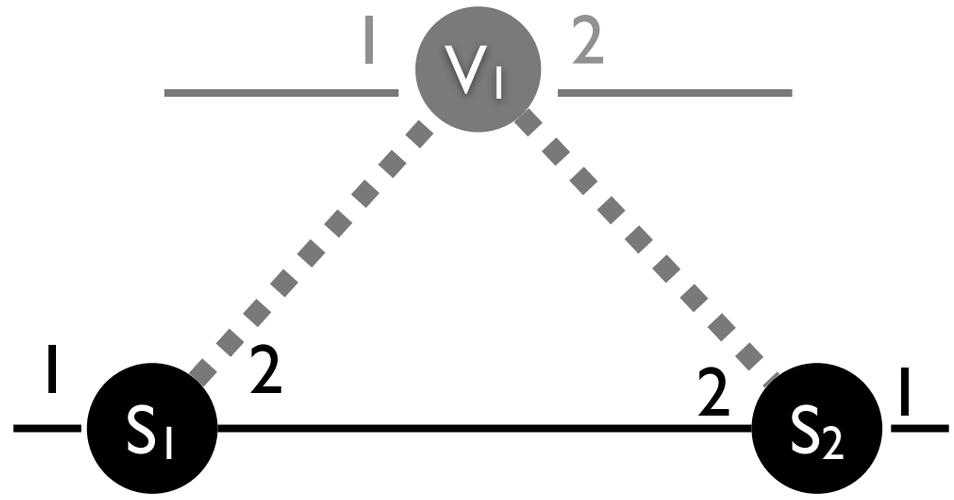
{switch:S1, outport:2,vswitch:V, vinport:1, voutport:2 }

egress_policy

{switch:S1, outport:2,vswitch:V, vinport:1, voutport:2 }

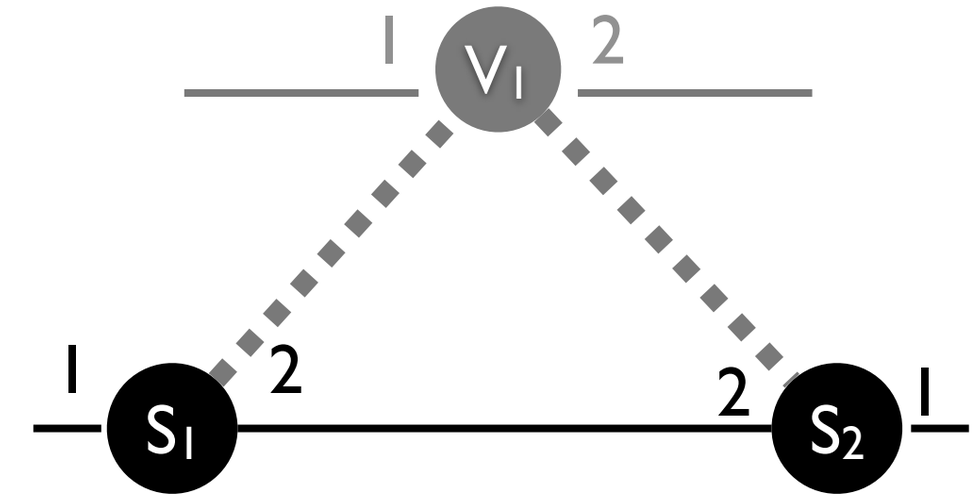
{switch:S2, inport:2,vswitch:V, vinport:1, voutport:2 }

# packet processing




```
ingress_policy >>

move(switch=vswitch,inport=vinport)>>

derived_policy (flood) >>

move(vswitch=switch,vinport=inport,vouptport=outport) >>

passthrough

fabric_policy >>

egress_policy
```

# packet processing

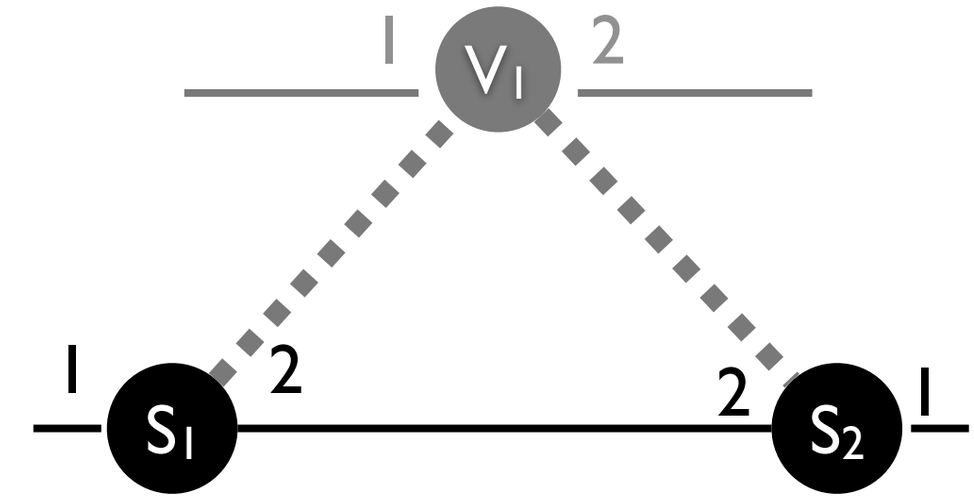



```
ingress_policy >>

move(switch=vswitch,inport=vinport)>>

derived_policy (flood) >>

move(vswitch=switch,vinport=inport,vouptport=outport) >>

fabric_policy >>

egress_policy
```

{switch:S2, inport:2,vswitch:V, vinport:1, voutport:

passthrough

# packet processing



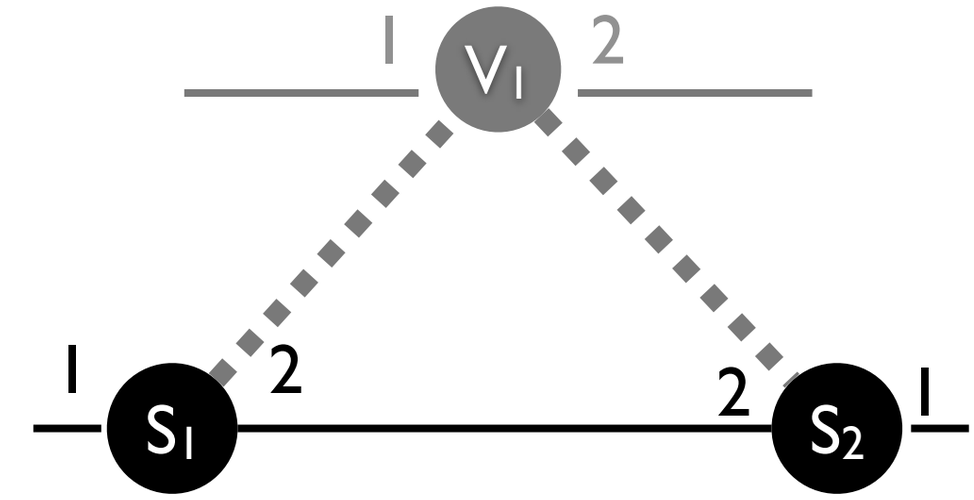

```
ingress_policy >>

move(switch=vswitch,inport=vinport)>>

derived_policy (flood) >>

move(vswitch=switch,vinport=inport,vouptport=outport) >>

fabric_policy >>

egress_policy
```

{switch:S2, inport:2,vswitch:V, vinport:1, voutport:

passthrough

{switch:S2, inport:2,vswitch:V, vinport:1, voutport:2

# packet processing



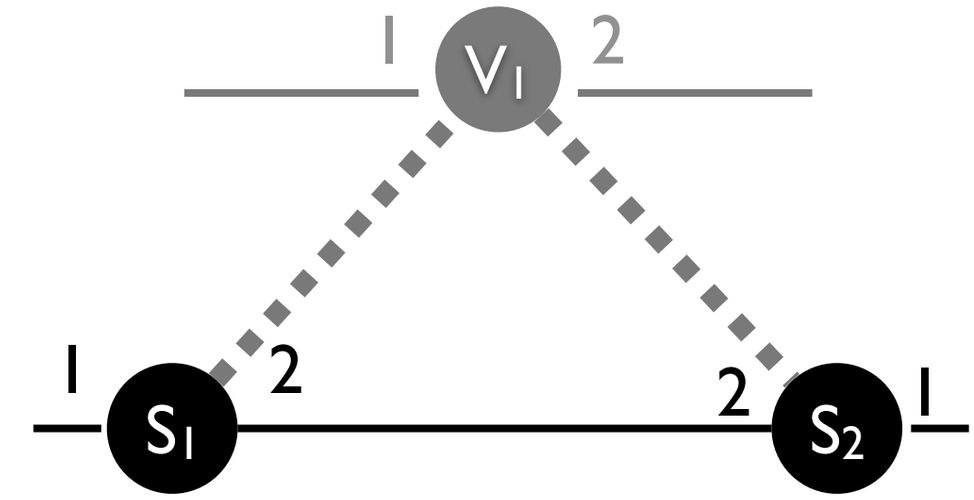

```
ingress_policy >>

move(switch=vswitch,inport=vinport)>>

derived_policy (flood) >>

move(vswitch=switch,vinport=inport,vouptport=outport) >>

fabric_policy >>

egress_policy

passthrough
```

{switch:S2, inport:2,vswitch:V, vinport:1, voutport:

{switch:S2, inport:2,vswitch:V, vinport:1, voutport:2

{switch:S2, inport:2,vswitch:V, output: 1, vinport:1, voutport:2 }

# packet processing




```
ingress_policy >>

move(switch=vswitch,inport=vinport)>>

derived_policy (flood) >>

move(vswitch=switch,vinport=inport,vouptport=outport) >>

fabric_policy >>

egress_policy

passthrough
```

{switch:S2, inport:2,vswitch:V, vinport:1, voutport:

{switch:S2, inport:2,vswitch:V, vinport:1, voutport:2

{switch:S2, inport:2,vswitch:V, output: 1, vinport:1, voutport:2 }

{switch:S2, output: 1}