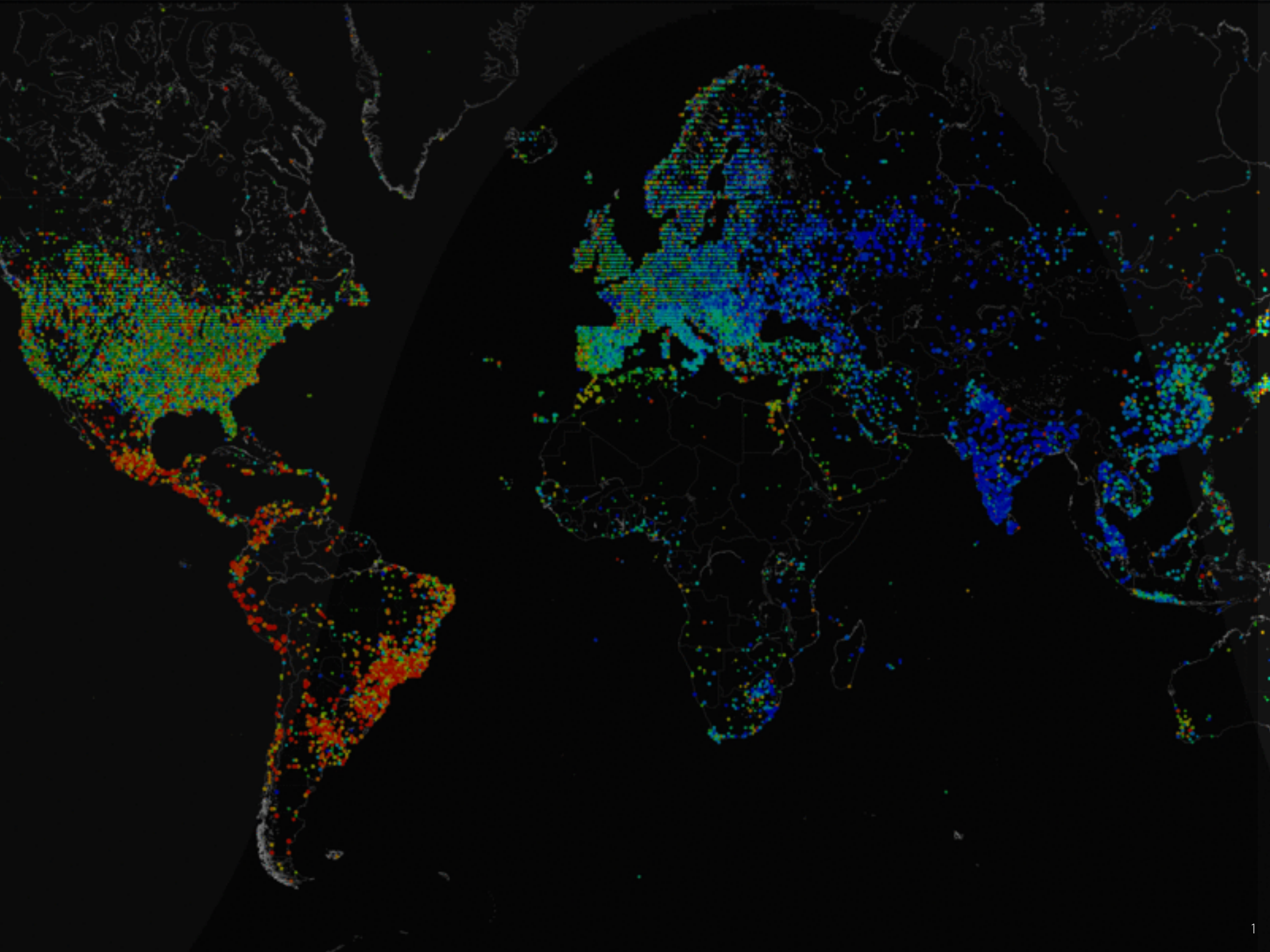
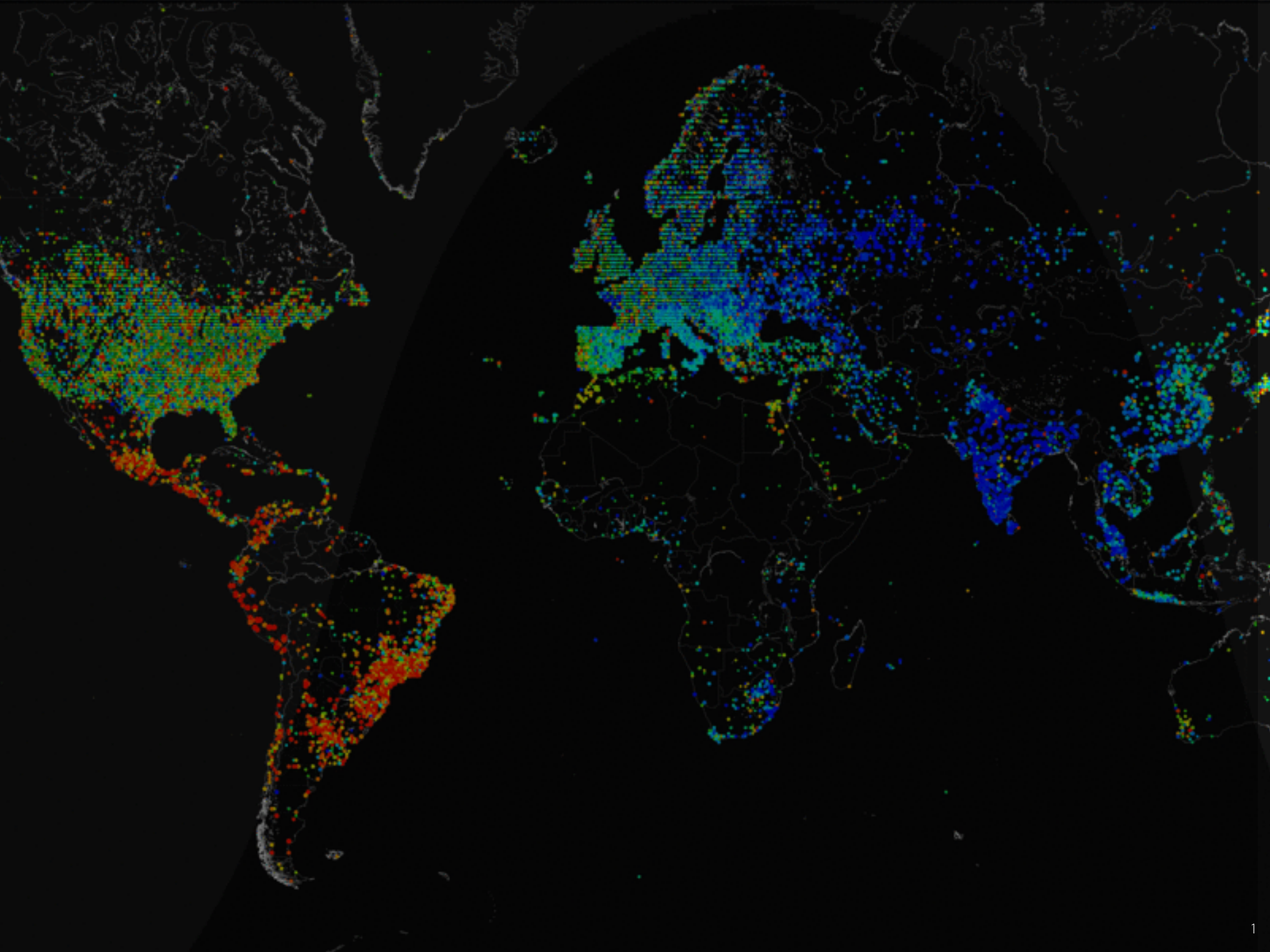
CS 6114
Course Overview

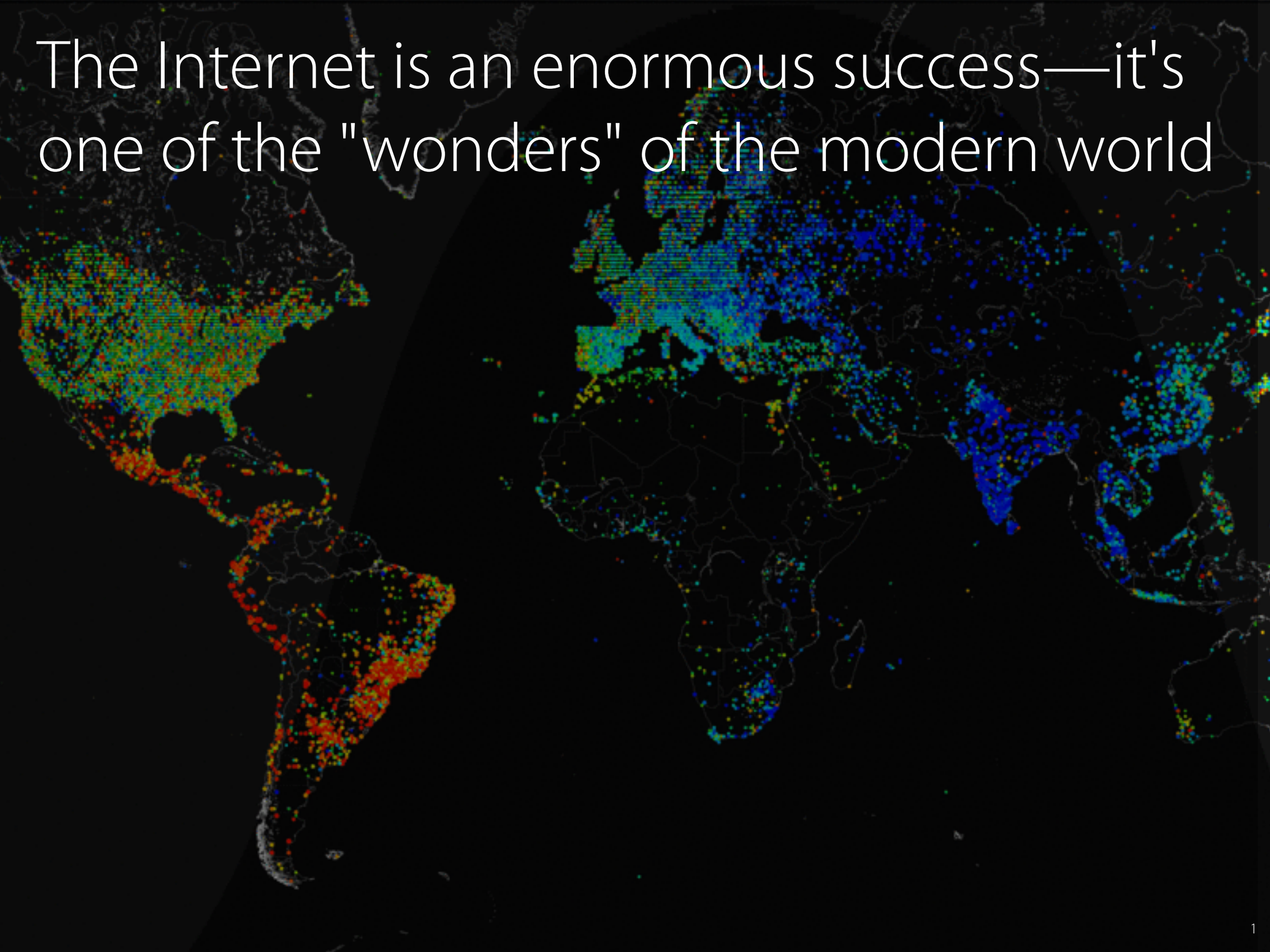
Nate Foster
Cornell University

Take I





The Internet is an enormous success—it's one of the "wonders" of the modern world



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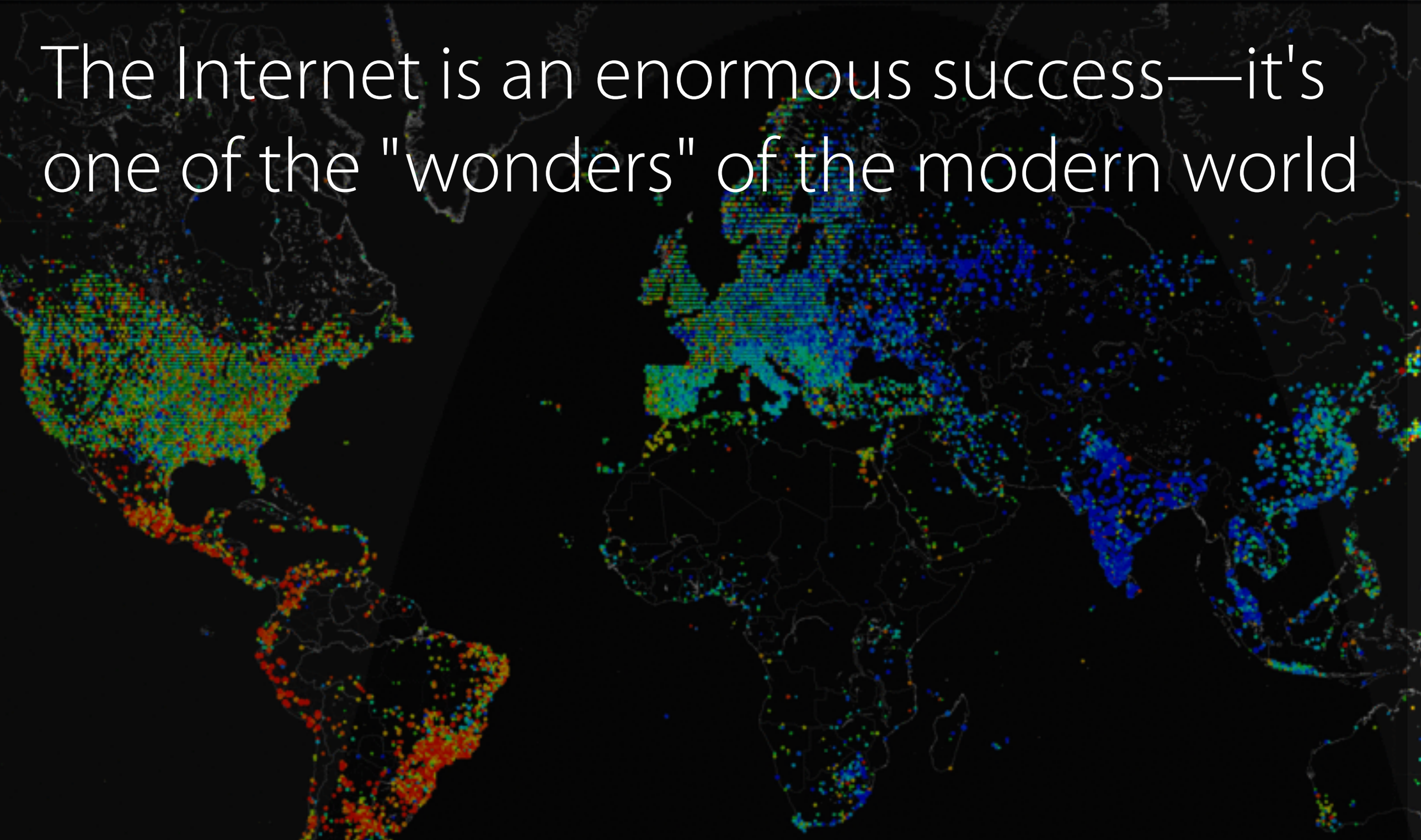

With a few notable exceptions, networking remains an **engineering discipline...**

Although many thorny problems remain...

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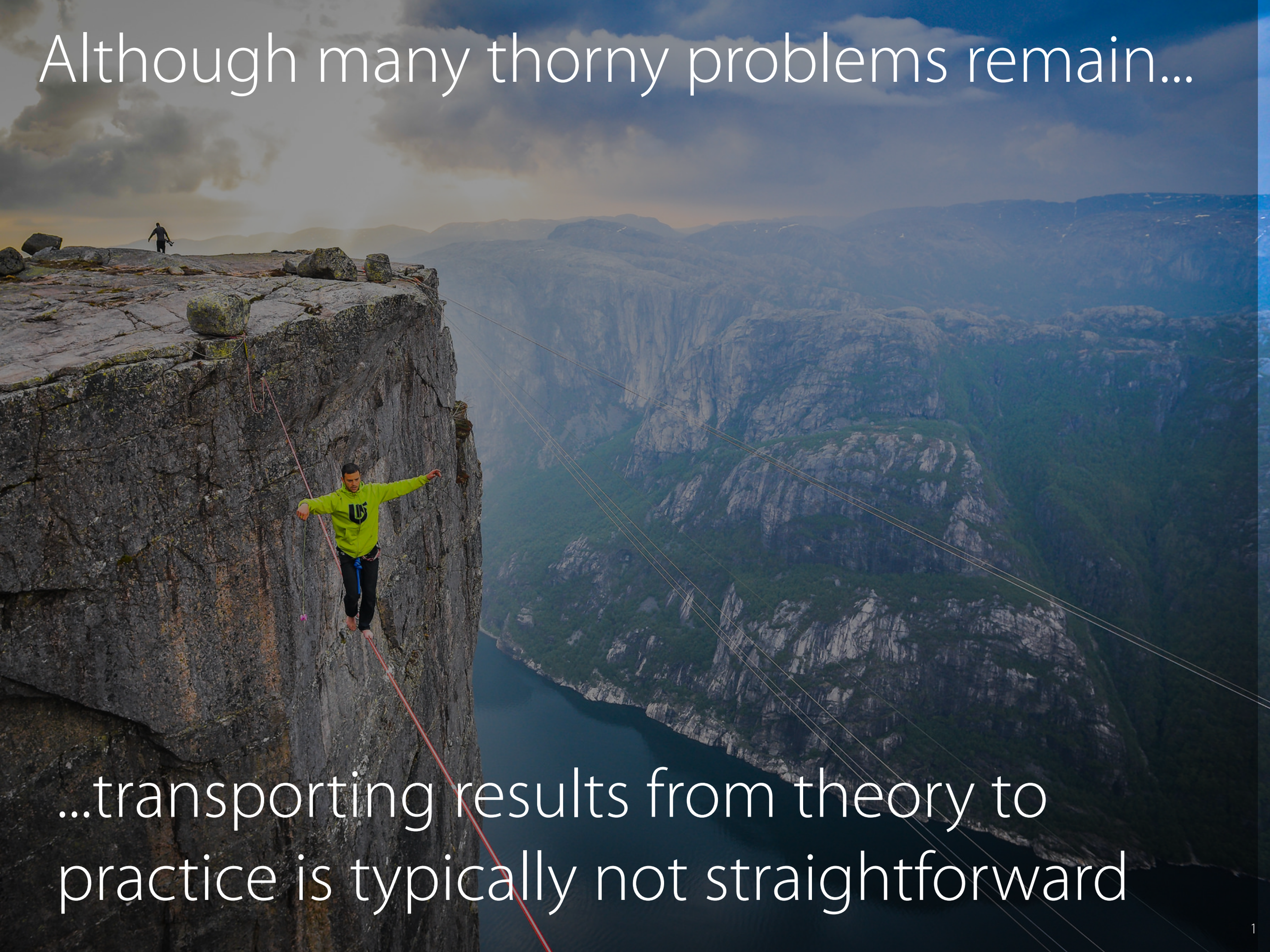


...transporting results from theory to practice is typically not straightforward

This started to change ~10 years ago with the emergence of large-scale data centers...

This started to change ~10 years ago with the emergence of large-scale data centers...

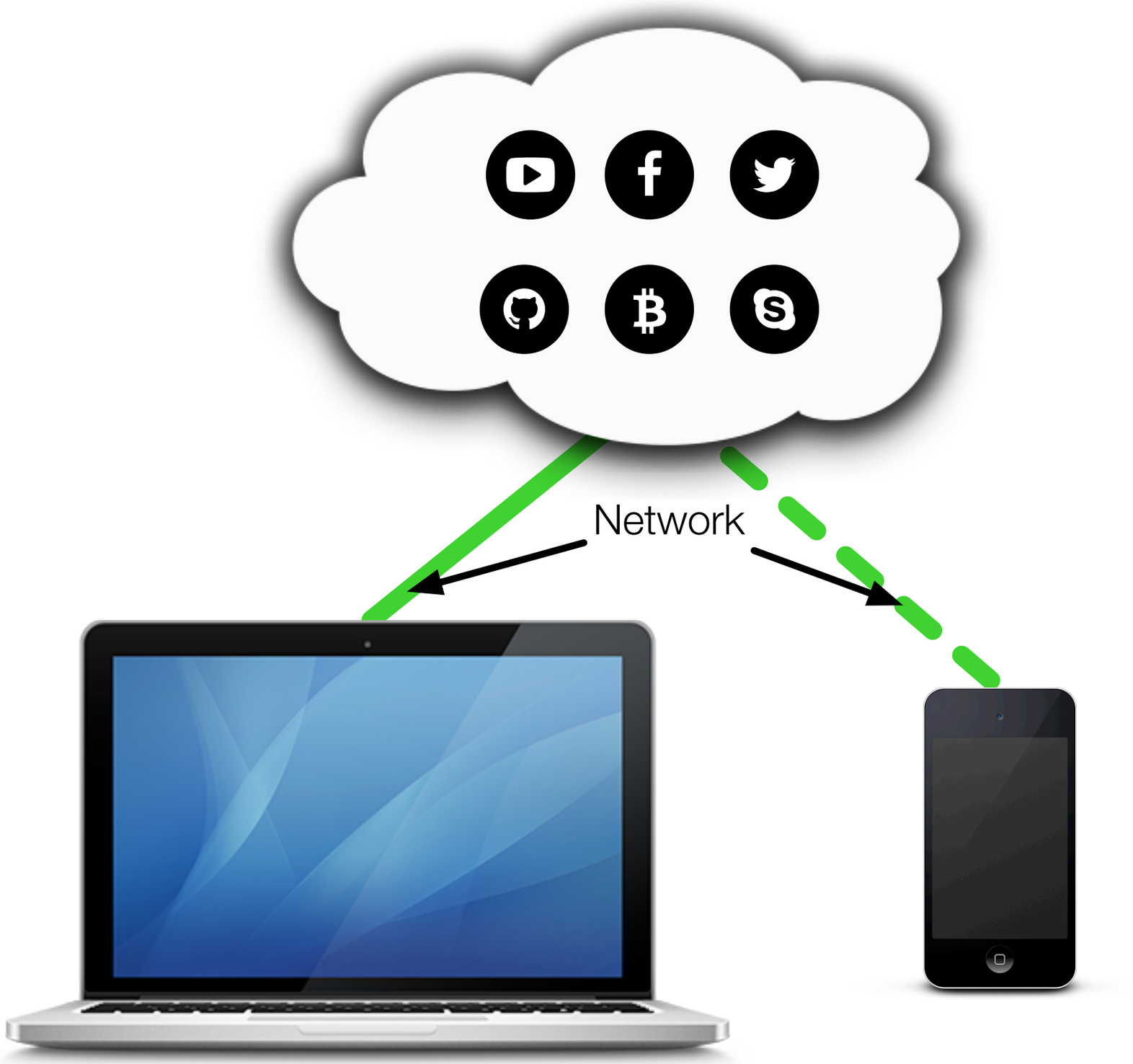
- Complexity became unmanageable
- Growing need to deploy new features
- Big players unhappy with market dynamics

Take II

Many programming languages were designed in an age when computers looked like this...

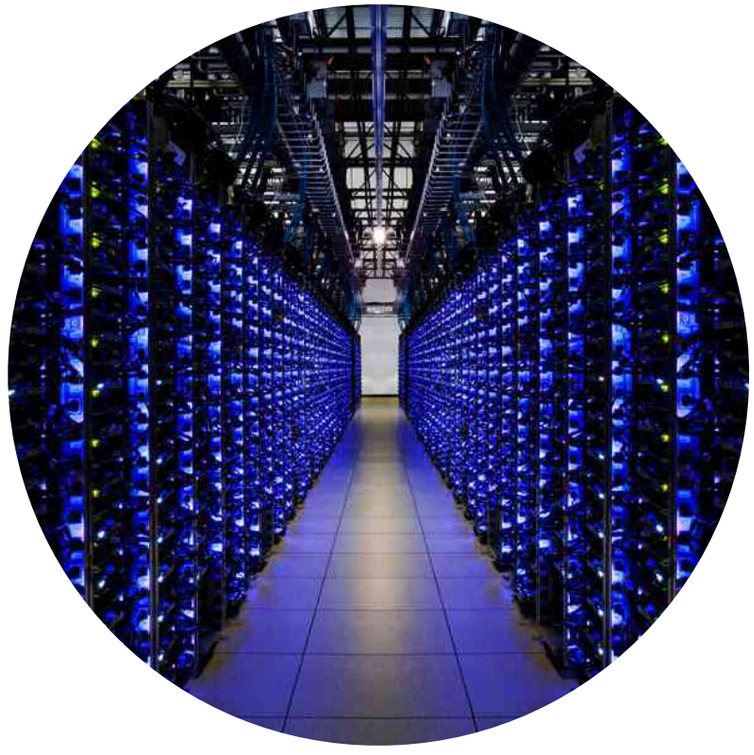
But nowadays, computers look like this...

And applications are built like this...




Sun
Sun
ULTRA 1

- Stand-alone
- Centralized
- Sequential



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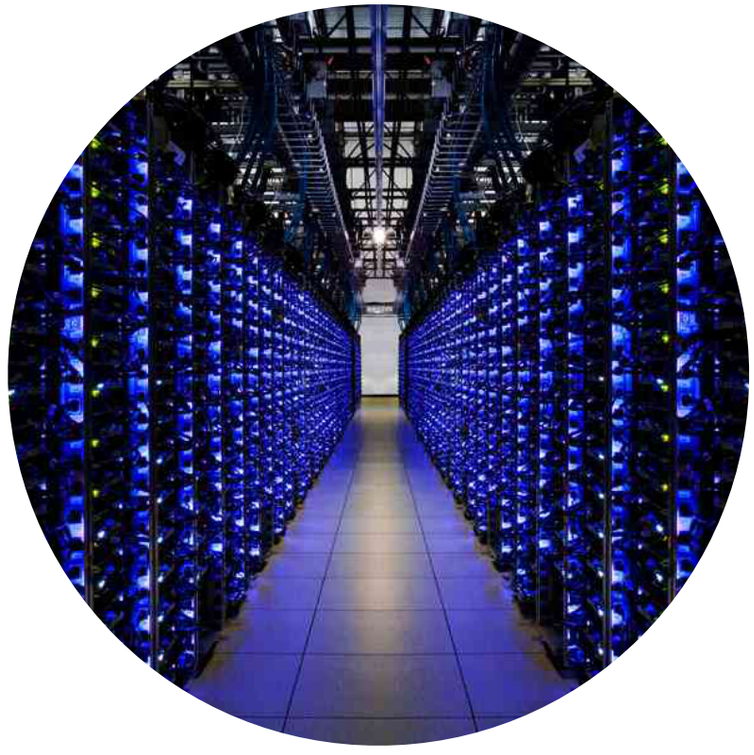
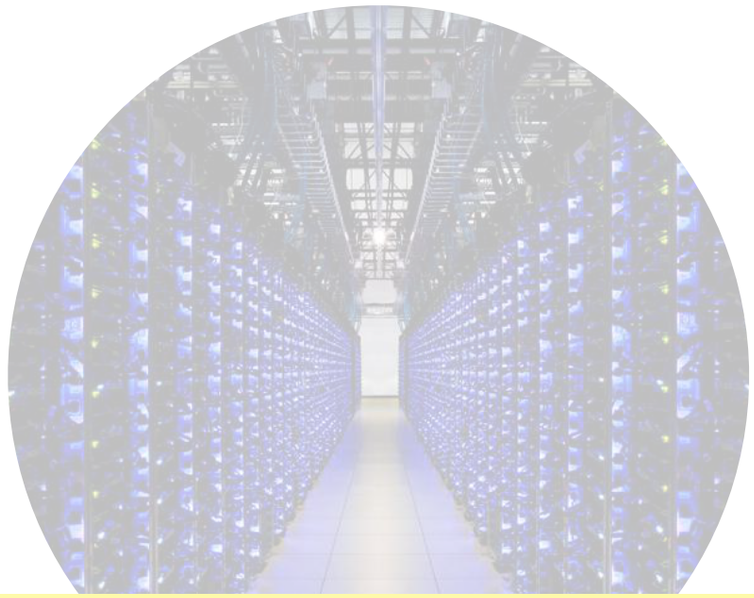


- Networked
- Distributed
- Concurrent



We need new kinds of abstractions and tools for programming these networked systems!

- Stand-alone
- Centralized
- Sequential

- Networked
- Distributed
- Concurrent

Take III


IBM
System 360

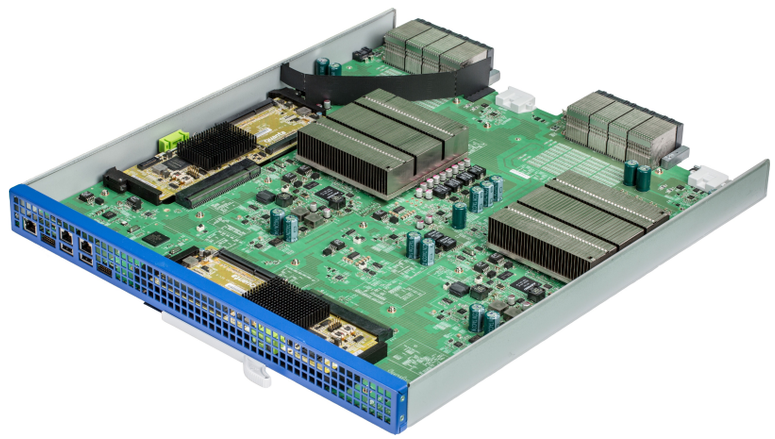

IBM
System 360


INTERFACE
MESSAGE
PROCESSOR


INTERFACE
MESSAGE
PROCESSOR

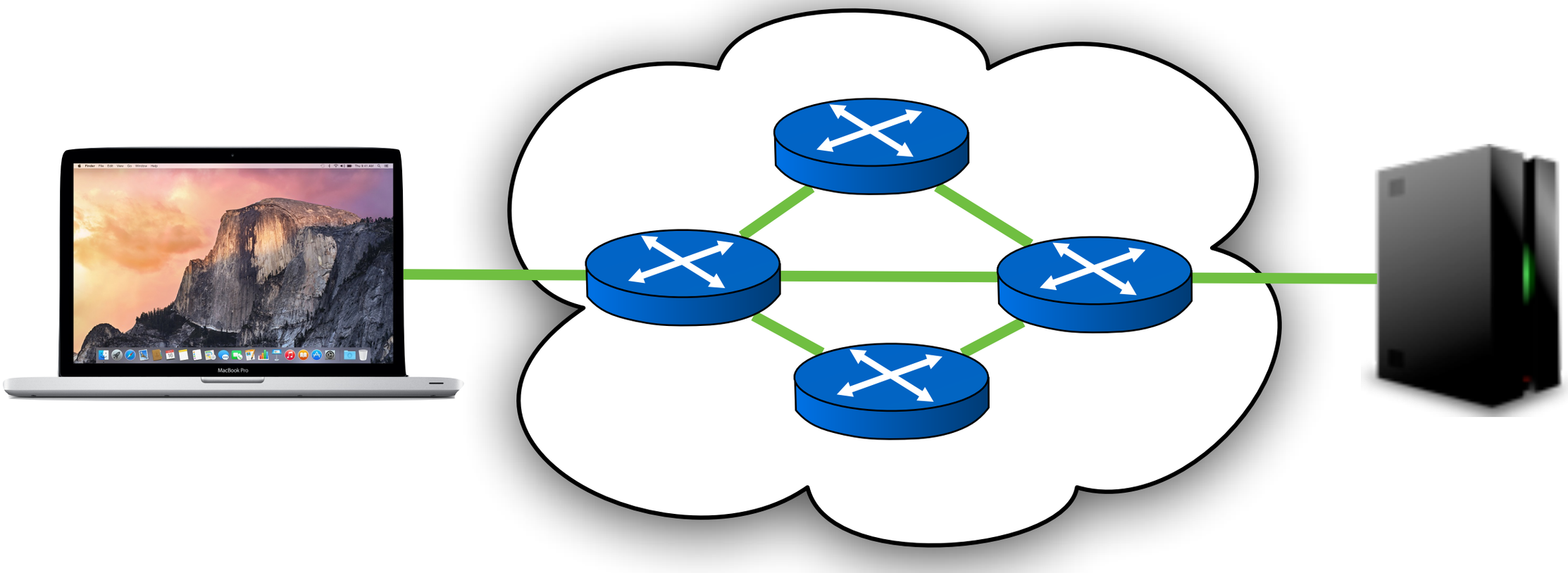

Cisco Systems
CISCO CRS-1


Cisco Systems
CISCO CRS-1
LINECARD CHASSIS



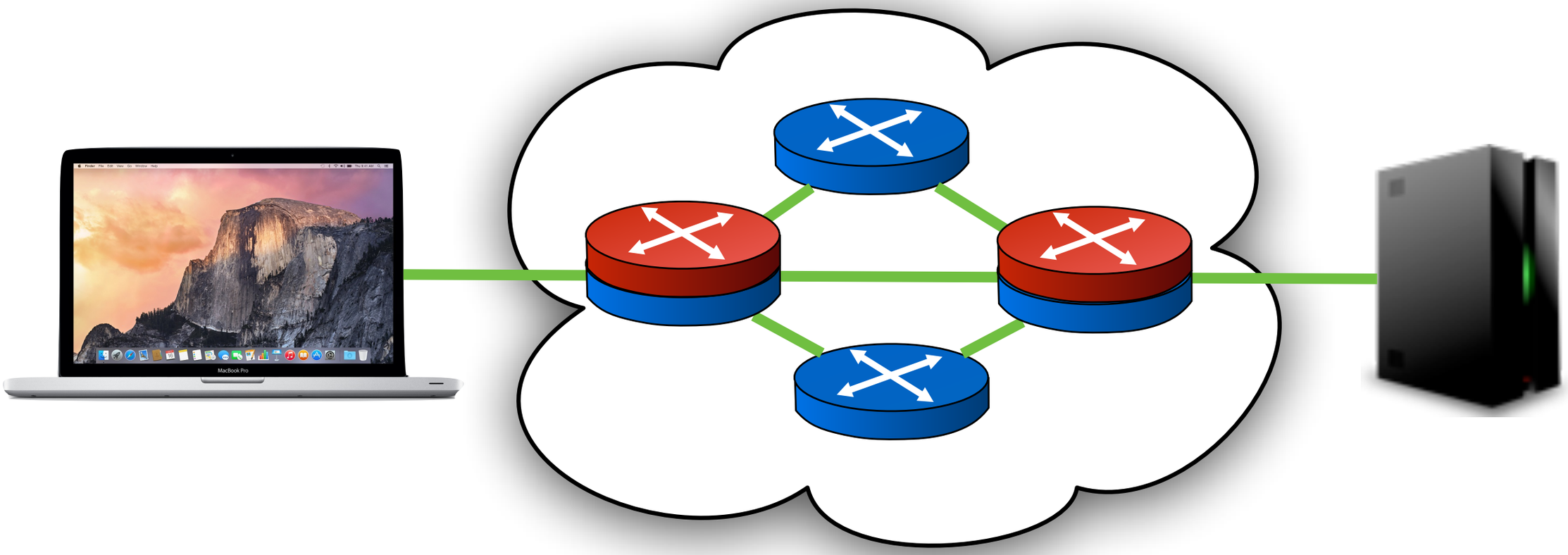
Network Programming

Network Programming



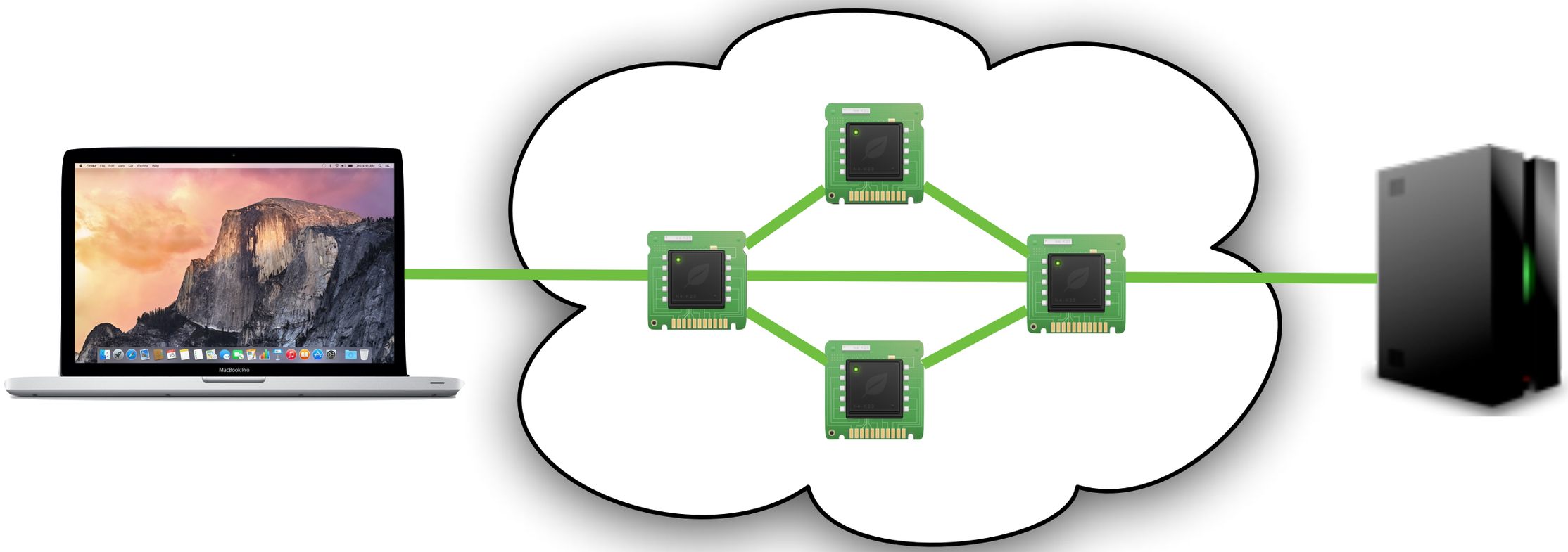
Data plane: forward packets, balances load, implements monitoring, etc.

Network Programming



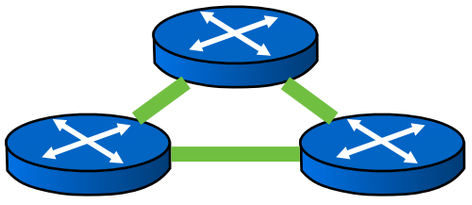
Control Plane: discovers topology, computes routes, enforces policies, etc.

Network Programming

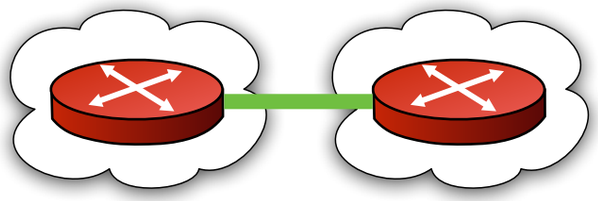


Network Devices: implement packet processing, buffering, queueing, etc. at line rate

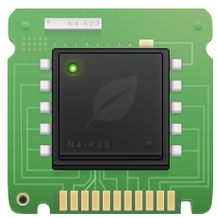
Network Programming Challenges



Networks are *distributed* systems with thousands of interacting nodes



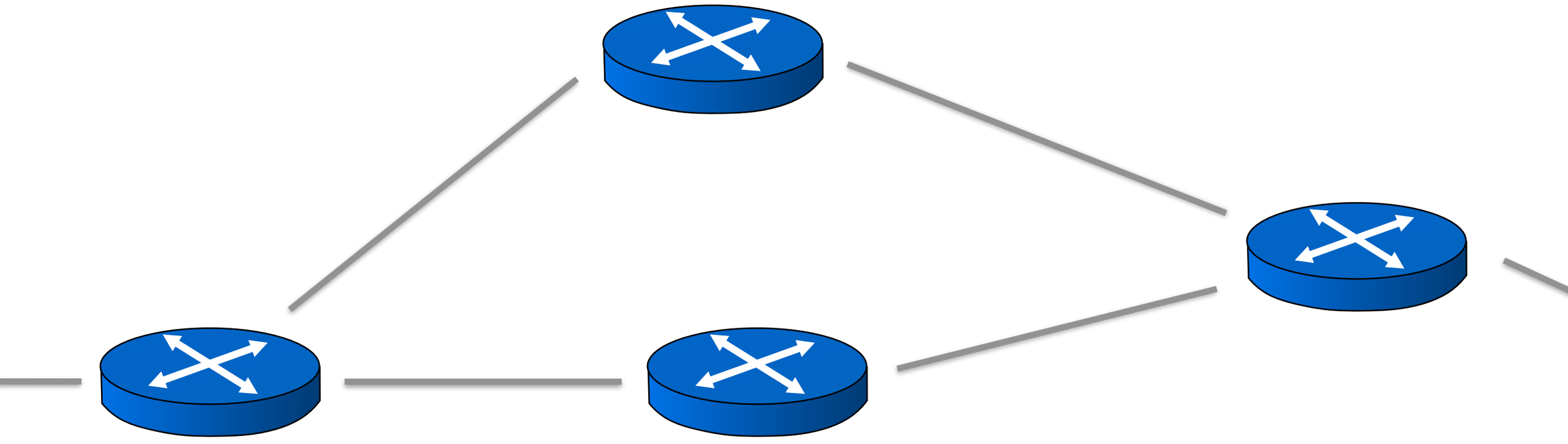
Networks enforce complex *security* policies that span trust boundaries



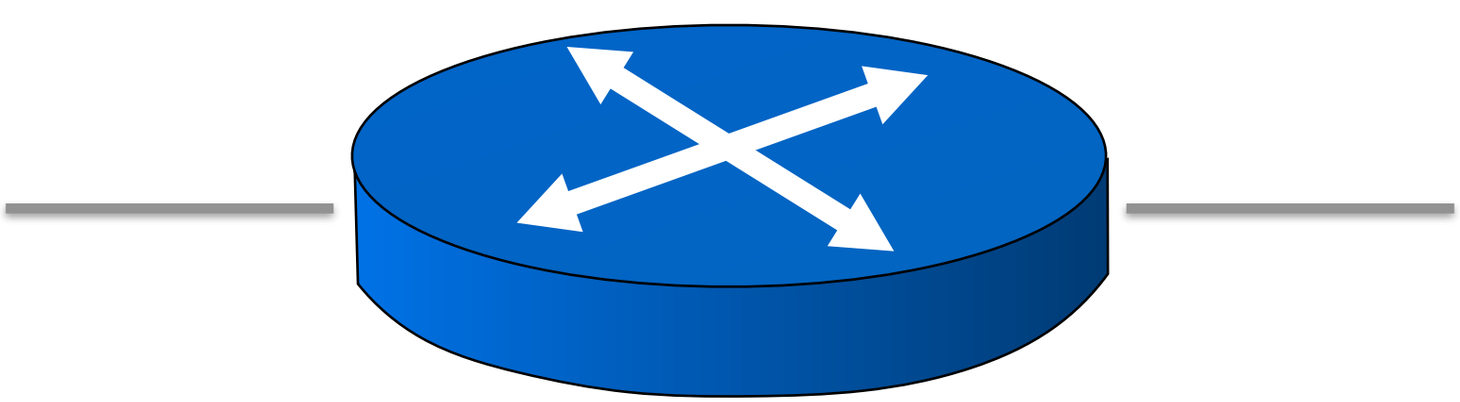
Networks are expected to offer good *performance* with limited resources

Software-Defined Networking

Conventional Networking

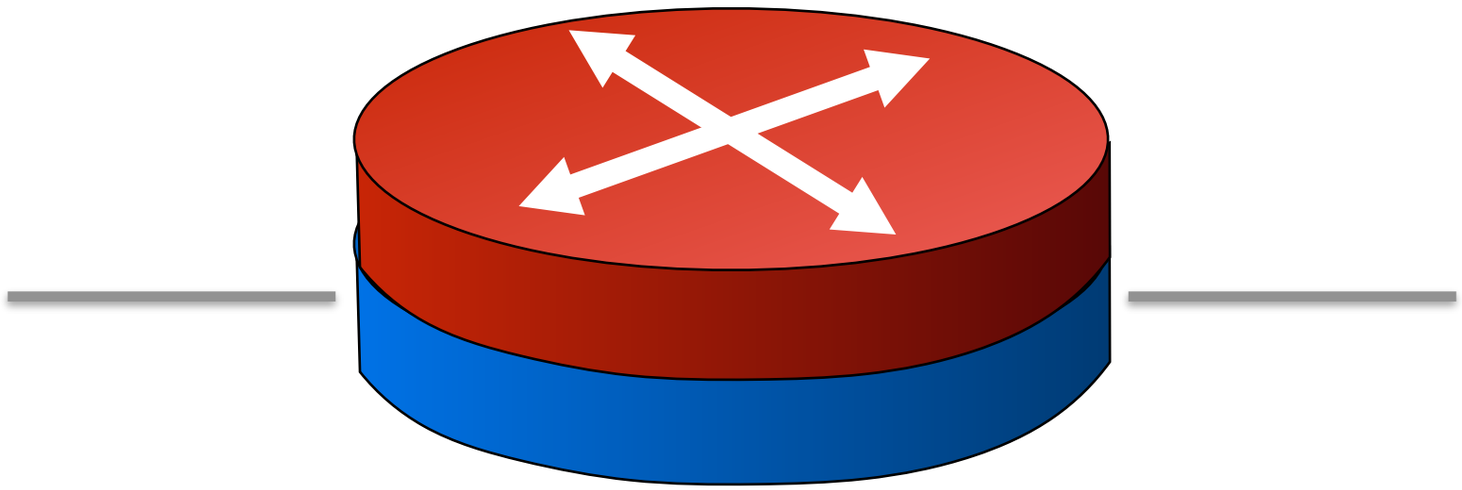


Conventional Networking



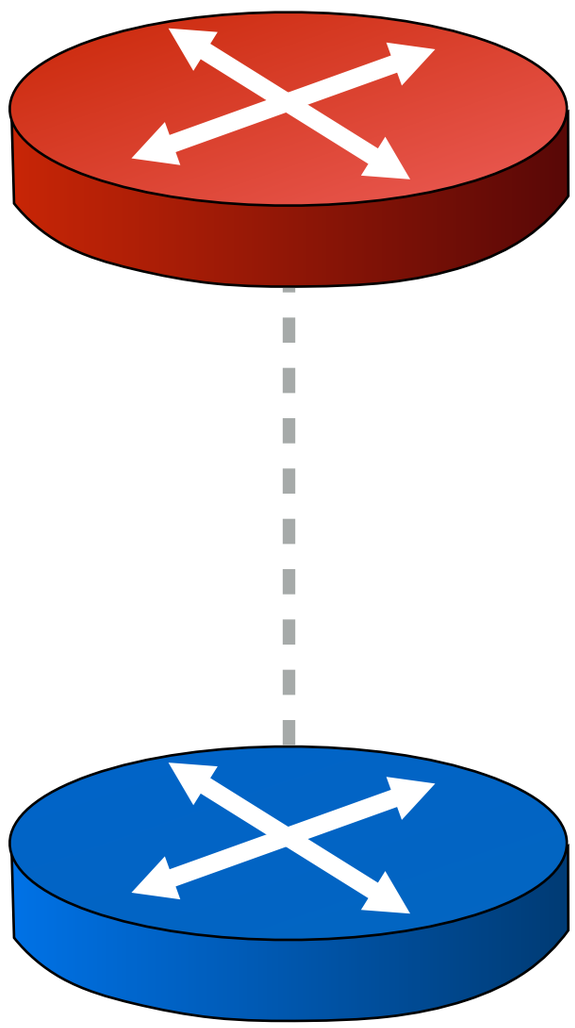
Conventional Networking

Control Plane: discovers topology, computes routes, manages policy, etc.



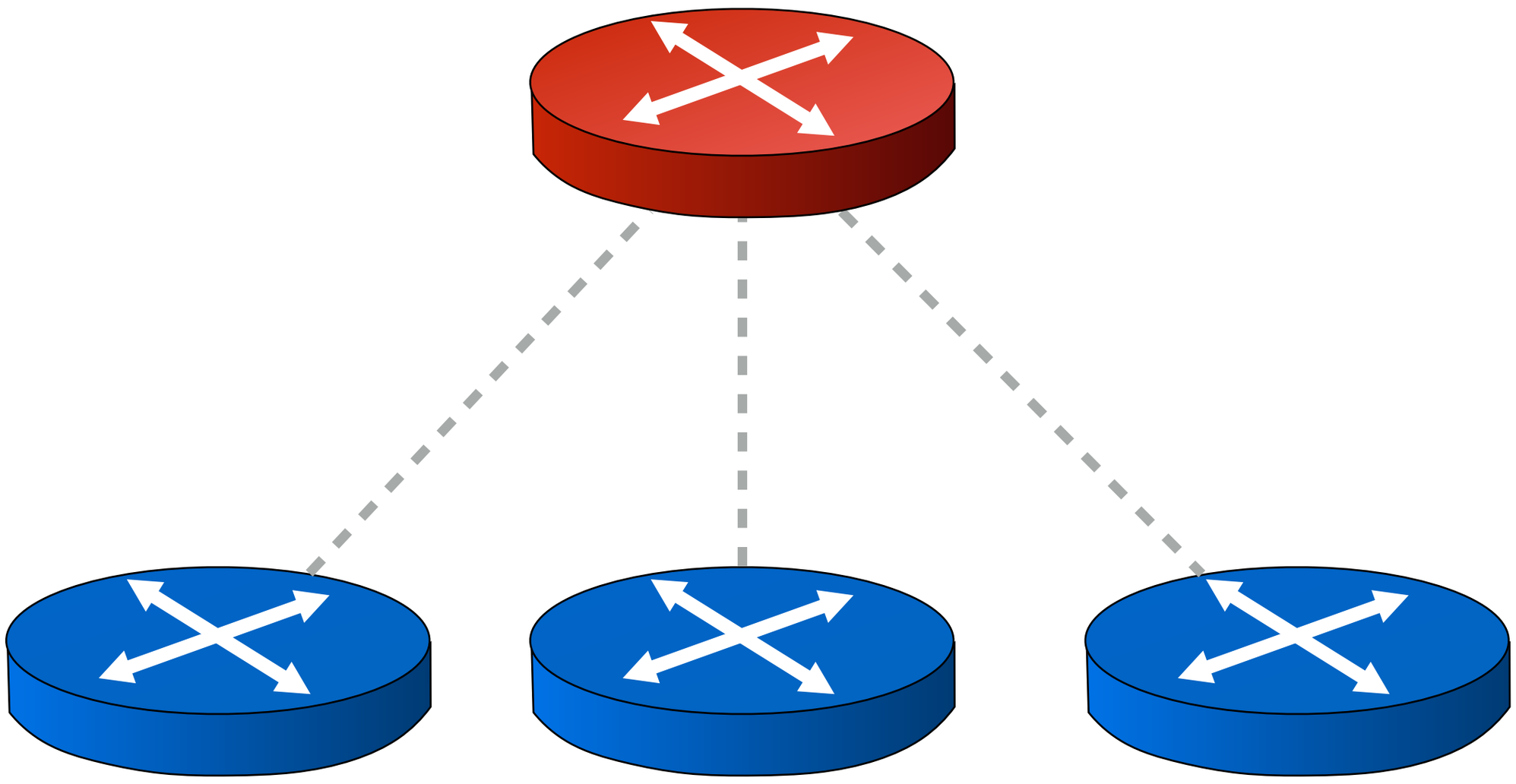
Data plane: forwards packets, enforces access control, monitors flows, etc.

Software-Defined Networking



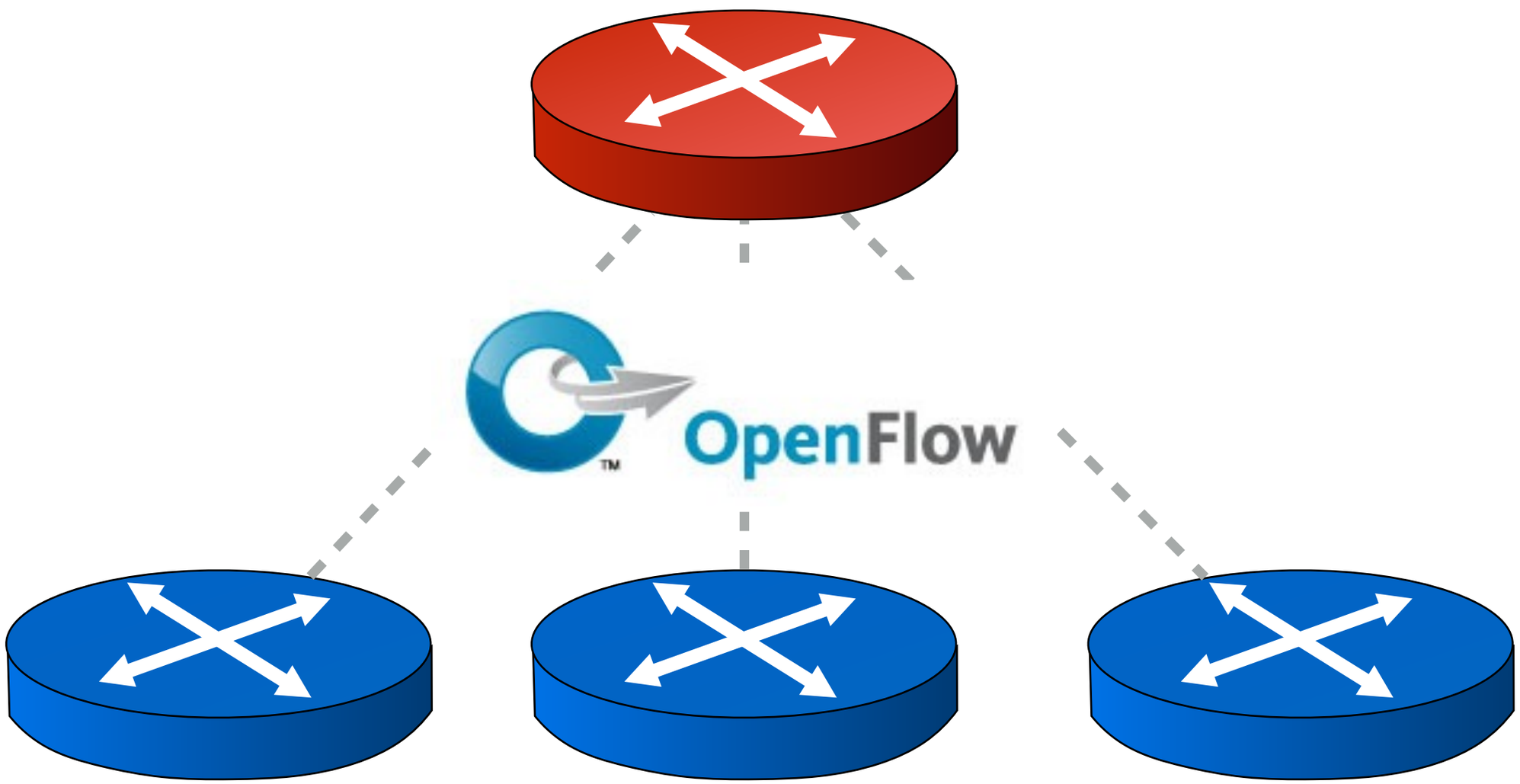
1. Separate control plane and data plane

Software-Defined Networking



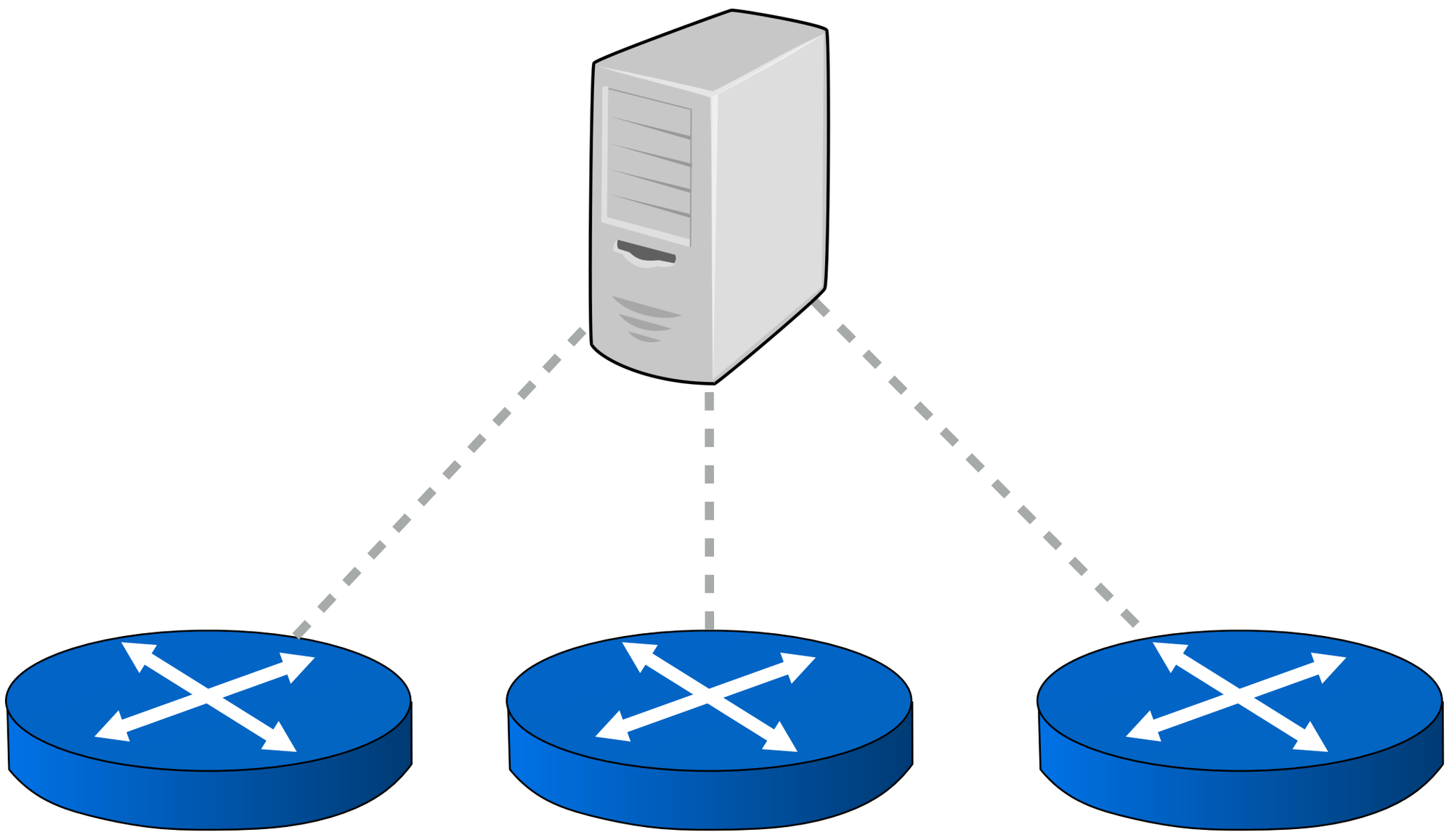
2. Use appropriate unit of abstraction for control plane

Software-Defined Networking



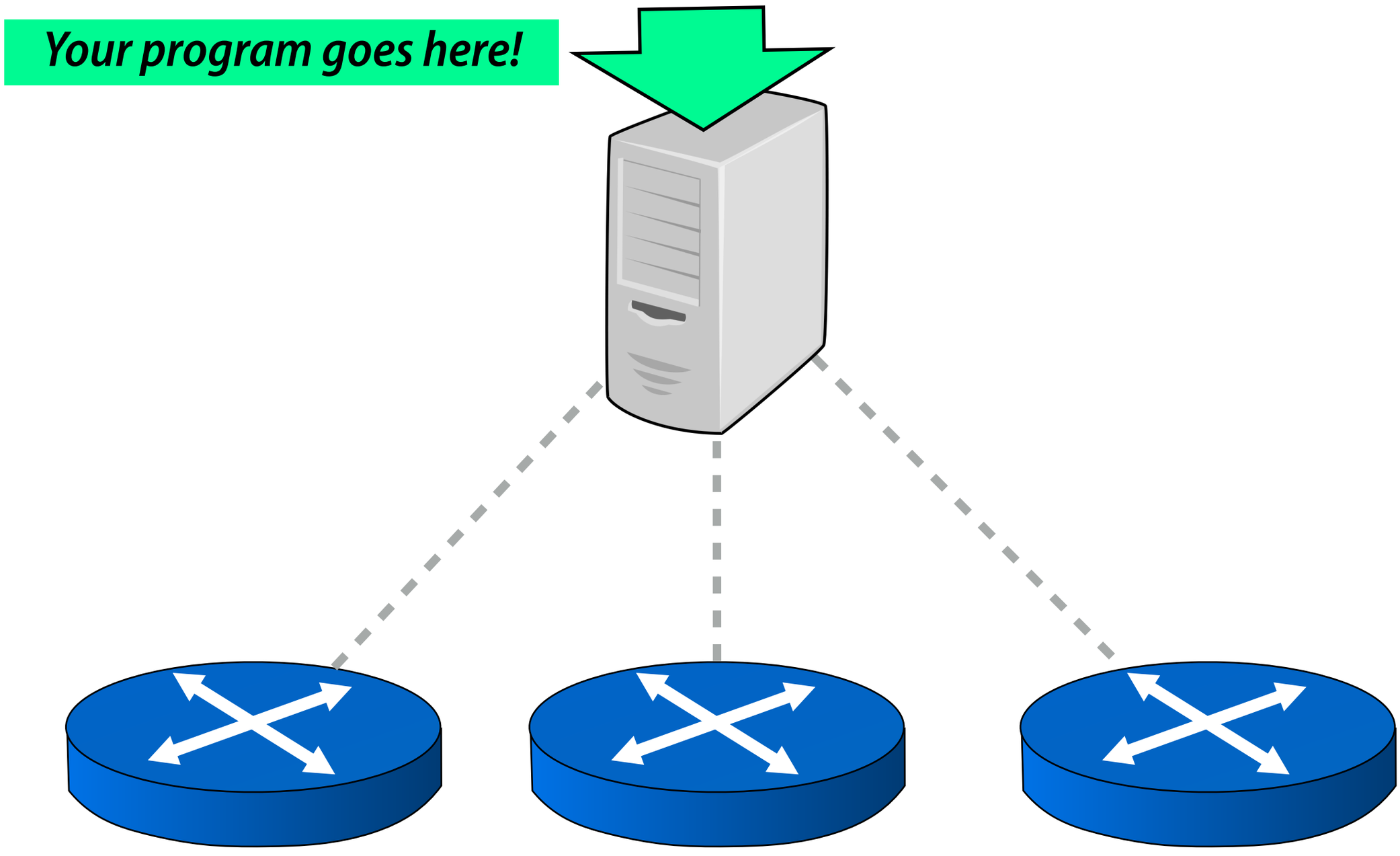
3. Generalize data plane and standardize configuration APIs

Software-Defined Networking



4. Implement control plane on general-purpose machine

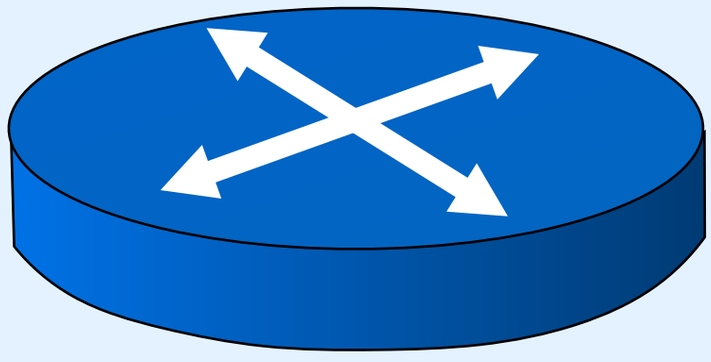
Software-Defined Networking



4. Implement control plane on general-purpose machine

SDN Switch

Programmable device that can be used to implement switches, routers, gateways, firewalls, load balancers, etc.



Match	Actions
10.0.0.1	Drop
10.0.0.2	Forward 2
10.0.0.3	Forward 3
*	Controller

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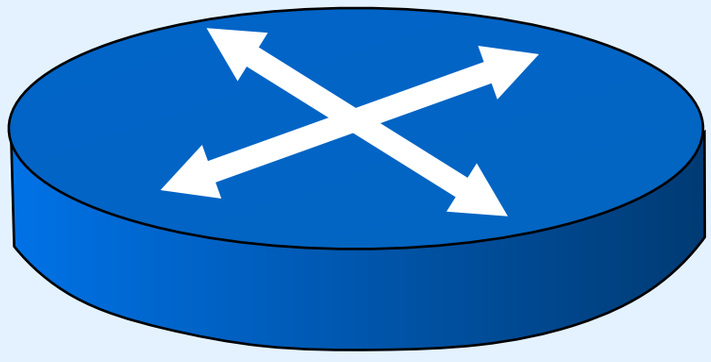


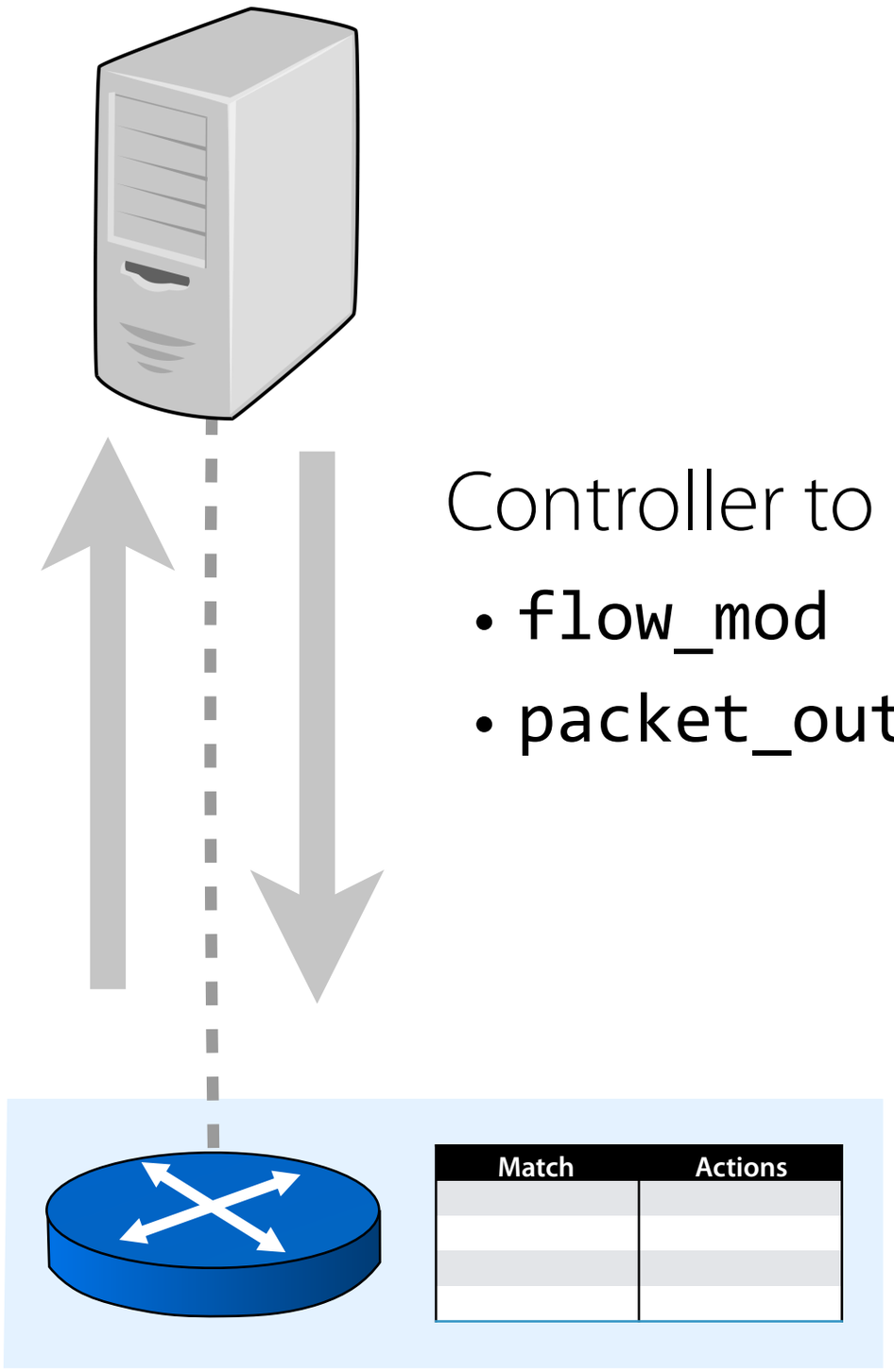
Match	Actions
10.0.0.1	Drop
10.0.0.2	Forward 2
10.0.0.3	Forward 3
*	Controller

Key construct is a *flow table* comprising a prioritized list of match-action *forwarding rules*

SDN Controller

Switch to controller:

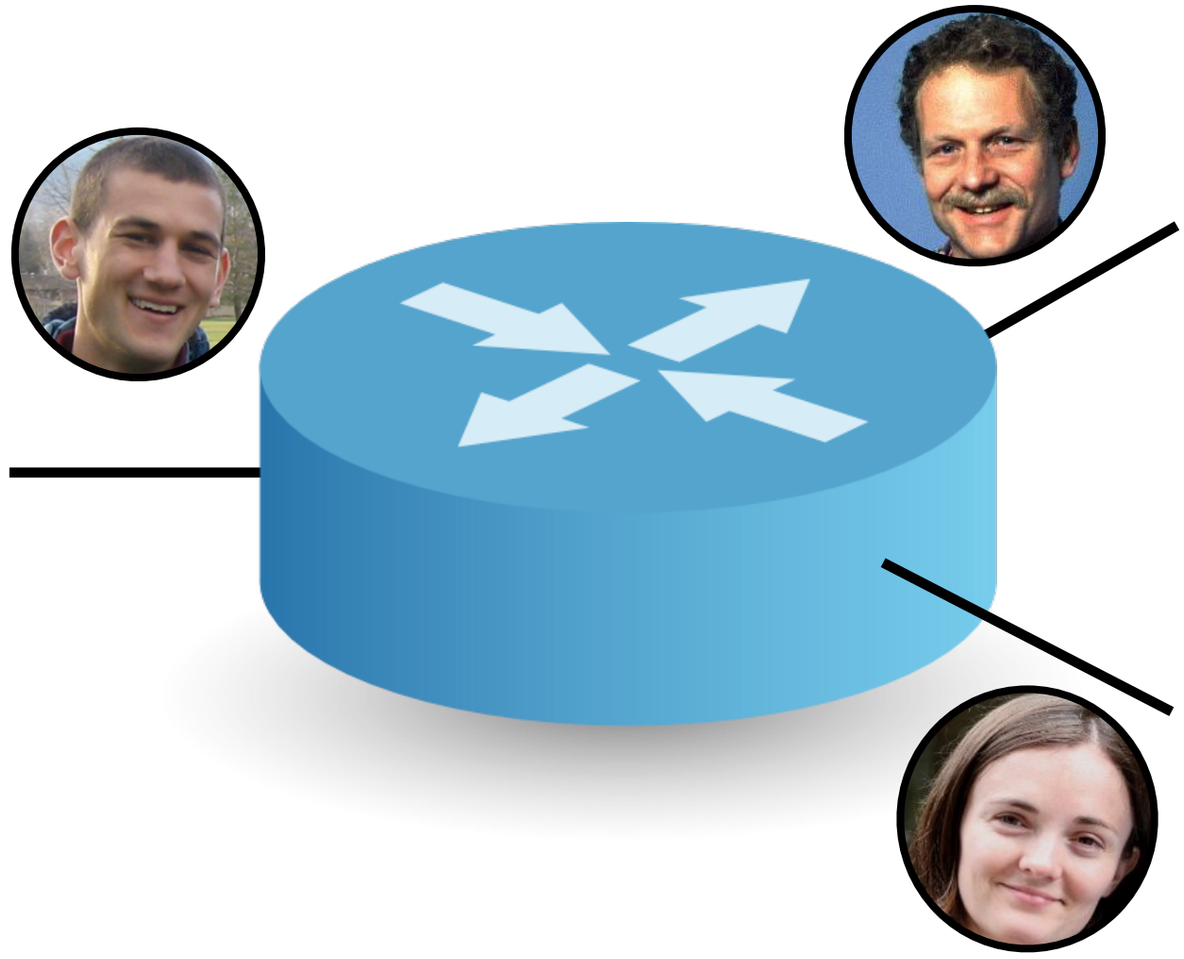
- `switch_connected`
- `switch_disconnected`
- `port_status`
- `packet_in`



Controller to switch:

- `flow_mod`
- `packet_out`

Repeater Hub



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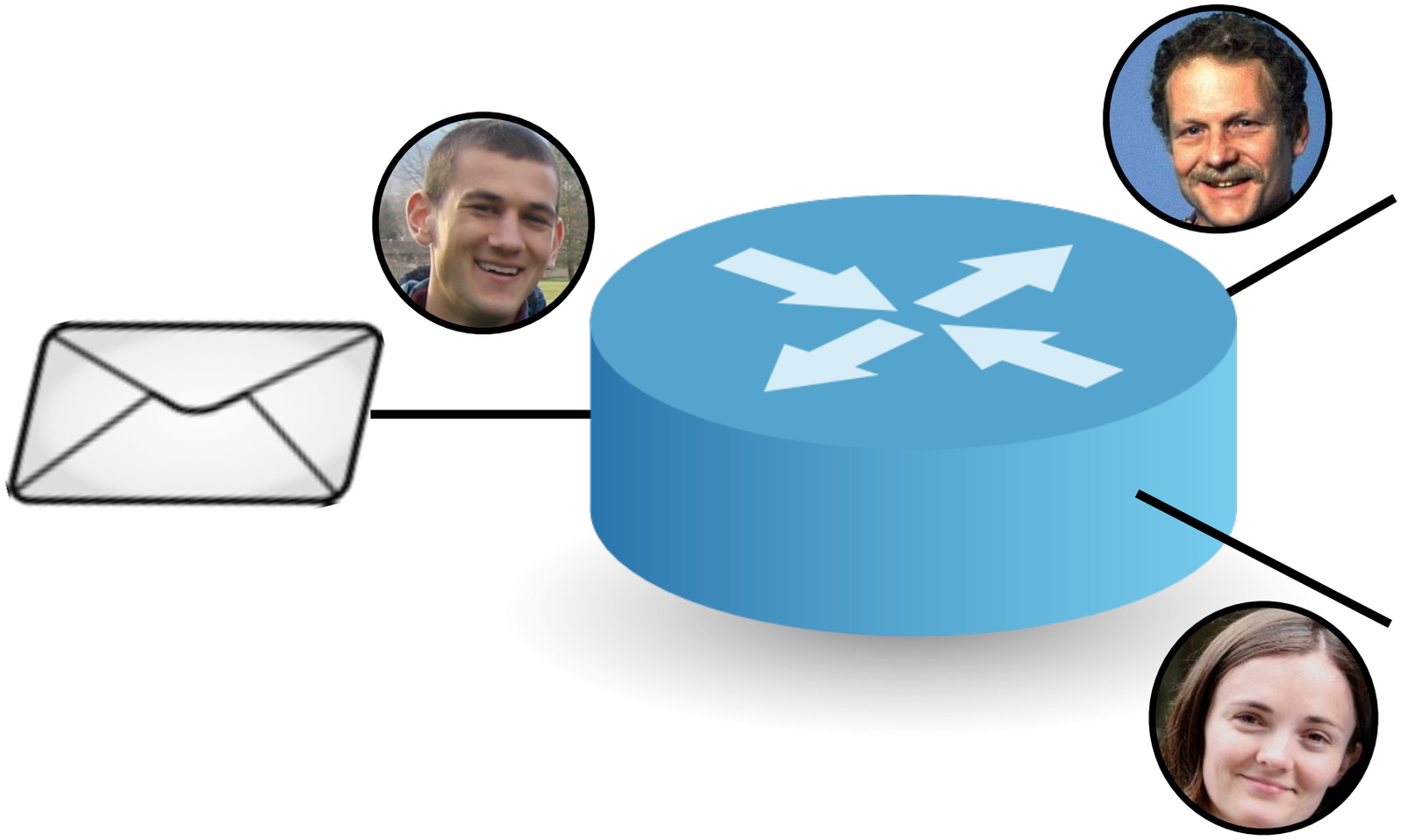

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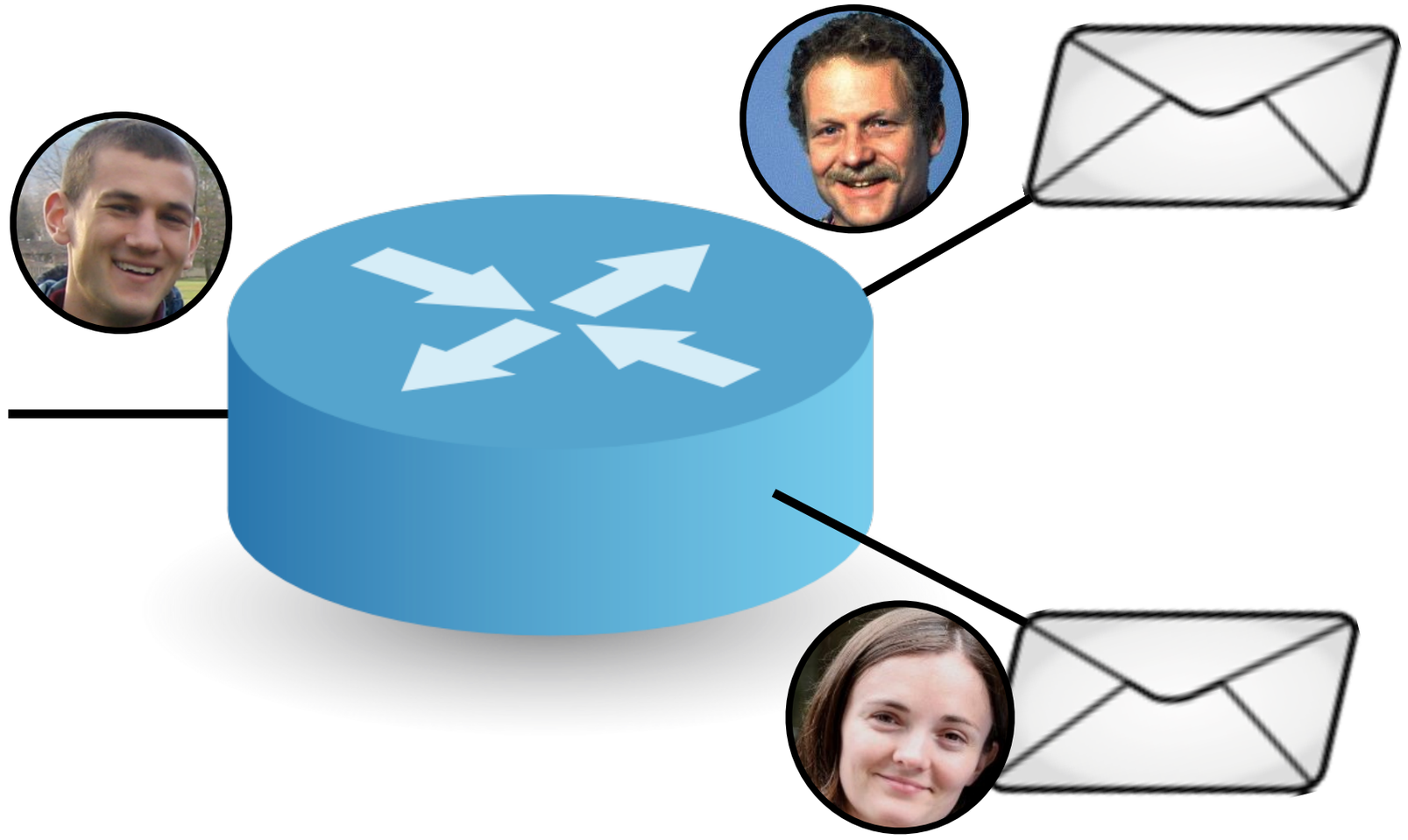
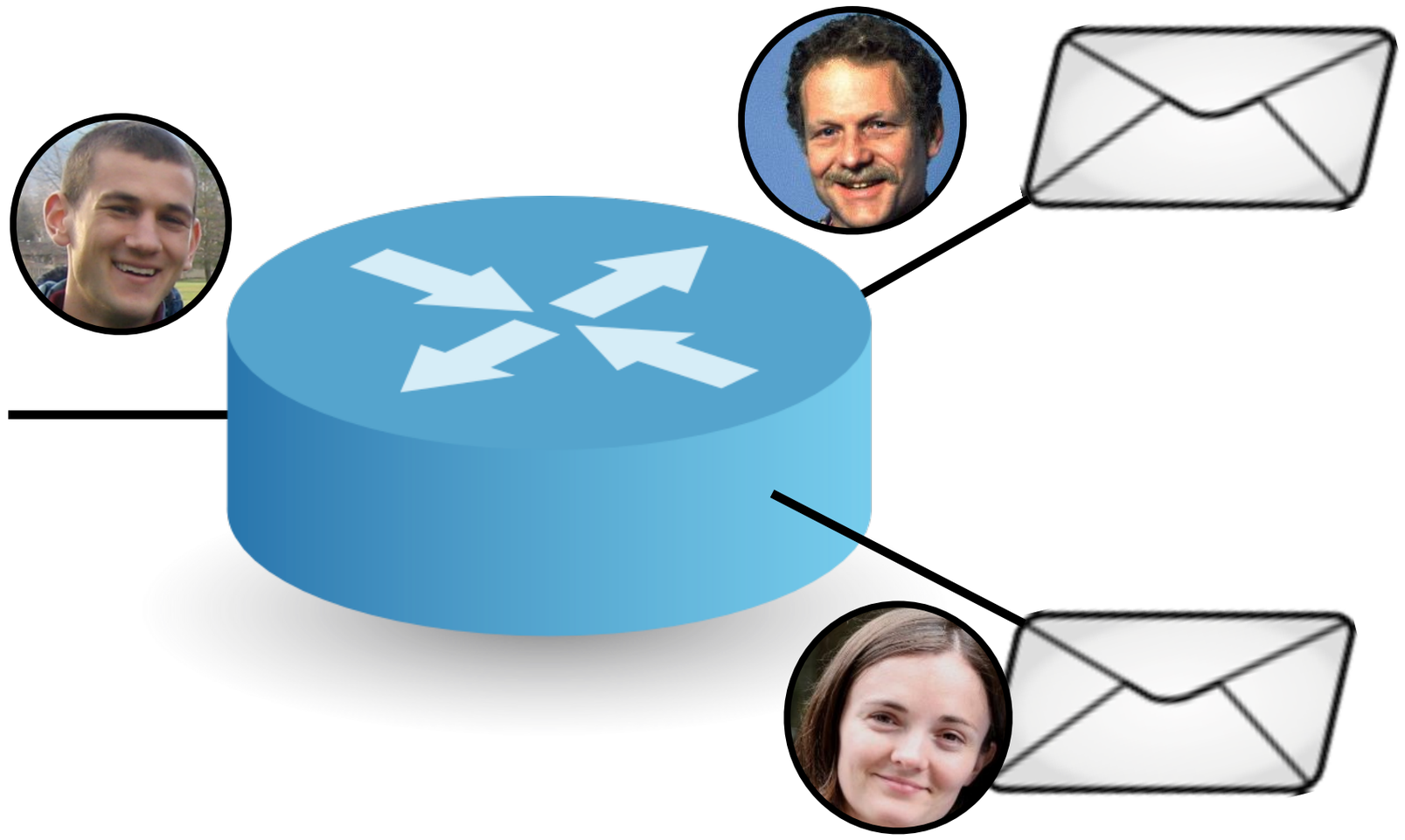
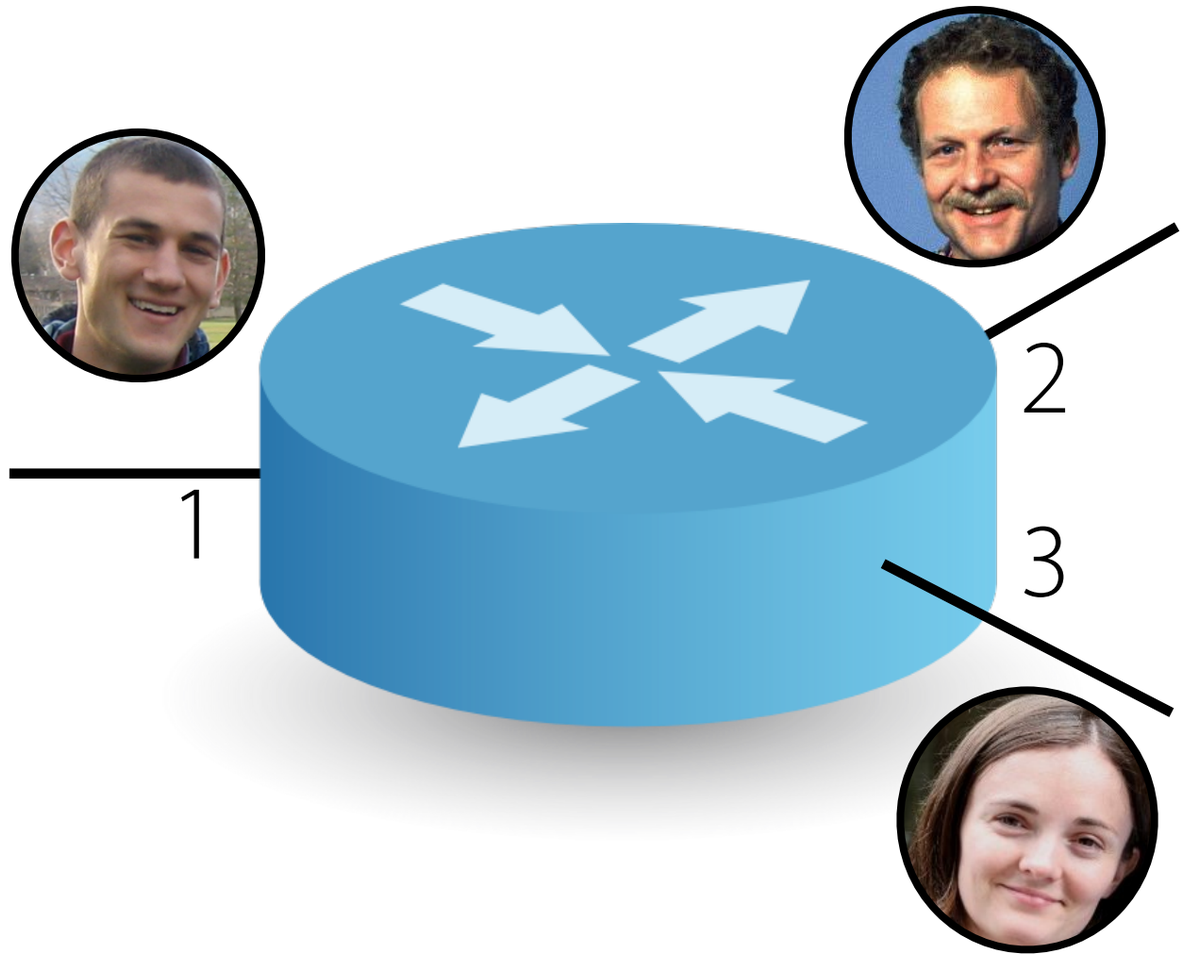


Repeater Hub

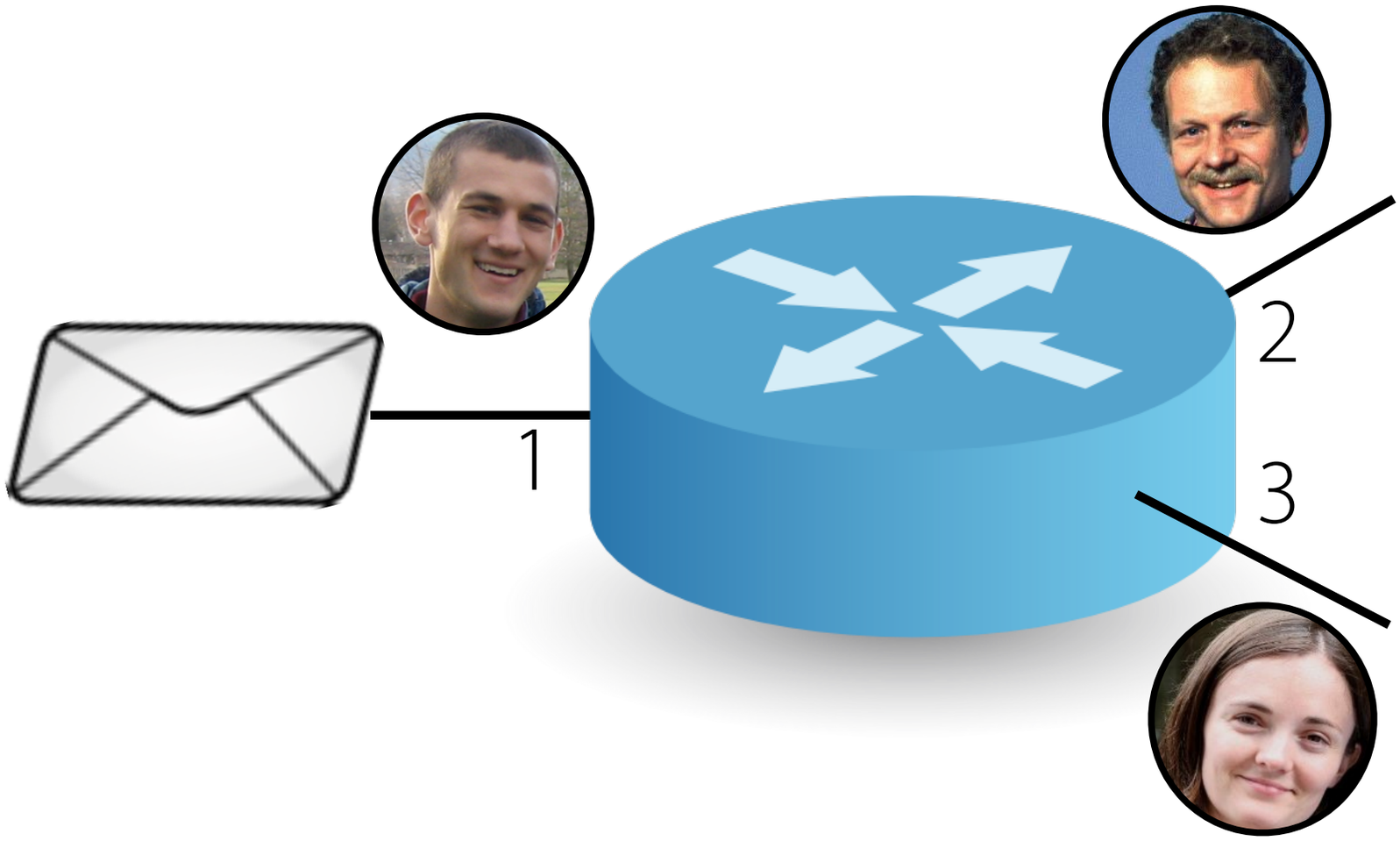


Floods packets out on all ports, except the ingress—i.e., the port it arrived on.

Ethernet Switch



Ethernet Switch



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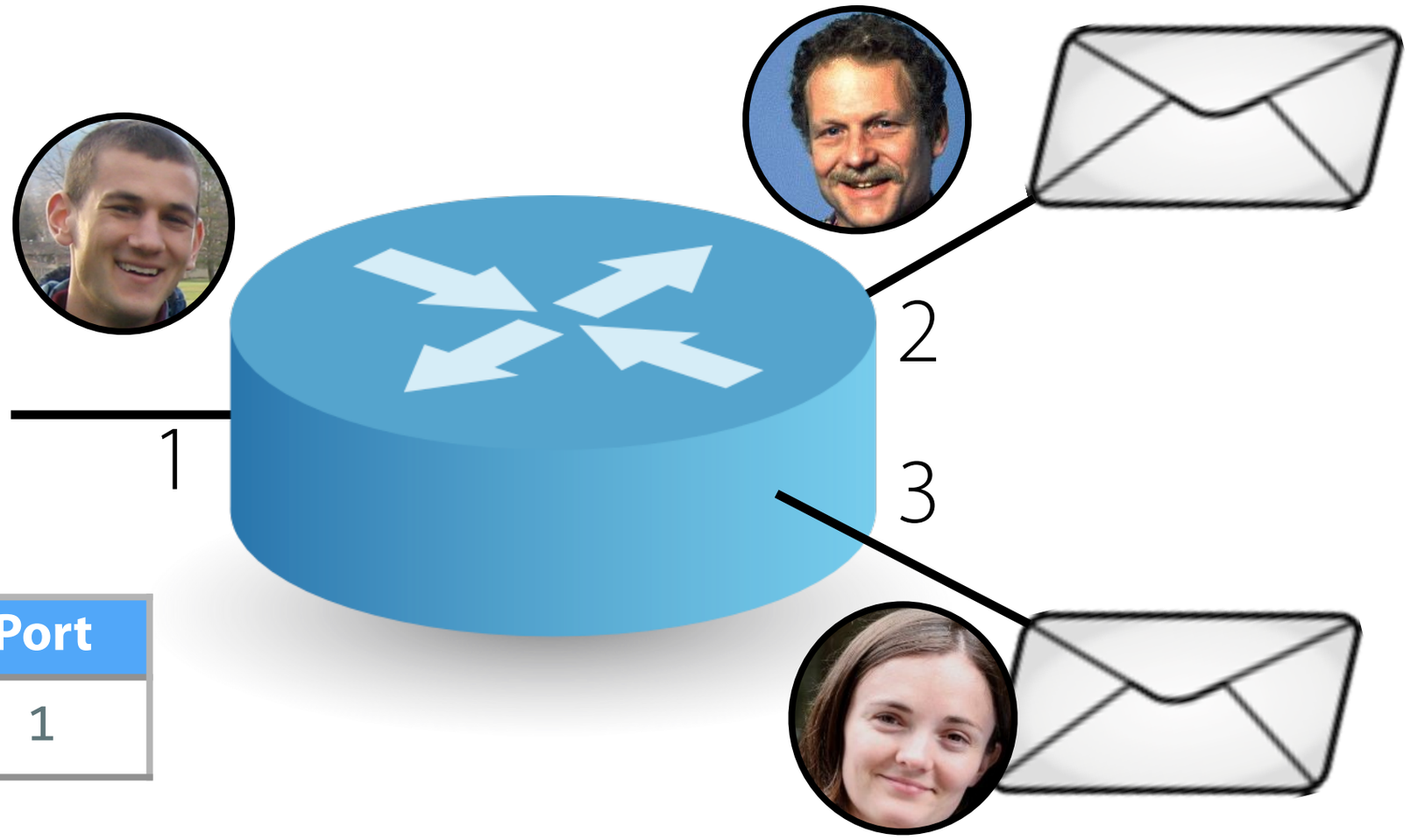
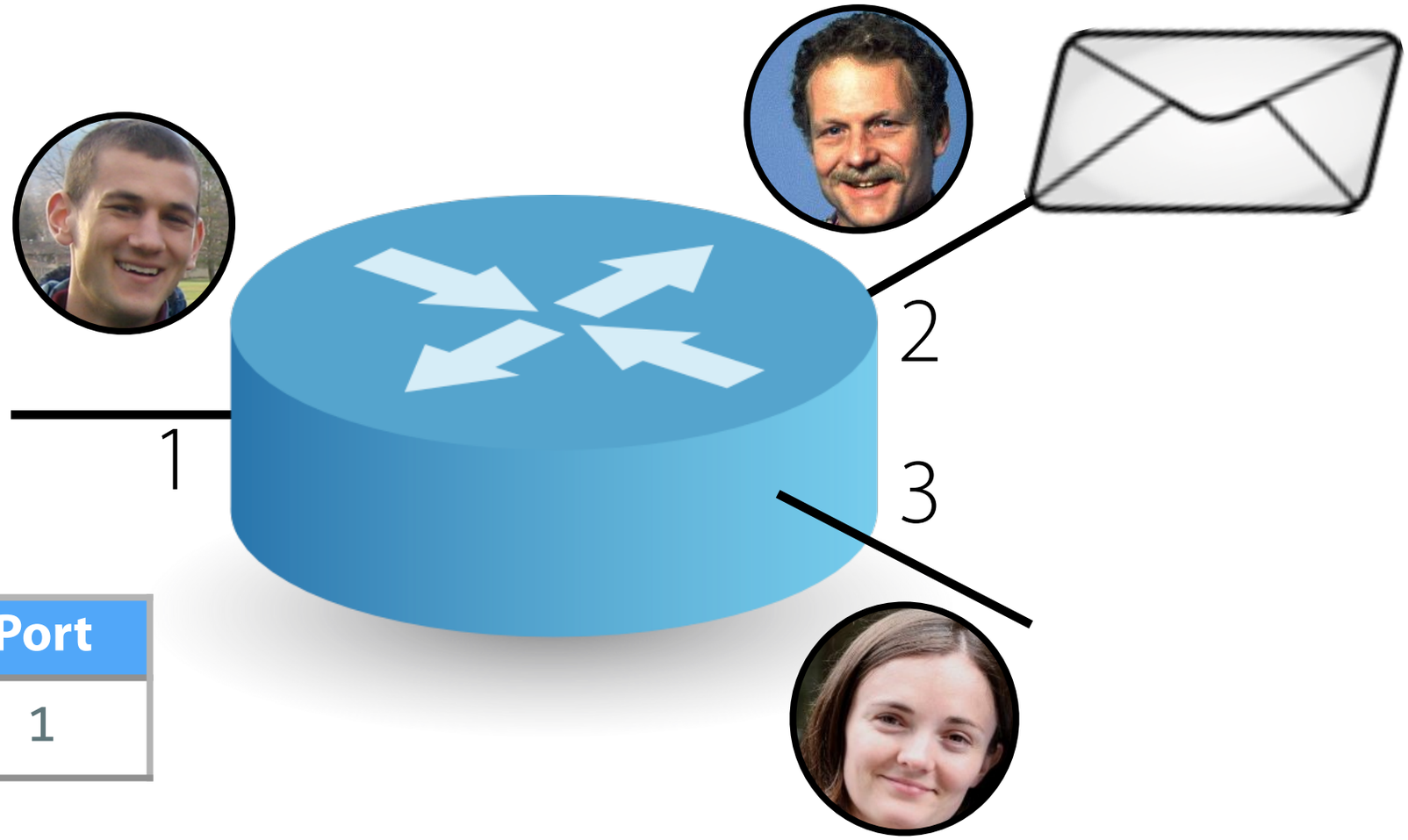


Src	Port
Nate	1

Ethernet Switch



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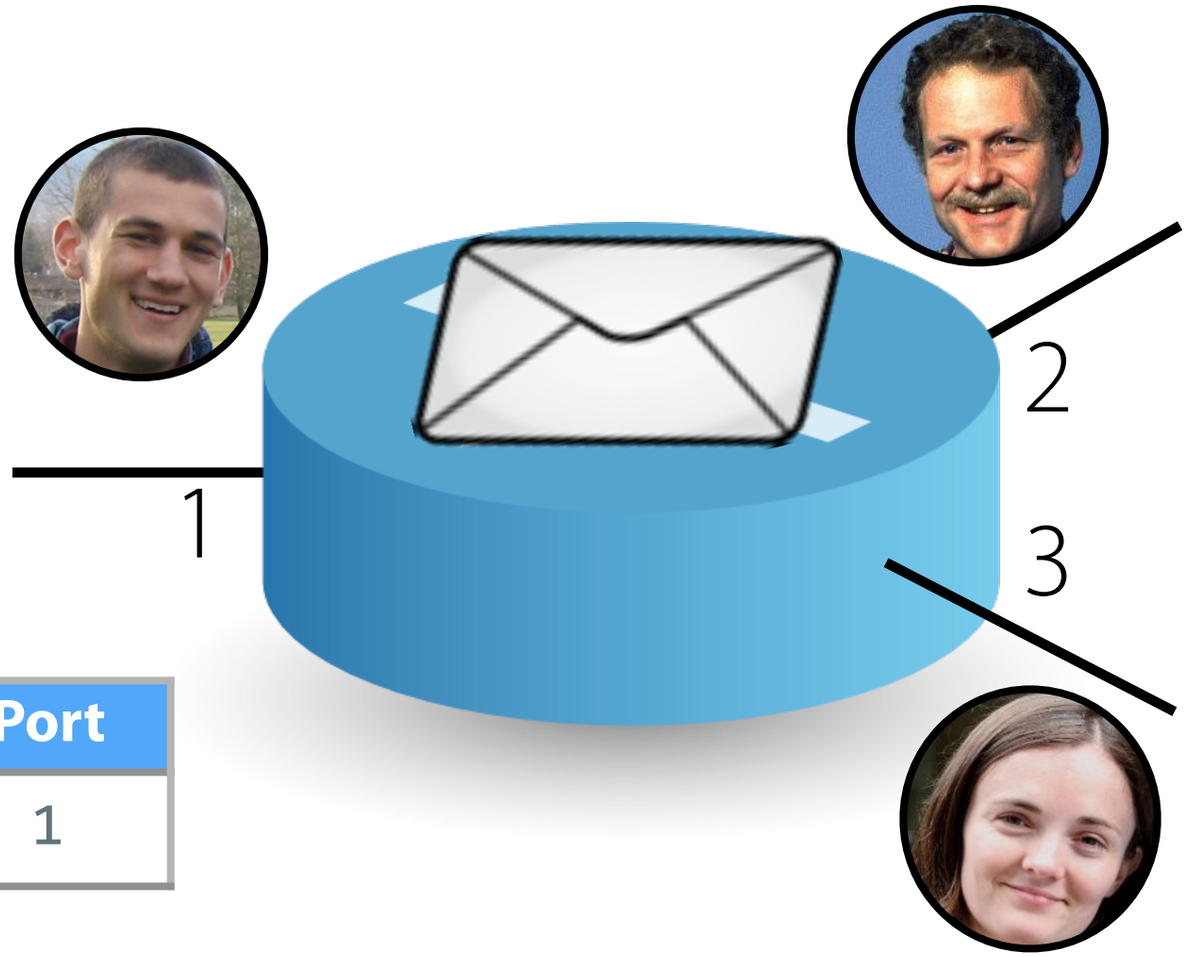
Ethernet Switch



Src	Port
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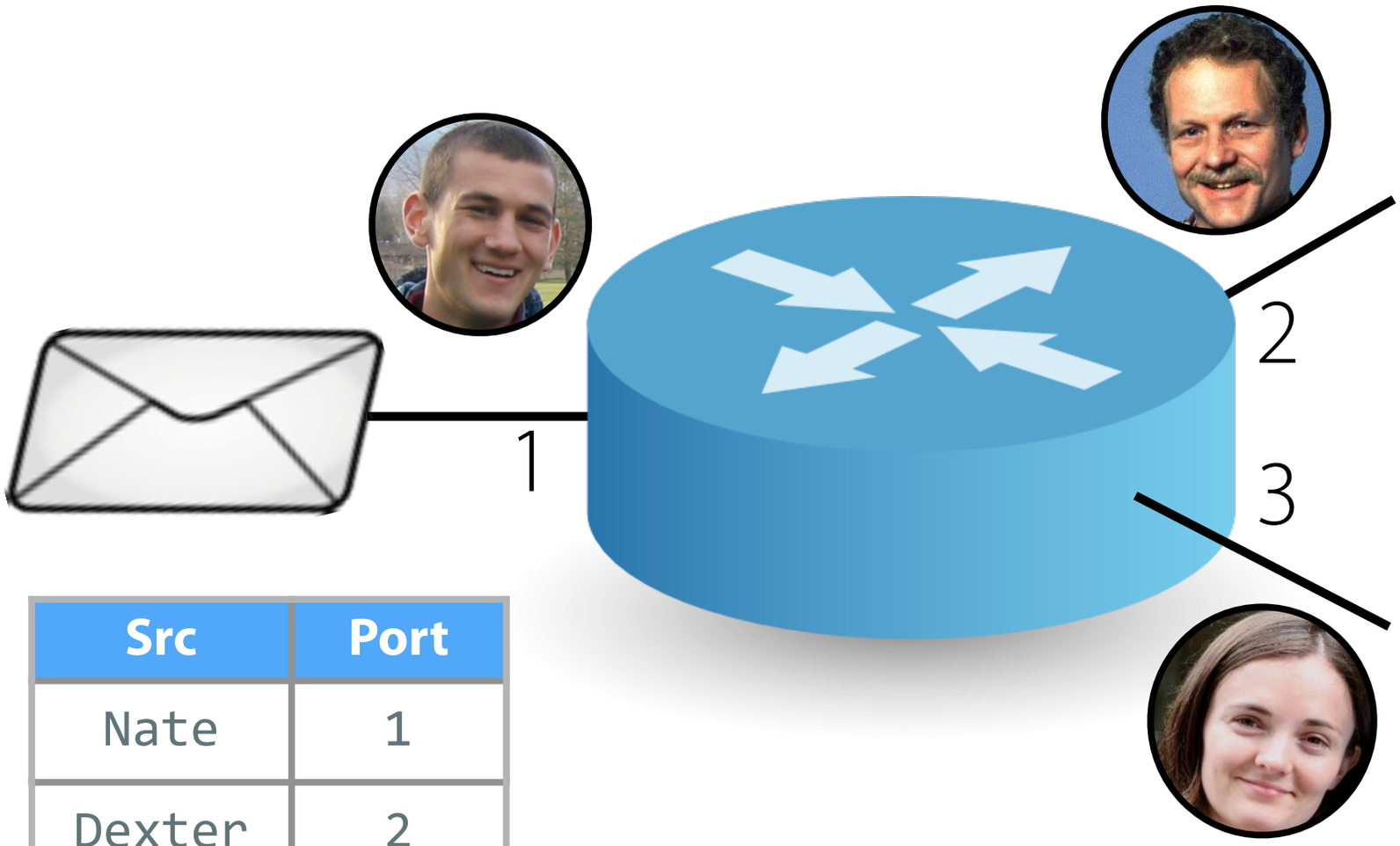
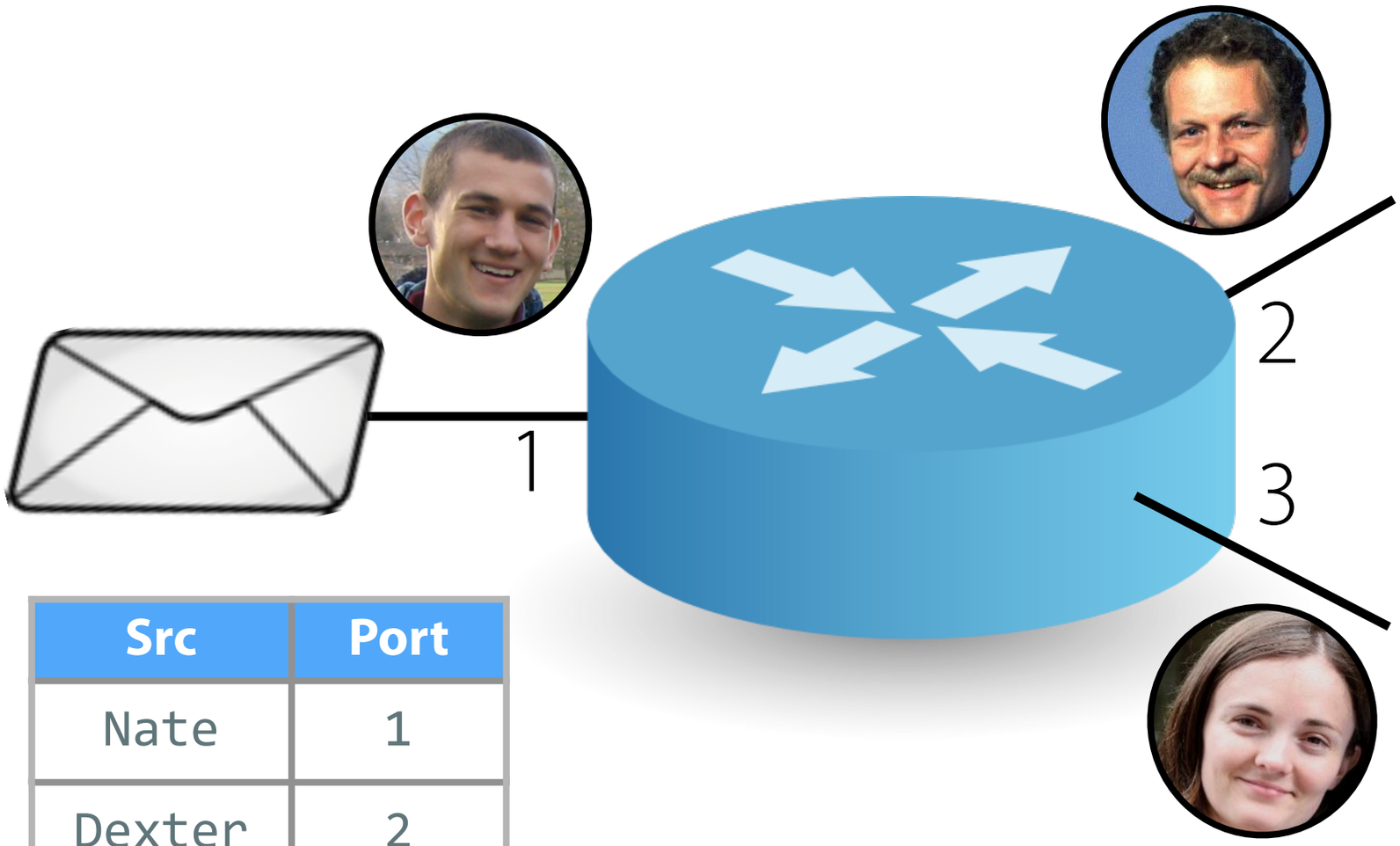
Ethernet Switch



Src	Port
Nate	1
Dexter	2

Ethernet Switch



Src	Port
Nate	1
Dexter	2

- Learn locations of hosts in a table
- Flood packets going to unknown hosts; forward packets directly to known hosts

Learning Switch

```
let known_hosts : (dlAddr,portId) Hashtbl.t = Hashtbl.create 101

let learning_packet_in (sw:switchId) (pktIn:packetIn) : unit =
  Hashtbl.add known_hosts pk.dlSrc pktIn.port

let routing_packet_in (sw:switchId) (pktIn : packetIn) : unit =
  try
    let out_port = Hashtbl.find known_hosts pk.dlDst in
    let sd = {match_all with dlDst=Some pk.dlDst; dlSrc=Some pk.dlSrc} in
    let ds = {match_all with dlDst=Some pk.DlSrc; dlSrc=Some pk.dlDst} in
    send_flow_mod sw 0l (add_flow 0 sd [Output out_port]);
    send_flow_mod sw 0l (add_flow 0 ds [Output pktIn.port]);
    send_packet_out sw 0l
      { output_payload = pktIn.input_payload;
        port_id = None;
        apply_actions = [Output out_port] }
  with Not_found ->
   send_packet_out sw 0l
   { output_payload = pktIn.input_payload;
     port_id = None;
     apply_actions = [Flood] }

let packet_in (sw:switchId) _ (pk:packetIn) : unit =
  learning_packet_in sw pk; routing_packet_in sw pk
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      { output_payload = pktIn.input_payload;
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    let out_port = Hashtbl.find known_hosts pk.dlDst in
    let sd = {match_all with dlDst=Some pk.dlDst; dlSrc=Some pk.dlSrc} in
    let ds = {match_all with dlDst=Some pk.DlSrc; dlSrc=Some pk.dlDst} in
    send_flow_mod sw 0l (add_flow 0 sd [Output out_port]);
    send_flow_mod sw 0l (add_flow 0 ds [Output pktIn.port]);
    send_packet_out sw 0l
      { output_payload = pktIn.input_payload;
        port_id = None;
        apply_actions = [Output out_port] }
  with Not_found ->
   send_packet_out sw 0l
   { output_payload = pktIn.input_payload;
     port_id = None;
     apply_actions = [Flood] }

let packet_in (sw:switchId) _ (pk:packetIn) : unit =
  learning_packet_in sw pk; routing_packet_in sw pk
```
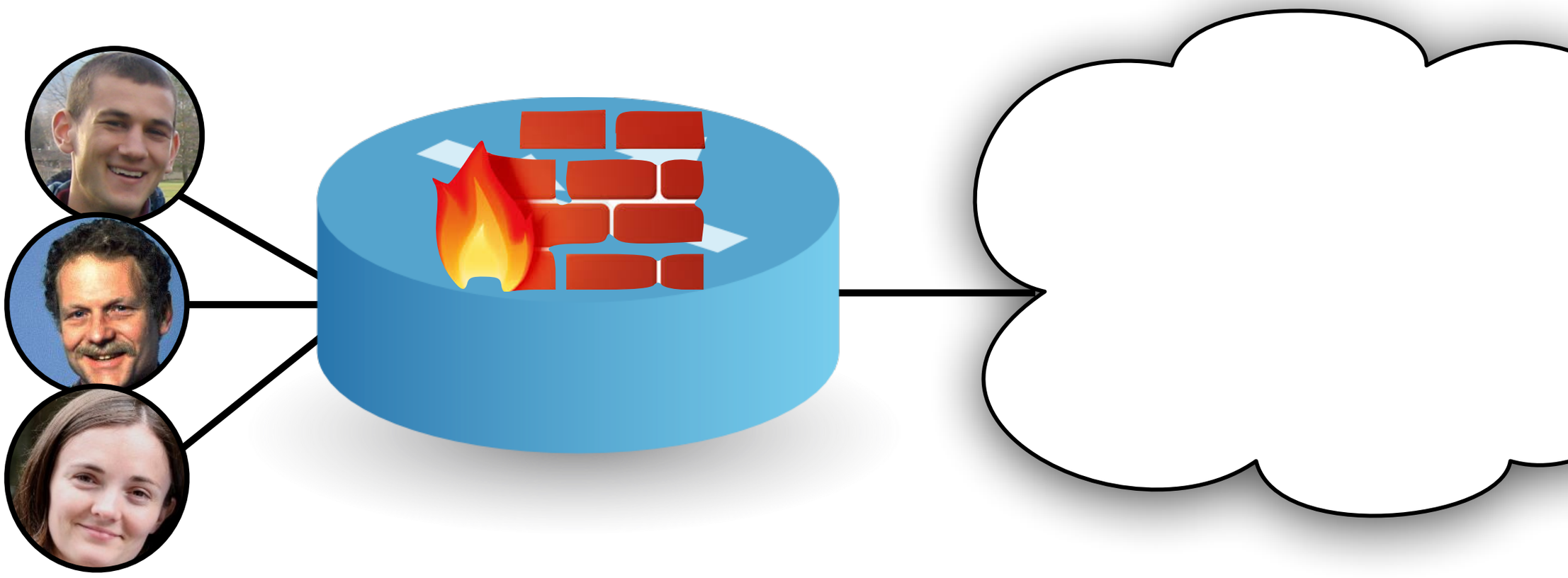
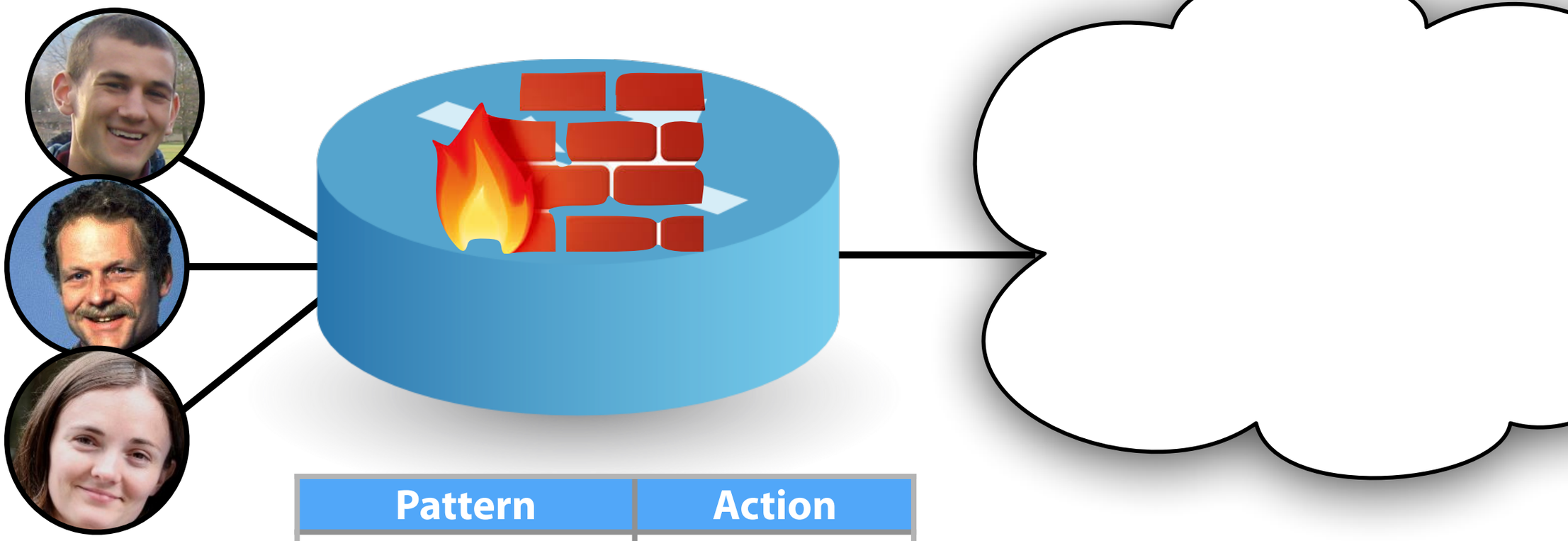

Learning Switch

```
let known_hosts : (dlAddr,portId) Hashtbl.t = Hashtbl.create 101

let learning_packet_in (sw:switchId) (pktIn:packetIn) : unit =
  Hashtbl.add known_hosts pk.dlSrc pktIn.port

let routing_packet_in (sw:switchId) (pktIn : packetIn) : unit =
  try
    let out_port = Hashtbl.find known_hosts pk.dlDst in
    let sd = {match_all with dlDst=Some pk.dlDst; dlSrc=Some pk.dlSrc} in
    let ds = {match_all with dlDst=Some pk.DlSrc; dlSrc=Some pk.dlDst} in
    send_flow_mod sw 0l (add_flow 0 sd [Output out_port]);
    send_flow_mod sw 0l (add_flow 0 ds [Output pktIn.port]);
    send_packet_out sw 0l
      { output_payload = pktIn.input_payload;
        port_id = None;
        apply_actions = [Output out_port] }
  with Not found ->
    send_packet_out sw 0l
    { output_payload = pktIn.input_payload;
      port_id = None;
      apply_actions = [Flood] }

let packet_in (sw:switchId) _ (pk:packetIn) : unit =
  learning_packet_in sw pk; routing_packet_in sw pk
```

Firewall

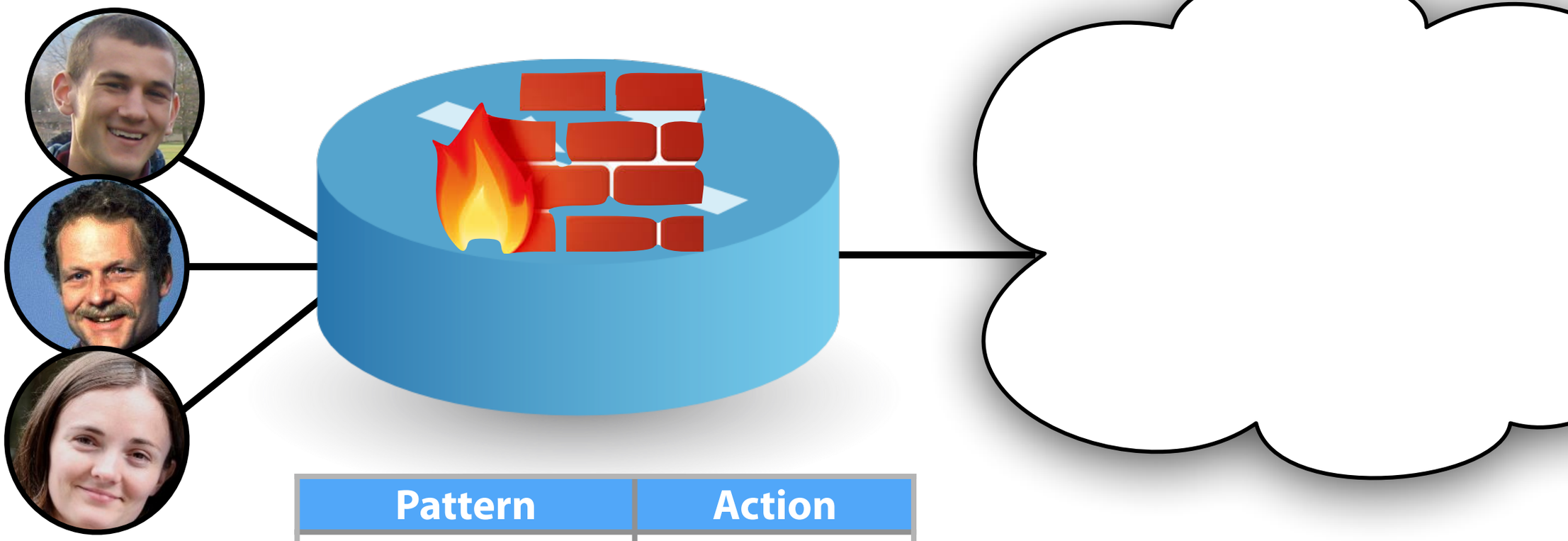


Firewall



Pattern	Action
dst=Nate	Allow
dst=Dexter	Deny
dst=Alexandra	Log

Firewall



Pattern	Action
dst=Nate	Allow
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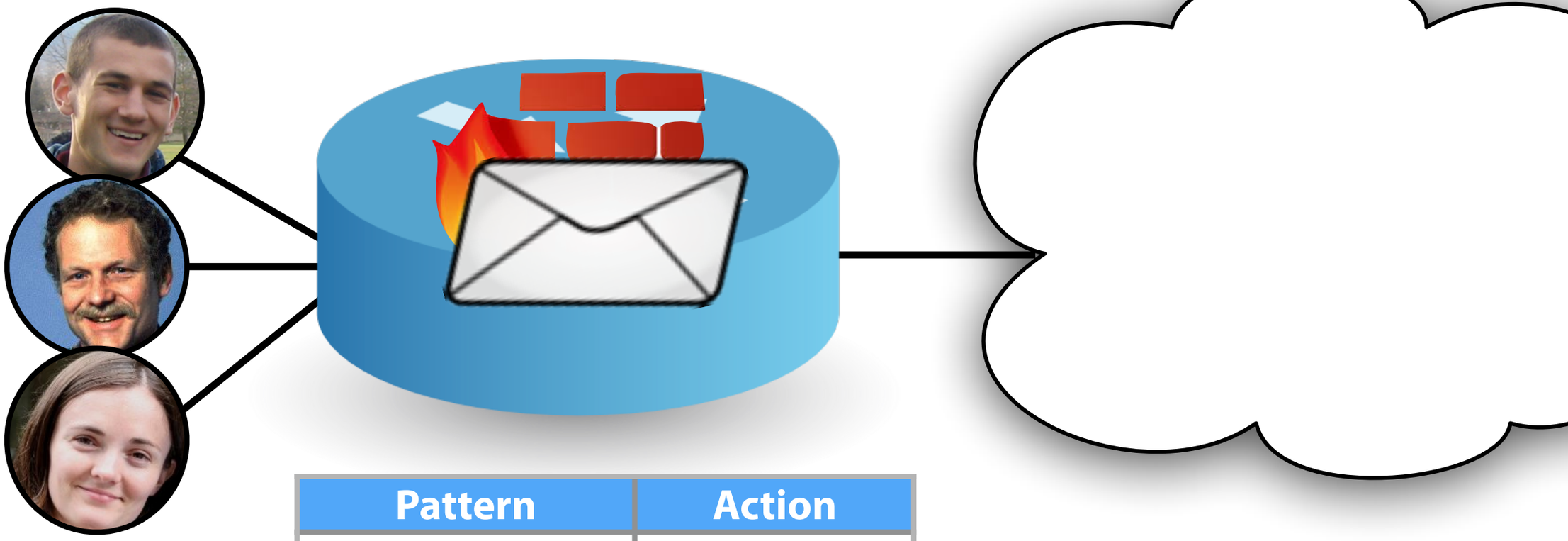
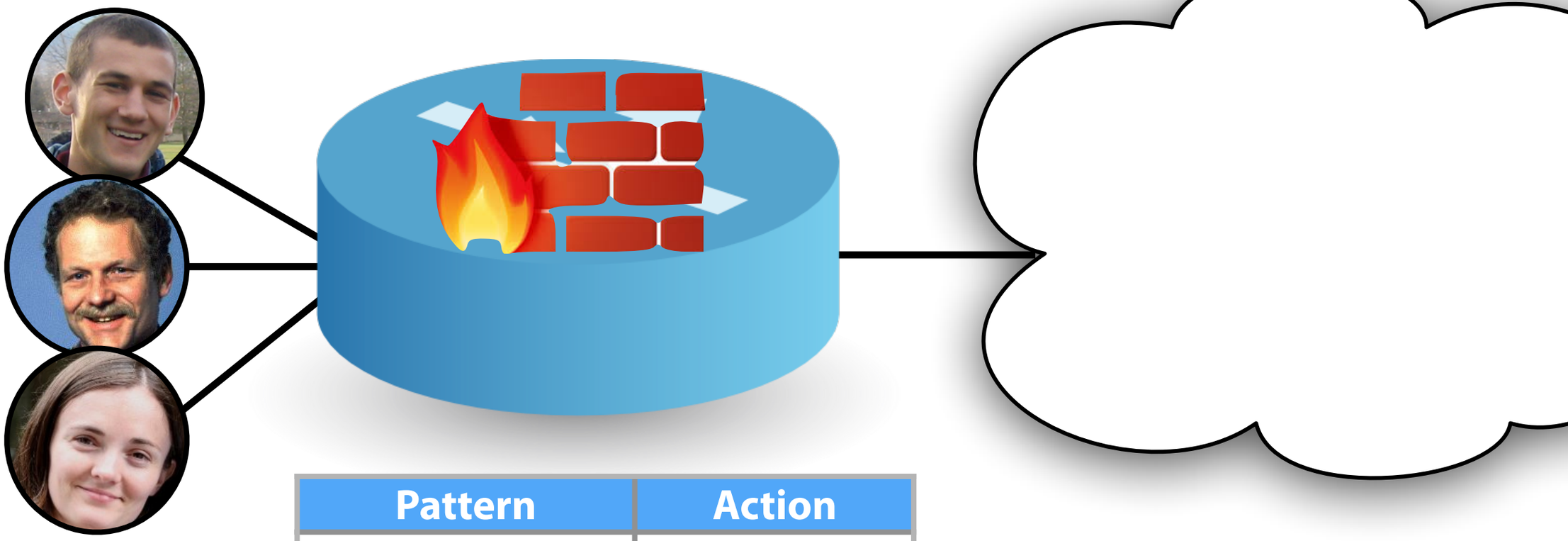
Firewall



Pattern	Action
dst=Nate	Allow
dst=Dexter	Deny
dst=Alexandra	Log

Firewall



Pattern	Action
dst=Nate	Allow
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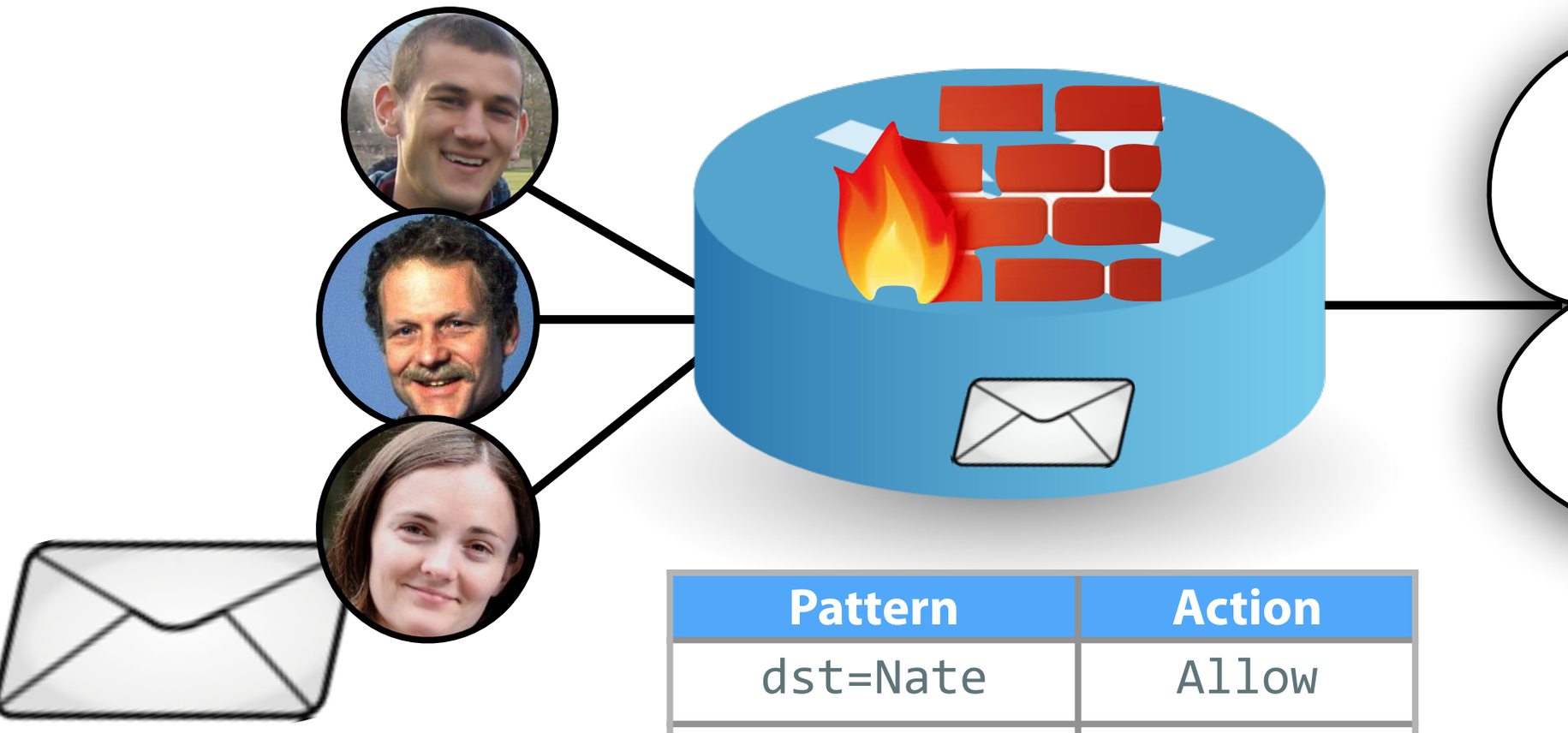
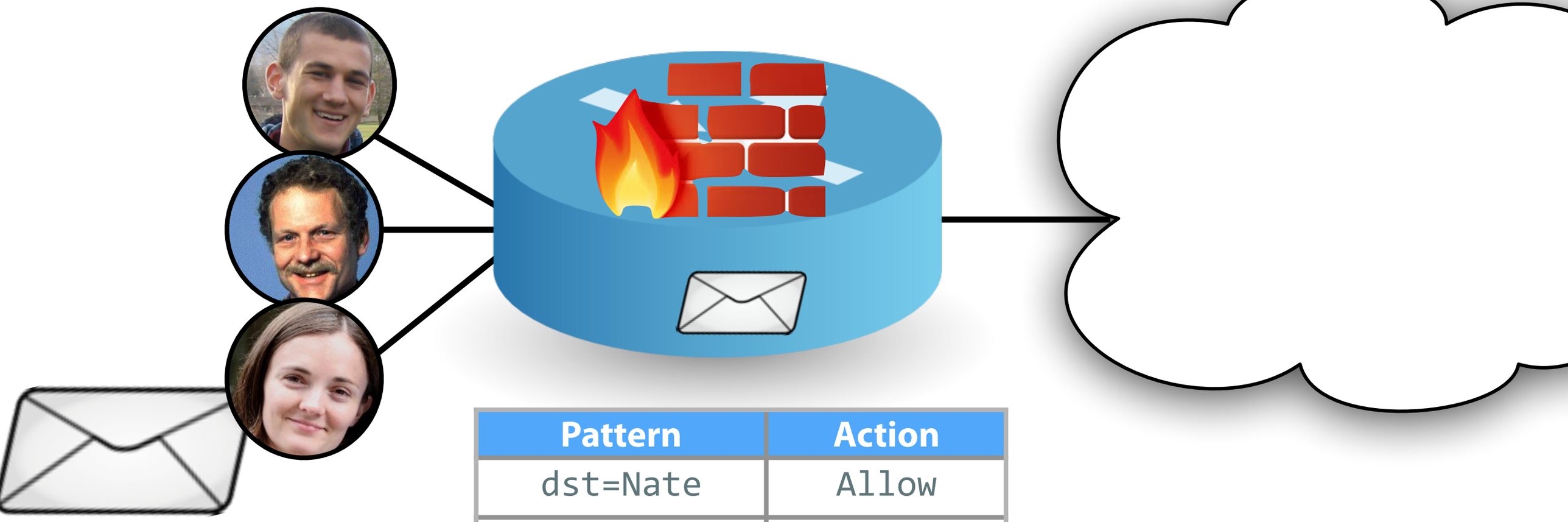
Firewall



Pattern	Action
dst=Nate	Allow
dst=Dexter	Deny
dst=Alexandra	Log

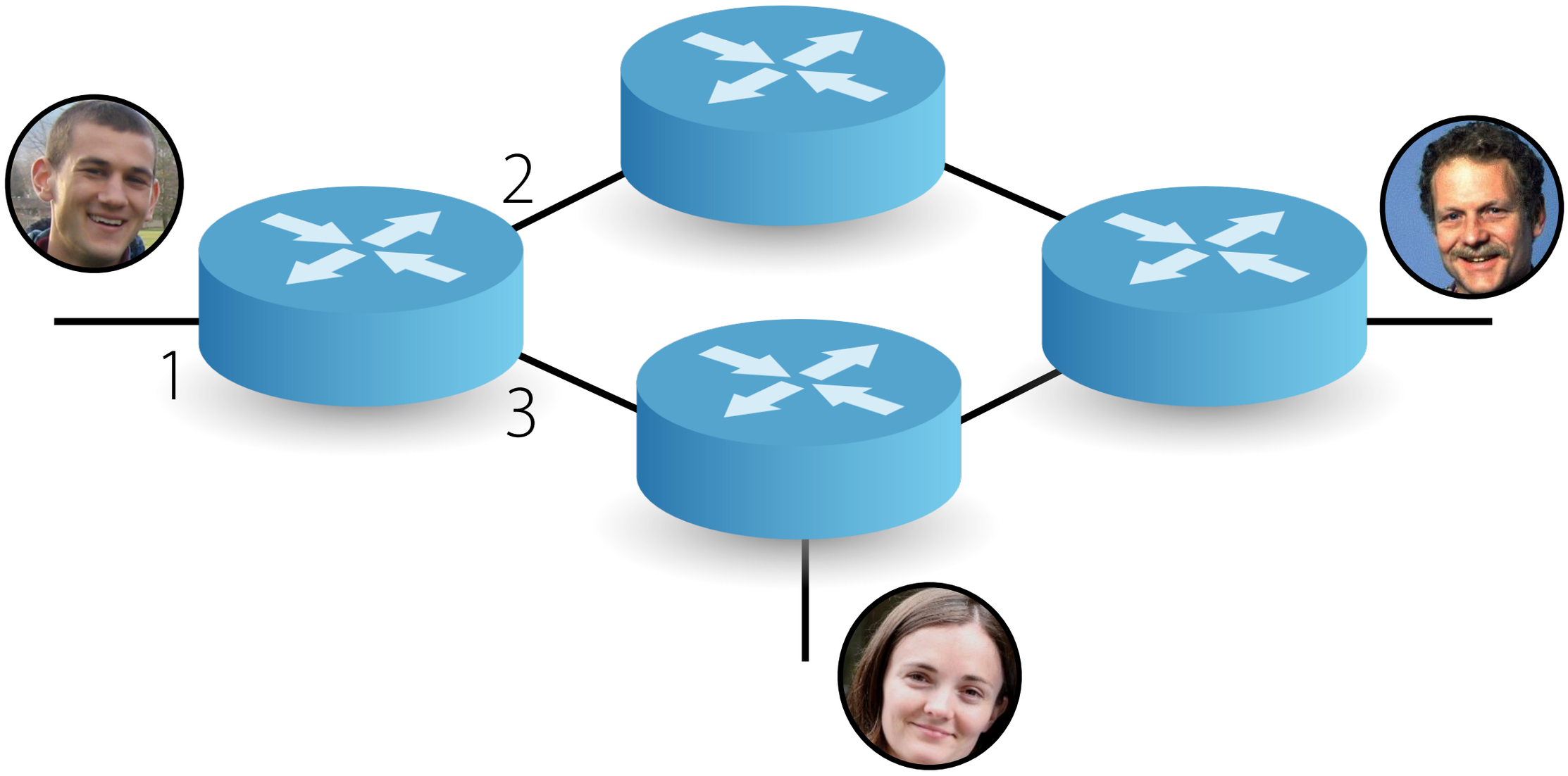
Firewall



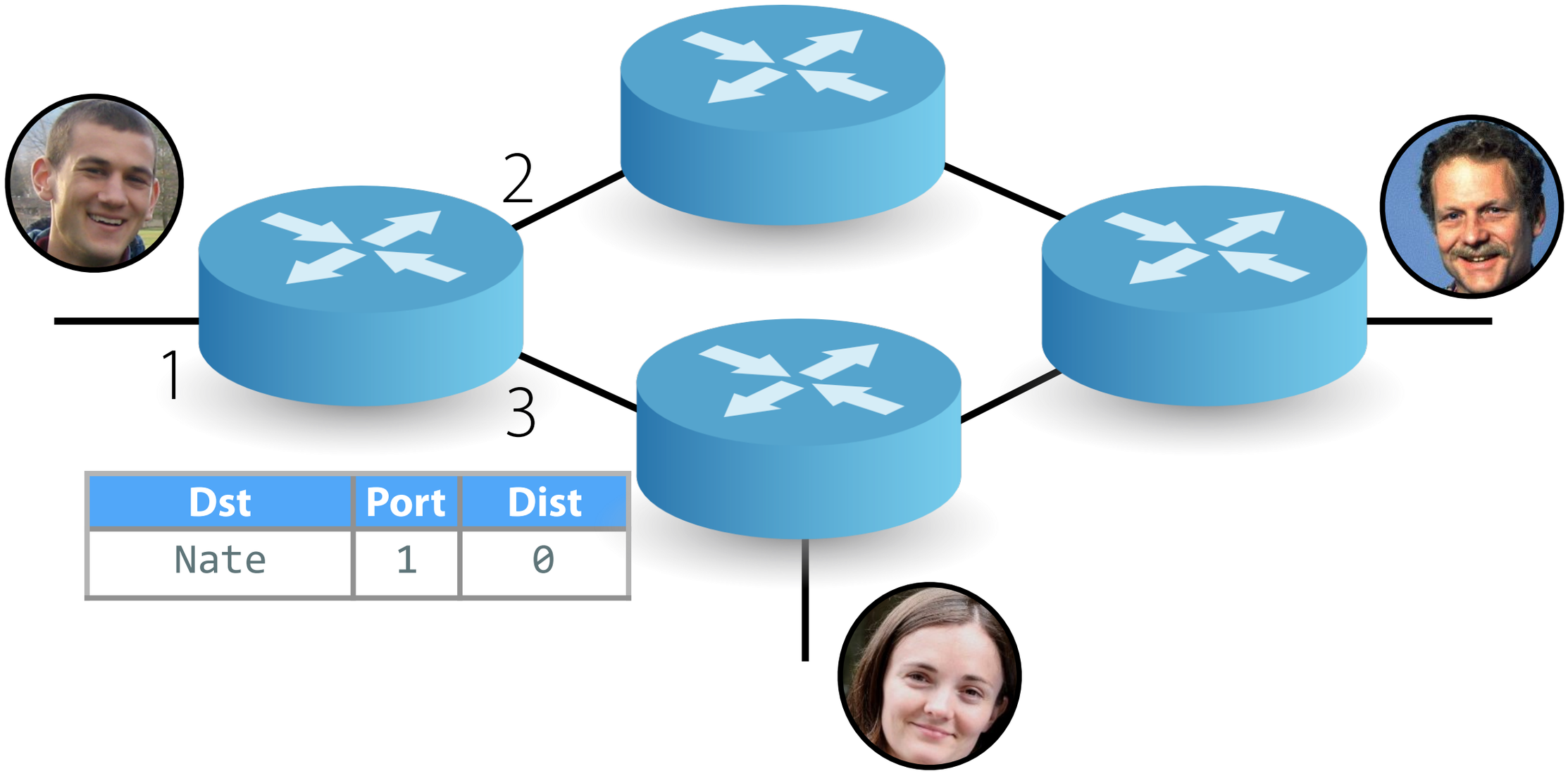
Pattern	Action
dst=Nate	Allow
dst=Dexter	Deny
dst=Alexandra	Log

Drops (or logs) packets from potentially malicious hosts

Router

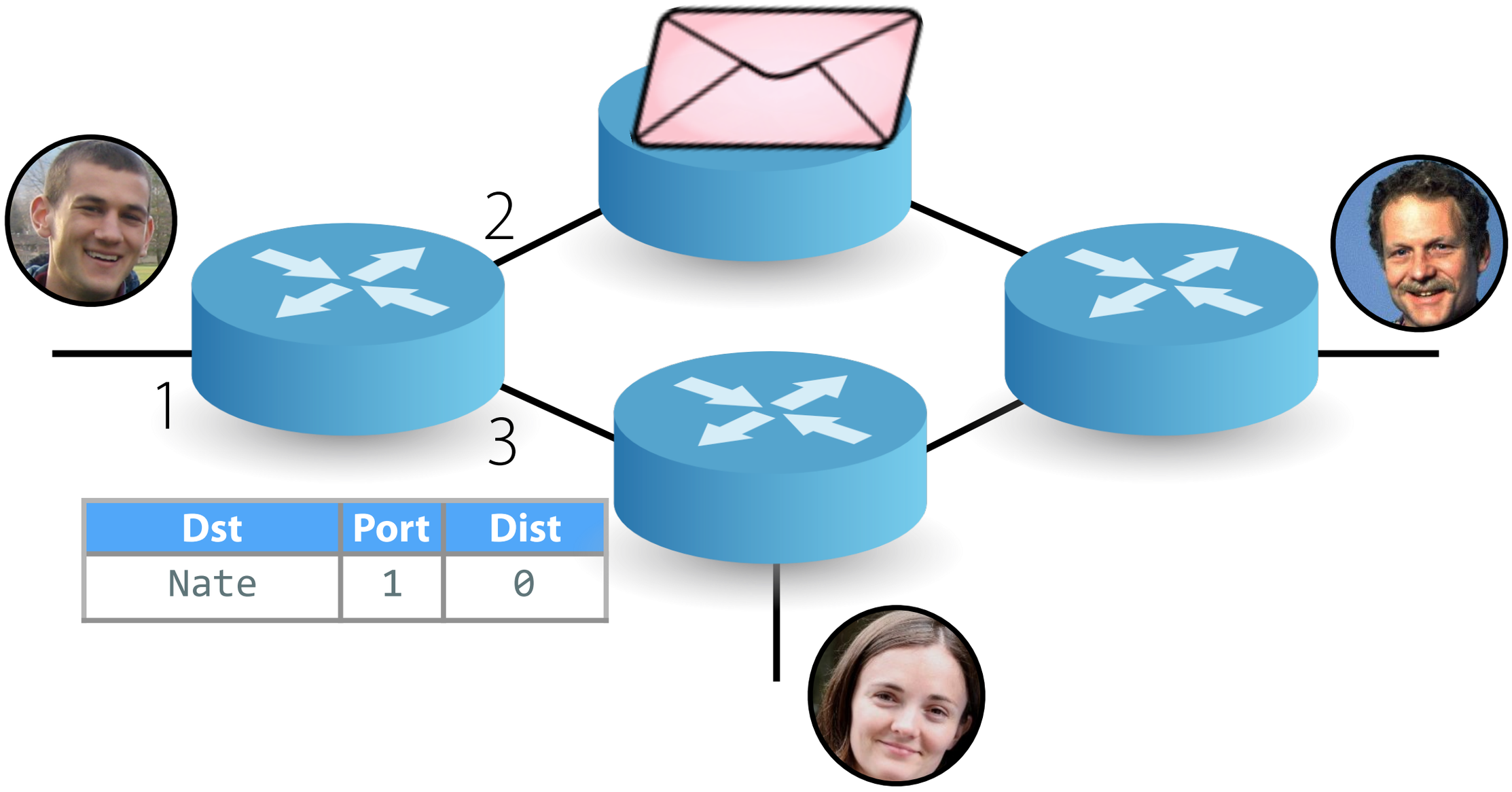


Router

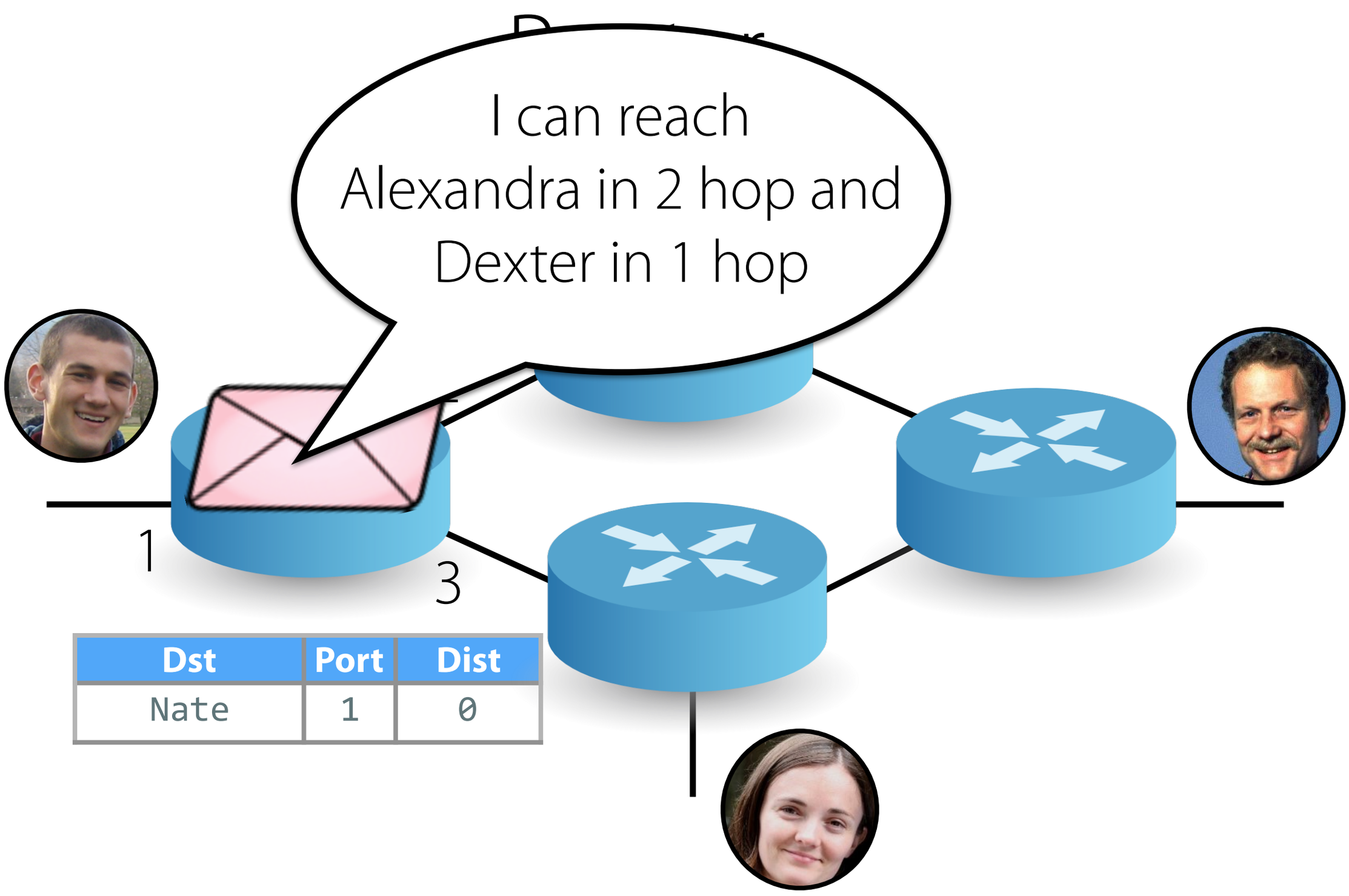


Dst	Port	Dist
Nate	1	0

Router

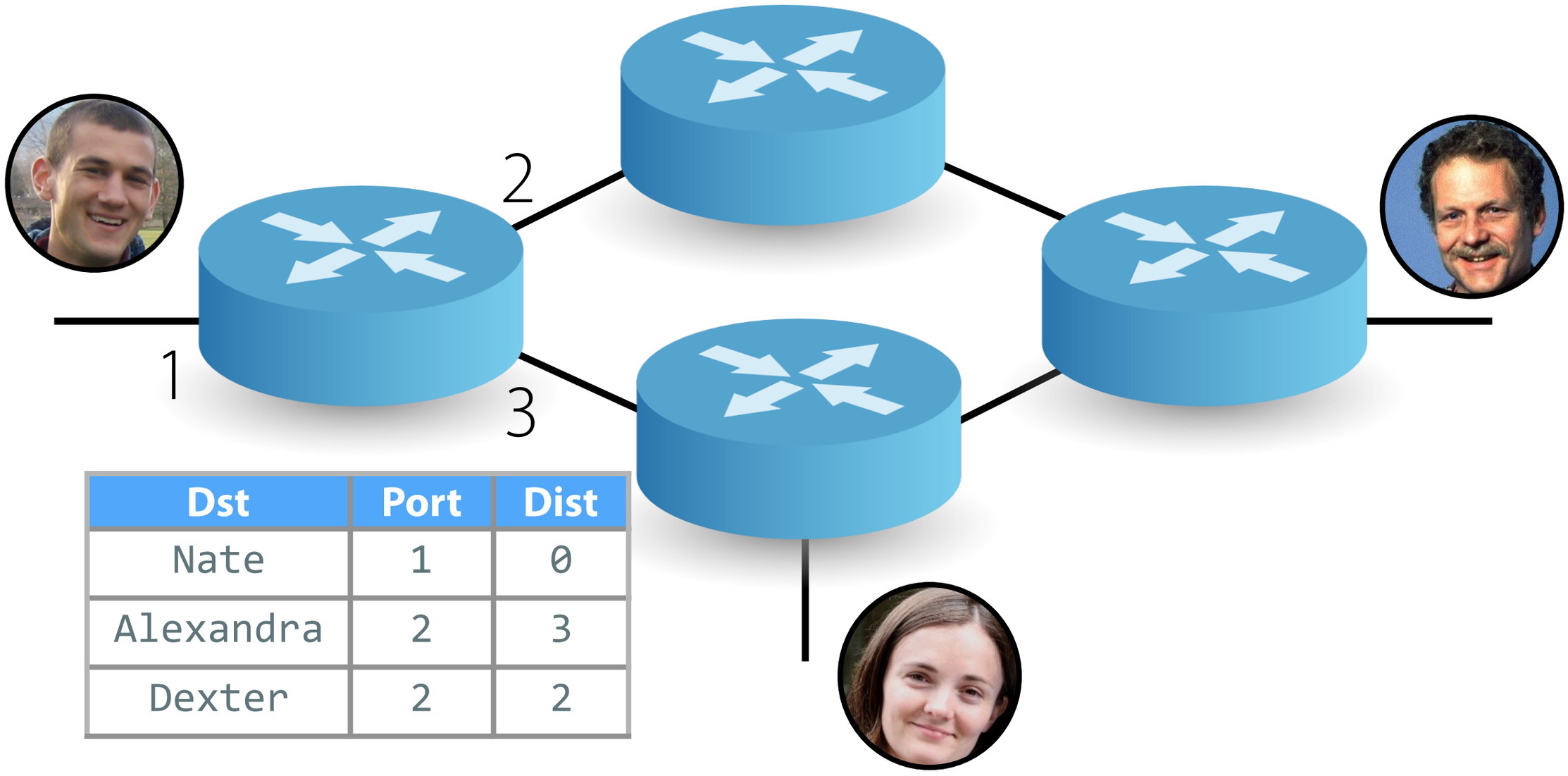


Dst	Port	Dist
Nate	1	0



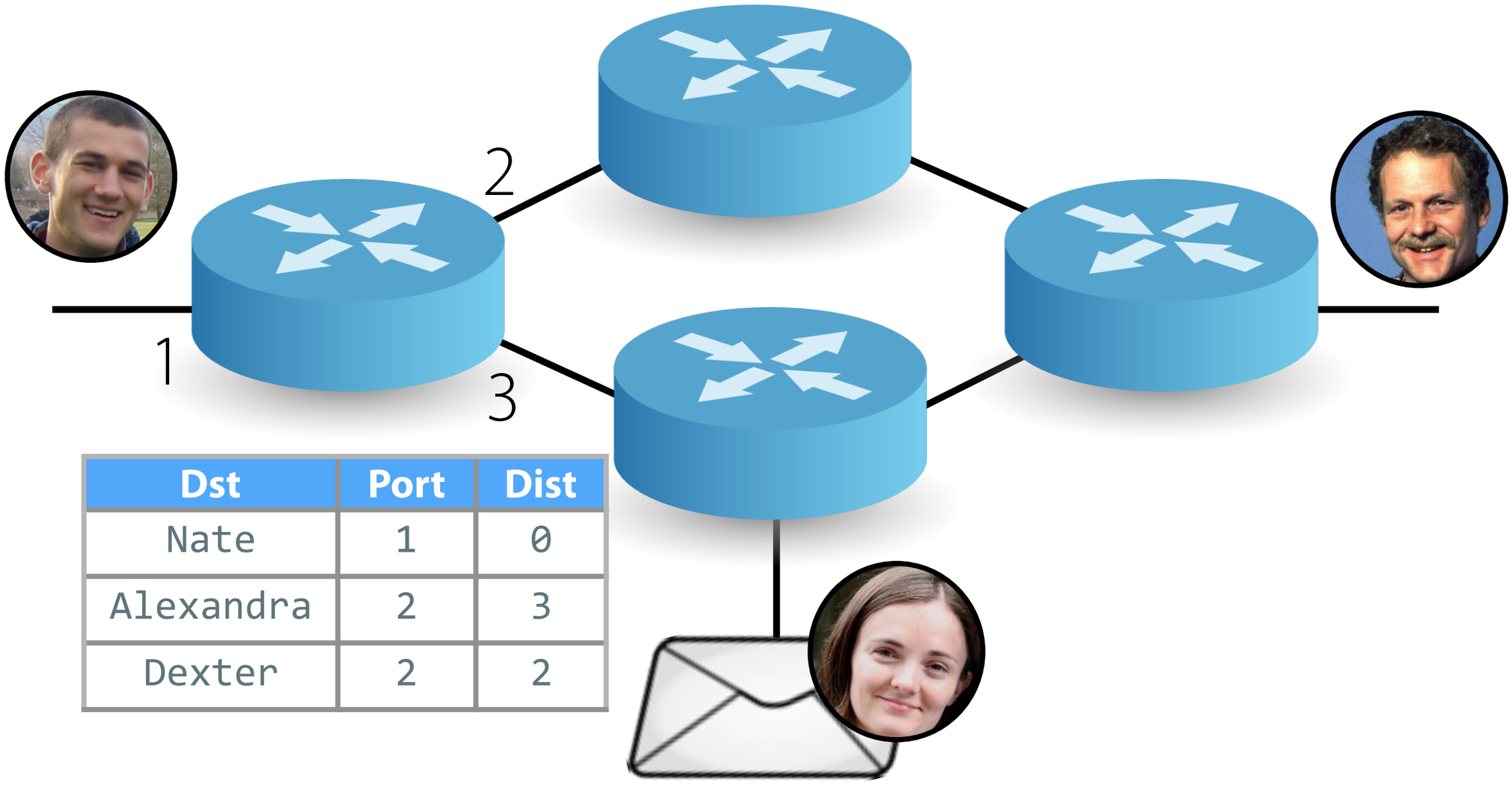
Dst	Port	Dist
Nate	1	0

Router



Dst	Port	Dist
Nate	1	0
Alexandra	2	3
Dexter	2	2

Router



Dst	Port	Dist
Nate	1	0
Alexandra	2	3
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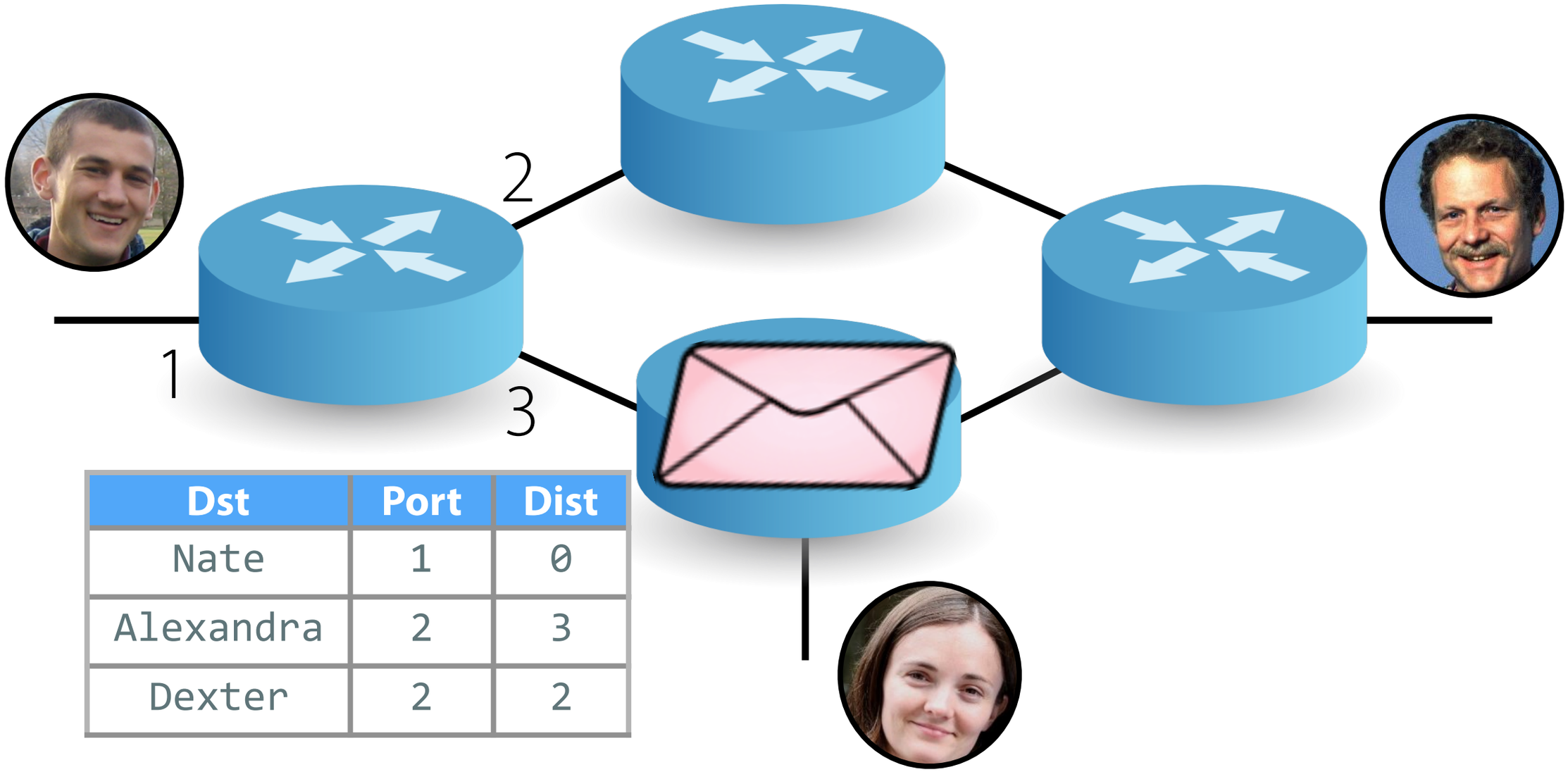
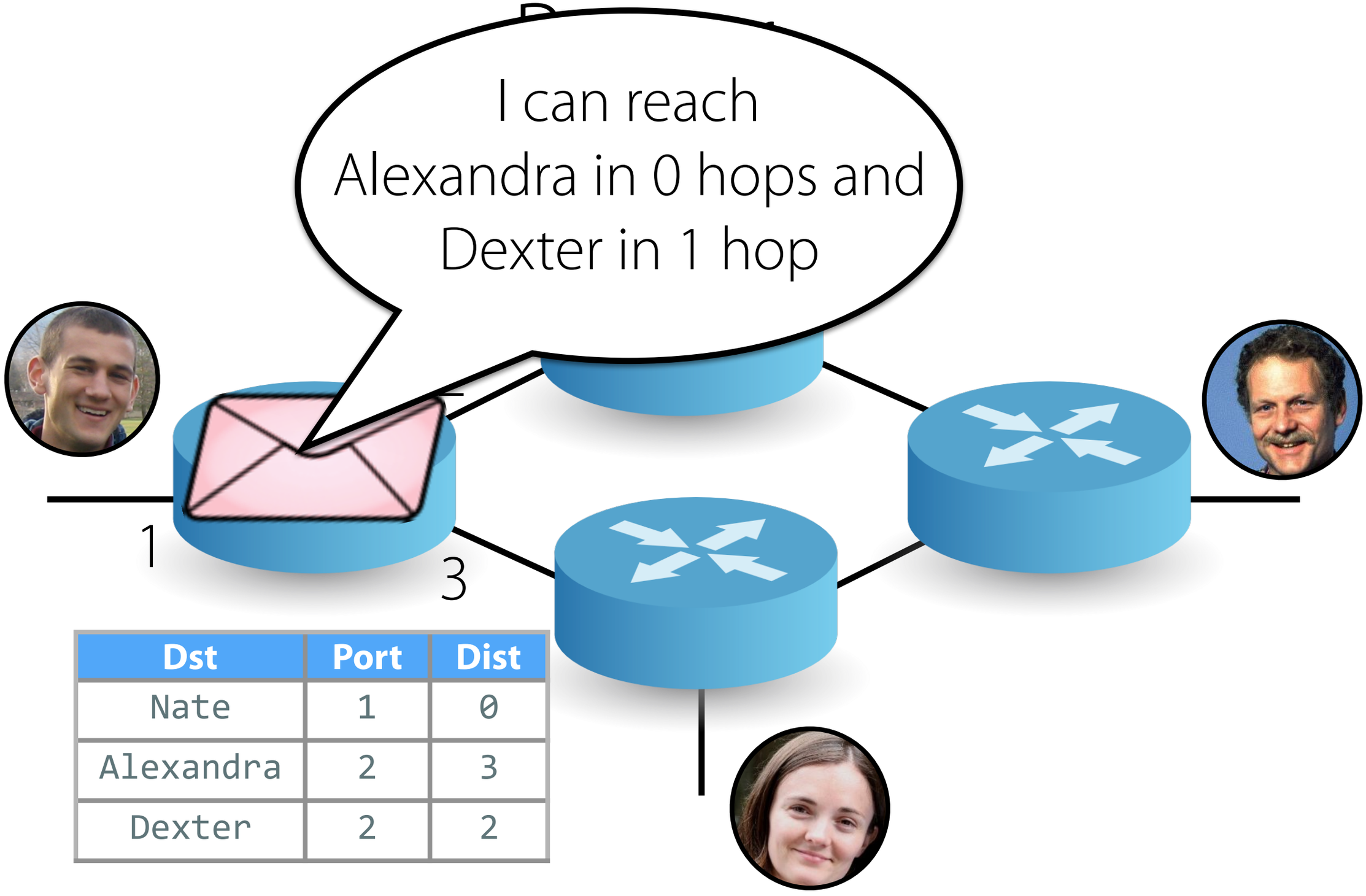
Router



Dst	Port	Dist
Nate	1	0
Alexandra	2	3
Dexter	2	2



Dst	Port	Dist
Nate	1	0
Alexandra	2	3
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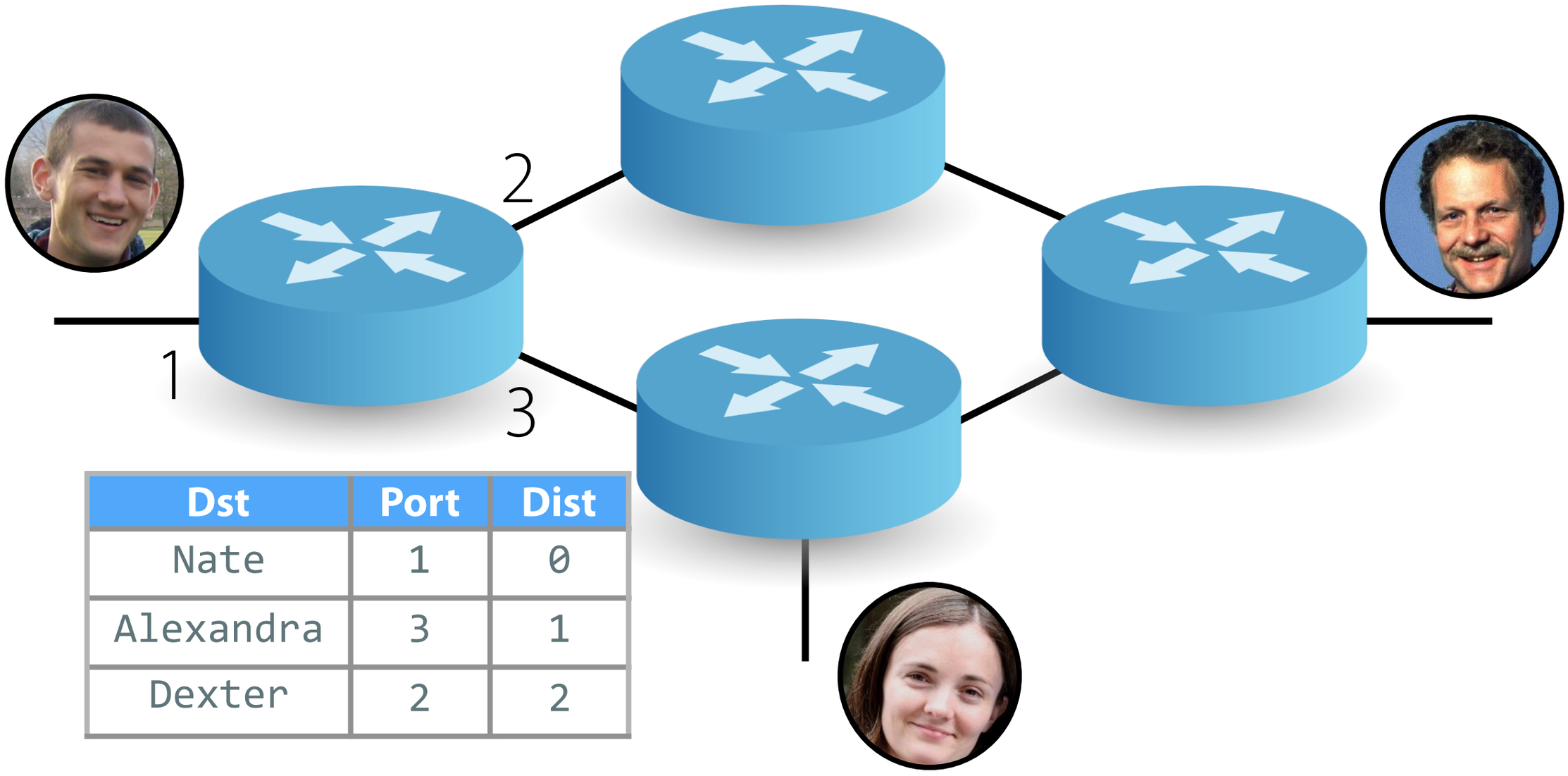
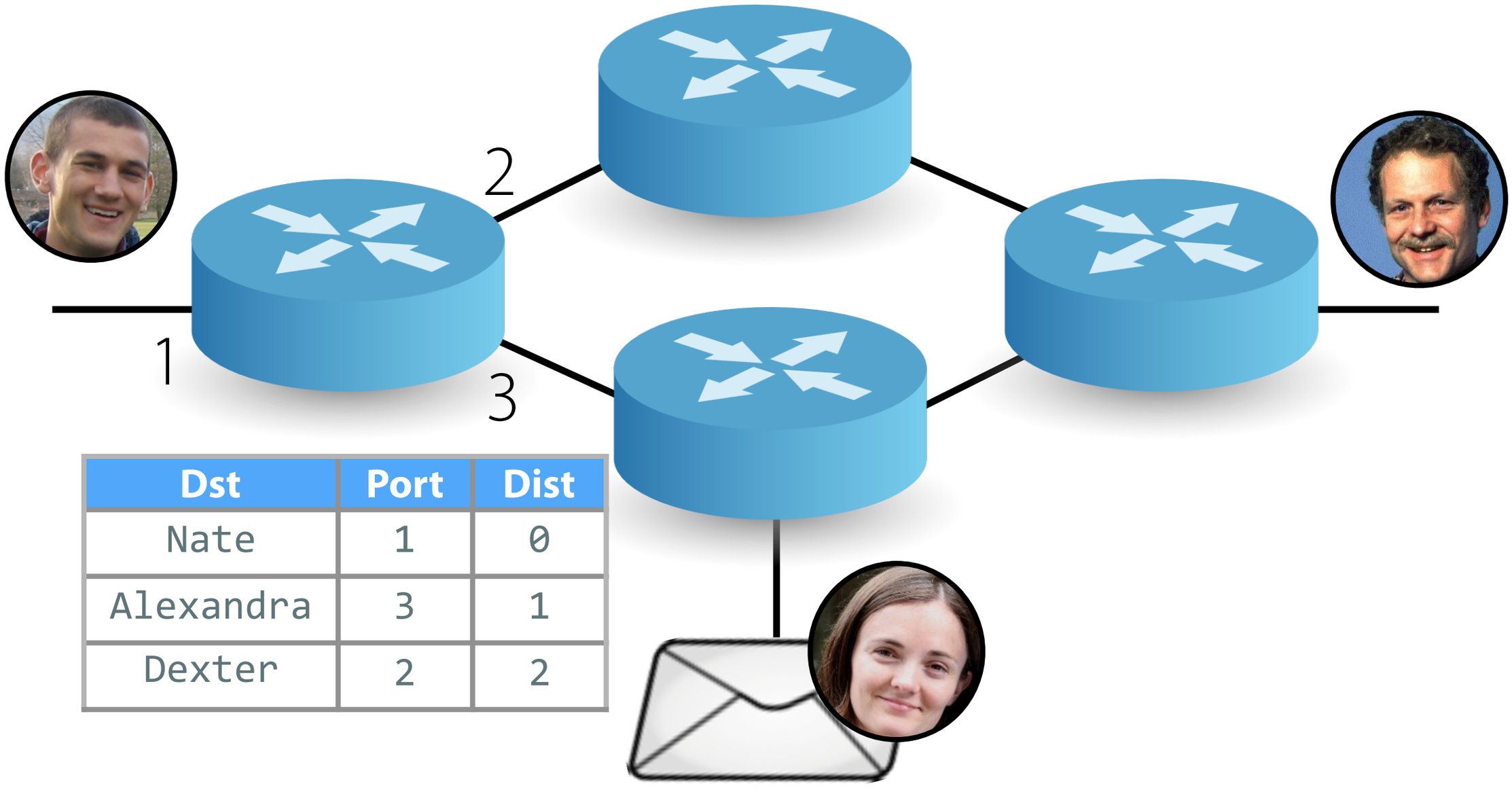
Router



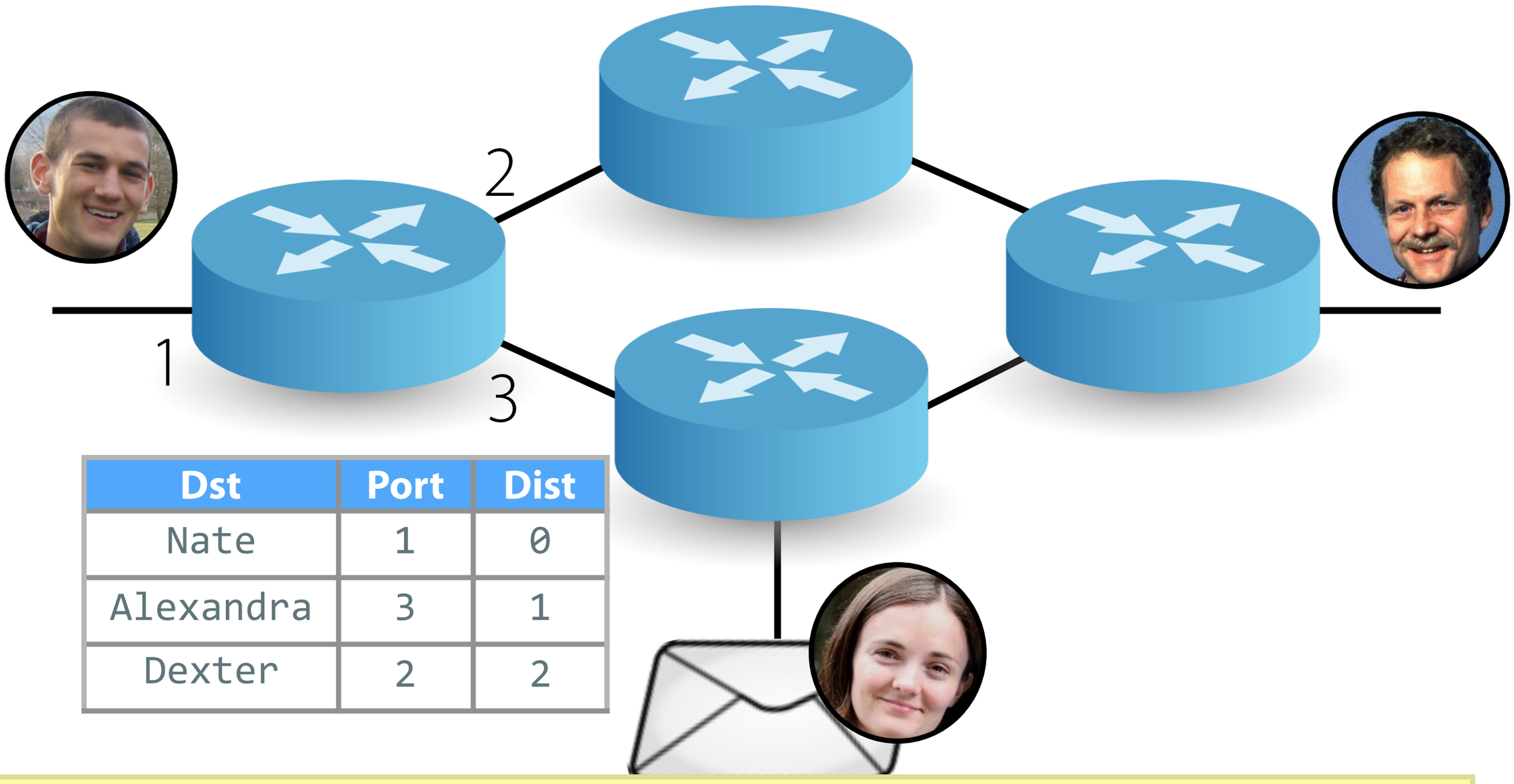
Dst	Port	Dist
Nate	1	0
Alexandra	3	1
Dexter	2	2

Router



Dst	Port	Dist
Nate	1	0
Alexandra	3	1
Dexter	2	2

Router



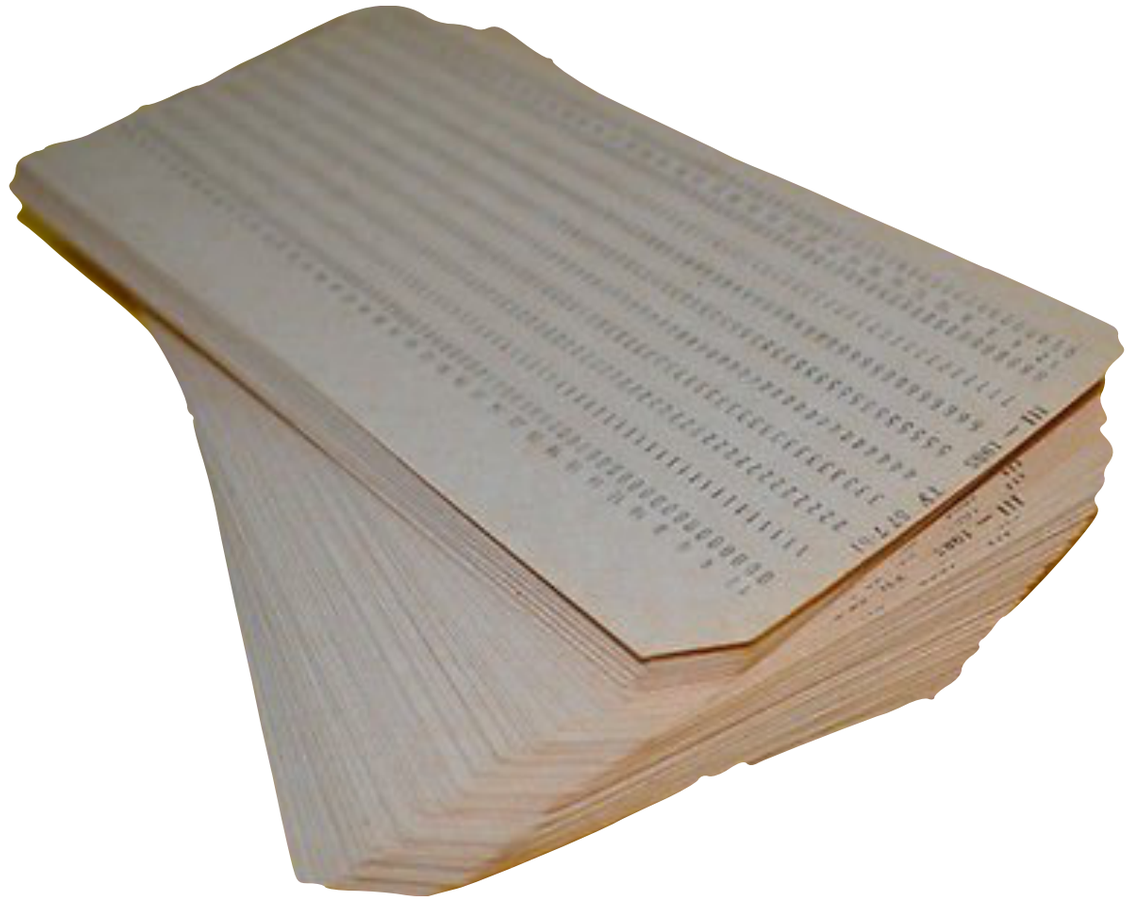
Dst	Port	Dist
Nate	1	0
Alexandra	3	1
Dexter	2	2

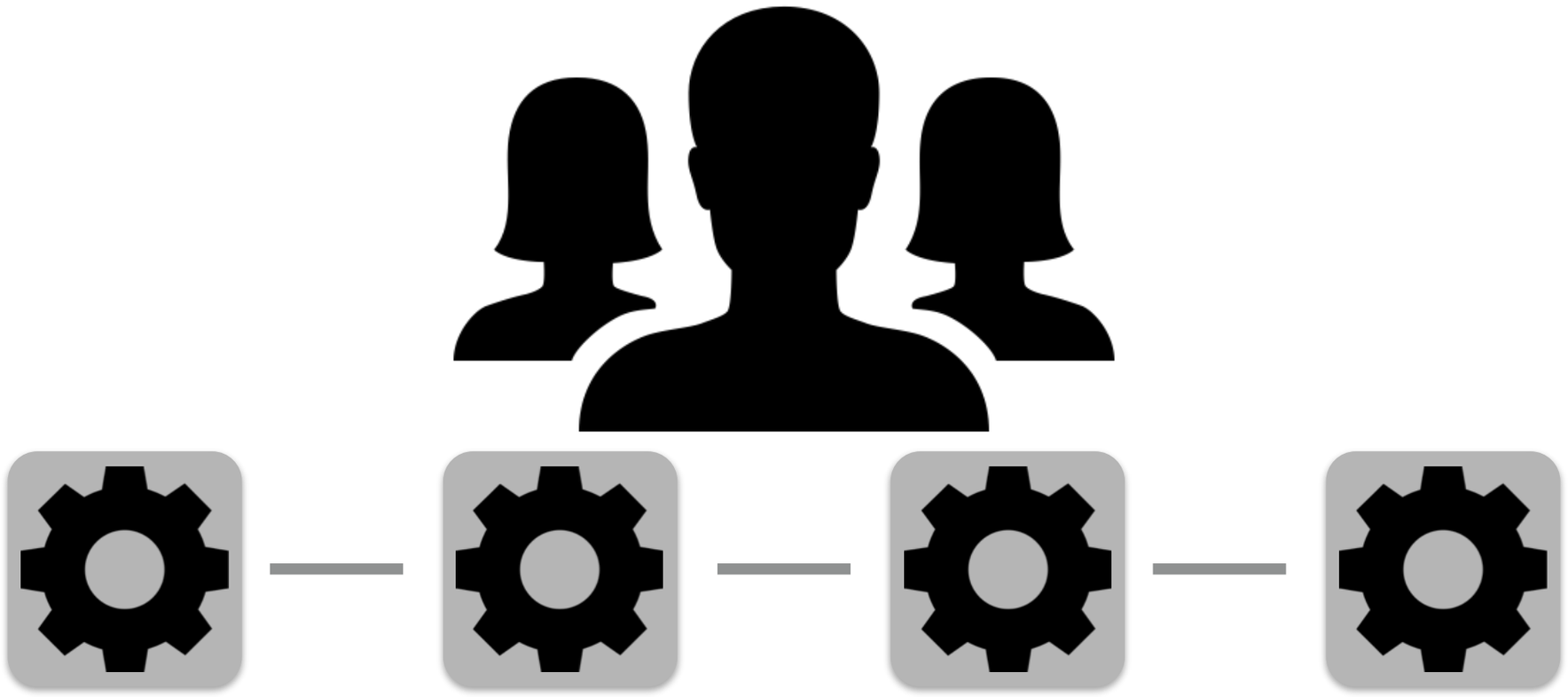
Forwards packets using tables that are computed and maintained by a distributed routing protocol

Another History Lesson...

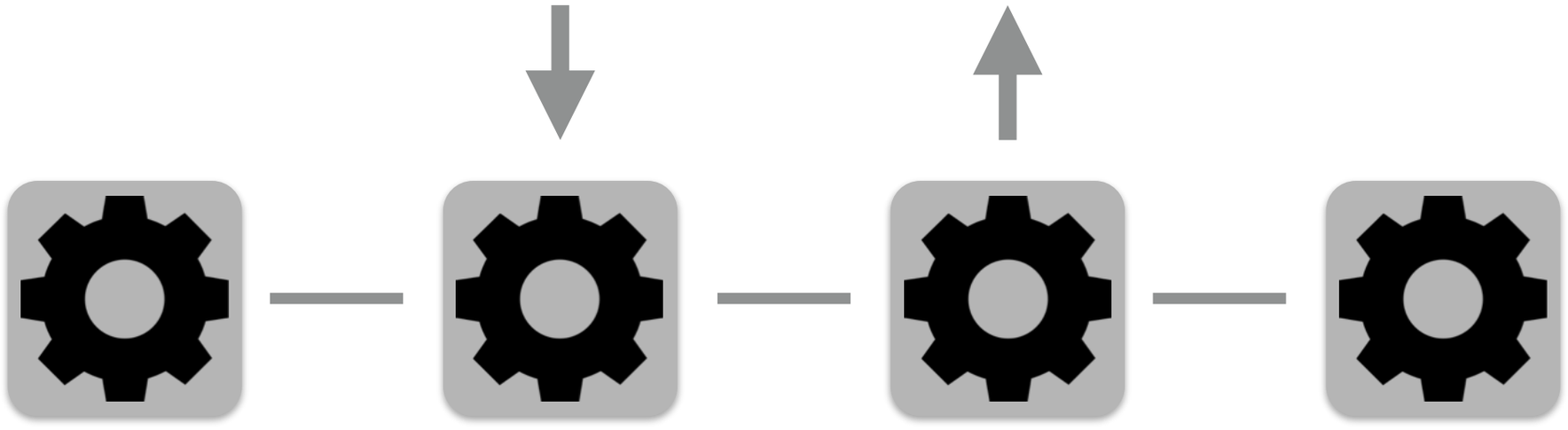
Another History Lesson...

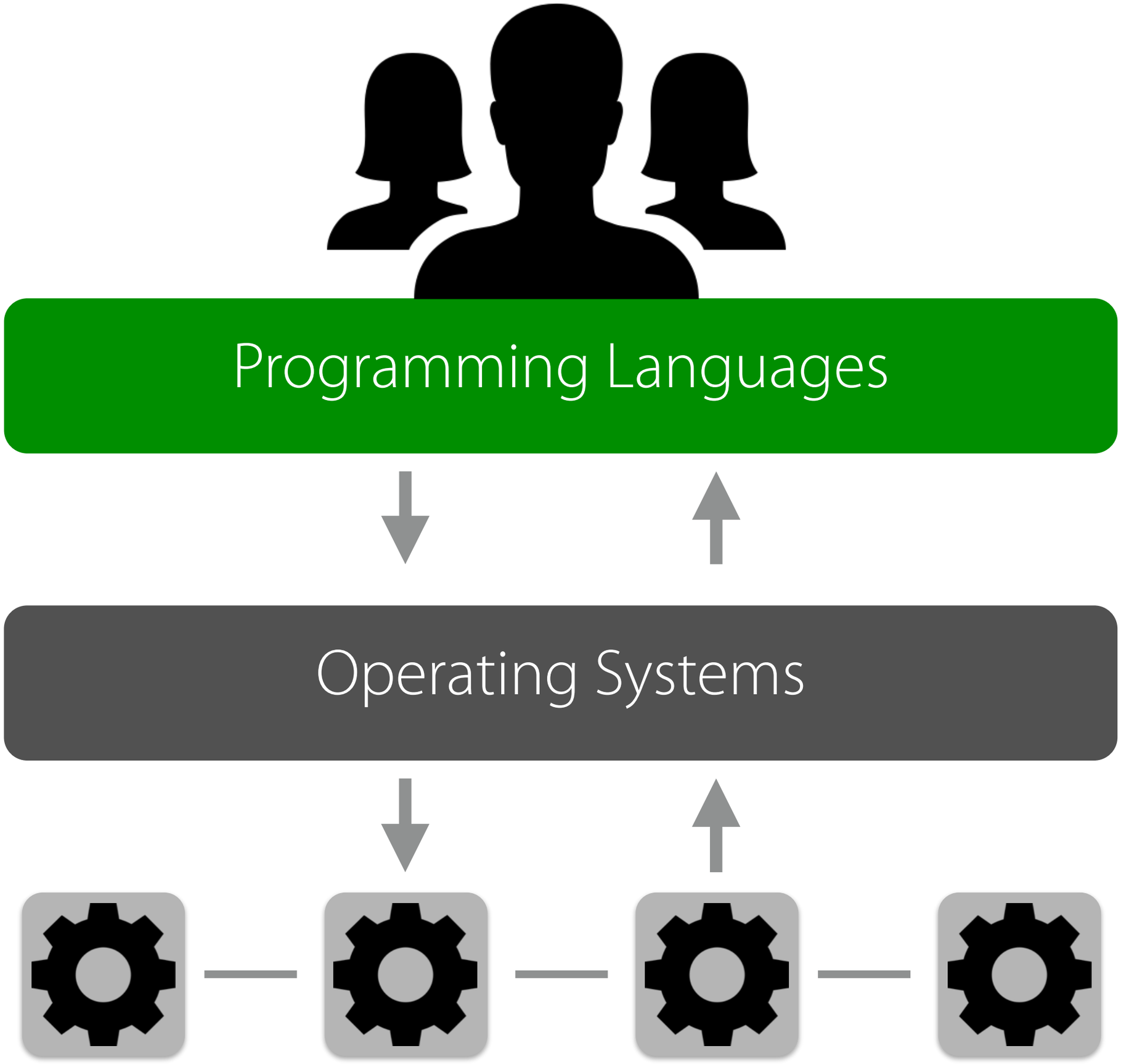
Another History Lesson...





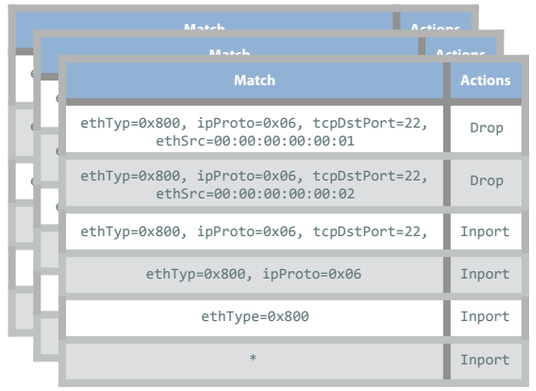
Operating Systems




Programming Languages
Operating Systems

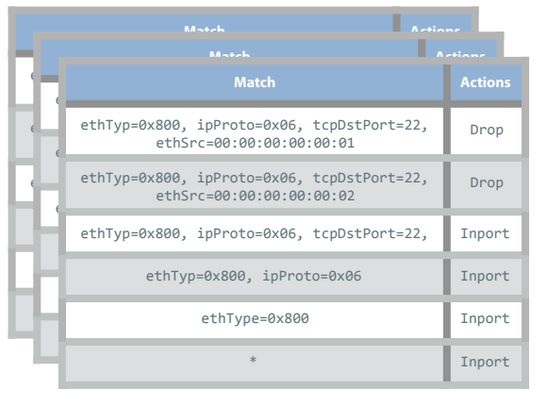
Hardware

A *hardware model* describes behavior in terms of concepts like pipelines of lookup tables



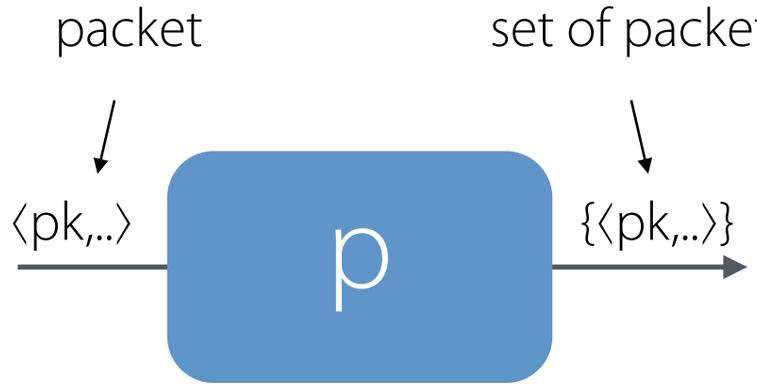
Hardware

A *hardware model* describes behavior in terms of concepts like pipelines of lookup tables



Language

A *language model* describes behavior in terms of concepts like mathematical functions on packets



Administrativa

Staff

Background

- BA Williams College
- MPhil Cambridge University
- PhD University of Pennsylvania
- Postdoc Princeton University

Office Hours

Gates 432

Tuesdays 1-2pm

Contact

jnfoster@cs.cornell.edu

http://www.cs.cornell.edu/~jnfoster/

Schedule

Lecture

- Tuesdays & Thursdays
- Hollister B14
- 8:40am-9:55am

Expectations

- Attend!
- Read papers
- Contribute to discussions

Breakfast

- I will buy bagels and coffee...
- ...if you pick it up from CTB ;-)

Coursework and Grades

Participation (20%)

- Attend lectures
- Contribute to discussions

Problem Sets (3 x 20% each)

- Mostly programming assignments, with some pencil-and-paper problems mixed in.
- I'll supply a virtual machine, starter code, etc.

Mini Project (20%)

- We'll build a basic router from scratch in P4
- You'll extend this router with some advanced feature (that you choose)

Academic Integrity

- Cheating is a lot easier to detect than you might imagine (I use automated tools to find similarities between submissions)
- Violations are unpleasant and painful for everyone involved
- To avoid pressure, start assignments early
- A simple guideline: provide attribution for everything you obtain from an outside source
- If you run into difficulty, speak up!

Rough Outline

Introduction

NetKAT Language

P4 Language

Advanced Topics

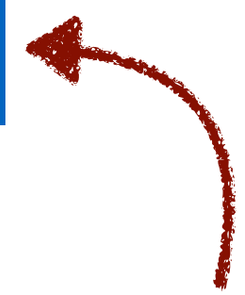
Rough Outline

Introduction

NetKAT Language

P4 Language

Advanced Topics



Guest Lectures!

Guest Lecturers

Andrew Ferguson
Google

Chang Kim
Barefoot

Tim Nelson
Brown

Pavol Cerny
Colorado

Themes

- **Language Design:** what abstractions should we use to program networks?
- **Compilation:** how do we map those abstractions down to effect packet-processing devices?
- **Semantics:** what mathematical objects do network programs denote?
- **Verification:** how do we check that a network behaves as expected?
- **Applications:** what innovative features can we implement with programmable networks?