# PISCES: A Programmable, Protocol-Independent Software Switch

[SIGCOMM 2016]

**Sean Choi**

Slide Credits to
Professor Nick McKeown and Muhammad Shahbaz

# Outline

- Motivations and history of SDN
- Use cases of SDN
- SDN and the change in the networking stack
- What is P4 and
  Protocol Independent Packet Processing?
- Introducing PISCES

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# What is Software-Defined Networking (SDN)?

# Software Defined Network

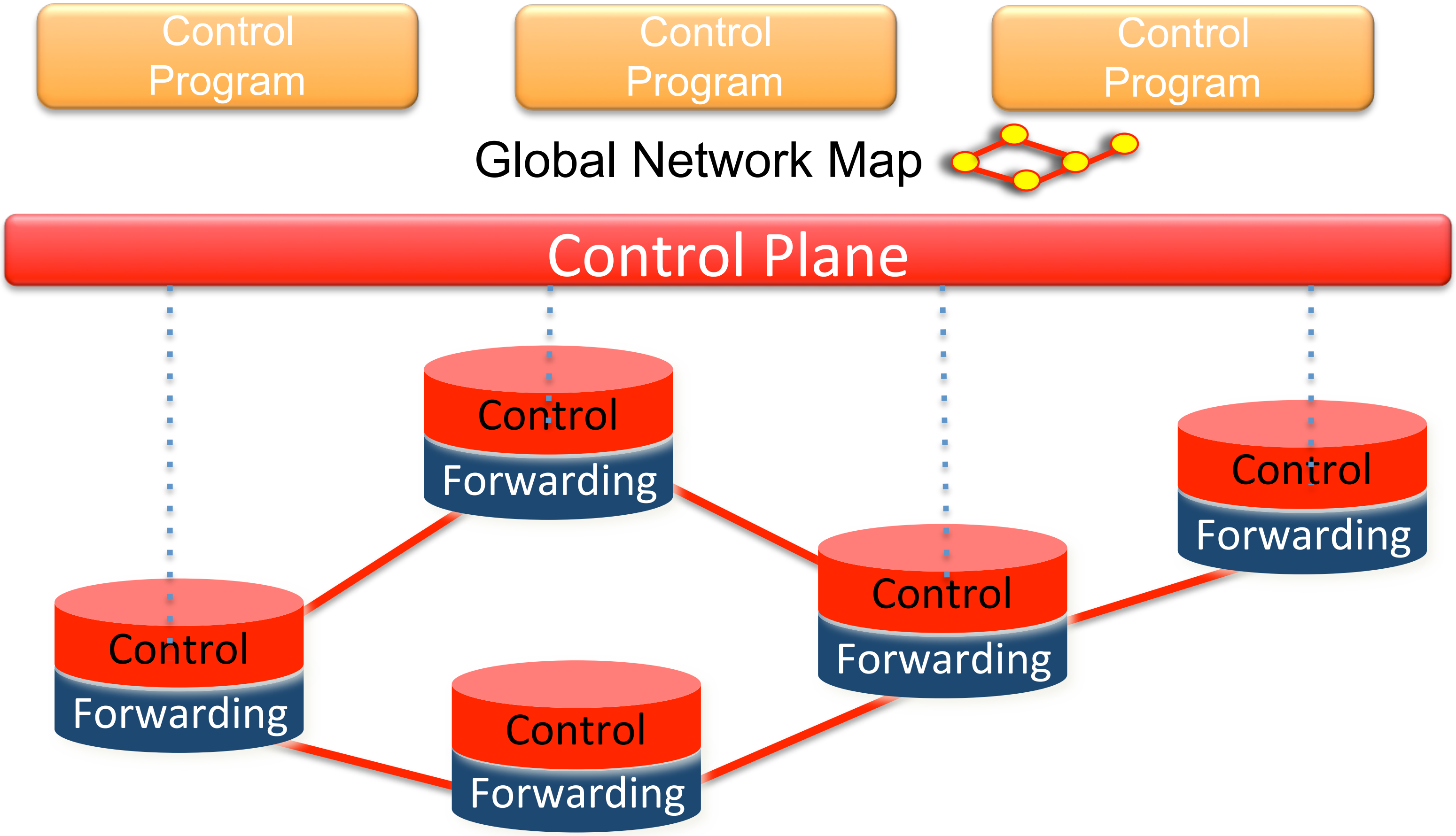
A network in which the control plane is physically separate from the forwarding plane.

*and*

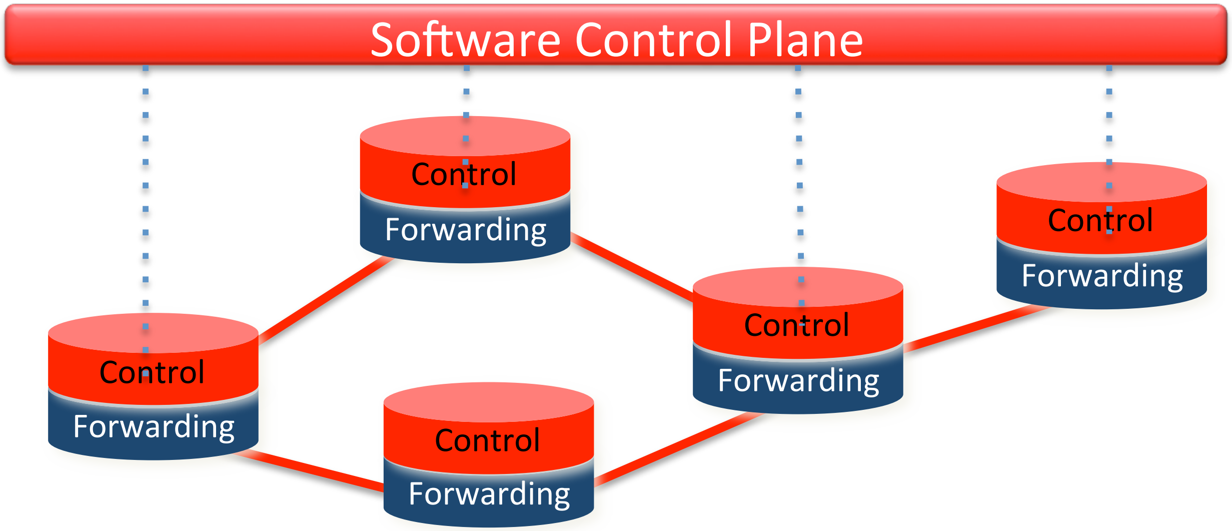
A single control plane controls several forwarding devices.

(That’s it)

# Software Defined Network (SDN)



# SDN



Intended consequences…

1. Put network owners and operators in control.
2. Networks that cost less: simpler, streamlined hardware.
3. Networks that cost less to operate (fewer features).
4. Networks that evolve faster.

# Origins of SDN

Martin Casado

The Ethane Project

[SIGCOMM 2007]

# How difficult is it to define all network operations in software, outside the data path?

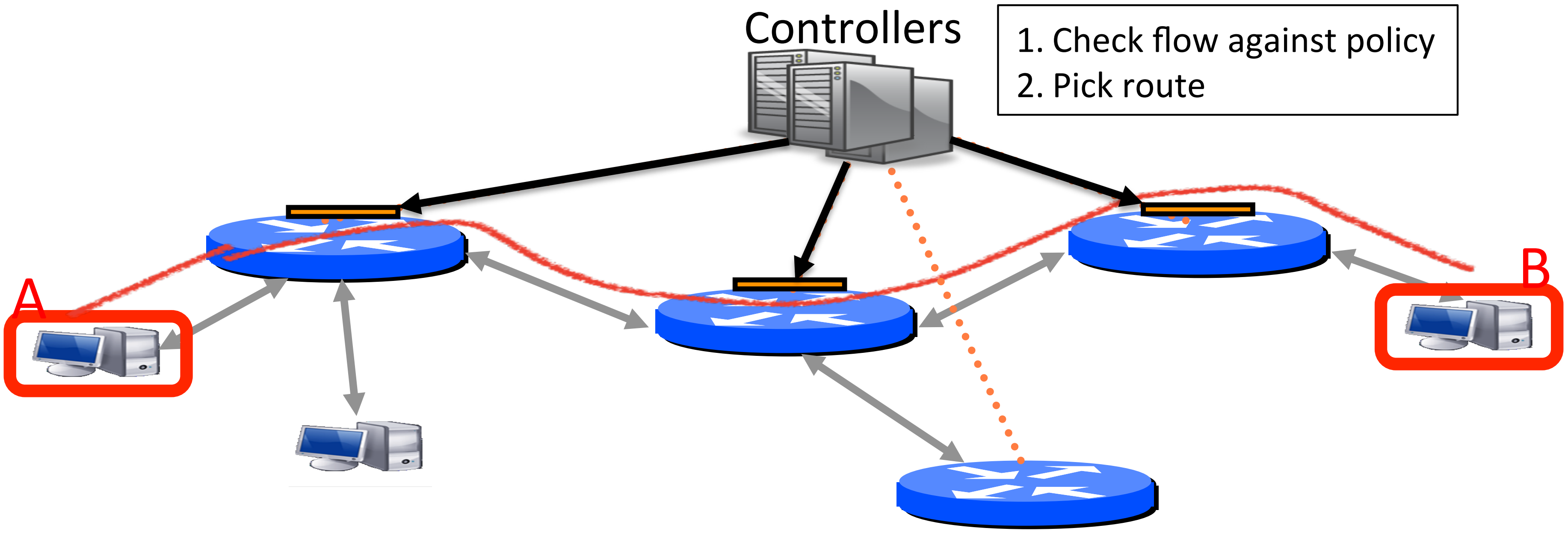
Stanford campus

2006

35,000 users
10,000 new flows/sec
137 network policies

2,000 switches
2,000 switch CPUs

# Crazy question: What if software decides whether to accept each flow, and how to route it?



1. Check flow against policy
2. Pick route

How many $400 controller servers do we need to service 35,000 users?

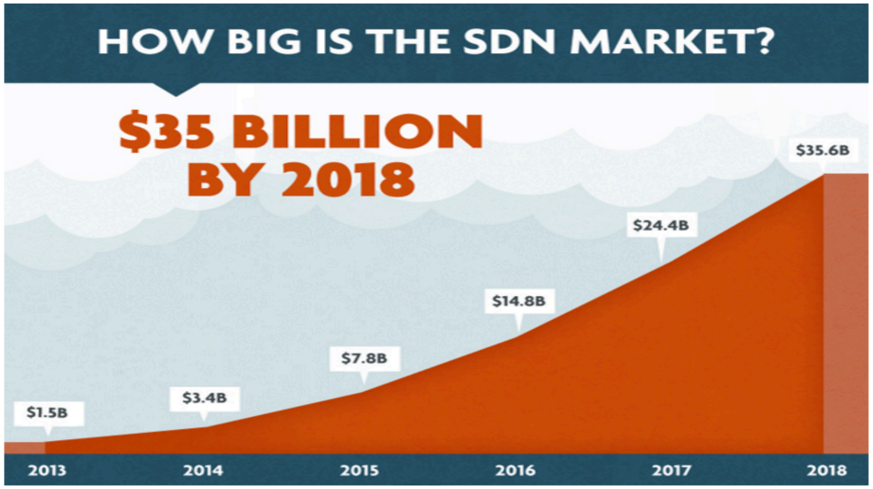
# Less than <u>One</u>

If we can define network behavior outside the data path, then eventually we will.

# What happened next

SDN, OpenFlow, Open vSwitch, Network Virtualization, …

About 250 startups so far.



Source: SDX Central

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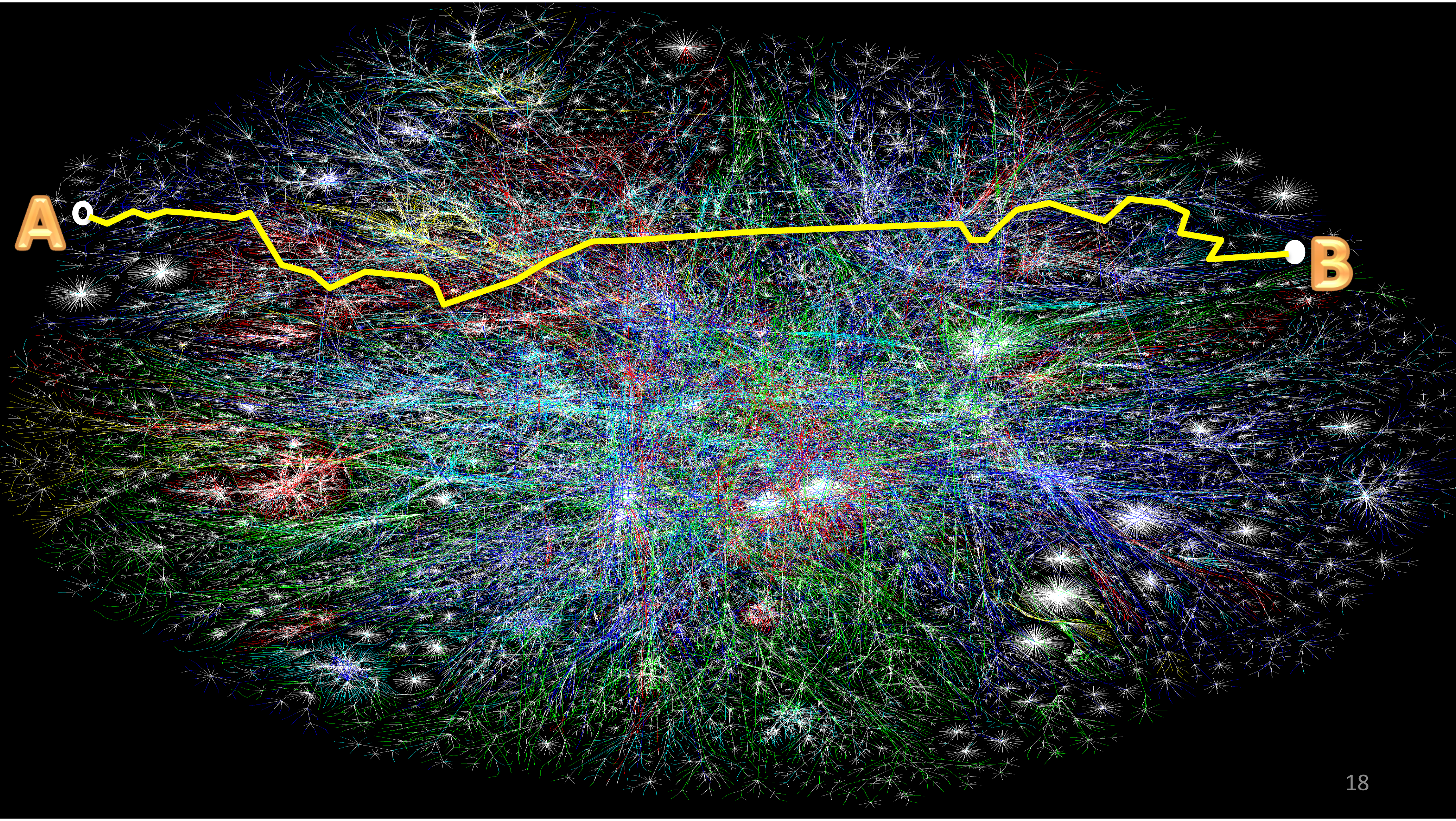
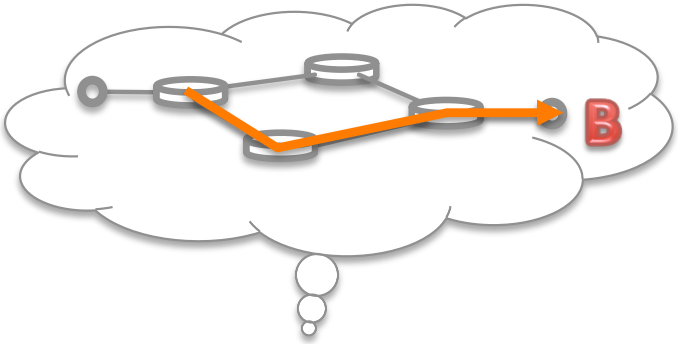
# SDN use cases
# Routing and NFV

Edsger Dikjstra
1930-2002

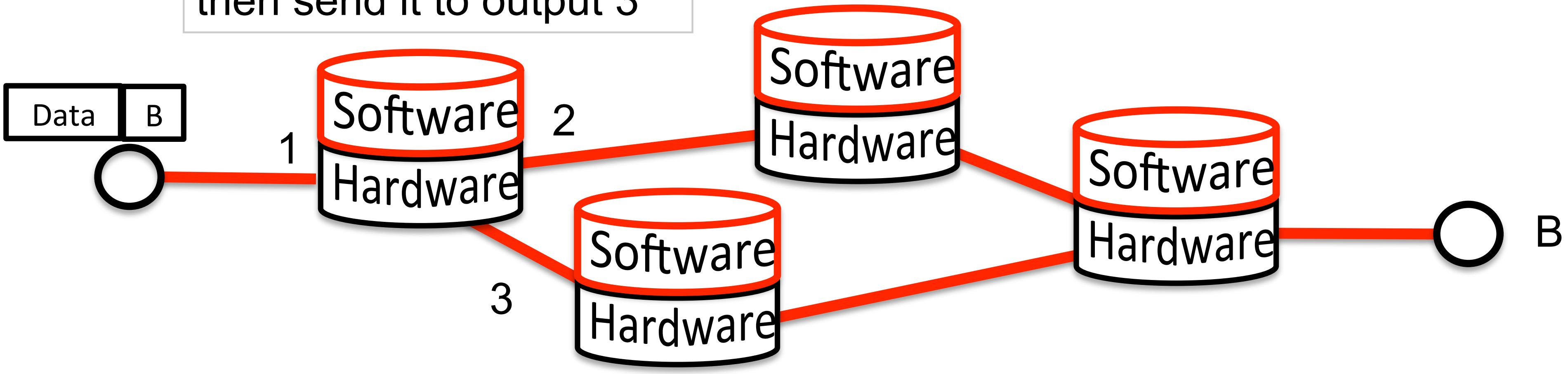
```
function Dijkstra(Graph, source):
for each vertex v in Graph:
        dist[v]  := infinity ;
        previous[v]  := undefined;

dist[source]  := 0 ;
Q := the set of all nodes in Graph ;
while Q is not empty:                              // The main loop
        u := vertex in Q with smallest distance in dist[] ;
        remove u from Q ;
        if dist[u] = infinity:
                break ;

        for each neighbor v of u:
                alt := dist[u] + dist_between(u, v) ;
                if alt < dist[v]:
                        dist[v]  := alt ;
                        previous[v]  := u ;
                        decrease-key v in Q;
return dist[], previous[];
end function
```


A
B



1. Figure out which routers and links are present.
2. Run Dijkstra’s algorithm to find shortest paths.

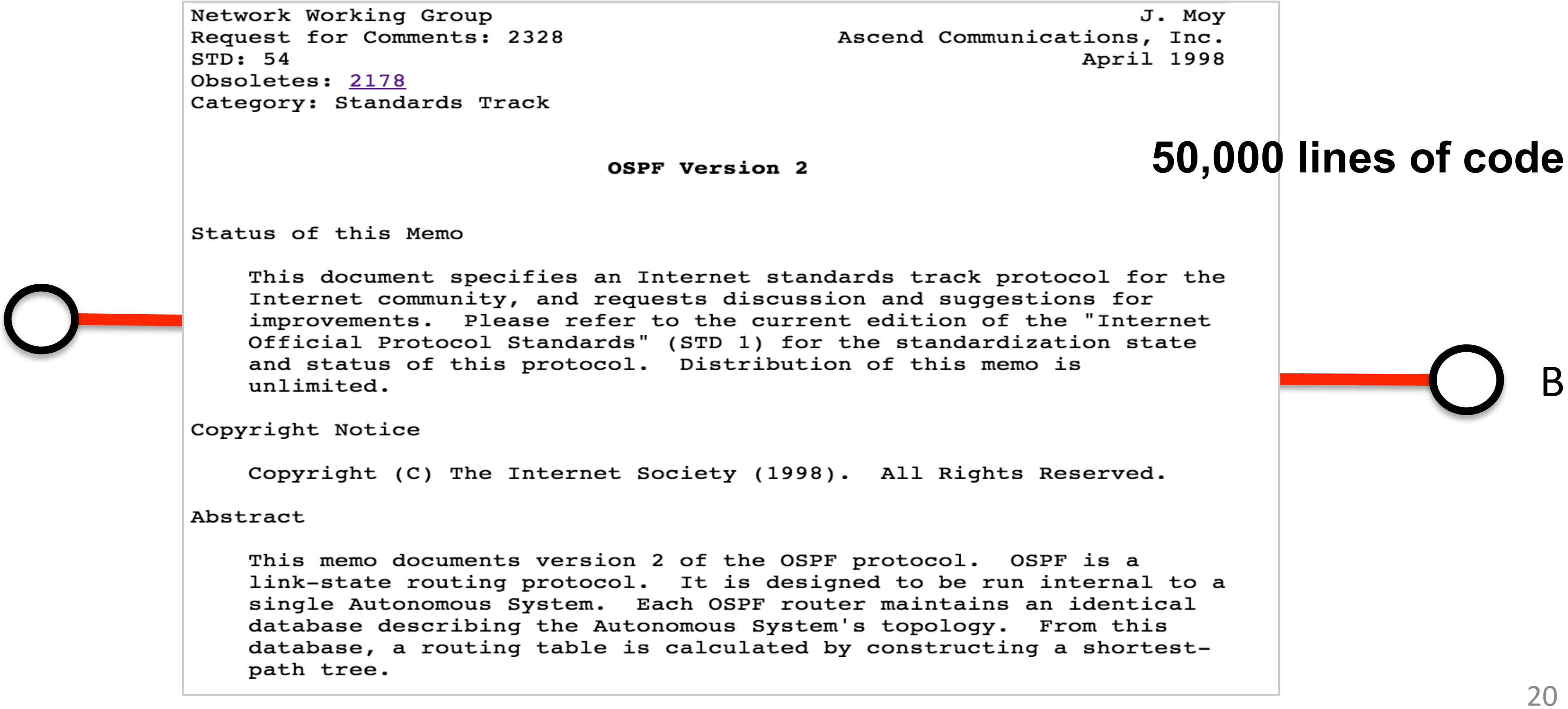
“If a packet is going to B, then send it to output 3”



95%

1. Figure out which routers and links are present.
2. Run Dijkstra’s algorithm to find shortest paths.

5%



Network Working Group<br>
Request for Comments: 2328<br>
STD: 54<br>
Obsoletes: 2178<br>
Category: Standards Track

J. Moy<br>
Ascend Communications, Inc.<br>
April 1998

OSPF Version 2

Status of this Memo

This document specifies an Internet standards track protocol for the Internet community, and requests discussion and suggestions for improvements. Please refer to the current edition of the "Internet Official Protocol Standards" (STD 1) for the standardization state and status of this protocol. Distribution of this memo is unlimited.

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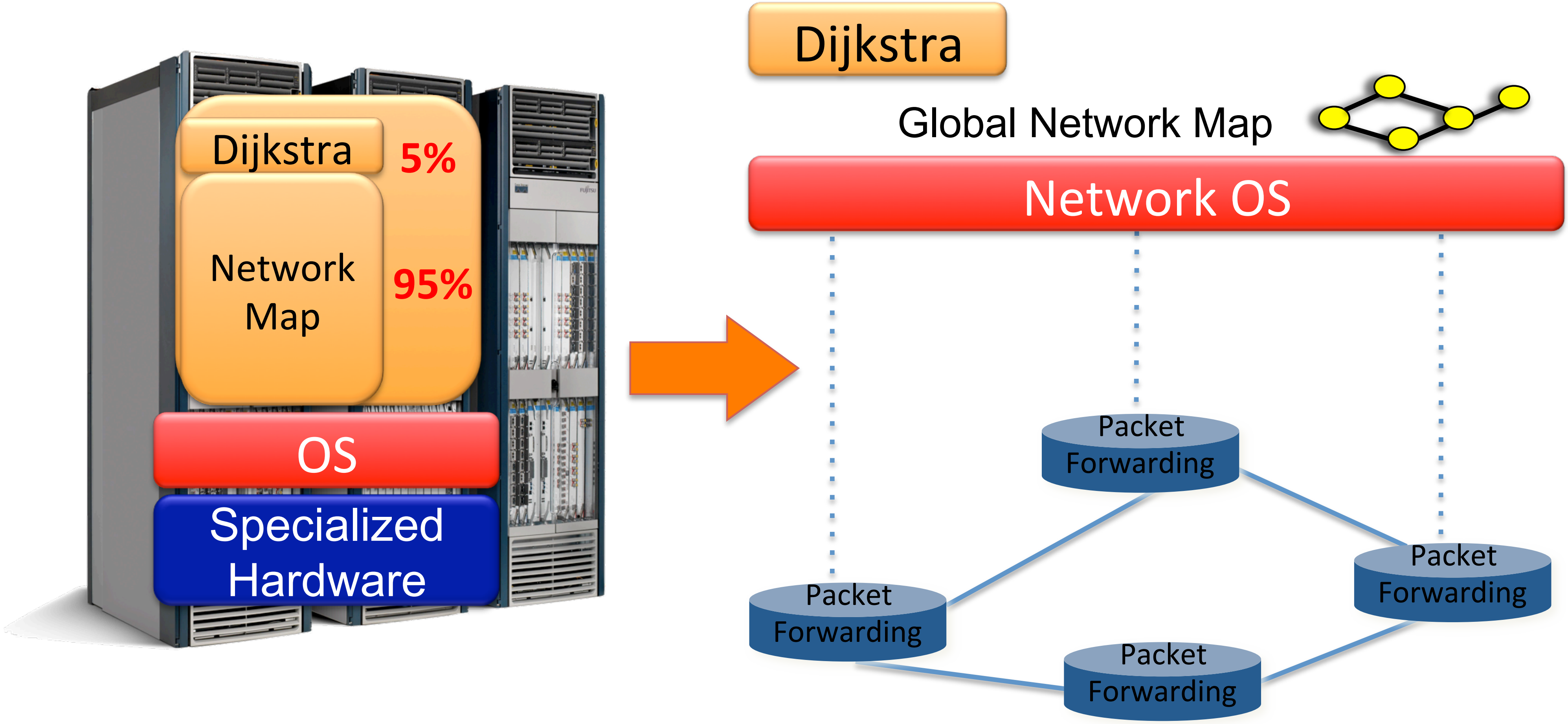
Abstract

This memo documents version 2 of the OSPF protocol. OSPF is a link-state routing protocol. It is designed to be run internal to a single Autonomous System. Each OSPF router maintains an identical database describing the Autonomous System's topology. From this database, a routing table is calculated by constructing a shortest-path tree.

**50,000 lines of code**



Dijkstra

5%

Network Map

95%

OS

Specialized Hardware

Dijkstra

Global Network Map

Network OS

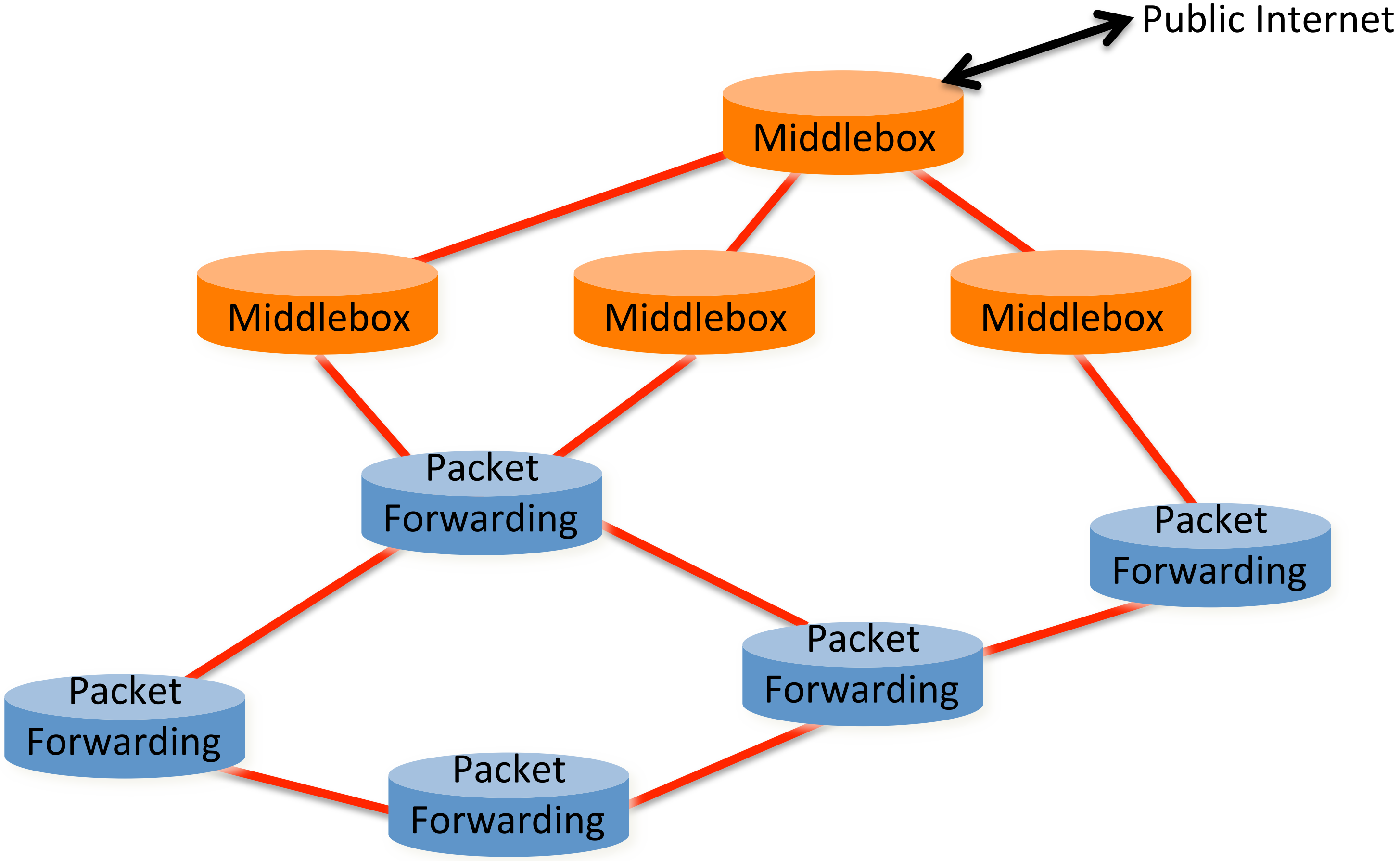
Packet Forwarding

Packet Forwarding

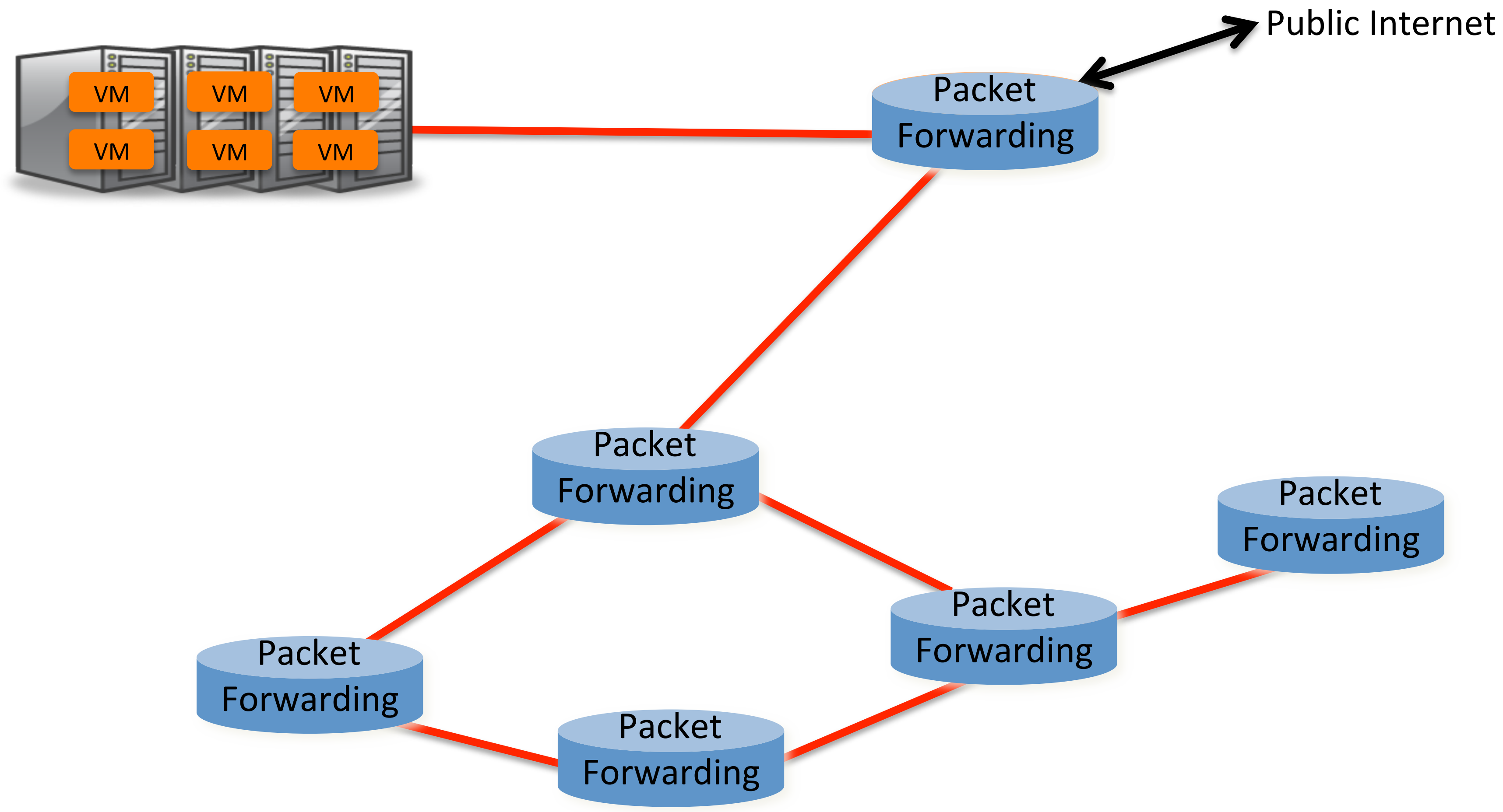
Packet Forwarding

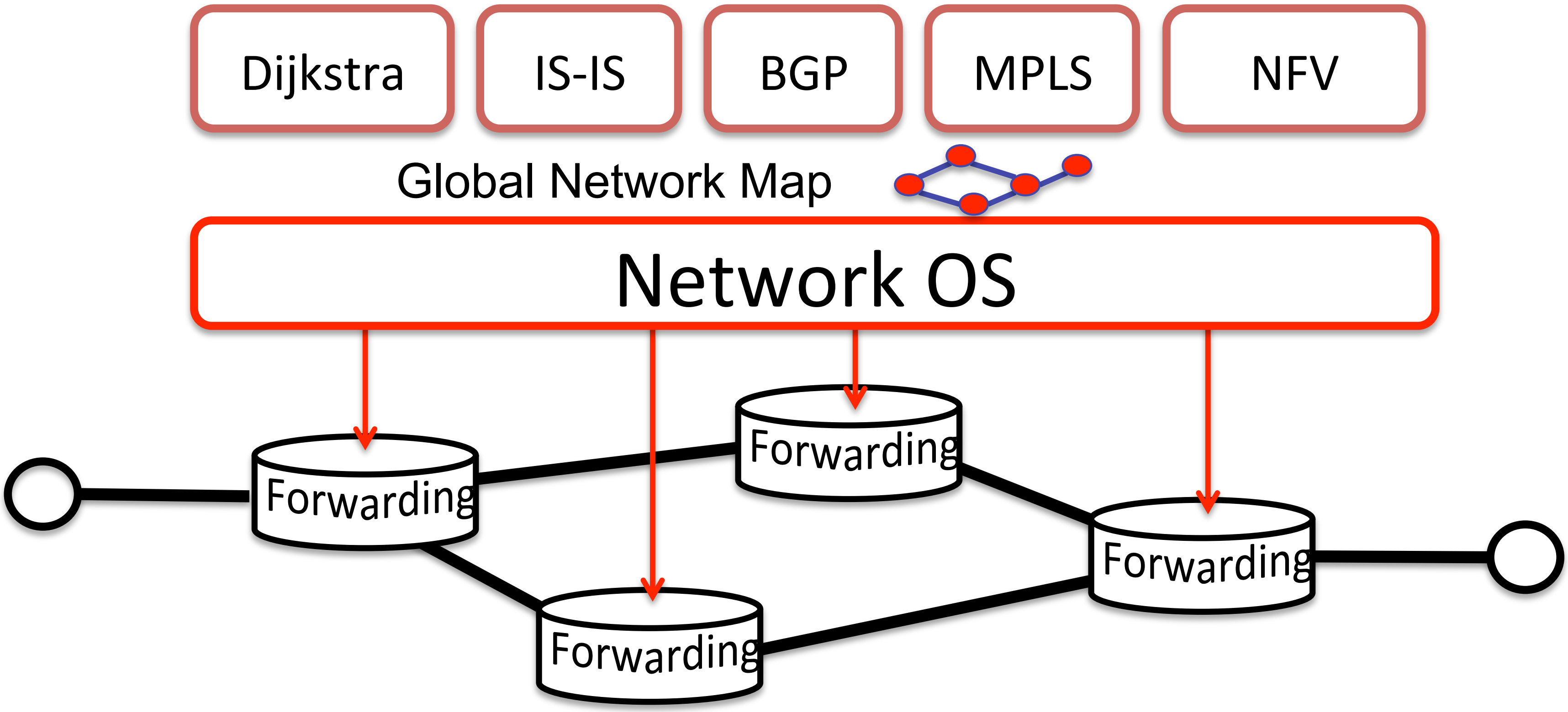
Packet Forwarding

# Network Function Virtualization (NFV)



# Network Function Virtualization (NFV)





Dijkstra

IS-IS

BGP

MPLS

NFV

Global Network Map

Network OS

Forwarding

Forwarding

Forwarding

Forwarding

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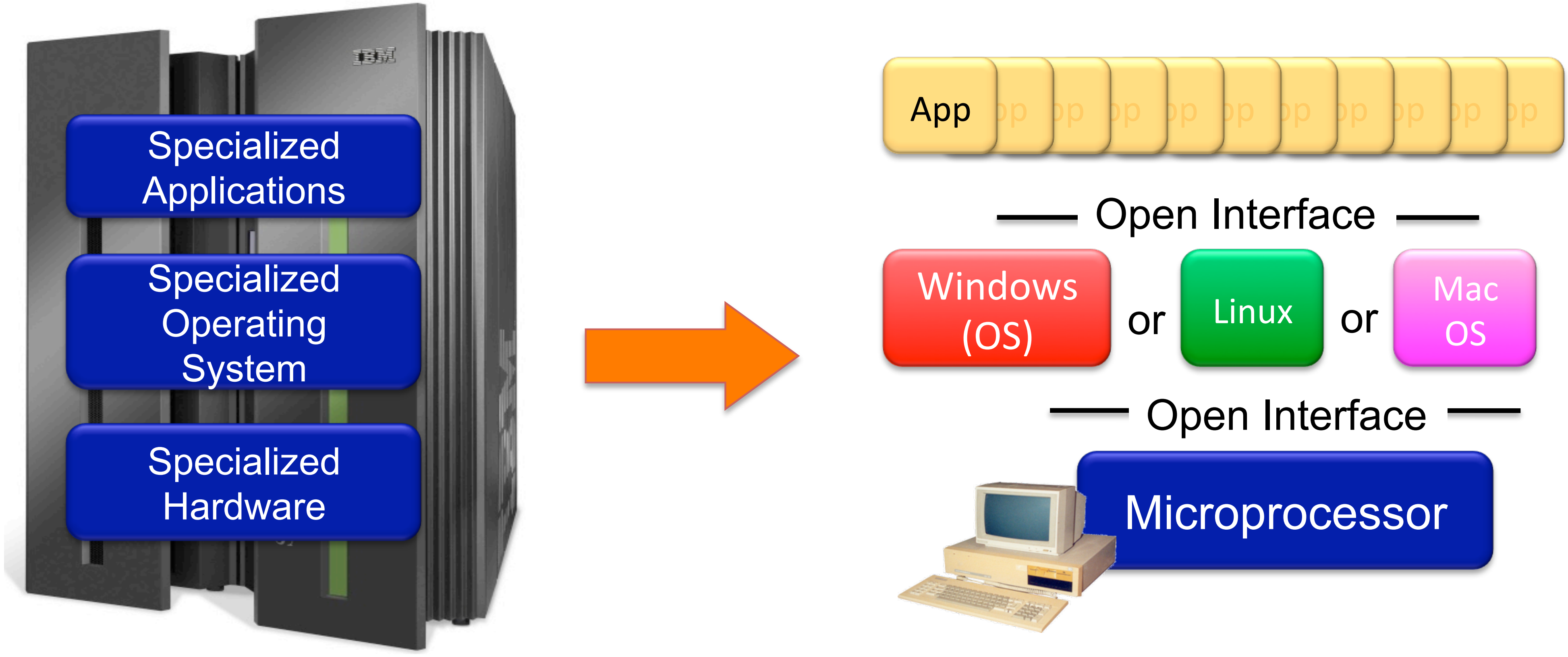
Hundreds of protocols
7,000 RFCs

Tens of millions of lines of code.
Closed, proprietary, outdated.

Billions of gates.
Power hungry and bloated.



Specialized Applications

Specialized Operating System

Specialized Hardware

App

Open Interface

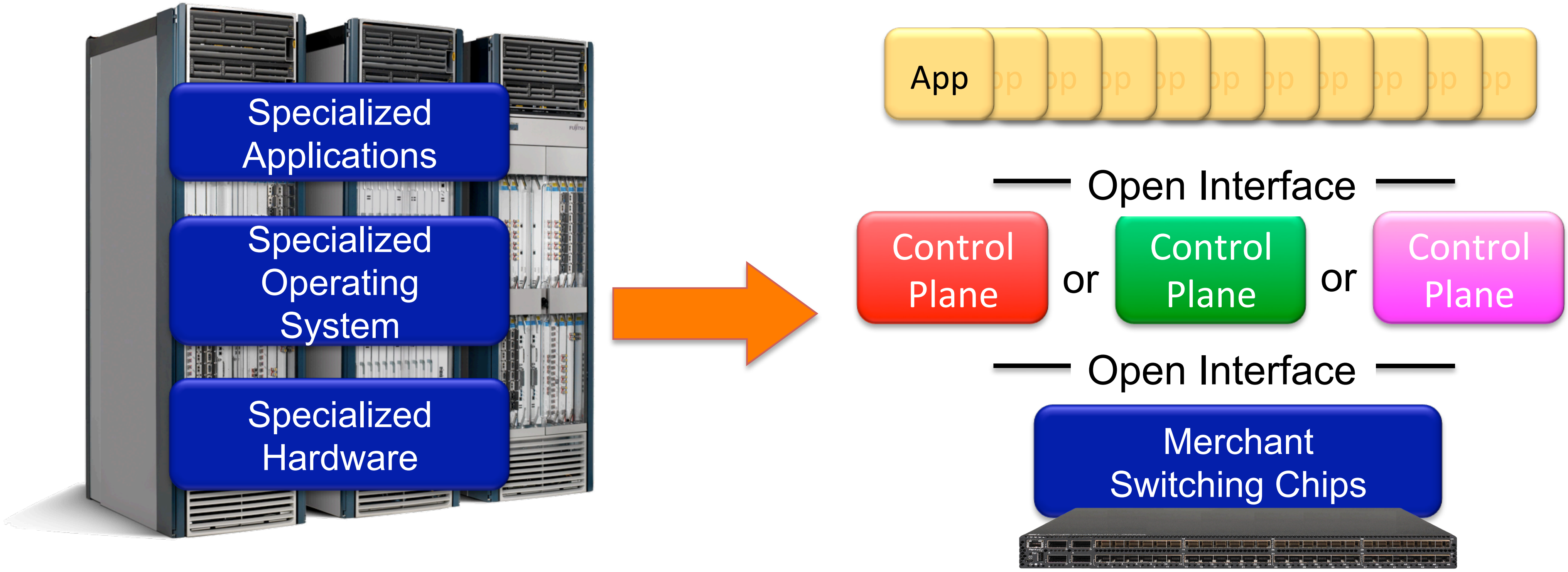
Windows (OS) or Linux or Mac OS

Open Interface

Microprocessor

Vertically integrated
Closed, proprietary
Slow innovation

Horizontal
Open interfaces
Rapid innovation



Specialized Applications

Specialized Operating System

Specialized Hardware

App

Open Interface

Control Plane or Control Plane or Control Plane

Open Interface

Merchant Switching Chips

Vertically integrated
Closed, proprietary
Slow innovation

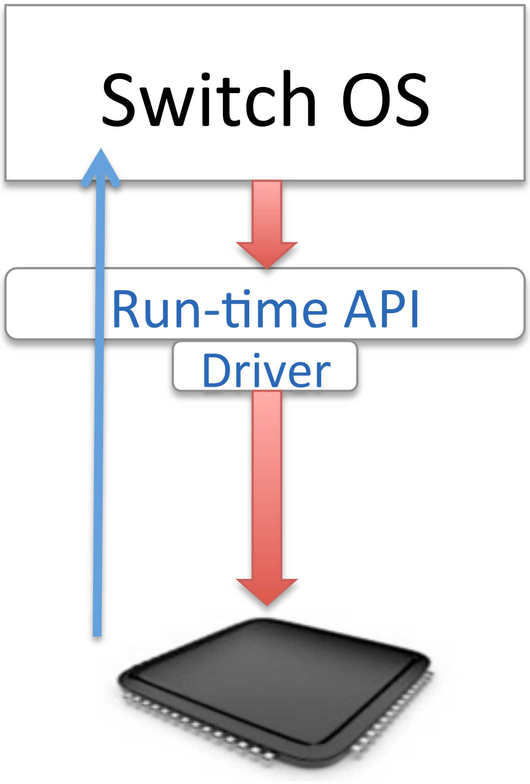
Horizontal
Open interfaces
Rapid innovation

# I can customize my networks!...?

1. See what my forwarding plane is doing.
2. Quickly deploy new protocols
3. Put expensive middlebox functions into the network.
4. Differentiate. Now I own my intellectual property.
5. Try out beautiful new ideas. Tailor my network to meet my needs.

# Not Really…

# What about the fixed function switch?



Switch OS

Run-time API

Driver

“This is how I process packets”

Fixed function switch

# Problems: Fixed function switch

1. Slow innovation

   Several months or years to add a new feature or protocol

2. Inefficient

   Match tables hard-wired to specific purpose

3. Complicated

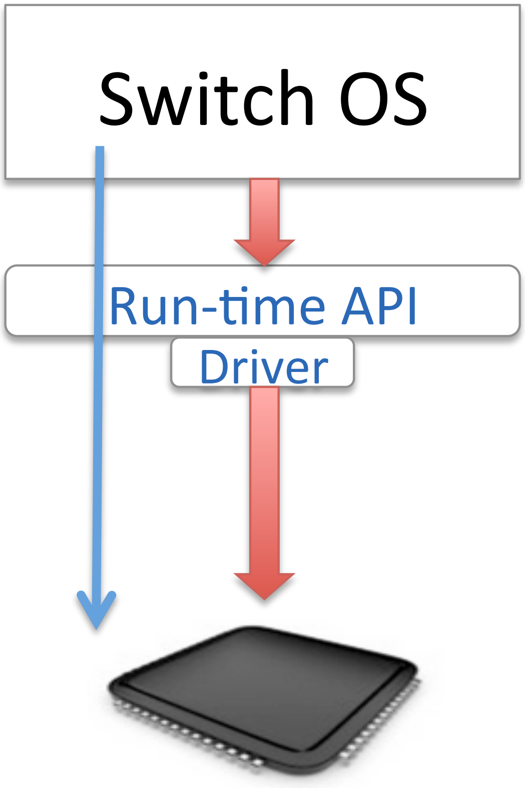
   Switch implements superset of all features

4. Leads to bottom-up design

   Frustrating for programmers

# What we want: Programmable Switch

"This is how the switch must process packets"



Switch OS

Run-time API

Driver

Programmable Switch

P4 can help us do this!

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# P4

## P4: Programming Protocol-Independent Packet Processors

ACM CCR. Volume 44, Issue #3 (July 2014)

Pat Bosshart, Glen Gibb, Martin Izzard, and Dan Talayco (Barefoot Networks), Dan Daly (Intel), Nick McKeown (Stanford), Cole Schlesinger and David Walker (Princeton), Amin Vahdat (Google), and George Varghese (Microsoft)

www.p4.org

# Phases for Protocol-Independent Packet Processing

**Phase 0.** Initially, the switch does not know what a protocol is, or how to process packets (Protocol Independence)

**Phase 1.** We tell the switch how we want it to process packets (Configuration)

**Phase 2.** The switch runs (Run-time)

# Three Goals

Protocol independence

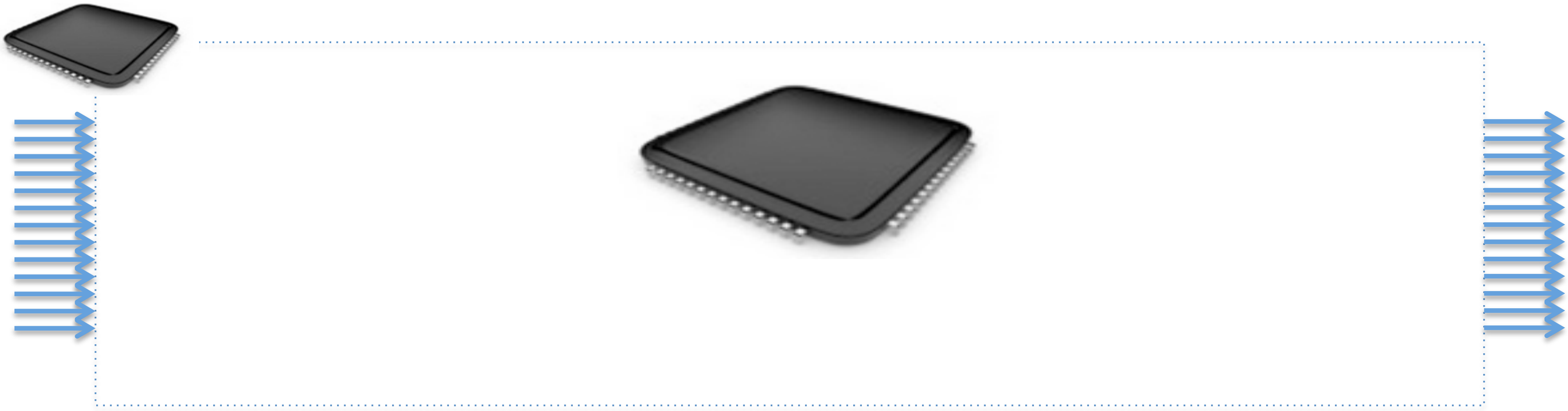
- Configure a packet parser
- Define a set of typed match+action tables

Target independence

- Program without knowledge of switch details
- Rely on compiler to configure the target switch

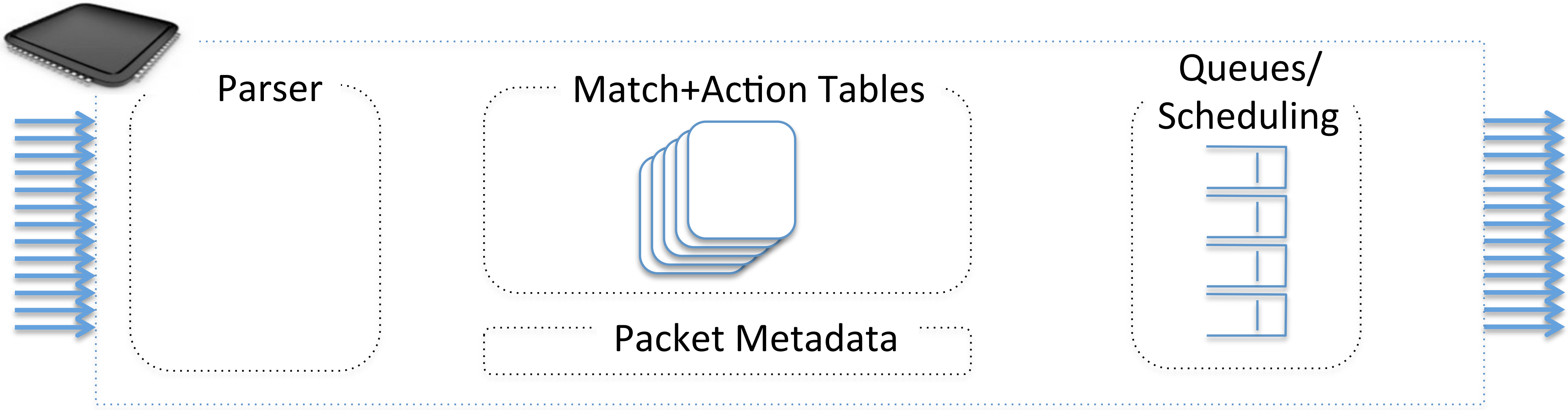
Reconfigurability

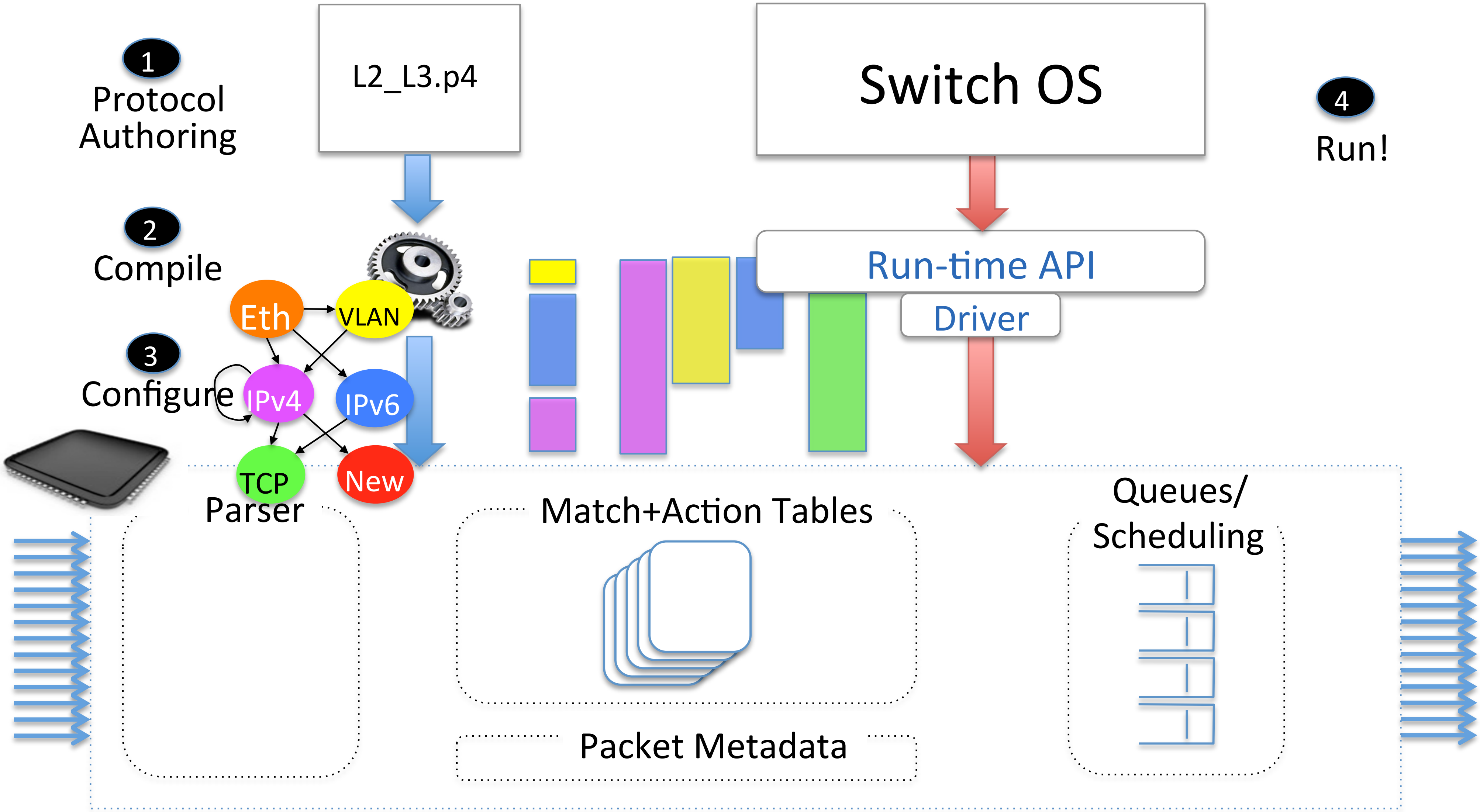
- Change parsing and processing in the field



# The Abstract Forwarding Model

Initially, a switch is unprogrammed
and does not know any protocols.





1 Protocol Authoring

L2_L3.p4

Switch OS

4 Run!

2 Compile

Run-time API

Driver

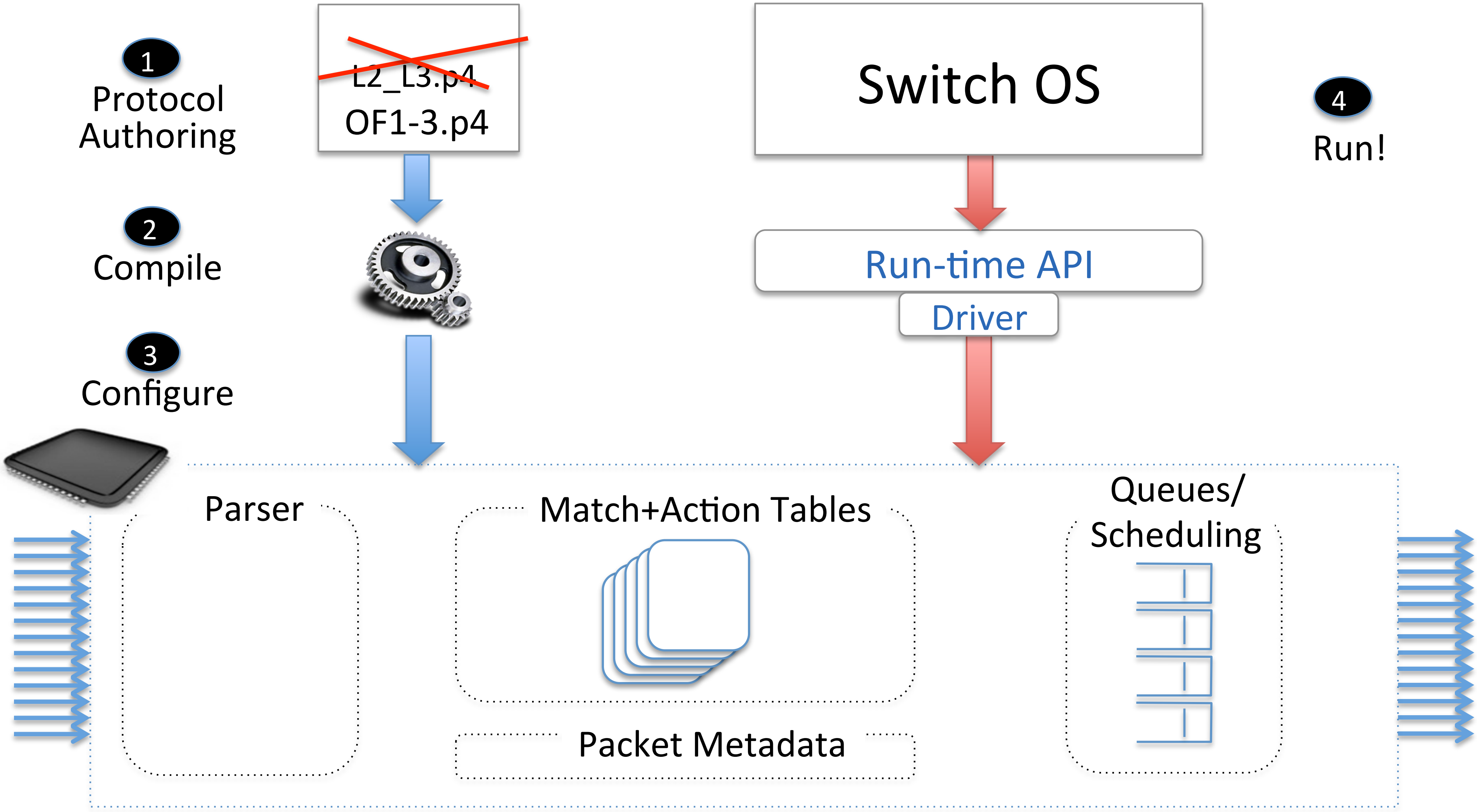
3 Configure

Parser

Match+Action Tables

Queues/ Scheduling

Packet Metadata



1 Protocol Authoring

~~L2_L3.p4~~

OF1-3.p4

2 Compile

3 Configure

Switch OS

Run-time API

Driver

4 Run!

Parser

Match+Action Tables

Packet Metadata

Queues/ Scheduling

# P4 in Detail

- Headers and Fields
- The Parser
- Match+Action Tables
- Control flow

# Headers and Fields

Header Fields: Ethernet

```
header_type ethernet_t {
  fields {
    dstAddr    : 48;
    srcAddr    : 48;
    etherType  : 16;
  }
}

/* Instance of eth header */
header ethernet_t first_ethernet;
```

Metadata

```
header_type standard_metadata_t {
  fields {
    ingress_port        : 32;
    packet_length       : 32;
    ingress_timestamp : 32;
    egress_spec         : 32;
    egress_port         : 32;
    egress_instance    : 32;
  }
}

metadata standard_metadata_t std_metadata;
```

# The Parser

Parser: Ethernet

```
parser parse_ethernet {
  extract(ethernet);
  return switch(latest.etherType) {
     ETHERTYPE_VLAN : parse_vlan;
     ETHERTYPE_MPLS : parse_mpls;
     ETHERTYPE_IPV4 : parse_ipv4;
     ETHERTYPE_IPV6 : parse_ipv6;
     ETHERTYPE_ARP  : parse_arp_rarp;
     ETHERTYPE_RARP : parse_arp_rarp;
  }
}
```

Parser: IPv4

```
parser parse_ipv4 {
  extract(ethernet);
  return switch(latest.etherType) {
     PROTO_TCP : parse_tcp;
     PROTO_UDP : parse_udp;
     ...
  }
}
```

# Match+Action Tables

Specifies

- Which fields to examine in each packet
- Actions that may be applied (by rule)
- Table size (optional)

Match+Action Table: VLAN

```
table port_vlan {
    reads {
        std_metadata.ingress_port : exact;
        vlan_tag[OUTER_VLAN].vid : exact;
    }
    actions {
        drop, ing_lif_extract;
    }
    size 16384;
}
```

Match+Action Table: Unicast RPF

```
table urpf_check {
    reads {
        routing_metadata.bd : ternary;
        ipv4.dstAddr : ternary;
    }
    actions {
        urpf_clear, urpf_set;
    }
}
```

# Actions

Built from primitives

- modify field (packet header or metadata)
- add/remove header
- clone/recirculate
- counter/meter/stateful memory operations

## Parallel semantics

Actions: LIF Extract

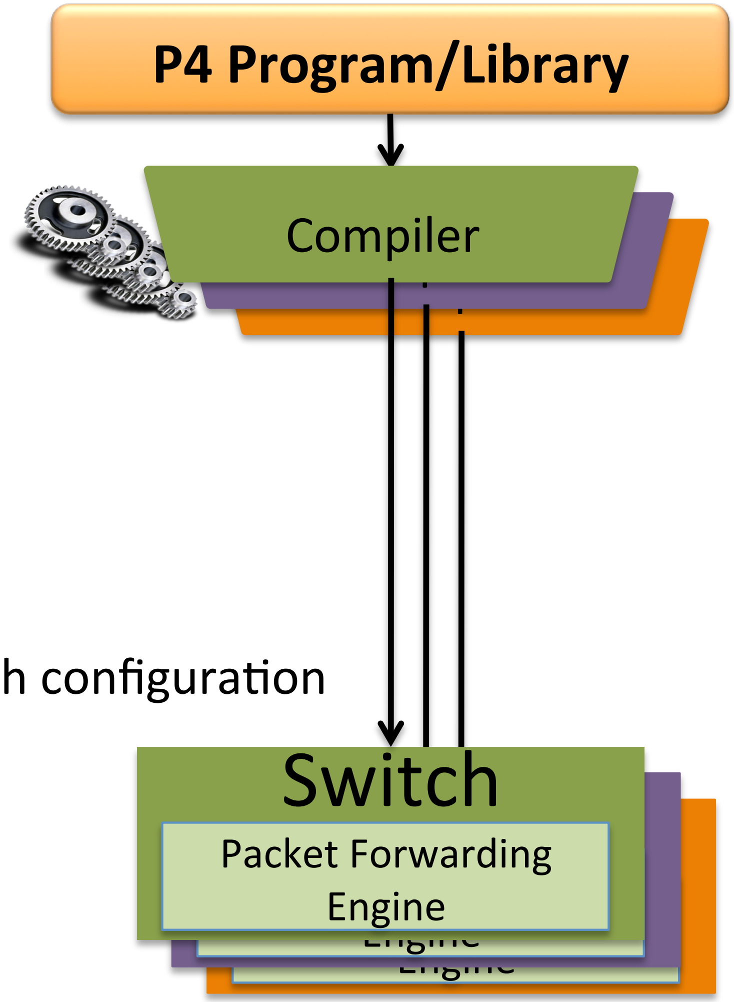
```
/* Ingress logical interface setup */
action ingress_lif_extract(i_lif, bd, vrf, v4term, v6term, igmp_snoop) {
  modify_field(route_md.i_lif, i_lif);
  modify_field(route_md.bd, bd);
  modify_field(route_md.vrf, vrf);
  modify_field(route_md.ipv4_term, v4term, 0x1);
  modify_field(route_md.ipv6_term, v6term, 0x1);
  modify_field(route_md.igmp_snoop, igmp_snoop, 0x1);
}
```

# Control Flow

Control Flow: Ingress

```
control ingress {
    apply_table(port);
    apply_table(bcast_storm);
    apply_table(ip_sourceguard);
    if (valid(vlan_tag[0])) {
        apply_table(port_vlan);
    }
    apply_table(bridge_domain);
    if (valid(mpls_bos)) {
        apply_table(mpls_label);
    }
    retrieve_tunnel_vni();
    if (valid(vxlan) or valid(genv) or valid(nvgre)) {
        apply_table(dest_vtep);
        apply_table(src_vtep);
    }
    . . . .
}
```

# The P4 View of the World



P4 Program/Library

Compiler

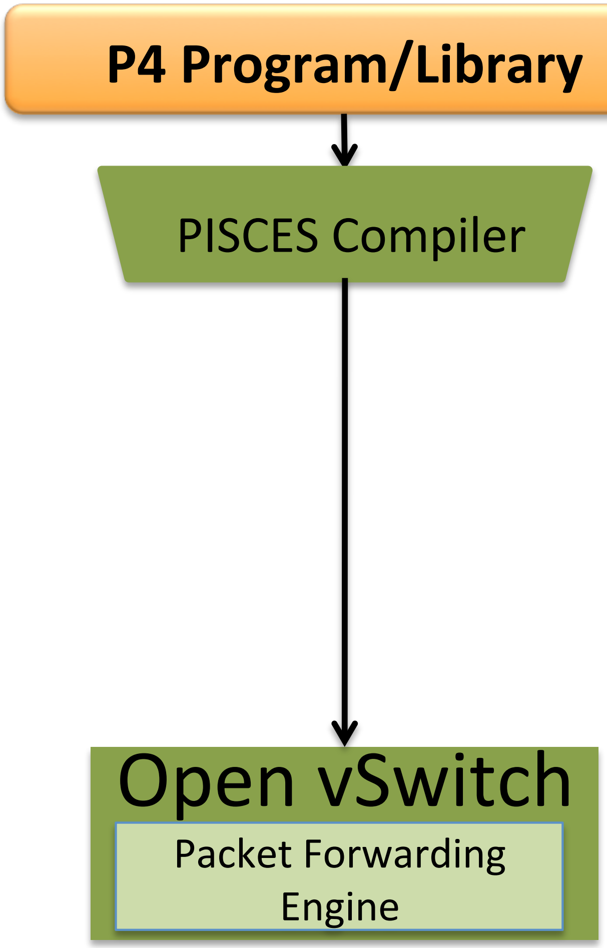
A compiler per target

Switch configuration

Switch

Packet Forwarding Engine

# PISCES: First Ever P4 to vSwitch Compiler



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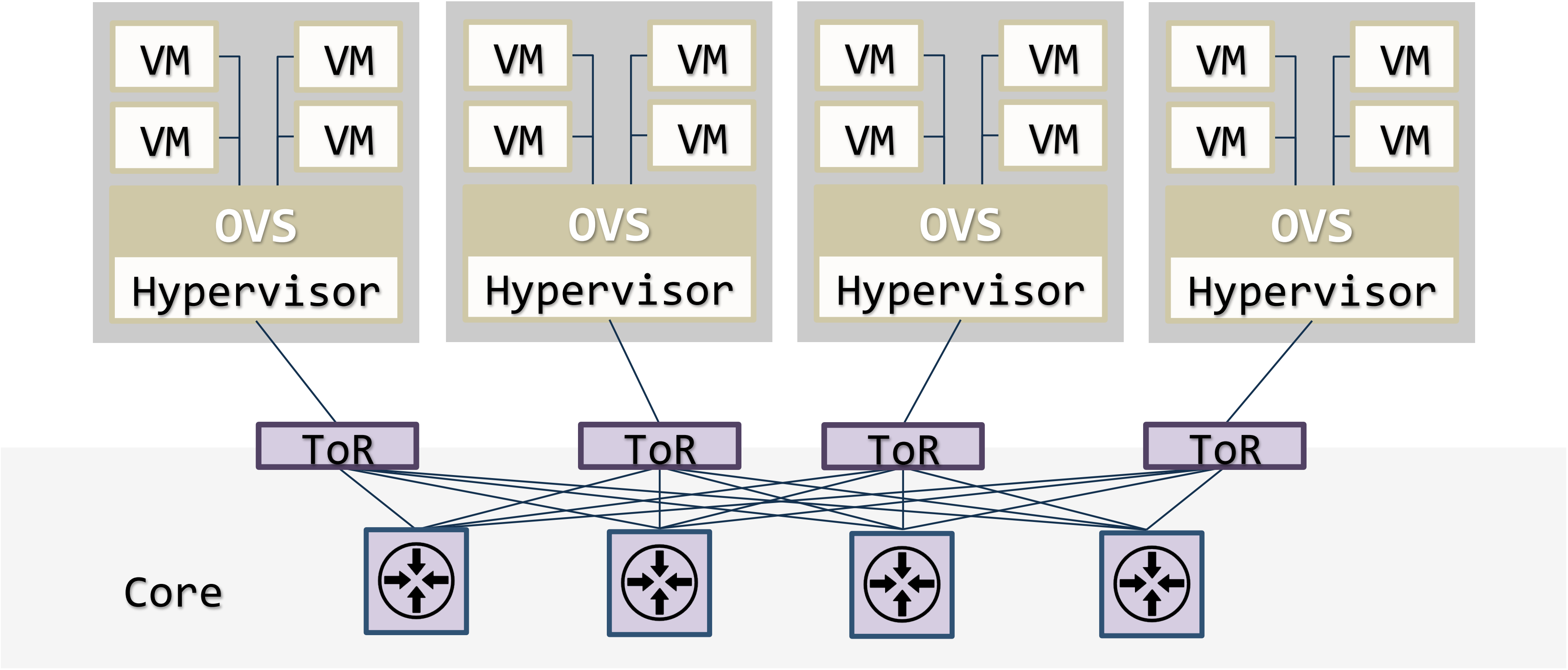
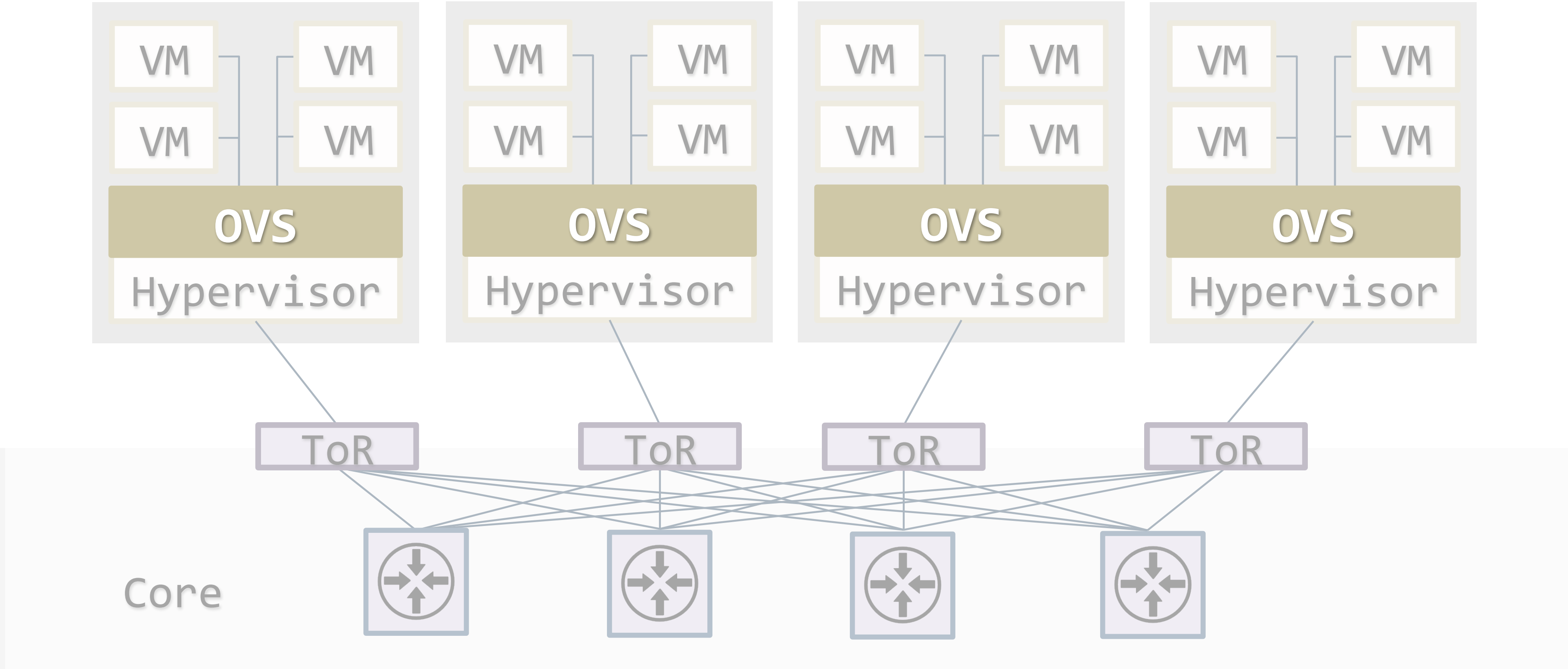
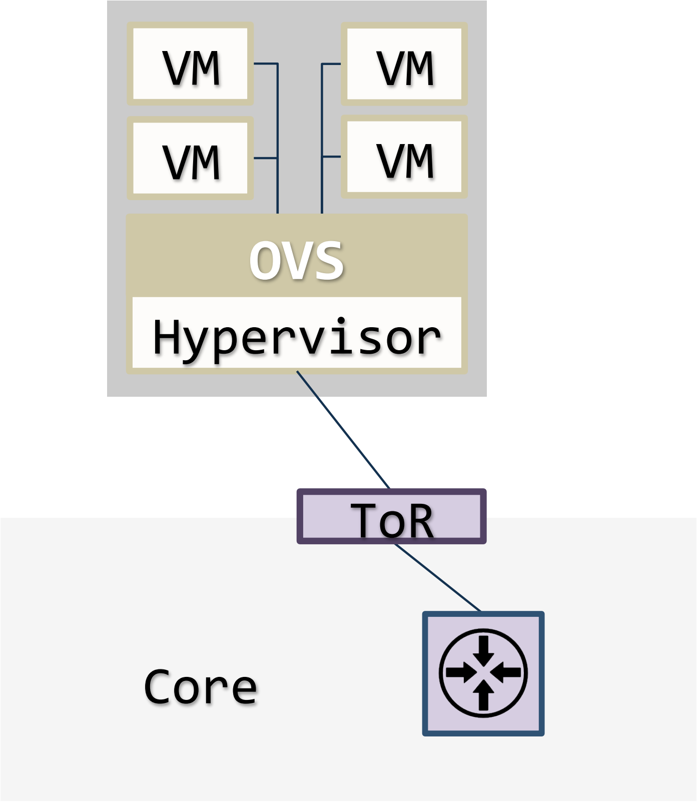
# Importance of Software Switches



# Importance of Software Switches



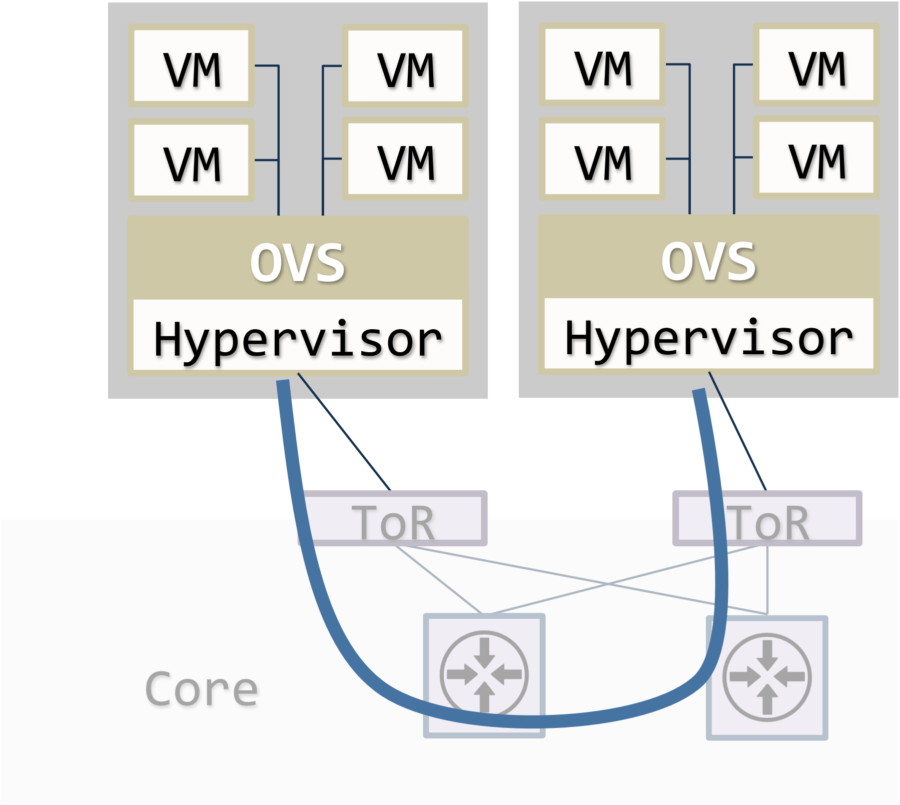
# Ease of Customization?



Enable **Rapid Development** and **Deployment** of **Network Features!**

**Is it REALLY the case?**

# Ease of Customization?

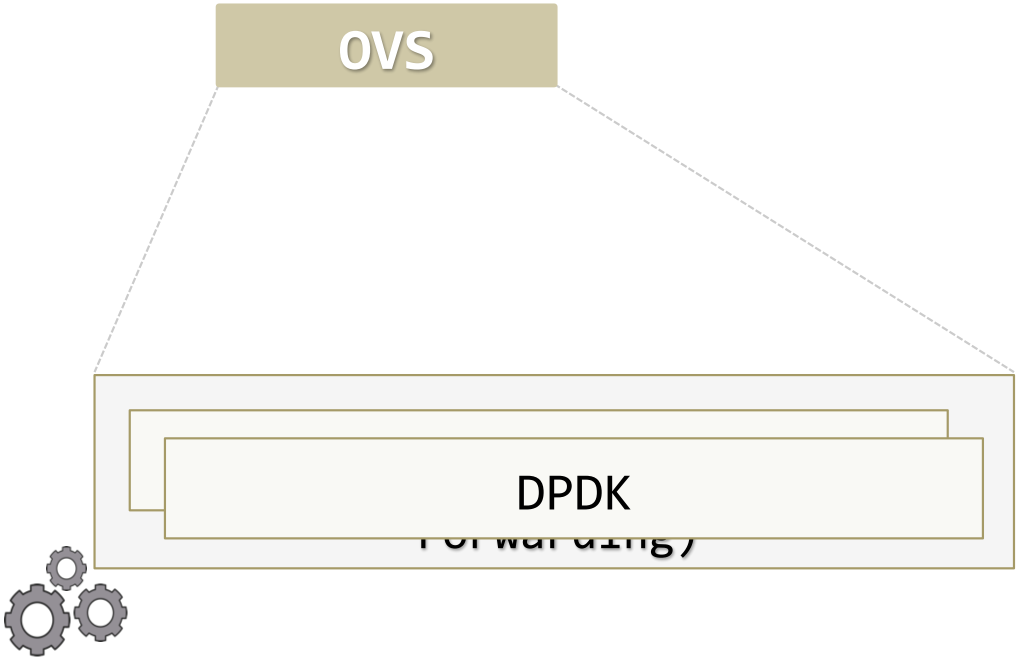


For example, OVS supports following tunneling protocols:

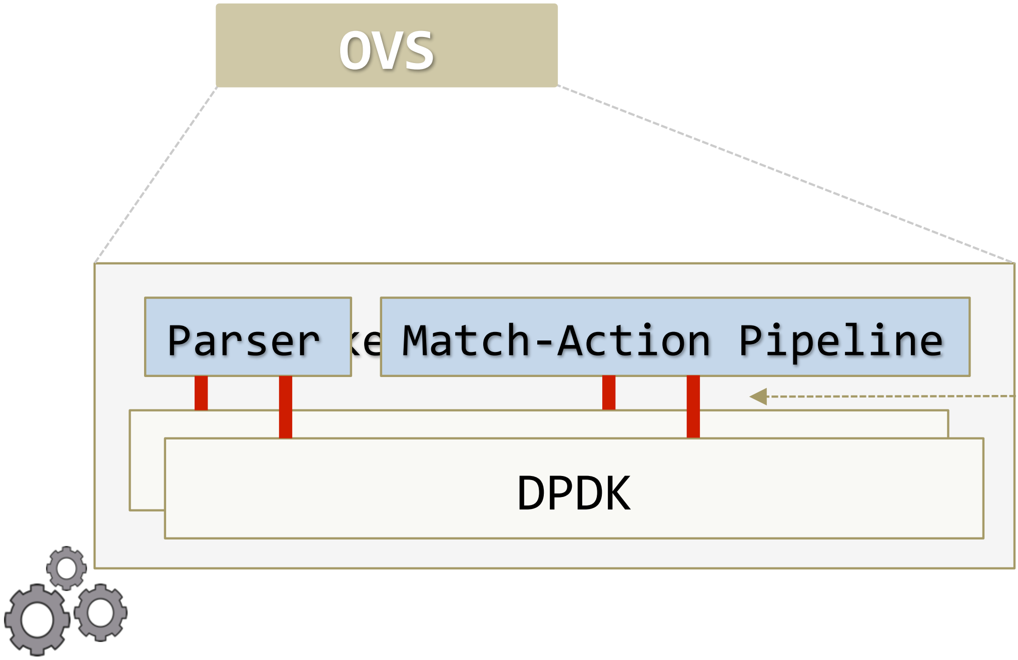
- **VXLAN**: Virtual Extensible LAN
- **STT**: Stateless Transport Tunneling
- **NVGRE**: Network Virtualization Generic Routing

**What about adding new protocols?**

# Rapid Development & Deployment?



# Rapid Development & Deployment?



**Requires domain expertize in:**

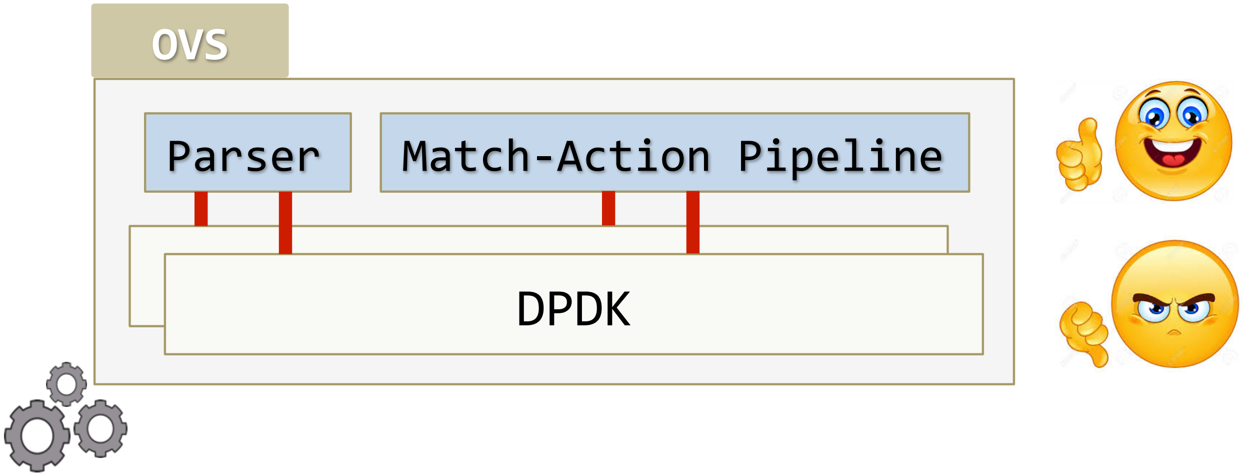
- Network **protocol design**
- Software development
  - **Develop**
  - **Test**
  - **Deploy**

  … large, complex codebases.

**Arcane APIs**

- Can take **3-6 months** to get a new feature in.
- **Maintaining changes** across releases

# Rapid Development & Deployment?



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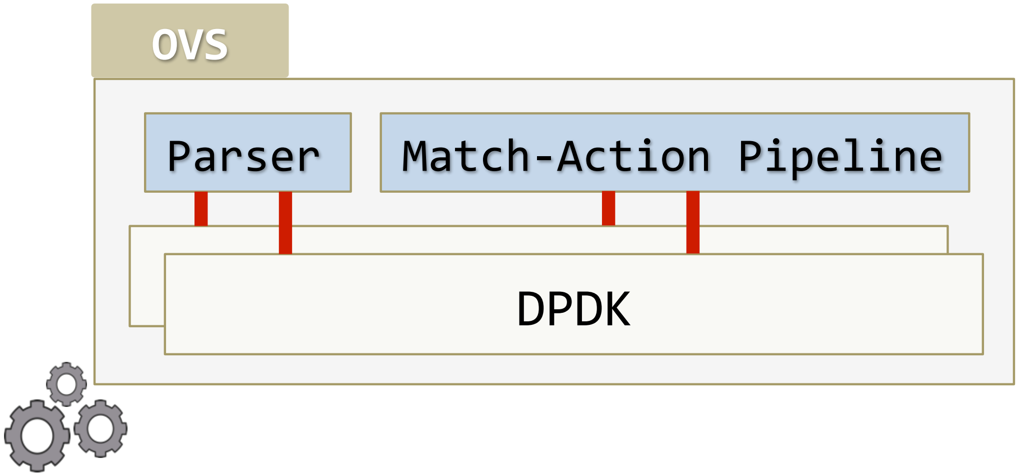

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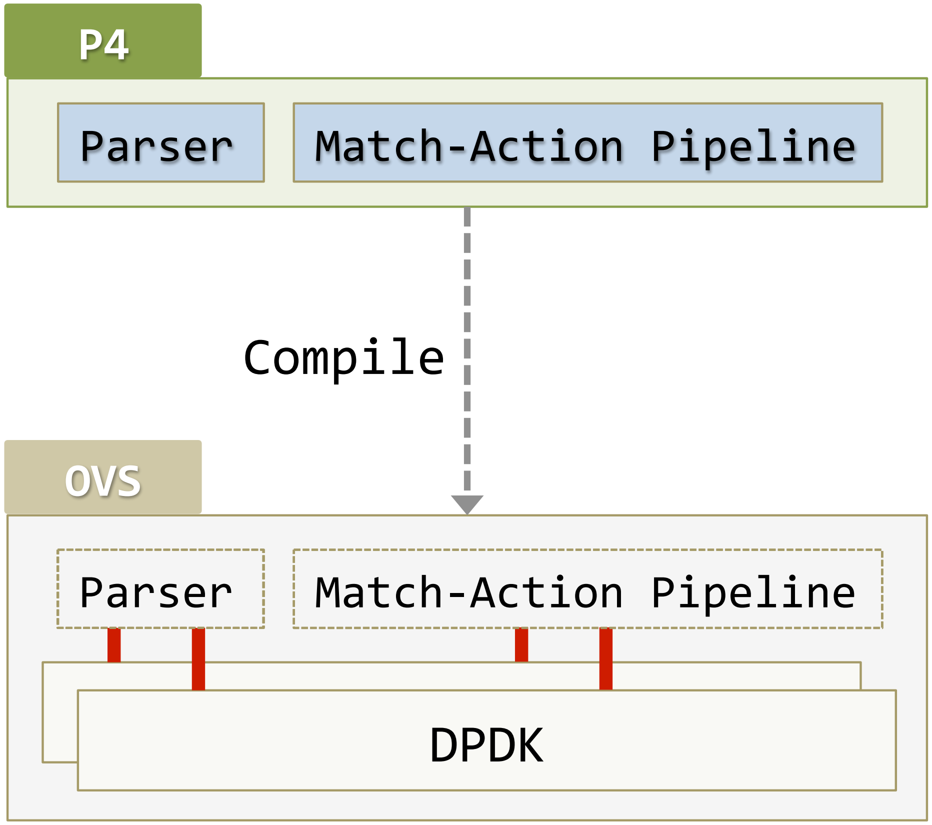
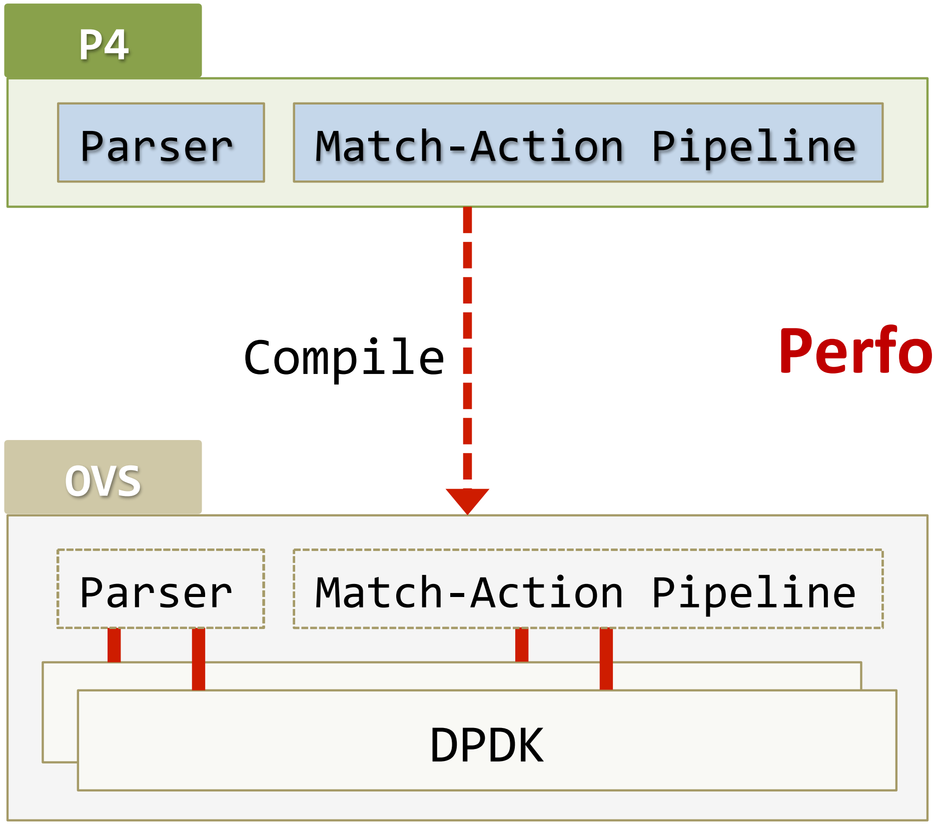


**341** lines of code

**Native OVS**

**14,535** lines of code

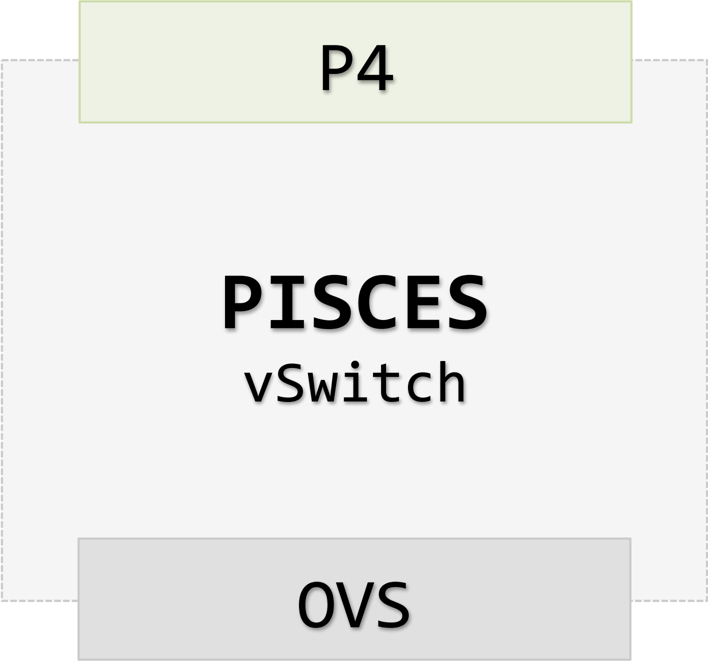
# Rapid Development & Deployment?



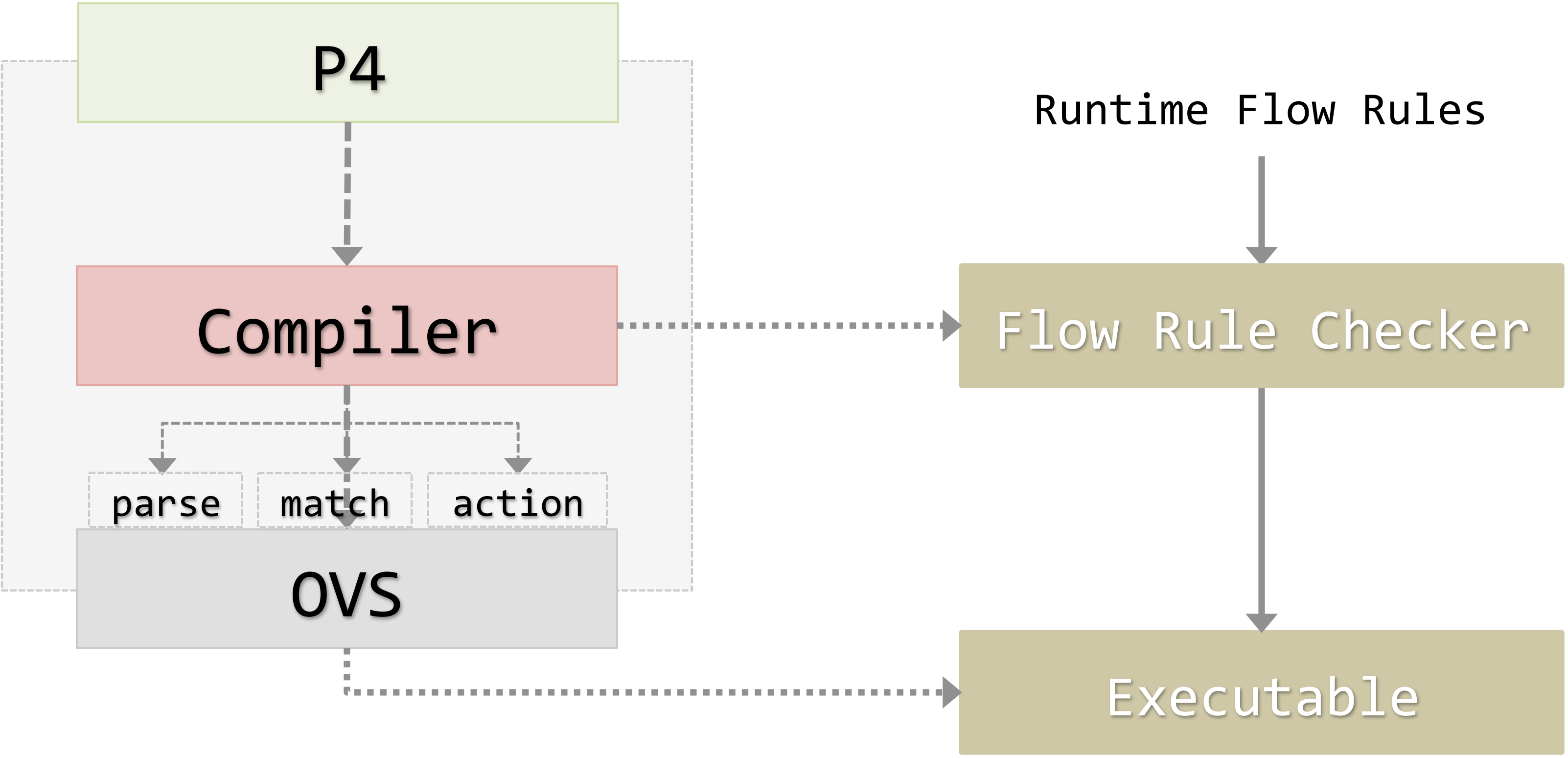
**Performance overhead!**

# What’s the cost of programmability on Performance?

# PISCES: A Protocol-Independent Software Switch



# PISCES: A Protocol-Independent Software Switch



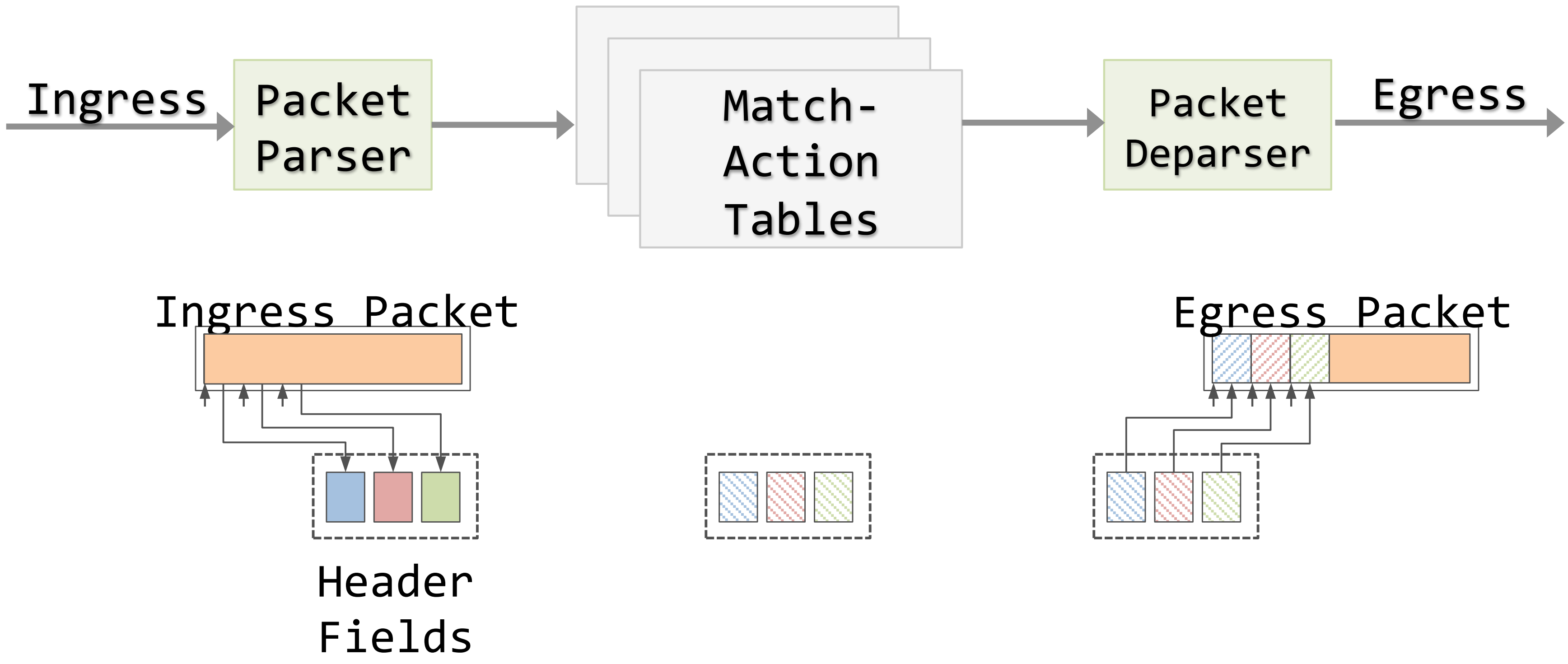
# PISCES: A Protocol-Independent Software Switch

- P4 and OVS **packet forwarding models**.

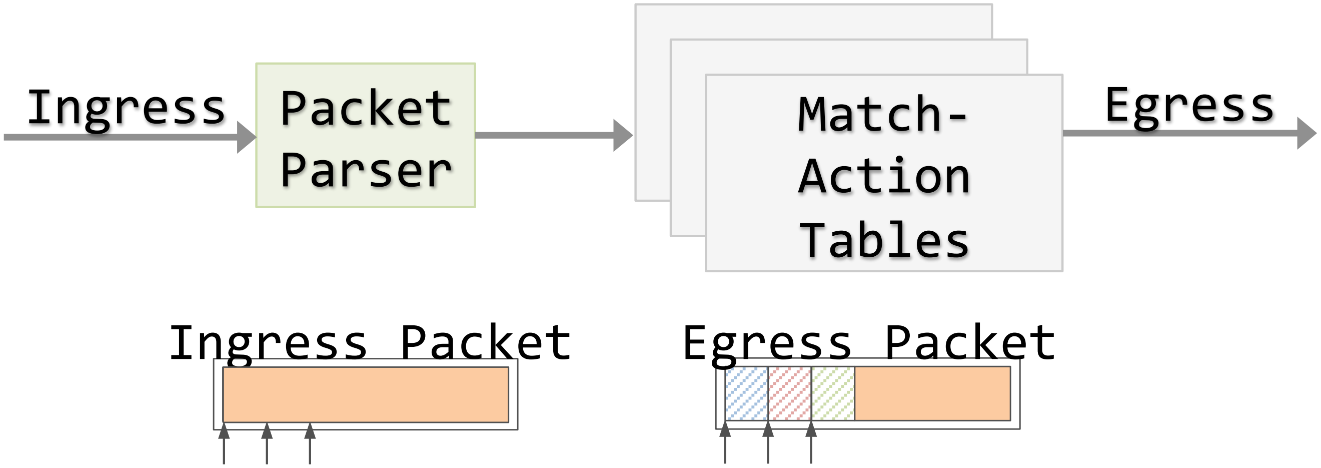
- **Performance overhead** of a **naïve mapping** from P4 to OVS.

- PISCES **compiler optimizations** to reduce the performance overhead.

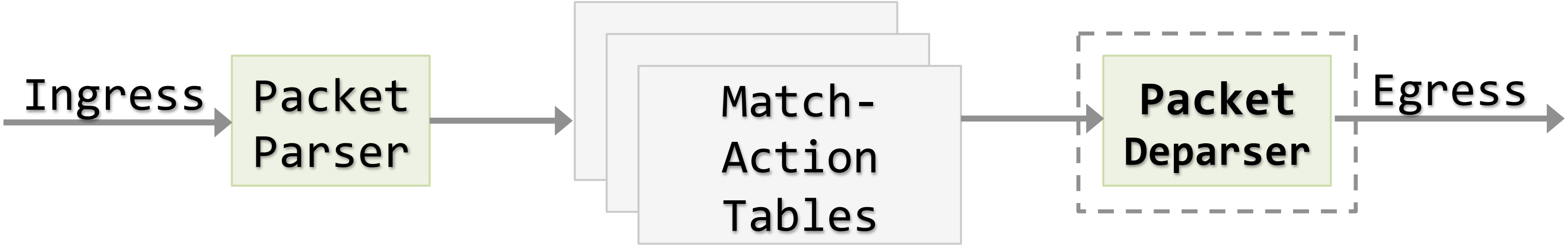
# P4 Forwarding Model (or Post-Pipeline Editing)



# OVS Forwarding Model (or Inline Editing)



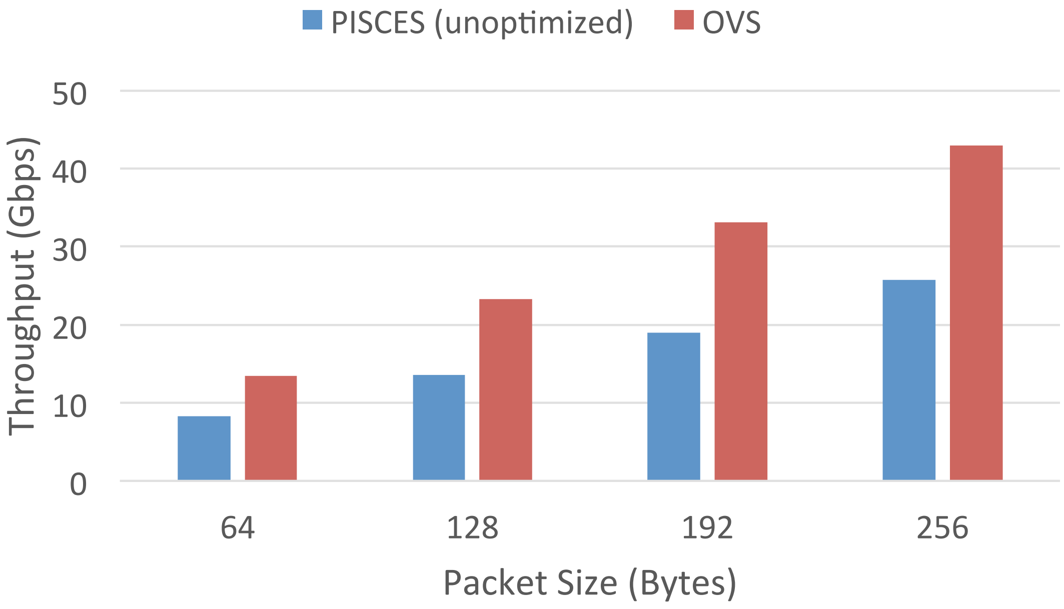
# (Modified) OVS Forwarding Model



- Supports both editing modes:
  - **Inline Editing**
  - **Post-pipeline Editing**

# Naïve Mapping from P4 to OVS

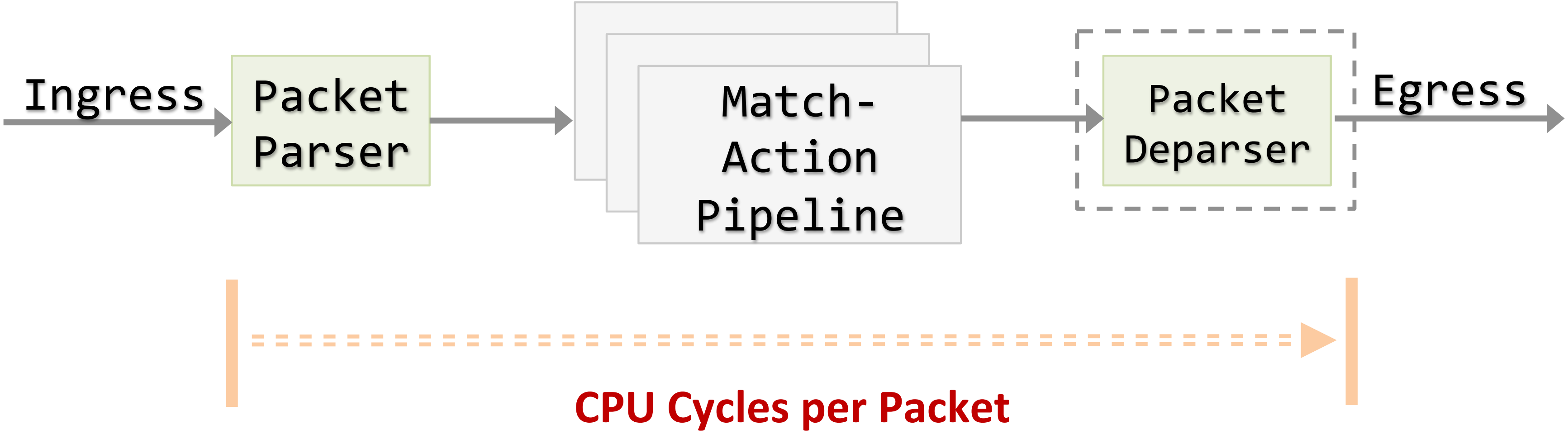
A naïve compilation of **L2L3-ACL** benchmark application



Performance overhead of

~ **40%**

# Causes of Performance Degradation



# Causes of Performance Degradation

- Factors affecting CPU cycles:
  - **Extra copy of headers** in the post-pipeline editing mode
  - **Fully-specified checksum** calculation
  - **Redundant parsing** of header fields and more …

# Causes of Performance Degradation

## Factor #1: **Extra copy of headers**

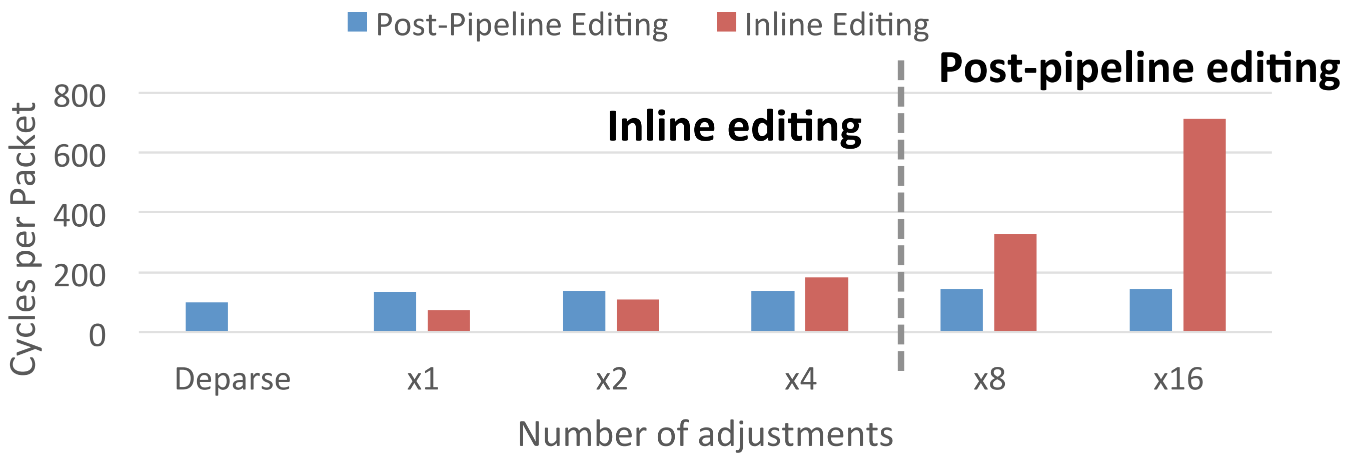
| Editing Mode | Pros | Cons |
|---|---|---|
| Post-Pipeline | | **Extra copy of headers** |
| Inline | **No extra copy of headers** | |

- **Post-pipeline** editing consumes **2x** more cycles than **inline** editing when **parsing VXLAN protocol**.

# Causes of Performance Degradation

## Factor #1: **Extra copy of headers**

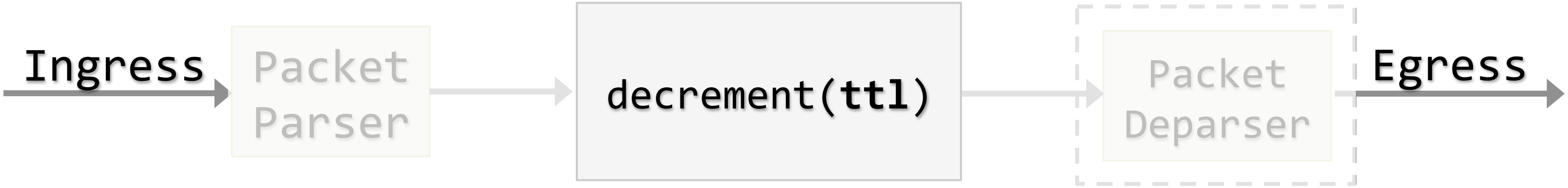
| Editing Mode | Pros | Cons |
|---|---|---|
| Post-Pipeline | **Packets are adjusted once** | Extra copy of headers |
| Inline | No extra copy of headers | **Multiple adjustments to packet** |



# Causes of Performance Degradation

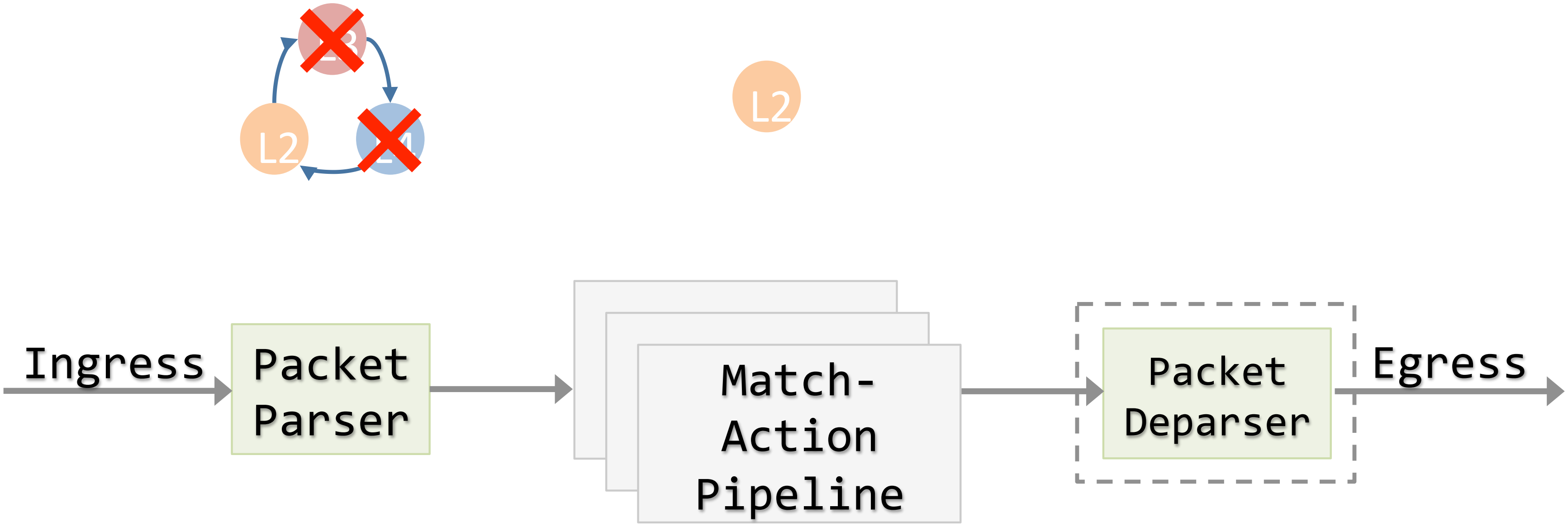
Factor #2: **Fully-Specified Checksums**

**Incremental-Checksum** (ttl)



# Causes of Performance Degradation

Factor #3: **Redundant parsing of headers**



Ingress

Packet Parser

Match-Action Pipeline

Packet Deparser

Egress

# Optimizing for CPU Cycles

| Optimizations |
|---|
| Inline vs. post-pipeline editing |
| Incremental checksum |
| Parser specialization |
| Action specialization |
| Action coalescing |

# Optimizing for CPU Cycles

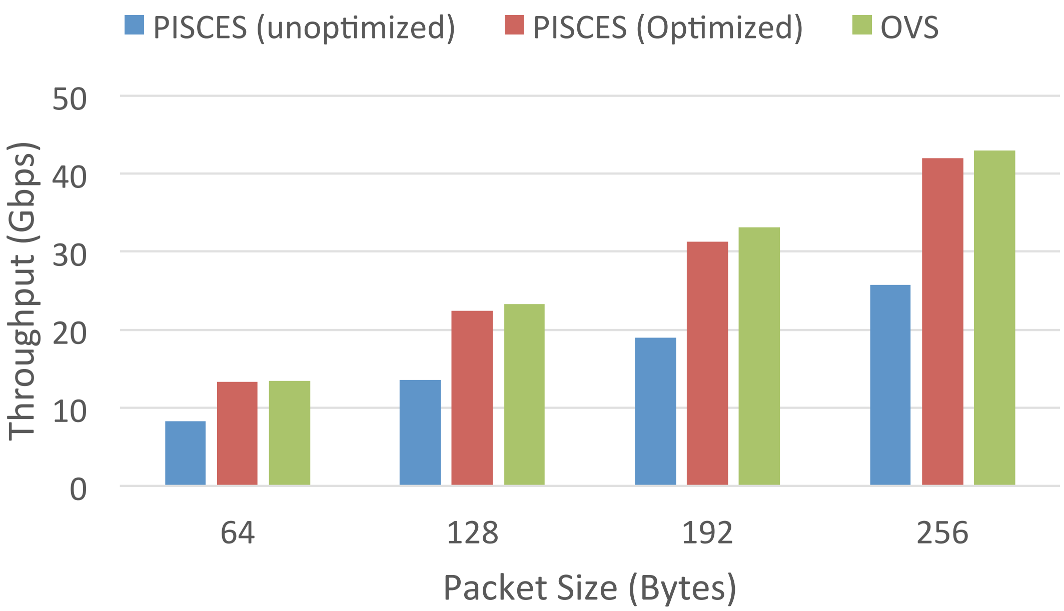
| Optimizations | |
|---|---|
| Inline vs. post-pipeline editing | Extra Copy of Headers |
| Incremental checksum | Fully-Specified Checksum |
| Parser specialization | Redundant Parsing |
| Action specialization | |
| Action coalescing | |

# Optimizing for CPU Cycles

| Optimizations |
|---|
| Inline vs. post-pipeline editing |
| Incremental checksum |
| Parser specialization |
| Action specialization |
| Action coalescing |

# Optimized Mapping from P4 to OVS

**All optimizations** together



Performance overhead of

**< 2%**

# Next Steps

- Support for **stateful memories** and **INT**
- **Integration** with the **mainline OVS**

# Summary

- SDN brought huge changes to how networks operate
- There is still a missing gap between the current state of SDN and a fully programmable network
- P4 is a new tool fill in the missing gap
- **PISCES** is **first** to show that programmability using P4 comes at a very small overhead while bringing huge benefits

# Questions?