# Software Transactional Networking

## A Robust and Distributed SDN Control Plane

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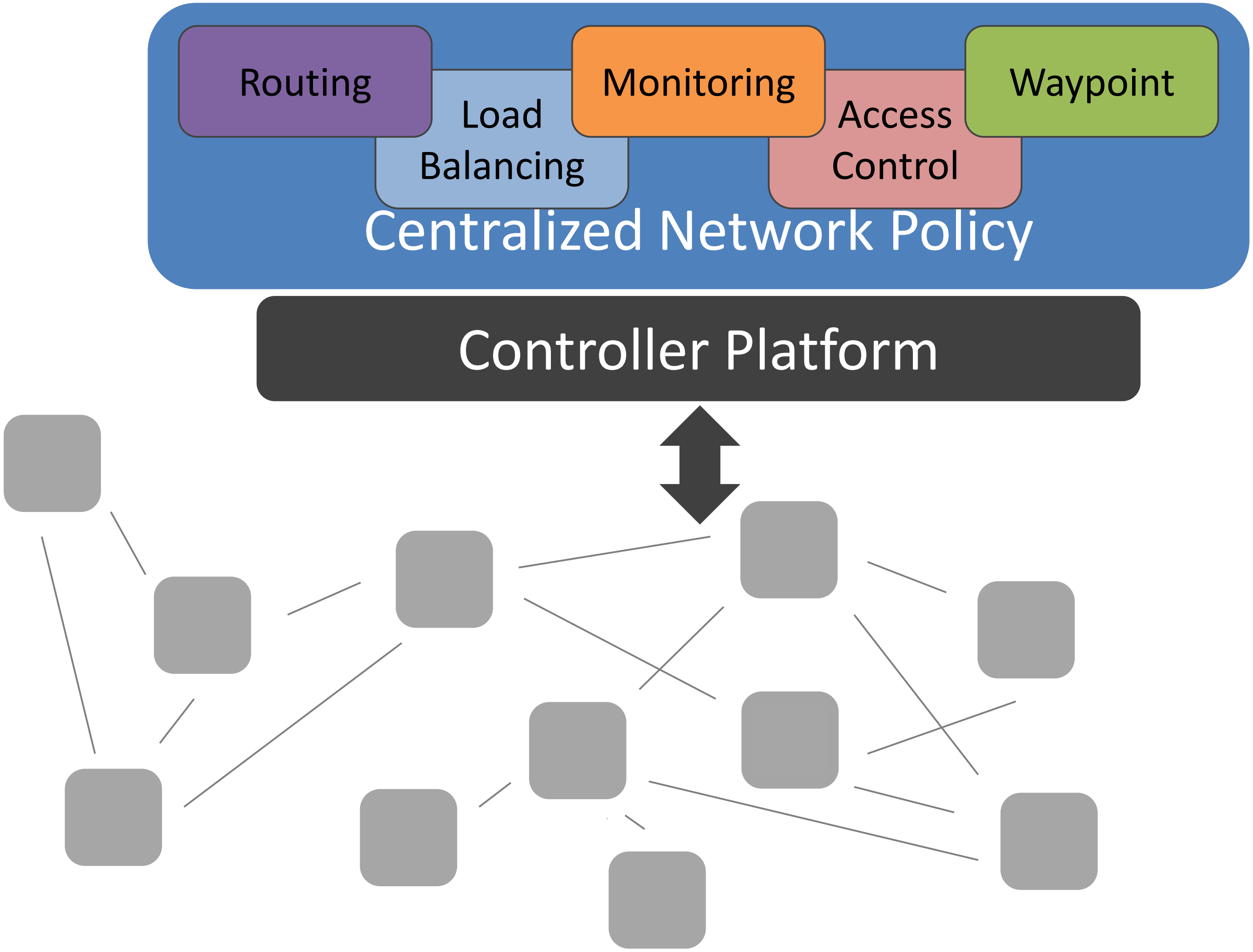
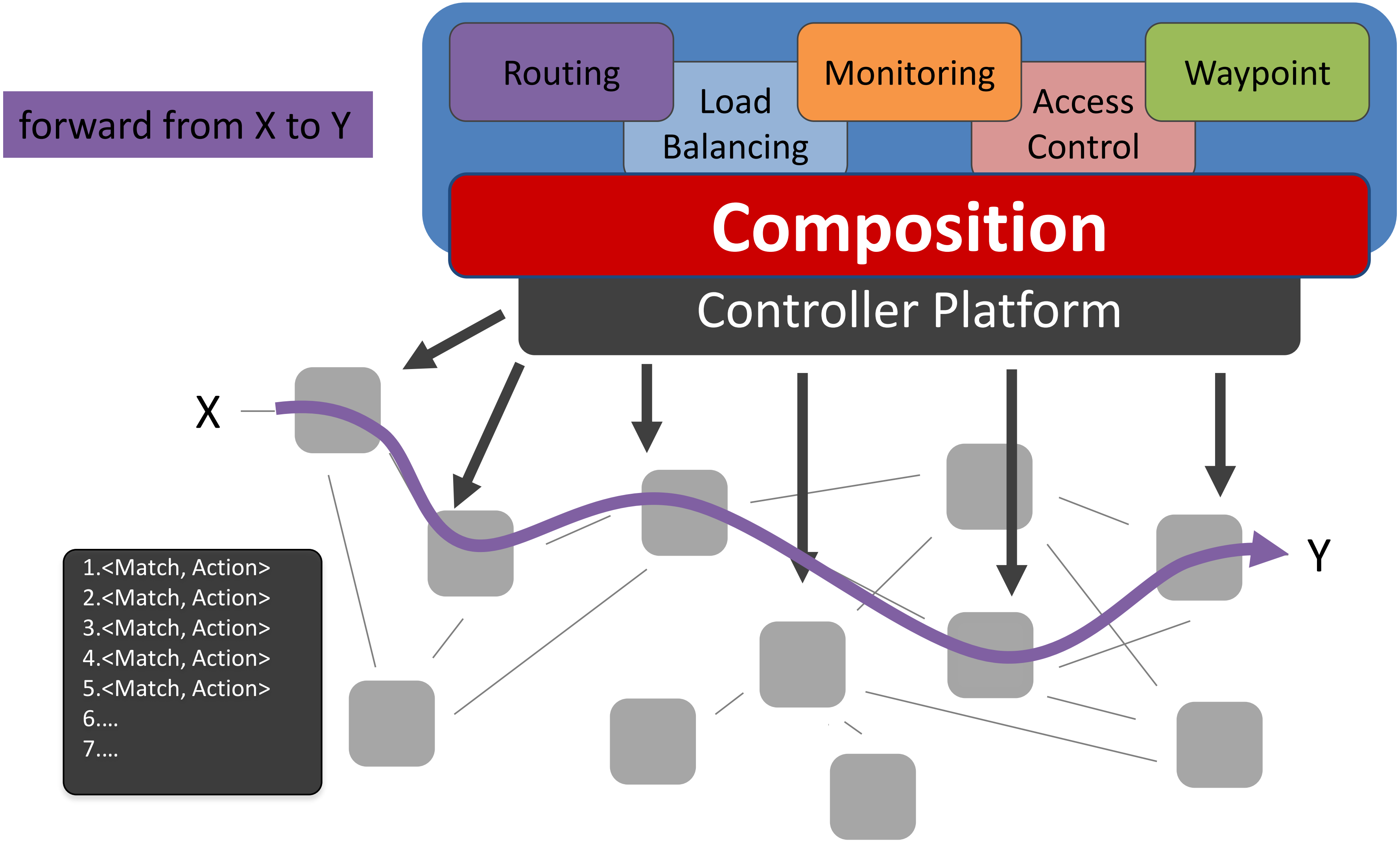
with Stefan Schmid, Petr Kuznetsov, Dan Levin

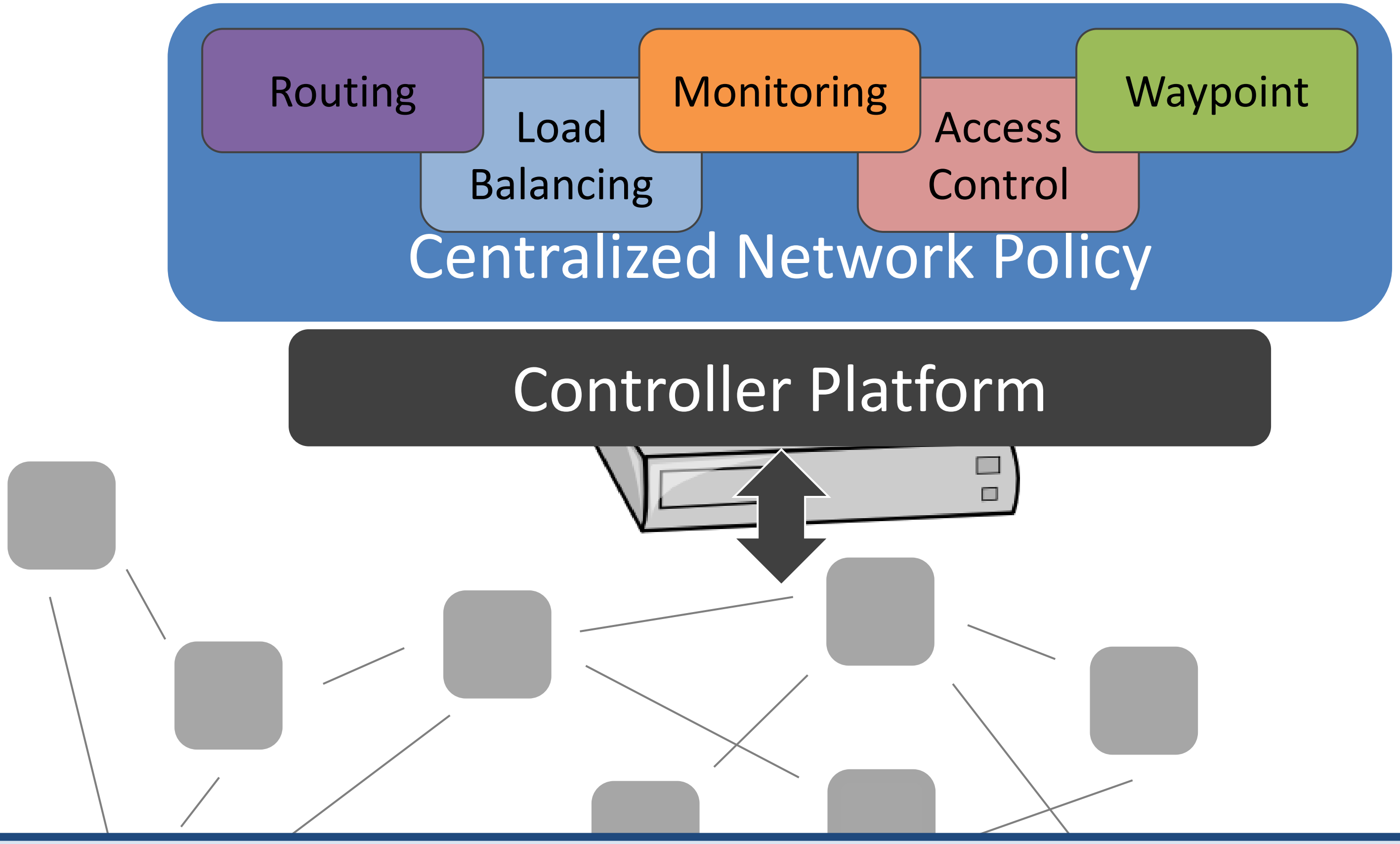
# Network Policy Specification



# Network Policy Specification

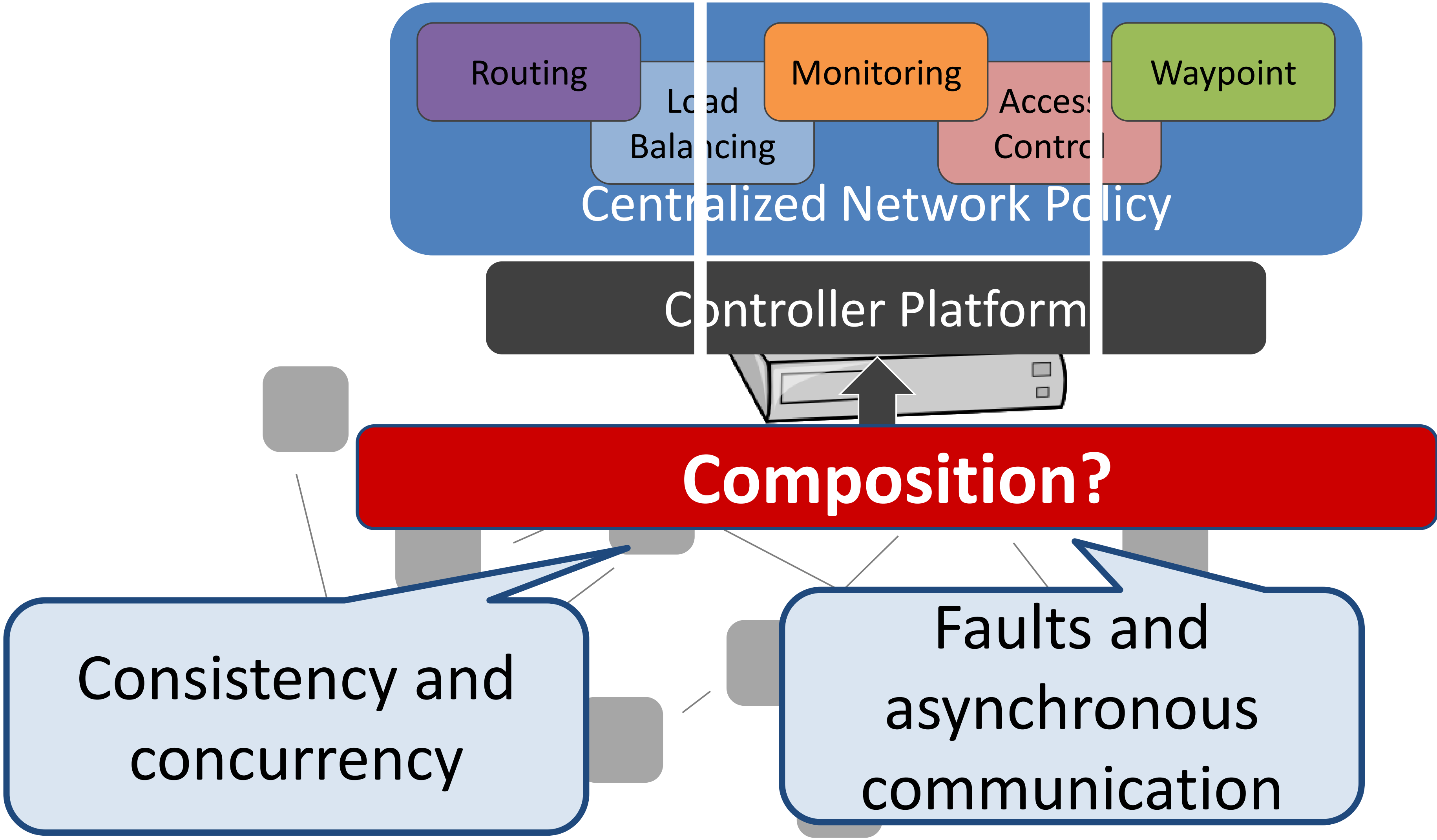


# Centralized Network Control?



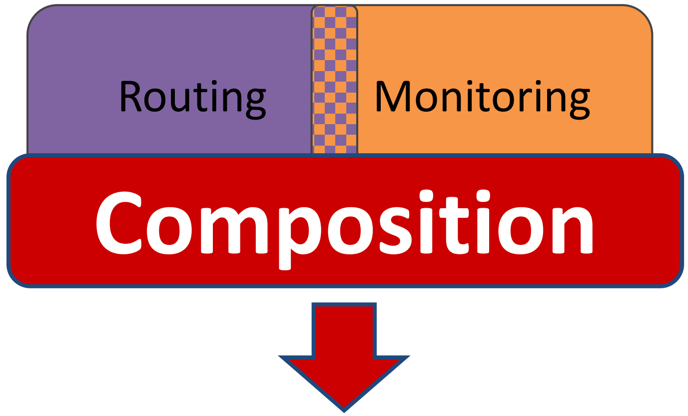

Fully centralized → Inadequate availability, scalability and responsiveness

# Distributed Network Control



# Composing Policies

dst = H → fwd(H)



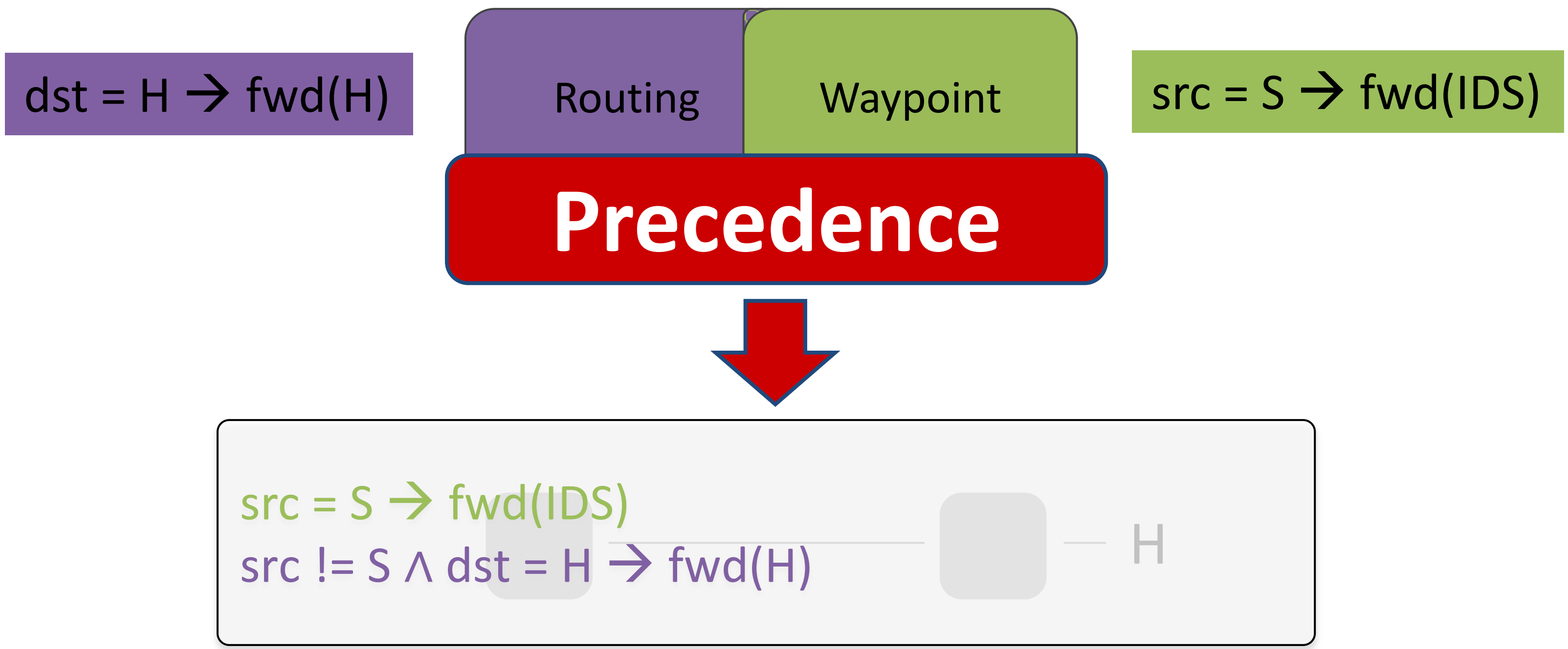

dport = 80 → count

dst = H ∧ dport = 80 → count; fwd(H)
dst = H → fwd(H)
dport = 80 → count

H

What to do with packet dst = H and dport = 80?
Can Routing and Monitoring compose?

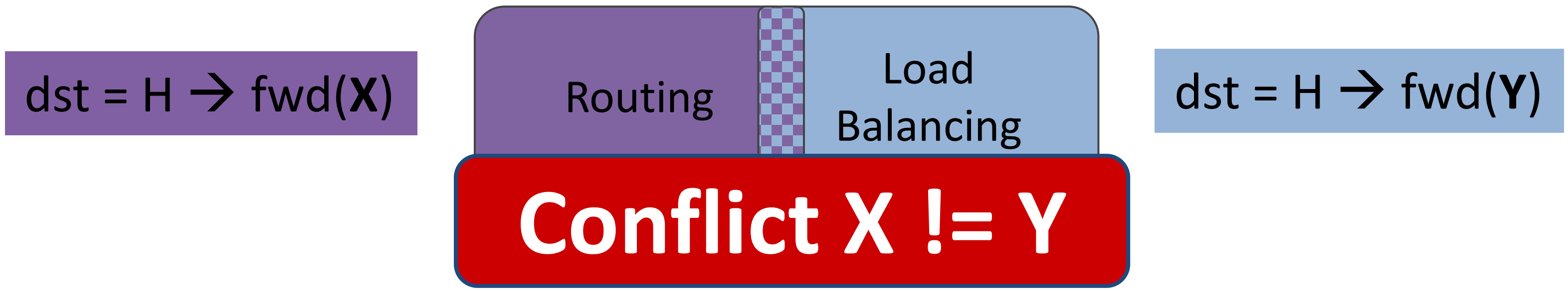
# Ordering Policies




What to do with packet dst = H and src = S?

Does Waypoint have precedence over Routing?

# Conflicting Policies




In the general case, policies might conflict

**Examples:**

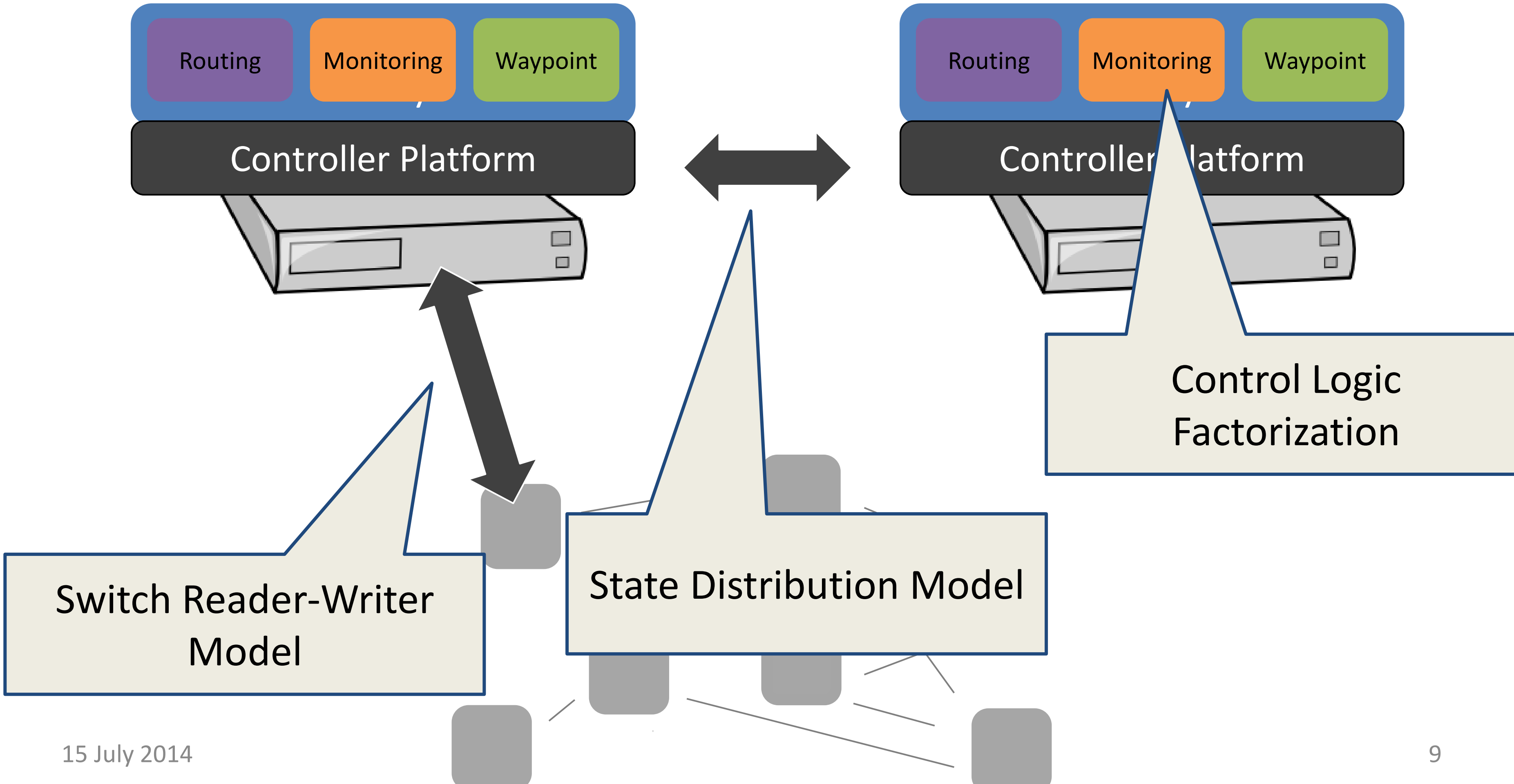
Overlapping domains and same precedence

Scarce flowtable resources

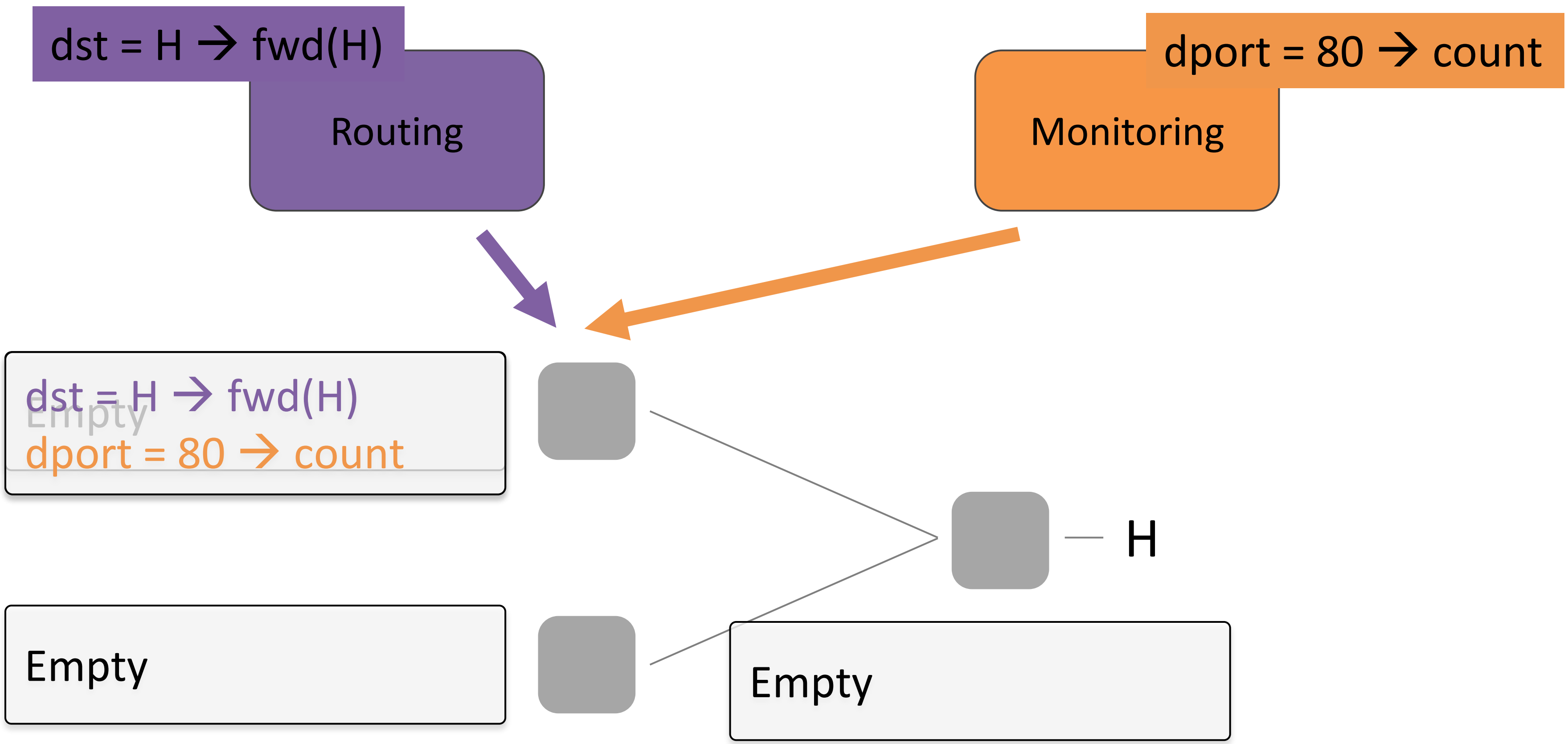
Must avoid conflicting policies

Pick one and reject the other?

# Now, consider policy composition in the distributed control plane...



# Concurrency Issues



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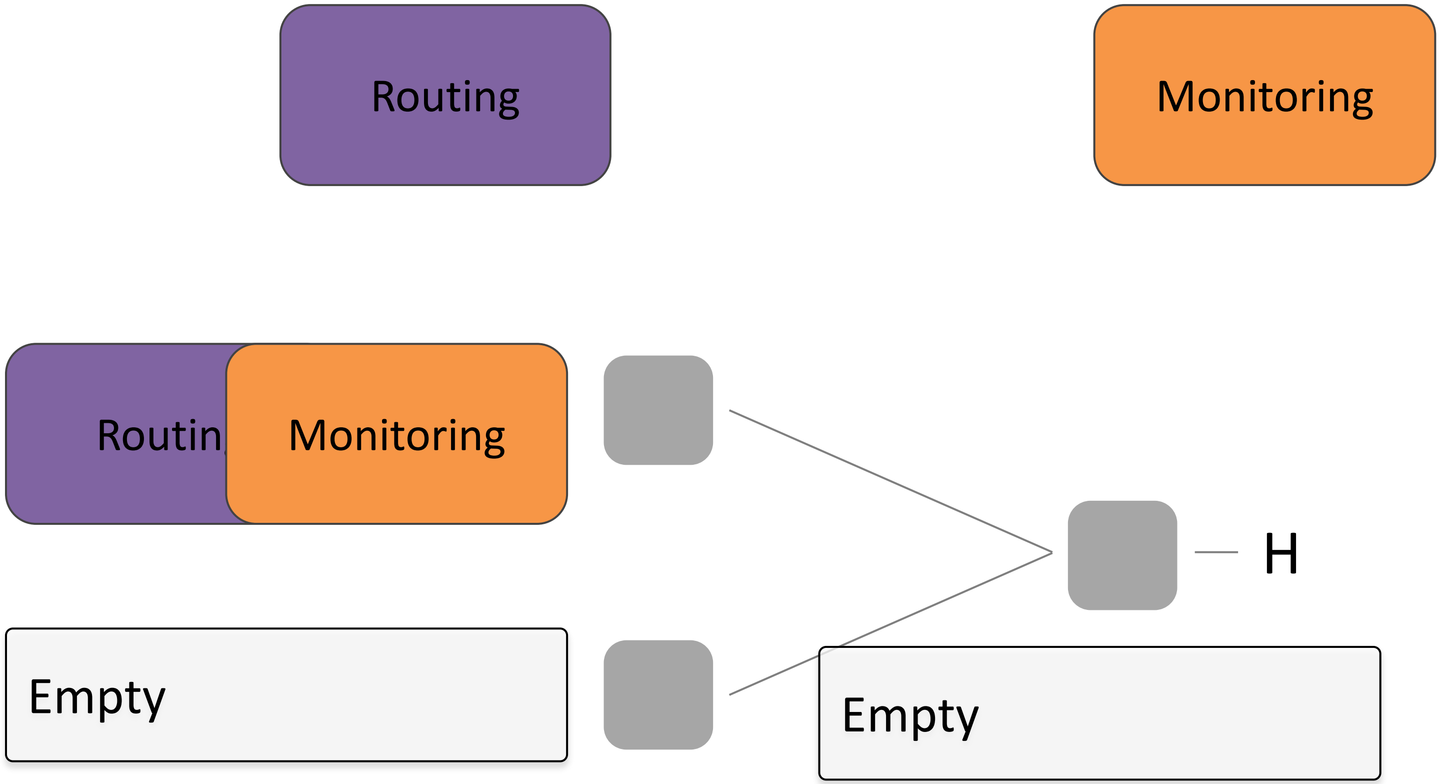

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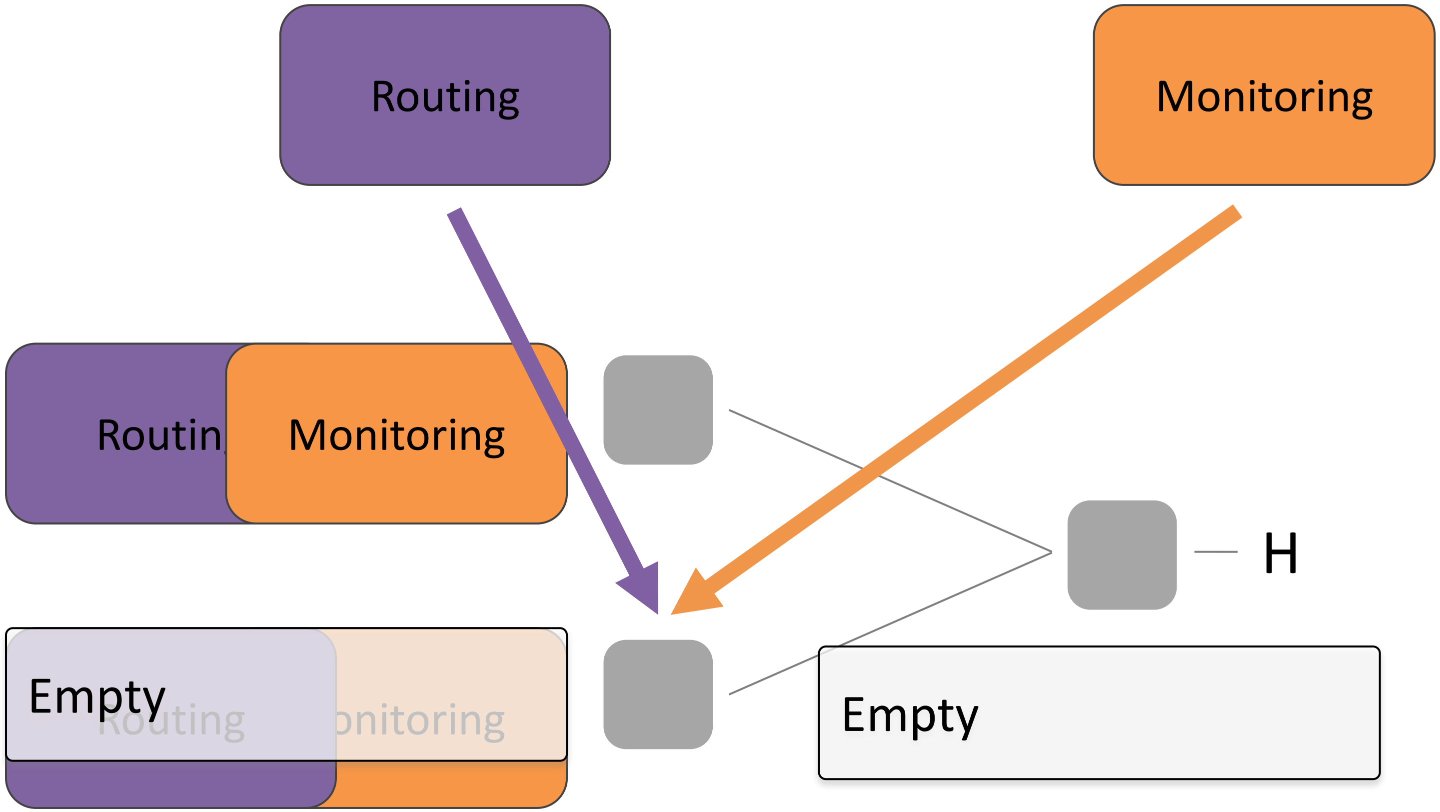

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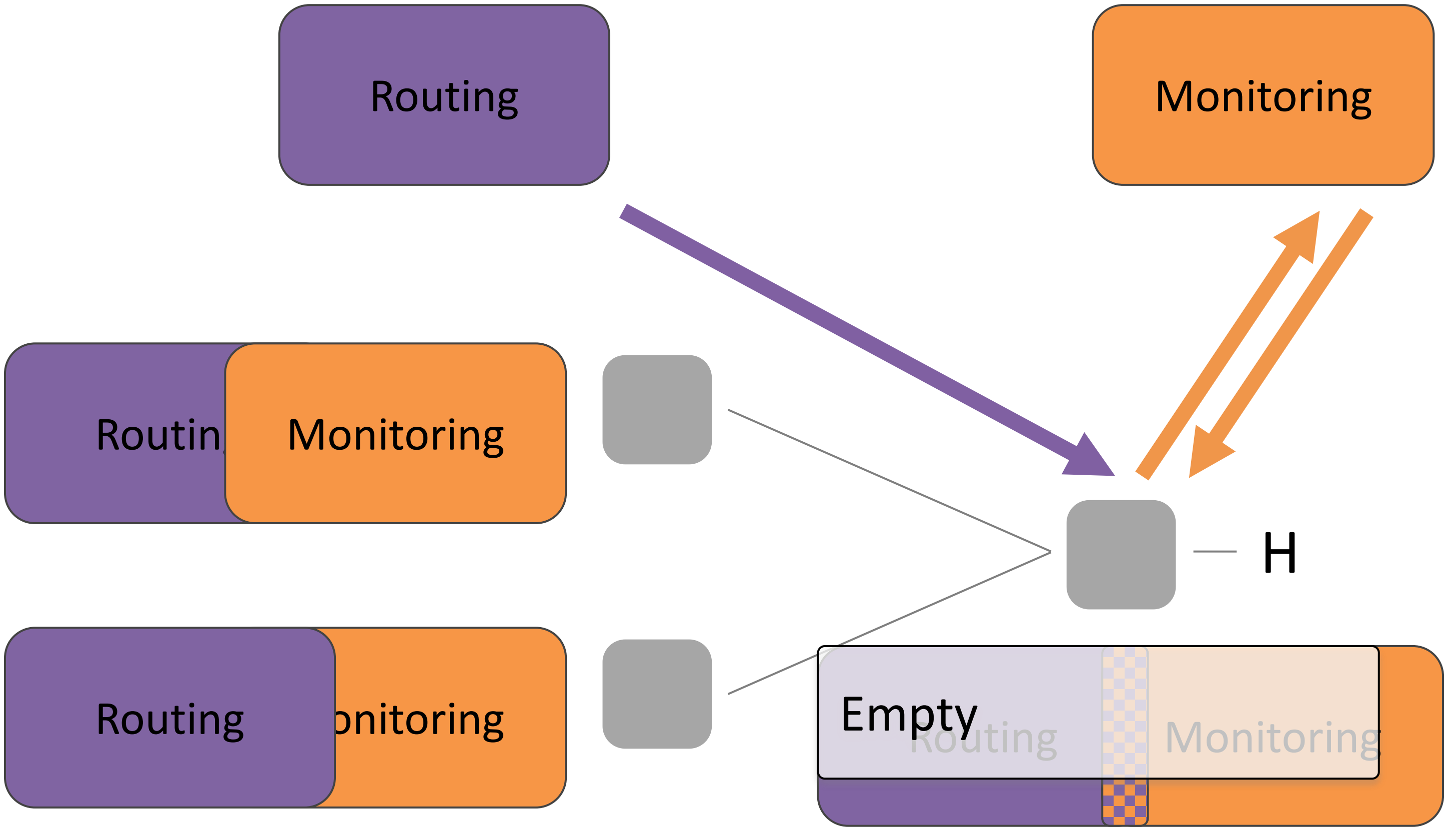



Impossible to guarantee a deterministic outcome **without synchronization**

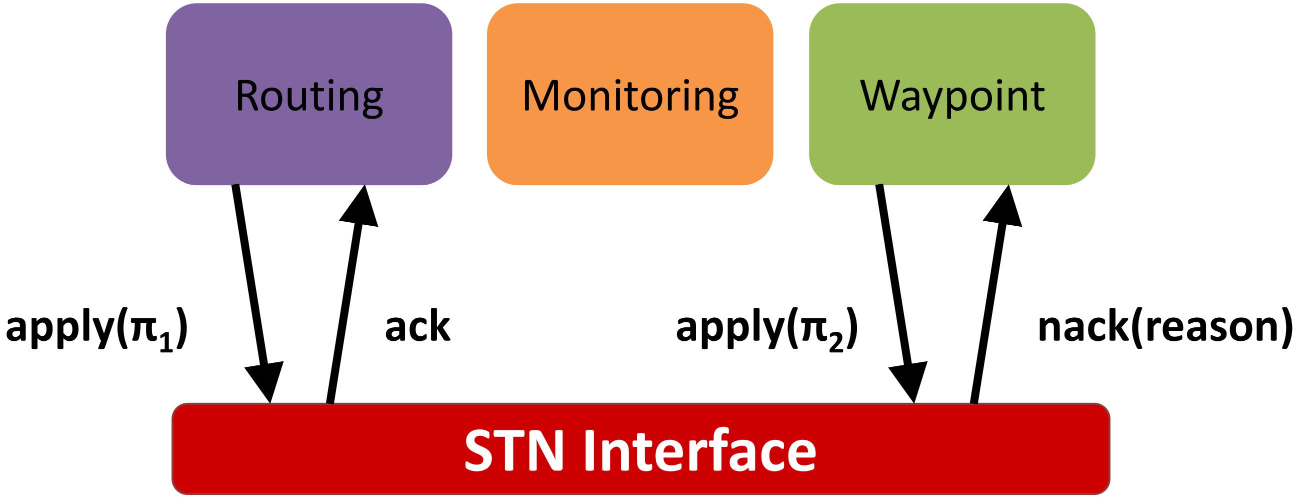
# Two Underlying Problems

1. Consistent and Concurrent Policy Composition

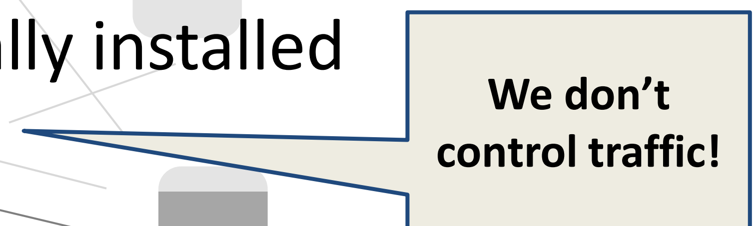
2. Consistent and Robust Policy Composition
   - In face of controller failures

Can we realize a general distributed policy composition interface that is agnostic to control logic, state distribution and reader-writer model?

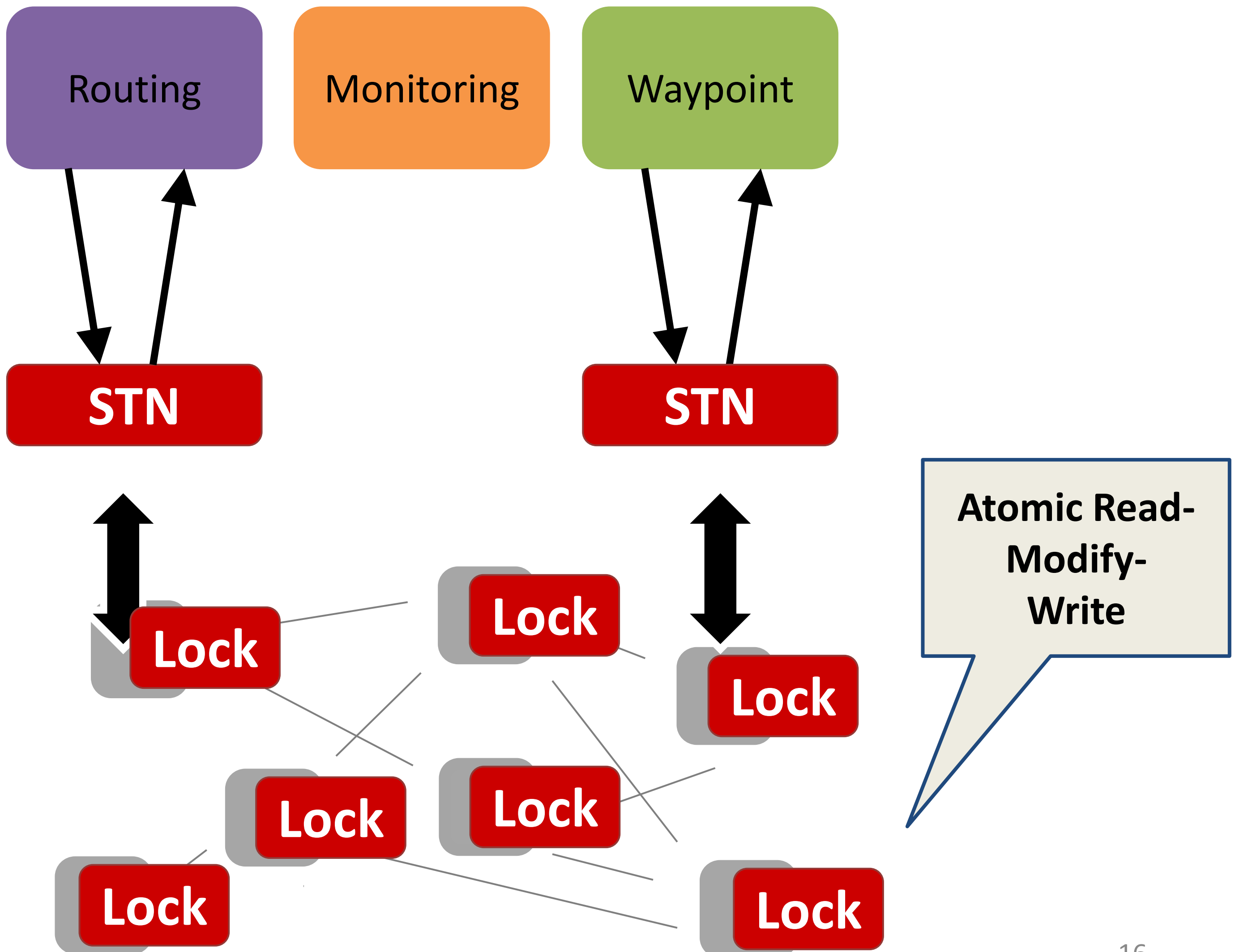
# Software Transactional Networking




1. All-or-nothing semantics
2. Optimistic concurrency for policy composition
3. Non conflicting policies eventually installed
4. Per-packet consistent updates



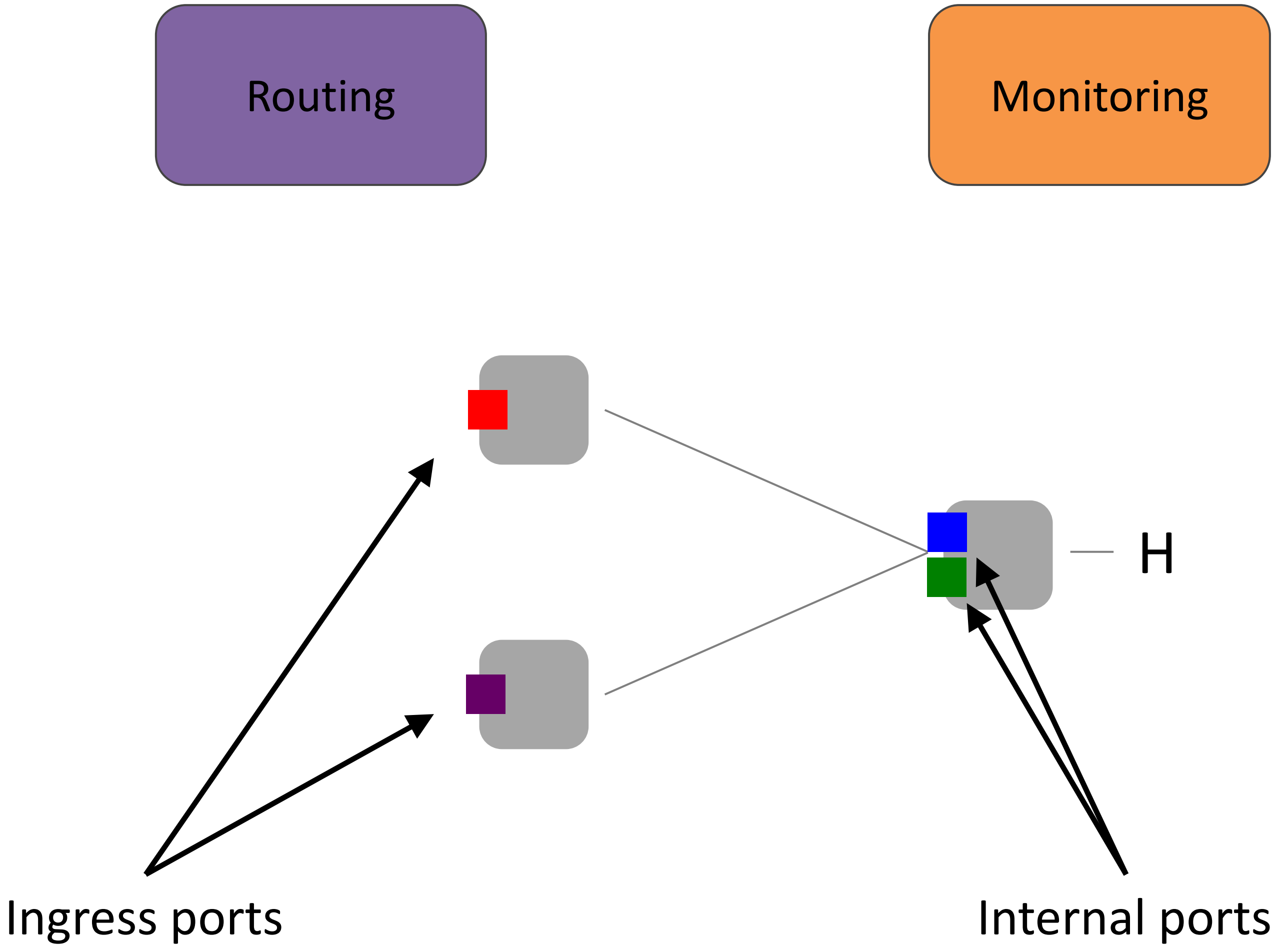
# Conceptualizing STN



# STN Algorithm

```
apply(π)
  tag = unique tag for π
  foreach internal port x do
    if policy at x can compose with π then
      foreach subset s of tagged policies at x do
        tag' = composition of tags of s and tag          } atomic
        add composed policy with π, tag' to x
      end
    else remove installed rules; return nack(reason)
  foreach ingress port y do
    tag' = composition of tags of y and tag
    add rules to tag packets with tag' composed with \   } atomic
      policy at y and π
  end
end
```

# STN Example



# STN Example

**$\pi_1$**

tag = $t_1$ ∧ dst = H → fwd(H)
tag = $t_1$ ∧ dst = H → fwd(H)
dst = H → tag = $t_1$; fwd( )
dst = H → tag = $t_1$; fwd( )

**$\pi_2$**

tag = $t_2$ ∧ dport = 80 → count
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dport = 80 → tag = $t_2$; count
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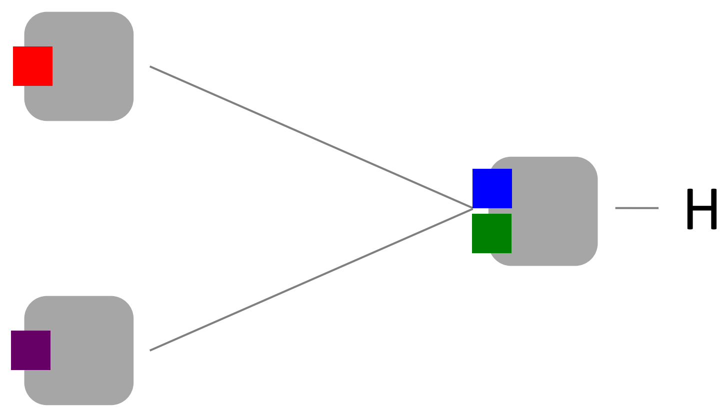

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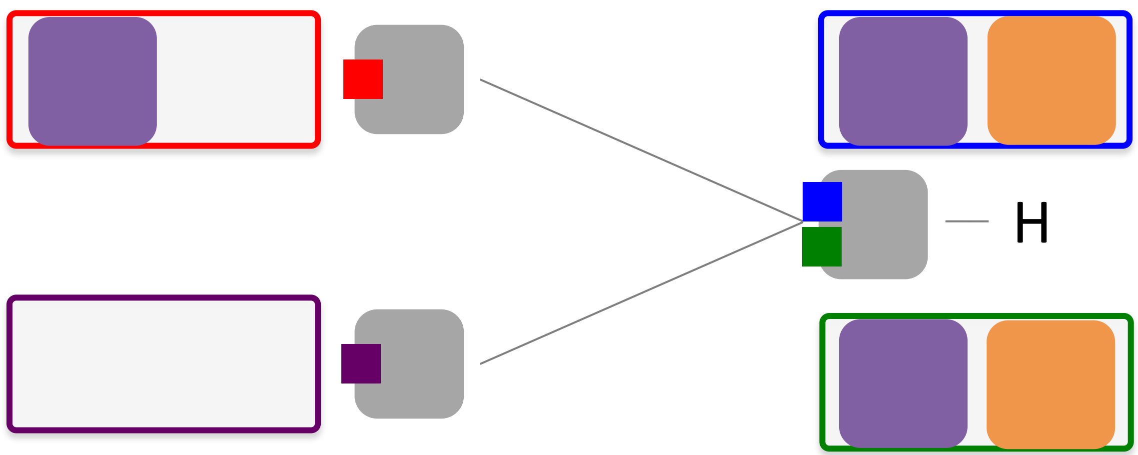

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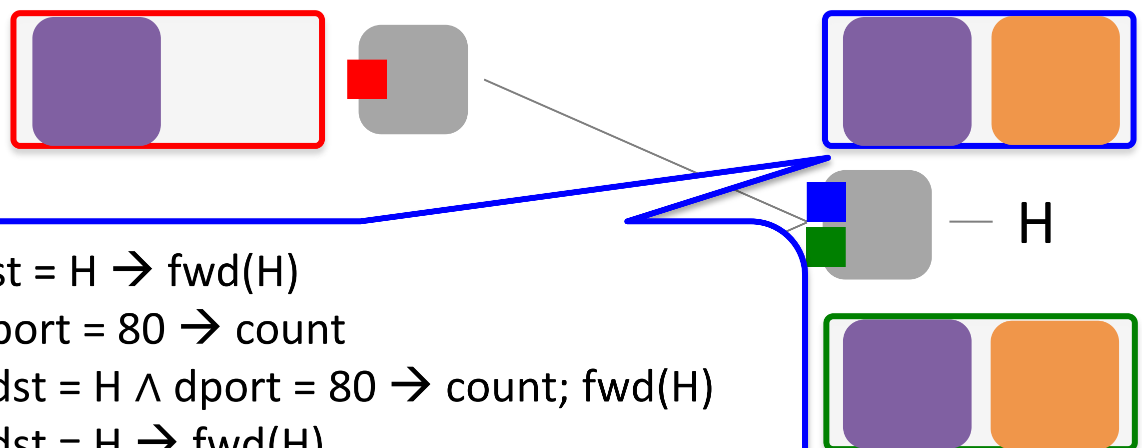



tag = $t_1$ ∧ dst = H → fwd(H)
tag = $t_2$ ∧ dport = 80 → count
tag = $t_{1,2}$ ∧ dst = H ∧ dport = 80 → count; fwd(H)
tag = $t_{1,2}$ ∧ dst = H → fwd(H)
tag = $t_{1,2}$ ∧ dport = 80 → count

**$\pi_1$** is incomplete but packets at ■ get tagged with $t_1$

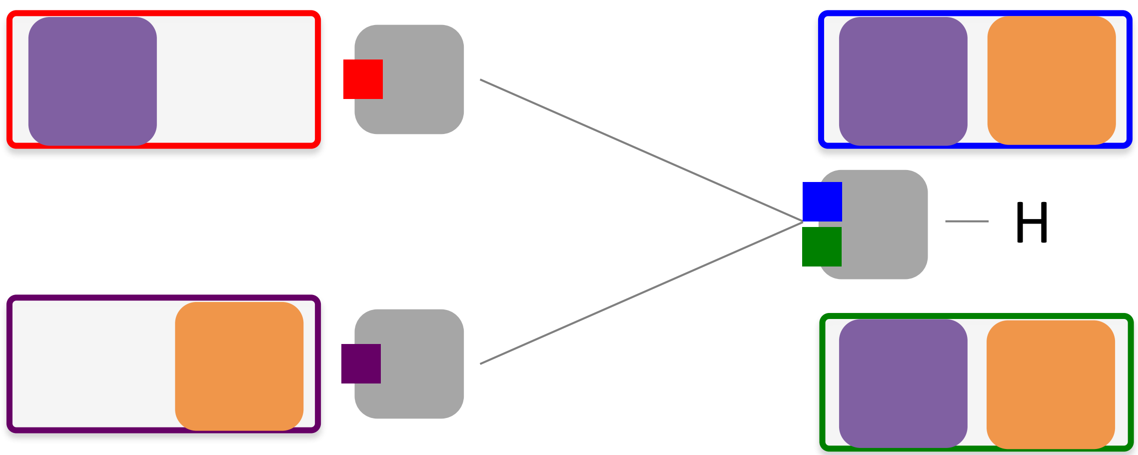
# STN Example

**$\pi_1$**

- tag = $t_1$ ∧ dst = H → fwd(H)
- tag = $t_1$ ∧ dst = H → fwd(H)
- dst = H → tag = $t_1$; fwd( )
- dst = H → tag = $t_1$; fwd( )

**$\pi_2$**

- tag = $t_2$ ∧ dport = 80 → count
- tag = $t_2$ ∧ dport = 80 → count
- dport = 80 → tag = $t_2$; count
- dport = 80 → tag = $t_2$; count




**$\pi_2$** is incomplete but packets at get tagged with $t_2$

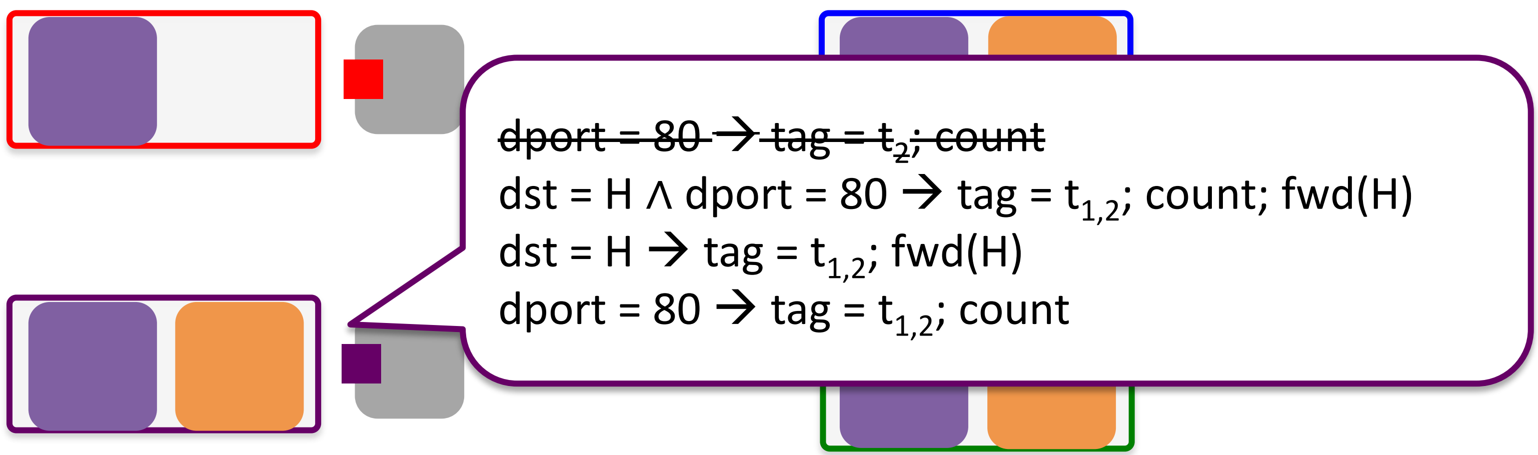
# STN Example

**$\pi_1$**

- tag = $t_1$ ∧ dst = H → fwd(H)
- tag = $t_1$ ∧ dst = H → fwd(H)
- dst = H → tag = $t_1$; fwd( )
- dst = H → tag = $t_1$; fwd( )

**$\pi_2$**

- tag = $t_2$ ∧ dport = 80 → count
- tag = $t_2$ ∧ dport = 80 → count
- dport = 80 → tag = $t_2$; count
- dport = 80 → tag = $t_2$; count




**$\pi_1$** is complete; packets at ■ get tagged with $t_{1,2}$

# STN Example

**$\pi_1$**

- ■ $tag = t_1 \wedge dst = H \rightarrow fwd(H)$
- ■ $tag = t_1 \wedge dst = H \rightarrow fwd(H)$
- ■ $dst = H \rightarrow tag = t_1; fwd($■$)$
- ■ $dst = H \rightarrow tag = t_1; fwd($■$)$

**$\pi_2$**

- ■ $tag = t_2 \wedge dport = 80 \rightarrow count$
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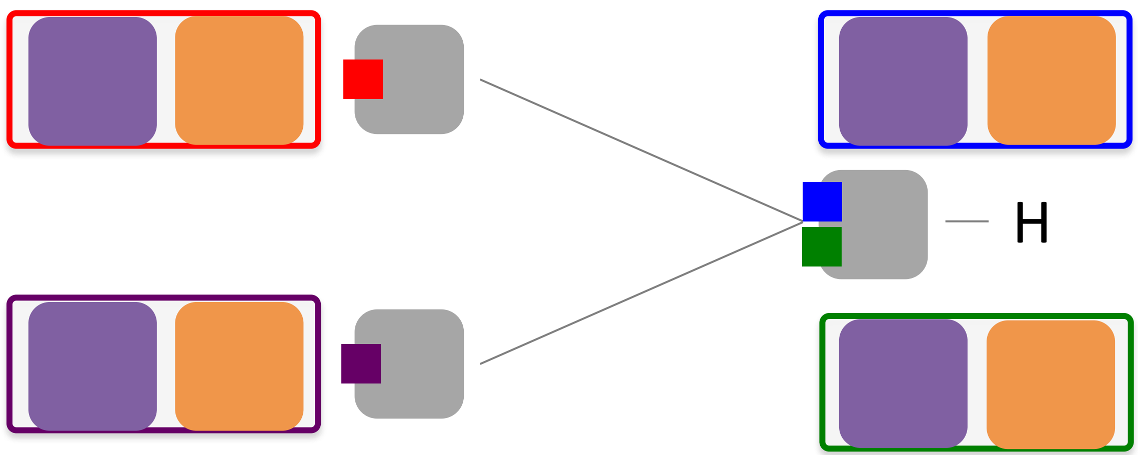
- ■ $dport = 80 \rightarrow tag = t_2; count$
- ■ $dport = 80 \rightarrow tag = t_2; count$

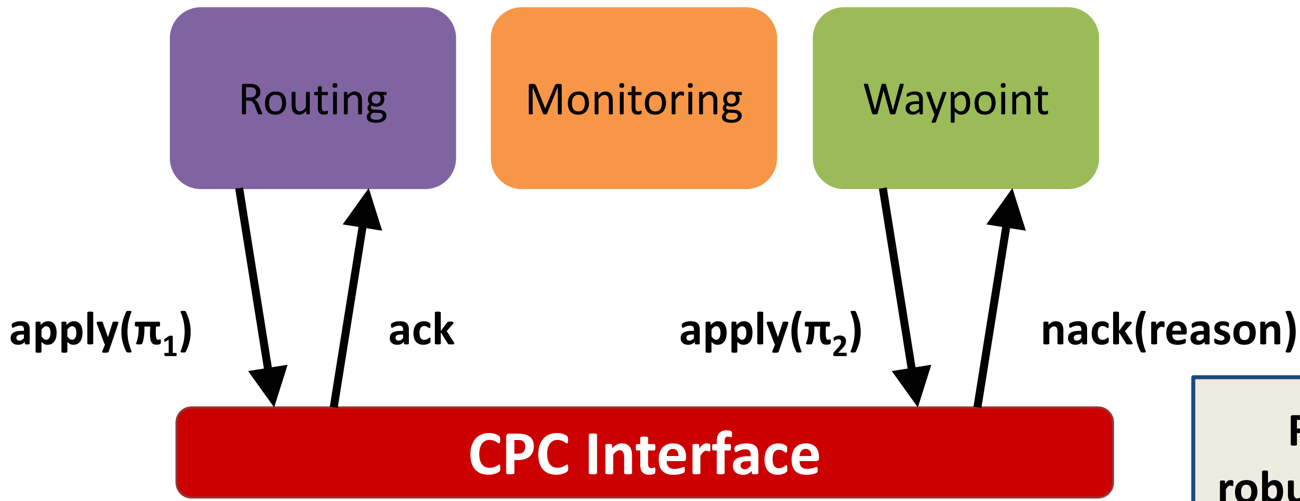



**$\pi_1$** and **$\pi_2$** are complete; packets at ■ and ■ get tagged with $t_{1,2}$

# Limitations of STN

- # tags grows exponentially with policies
- No fault tolerance

# Consistent Policy Composition

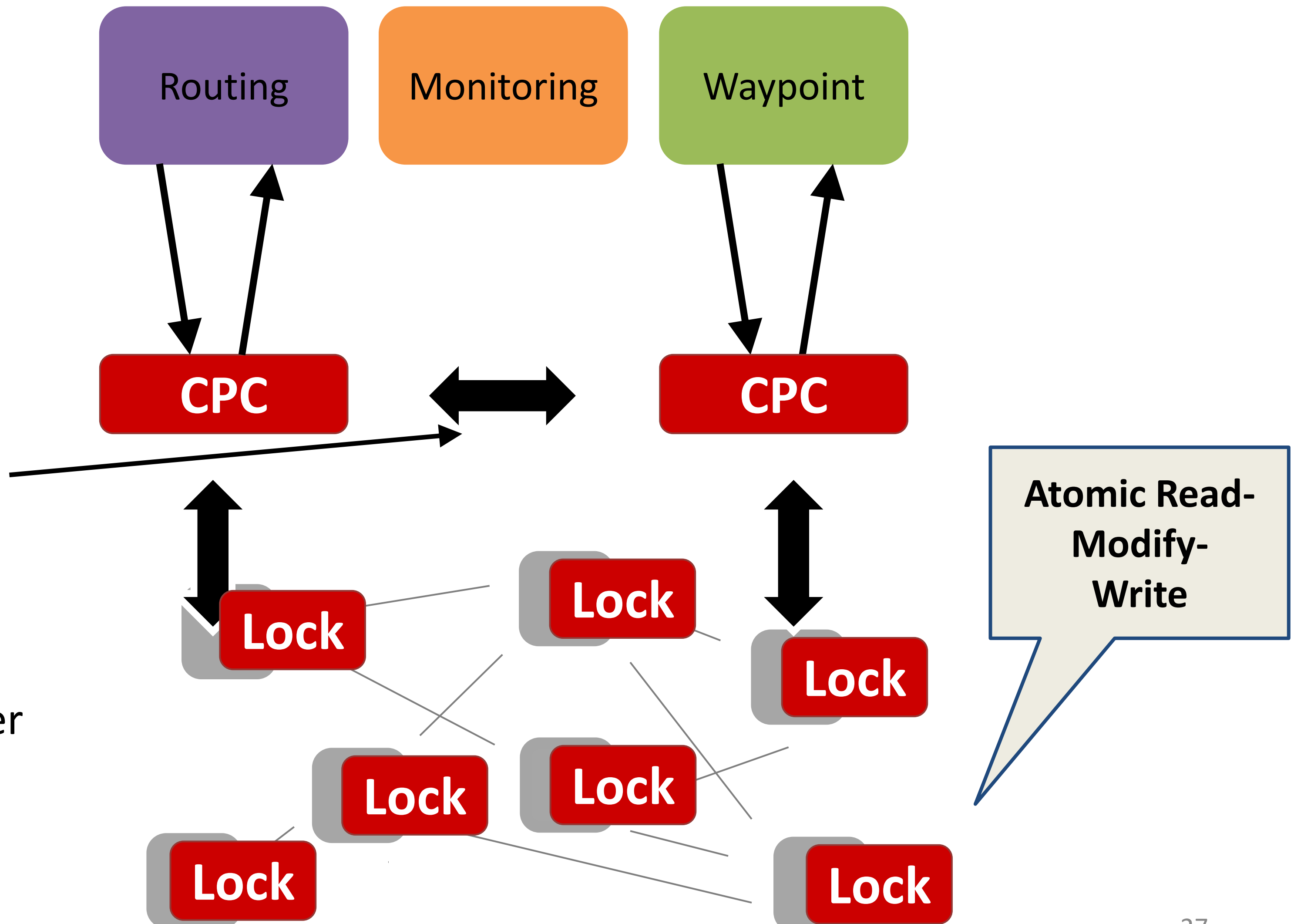



Require robustness but not efficiency

1. All-or-nothing semantics
2. Tolerate up to *f* controller crash failures
3. Non conflicting policies eventually installed and **at least one policy commits (among conflicting ones)**
4. Ensure updates affect traffic as a sequential composition of their policies

Per-packet consistency

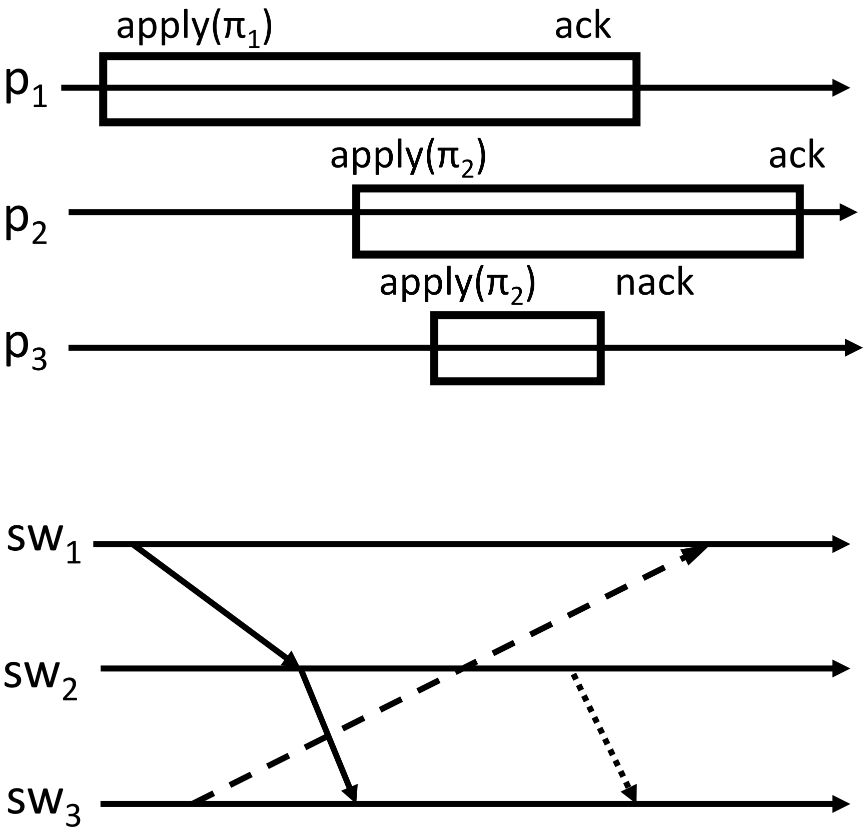
# Conceptualizing CPC



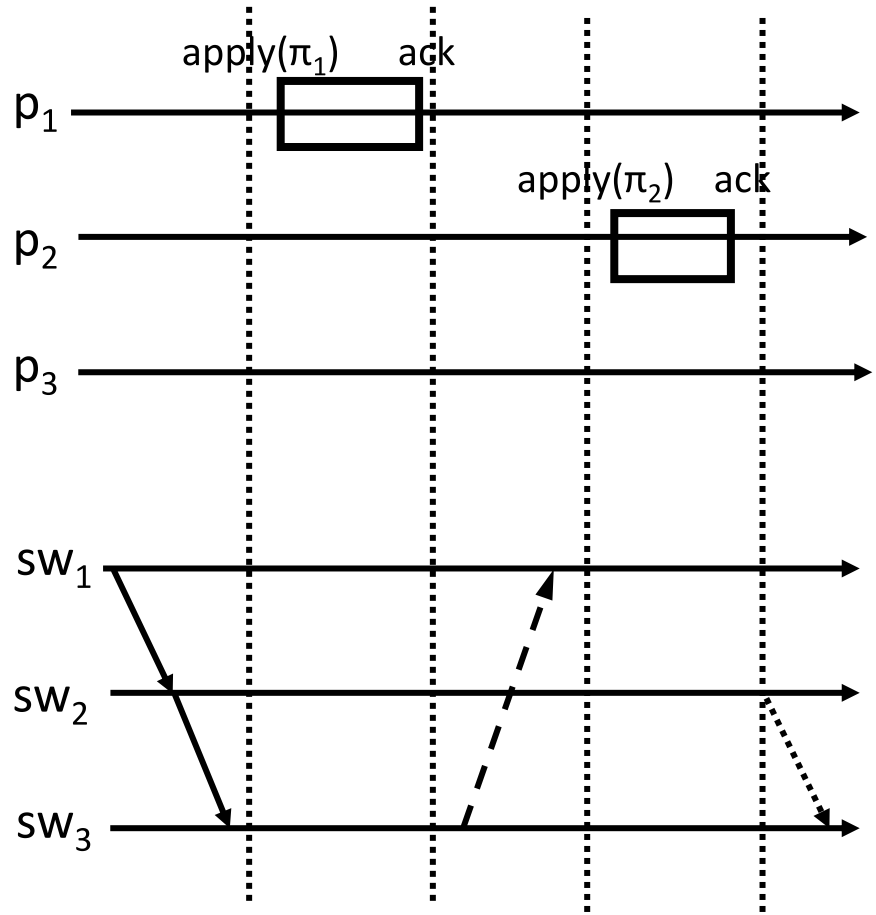

Reliable but asynchronous channel

Every controller receives and installs every policy

# CPC Example




Original history




Sequential equivalent

# CPC implementation: model v1

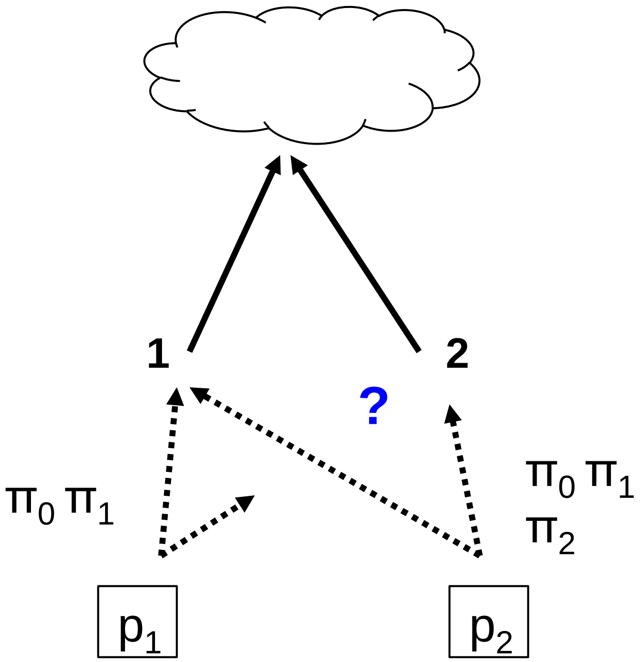
- Controllers access switch ports with read and write operations
- Controllers can communicate via asynchronous message-passing
- Controllers may fail by crashing
- No synchrony assumptions
- Restrict policies to forwarding
  - Compose if domains are disjoint or related by precedence
  - Reject otherwise

# Asynchronous read-write CPC

**Theorem:** 1-resilient read-write CPC is impossible

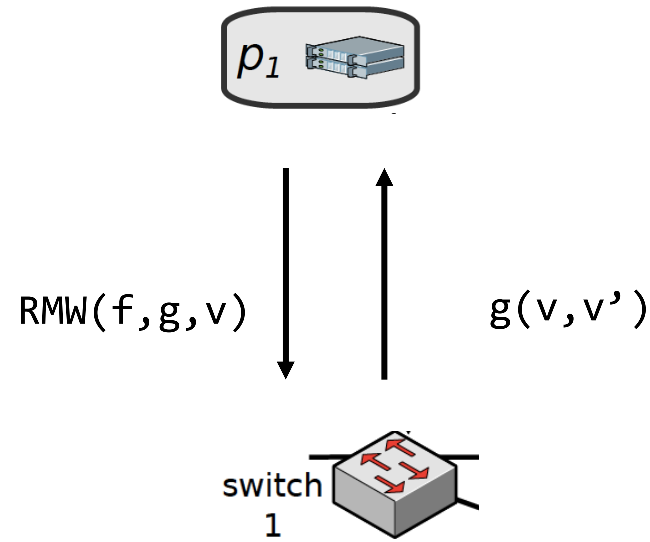
**Proof sketch:**

- Two ingress ports 1 and 2 initially forward all to the internal ports ($\pi_0$)
- $\pi_1$ installed by $p_1$ and $\pi_2$ installed by $p_2$, $\pi_2$ refines $\pi_1$ (higher precedence, same domain)
- $\pi_1$ and $\pi_2$ propose different paths
- $p_1$ changes port 1 and is just about to change 2 (with a composition of $\pi_0$ and $\pi_1$), $p_2$ takes no steps
- $p_2$ wakes up and installs of $\pi_0 \pi_1 \pi_2$, $p_1$ takes no steps
- $p_1$ changes port 2 with $\pi_0 \pi_1$: $\pi_2$ is forgotten!



# CPC implementation: model v2

- Controllers access ports with atomic read-modify-write ops RMW(f,g,v):
  - read the state v’
  - write f(v,v’)
  - return g(v,v’)




- Intuition: do not update if conflicts with currently installed policy

# Upper bound: FixTag algorithm

Operation:

1. Unique tag per path
2. Broadcast policy π to all other controllers
3. Update ingress ports in predefined order
4. … add rule to tag all packets matching dom(π) with the tag corresponding to the path(π, i) for ingress port i

Upsides: wait-free (tolerates all failure patterns)

Downsides: overhead can be huge

– Super-exponential in the size of the network

# Can we do better?

- No, if we get no feedback from the network
  - ✓ Tag t cannot be reused if a packet tagged with t is still “in flight”

- Suppose, we can correctly evaluate the set of active tags
  - ✓ Correct (but asynchronous) oracle
- Single-controller scenario: one bit is enough!
  - ✓ Upon policy update $\pi_i$ wait until (i mod 2)-traffic is over, and use tag i mod 2

- Two or more controllers: inherent price of concurrency?
  - Between constant and super-exponential?
  - Yes, if controllers coordinate use of tags

# ReuseTag: linear complexity

- Proportional to the level of resilience:
  - Up to f failures: f+2 tags needed (proved optimal)

- Controllers use consensus instances (eventual synchrony or « eventual leader »)
  - Replicated state machine that imposes a global order on the policy updates and ensure coordinated use and reuse of tags
- All requests are serialized
  - Even non-conflicting ones
  - Can we do better?

# Summary

- Framework for concurrent and consistent policy composition in distributed SDN
- Transactional interface to manipulate the network as though there is no concurrency
  - Policies compose or conflict (and abort)

# Acknowledgements

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# References

Software Transactional Networking: Concurrent and Consistent Policy Composition

HotSDN'13

STN: A Robust and Distributed SDN Control Plane

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A Distributed SDN Control Plane for Consistent Policy Updates

ArXiv technical report 1305.7429