Machine-Verified Controllers

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Cornell University

Networks in the News

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service outage was due to a series of internal network events that corrupted router data tables

SDN Facilitates Formal Methods

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Run-time Monitoring: VeriFlow

by Khurshid, Zhou, Caesar, and Godfrey

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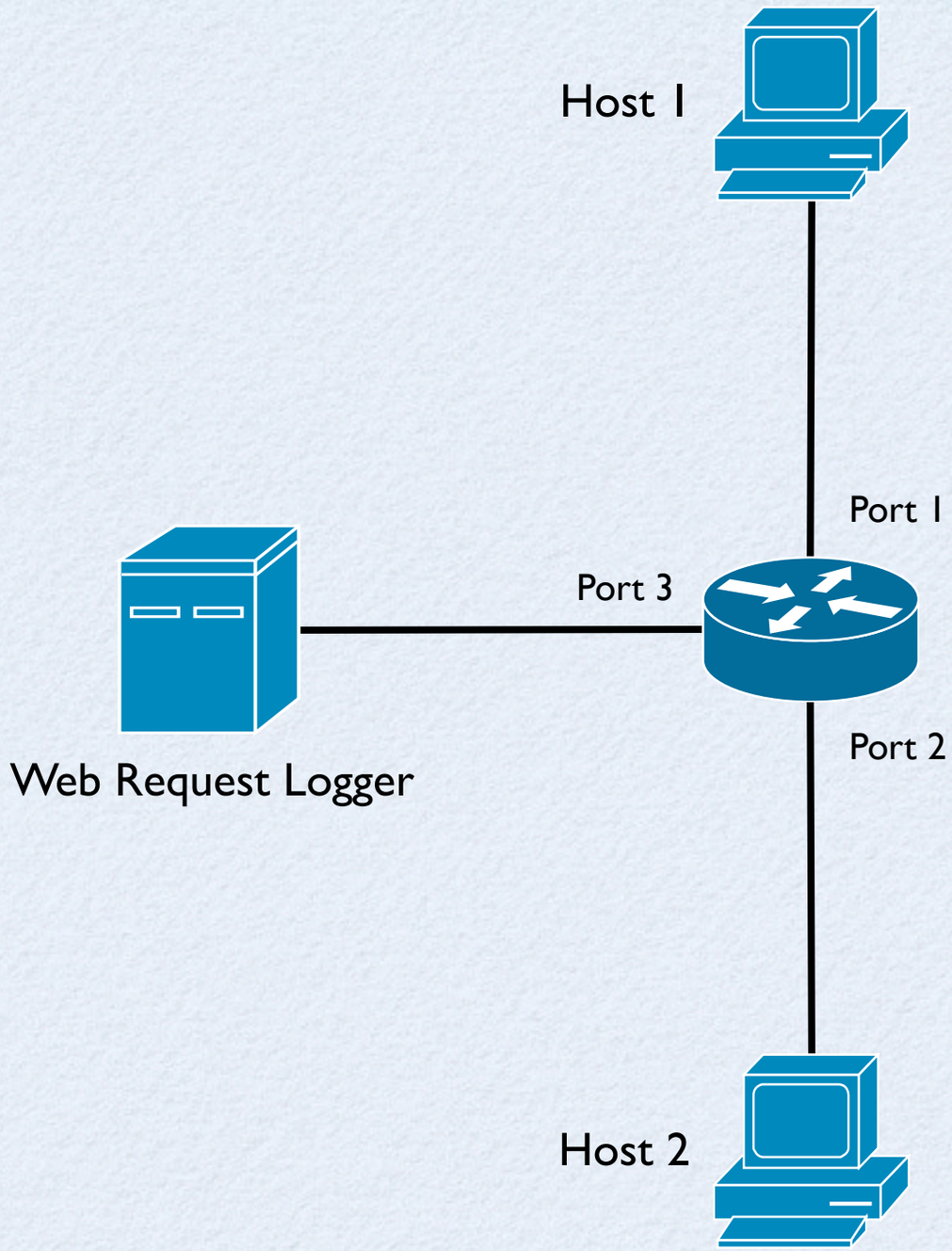
Verified Controllers: this talk

- program verification
- proof of correctness
- no runtime cost
- proof *w.r.t.* a detailed model of OpenFlow forwarding

Bugs in Controllers

Running Example



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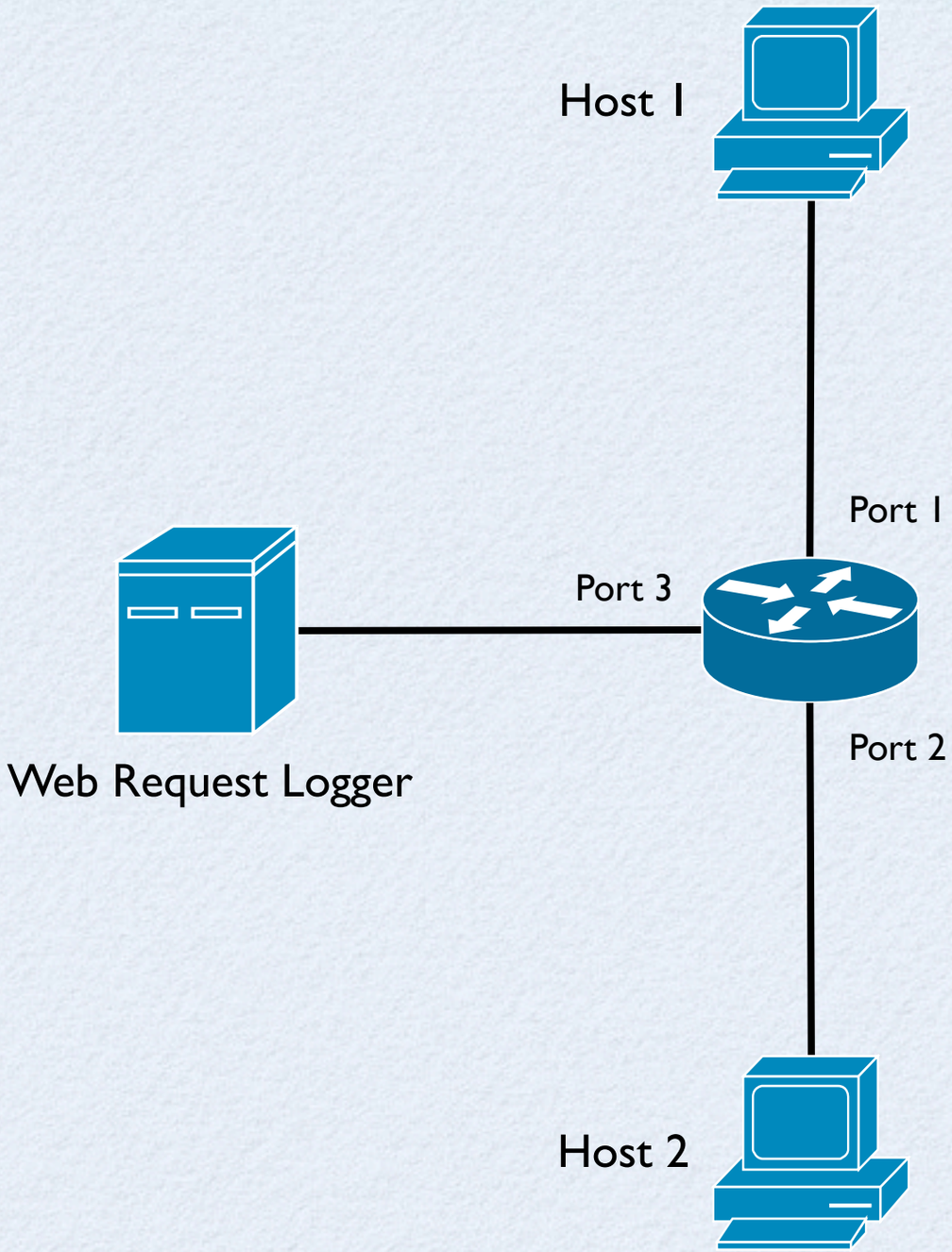

- Block SSH traffic
- Forward other traffic normally
- Log Web requests

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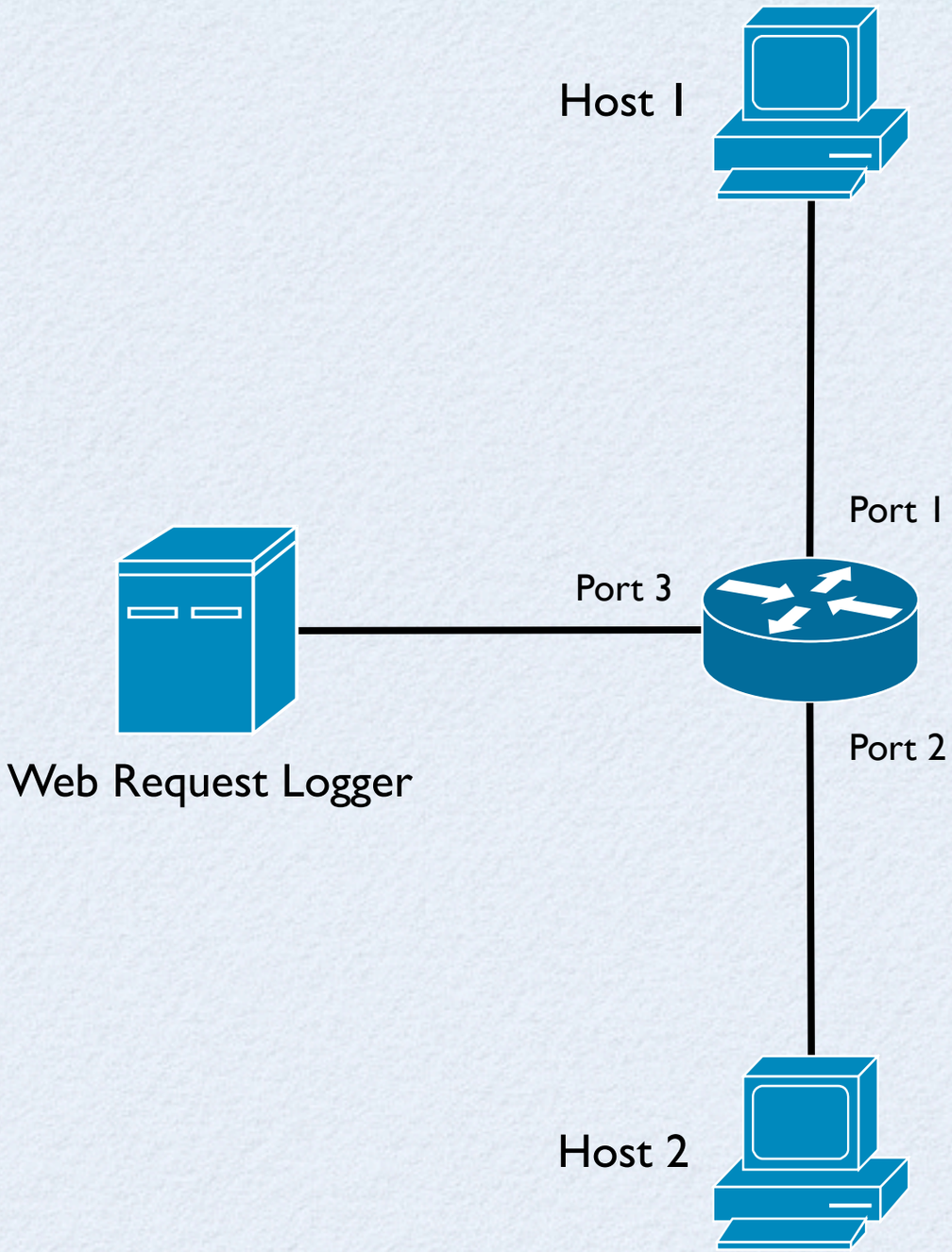

- Block SSH traffic

  dstPort == 22 ⟹ Drop

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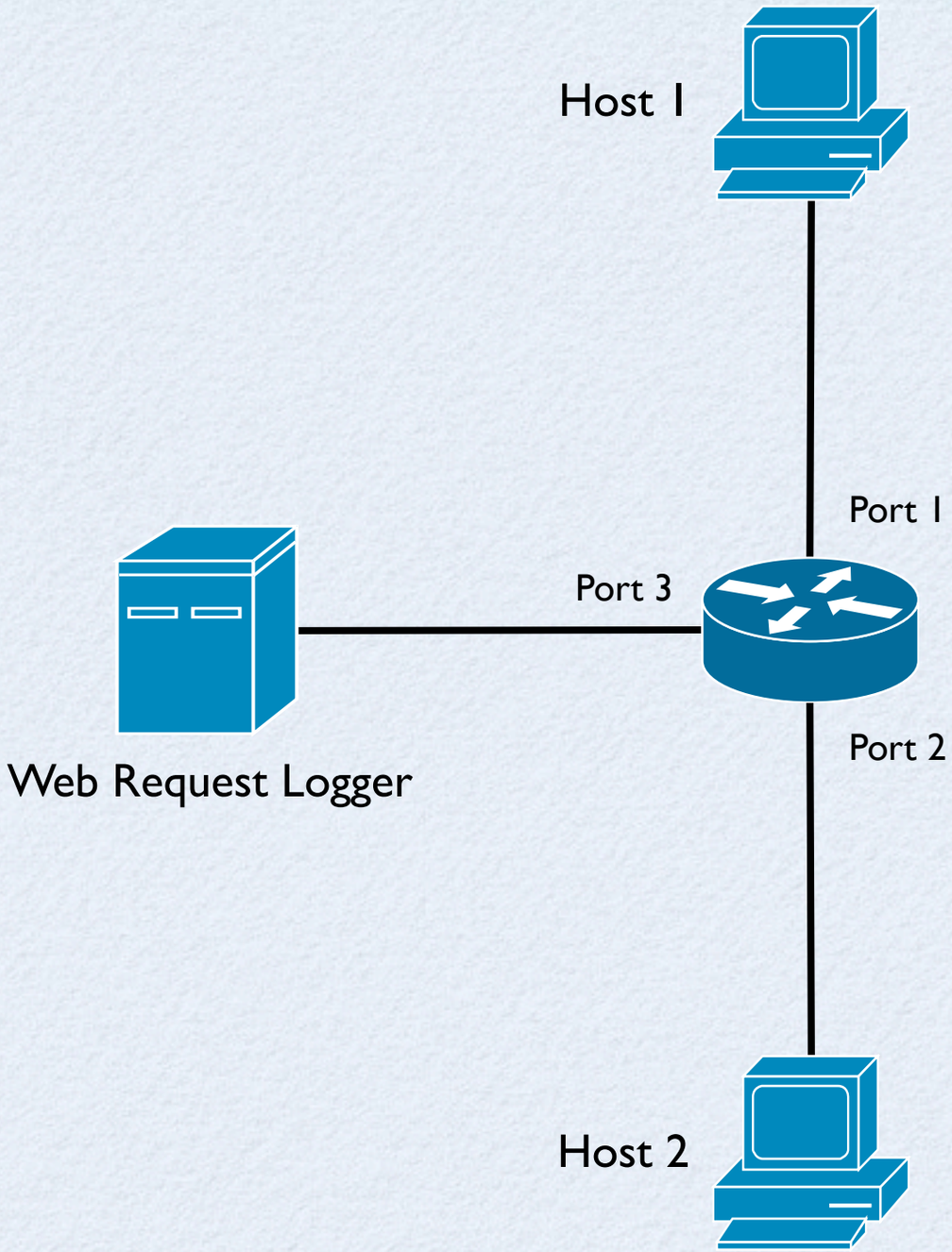

- Block SSH traffic

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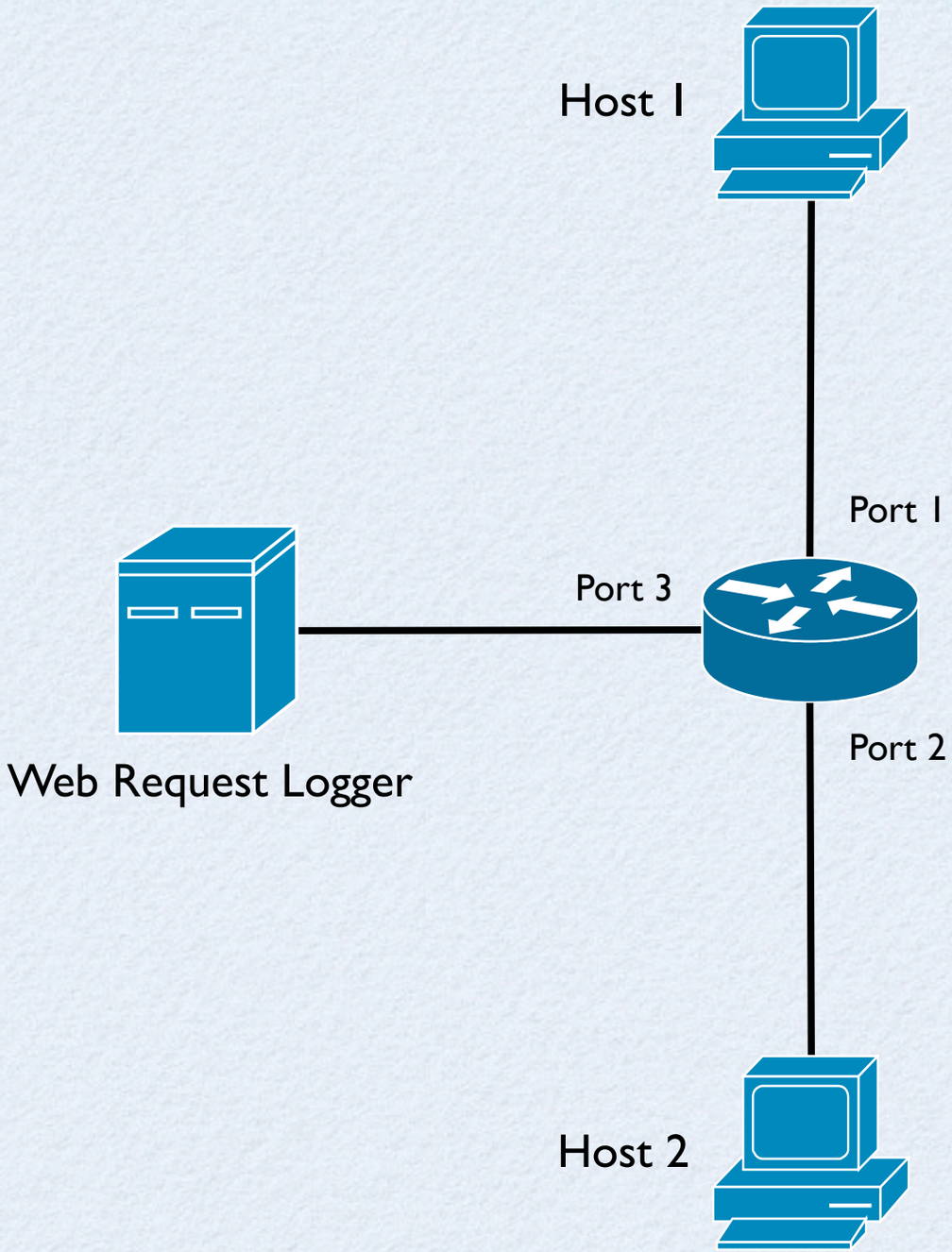

- Block SSH traffic

  dstPort == 22 ⟹ Drop

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- Log Web requests

  dstPort == 80 ⟹ Fwd 3

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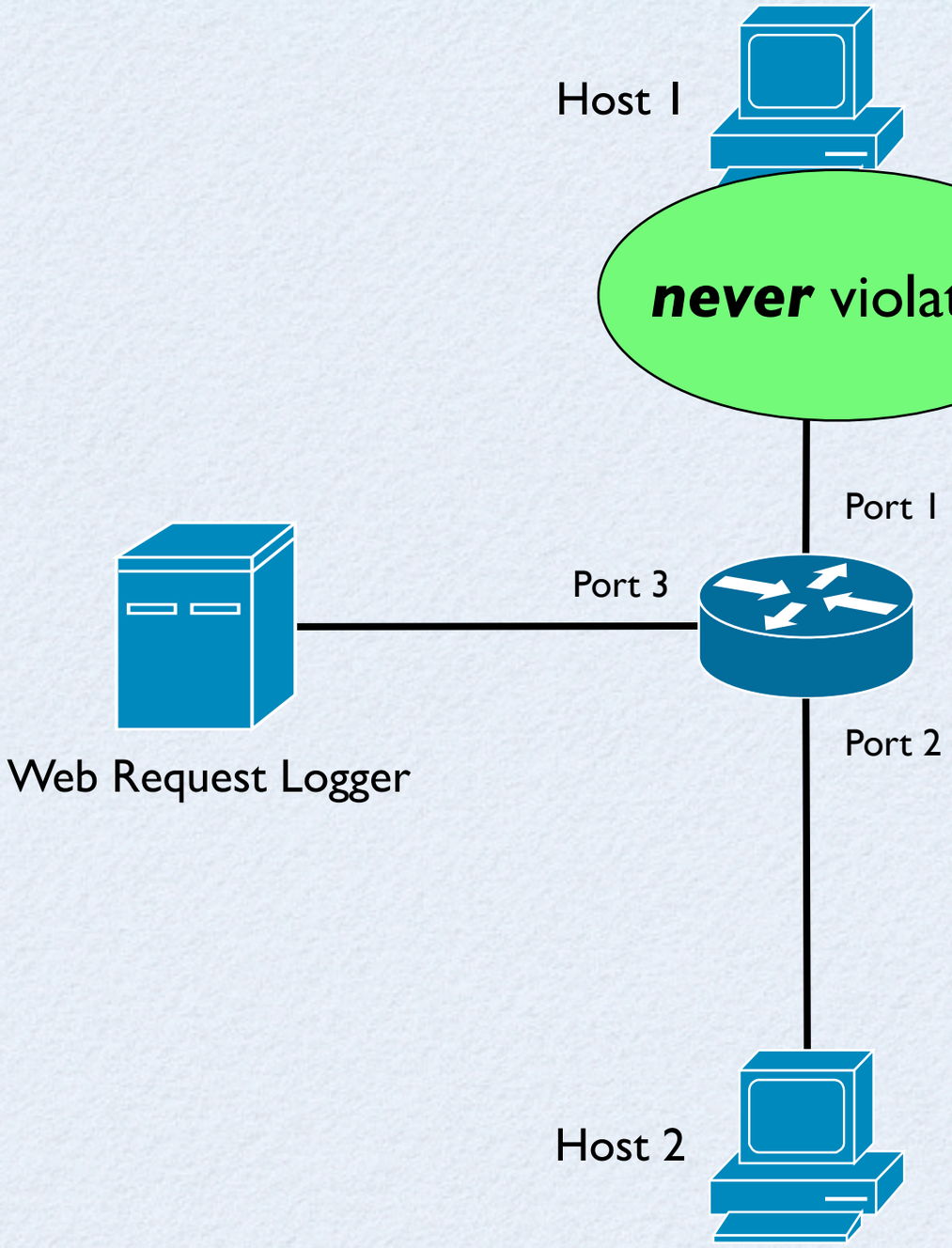

never violated

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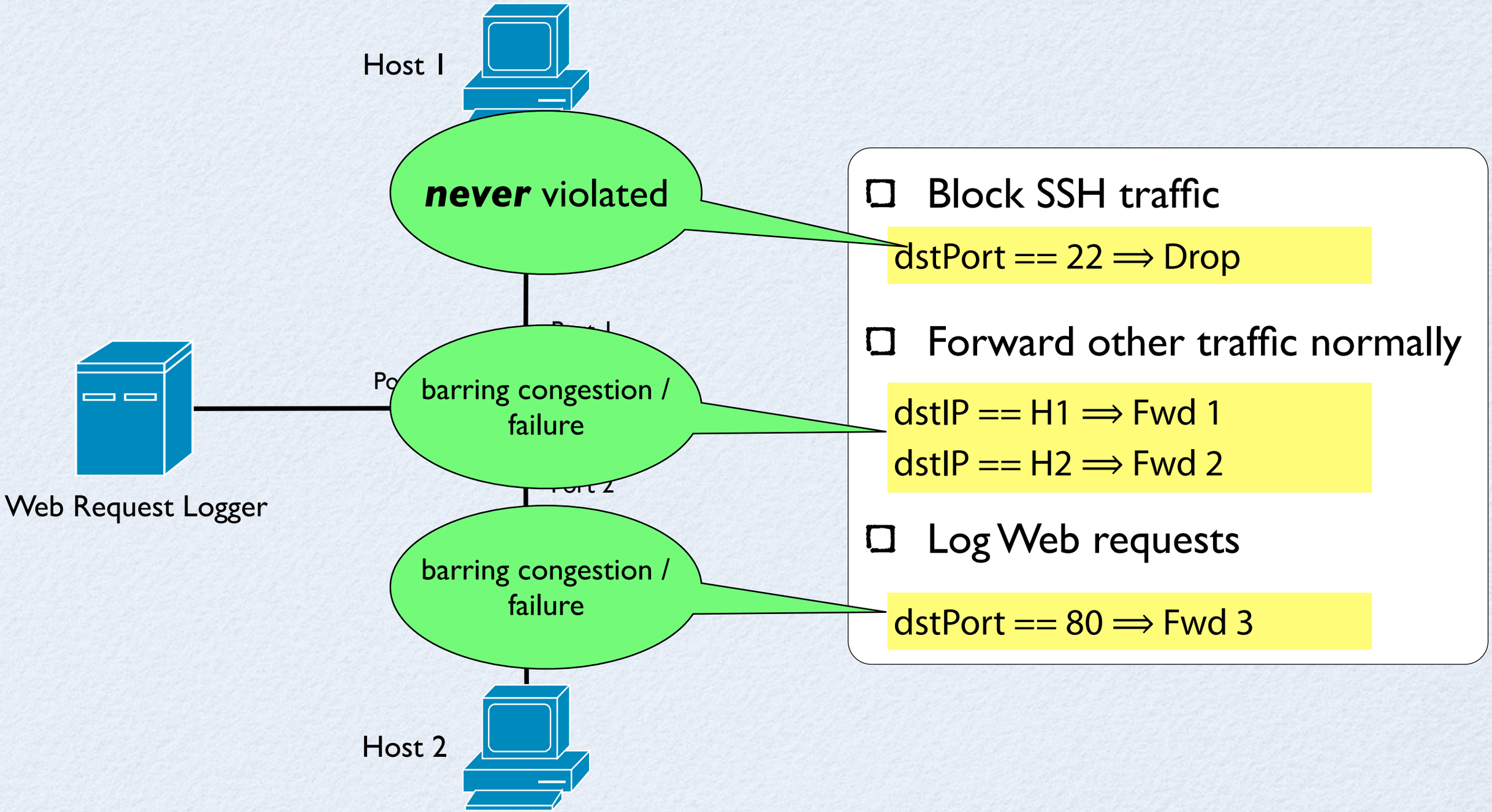

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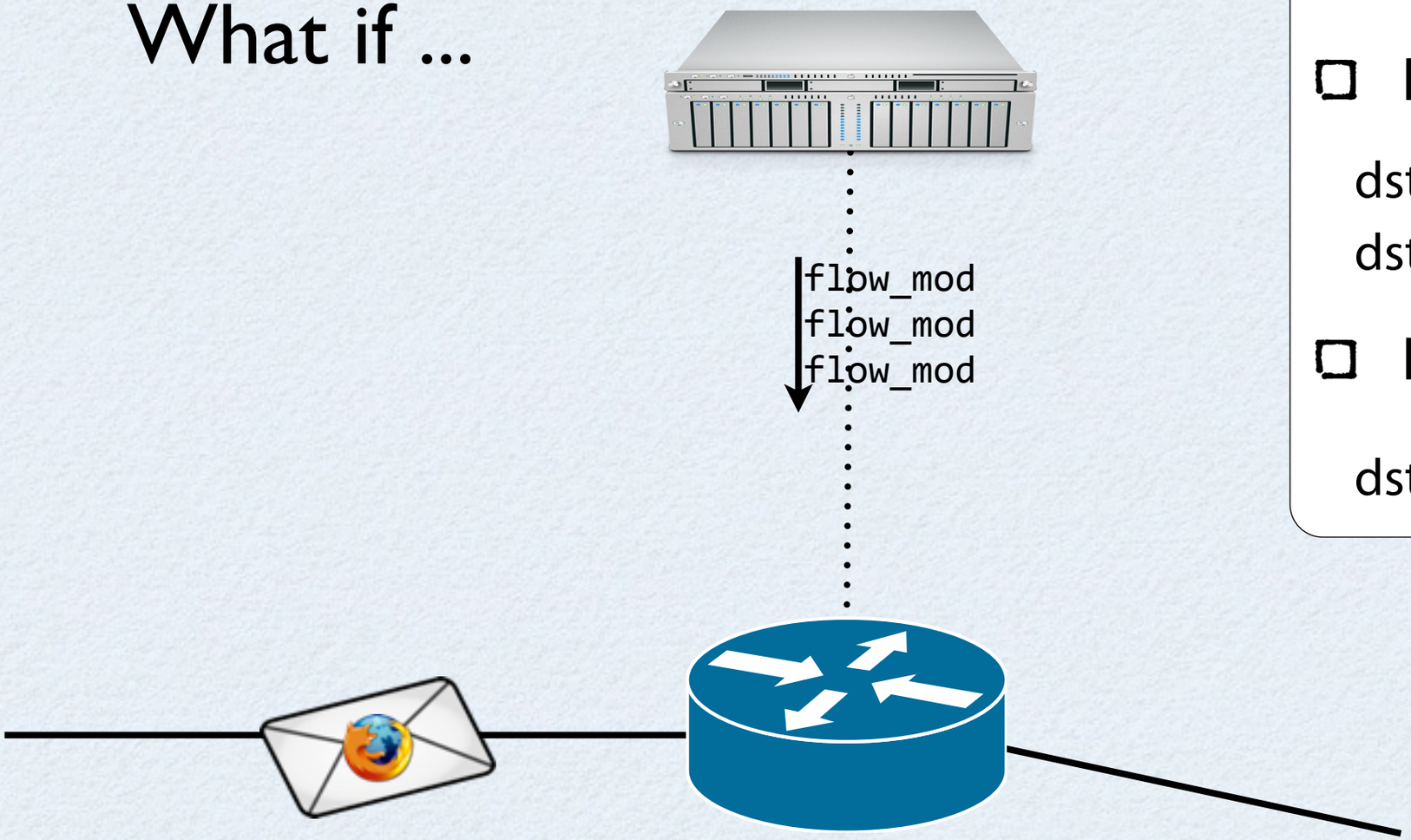

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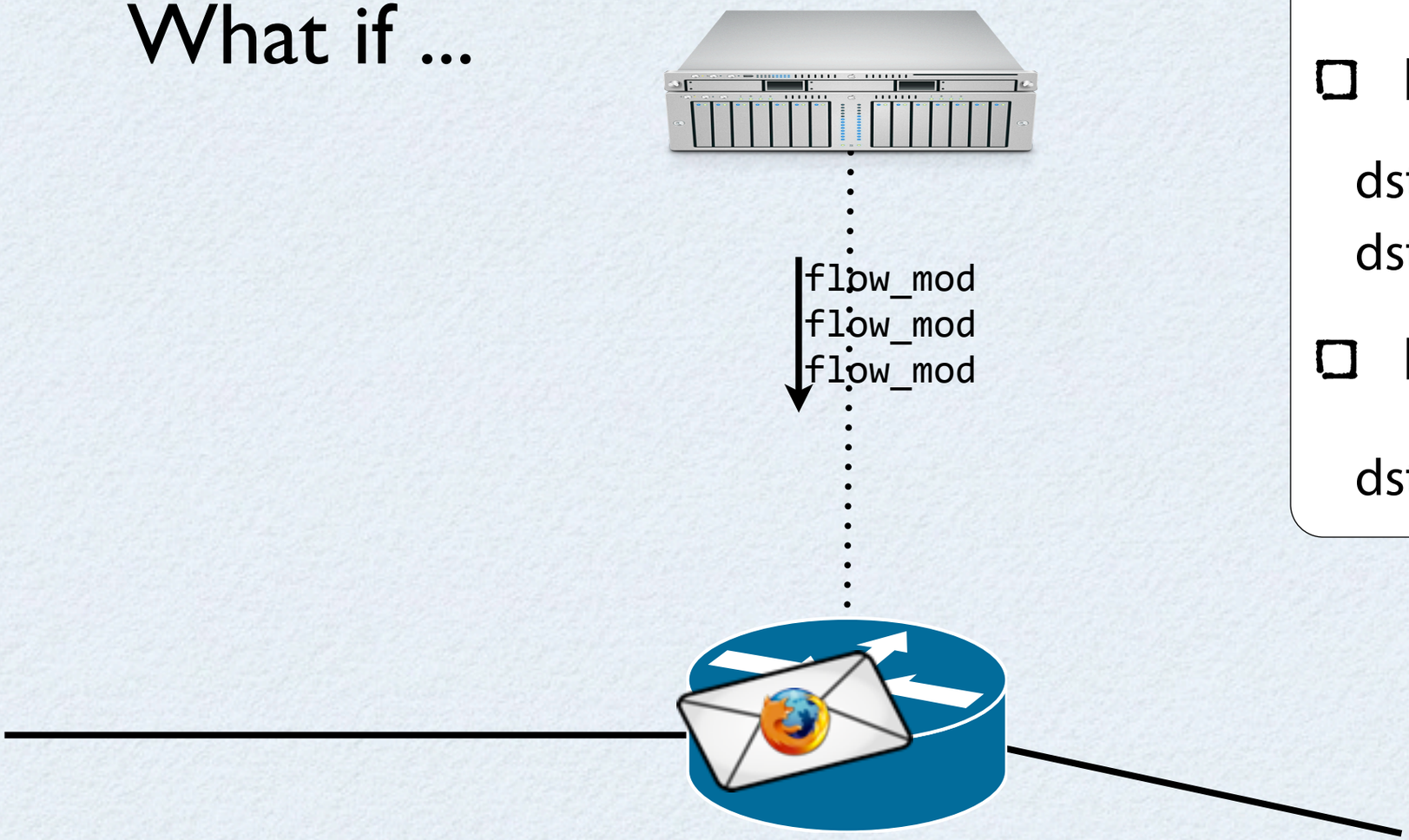

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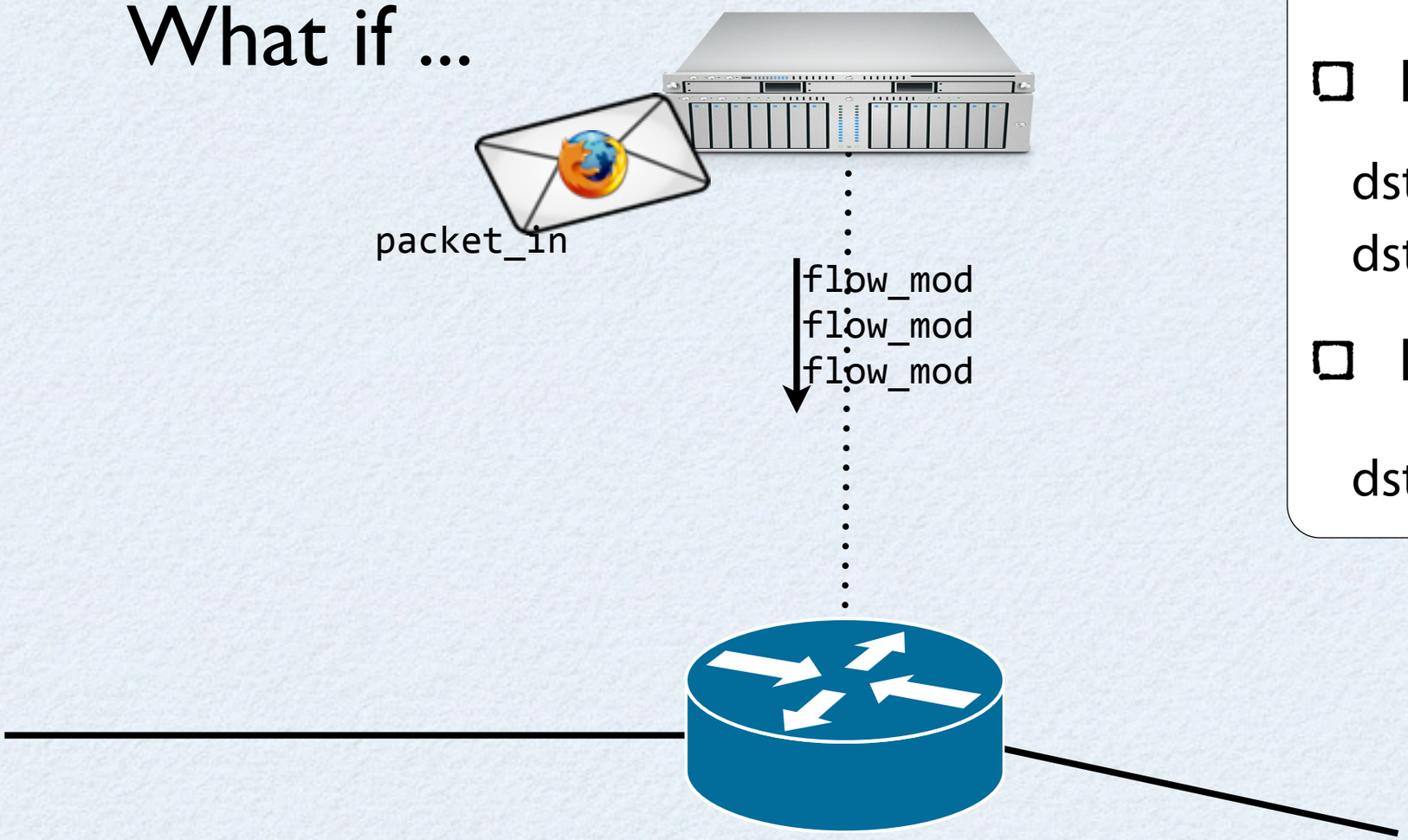

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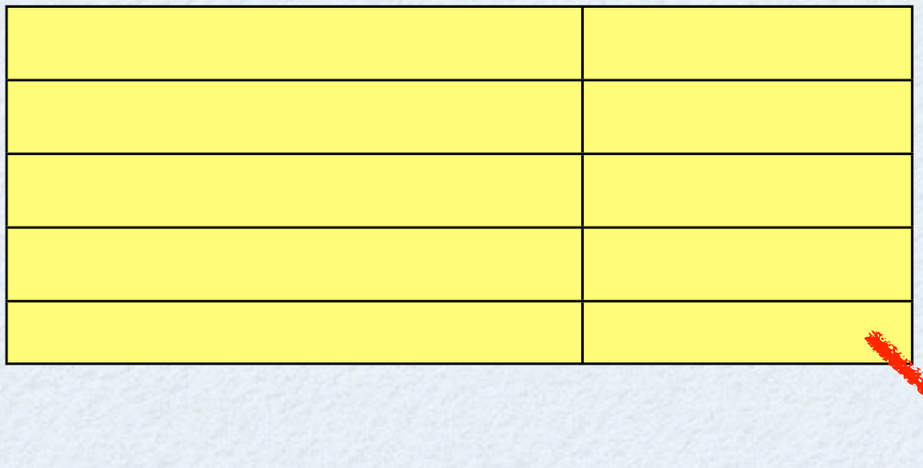

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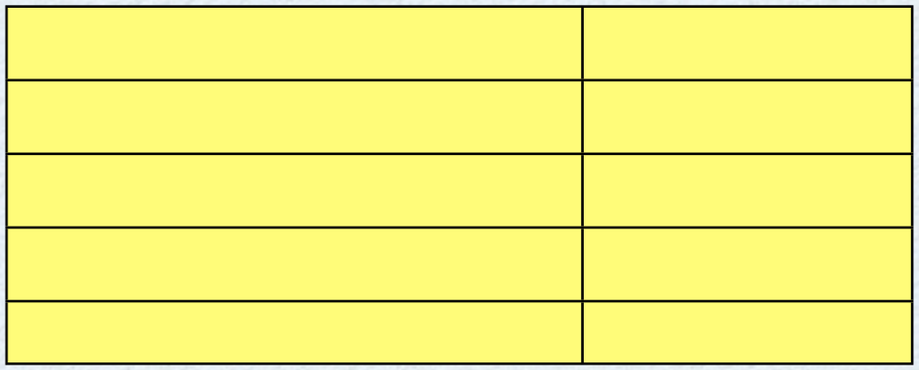

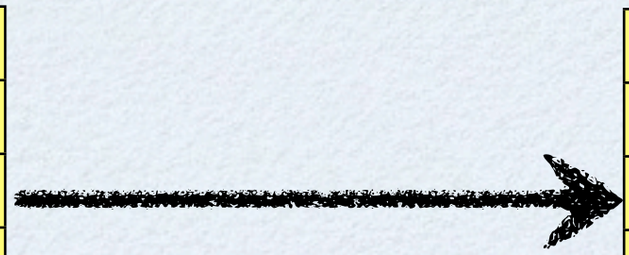

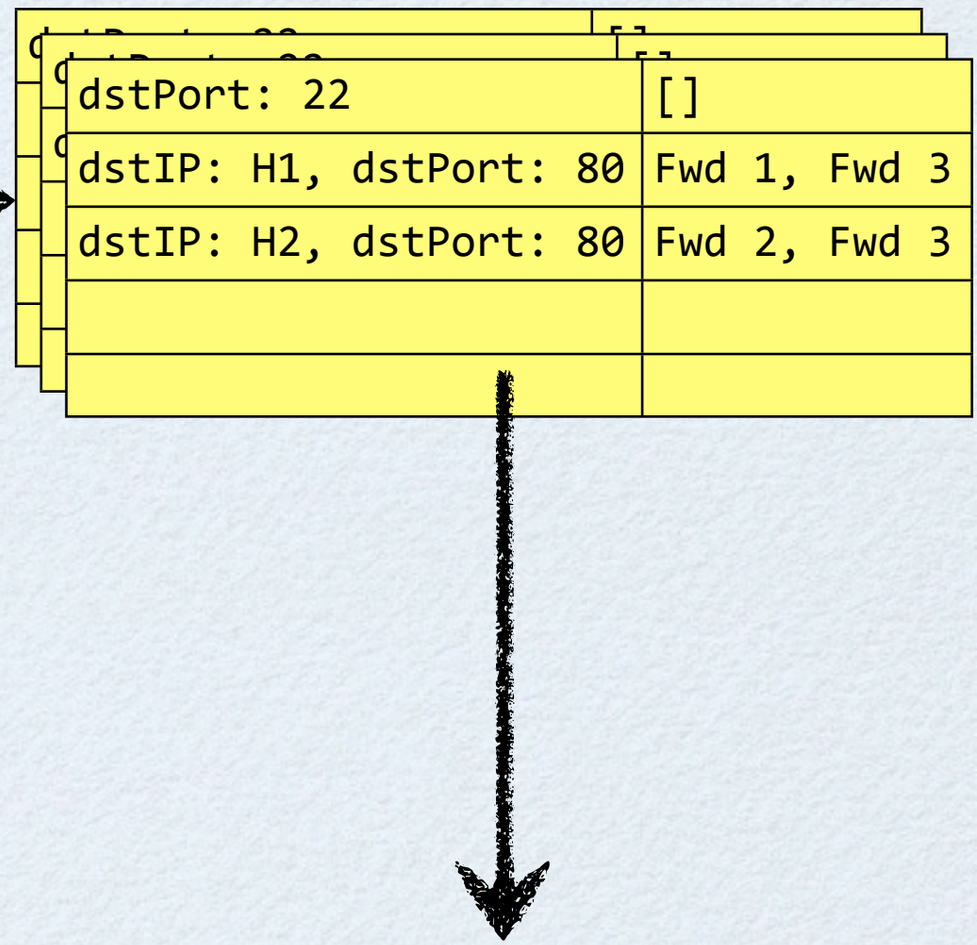

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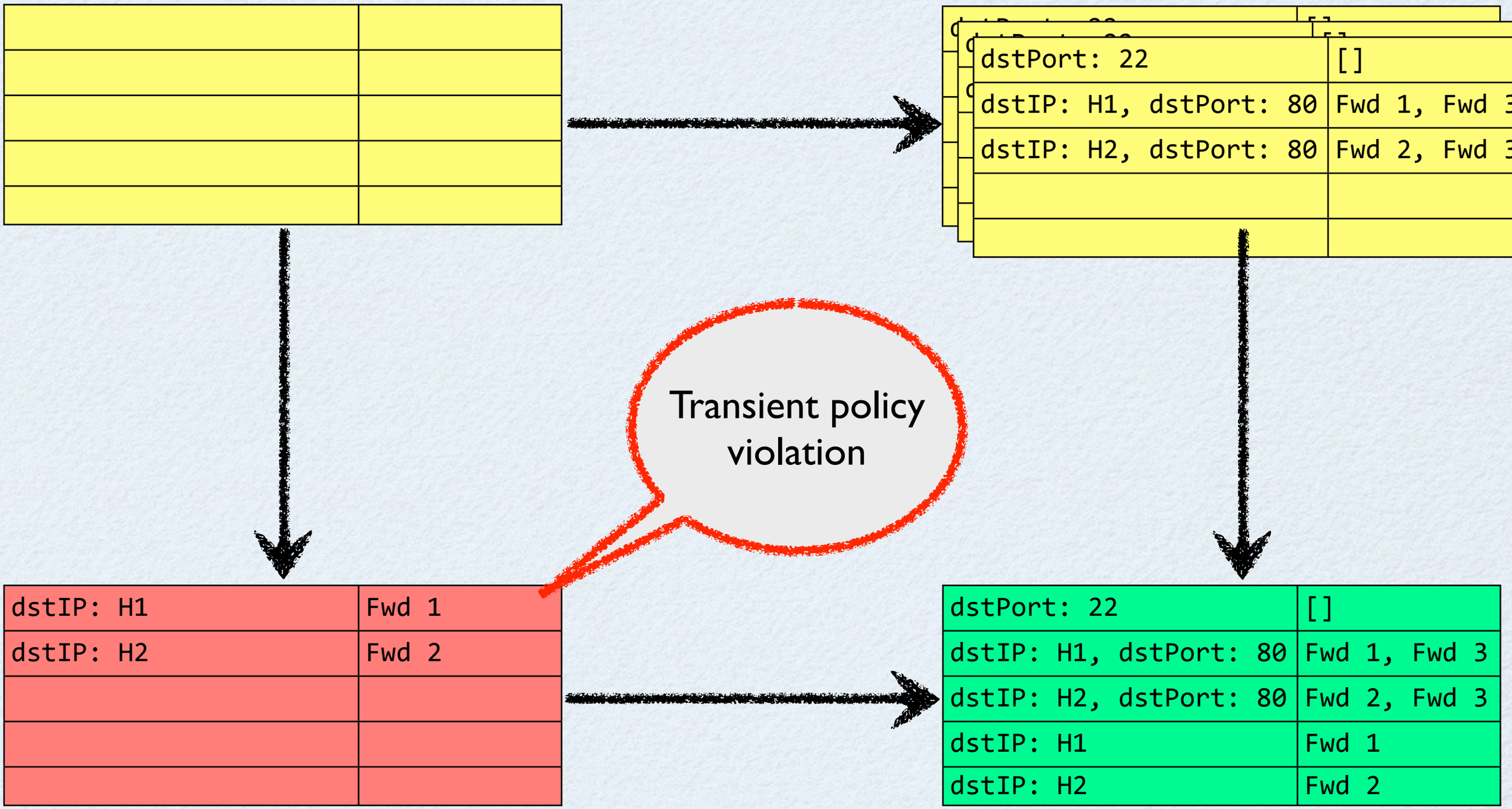

```
def switch_join(sw):
  sw.flow_mod(10, { dstPort: 22 }, [])
  sw.barrier_request()
  sw.flow_mod(9, { dstIP: H1, dstPort: 80 }, [Fwd 1, Fwd 3])
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  sw.flow_mod(9, { dstIP: H2, dstPort: 80 }, [Fwd 2, Fwd 3])
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def packet_in(sw, pkt):
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```

Match *all* packets!?

```
def switch_join(sw):
  sw.flow_mod(10, { eth: 0x800, proto: 6, dstPort: 22 }, [])
  sw.barrier_request()
  sw.flow_mod(9, { eth: 0x800, proto: 6, dstIP: H1, dstPort: 80 }, [Fwd 1, Fwd 3])
  sw.barrier_request()
  sw.flow_mod(9, { eth: 0x800, proto: 6, dstIP: H2, dstPort: 80 }, [Fwd 2, Fwd 3])
  sw.barrier_request()
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  sw.flow_mod(
  sw.barrier_r
  sw.flow_mod(                                          Fwd 1, Fwd 3])
  sw.barrier_r
  sw.flow_mod(                                          Fwd 2, Fwd 3])
  sw.barrier_r
  sw.flow_mod(
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  actions =
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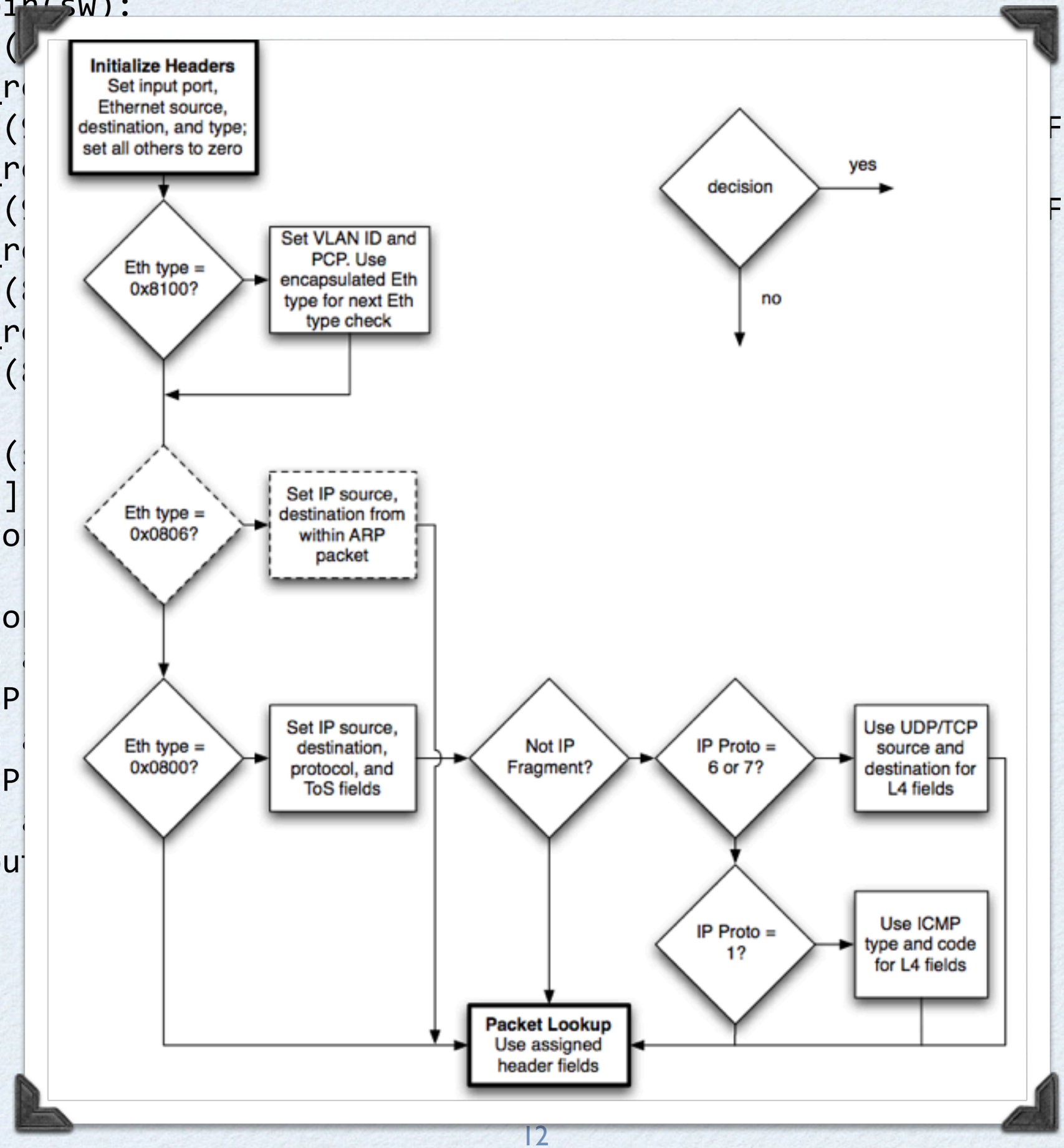

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Violation	**Guilty Controllers**

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handles packet_in incorrectly	

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Violation	**Guilty Controllers**
handles packet_in incorrectly	PANE (absolved)
does not use barriers	

Recap: Bugs in Controllers

Violation	**Guilty Controllers**
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discovered by formalizing OpenFlow

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SDN Facilitates Formal Methods

Run-time Monitoring: VeriFlow

by Khurshid, Zhou, Caesar, and Godfrey

- runtime property checking
- detects errors dynamically
- small runtime overhead
- fixes must be out-of-band

Static Bug-Finding: NICE

by Canini, Venzano, Perešíni, Kostić, and Rexford

- symbolic execution / model checking
- finds several bugs statically
- seconds to days to test, no runtime cost
- cannot prove the absence of bugs

Verified Controllers: this talk

- program verification
- proof of correctness
- no runtime cost
- proof *w.r.t.* a detailed model of OpenFlow

VeriFlow: Reachability

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VeriFlow: Reachability

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liveness:
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"acceptable violation"?

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optimizer breaks flow tables	

assumes FIFO message processing

requires high-level policy

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A Sample of Recent Verification

Successes:

Tools:

Textbooks:

A Sample of Recent Verification

Successes:

Operating Systems	Compilers
seL4 SOSP 2009	CompCert CACM, July 2009
Verve PLDI 2010	F* POPL 2012

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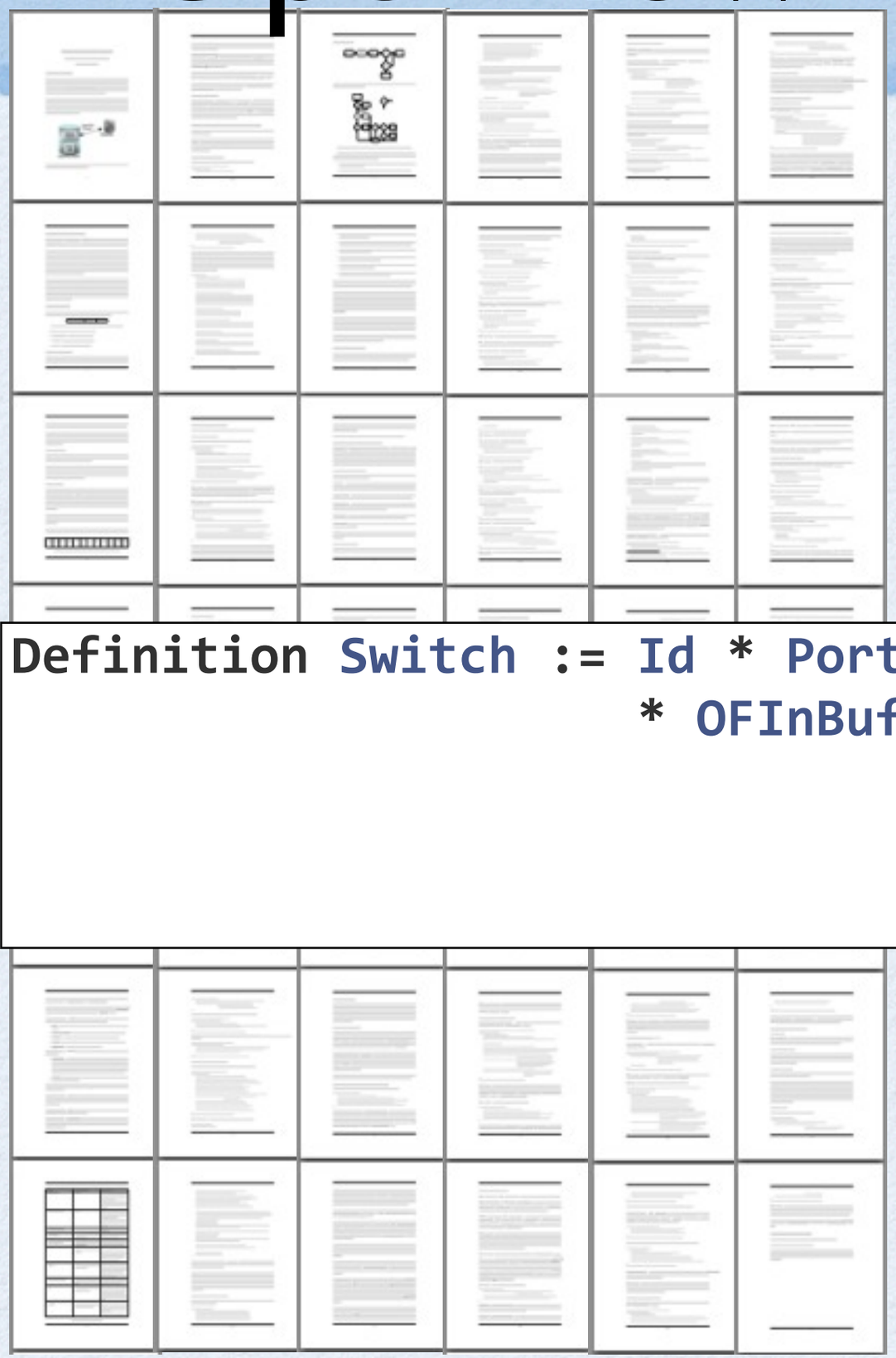
Certified Programming with Dependent Types

Mathematical Foundations of SDN

OpenFlow 1.0 specification

42 pages of prose and C structs ...

OpenFlow 1.0 specification



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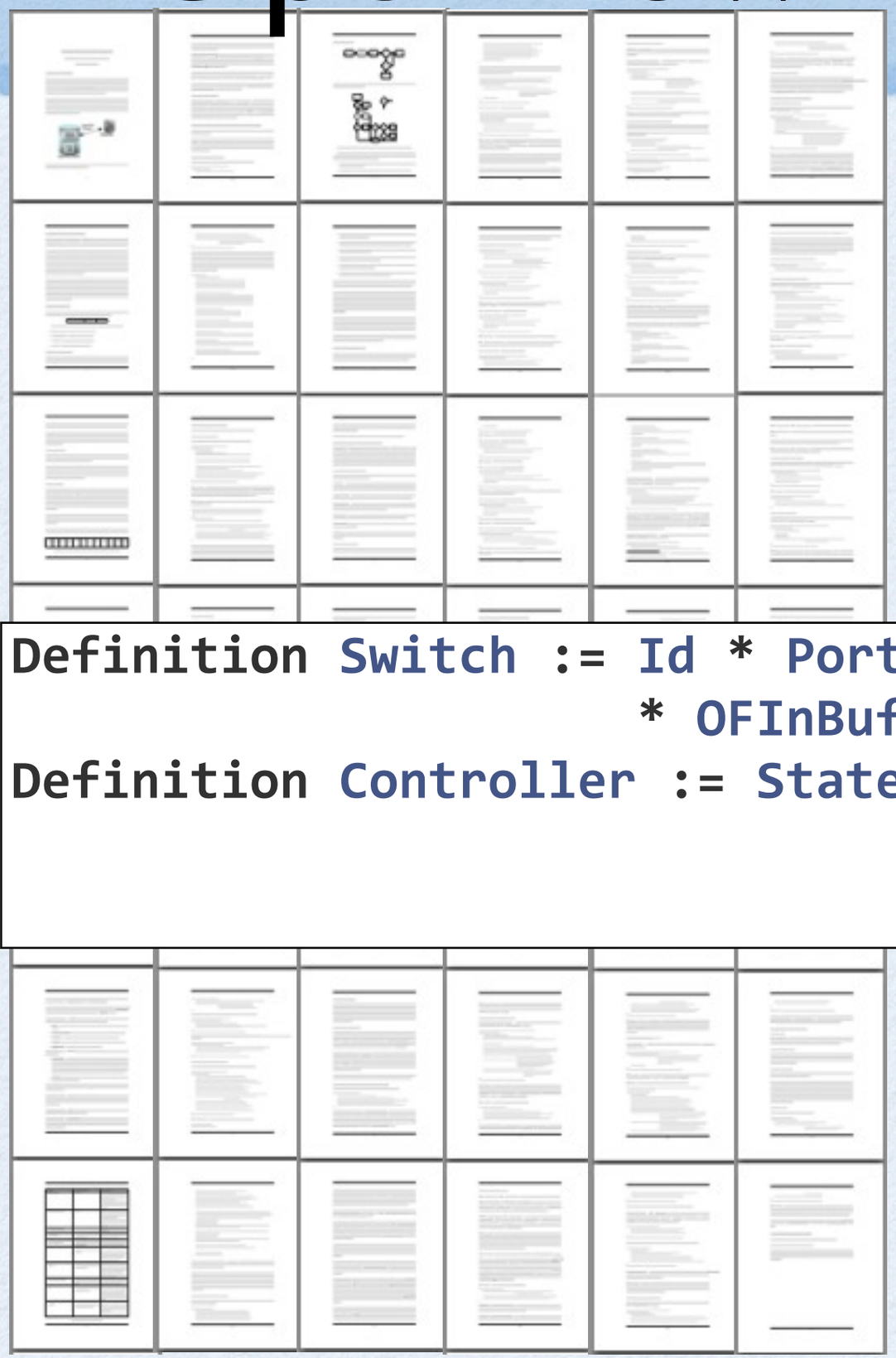
OpenFlow 1.0 specification



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Definition Switch := Id * Ports * FlowTbl * InBuf * OutBuf
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Definition Controller := State * InFunc * OutFunc.
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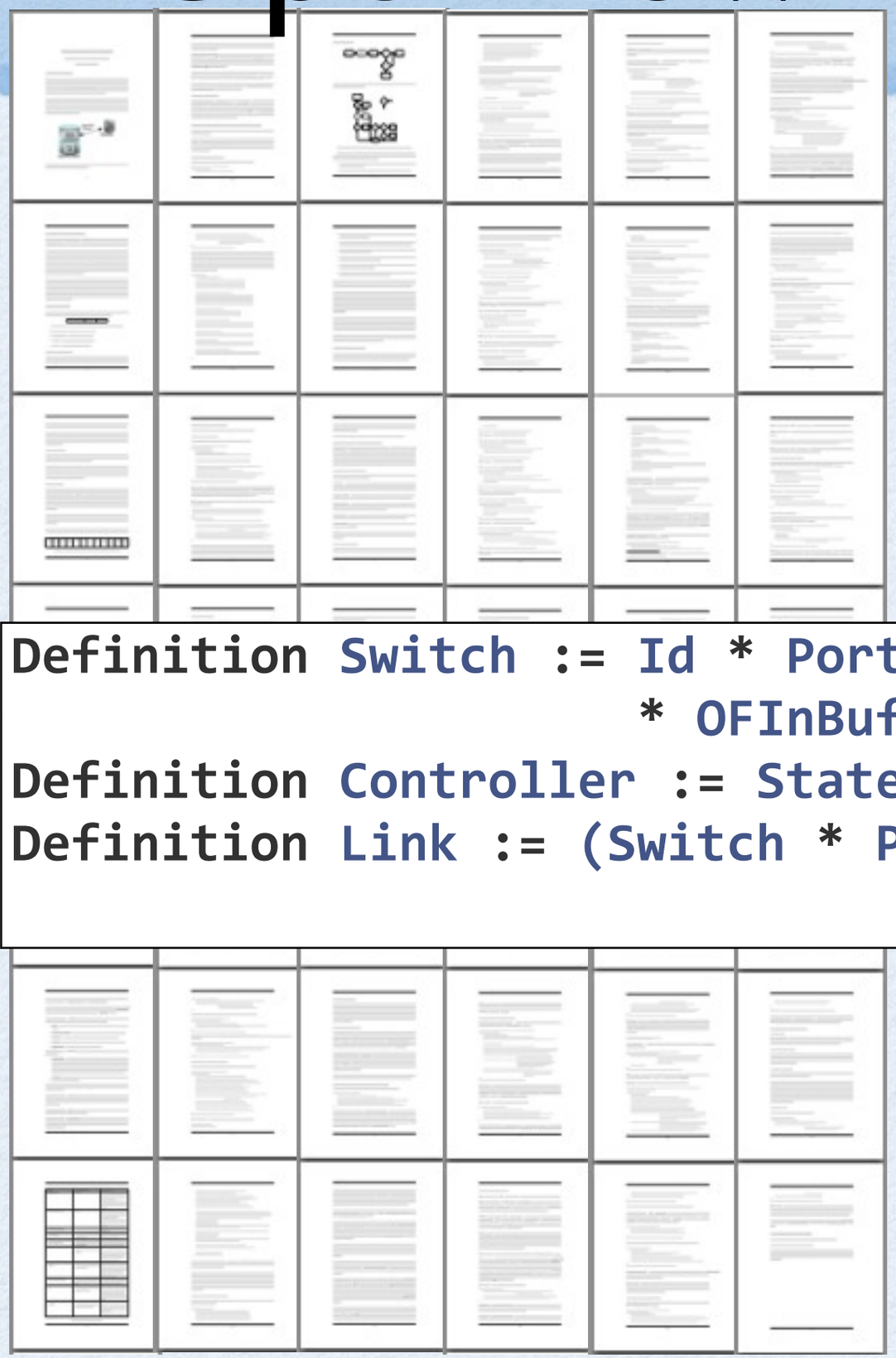

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```
Definition Switch := Id * Ports * FlowTbl * InBuf * OutBuf
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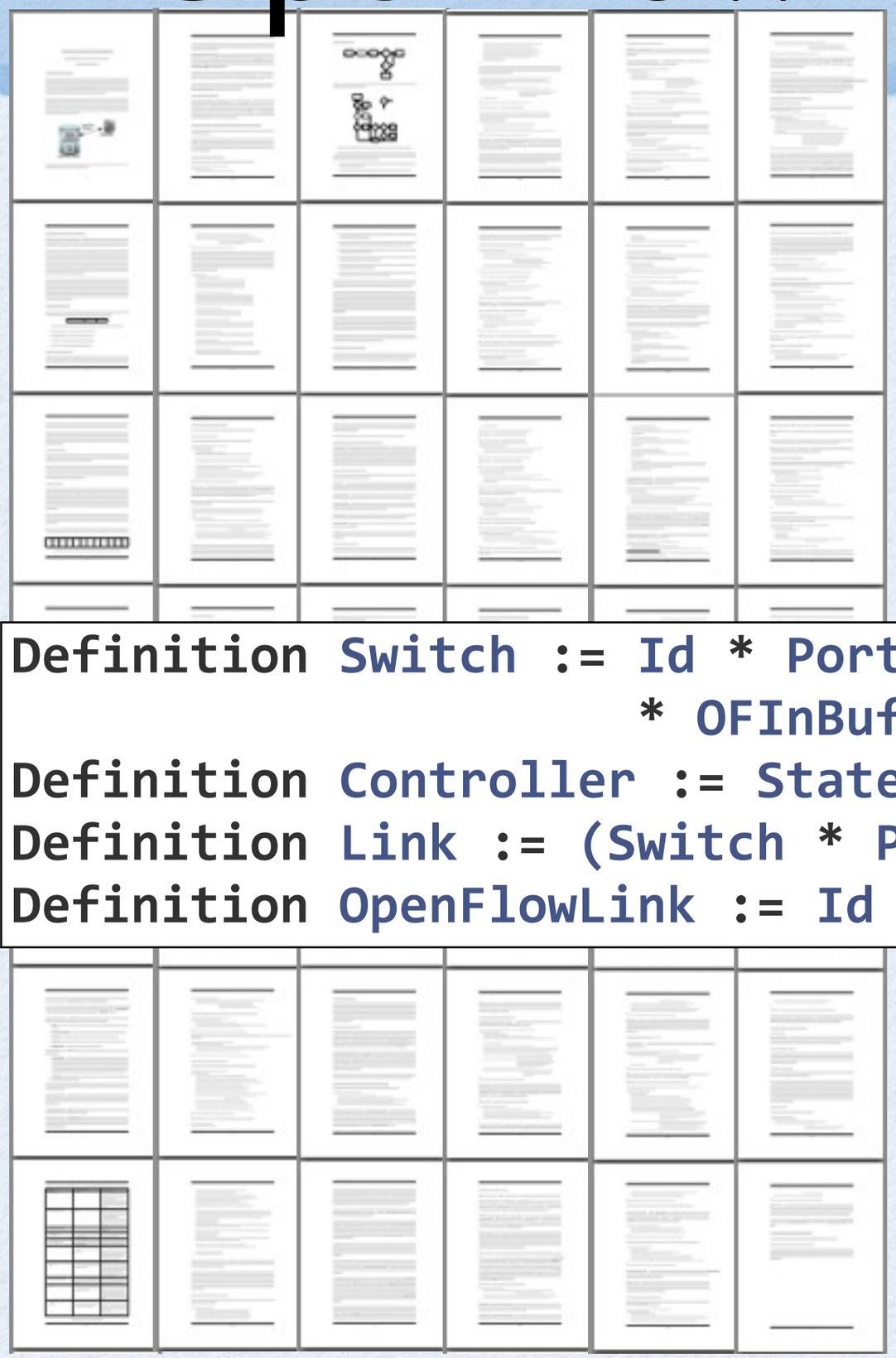
Definition Controller := State * InFunc * OutFunc.
Definition Link := (Switch * Port) * list Packet * (Switch * Port).
```

OpenFlow 1.0 specification



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Definition Link := (Switch * Port) * list Packet * (Switch * Port).
Definition OpenFlowLink := Id * list SwitchMsg * list CtrlMsg.
```

```c
/* Fields to match against flows */
struct ofp_match {
    uint32_t wildcards;         /* Wildcard fields. */
    uint16_t in_port;           /* Input switch port. */
    uint8_t dl_src[OFP_ETH_ALEN]; /* Ethernet source address. */
    uint8_t dl_dst[OFP_ETH_ALEN]; /* Ethernet destination address. */
    uint16_t dl_vlan;           /* Input VLAN. */
    uint8_t dl_vlan_pcp;        /* Input VLAN priority. */
    uint8_t pad1[1];            /* Align to 64-bits. */
    uint16_5 dl_type;           /* Ethernet frame type. */
    uint8_t nw_tos;             /* IP ToS (DSCP field, 6 bits). */
    uint8_t nw_proto;           /* IP protocol or lower 8 bits of
                                   ARP opcode. */
    uint8_t pad2[2];            /* Align to 64-bits. */
    uint32_t nw_src;            /* IP source address. */
    uint32_t nw_dst;            /* IP destination address. */
    uint16_t tp_src;            /* TCP/UDP source port. */
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};
OFP_ASSERT(sizeof(struct ofp_match) == 40);
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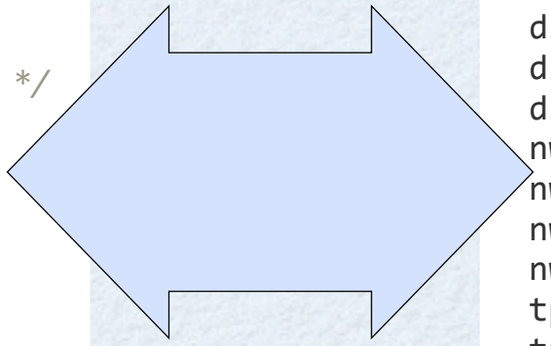

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  dlSrc : Wildcard EthernetAddress;
  dlDst : Wildcard EthernetAddress;
  dlType : Wildcard EthernetType;
  dlVlan : Wildcard VLAN;
  dlVlanPcp : Wildcard VLANPriority;
  nwSrc : Wildcard IPAddress;
  nwDst : Wildcard IPAddress;
  nwProto : Wildcard IPProtocol;
  nwTos : Wildcard IPTypeOfService;
  tpSrc : Wildcard TransportPort;
  tpDst : Wildcard TransportPort;
  inPort : Wildcard Port
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```

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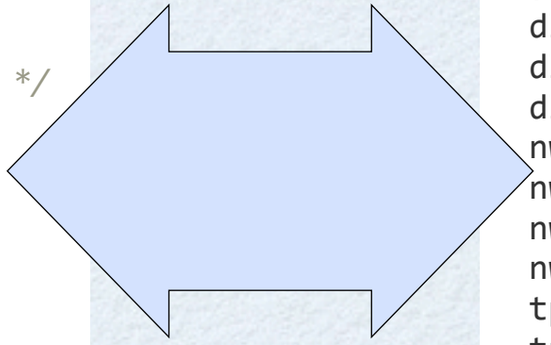

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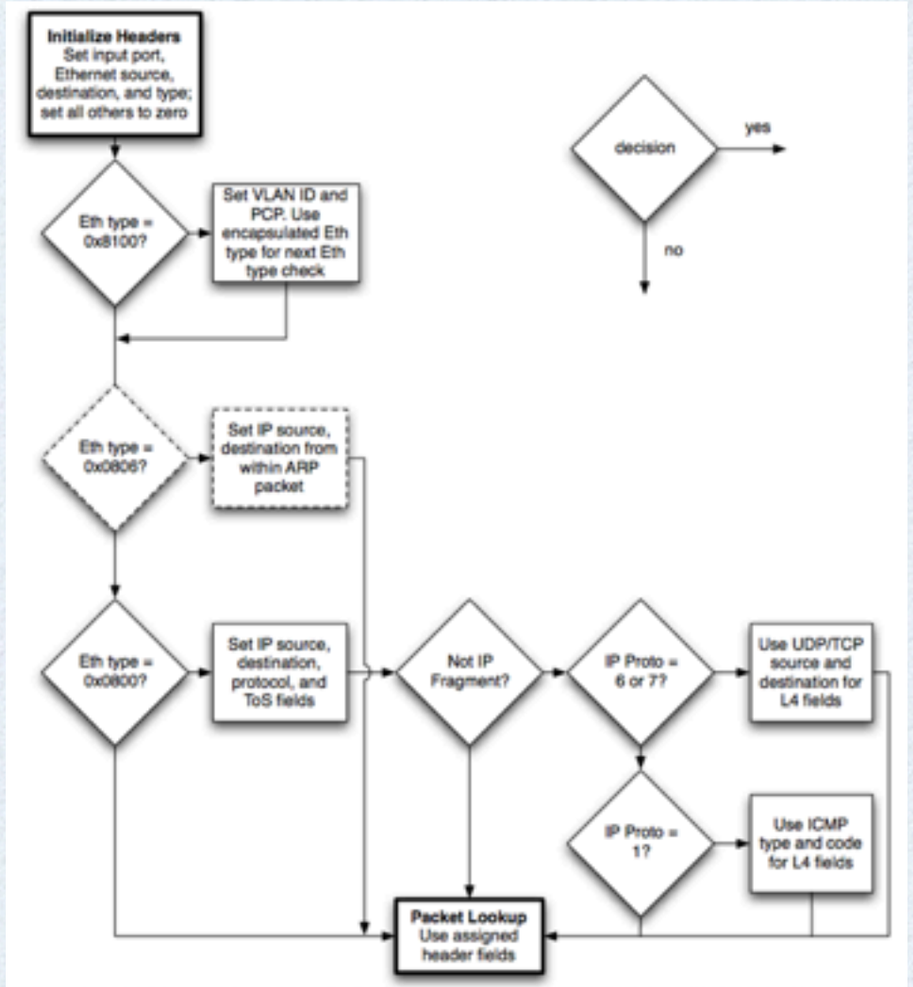

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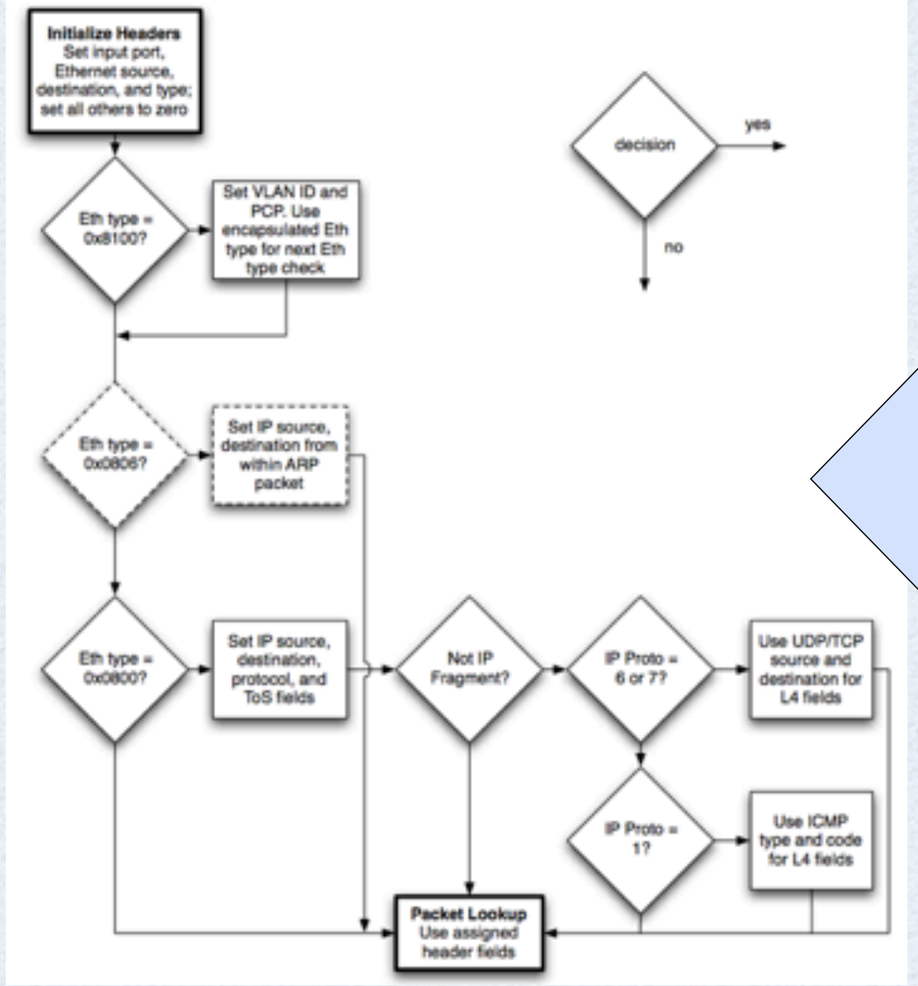


```
Definition Pattern_inter (p p':Pattern) :=
  let dlSrc := Wildcard_inter EthernetAddress.eqdec (ptrnDlSrc p) (ptrnDlSrc p') in
  let dlDst := Wildcard_inter EthernetAddress.eqdec (ptrnDlDst p) (ptrnDlDst p') in
  let dlType := Wildcard_inter Word16.eqdec (ptrnDlType p) (ptrnDlType p') in
  let dlVlan := Wildcard_inter Word16.eqdec (ptrnDlVlan p) (ptrnDlVlan p') in
  let dlVlanPcp := Wildcard_inter Word8.eqdec (ptrnDlVlanPcp p) (ptrnDlVlanPcp p') in
  let nwSrc := Wildcard_inter Word32.eqdec (ptrnNwSrc p) (ptrnNwSrc p') in
  let nwDst := Wildcard_inter Word32.eqdec (ptrnNwDst p) (ptrnNwDst p') in
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Definition exact_pattern (pk : Packet) (pt : Word16.T) : Pattern :=
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    (Wildcard_of_option (pktTpSrc pk))
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    (WildcardExact pt).

Definition match_packet (pt : Word16.T) (pk : Packet) (pat : Pattern) : bool :=
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```

detailed model of matching, forwarding, and flow table update

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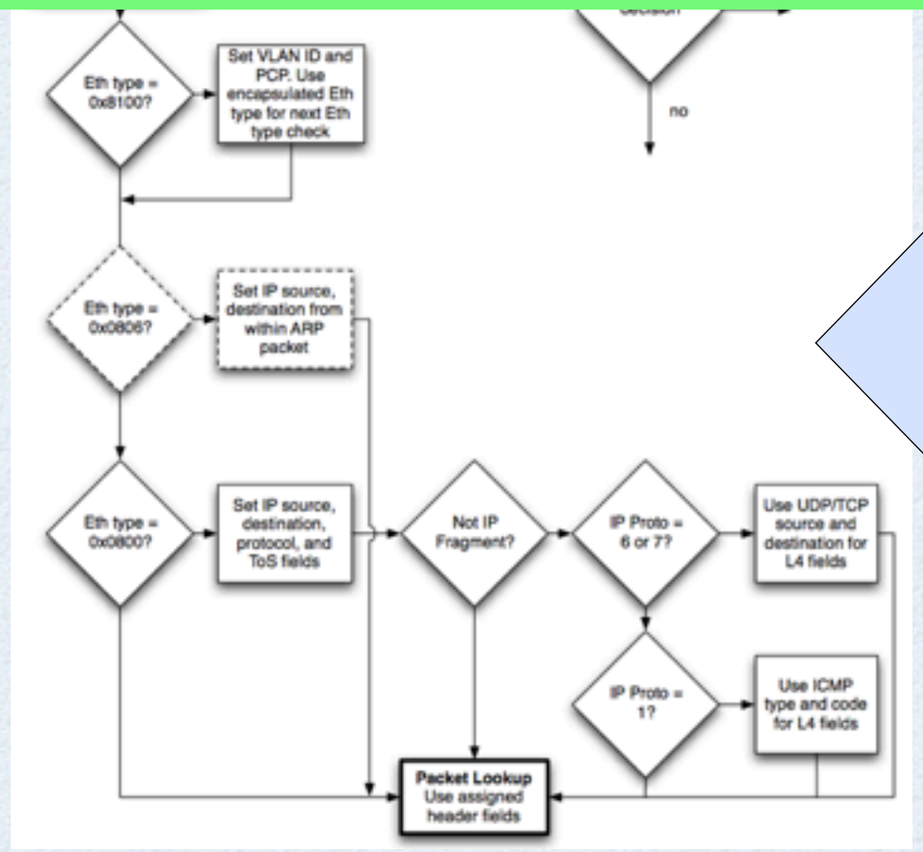


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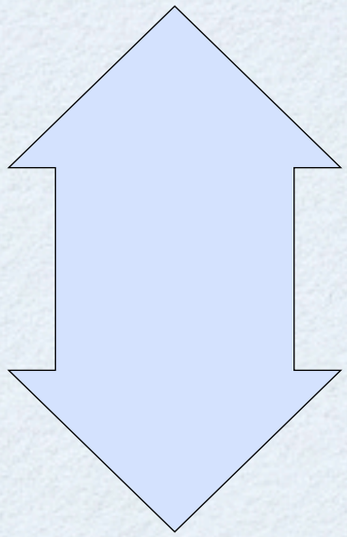

```
Definition InBuf := MultiSet Packet.
Definition OutBuf := MultiSet Packet.
Definition OFInBuf := MultiSet SwitchMsg.
Definition OFOutBuf := MultiSet CtrlMsg.
```

"In the absence of barrier messages, switches may arbitrarily reorder messages to maximize performance."

"There is no packet output ordering guaranteed within a port."

essential asynchrony: packet buffers, message reordering, and barriers

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Definition InBuf := MultiSet Packet.
Definition OutBuf := MultiSet Packet.
Definition OFInBuf := MultiSet SwitchMsg.
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```

State : abstract type

f_{out} : State → Switch × CtrlMsg × State'

f_{in} : Switch × SwitchMsg × State → State'

controller model: fully abstract

Featherweight OpenFlow

- ☑ detailed model of matching, forwarding, and flow table update
- ☑ essential asynchrony: packet buffers, message reordering, and barriers
- ☑ controller model: fully abstract

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Only possible because the specification is simple and open

Featherweight OpenFlow

☑ detailed model of matching, forwarding, and flow table update

☑ essential asynchrony: packet buffers, message reordering, and barriers

☑ controller model: fully abstract

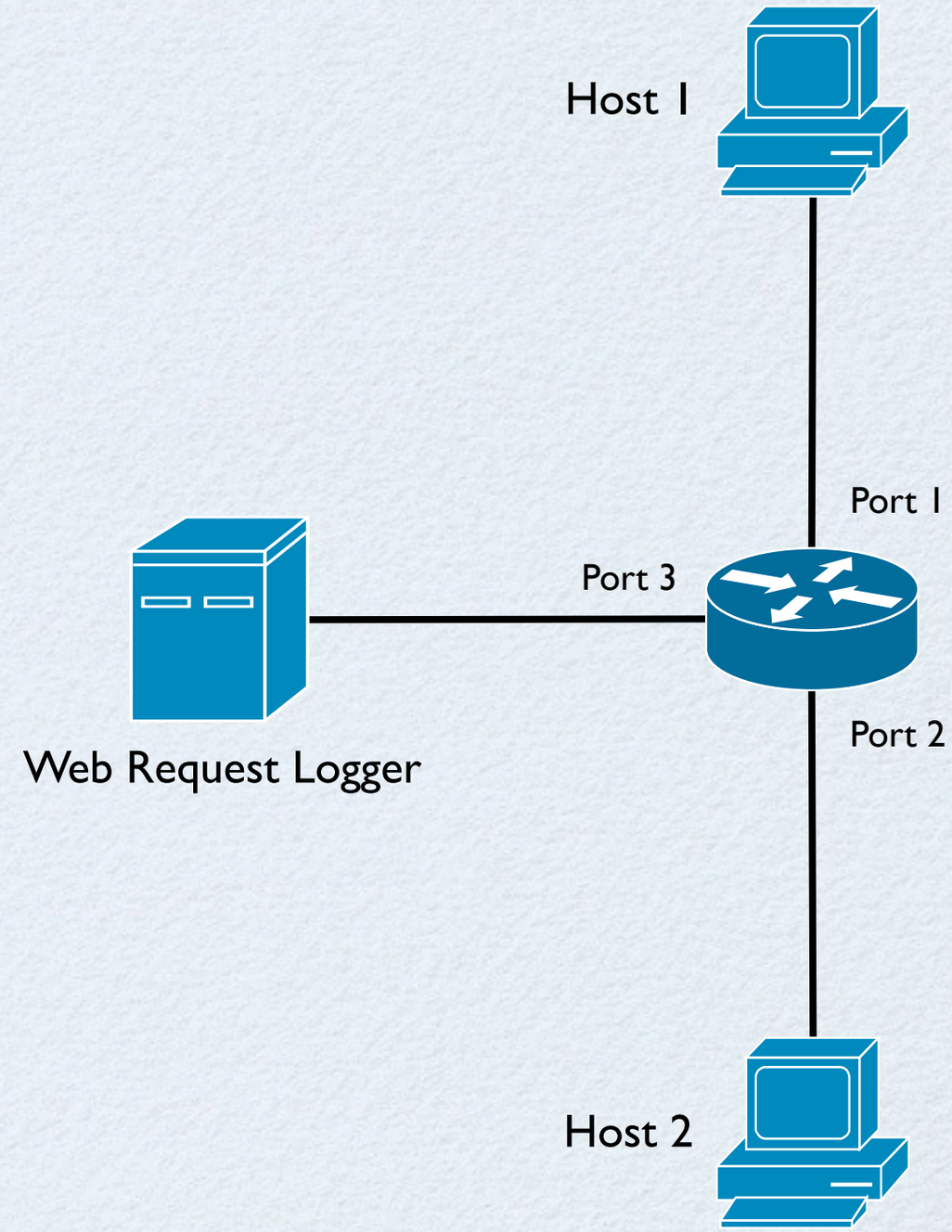
Only possible because the specification is simple and open

- **Future Work:** counters and failures
- **Intentionally Omitted** serializing OpenFlow messages

A Verified Controller

Desired Policy:

- ☐ Block SSH traffic
- ☐ Forward other traffic normally
- ☐ Log Web requests



Desired Policy:

- ☐ Block SSH traffic
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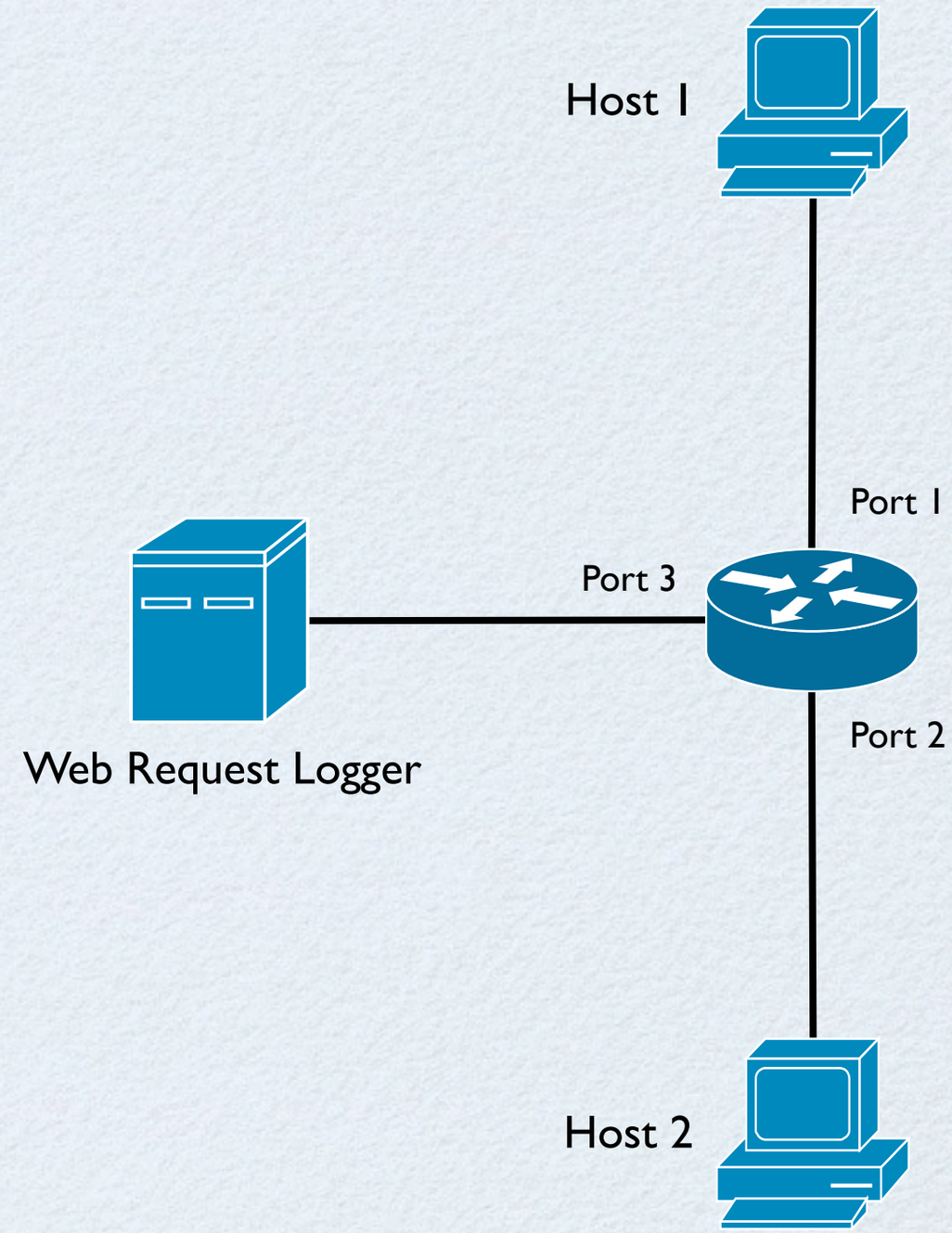
Desired Flow Table:

`dstPort: 22`	`[]`
`dstIP: H1, dstPort: 80`	`Fwd 1, Fwd 3`
`dstIP: H2, dstPort: 80`	`Fwd 2, Fwd 3`
`dstIP: H1`	`Fwd 1`
`dstIP: H2`	`Fwd 2`



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Desired Flow Table:

`dstPort: 22`	`[]`
`dstIP: H1, dstPort: 80`	`Fwd 1, Fwd 3`
`dstIP: H2, dstPort: 80`	`Fwd 2, Fwd 3`
`dstIP: H1`	`Fwd 1`
`dstIP: H2`	`Fwd 2`

Actual Controller ...

```
def switch_join(sw):
  sw.flow_mod(10, { eth: 0x800, proto: 6, dstPort: 22 }, [])
  sw.barrier_request()
  sw.flow_mod(9, { eth: 0x800, proto: 6, dstIP: H1, dstPort: 80 }, [Fwd 1, Fwd 3])
  sw.barrier_request()
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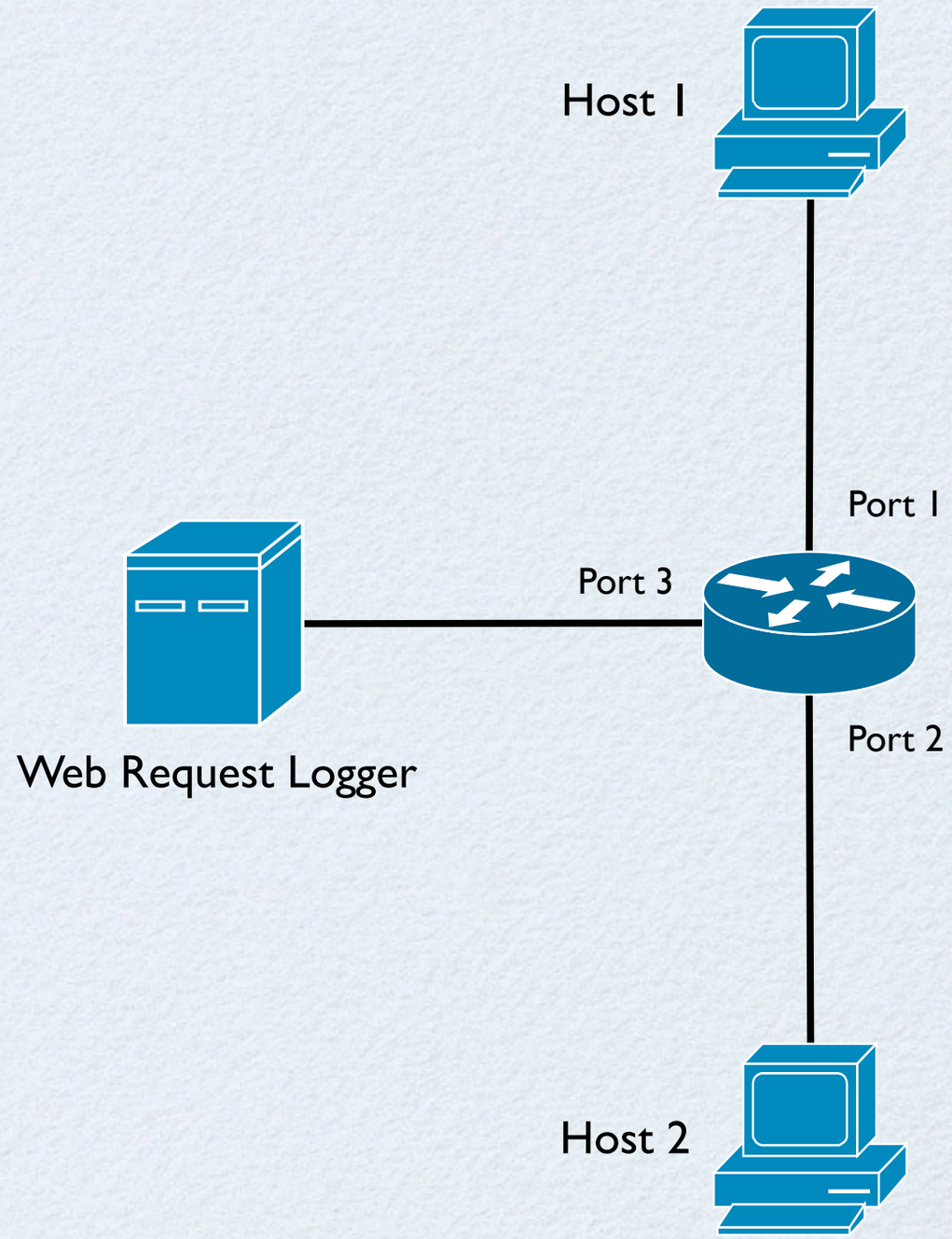

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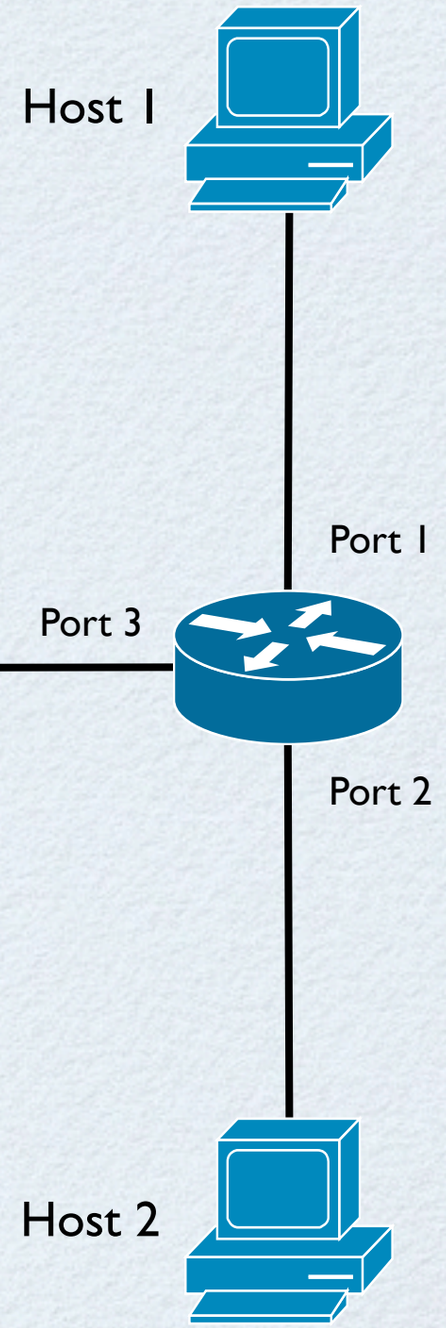

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formally verified

- ☑ Barriers
- ☑ packet_in handler
- ☑ Frame type / protocol numbers
- ☑ transparent optimizations

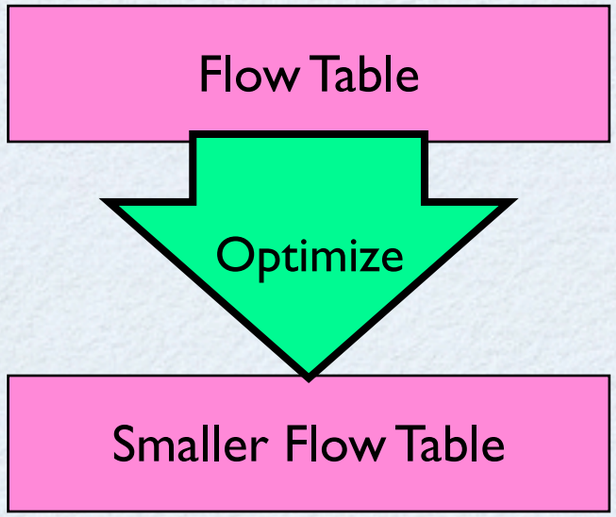
verified code

serialization and physical network

Flow Table

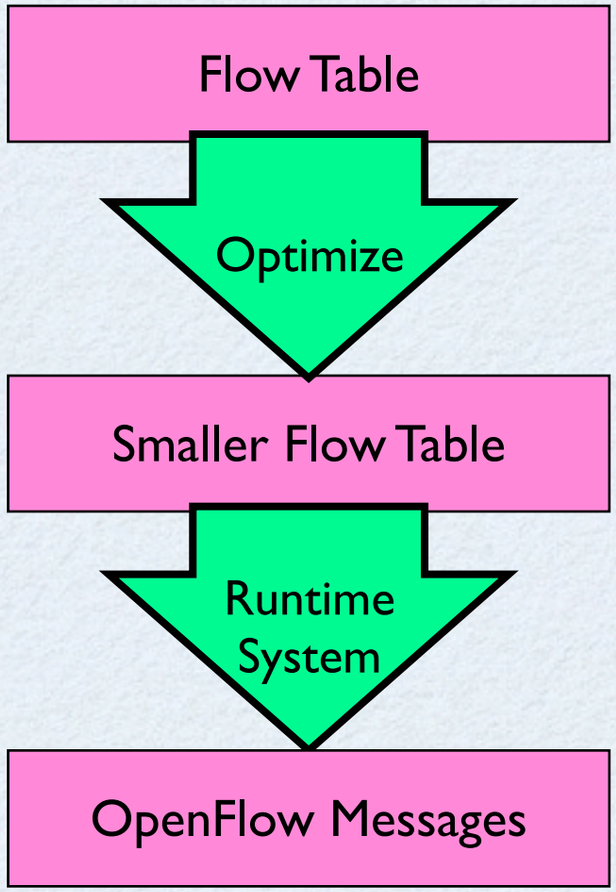
verified code

serialization and physical network



verified code

serialization and physical network



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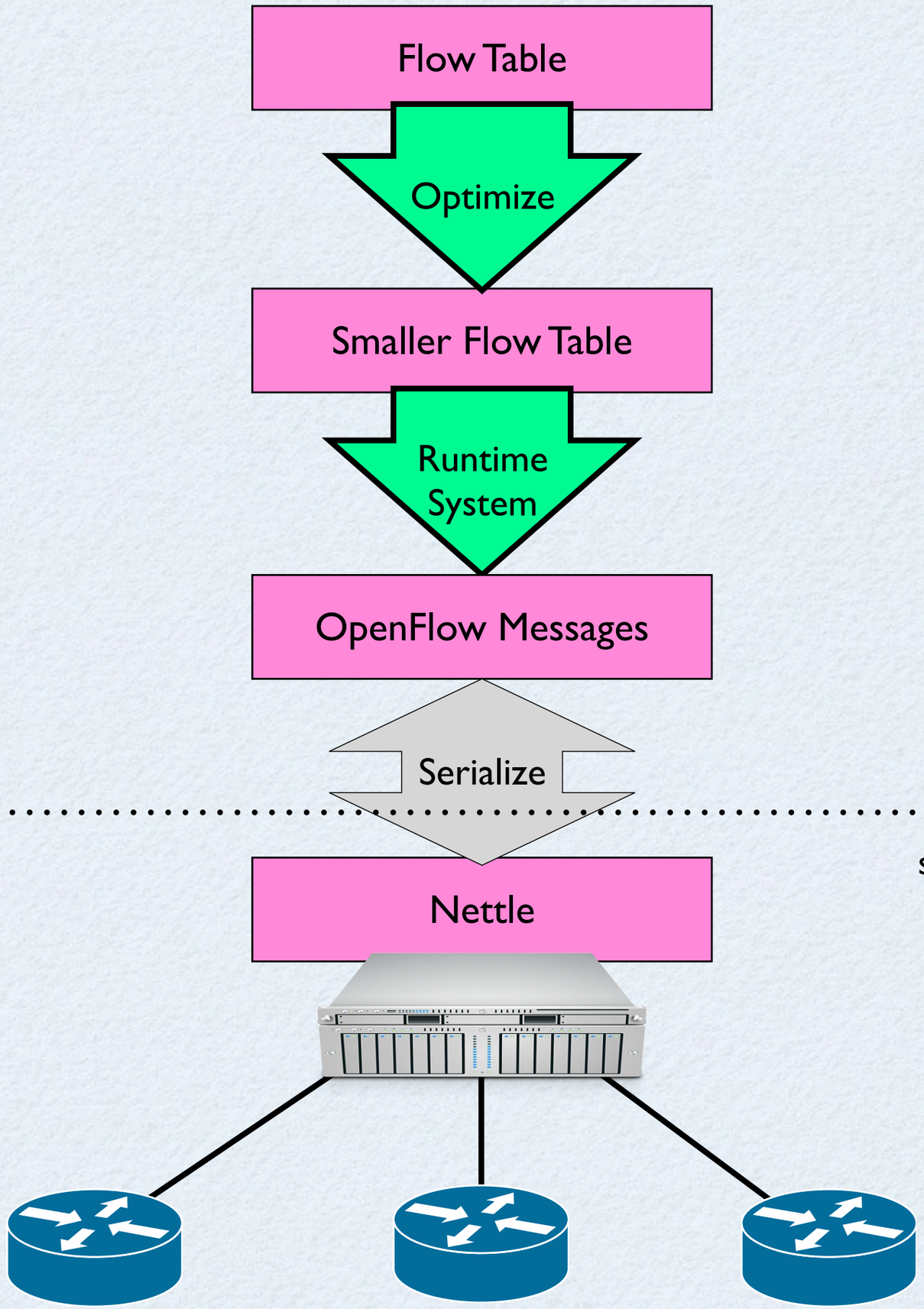

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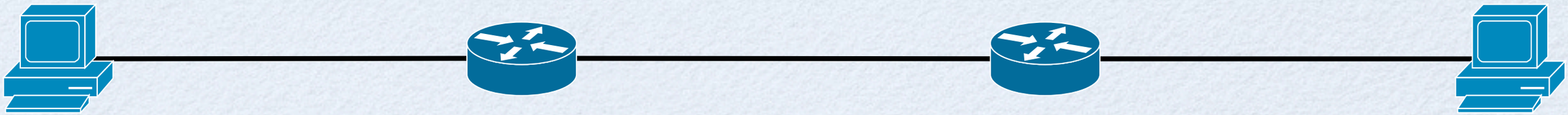
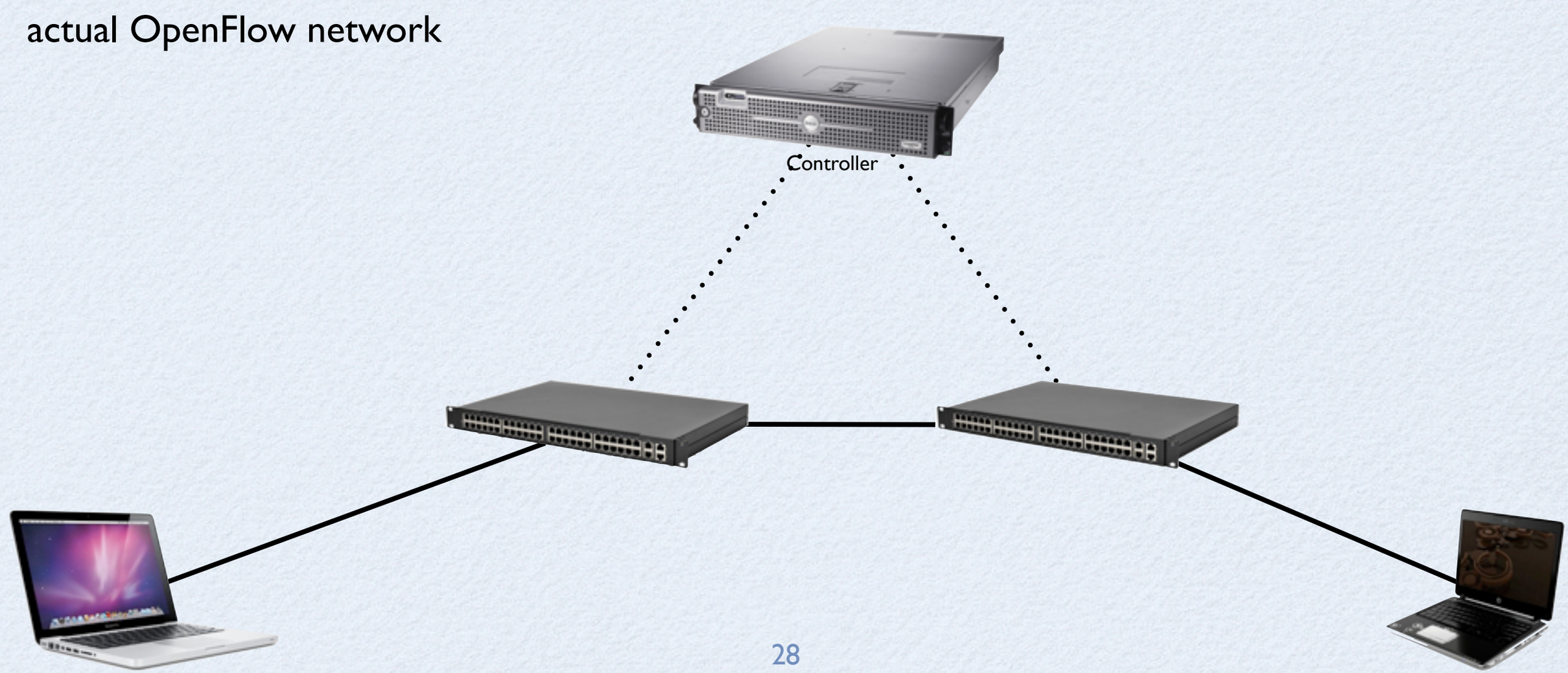
serialization and physical network

Bisimulation

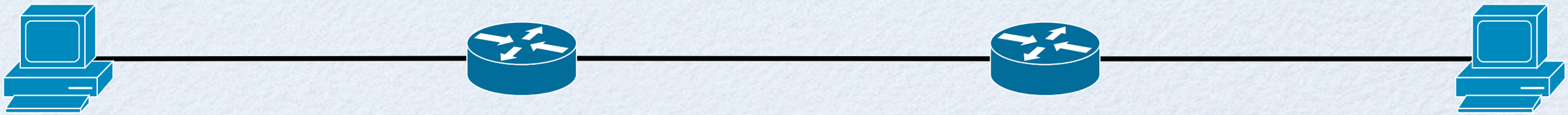


abstract model

actual OpenFlow network



Bisimulation



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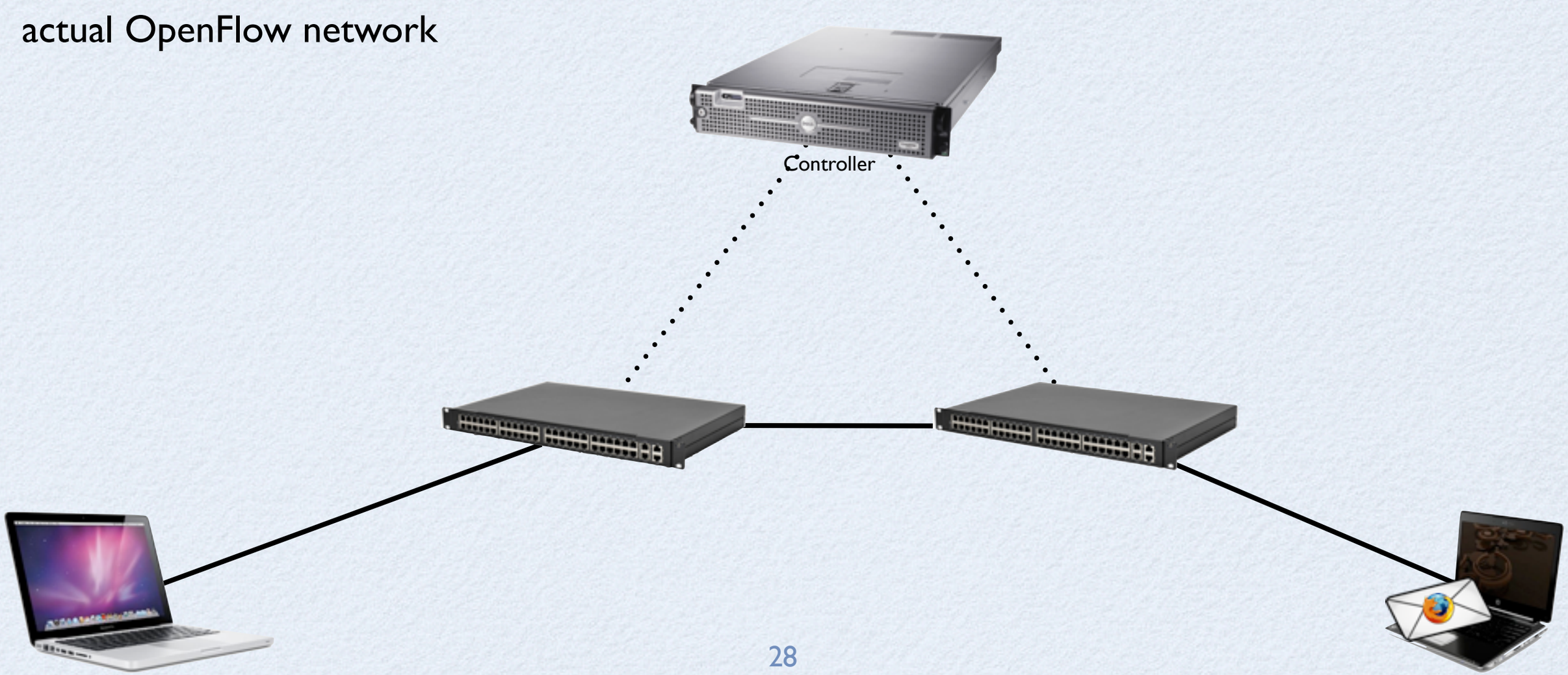

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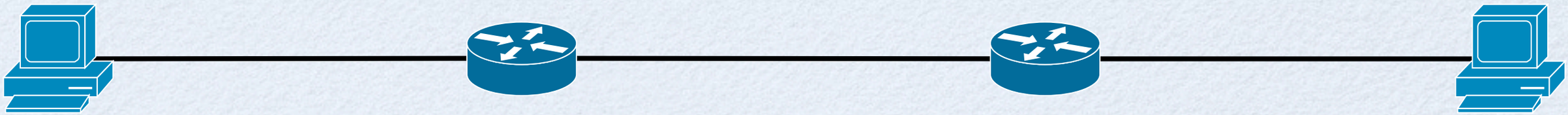

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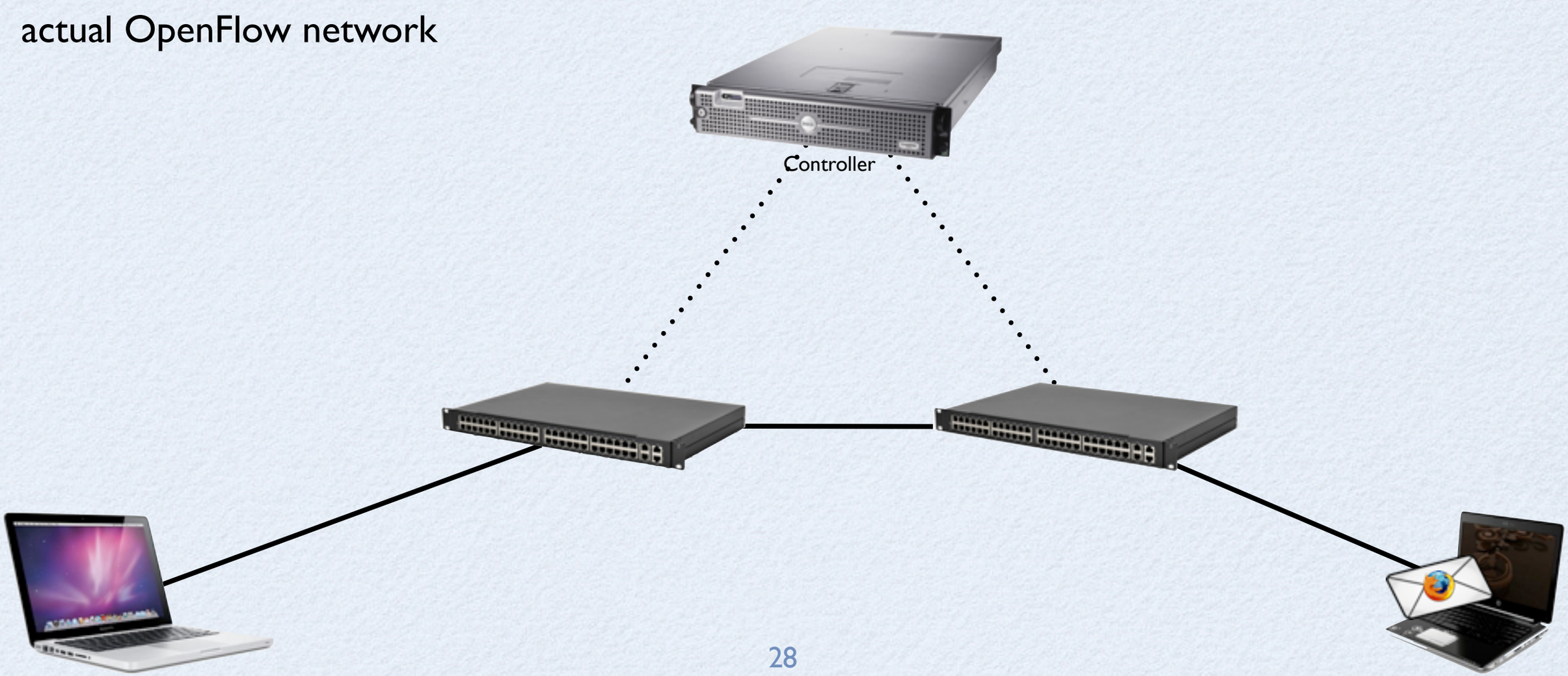

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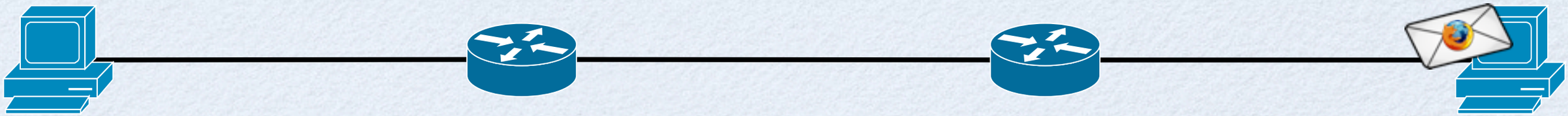

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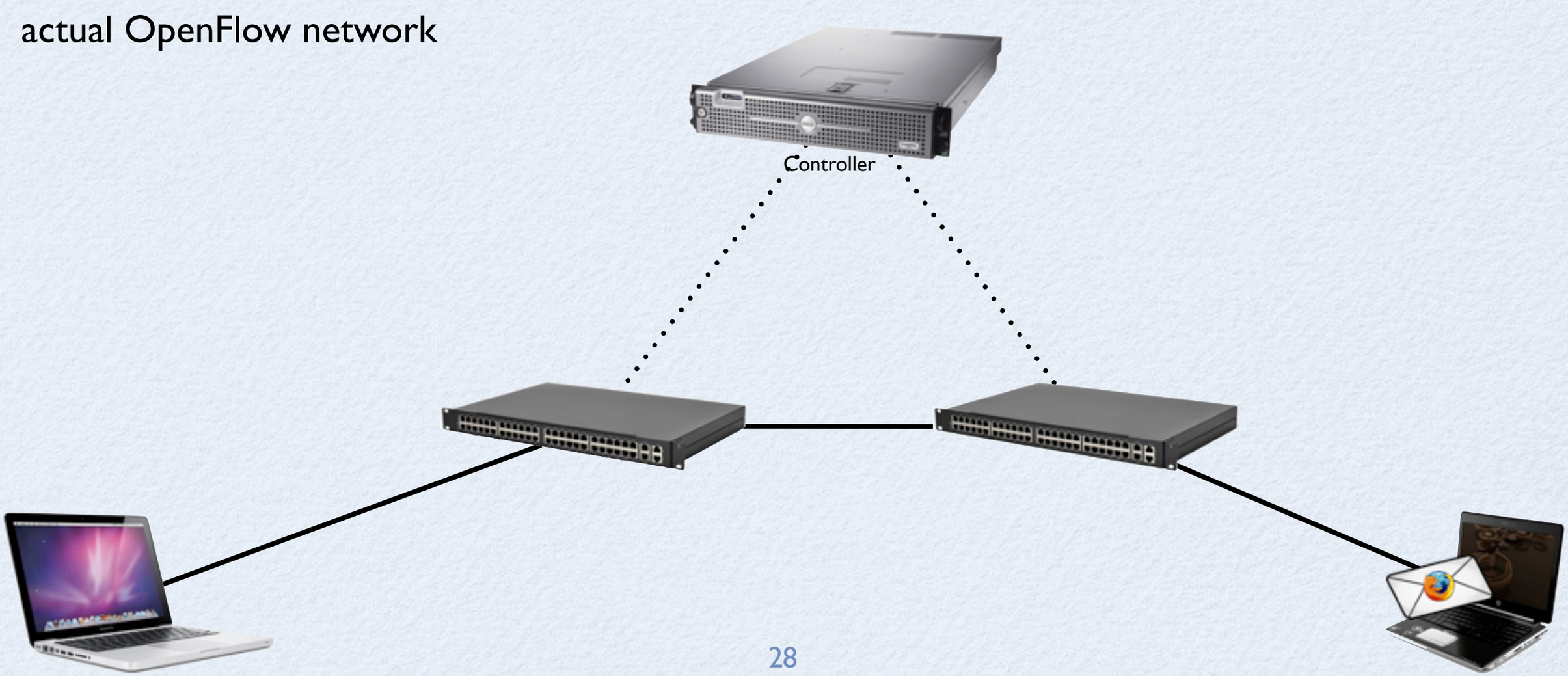

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Throughput (CBench):

Verified Controller	3.5K messages / second
NetCore Controller	3.0K messages / second

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Controller Traffic

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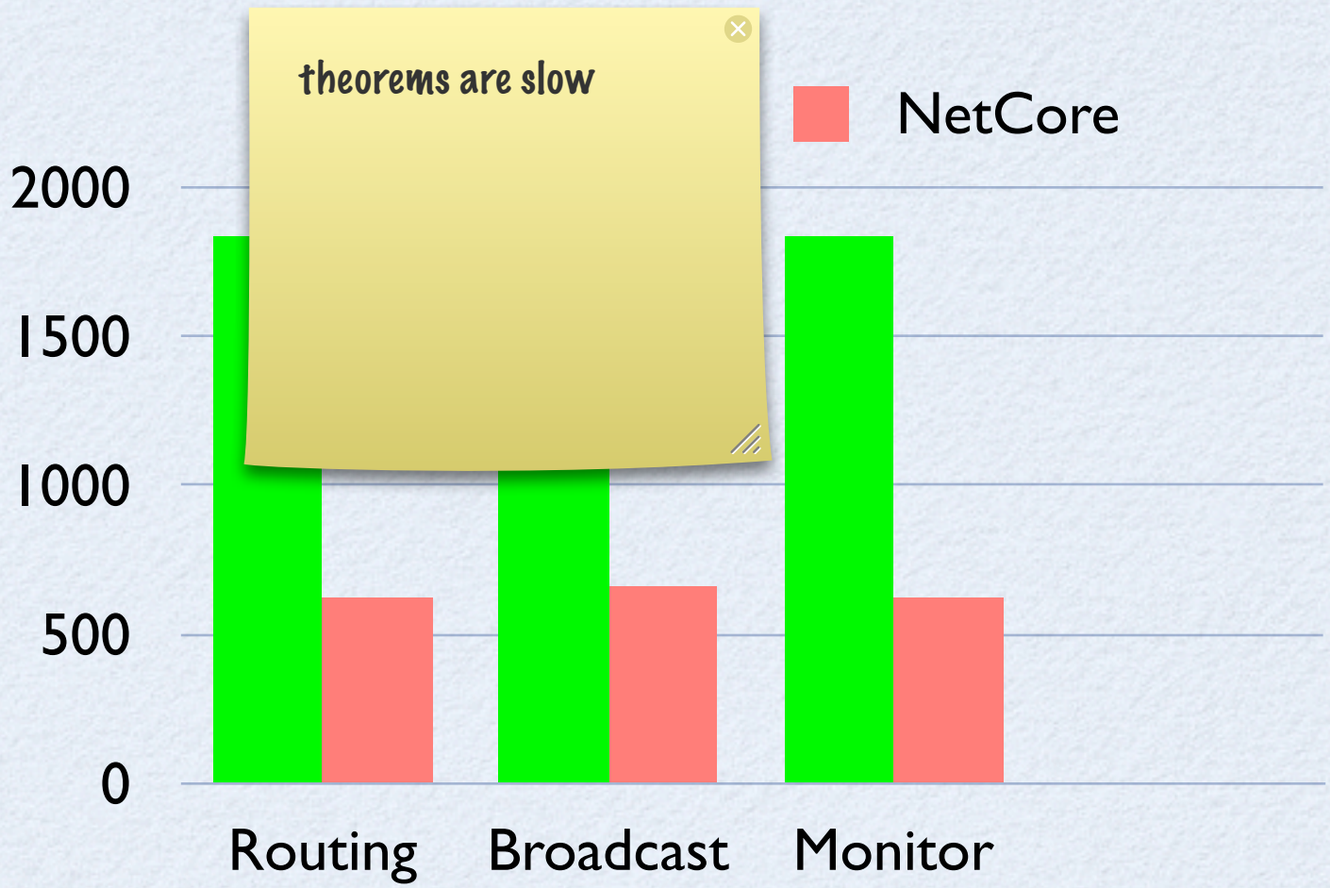

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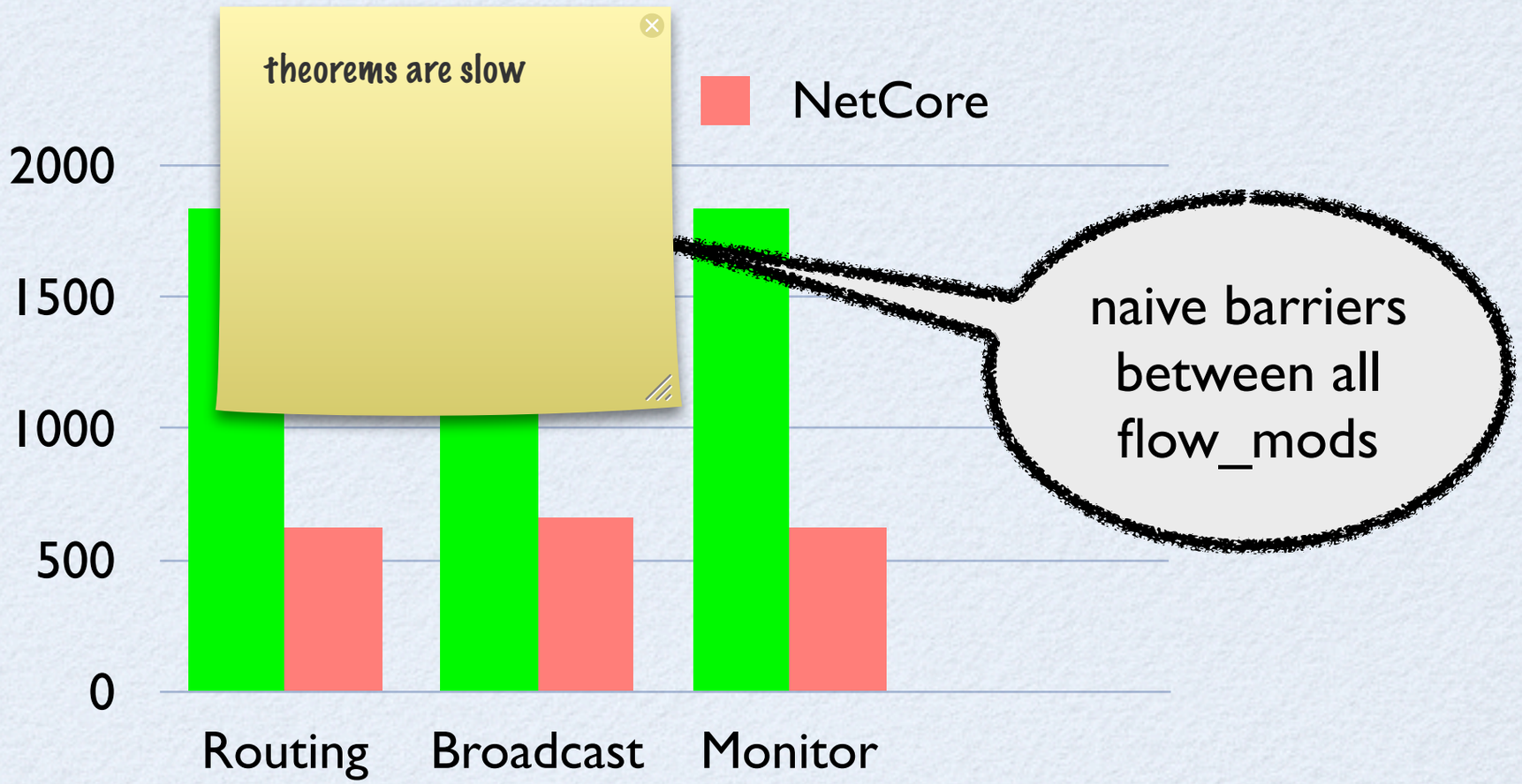

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  dstPort == 22 ⟹ Drop
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  dstIP == H1 ⟹ Fwd 1
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NetCore. Monsanto et al., POPL 2012.

```
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new, verified compiler

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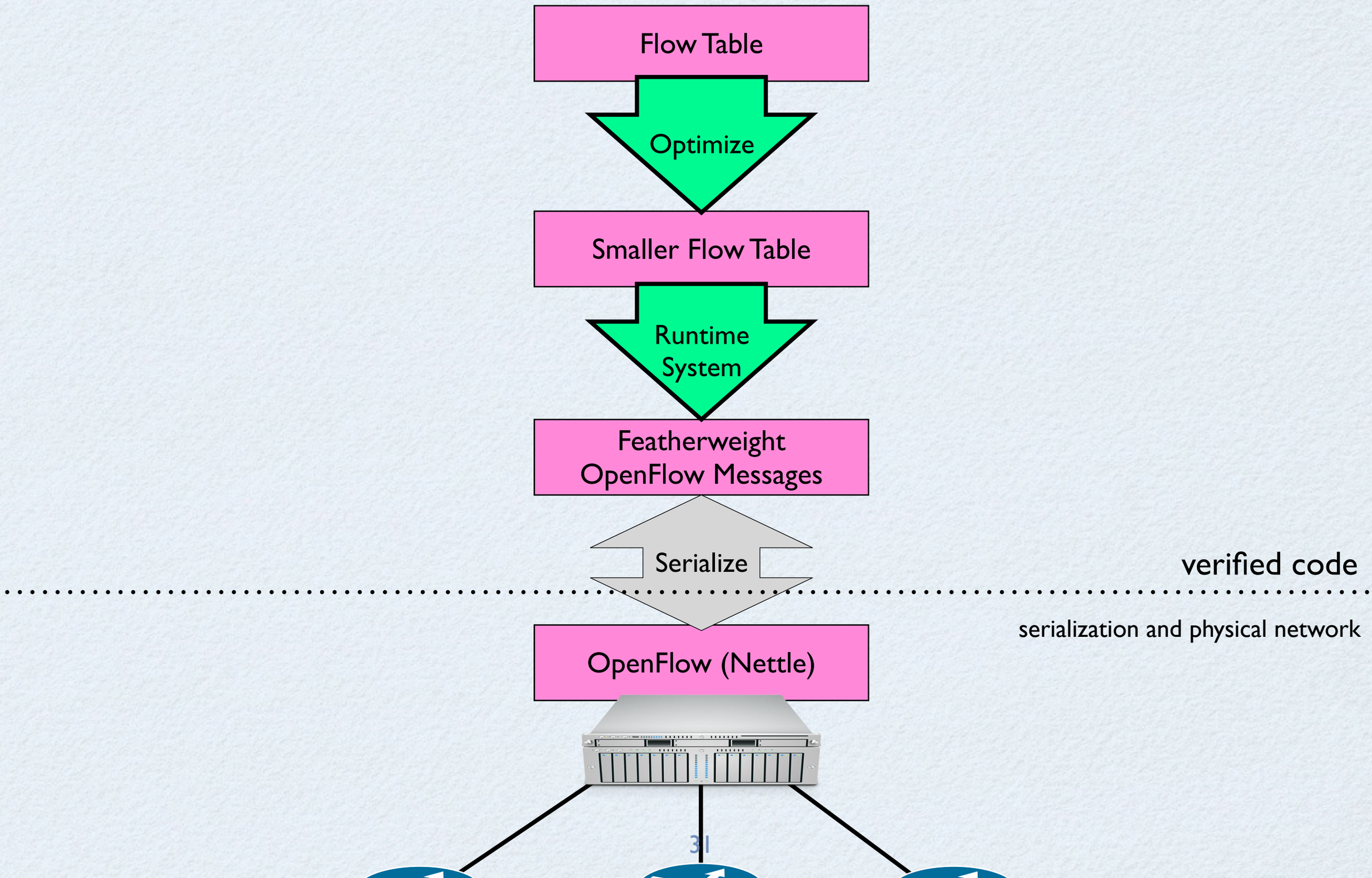
Flow Table
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Featherweight OpenFlow Messages
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OpenFlow (Nettle)

NetCore

Compiler

Flow Table

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Conclusion

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Featherweight OpenFlow

A foundational model for verifying SDN

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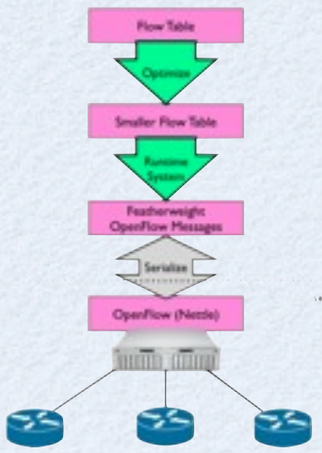
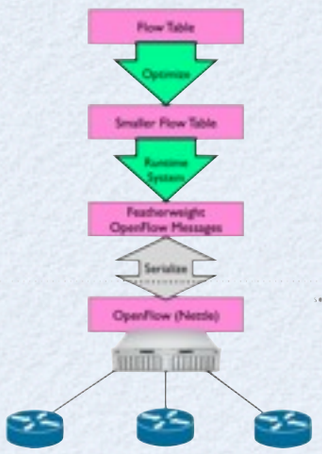


Verified Controller
inserts barriers, handles packet_in messages, and optimizes flow tables

Conclusion

Featherweight OpenFlow

A foundational model for verifying SDN



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Verified NetCore Compiler

compiles to flow tables, uses the verified controller

A Grand Collaboration:

Languages + Networking

Frenetic Cornell

Shrutarshi Basu (PhD)
Nate Foster (Faculty)
Arjun Guha (Postdoc)
Stephen Gutz (Undergrad)
Mark Reitblatt (PhD)
Robert Soulé (Postdoc)
Alec Story (Undergrad)

Frenetic Princeton

Chris Monsanto (PhD)
Joshua Reich (Postdoc)
Jen Rexford (Faculty)
Cole Schlesinger (PhD)
Dave Walker (Faculty)
Naga Praveen Katta (PhD)

frenetic >>

http://frenetic-lang.org