Refactoring Router Software to Minimize Disruption

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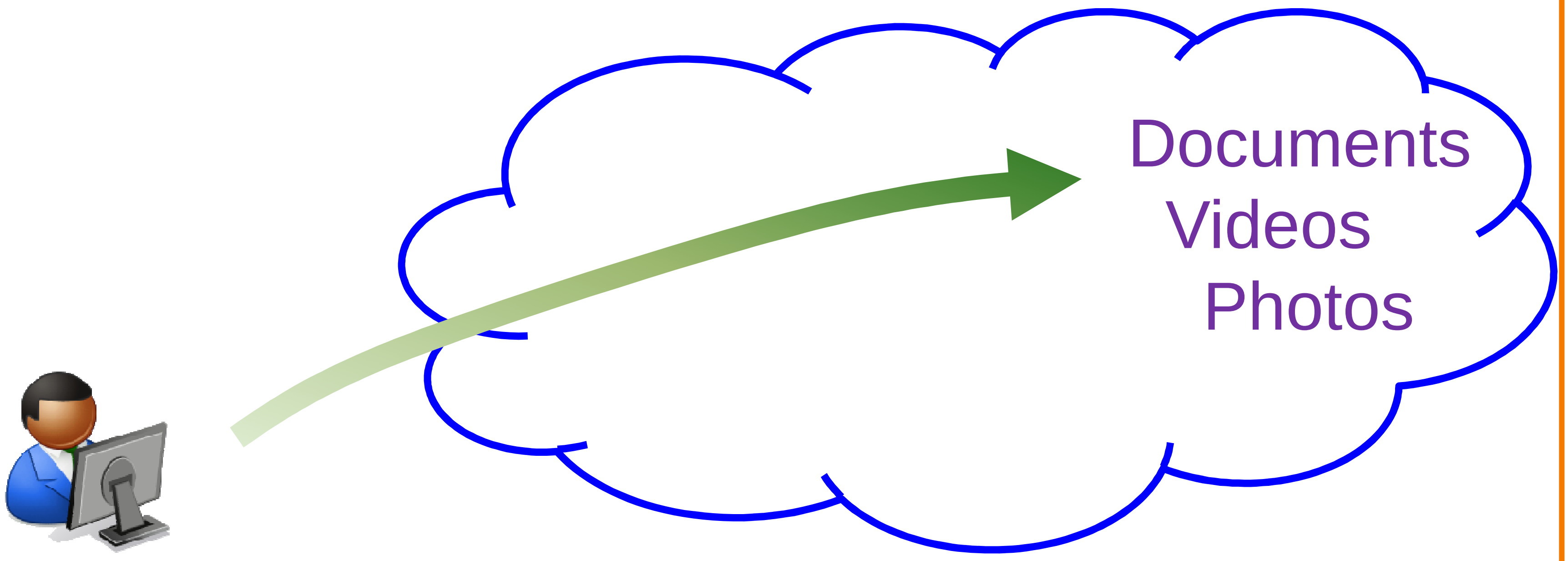
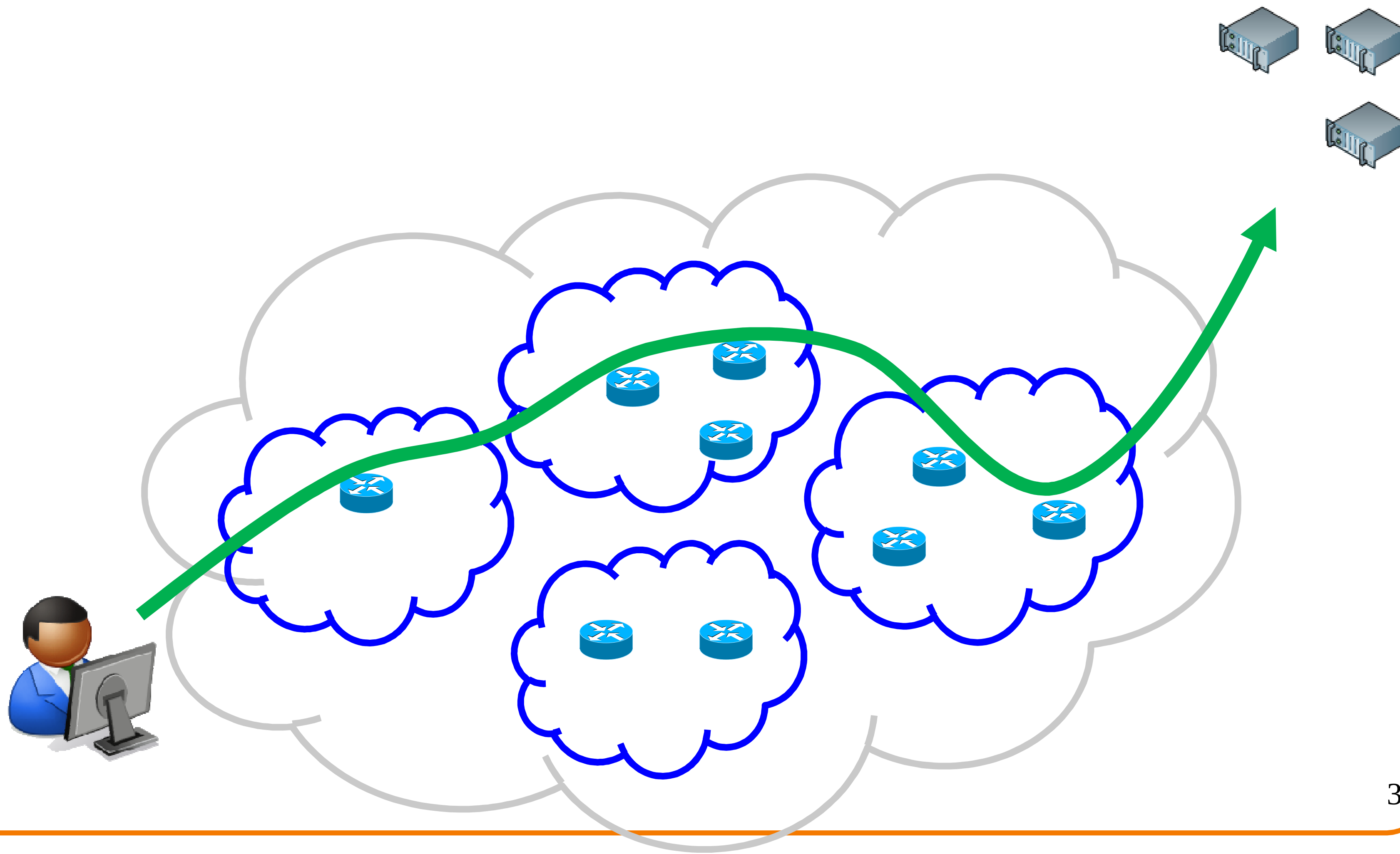
Final Public Oral - 8/26/2011

User's Perspective of The Internet



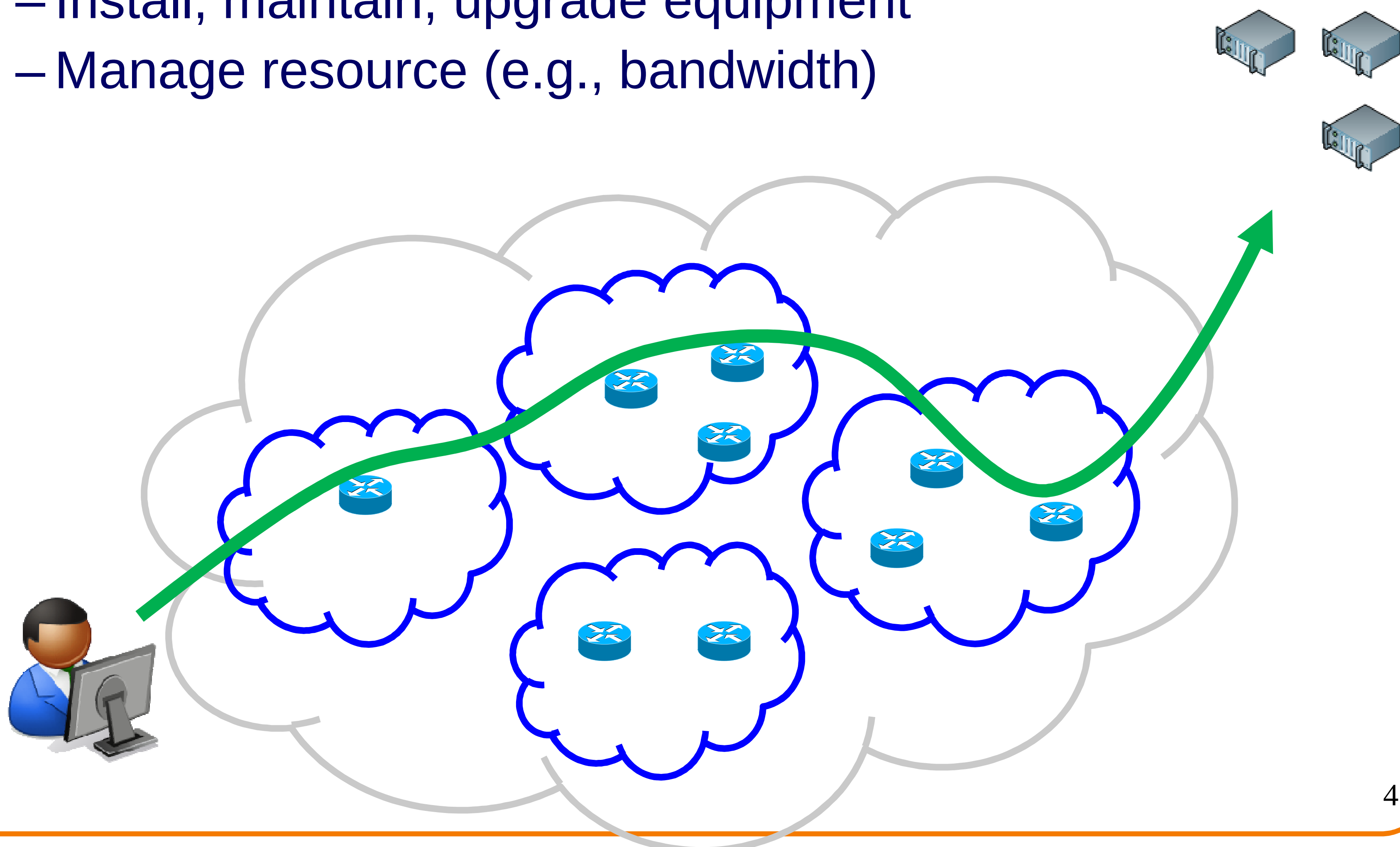
The Actual Internet

- Real infrastructure with real problems



Change Happens

- Network operators need to make changes
  - Install, maintain, upgrade equipment
  - Manage resource (e.g., bandwidth)



Change is Painful

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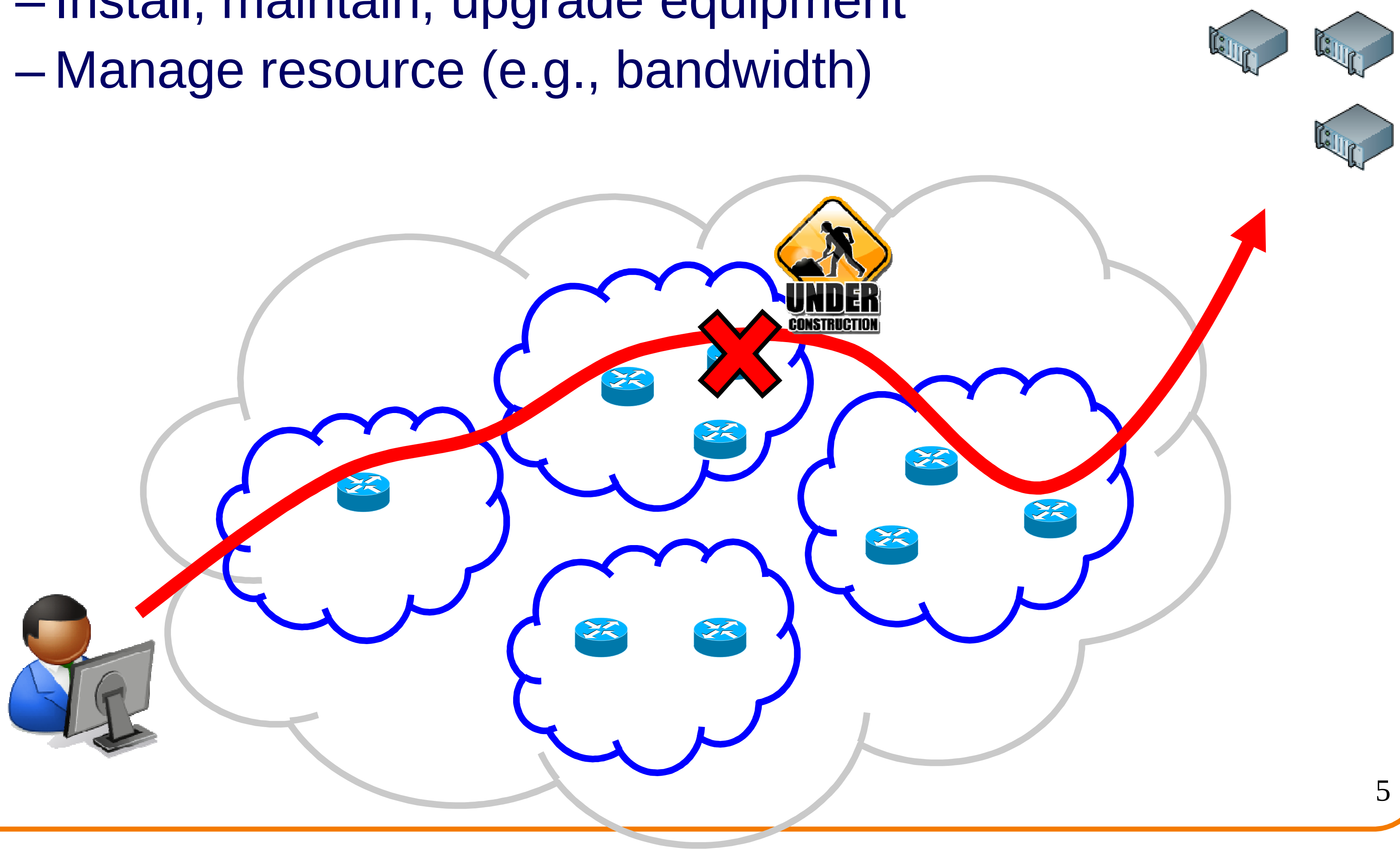

Change is Painful -- Loops

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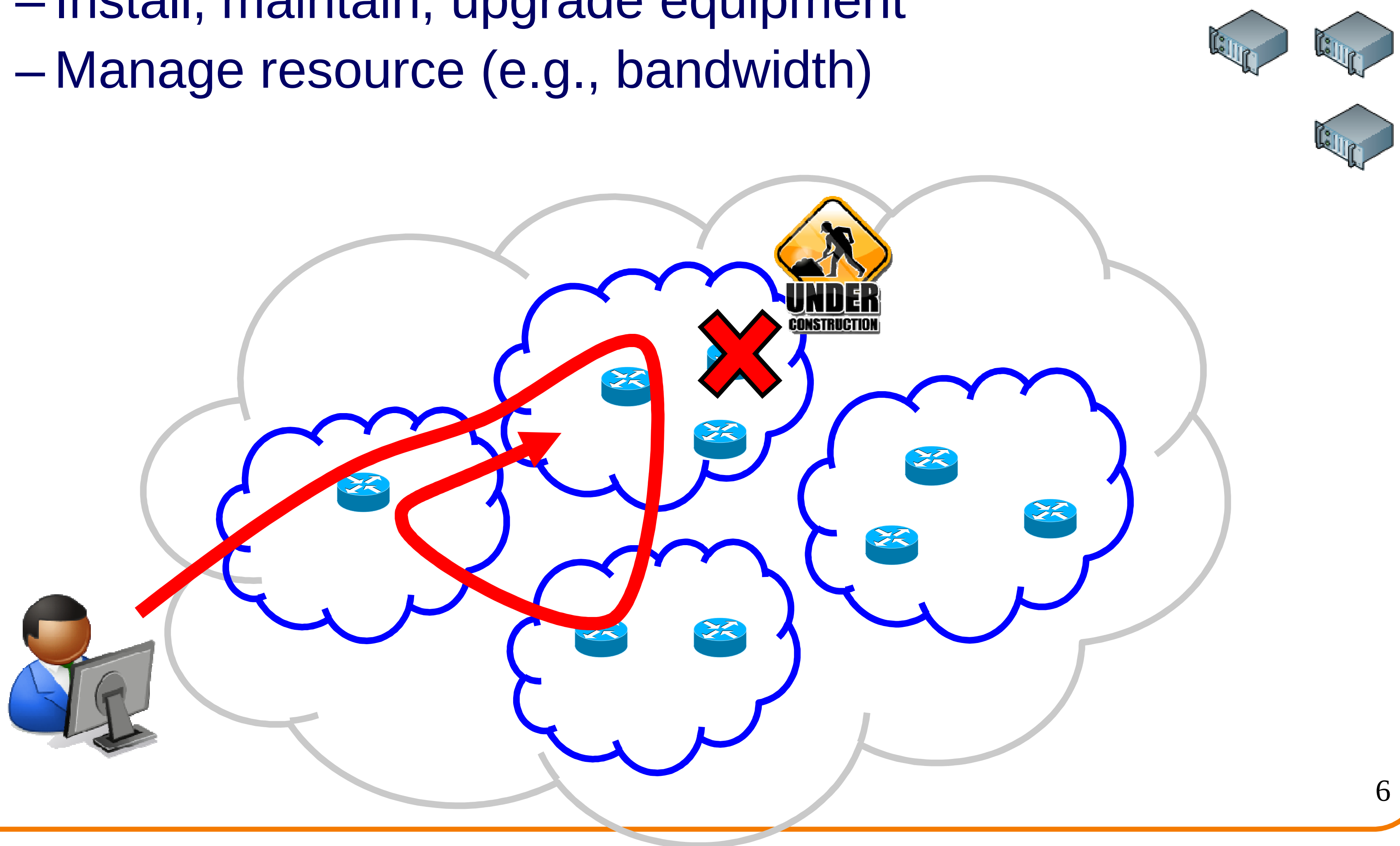

Change is Painful -- Blackholes

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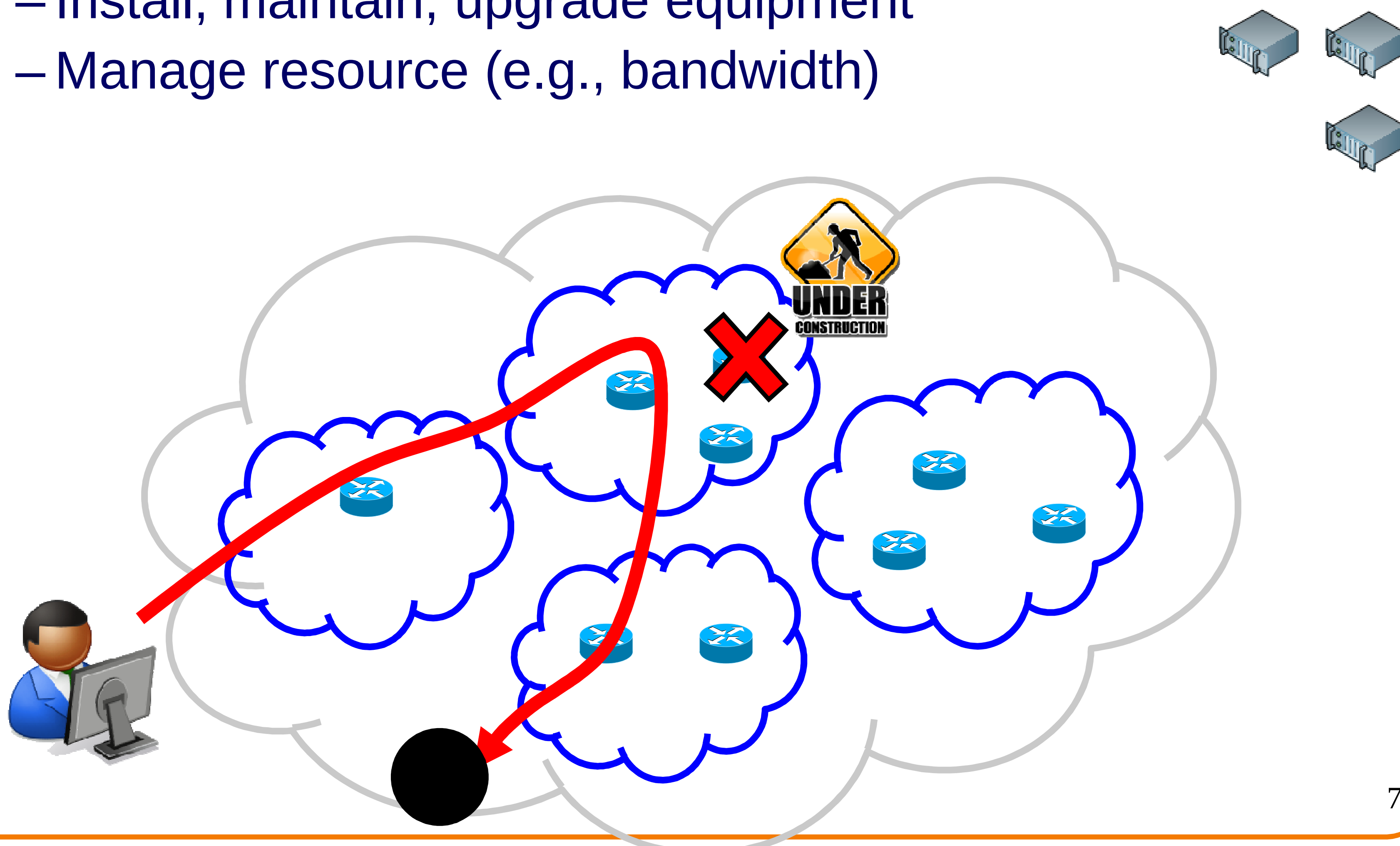
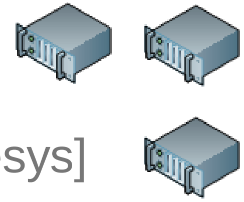
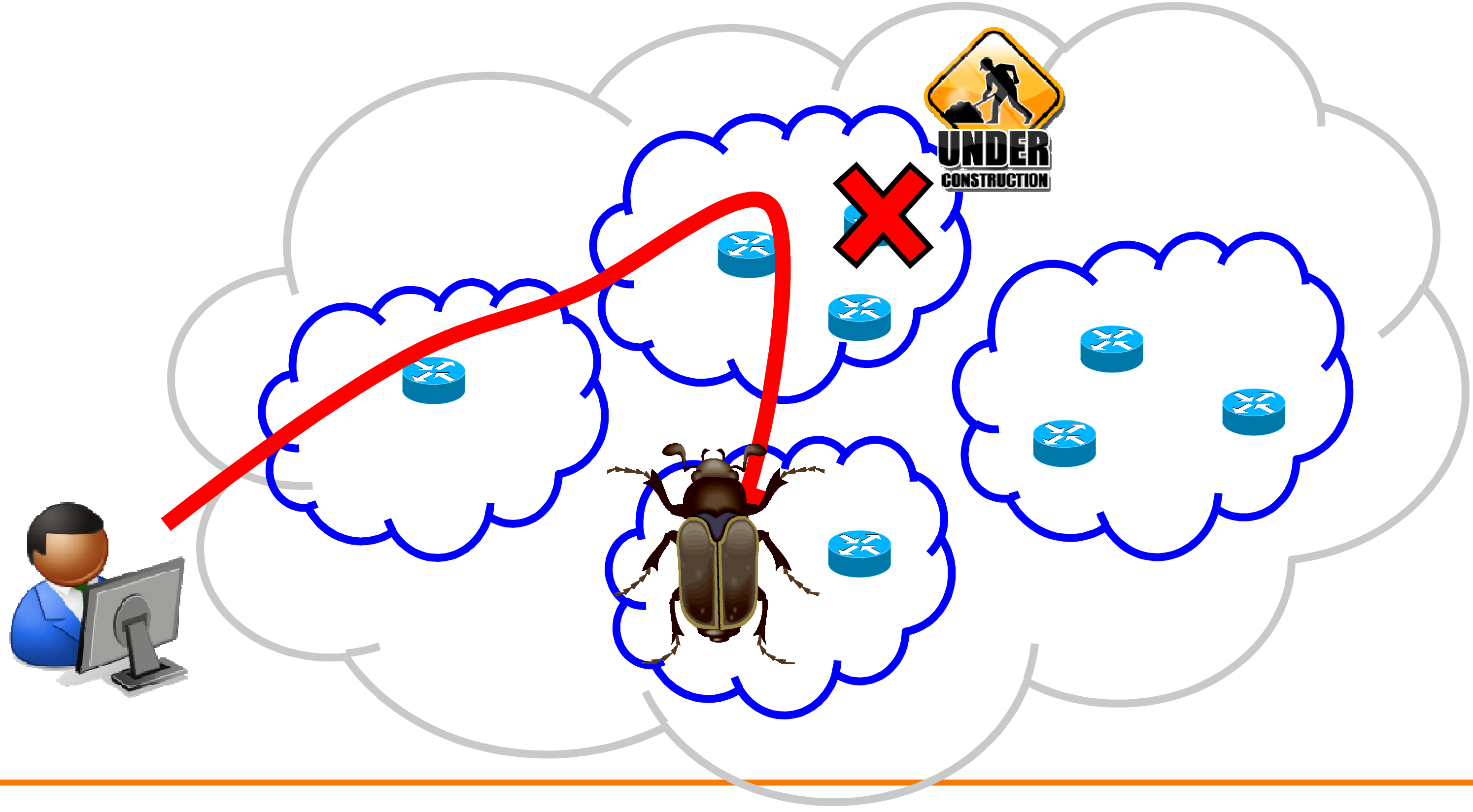


Change is Painful -- Bugs

- Single update partially brought down Internet
  - 8/27/10: House of Cards
  - 5/3/09: AfNOG Takes Byte Out of Internet
  - 2/16/09: Reckless Driving on the Internet [Renesys]





Degree of the Problem Today

- Tireless effort of network operators
  - Majority of the cost of a network is management [yankee02]

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- Tireless effort of network operators
  - Majority of the cost of a network is management [yankee02]
- Skype call quality is an order of magnitude worse (than public phone network) [CCR07]
  - Change as much to blame as congestion
  - 20% of unintelligible periods lasted for 4 minutes

The problem will get worse

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- More devices and traffic
  - Means more equipment, more networks, more change

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- More devices and traffic
- More demanding applications

  e-mail → social media → streaming (live) video

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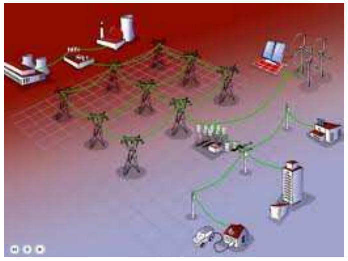
- More devices and traffic
- More demanding applications

  e-mail → social media → streaming (live) video
- More critical applications

  business software → smart power grid → healthcare



Minimizing the Disruption

Goal:

Make change pain free
(minimize disruption)

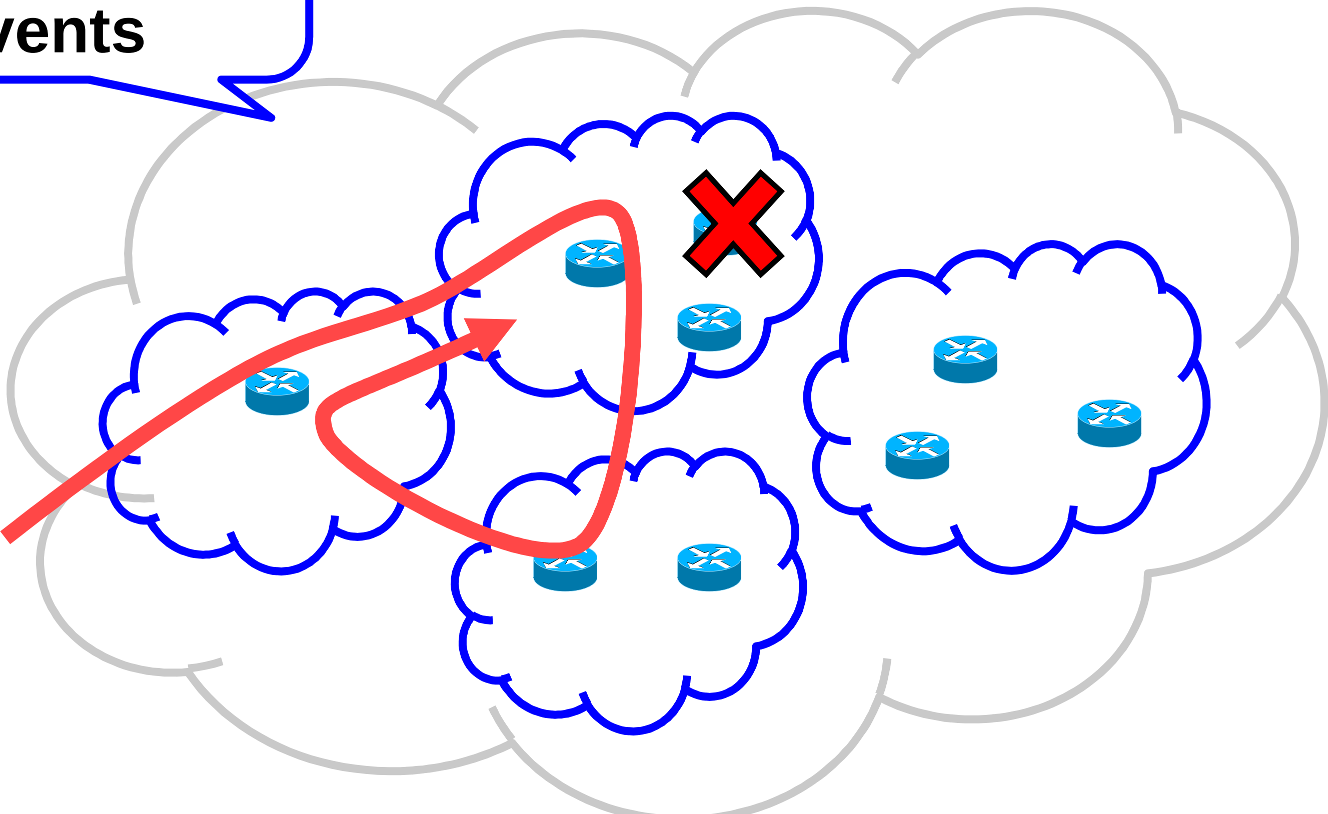
Refactoring Router Software to Minimize Disruption

Goal: Make change pain free (minimize disruption)

Approach: Refactoring router software

Change without…

Unnecessary reconvergence events



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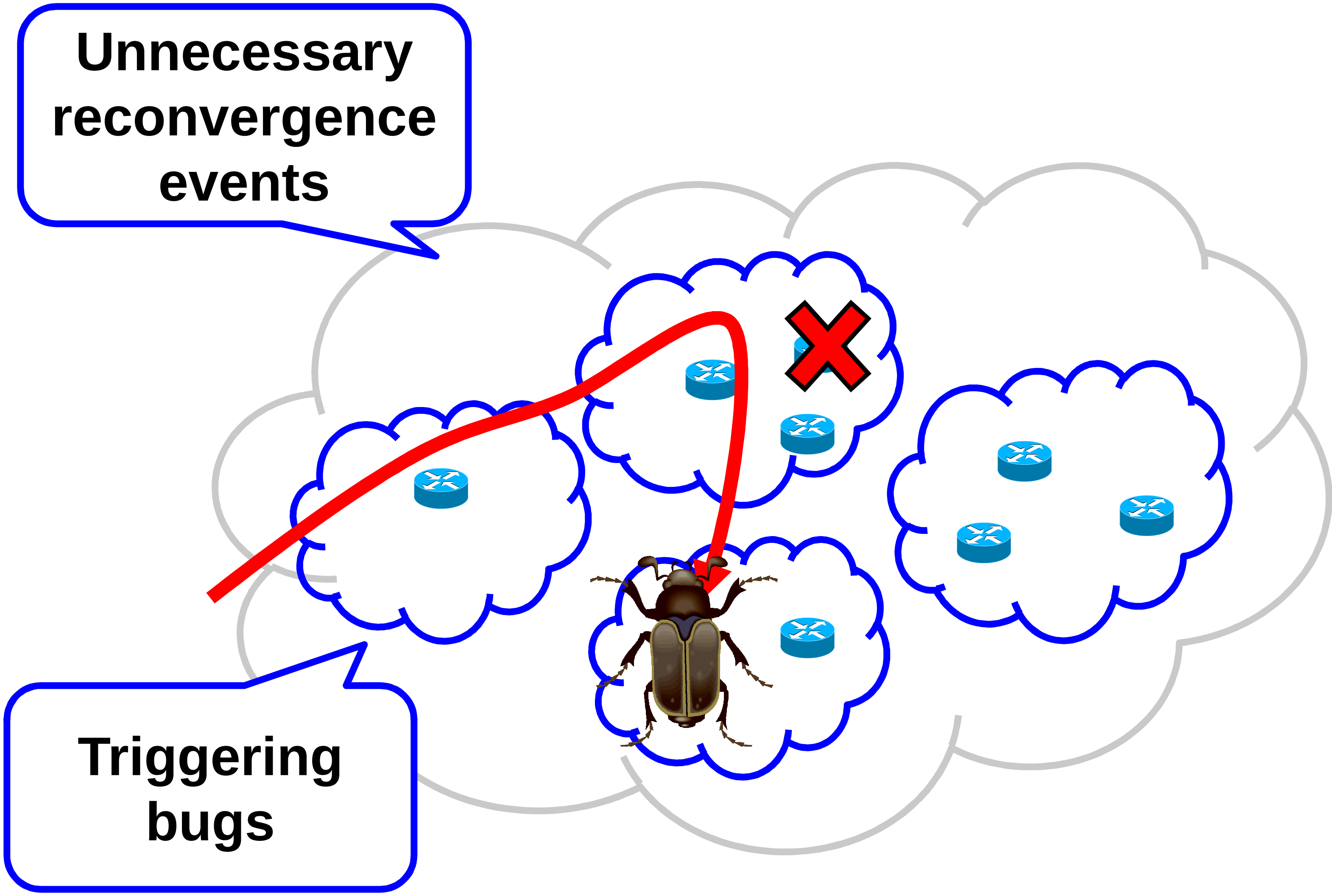

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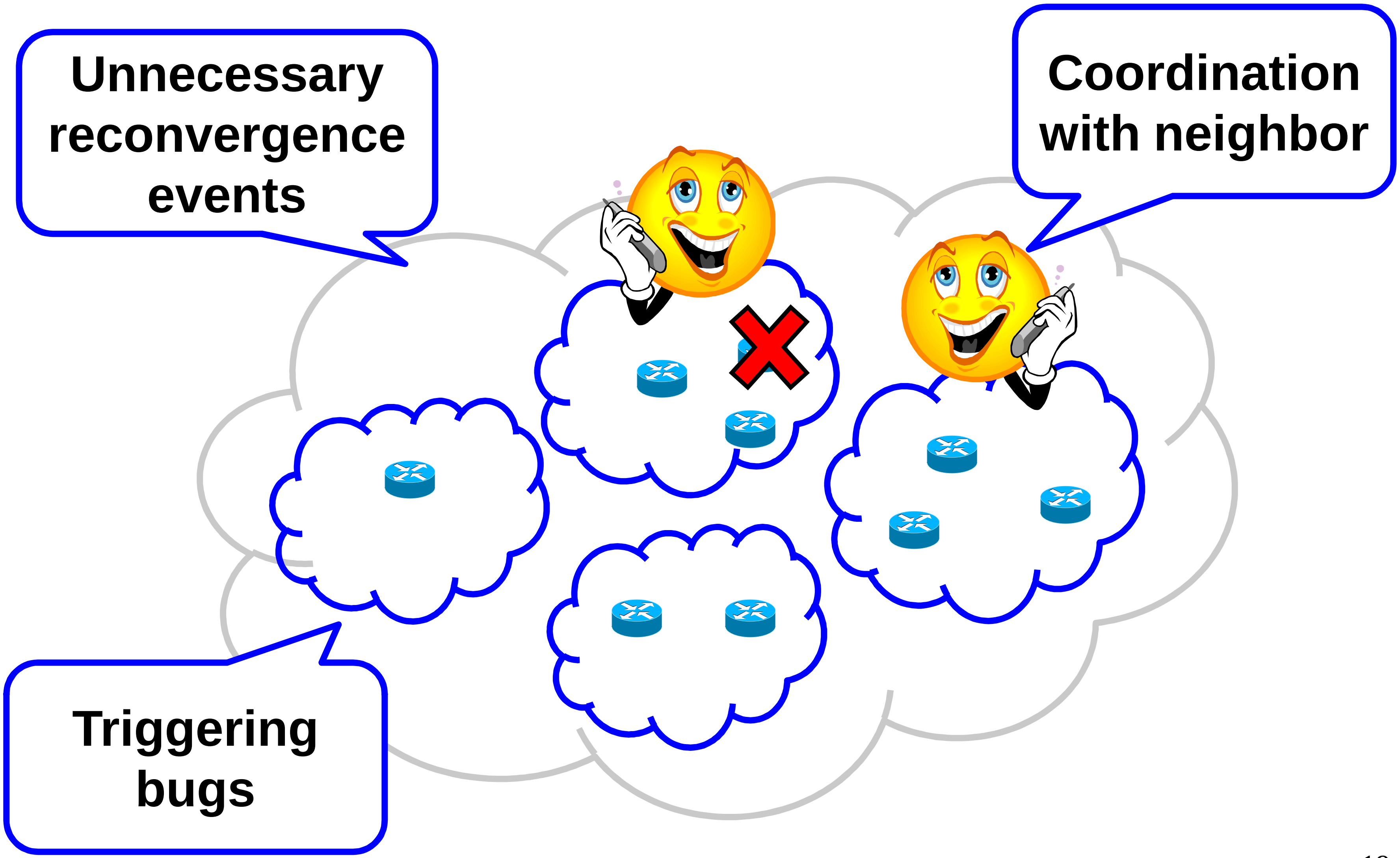

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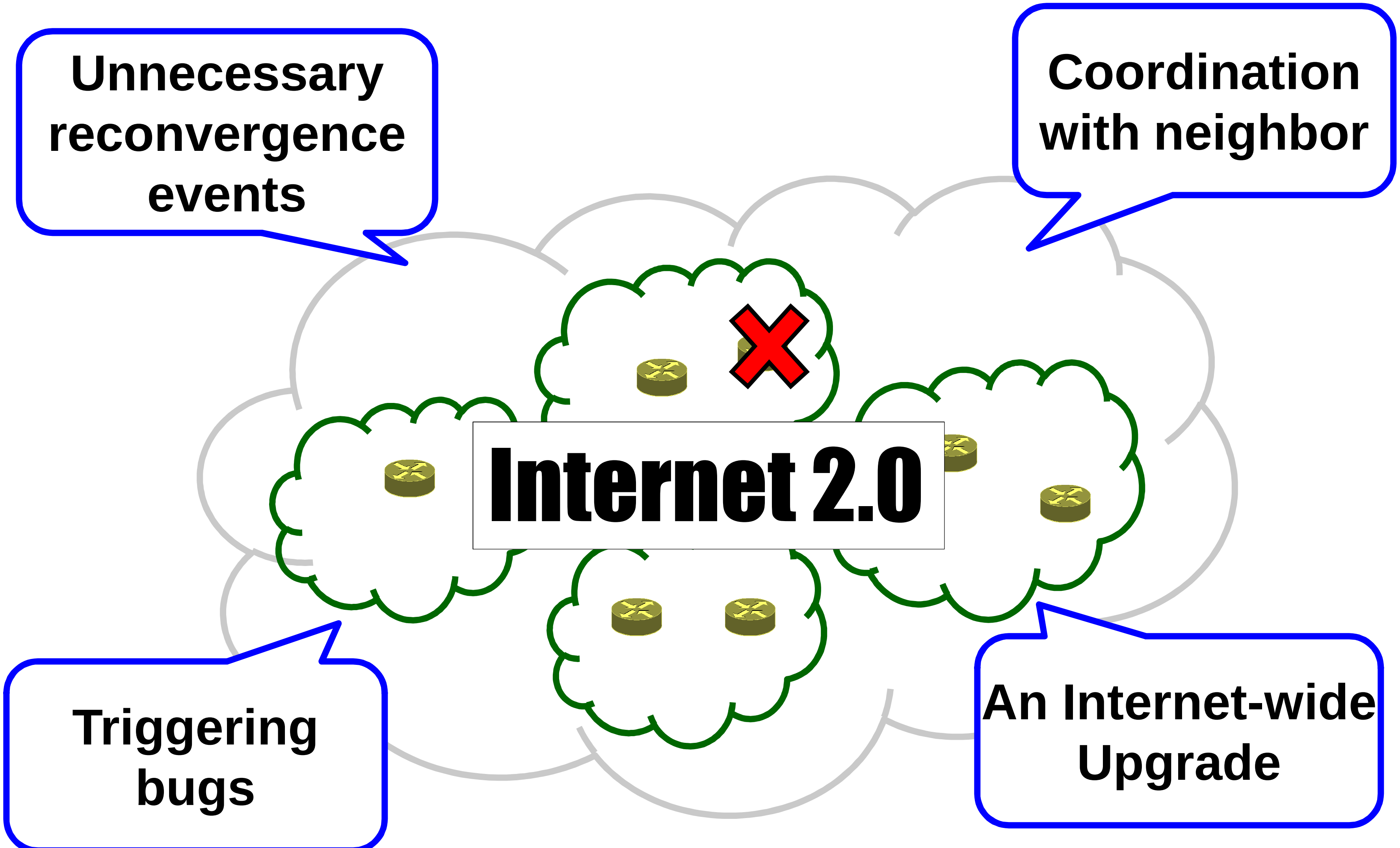
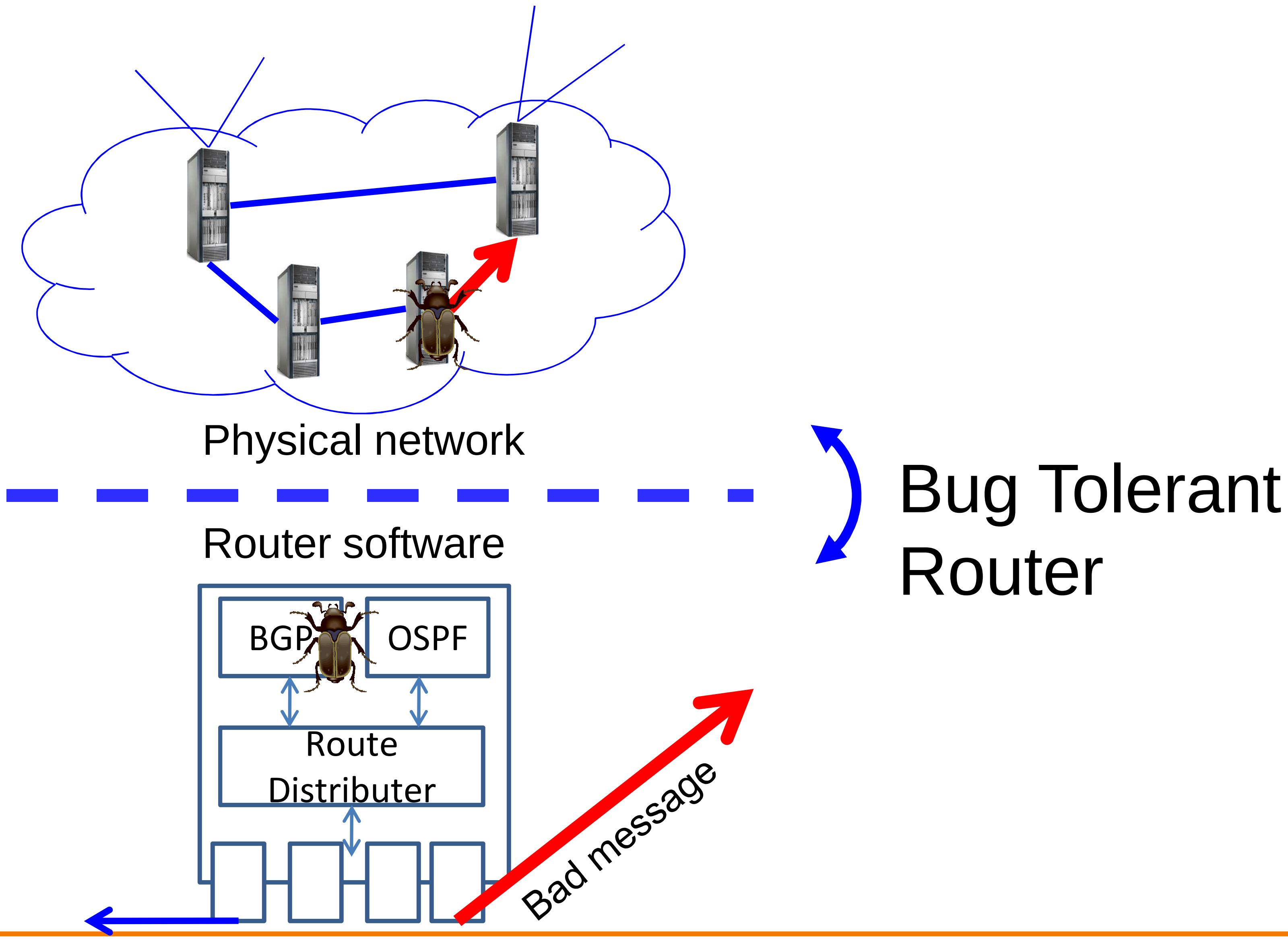
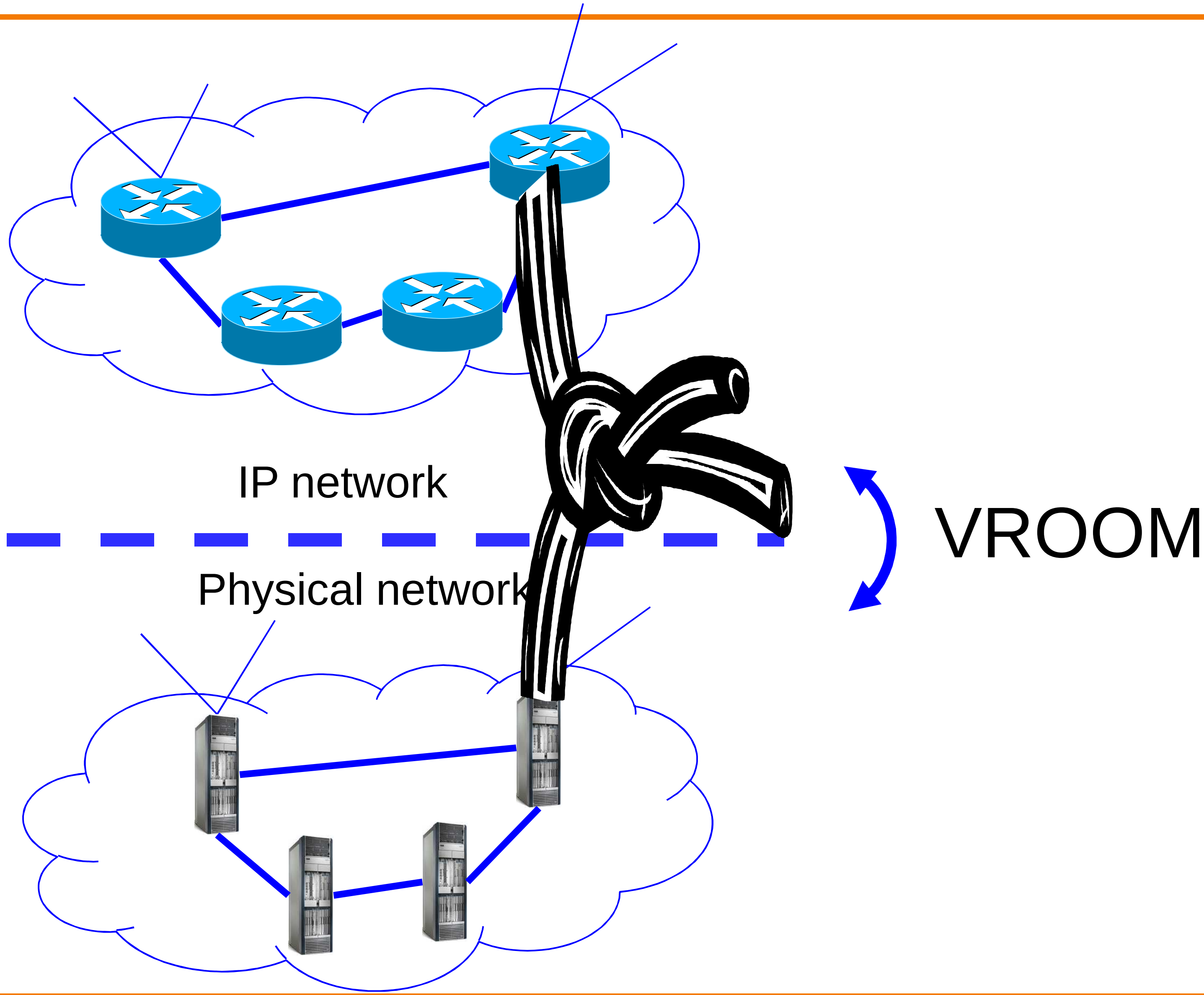


Refactor Router Software?

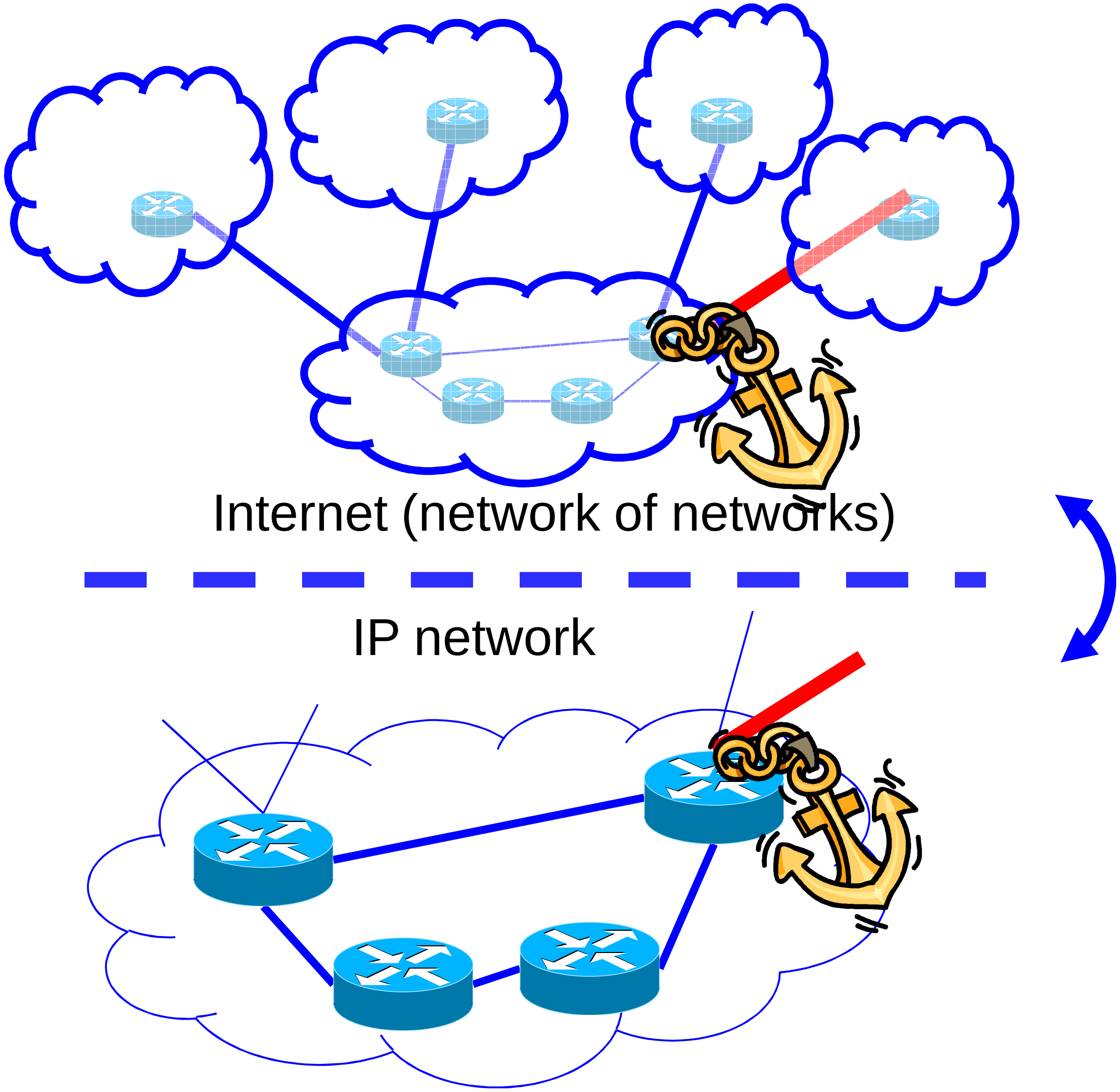
Hiding Router Bugs



Decouple Physical and Logical



Unbind Links from Routers



Router Grafting

Outline of Contributions

Bug Tolerant Router	VROOM	Router Grafting
Hide (router bugs)	Decouple (logical and physical)	Break binding (link to router)
Software and Data Diversity	Virtual Router Migration	Seamless Edge Link Migration
[CoNext09]	[SIGCOMM08]	[NSDI10]

Part I:
Hiding Router Software Bugs with the Bug Tolerant Router

With Minlan Yu, Matthew Caesar, Jennifer Rexford

[CoNext 2009]

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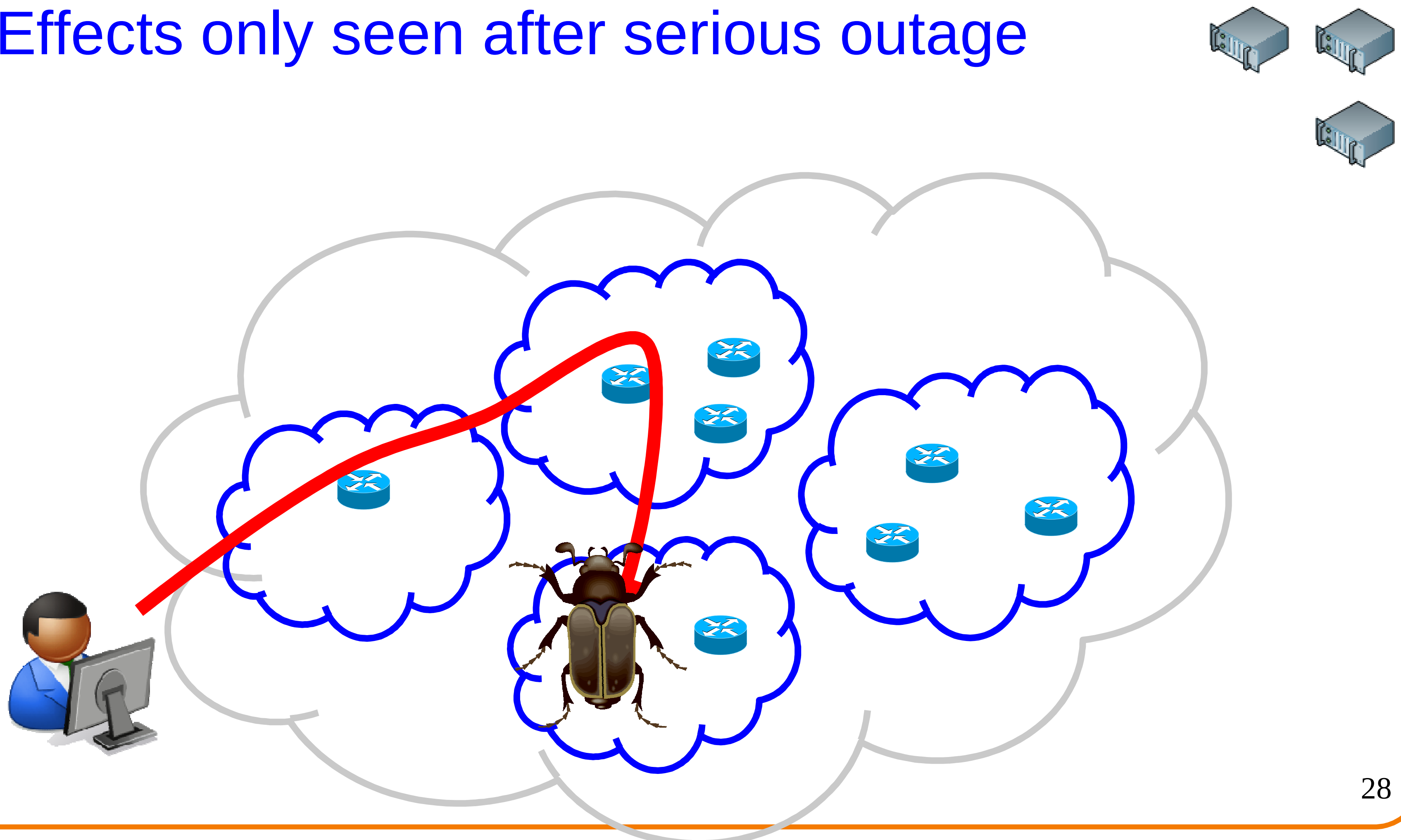
Dealing with Router Bugs

- Cascading failures
- Effects only seen after serious outage



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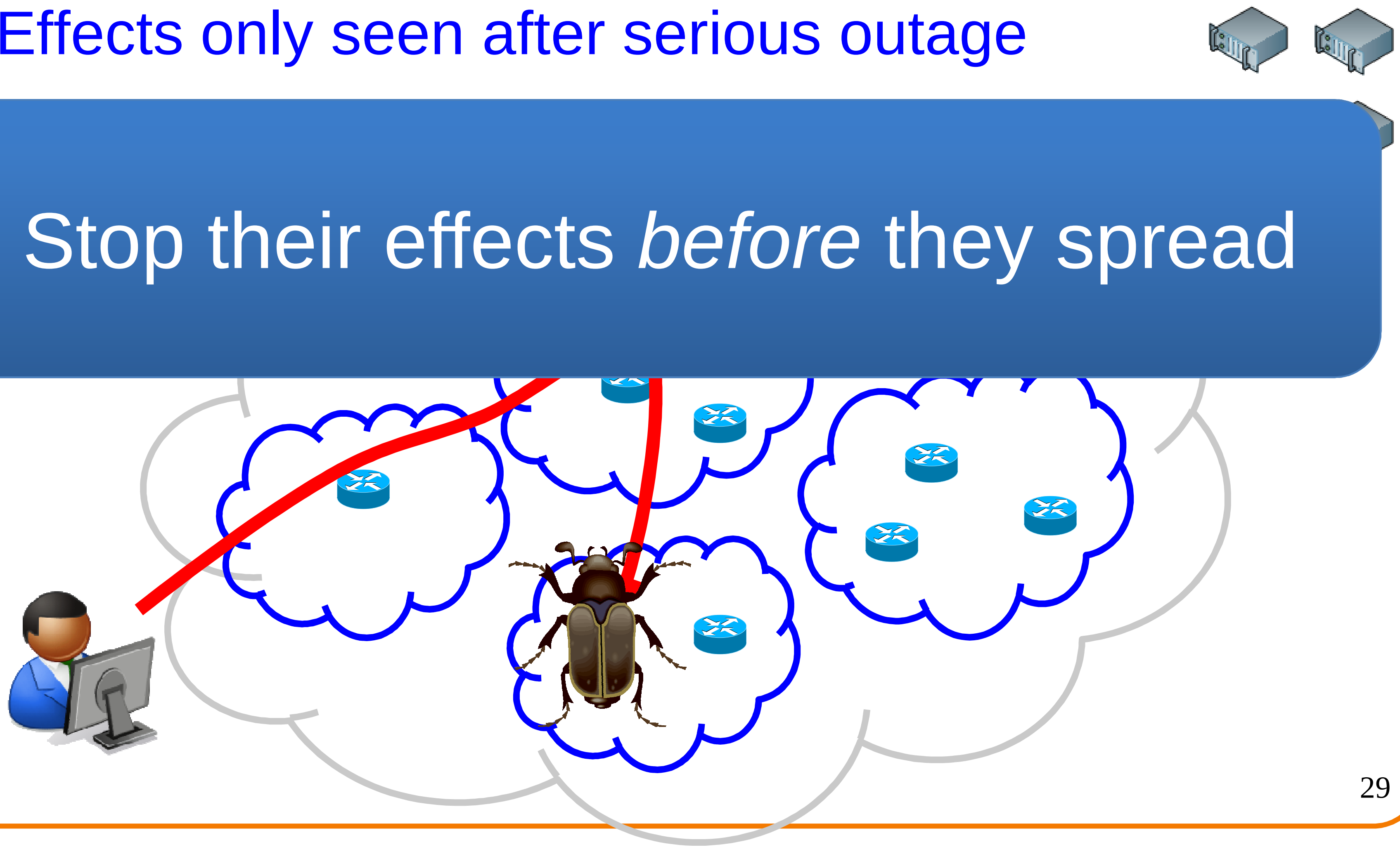

Stop their effects *before* they spread

Avoiding Bugs via Diversity

- Run *multiple, diverse* instances of router software
- Instances “vote” on routing updates
- Software and Data Diversity used in other fields

Approach is a Good Fit for Routing

- Easy to vote on standardized output
  - Control plane: IETF-standardized routing protocols
  - Data plane: forwarding-table entries
- Easy to recover from errors via bootstrap
  - Routing has limited dependency on history
  - Don’t need much information to bootstrap instance
- Diversity is effective in avoiding router bugs
  - Based on our studies on router bugs and code

Approach is *Necessary* for Routing

- Easy to vote on standardized output
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60% of bugs do not crash the router

Achieving Diversity

Type of diversity	Examples
Execution Environment	Operating system, memory layout
Data Diversity	Configuration, timing of updates/connections
Software Diversity	Version (0.98 vs 0.99), implementation (Quagga vs XORP)

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Effectiveness of Data Diversity

Taxonomized XORP and Quagga bug database

Diversity Mechanism	Bugs avoided (est.)
Timing/order of messages	39%
Configuration	25%
Timing/order of connections	12%

Selected two from each to reproduce and avoid

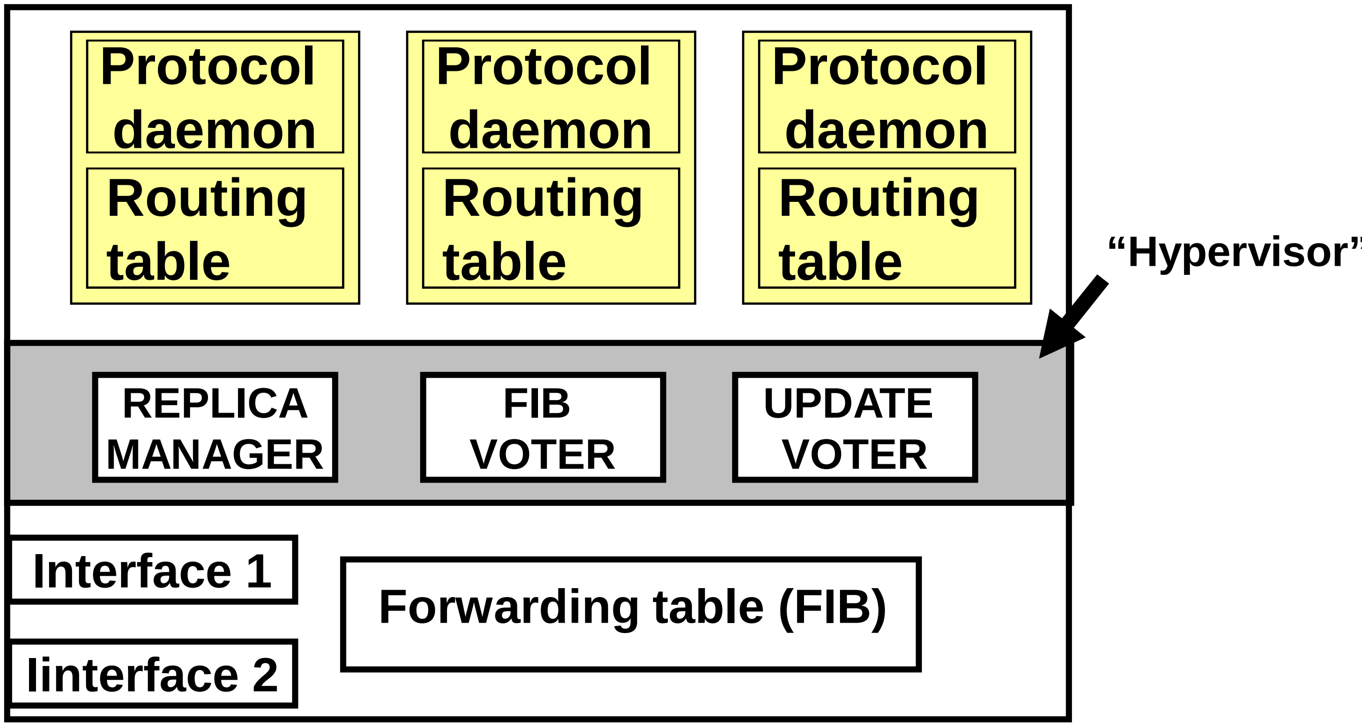
Effectiveness of Software Diversity

- Sanity check on *implementation diversity*
  - Picked 10 bugs from XORP, 10 bugs from Quagga
  - None were present in the other implementation
- Static code analysis on *version diversity*
  - Overlap decreases quickly between versions
  - 75% of bugs in Quagga 0.99.1 are *fixed* in 0.99.9
  - 30% of bugs in Quagga 0.99.9 are *newly introduced*
- Vendors can also achieve software diversity
  - Different code versions
  - Code from acquired companies, open-source

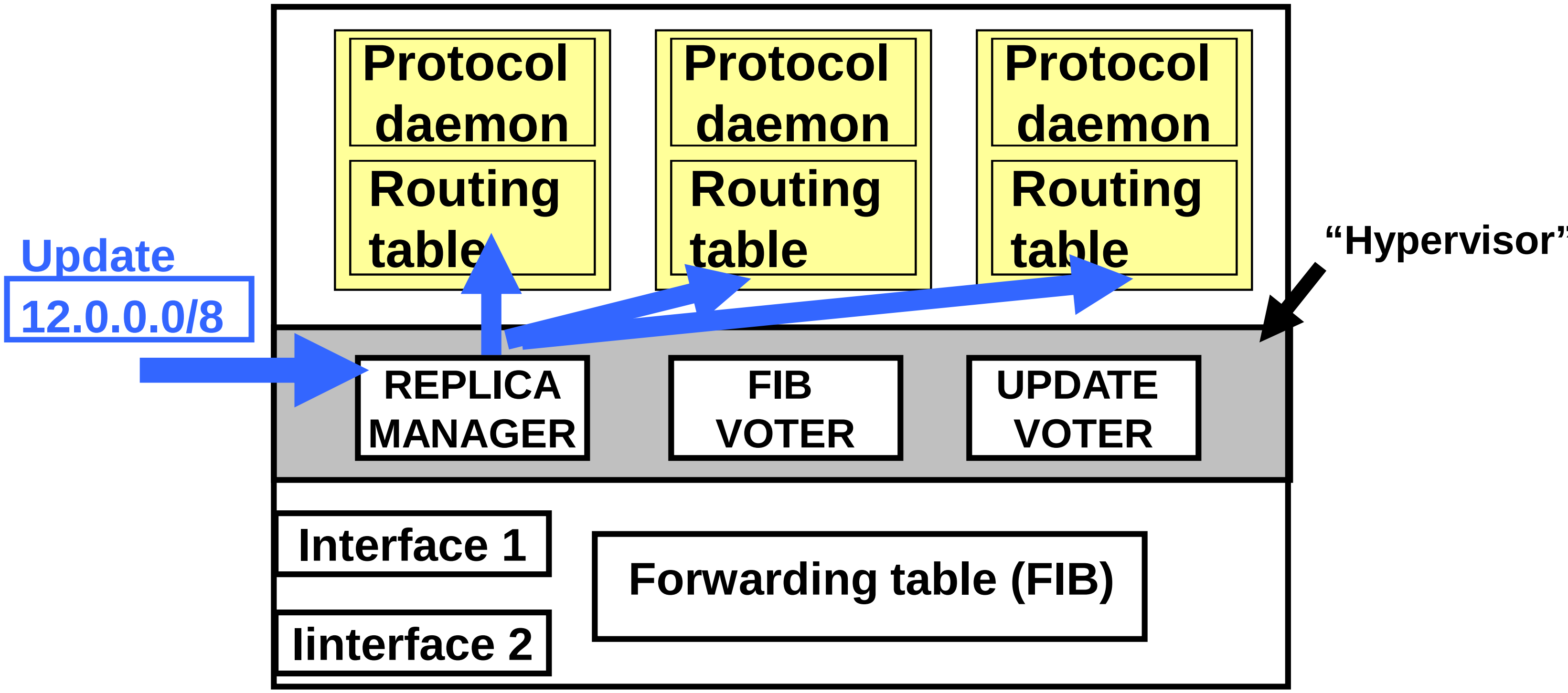
BTR Architecture Challenge #1

- Making replication transparent
  - Interoperate with existing routers
  - Duplicate network state to routing instances
  - Present a common configuration interface

Architecture

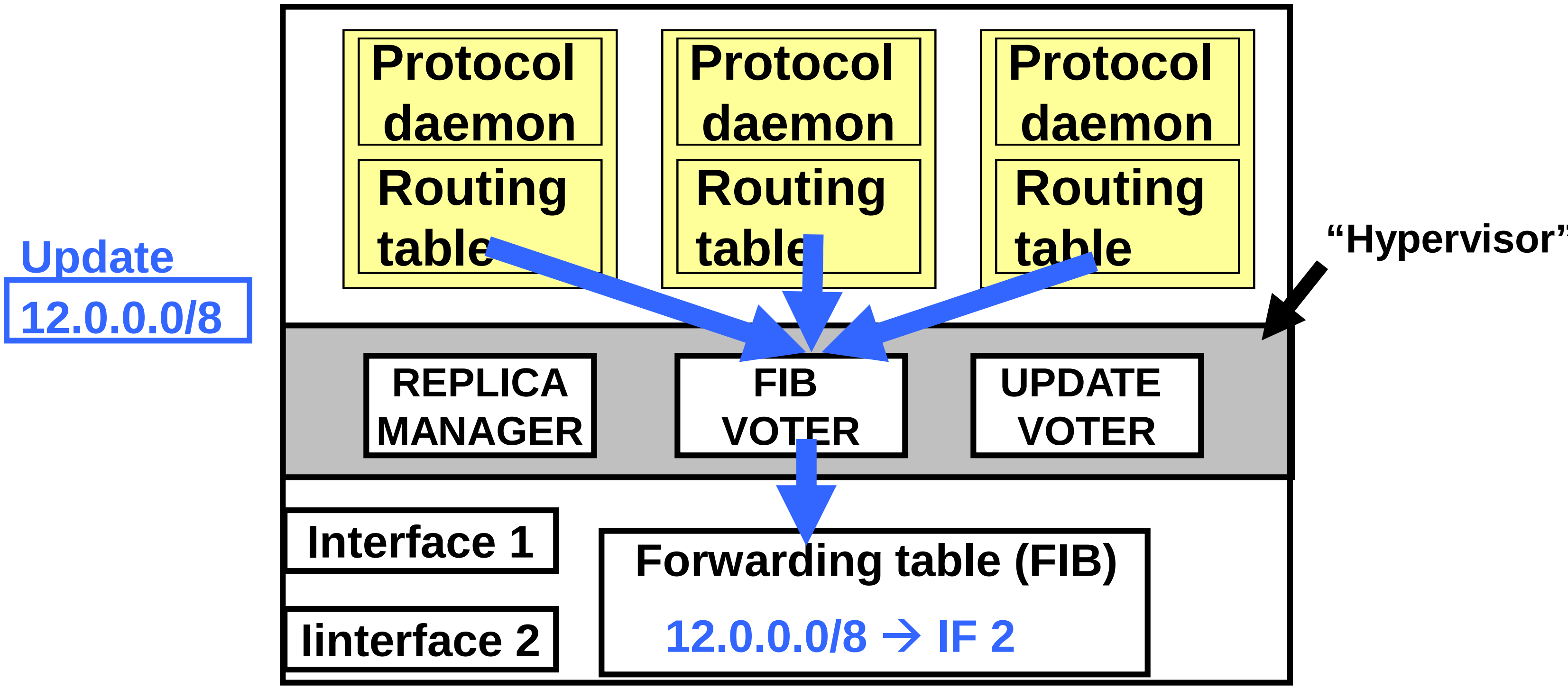


Replicate Incoming Routing Messages



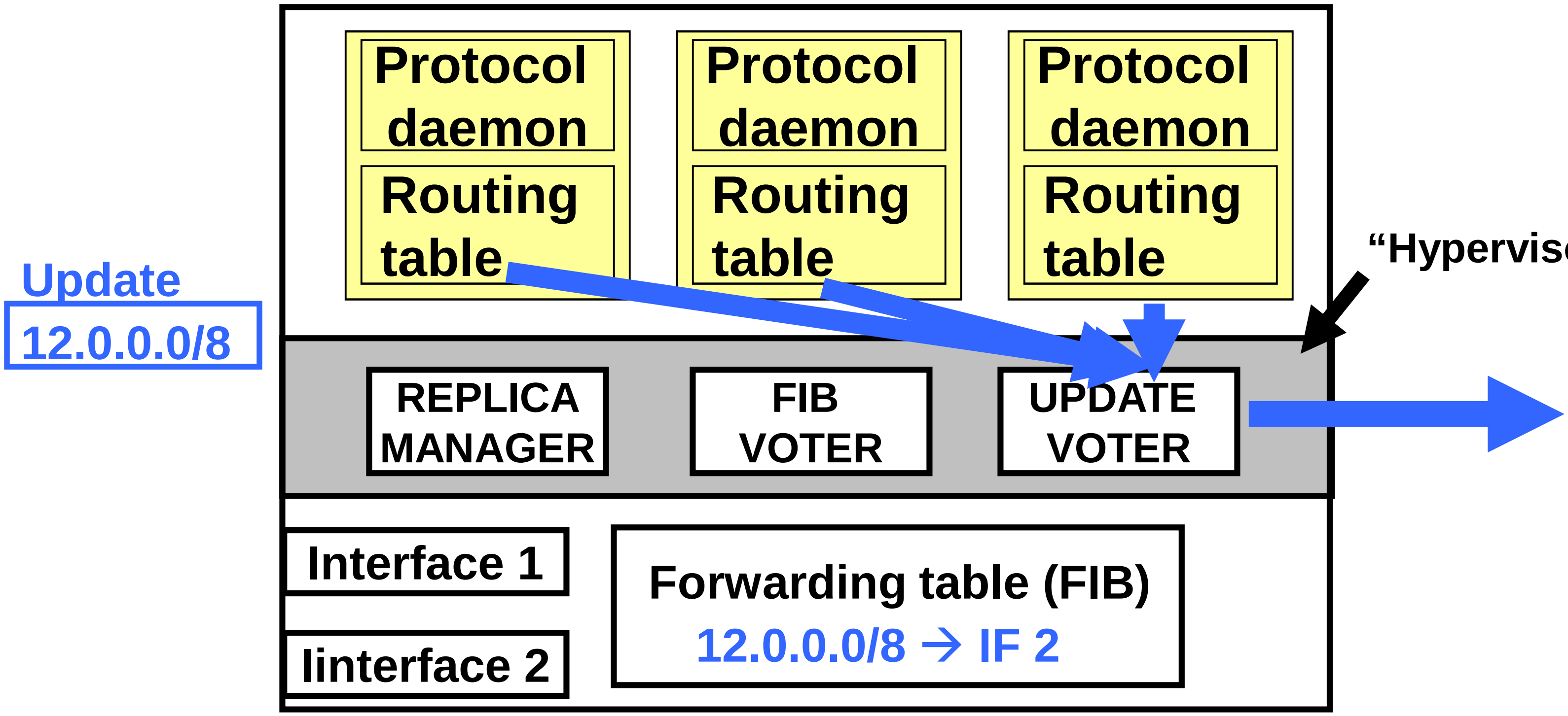
No protocol parsing – operates at socket level

Vote on Forwarding Table Updates



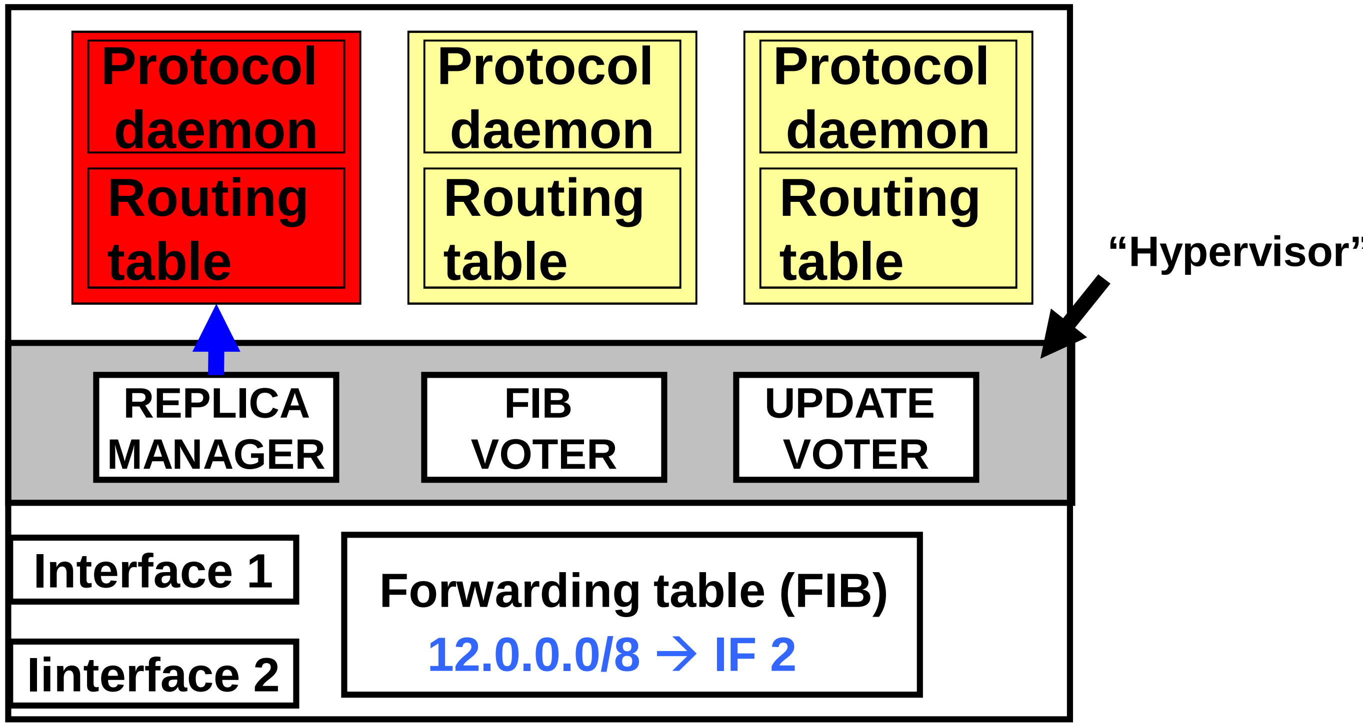
Transparent by intercepting calls to "Netlink"

Vote on Control-Plane Messages



Transparent by intercepting socket system calls

Hide Replica Failure



Kill/Bootstrap instances

BTR Architecture Challenge #2

- Making replication transparent
  - Interoperate with existing routers
  - Duplicate network state to routing instances
  - Present a common configuration interface
- Handling transient, real-time nature of routers
  - React *quickly* to network events
  - But not *over-react* to *transient* inconsistency

Simple Voting Mechanisms

- Master-Slave: speeding reaction time
  - Output Master's answer
  - Slaves used for detection
  - Switch to slave on buggy behavior
- Continuous Majority : handling transience
  - Voting rerun when any instance sends an update
  - Output when majority agree (among responders)

Evaluation with Prototype

- Prototype
  - Built on Linux with XORP, Quagga, and BIRD
  - No modification of routing software
  - Simple hypervisor (hundreds of lines of code)
- Evaluation
  - Which algorithm is best?
  - What is the processing overhead?
- Setup
  - Inject bugs with some frequency and duration
  - Evaluated in 3GHz Intel Xeon
  - BGP trace from Route Views on March, 2007

Which algorithm is best?

Depends… there are tradeoffs

Voting algorithm	Avg wait time (sec)	Fault rate
Single router	-	0.06600%
Master-slave	0.020	0.00060%
Continuous-majority	0.035	0.00001%

What is the processing overhead?

- Overhead of hypervisor
  - 1 instance ==> 0.1%
  - 5 routing instances ==> 4.6%
  - 5 instances in heavy load ==> 23%
  - Always, less than 1 second
- Little effect on network-wide convergence
  - ISP networks from Rocketfuel, and cliques
  - Found no significant change in convergence (beyond the pass through time)

Bug tolerant router Summary

- Router bugs are serious
  - Cause outages, misbehaviors, vulnerabilities
- Software and data diversity (SDD) is effective
- Design and prototype of bug-tolerant router
  - Works with Quagga, XORP, and BIRD software
  - Low overhead, and small code base

Part II: Decoupling the Logical from Physical with VROOM

With Yi Wang, Brian Biskeborn,
Kobus van der Merwe, Jennifer Rexford

[SIGCOMM 08]

Outline of Contributions

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[CoNext09]	[SIGCOMM08]	[NSDI10]

(Recall) Change Happens

- Network operators need to make changes
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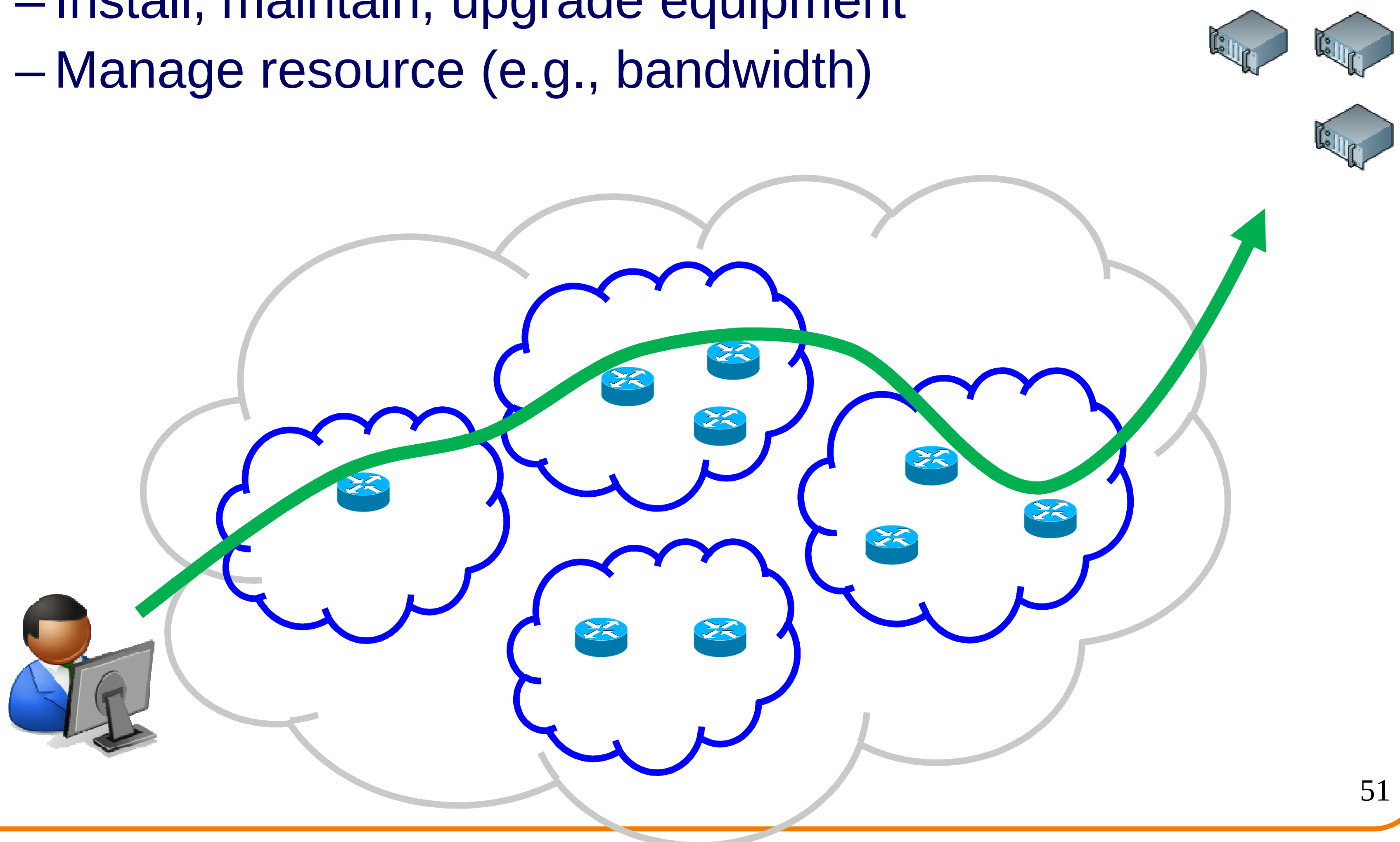

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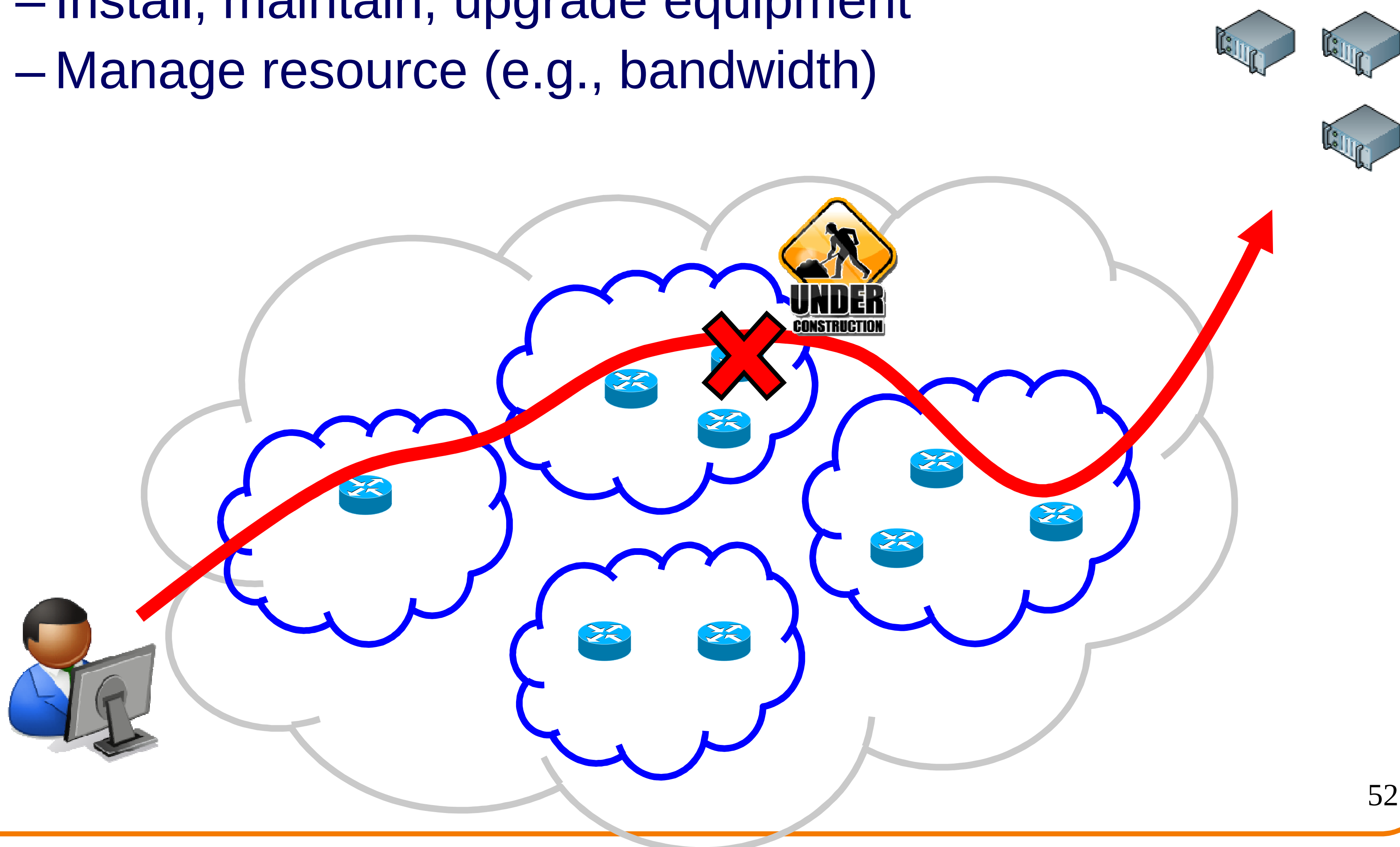
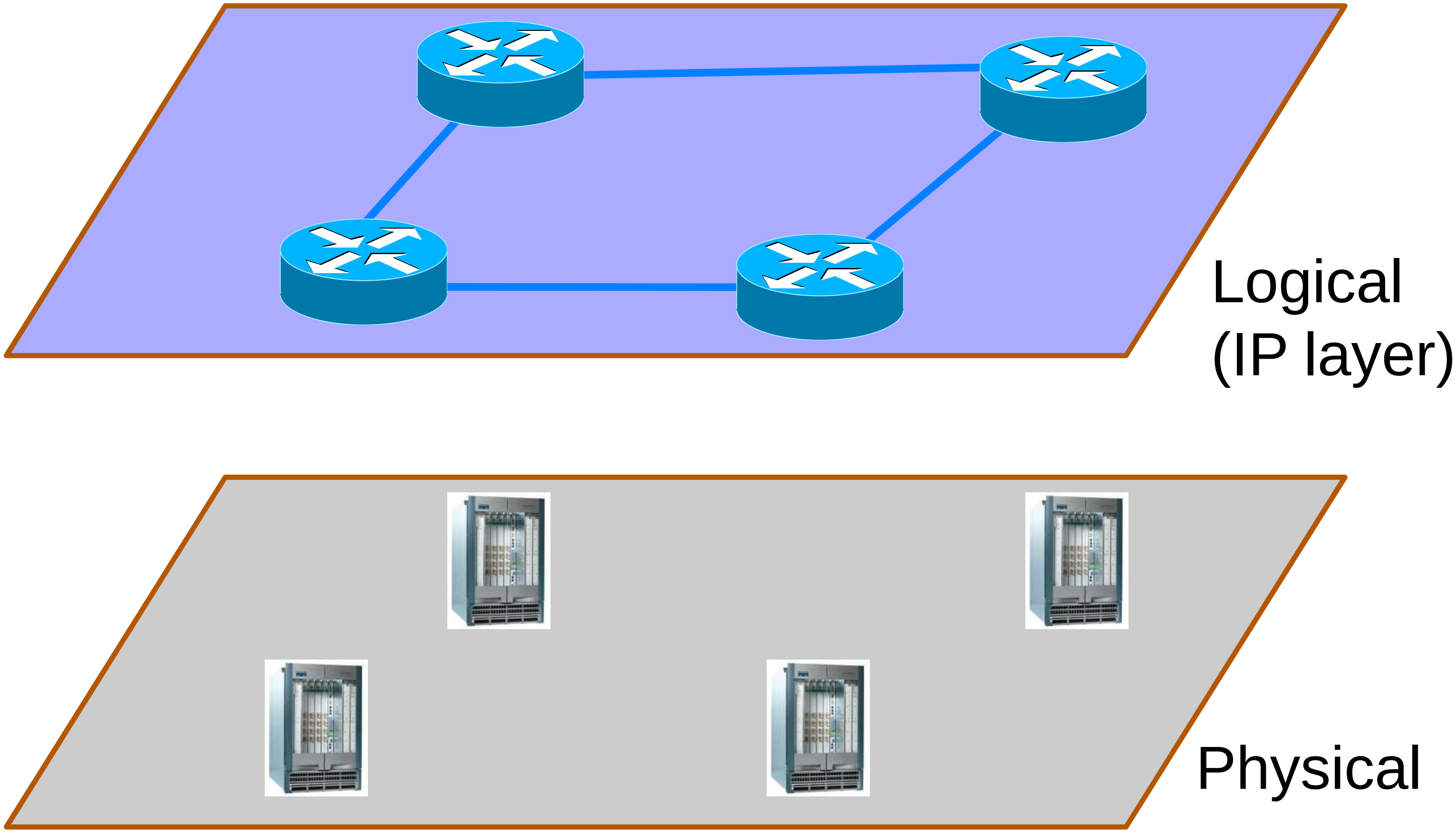


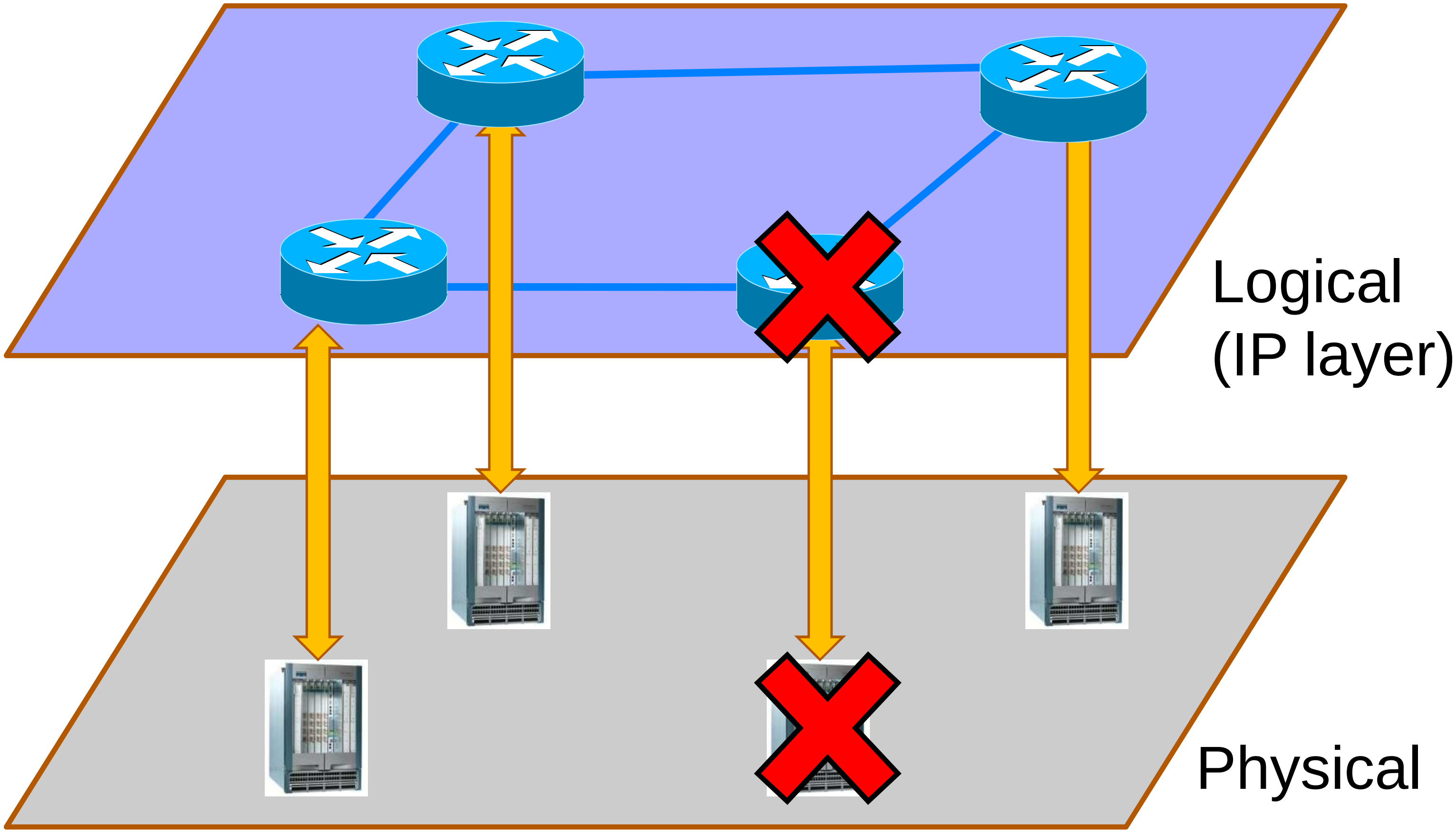
The Two Notions of “Router”

IP-layer logical functionality & the physical equipment



The Tight Coupling of Physical & Logical

Root of many network adaptation challenges



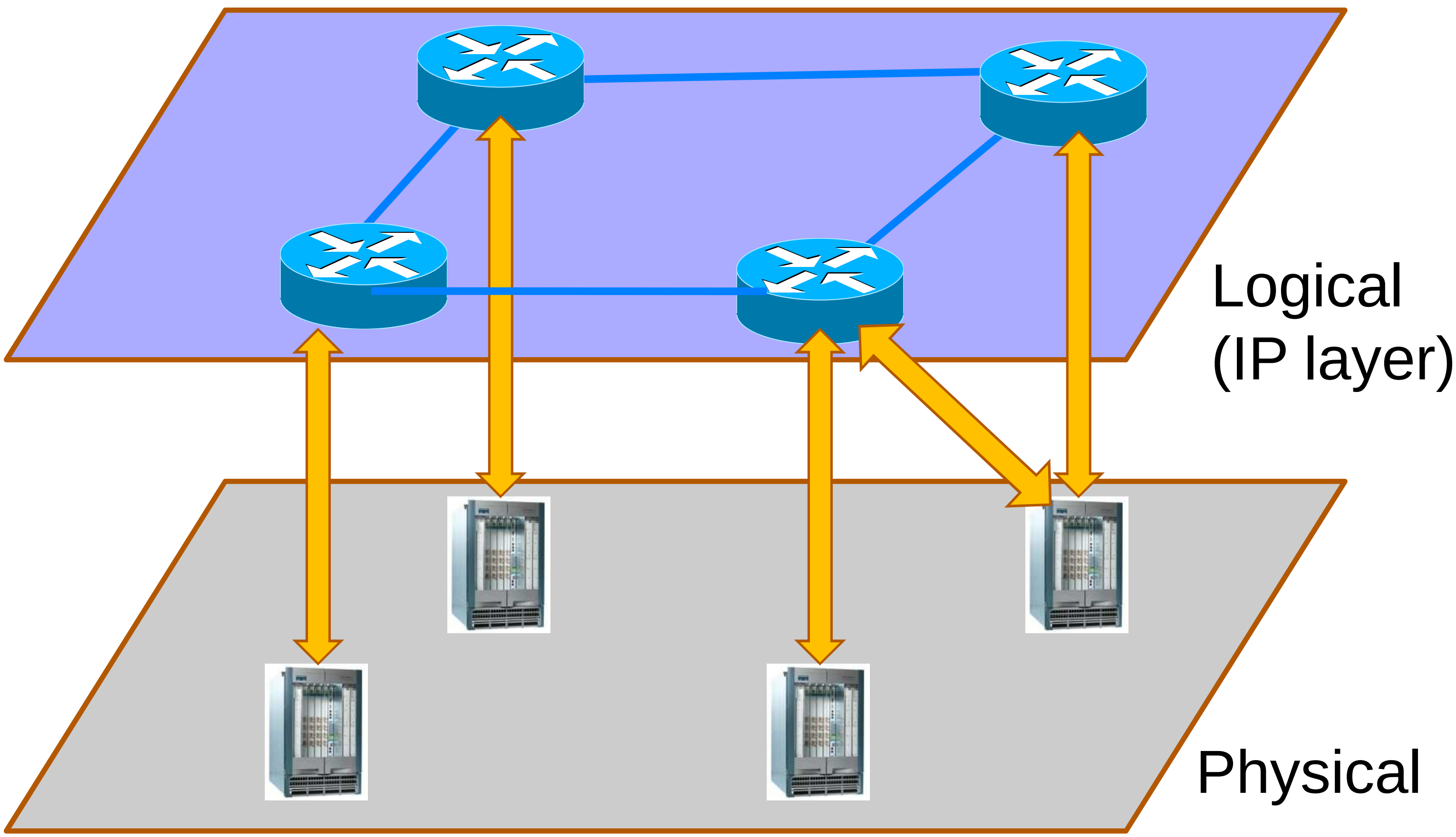
Decouple the "Physical" and "Logical"

- Whenever physical changes are the goal, e.g.,
  - Replace a hardware component
  - Change the physical location of a router

- A router's logical configuration stays intact
  - Routing protocol configuration
  - Protocol adjacencies (sessions)

VROOM: Breaking the Coupling

Re-map the logical node to another physical node



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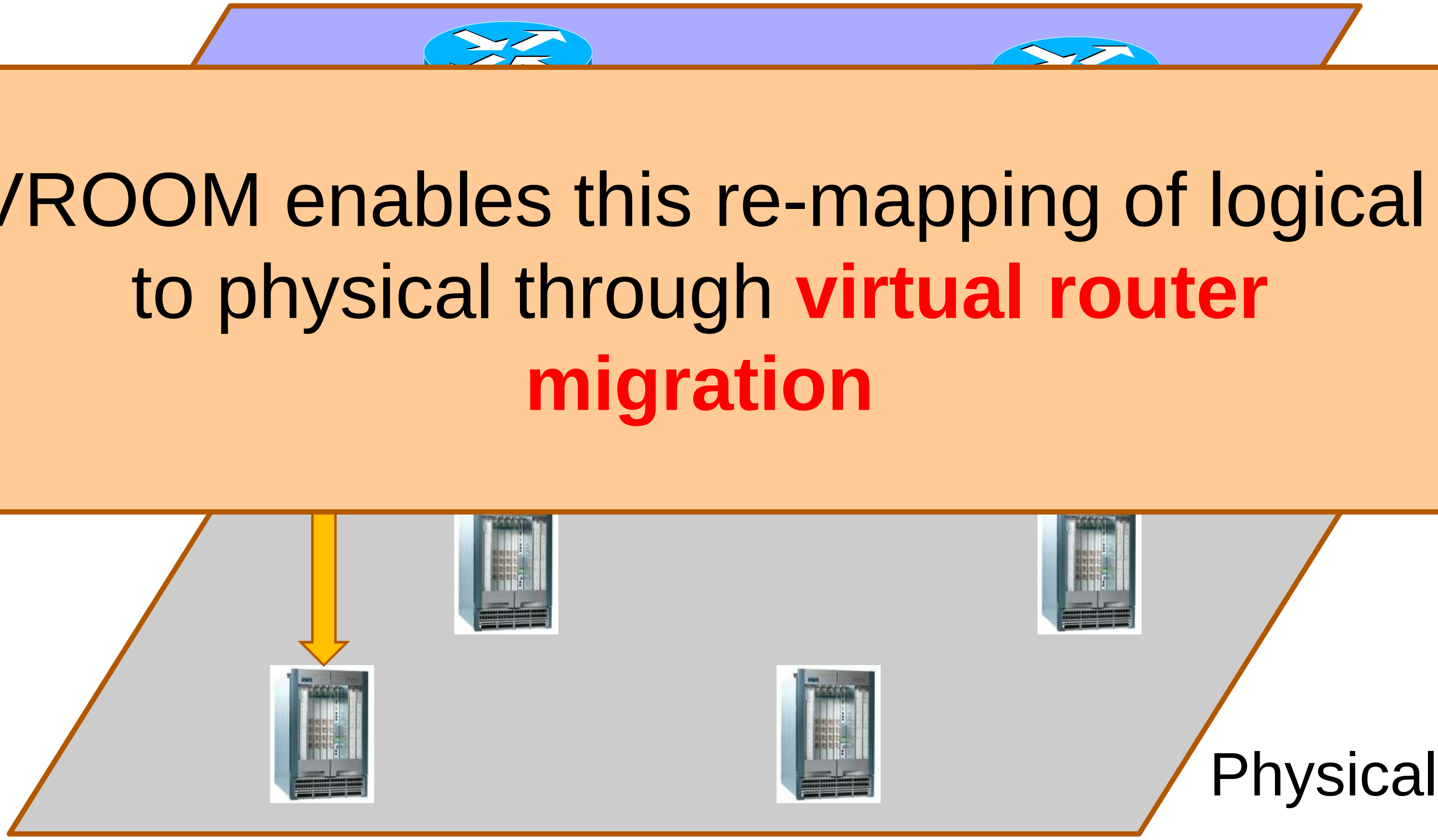
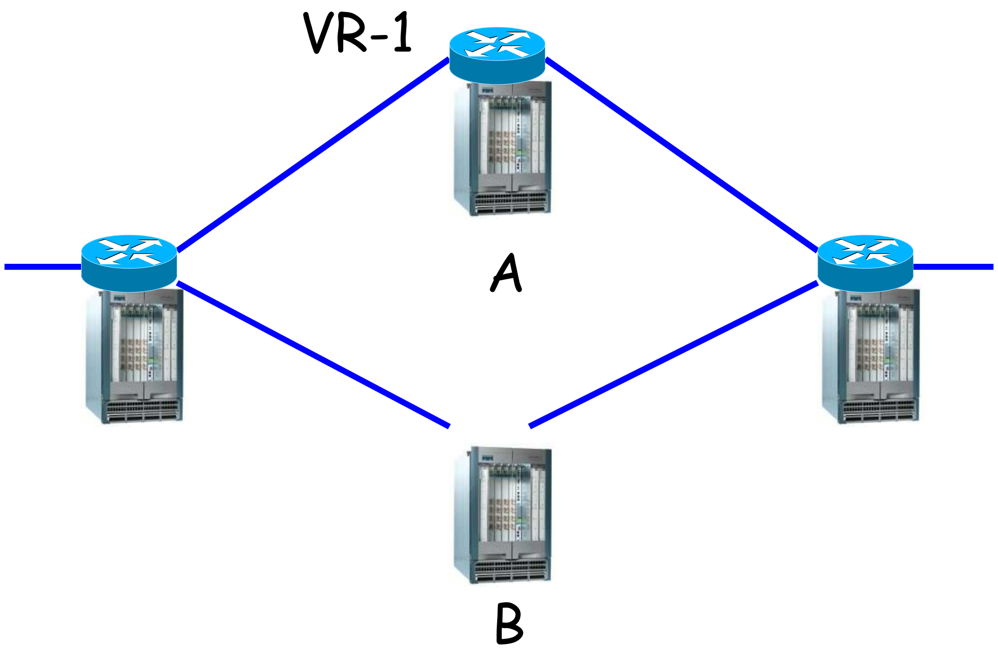
Re-map the logical node to another physical node



VROOM enables this re-mapping of logical to physical through **virtual router migration**

Example: Planned Maintenance

- NO reconfiguration of VRs, NO disruption



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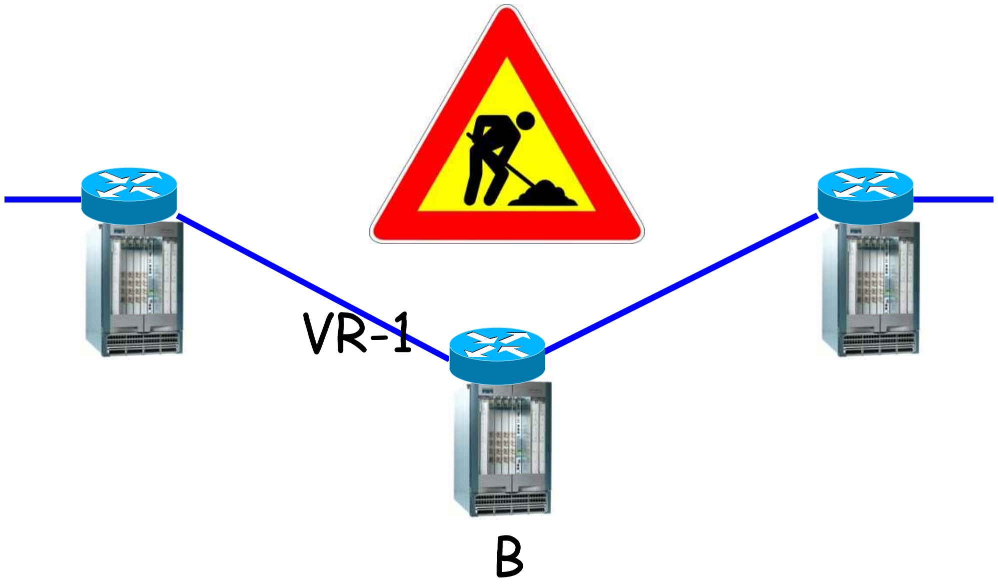

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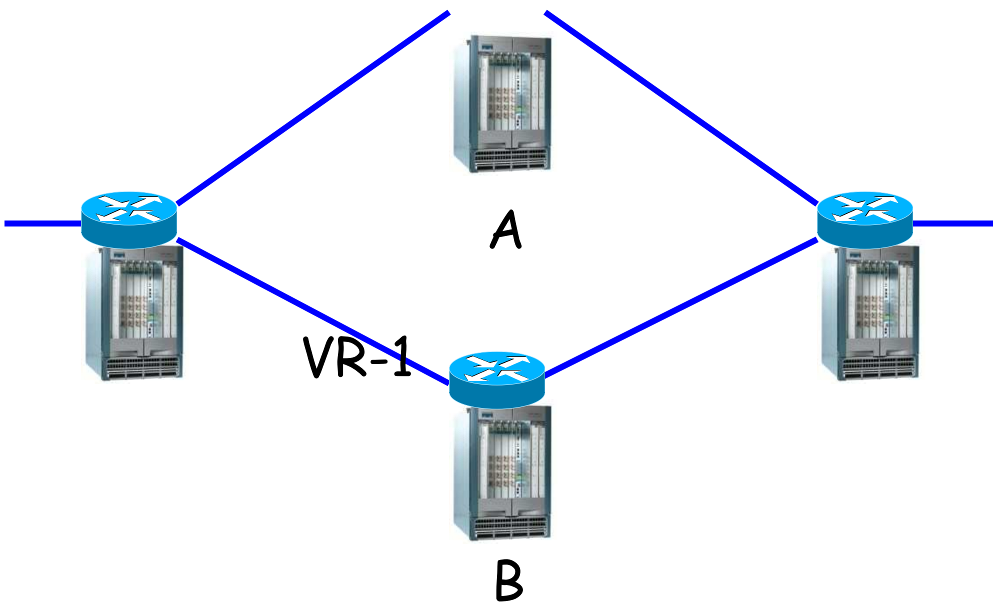
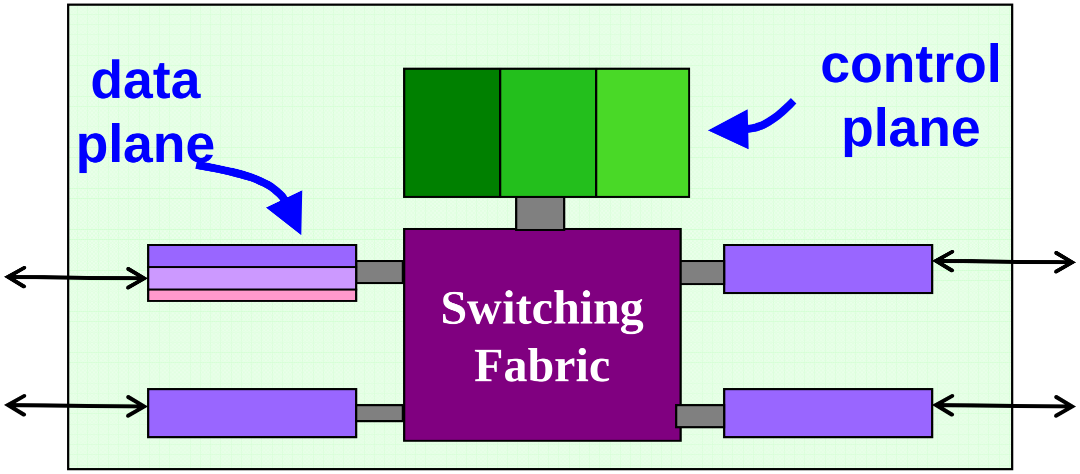


Virtual Router Migration: the Challenges

1. Migrate an entire virtual router instance
    - All control plane & data plane processes / states

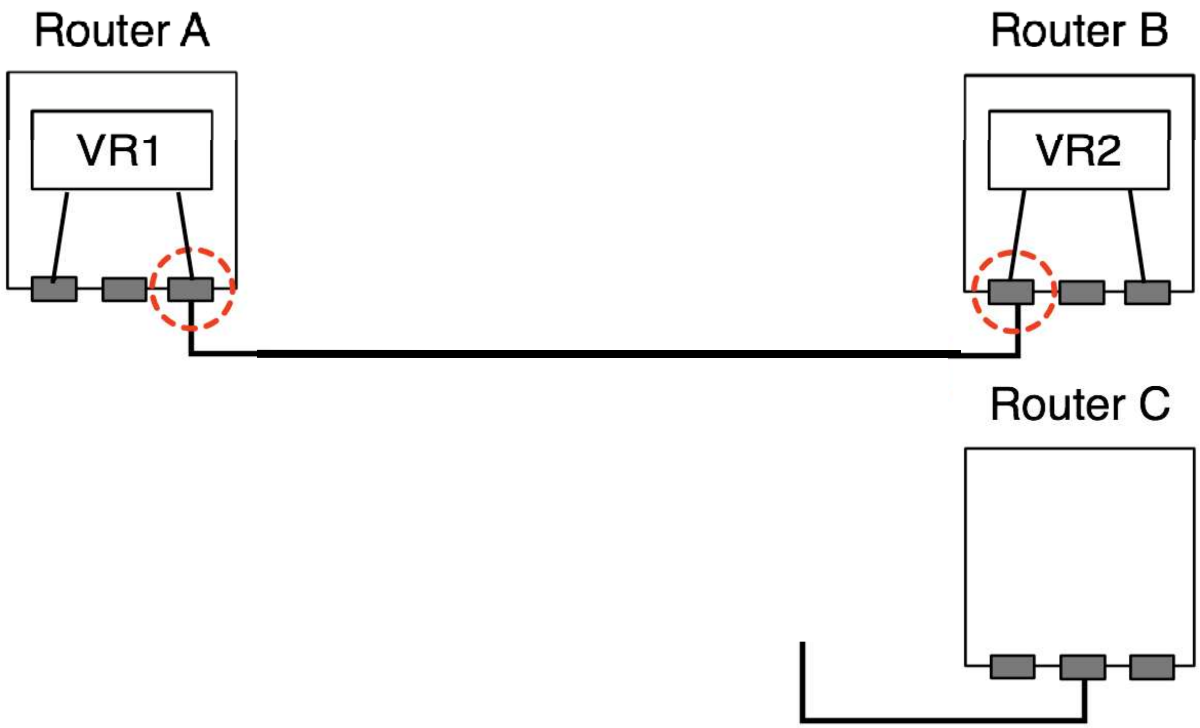


Virtual Router Migration: the Challenges

1. Migrate an entire virtual router instance
2. Minimize disruption
   - Data plane: millions of packets/second on a 10Gbps link
   - Control plane: less strict (with routing message retransmission)

Virtual Router Migration: the Challenges

1. Migrate an entire virtual router instance
2. Minimize disruption
3. Link migration



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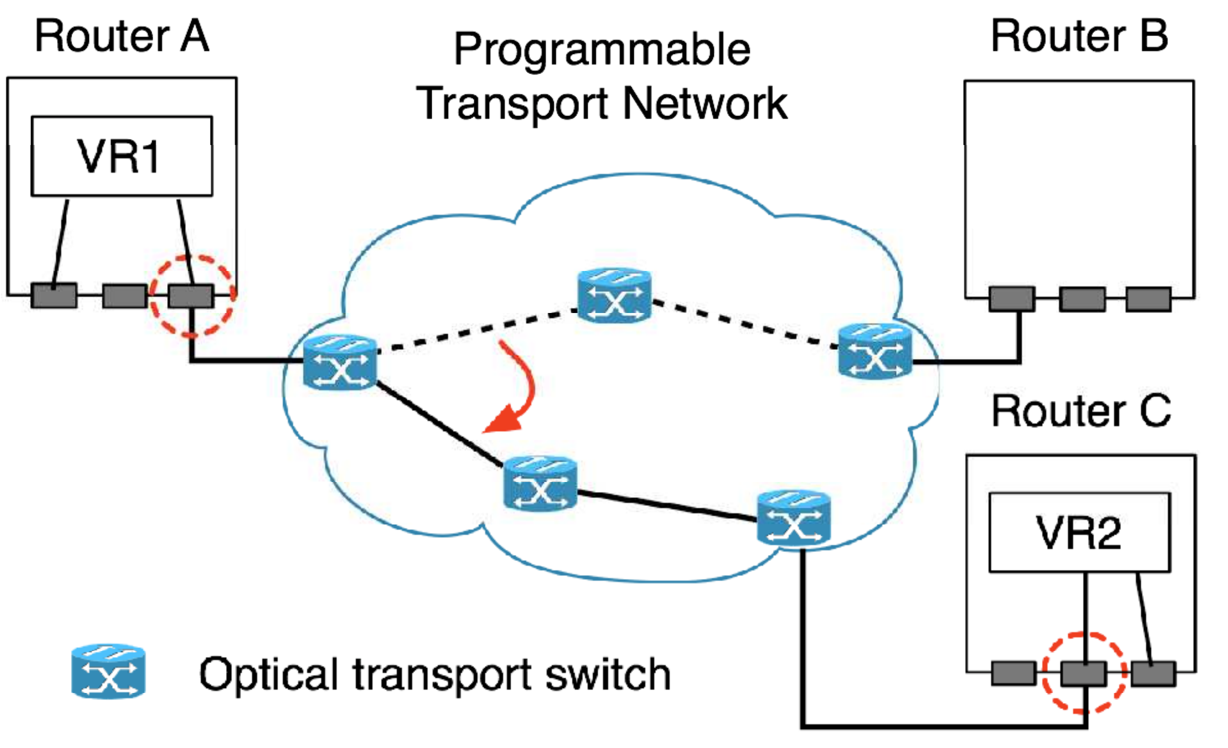
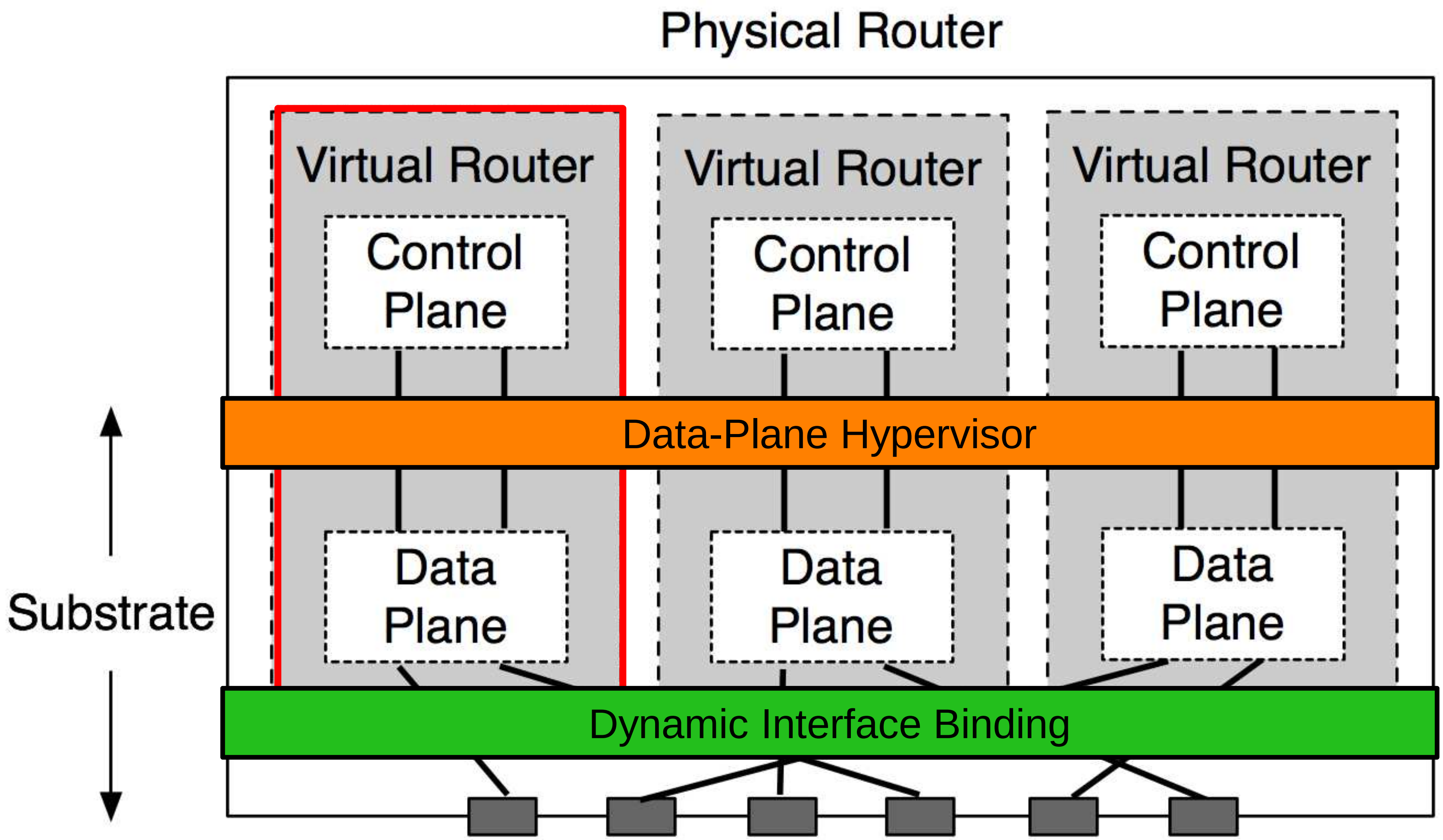


VROOM Architecture



VROOM's Migration Process

- Key idea: separate the migration of control and data planes

1. Migrate the control plane
2. Clone the data plane
3. Migrate the links

Control-Plane Migration

Leverage virtual server migration techniques

- Router image
  - Binaries, configuration files, etc.

Control-Plane Migration

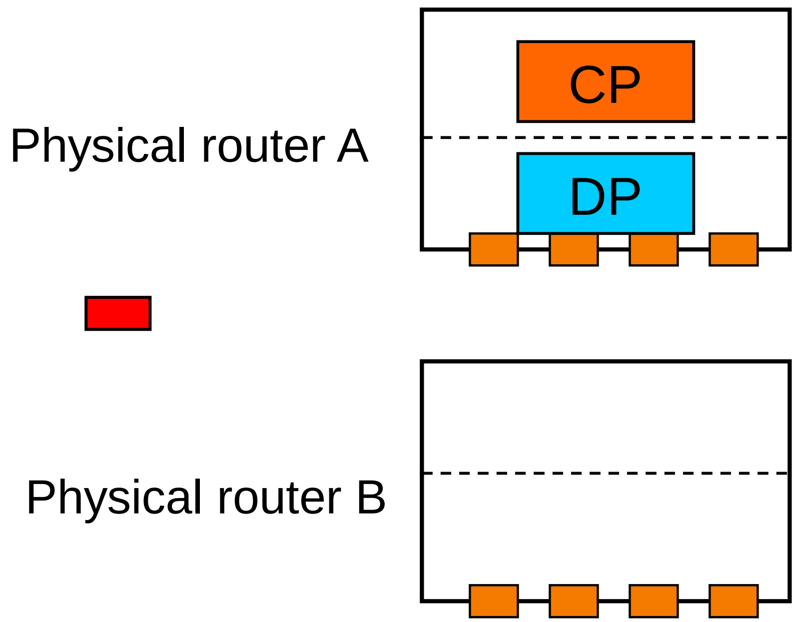
Leverage virtual server migration techniques

- Router image
- Memory
  - 1st stage: iterative pre-copy
  - 2nd stage: stall-and-copy (when the control plane is "frozen")

Control-Plane Migration

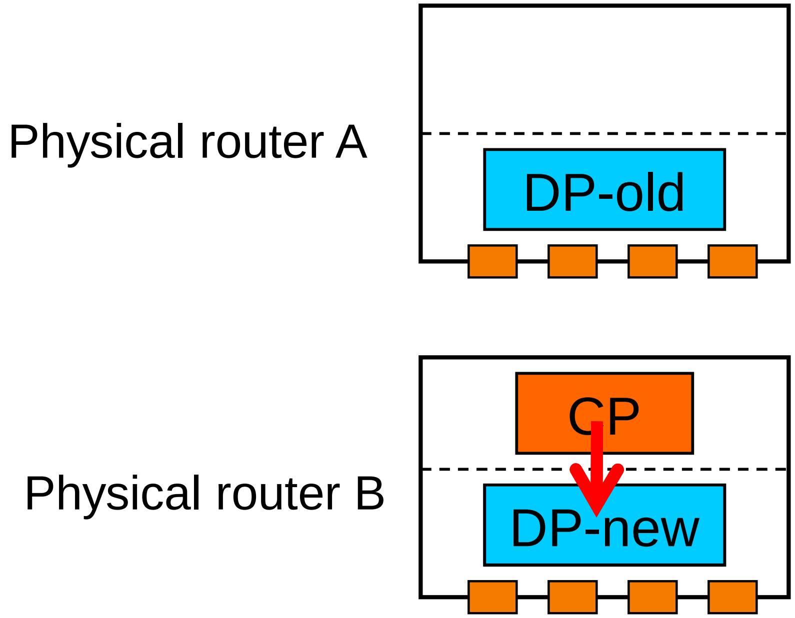
Leverage virtual server migration techniques

- Router image
- Memory



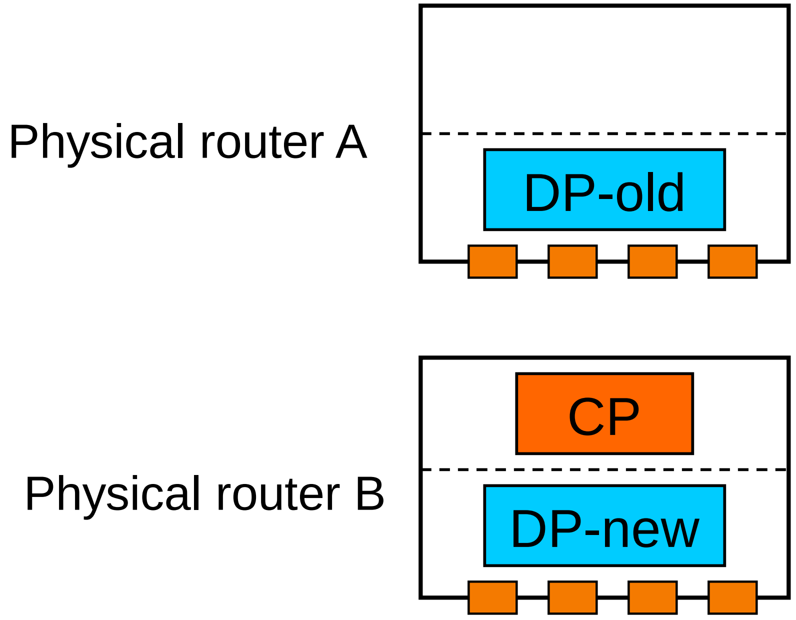
Data-Plane Cloning

- Clone the data plane by repopulation
  - Enable migration across different data planes



Remote Control Plane

- Data-plane cloning takes time
  - Installing 250k routes takes over 20 seconds*
- The control & old data planes need to be kept "online"
- Solution: redirect routing messages through tunnels



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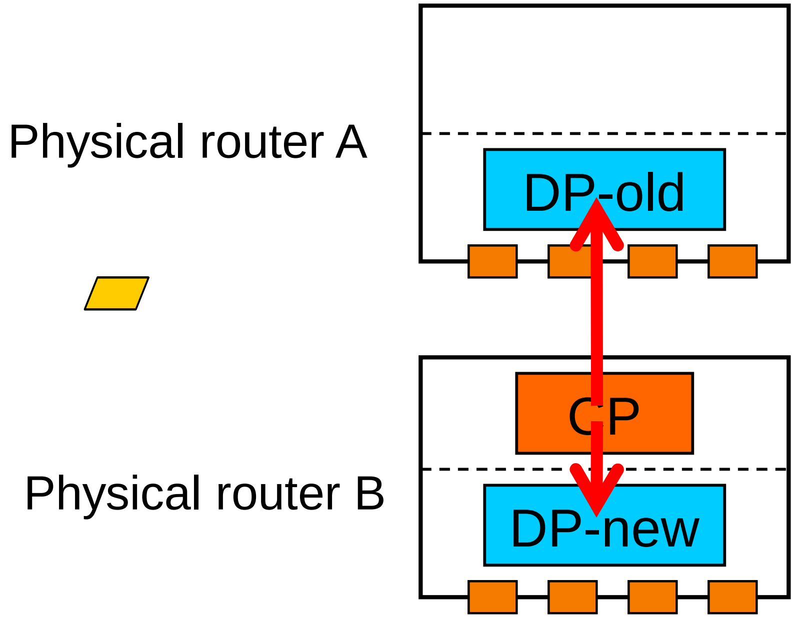

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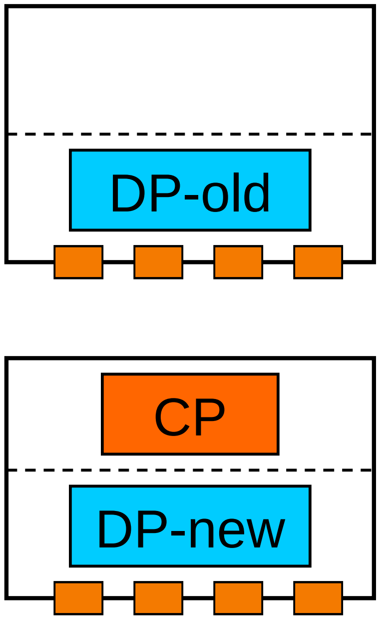
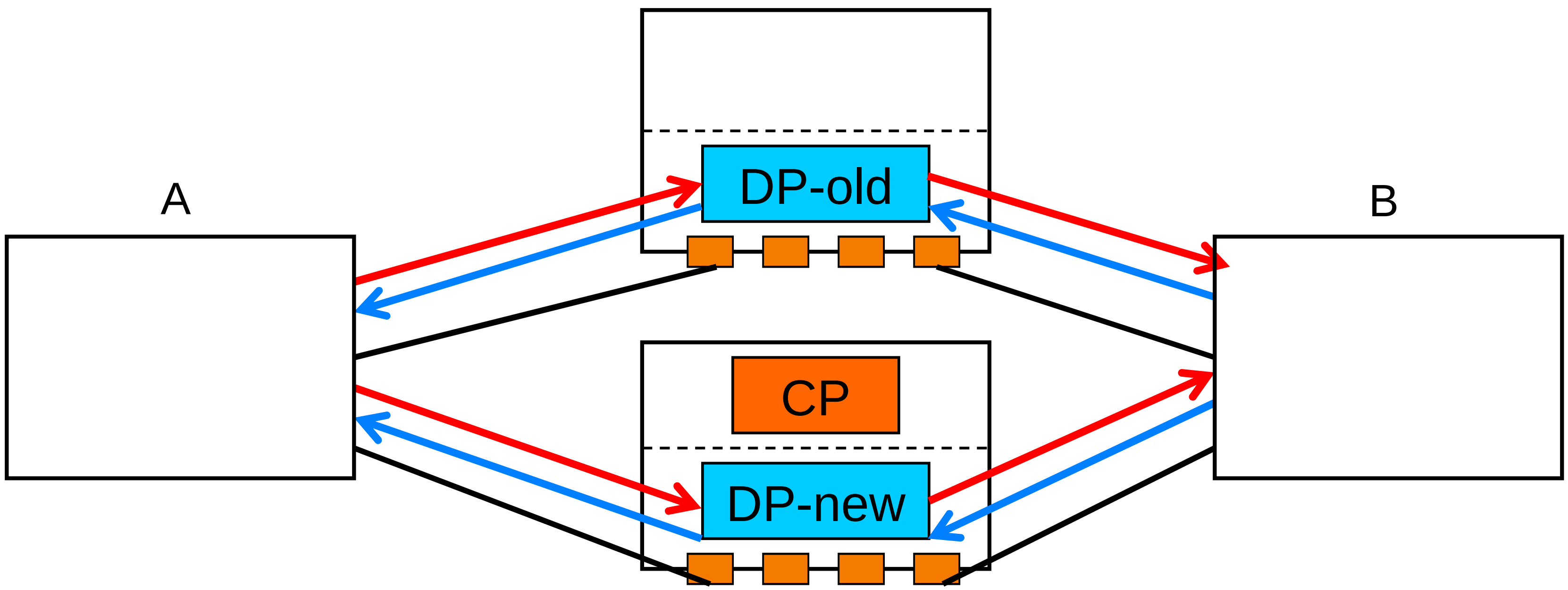
Double Data Planes

- At the end of data-plane cloning, both data planes are ready to forward traffic



Asynchronous Link Migration

- With the double data planes, links can be migrated independently



Prototype Implementation

- Control plane: OpenVZ + Quagga
- Data plane: two prototypes
  - Software-based data plane (SD): Linux kernel
  - Hardware-based data plane (HD): NetFPGA
- Why two prototypes?
  - To validate the data-plane hypervisor design (e.g., migration between SD and HD)

Evaluation

- Impact on data traffic
  - SD: Slight delay increase due to CPU contention
  - HD: no delay increase or packet loss
- Impact on routing protocols
  - Average control-plane downtime: 3.56 seconds (performance lower bound)
  - OSPF and BGP adjacencies stay up

VROOM Summary

- Simple abstraction
- No modifications to router software (other than virtualization)
- No impact on data traffic
- No visible impact on routing protocols

Part III: Seamless Edge Link Migration with Router Grafting

With Jennifer Rexford, Kobus van der Merwe

[NSDI 2010]

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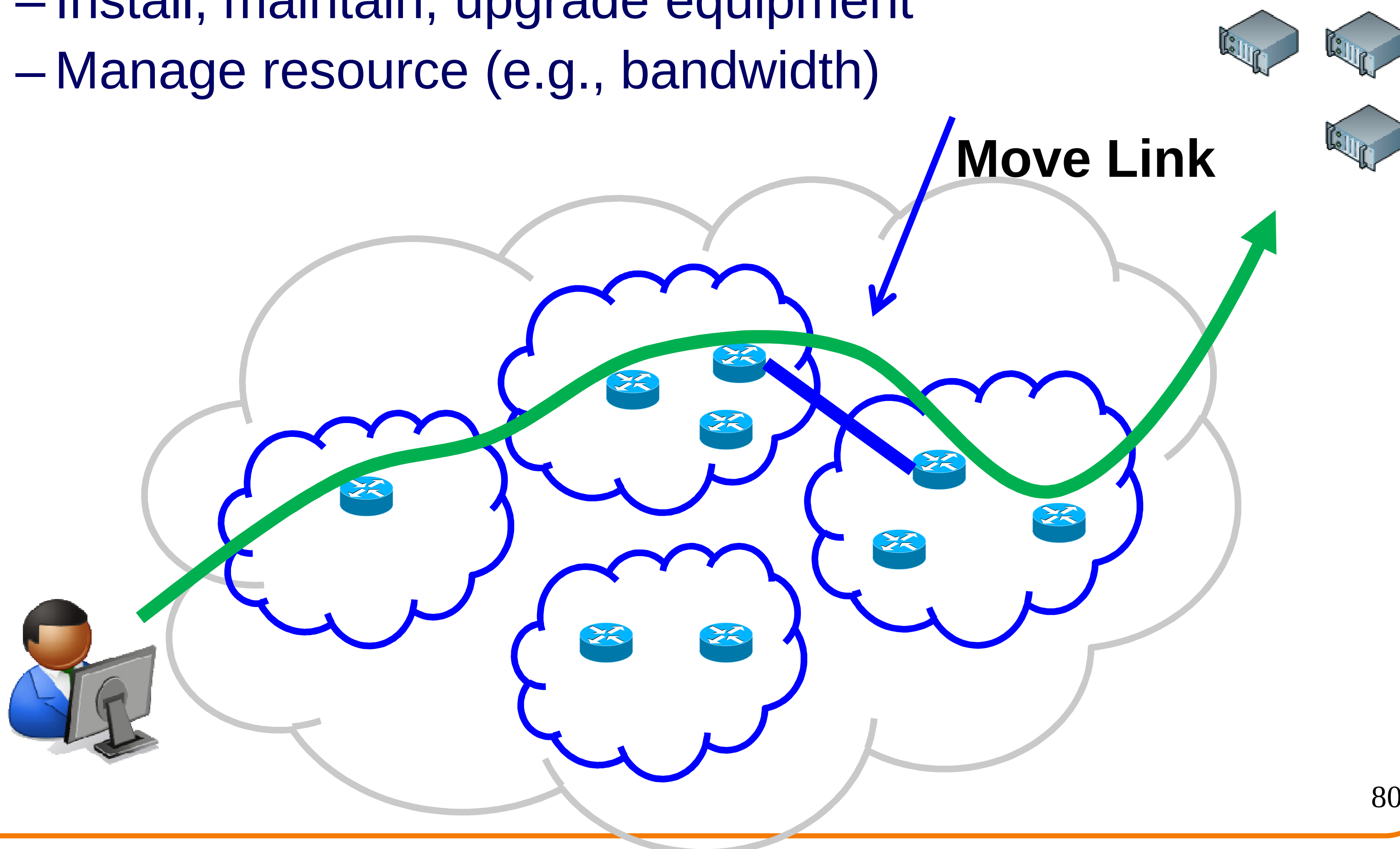

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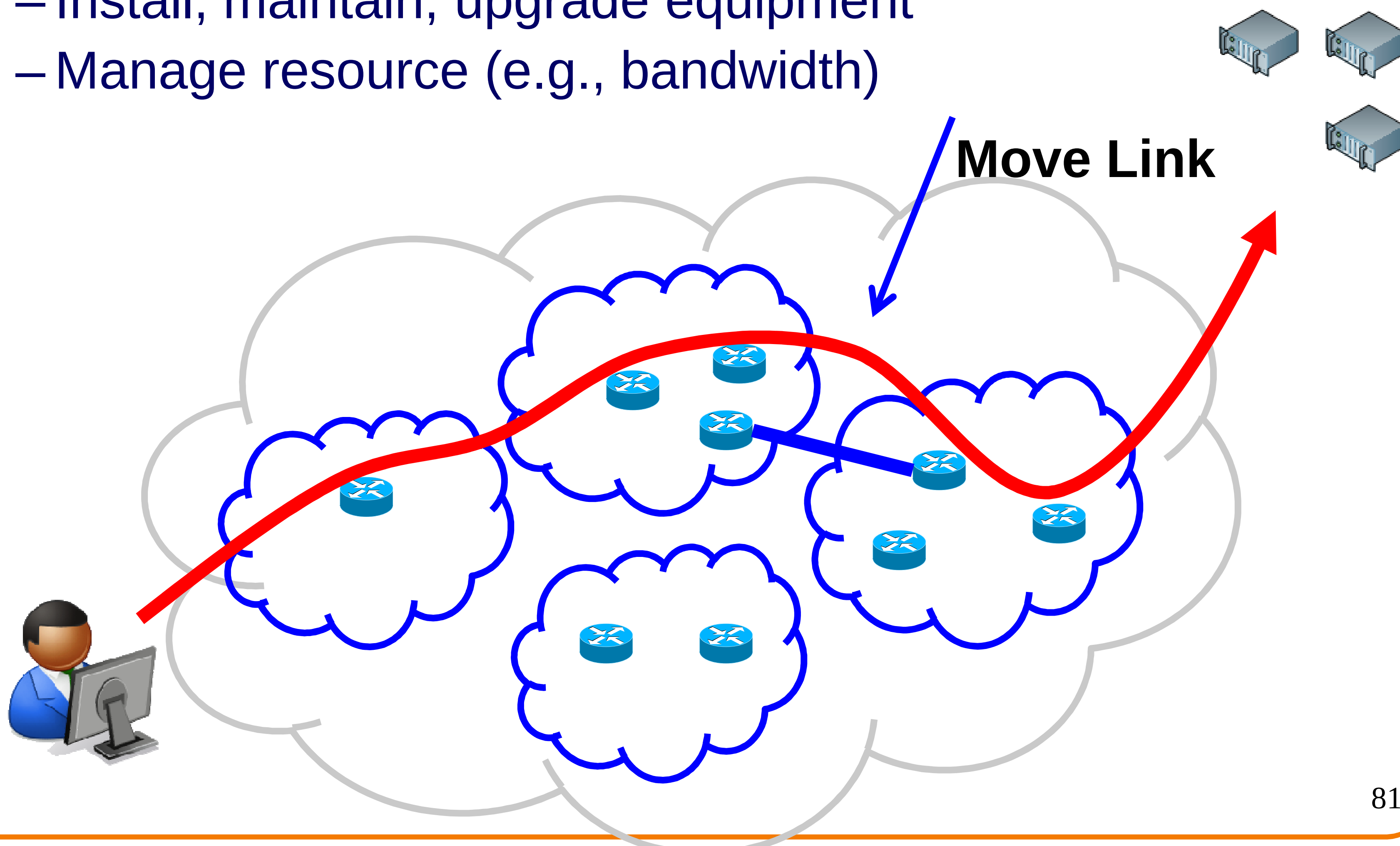
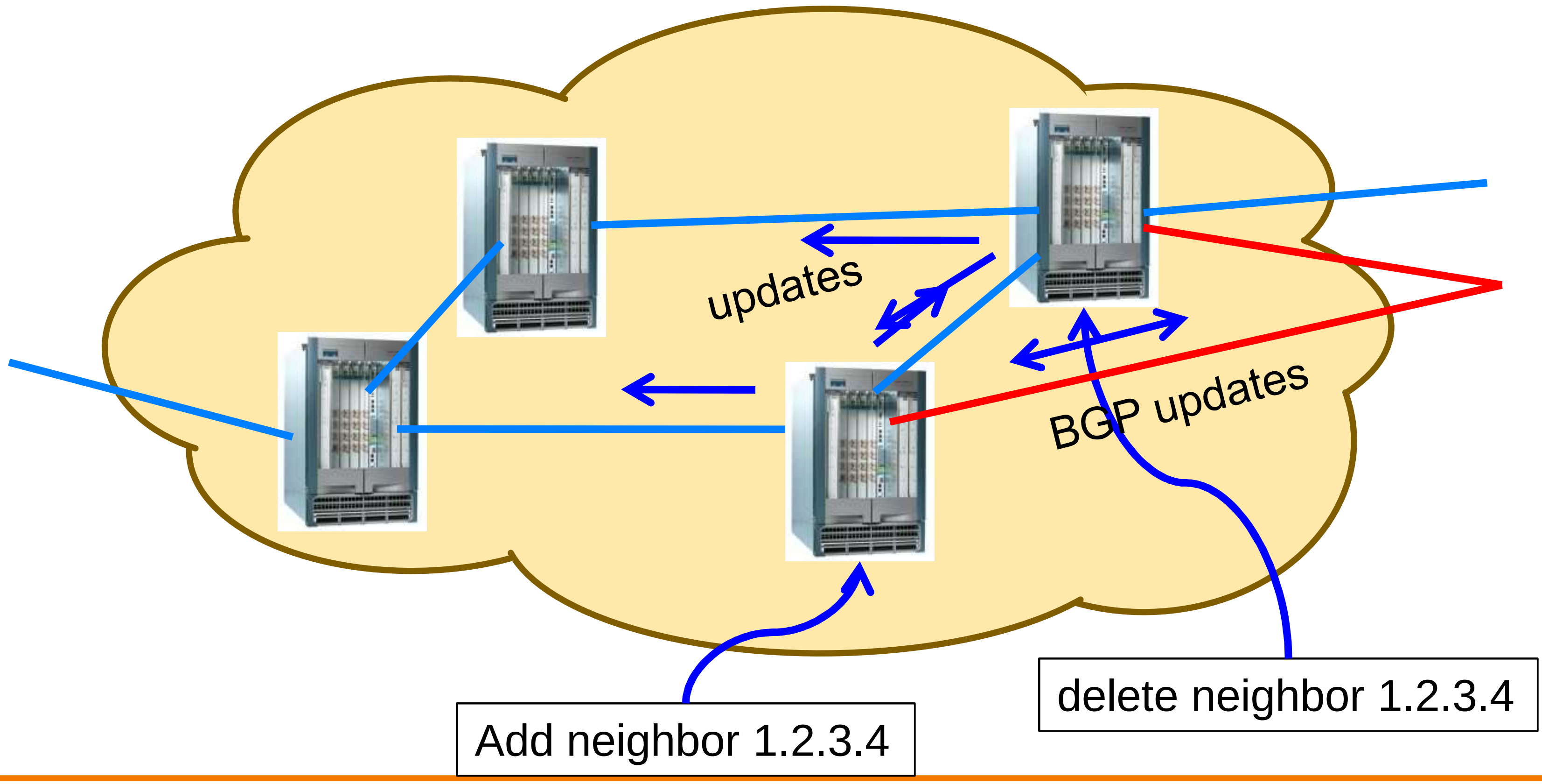
- Network operators need to deal with change
  - Install, maintain, upgrade equipment
  - Manage resource (e.g., bandwidth)



Understanding the Disruption (today)

1) Reconfigure old router, remove old link
2) Add new link, configure new router
3) Establish new BGP session (exchange routes)



Understanding the Disruption (today)

1) Reconfigure old router, remove old link
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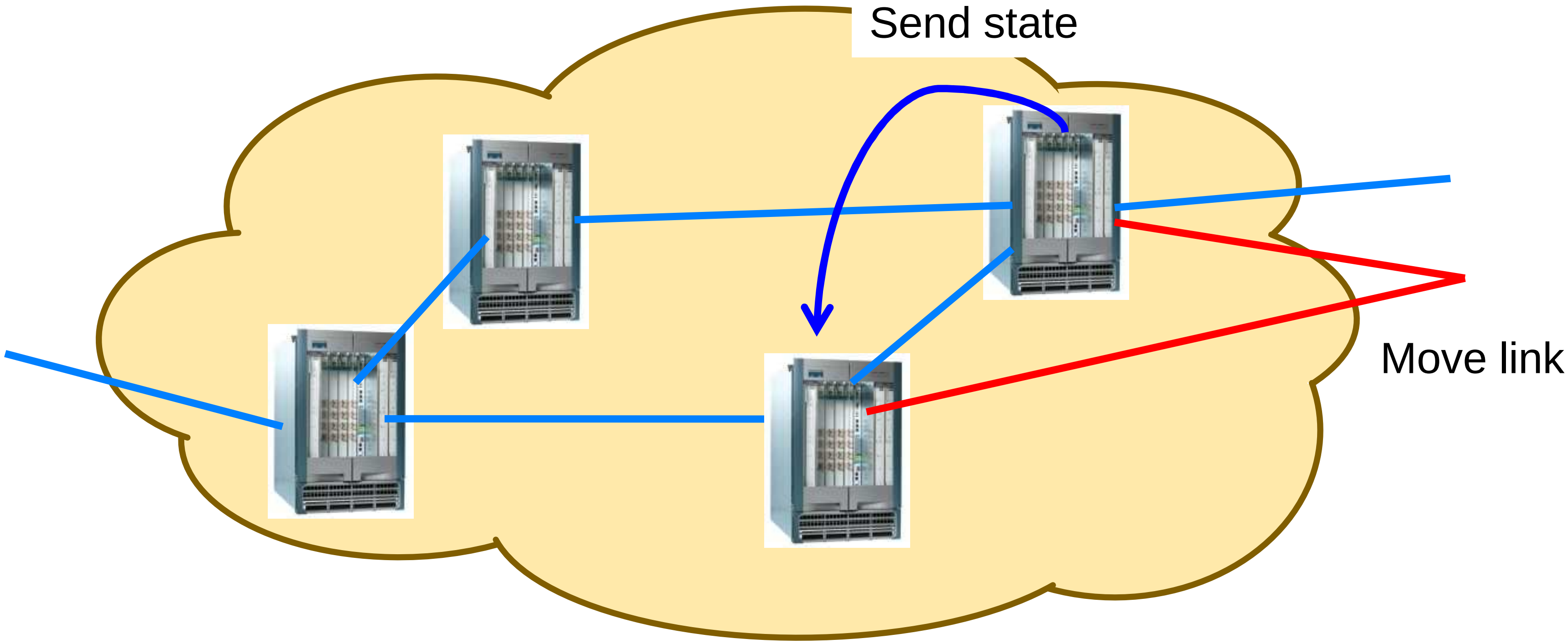
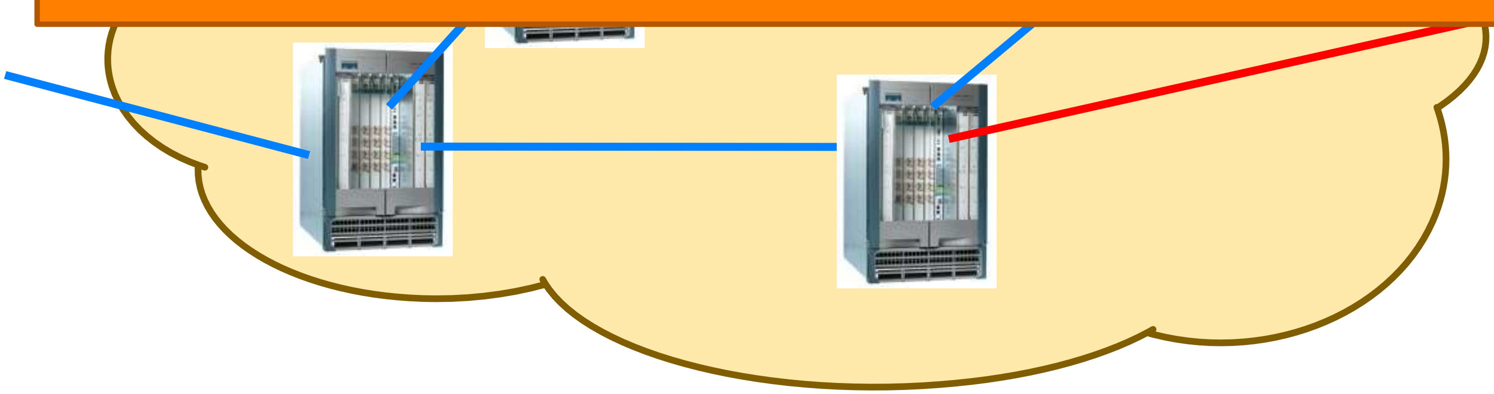
Downtime (Minutes)

Breaking the Link to Router Binding

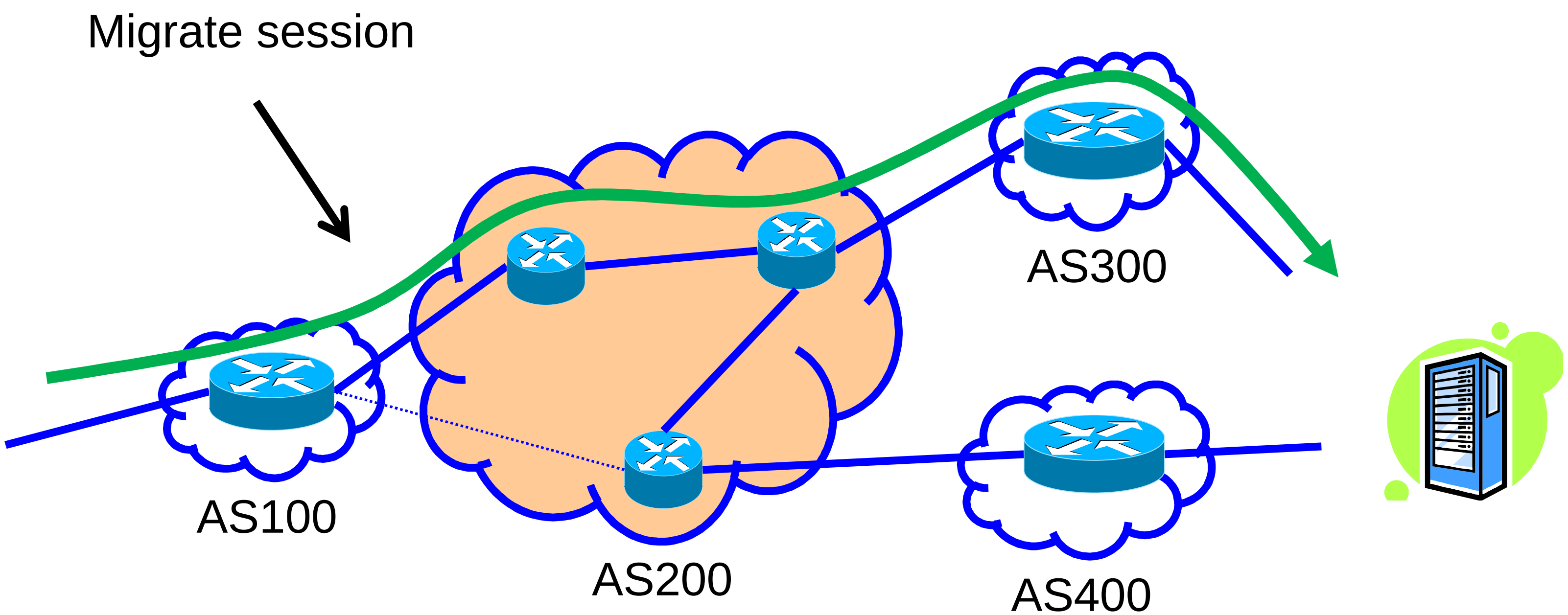


Breaking the Link to Router Binding

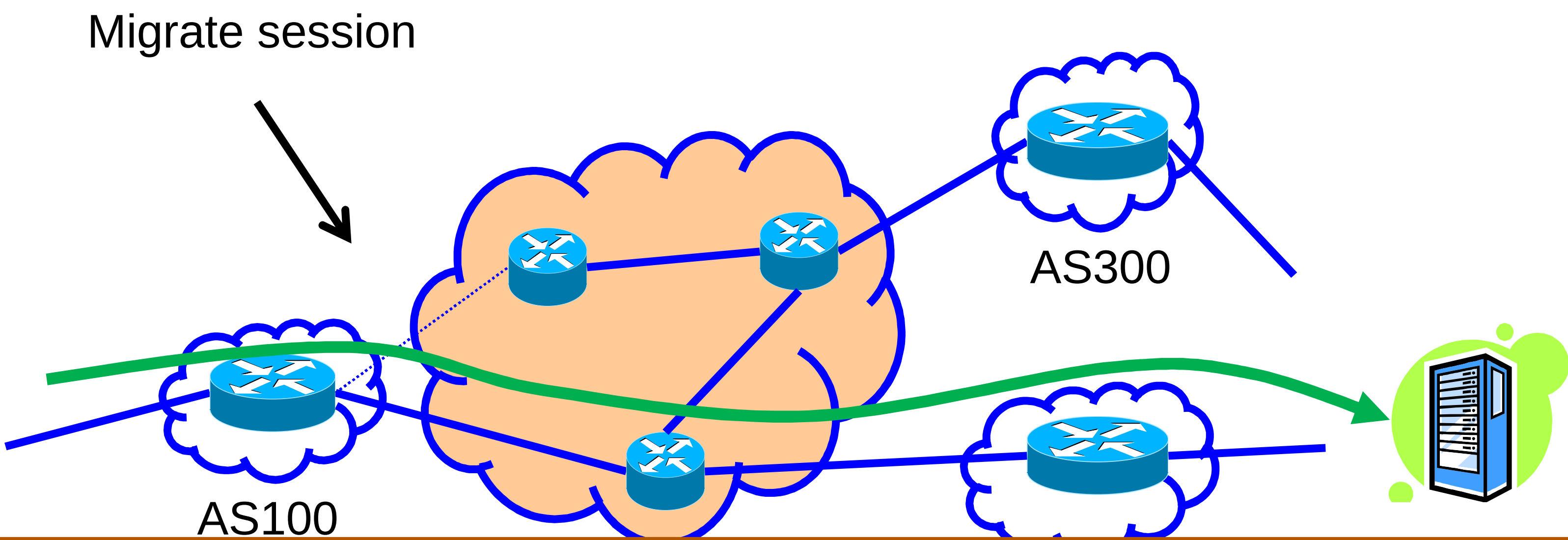


Router Grafting enables this breaking apart a router (splitting/merging).

Not Just State Transfer



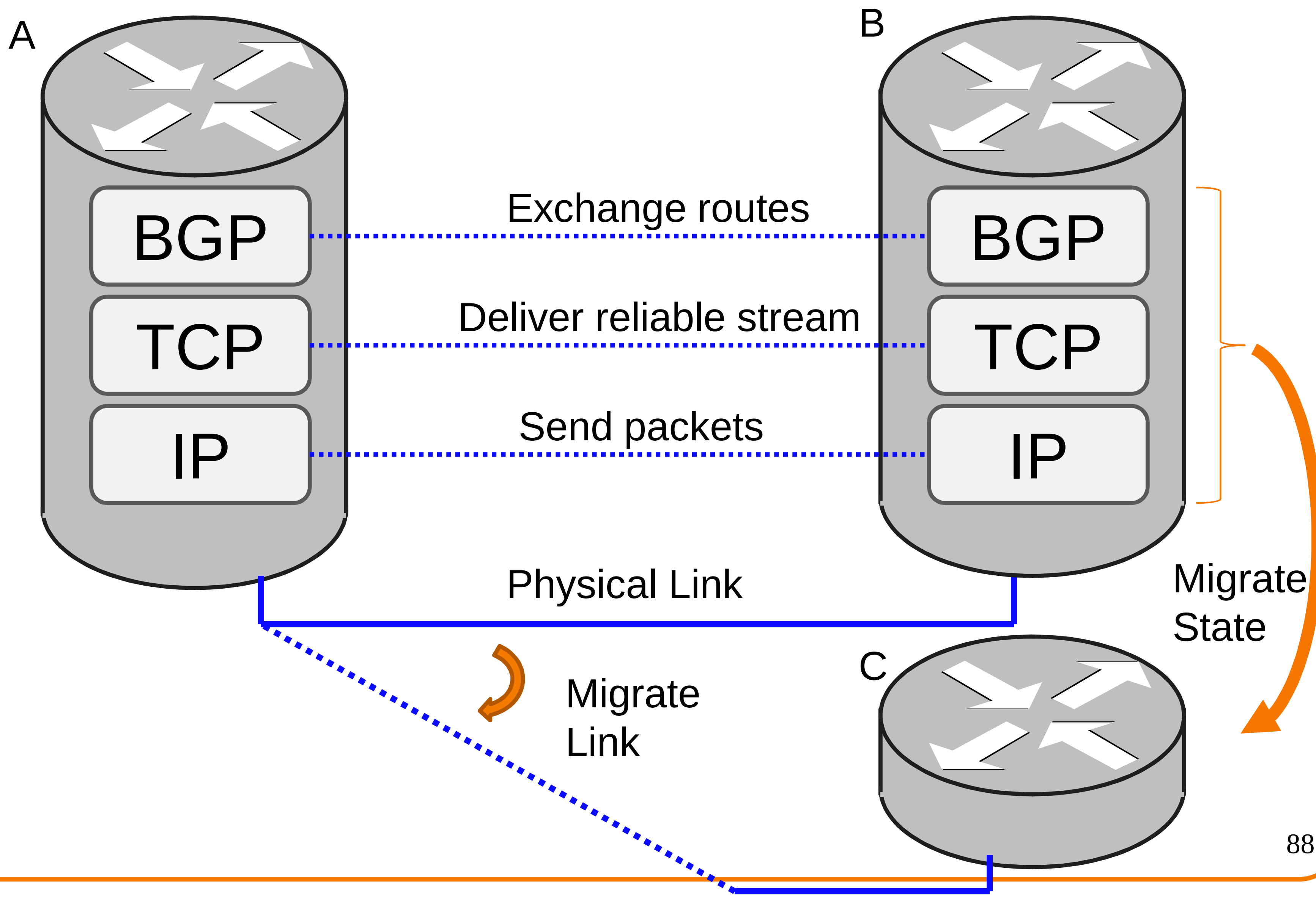
Not Just State Transfer



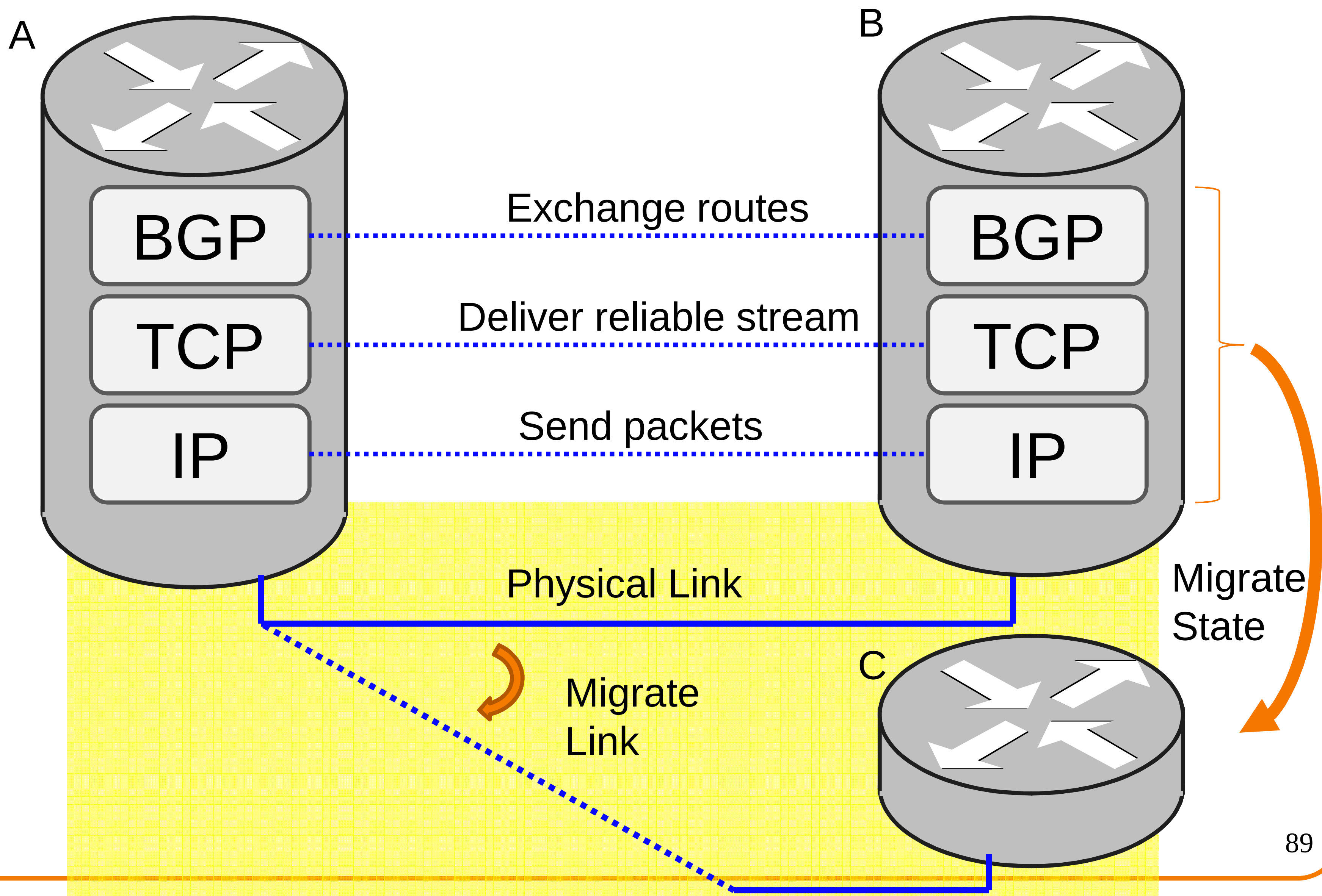
The topology changes

(Need to re-run decision processes)

Challenge: Protocol Layers

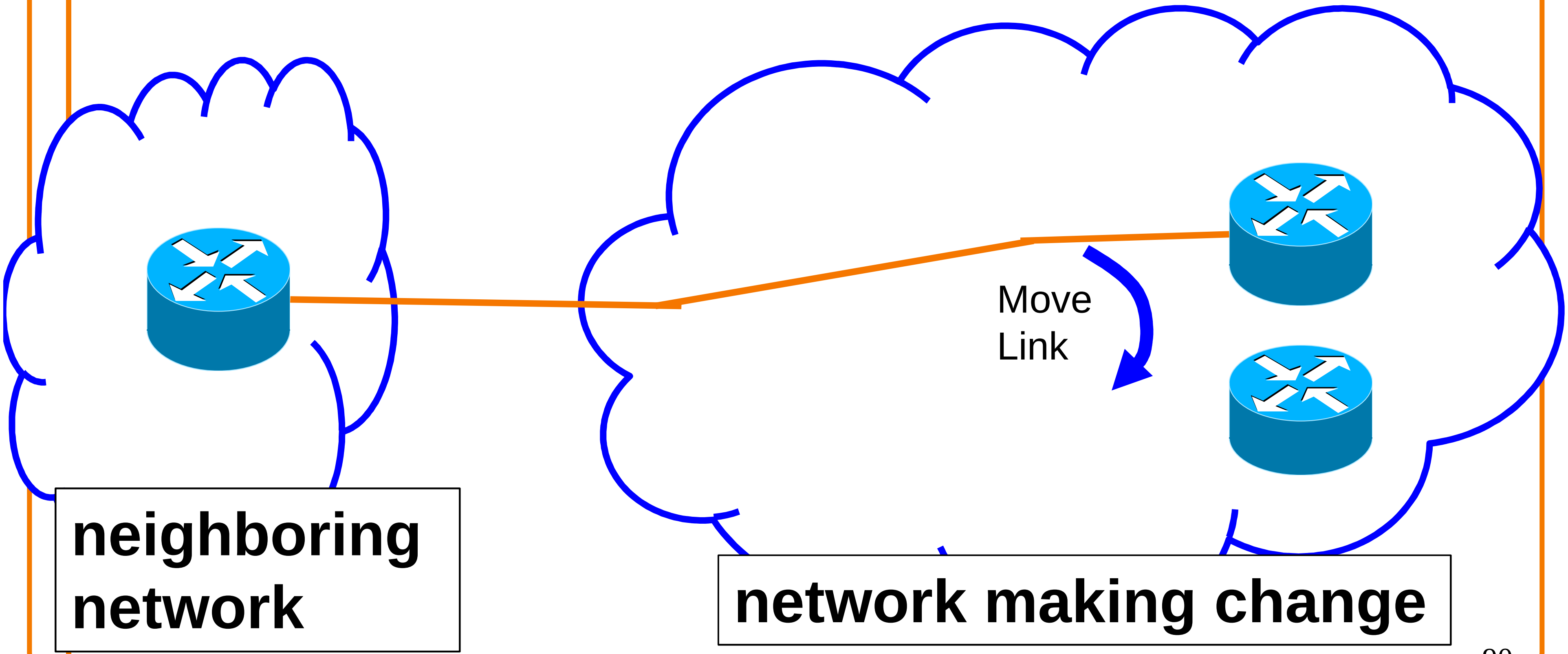


Physical Link



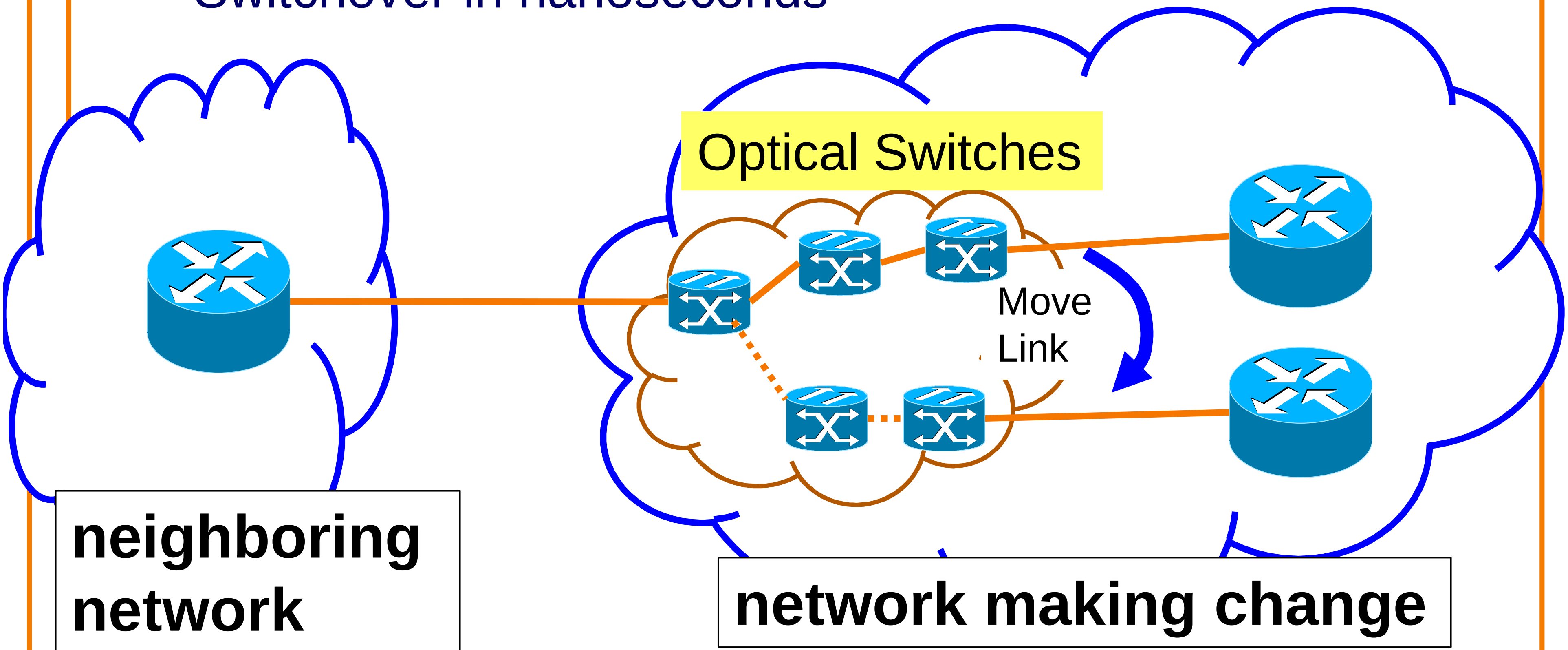
Physical Link

- Unplugging cable would be disruptive

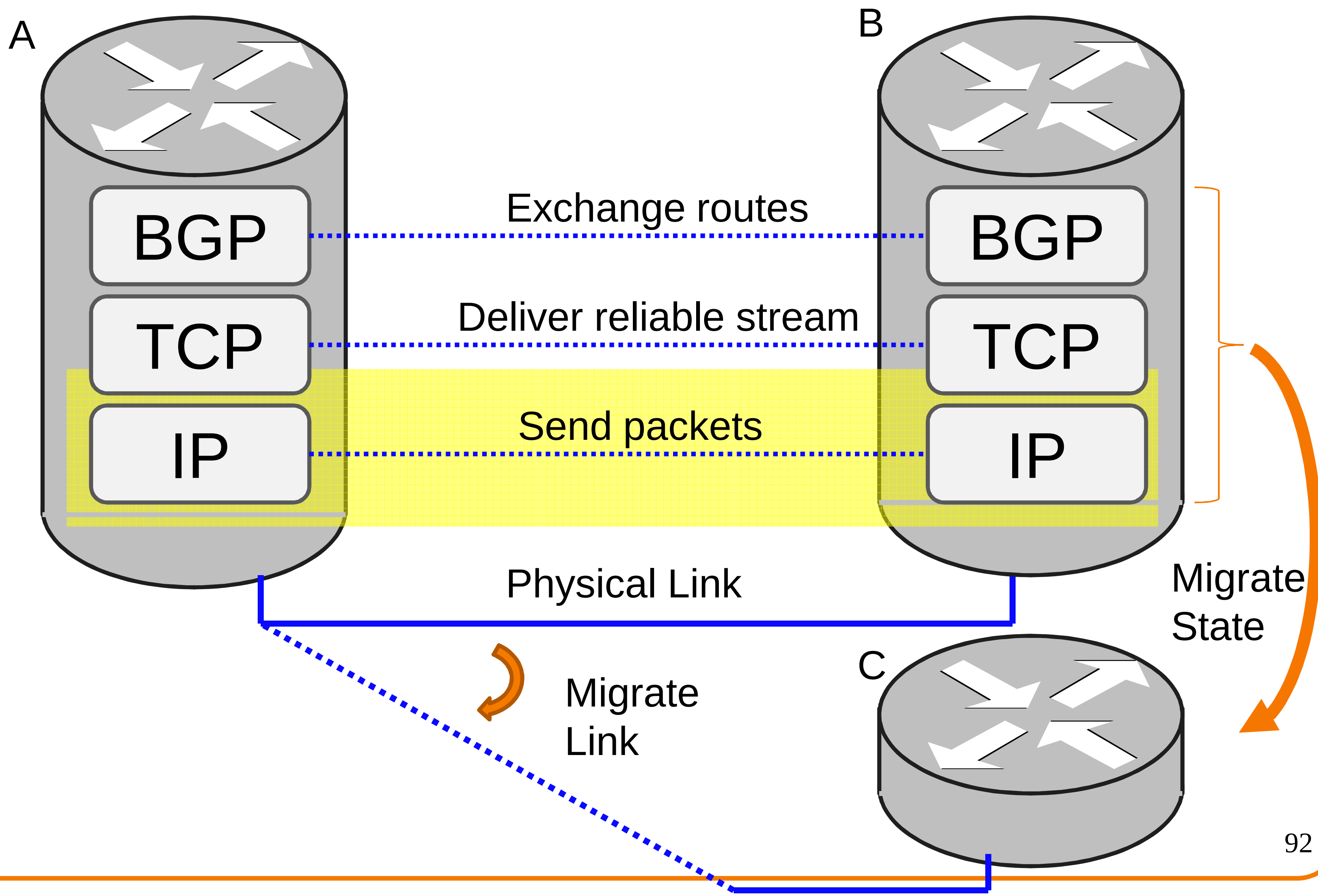


Physical Link

- Unplugging cable would be disruptive
- Links are not physical wires
  - Switchover in nanoseconds



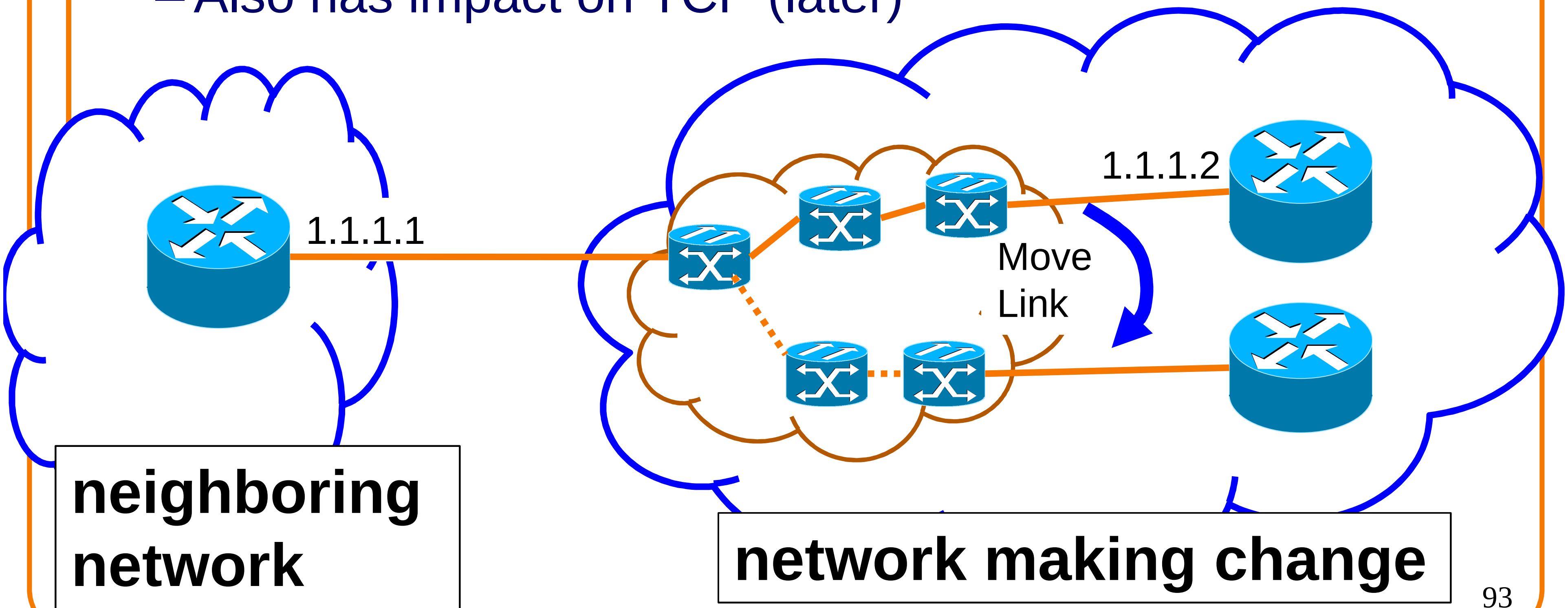
IP



A
B
BGP
TCP
IP
BGP
TCP
IP
Exchange routes
Deliver reliable stream
Send packets
Physical Link
Migrate
State
C
Migrate
Link

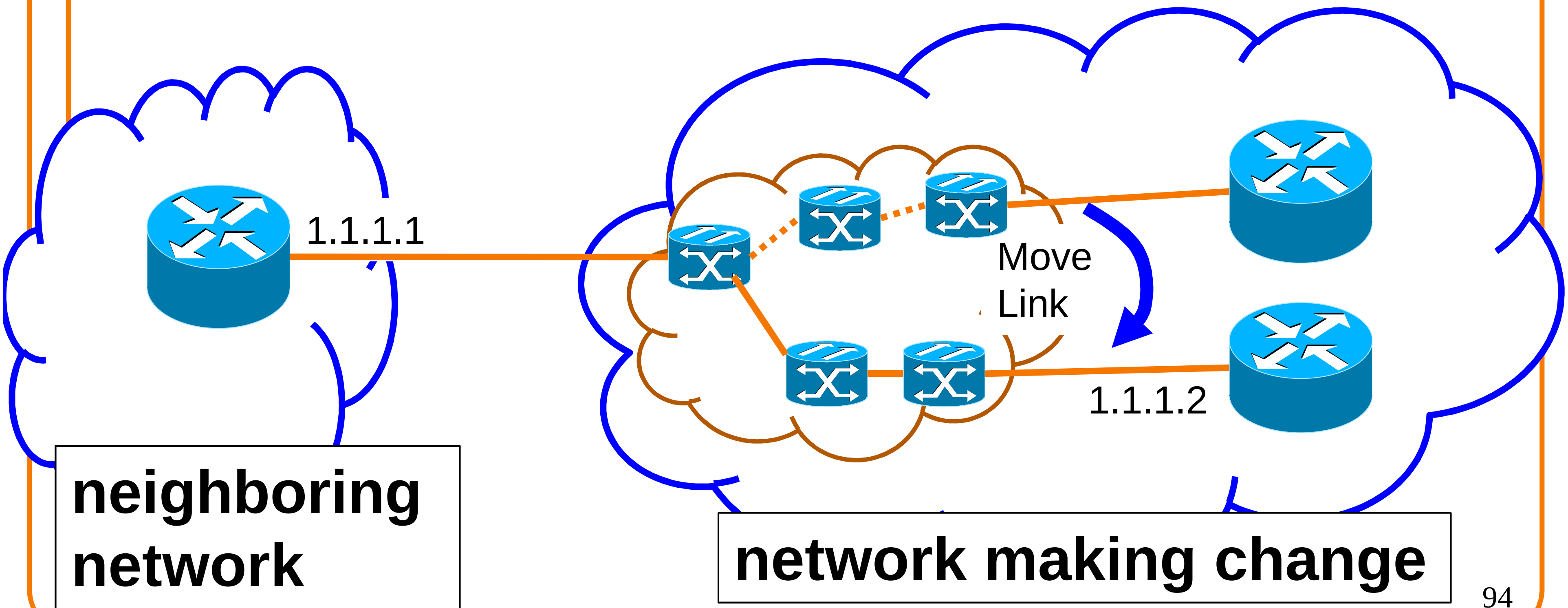
Changing IP Address

- IP address is an identifier in BGP
- Changing it would require neighbor to reconfigure
  - Not transparent
  - Also has impact on TCP (later)

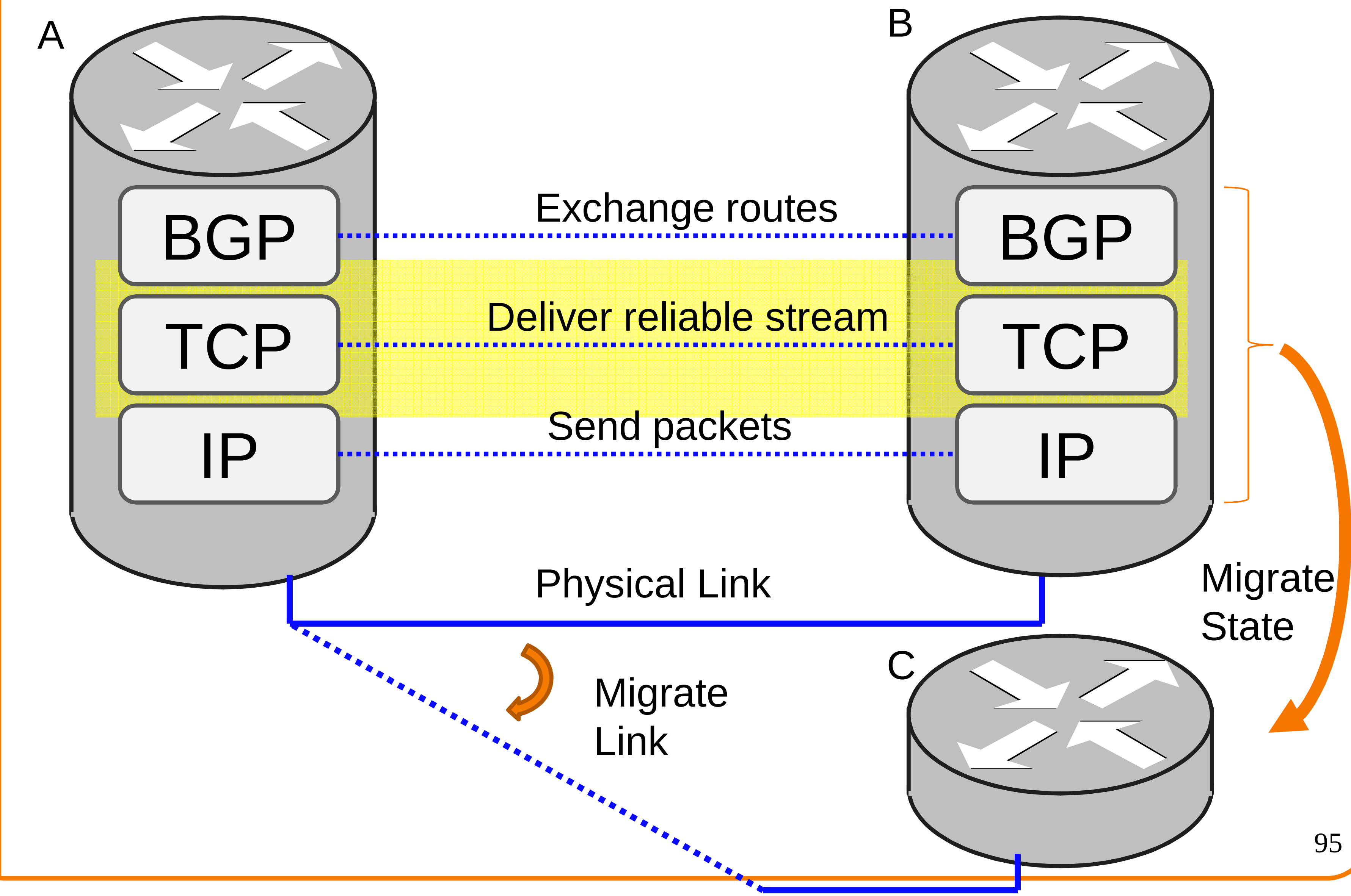


Re-assign IP Address

- IP address not used for global reachability
  - Can move with BGP session
  - Neighbor doesn't have to reconfigure



TCP



A
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Migrate
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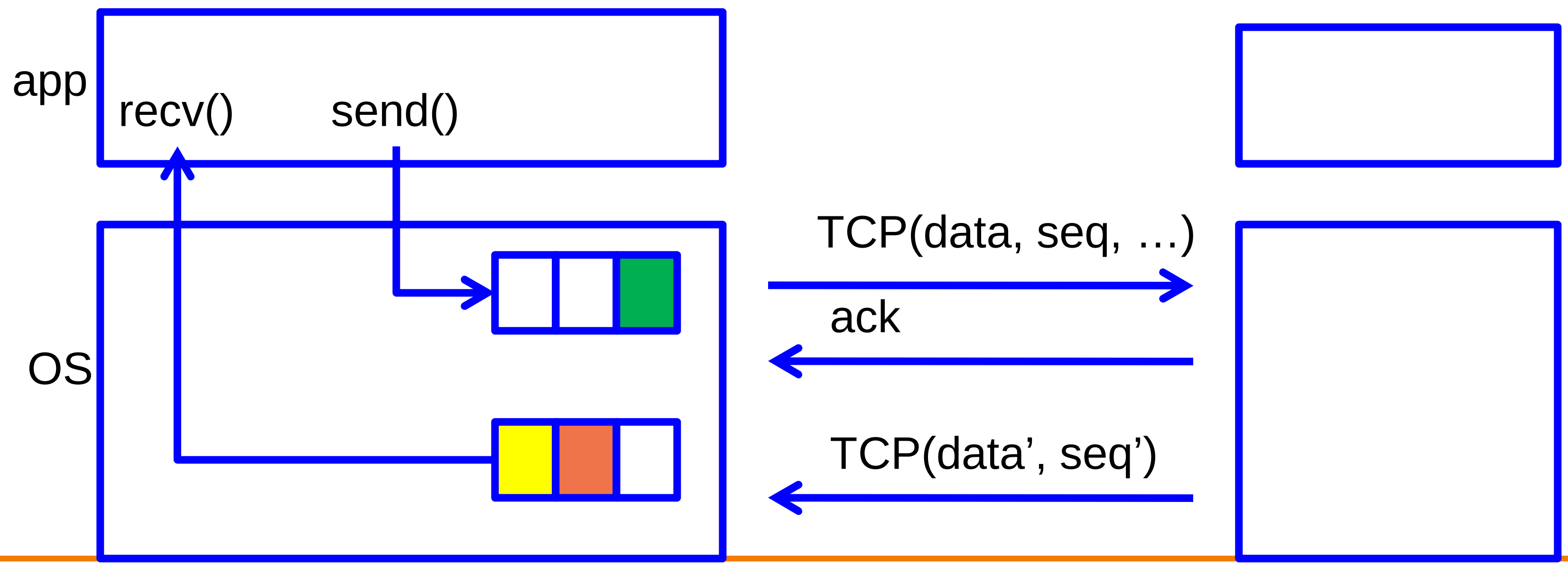
C
Migrate
Link

Dealing with TCP

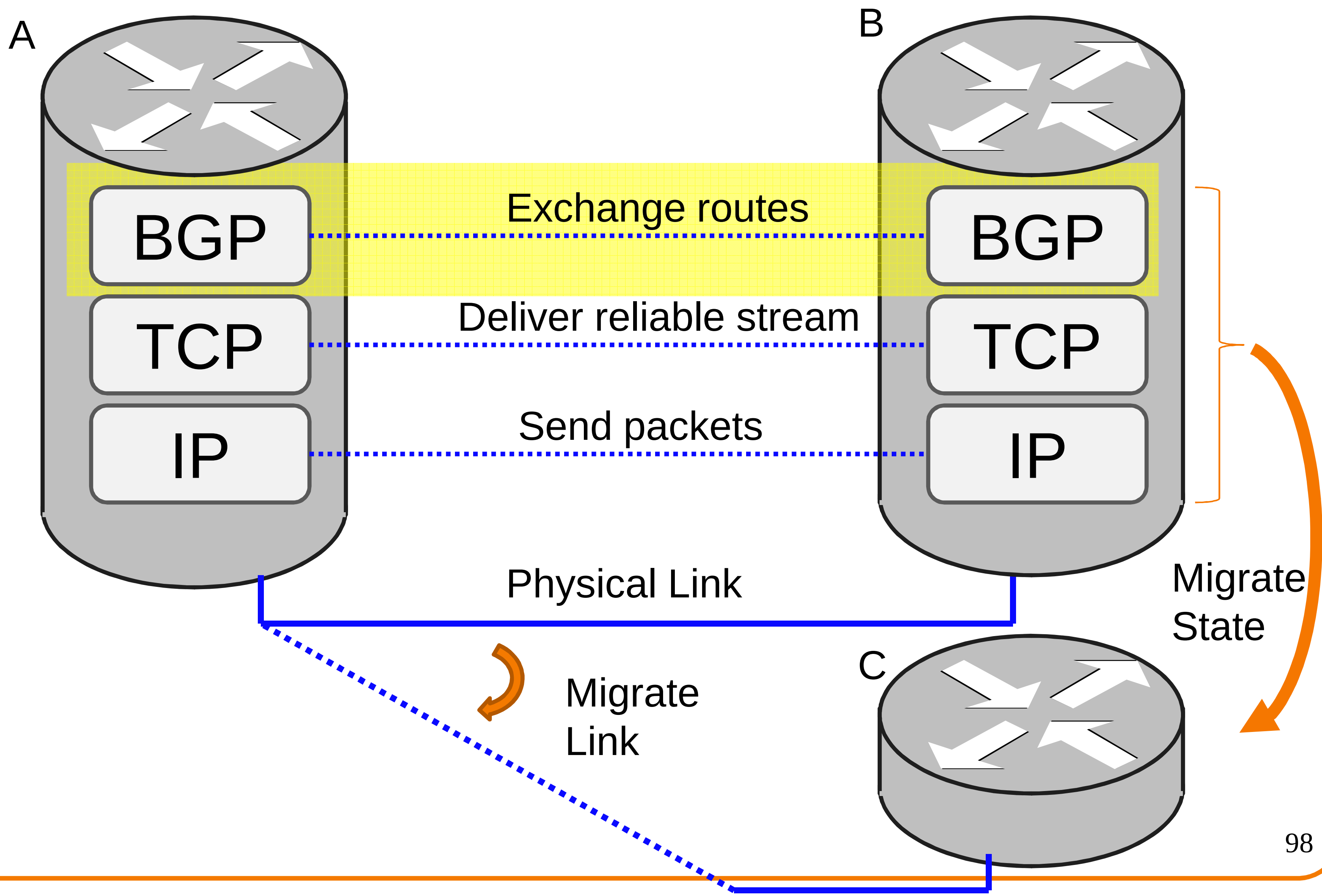
- TCP sessions are long running in BGP
  - Killing it implicitly signals the router is down
- BGP graceful restart and TCP migrate are possible workarounds
  - Requires the neighbor router to support it
  - Not available on all routers

Migrating TCP Transparently

- Capitalize on IP address not changing
  - To keep it completely transparent
- Transfer the TCP session state
  - Sequence numbers
  - Packet input/output queue (packets not read/ack'd)



BGP


A
B
C
BGP
TCP
IP
Exchange routes
Deliver reliable stream
Send packets
BGP
TCP
IP
Physical Link
Migrate State
Migrate Link

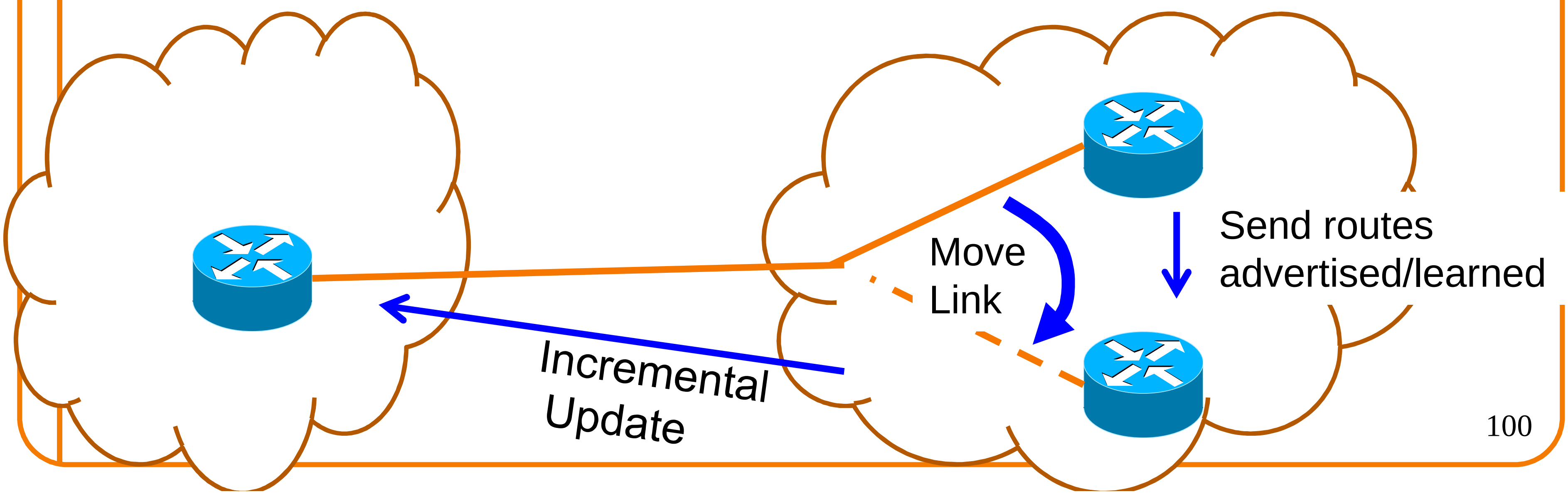
BGP: What (not) to Migrate

- Requirements
  - Want data packets to be delivered
  - Want routing adjacencies to remain up
- Need
  - Configuration
  - Routing information
- Do not need (but can have)
  - State machine
  - Statistics
  - Timers
- Keeps code modifications to a minimum

Routing Information

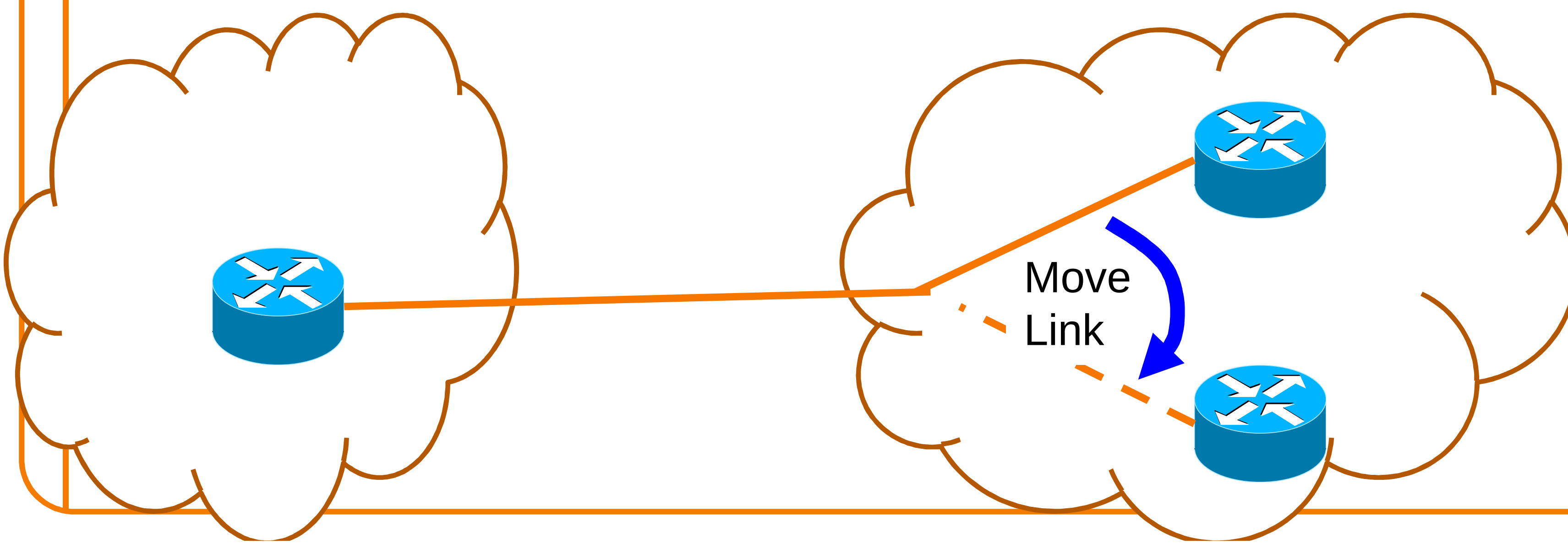
Migrate-from router send the migrate-to router:

- The routes it learned
  - Instead of making remote end-point re-announce
- The routes it advertised
  - So able to send just an incremental update



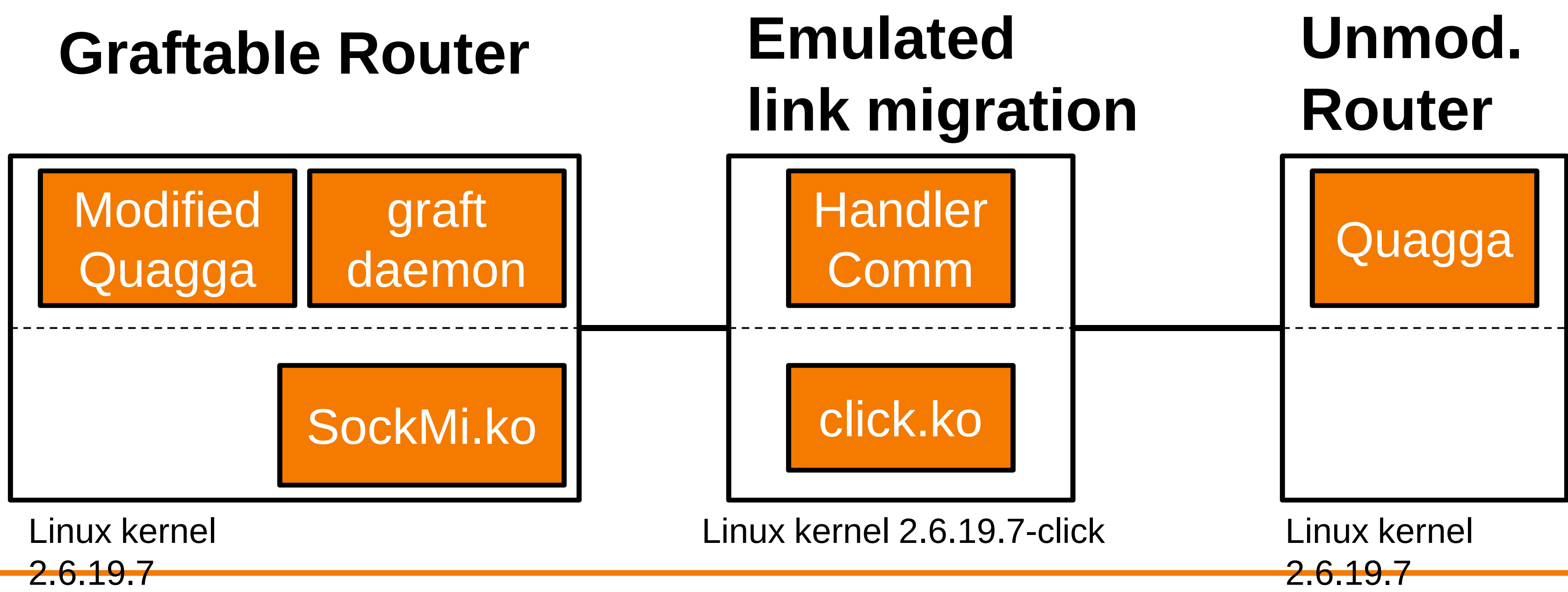
Migration in The Background

- Migration takes a while
  - A lot of routing state to transfer
  - A lot of processing is needed
- Routing changes can happen at any time
- Migrate in the background



Prototype

- Added grafting into Quagga
  - Import/export routes, new ‘inactive’ state
  - Routing data and decision process well separated
- Graft daemon to control process
- SockMi for TCP migration



Evaluation

Mechanism:

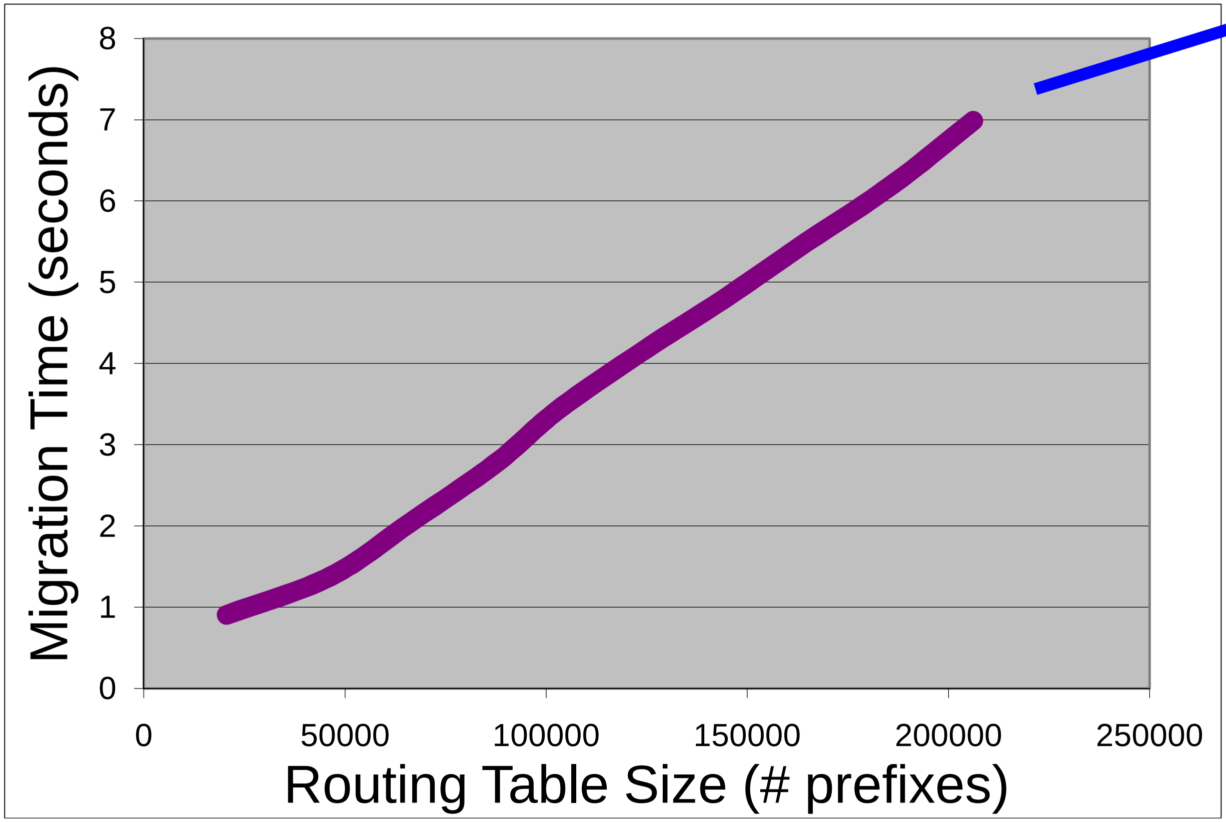
- Impact on migrating routers
- Disruption to network operation

Application:

- Traffic engineering

Impact on Migrating Routers

- How long migration takes
  - Includes export, transmit, import, lookup, decision
  - CPU Utilization roughly 25%



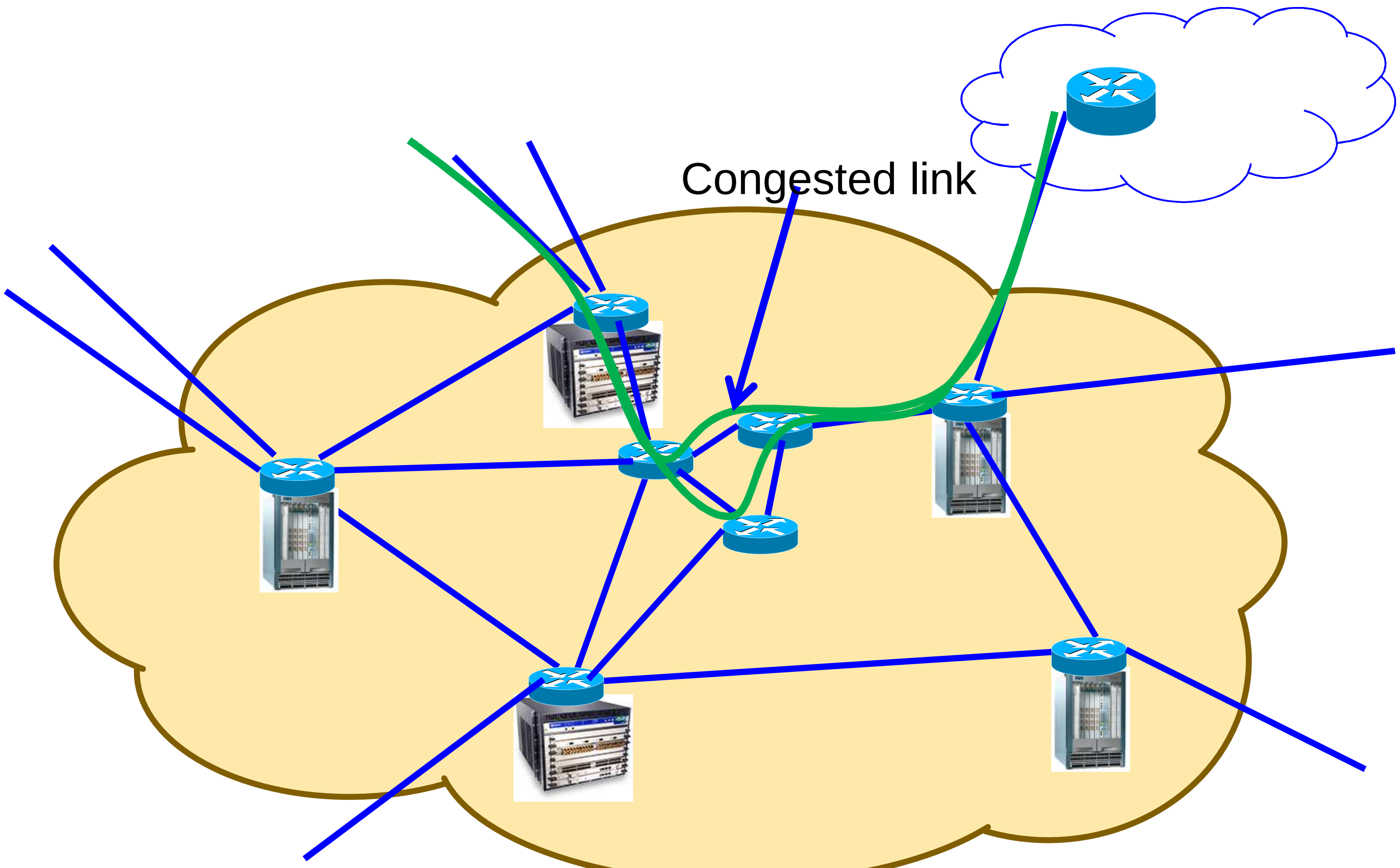
Between Routers
0.9s (20k)
6.9s (200k)

Disruption to Network Operation

- Data traffic affected by not having a link
  - nanoseconds
- Routing protocols affected by unresponsiveness
  - Set old router to “inactive”, migrate link, migrate TCP, set new router to “active”
  - milliseconds

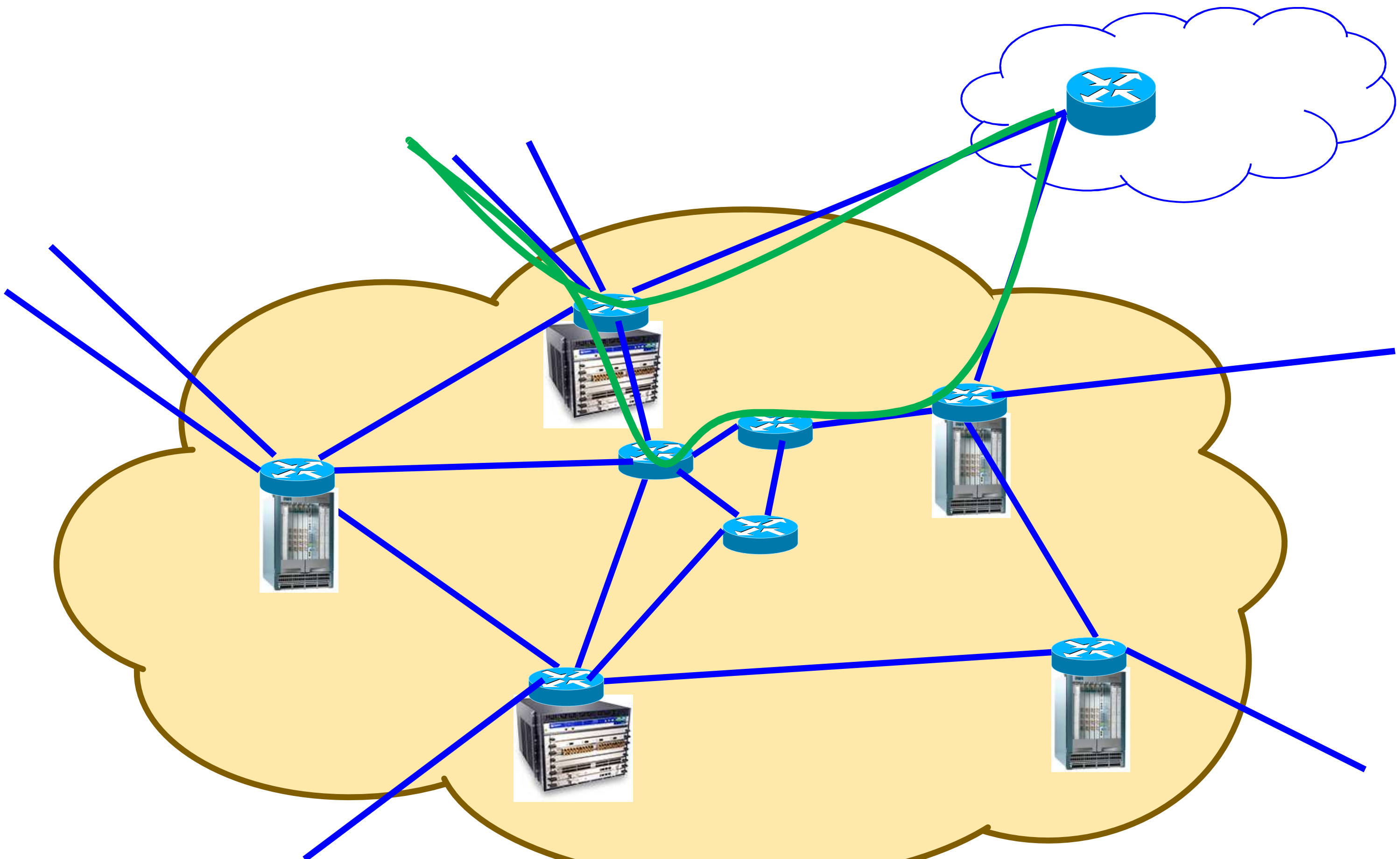
Traffic Engineering (traditional)

* adjust routing protocol parameters based on traffic



Traffic Engineering w/ Grafting

* Rehome customer to change where traffic enters/exits



Traffic Engineering Evaluation

- Setup
  - Internet2 topology and 1 week of traffic data
  - Simple greedy heuristic
- Findings
  - Network can handle more traffic (18.8%)
  - Don’t need frequent re-optimization (2-4/day)
  - Don’t need to move many links (<10%)

Router Grafting Summary

- Enables moving a single link with…
  - Minimal code change
  - No impact on data traffic
  - No visible impact on routing protocol adjacencies
  - Minimal overhead on rest of network
- Applying to traffic engineering…
  - Enables changing ingress/egress points
  - Networks can handle more traffic

Part IV:
A Unified Architecture

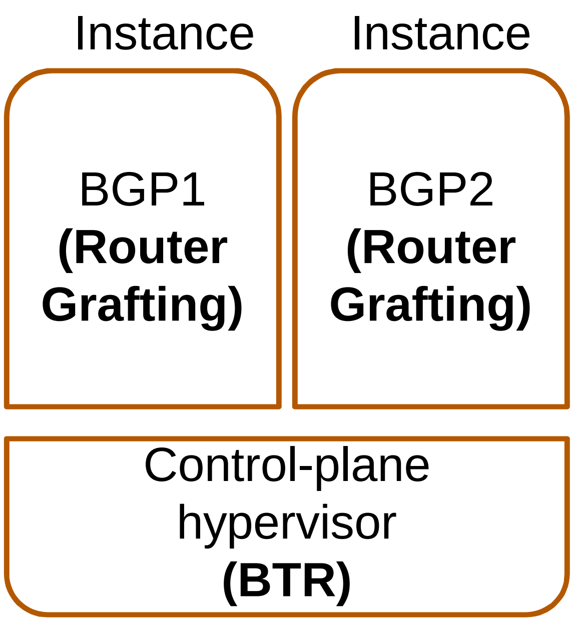
Grafting

Seamless Link Migration

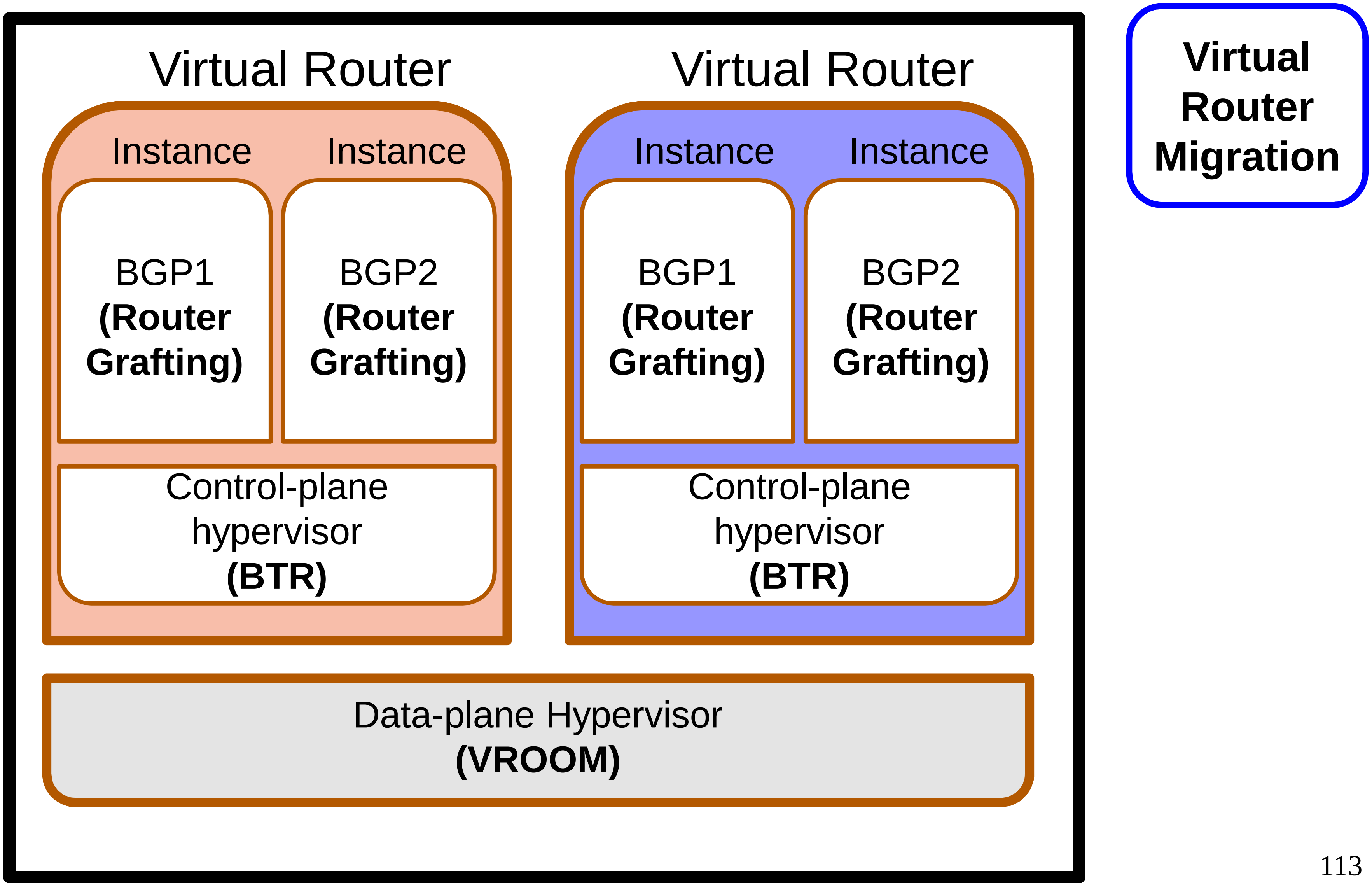
BGP1
(Router Grafting)

Grafting + BTR

Multiple Diverse Instances



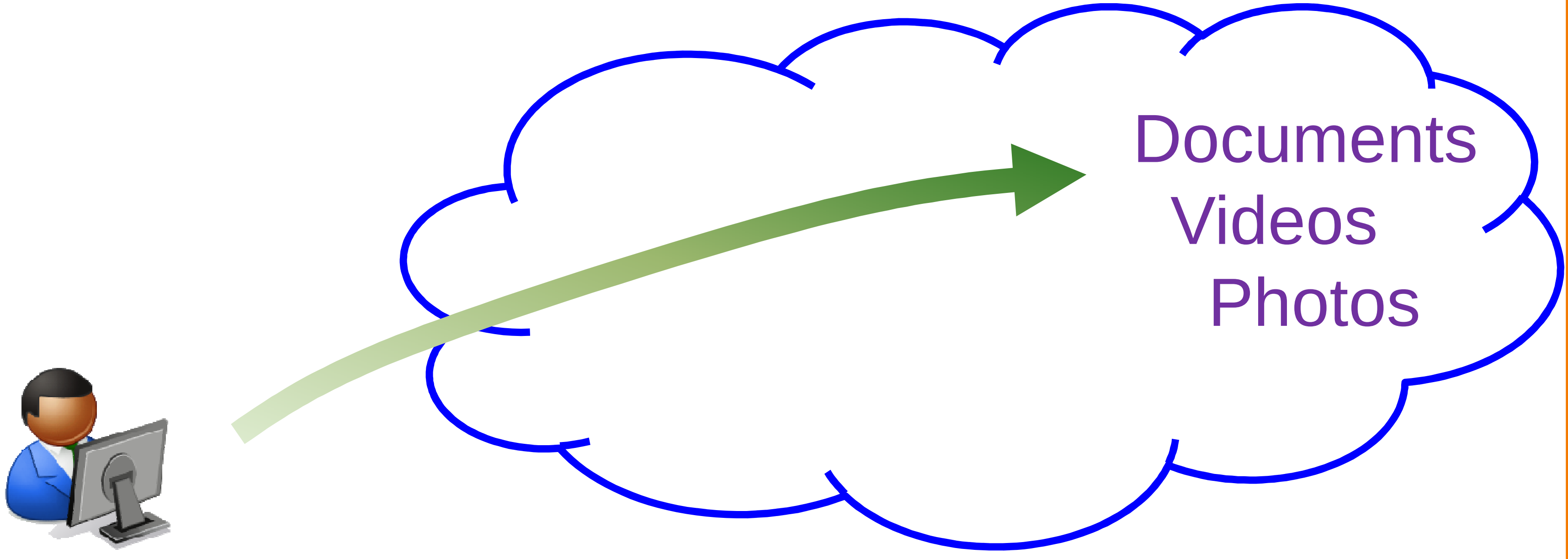
Grafting + BTR + VROOM



Summary of Contributions

- New refactoring concepts
  - Hide (router bugs) with ***Bug Tolerant Router***
  - Decouple (logical and physical) with ***VROOM***
  - Break binding (link to router) with ***Router Grafting***
- Working prototype and evaluation for each
- Incrementally deployable solution
  - "Refactored router" can be drop in replacement
  - Transparent to neighboring routers

Final Thoughts



Questions