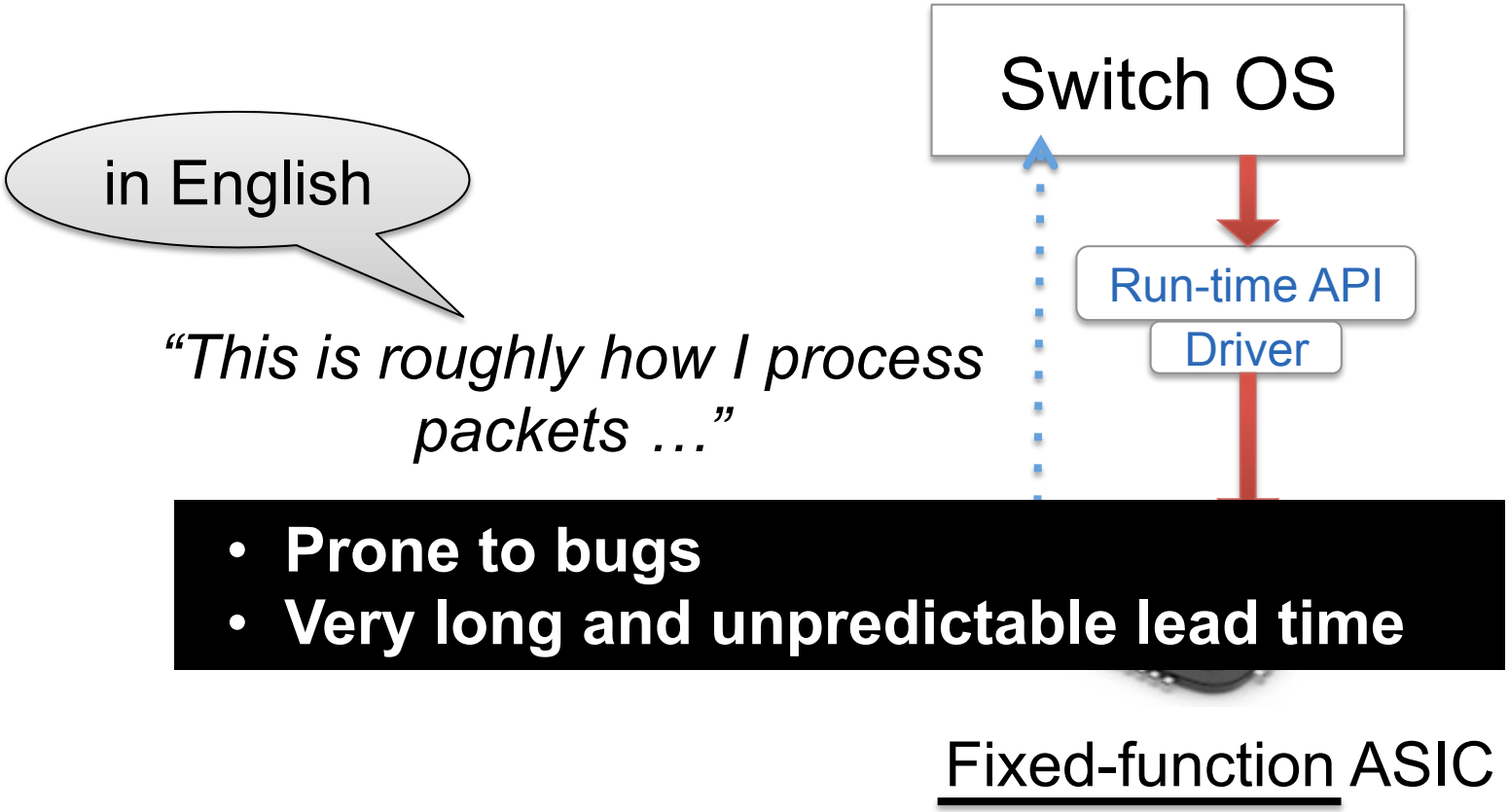
Programming
The Network Data Plane In P4

Changhoon Kim

chang@barefootnetworks.com

Status quo


Switch OS
in English
Run-time API
Driver
"This is roughly how I process packets …"
• Prone to bugs
• Very long and unpredictable lead time
Fixed-function ASIC

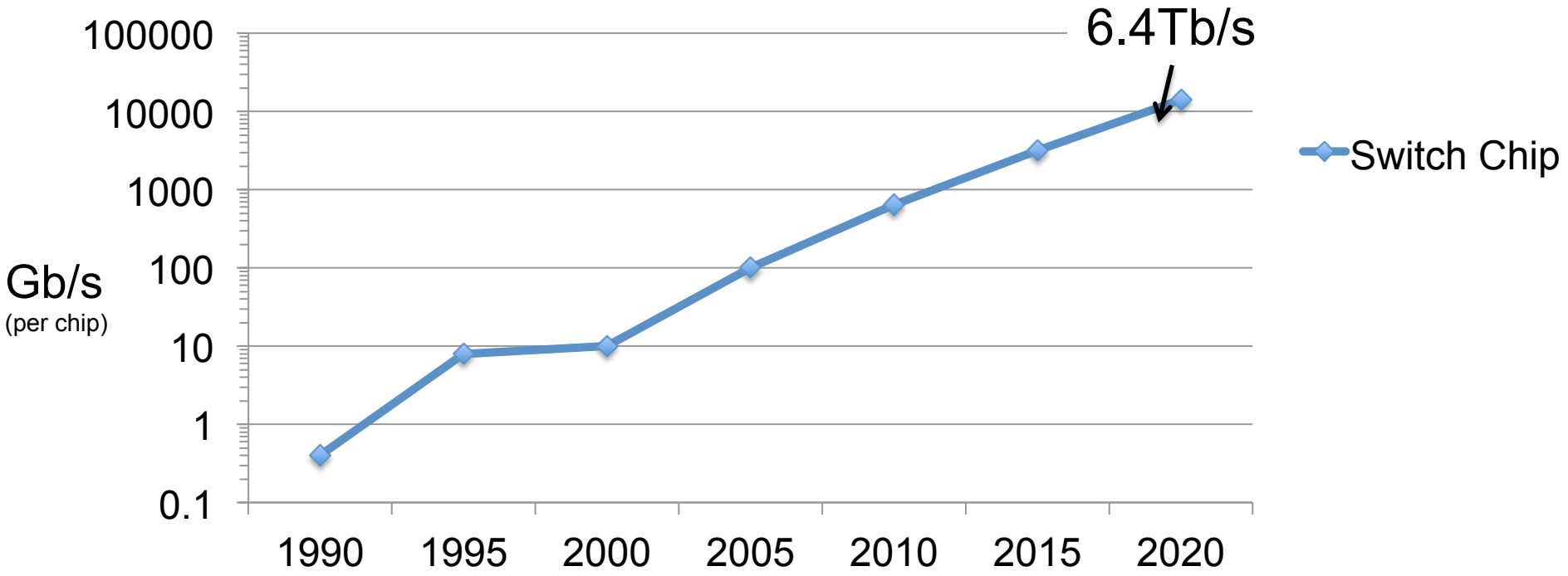
Extremely limited way of turning “beautiful ideas” into reality

- No DIY – must work with vendors at *feature* level
- Excruciatingly complicated and involved process to build consensus and pressure for *features*
- Painfully long and unpredictable lead time
- To use new features, you must get new switches
- What you finally get != what you asked for

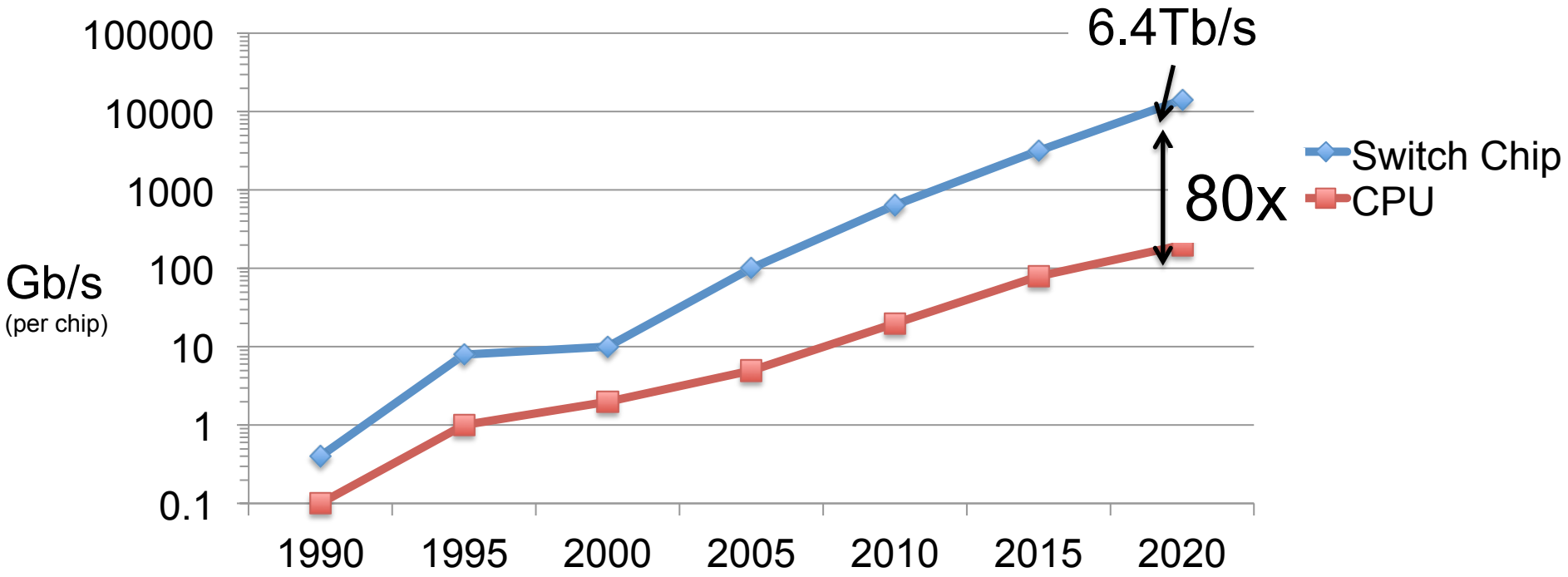
Programmable network devices come to rescue

- CPUs: 10s of Gb/s
- FPGAs, NPUs: 100s of Gb/s
- **Protocol-Independent Switch Architecture (PISA) chips: a few Tb/s**
  - Initial architecture introduced in RMT [SIGCOMM'13]
  - Packet processing machine with fully programmable parser and generic match-action logic
  - No penalty in size, cost, and power compared to fixed-function ASICs
  - PISA products available now -- in next few years this kind of silicon will dominate

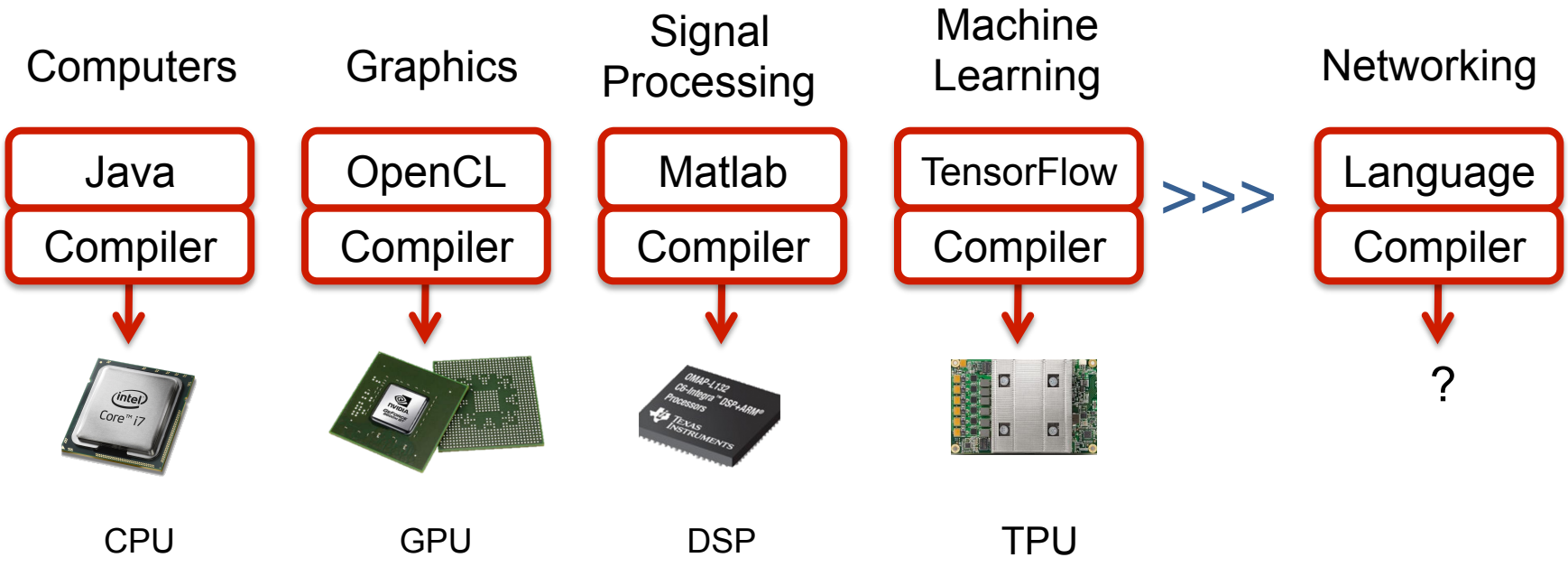
Packet forwarding speeds



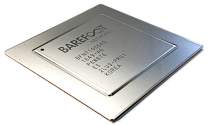
Packet forwarding speeds



Domain-specific processors



Domain-specific processors

Computers	Graphics	Signal Processing	Machine Learning		Networking
Java	OpenCL	Matlab	TensorFlow	>>>	P4 Program
Compiler	Compiler	Compiler	Compiler		Compiler
					 …
CPU	GPU	DSP	TPU		PISA

ACM Sigcomm Computer Communications Review July 2014

P4: Programming Protocol-Independent Packet Processors

Pat Bosshart†, Dan Daly*, Glen Gibb†, Martin Izzard†, Nick McKeown‡, Jennifer Rexford**, Cole Schlesinger**, Dan Talayco†, Amin Vahdat¶, George Varghese§, David Walker**
†Barefoot Networks *Intel ‡Stanford University **Princeton University ¶Google §Microsoft Research

ABSTRACT

P4 is a high-level language for programming protocol-independent packet processors. P4 works in conjunction with SDN control protocols like OpenFlow. In its current form, OpenFlow explicitly specifies protocol headers on which it operates. This set has grown from 12 to 41 fields in a few years, increasing the complexity of the specification while still not providing the flexibility to add new headers. In this paper we propose P4 as a strawman proposal for how OpenFlow should evolve in the future. We have three goals: (1) Reconfigurability in the field: Programmers should be able to change the way switches process packets once they are deployed. (2) Protocol independence: Switches should not be tied to any specific network protocols. (3) Target independence: Programmers should be able to describe packet-processing functionality independently of the specifics of the underlying hardware. As an example, we describe how to use P4 to configure a switch to add a new hierarchical label.

1. INTRODUCTION

Software-Defined Networking (SDN) gives operators programmatic control over their networks. In SDN, the control plane is physically separate from the forwarding plane, and one control plane controls multiple forwarding devices. While forwarding devices could be programmed in many ways, having a common, open, vendor-agnostic interface (like OpenFlow) enables a control plane to control forwarding devices from different hardware and software vendors.

Version	Date	Header Fields
OF 1.0	Dec 2009	12 fields (Ethernet, TCP/IPv4)
OF 1.1	Feb 2011	15 fields (MPLS, inter-table metadata)
OF 1.2	Dec 2011	36 fields (ARP, ICMP, IPv6, etc.)
OF 1.3	Jun 2012	40 fields
OF 1.4	Oct 2013	41 fields

Table 1: Fields r

multiple stages of rule tables, to allow switches to expose more of their capabilities to the controller.

The proliferation of new header fields shows no signs of stopping. For example, data-center network operators increasingly want to apply new forms of packet encapsulation (e.g., NVGRE, VXLAN, and STT), for which they resort to deploying software switches that are easier to extend with new functionality. Rather than repeatedly extending the OpenFlow specification, we argue that future switches should support flexible mechanisms for parsing packets and matching header fields, allowing controller applications to leverage these capabilities through a common, open interface (i.e., a new "OpenFlow 2.0" API). Such a general, extensible approach would be simpler, more elegant, and more future-proof than today's OpenFlow 1.x standard.

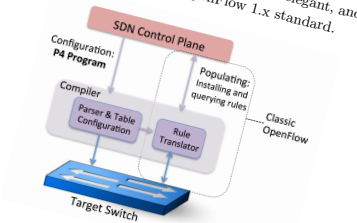
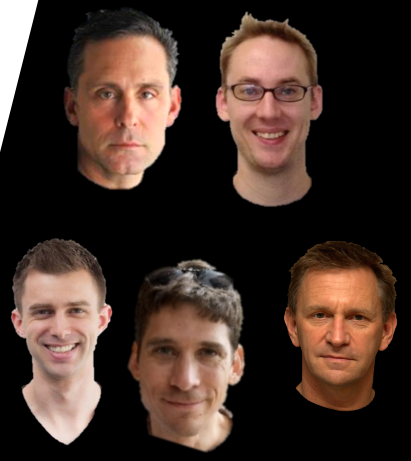


Figure 1: P4 is a language to c

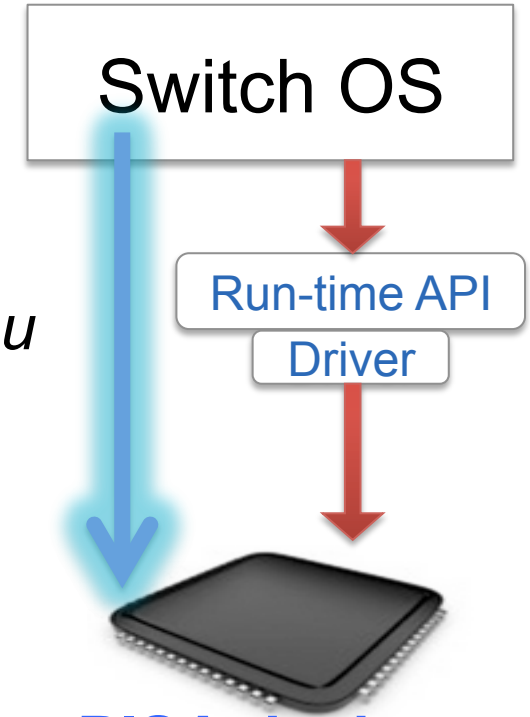
Recent chip



Turning the tables “upside down”

in P4

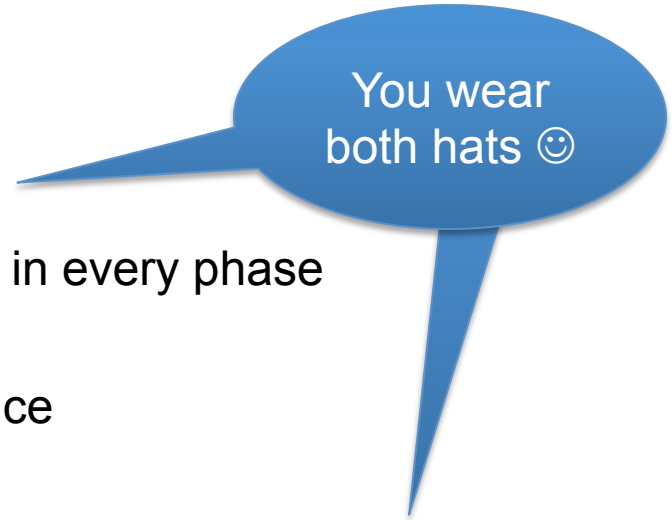
“*This is precisely how you must process packets*”



PISA device

(Protocol-Independent Switch Architecture)

What does this mean?



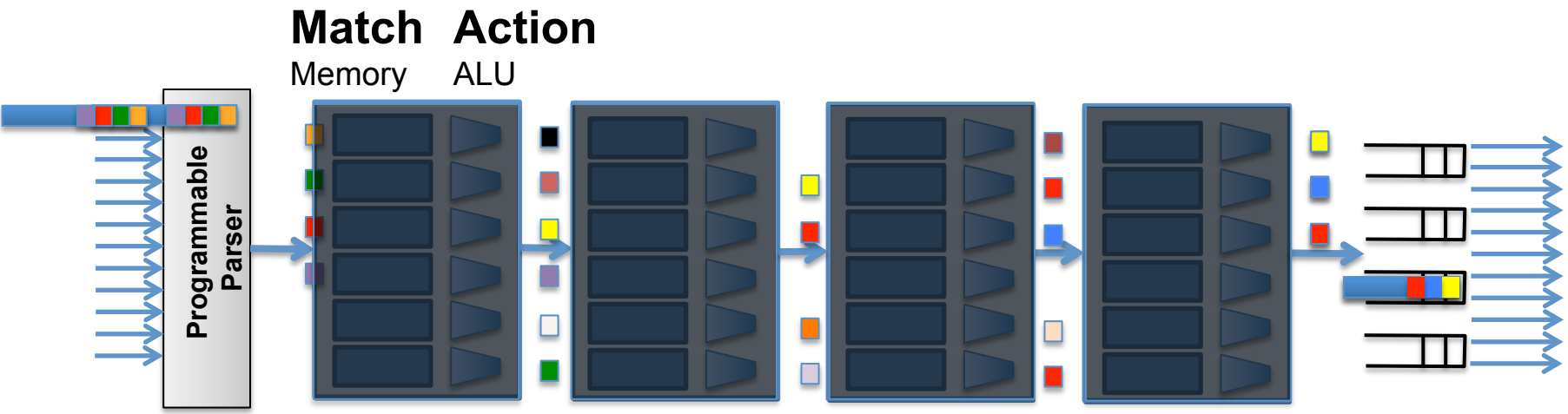
- **To network device vendors**
  - S/W programming practices and tools used in every phase
  - Extremely fast iteration and feature release
  - Differentiation in capabilities and performance
  - Can fix even data-plane bugs in the field
- **To large on-line service providers and carriers**
  - No more “black boxes” in the “white boxes”
  - Your devs can program, test, and debug your network devices all the way down
  - You keep your own ideas

The rest of the talk:

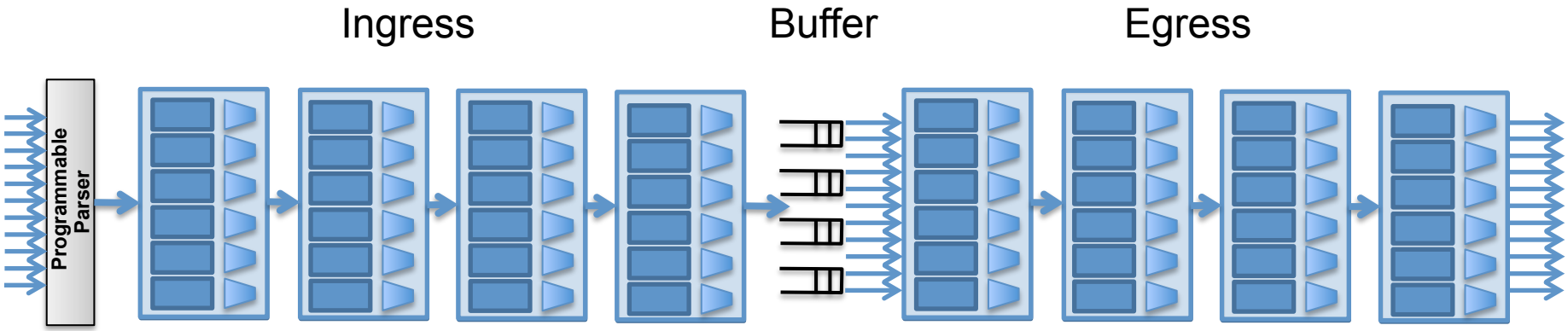
- *How PISA works*
- *Why we call it protocol-independent forwarding*
- *What kind of cool things you can do with PISA and P4*
- *Demo!*

PISA: An architecture for high-speed programmable packet forwarding

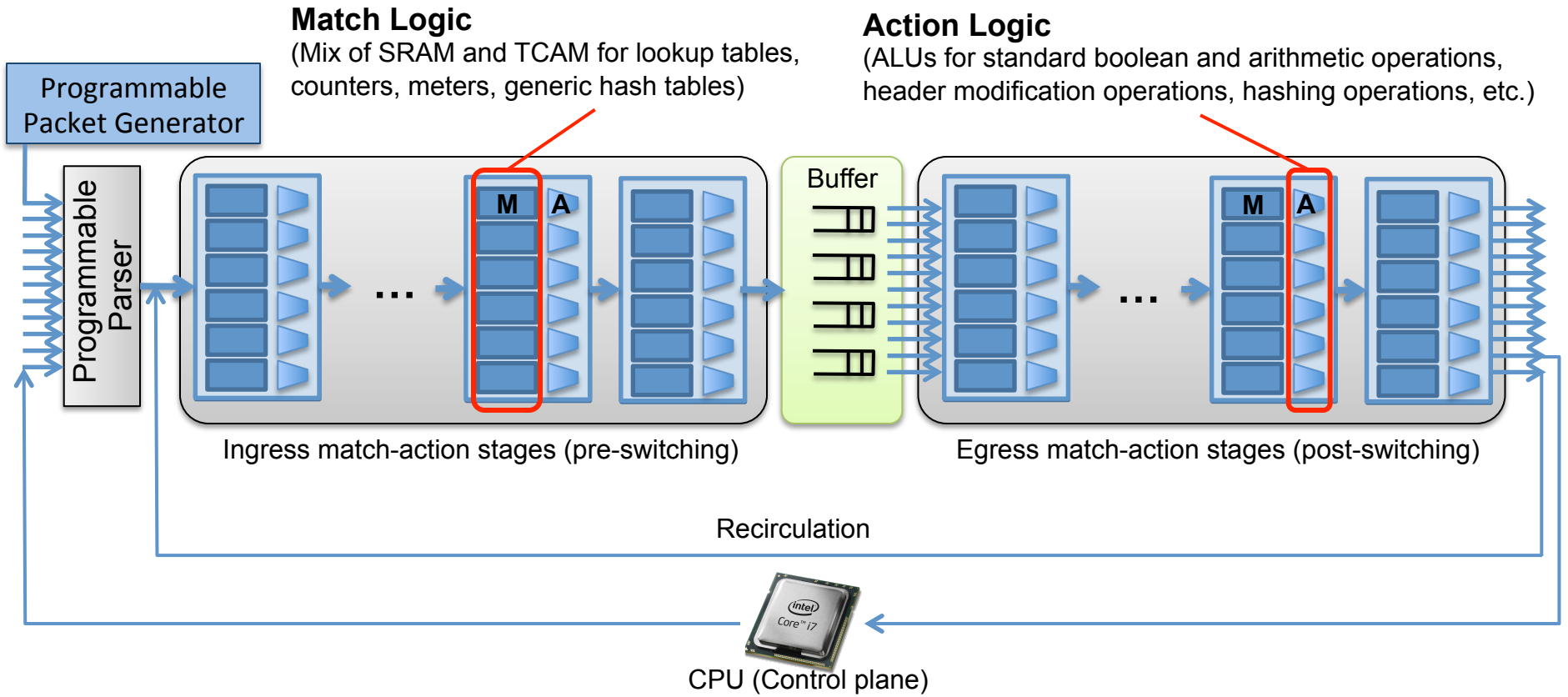
PISA: Protocol Independent Switch Architecture



PISA: Protocol Independent Switch Architecture

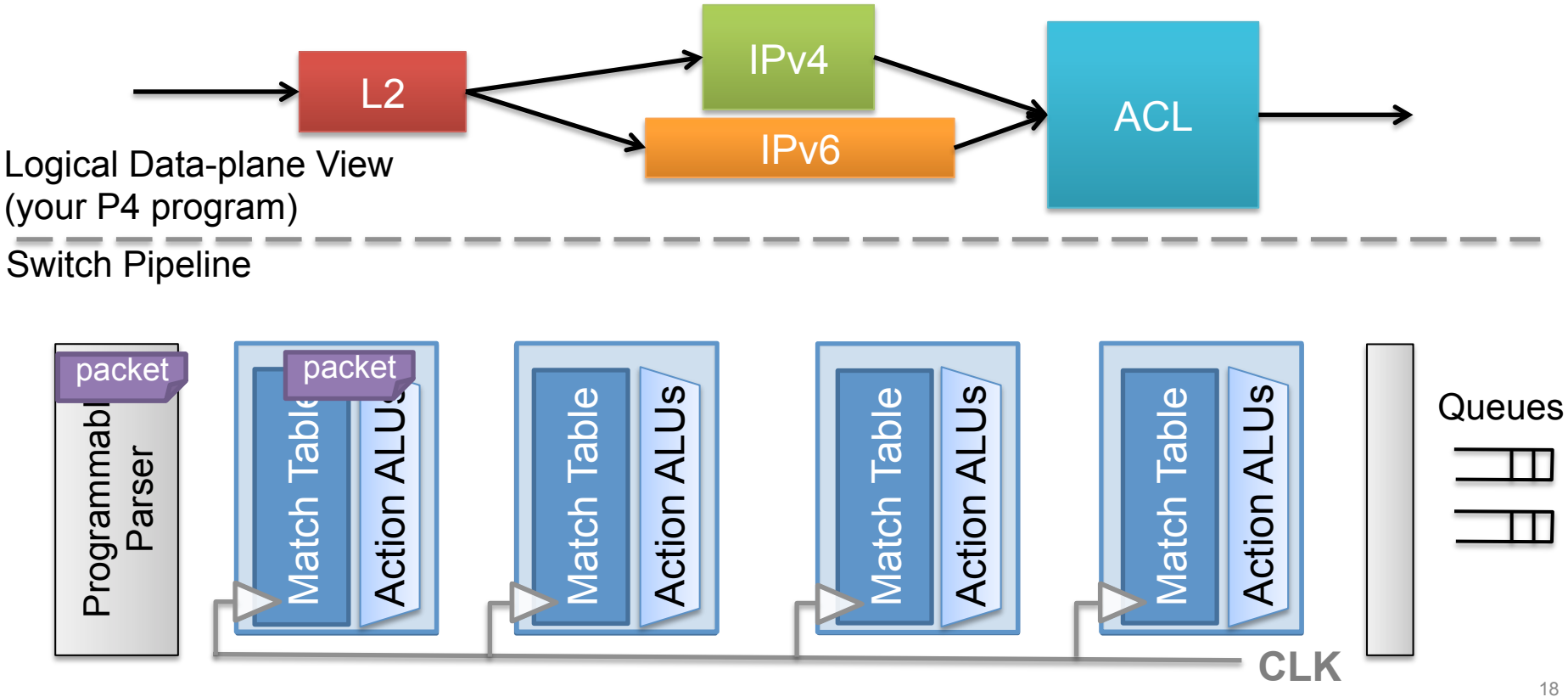


PISA: Protocol Independent Switch Architecture

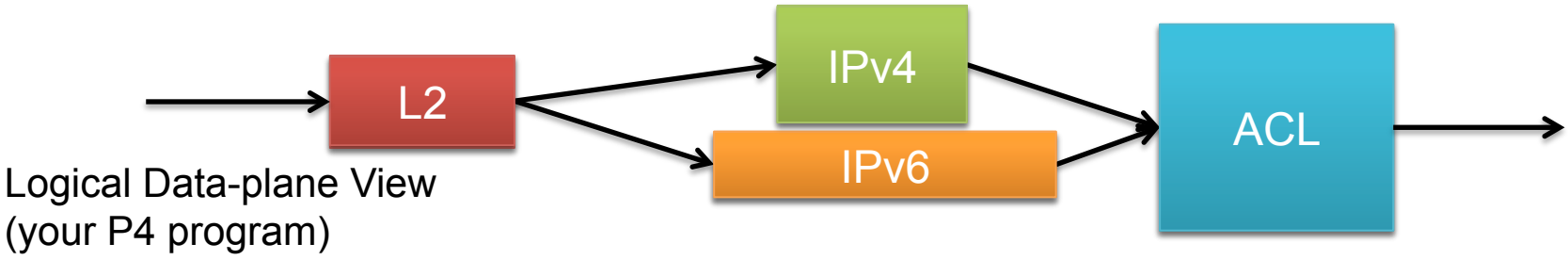


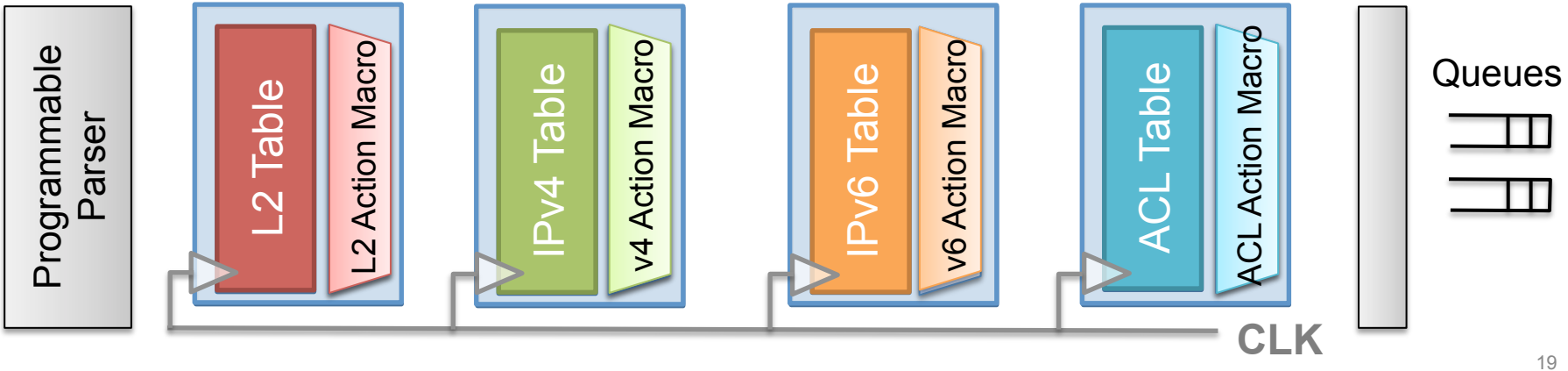
Why we call it protocol-independent packet processing

Device does not understand any protocols until it gets programmed

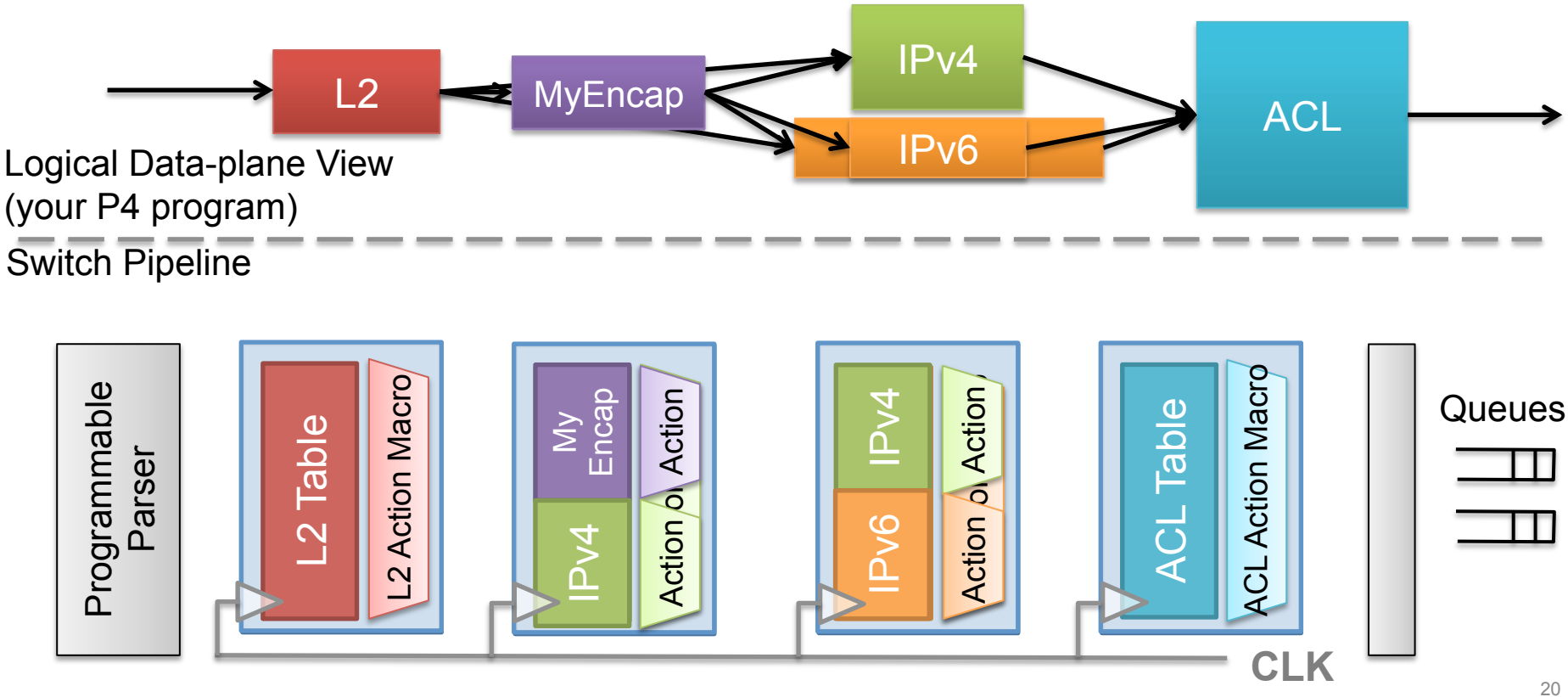


Mapping logical data-plane design to physical resources

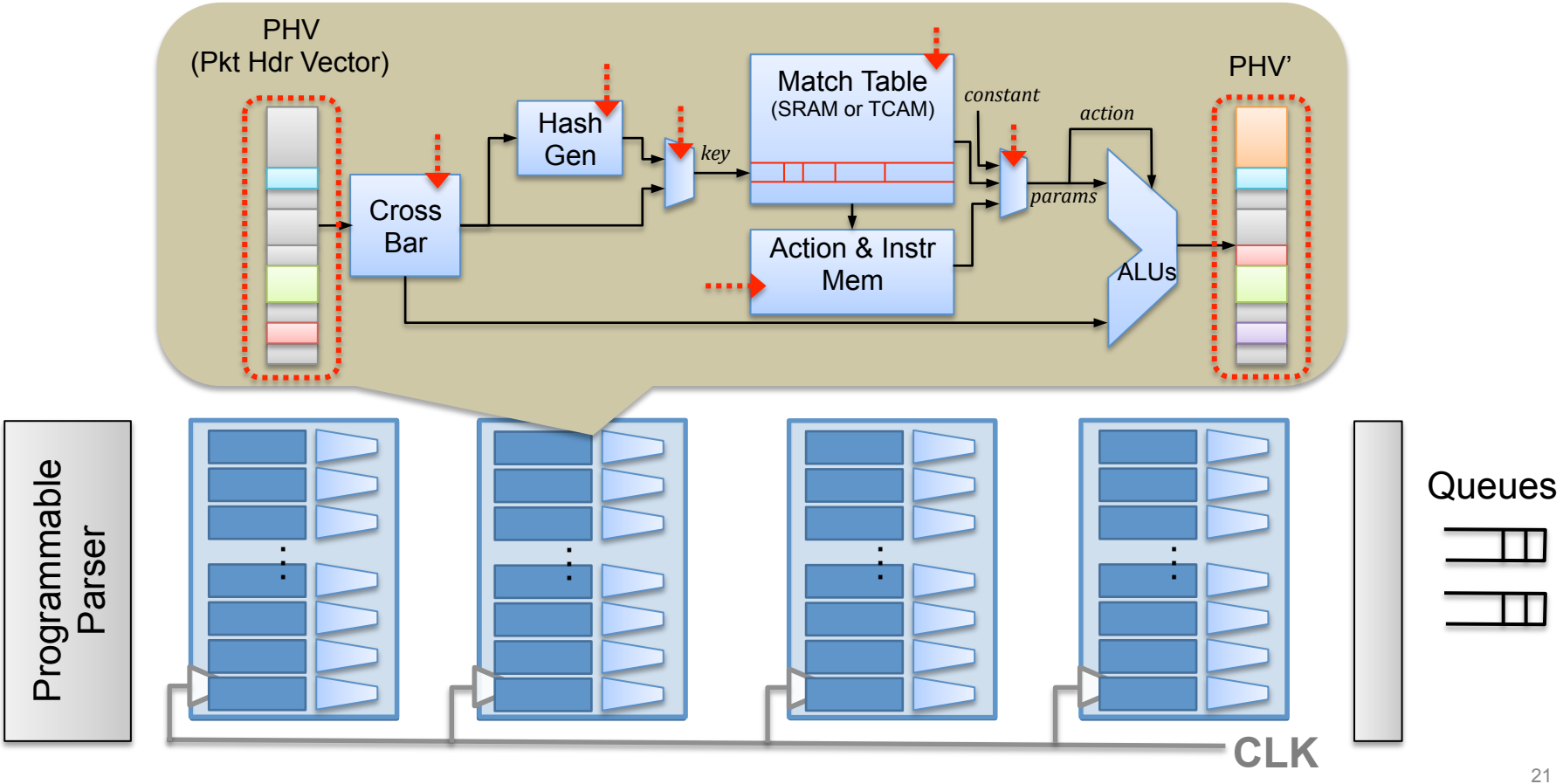




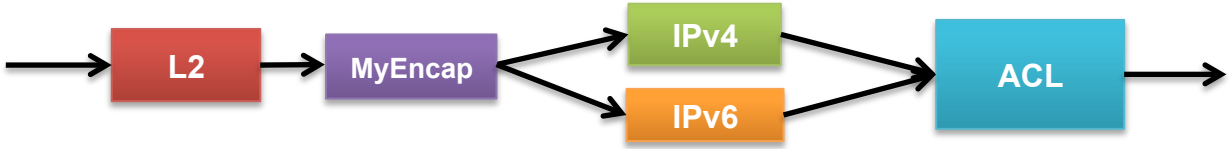
Re-program in the field

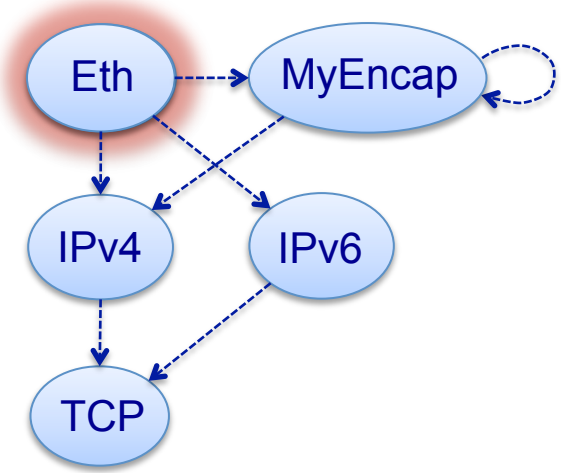


What exactly does the compiler do?



What does a P4 program look like?

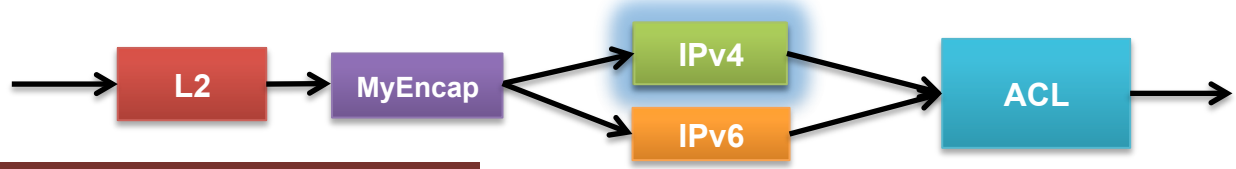





```
header_type ethernet_t {
      fields {
            dstAddr : 48;
            srcAddr : 48;
}
    parser parse_ethernet {
      extract(ethernet);
      return select(latest.etherType) {
        0x8100 : parse_vlan;
```

```
header_type my_encap_t {
      fields {
            foo : 12;
            bar : 8;
            baz : 4;
            qux : 4;
            next_protocol : 4;
    }
}
```

What does a P4 program look like?




```
table ipv4_lpm
{
      reads {
         ipv4.dstAddr
      }
      actions {
         set_next_hop;
      }
}
```

```
control ingress
{
      apply(l2);
      apply(my_encap);
      if (valid(ipv4) {
            apply(ipv4_lpm);
      } else {
            apply(ipv6_lpm);
      }
      apply(acl);
}
```

```
action set_next_hop(nhop_ip
{
      modify_field(metadata.nhop_ipv4_addr, nhop_ipv4_addr);
      modify_field(standard_metadata.egress_port, port);
      add_to_field(ipv4.ttl, -1);
}
```

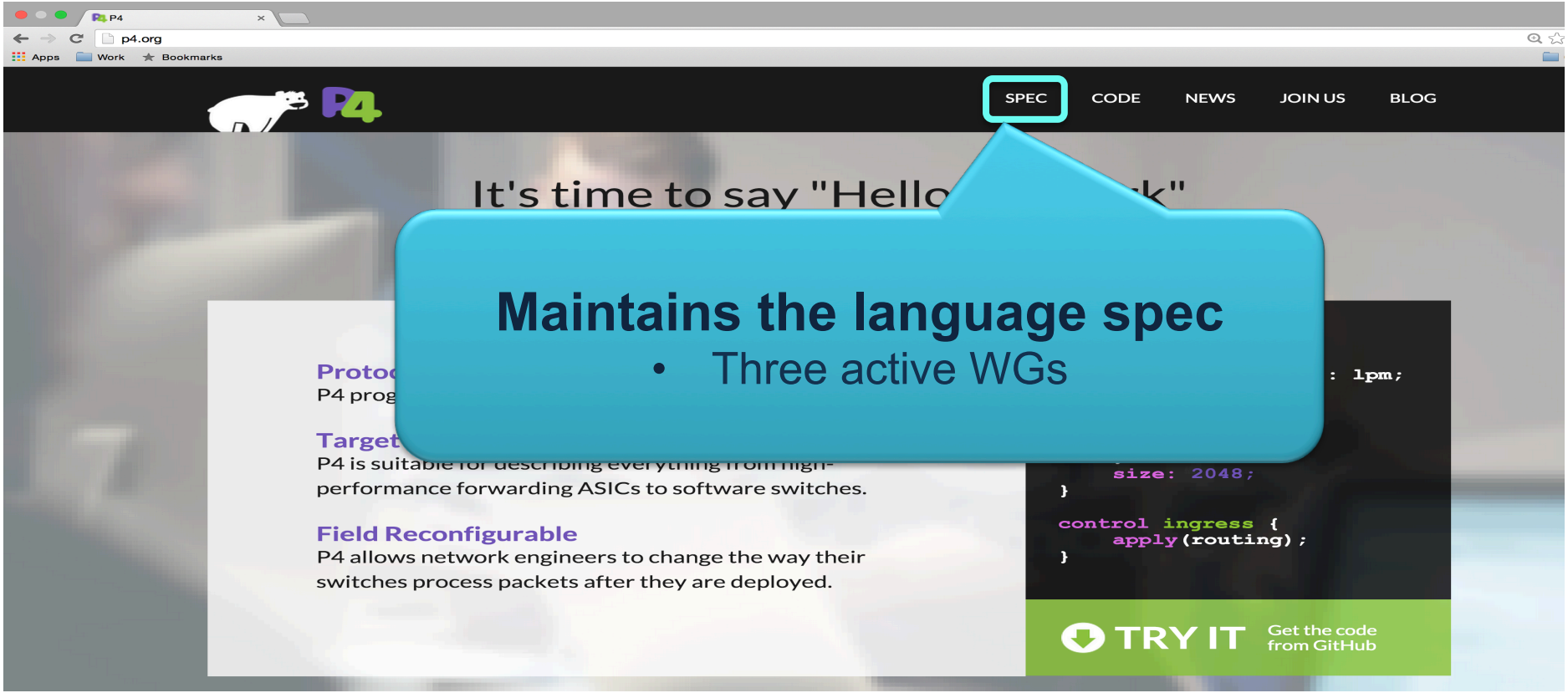
What does a P4 program look like?

```
/* Example: A typical IPv4 routing table */
table ipv4_lpm {
    reads {
        ingress_metadata.vrf    : exact;
        ipv4.dstAddr            : lpm;
    }
    actions {
        nop;
        l3_l2_switch;
        l3_multicast;
        l3_nexthop;
        l3_ecmp;
        l3_drop;
    }
    size : 65536;
}
```

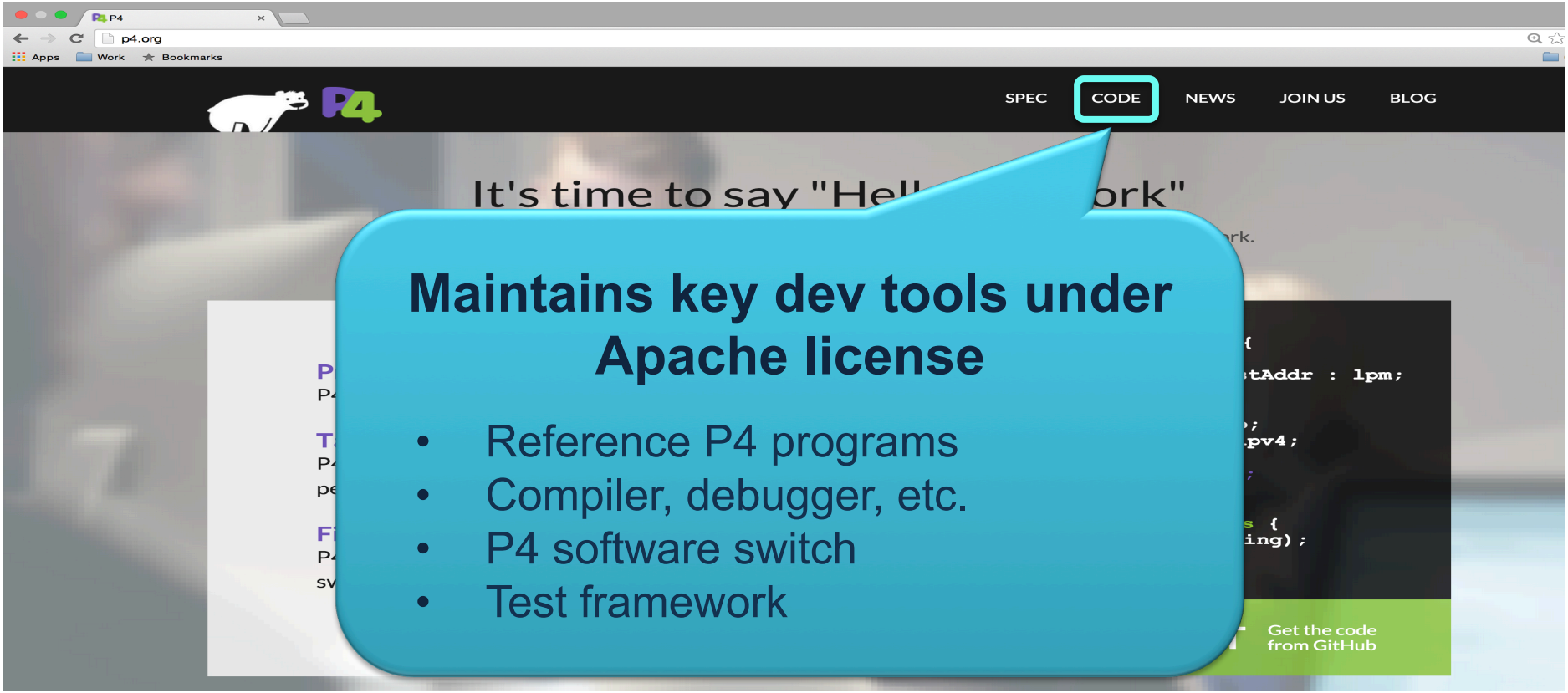
These are the only possible actions. Each particular entry in the table is associated with ONE of these

vrf	ipv4.dstAddr / prefix	action	data
1	192.168.1.0 / 24	l3_l2_switch	port_id=64
10	10.0.16.0 / 22	l3_ecmp	ecmp_index=12
1	192.168.0.0 / 16	l3_nexthop	nexthop_index=451
1	0.0.0.0 / 0	l3_nexthop	nexthop_index=1

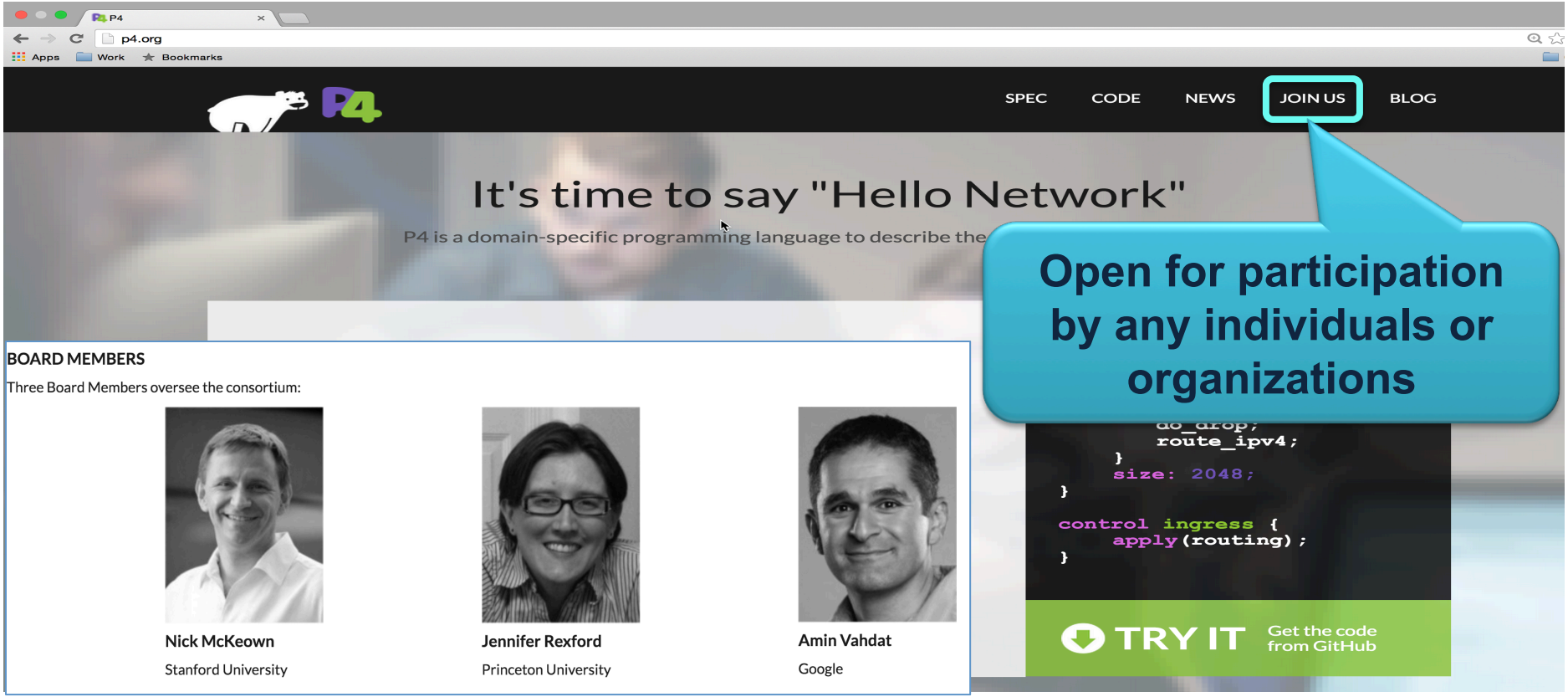
P4.org – P4 Language Consortium



P4.org – P4 Language Consortium



P4.org – P4 Language Consortium



P4.org Members

Original P4 Paper Authors:

BAREFOOT NETWORKS, Google, intel, Microsoft, PRINCETON UNIVERSITY, Stanford University

Operators/ End Users

Alibaba Group 阿里巴巴集团, Baidu 百度, FOX, Goldman Sachs, at&t, COMCAST, Google, kt, Microsoft, Tencent 腾讯, SK telecom

Systems

BROCADE, cisco, CORSA, DAHC Networks, DELL, Hewlett Packard Enterprise, HUAWEI, Inventec, JUNIPER NETWORKS, NETBERG, NoviFlow SDN made smarter

Targets

AEPONYX Moving the Cloud at the Speed of Light, Atomic Rules, BAREFOOT NETWORKS, CAVIUM, EZCHIP, intel, Mellanox TECHNOLOGIES, BROADCOM connecting everything, centec networks, freescale, MARVELL, MoSys, NETRONOME, PLUMgrid, vmware, XILINX

Solutions/ Services

EstiNet, happiest minds, HGLOBAL HITECH, SDNLAB 专注网络创新技术, FLOW RESEARCH

Academia/ Research

Bii 天地互连, Cornell University Founded A.D. 1865, National Chiao Tung University 國立交通大學, PRINCETON UNIVERSITY, salzburgresearch, uni.lu UNIVERSITÉ DU LUXEMBOURG, Università della Svizzera italiana, Eötvös Loránd University, POLITECNICO MILANO 1863, POLYTECHNIQUE MONTRÉAL, Stanford University, UFRGS UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL, VirginiaTech Invent the Future

P4 development environment

- **Open-source P4 development tools**
  - P4 compilers & dev tools, reference P4 programs, P4-programmable S/W switch, test framework, etc.
  - Apache 2.0 license
  - Available at http://github.com/p4lang
- **Several other programmable forwarding targets**
  - Both hardware and software devices (OVS, eBPF, VPP etc.)
  - Switches, NICs, etc.

What kind of cool things can you do by programming data planes?

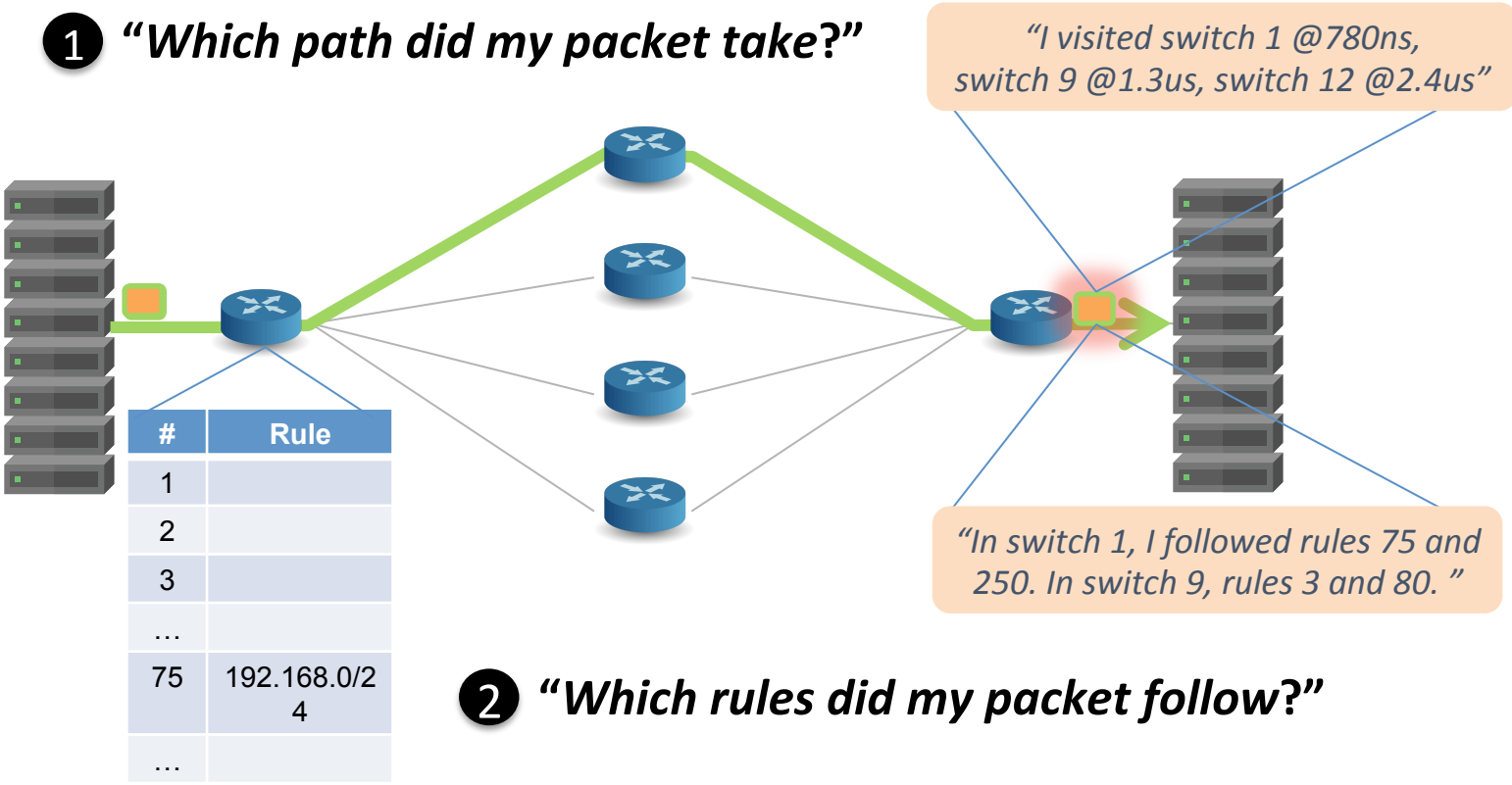
- **Advanced network monitoring, analysis, and diagnostics**
- **Custom traffic monitoring and filtering**
  - FlowRadar [NSDI'16]
- **Various modes of congestion control**
  - RCP, XCP, TeXCP, DCQCN++, Timely++
- **Dynamic source routing**
  - Flowlet switching, CONGA [SIGCOMM'15], HULA [SOSR'16]
- **Embedding middlebox functions into switches**
  - In-switch L4 connection load balancing, TCP SYN authentication, etc.
- **Offloading parts of the distributed apps**
  - SwitchPaxos [SOSR'15, ACM CCR'16] , SwitchKV [NSDI'16]
- **Jointly optimizing network and the apps running on it**
- **And many more** … -- we're just starting to scratch the surface!

Very natural questions

*"Is **every packet** delivered correctly and timely? If not, when and why? If yes, how well?"*

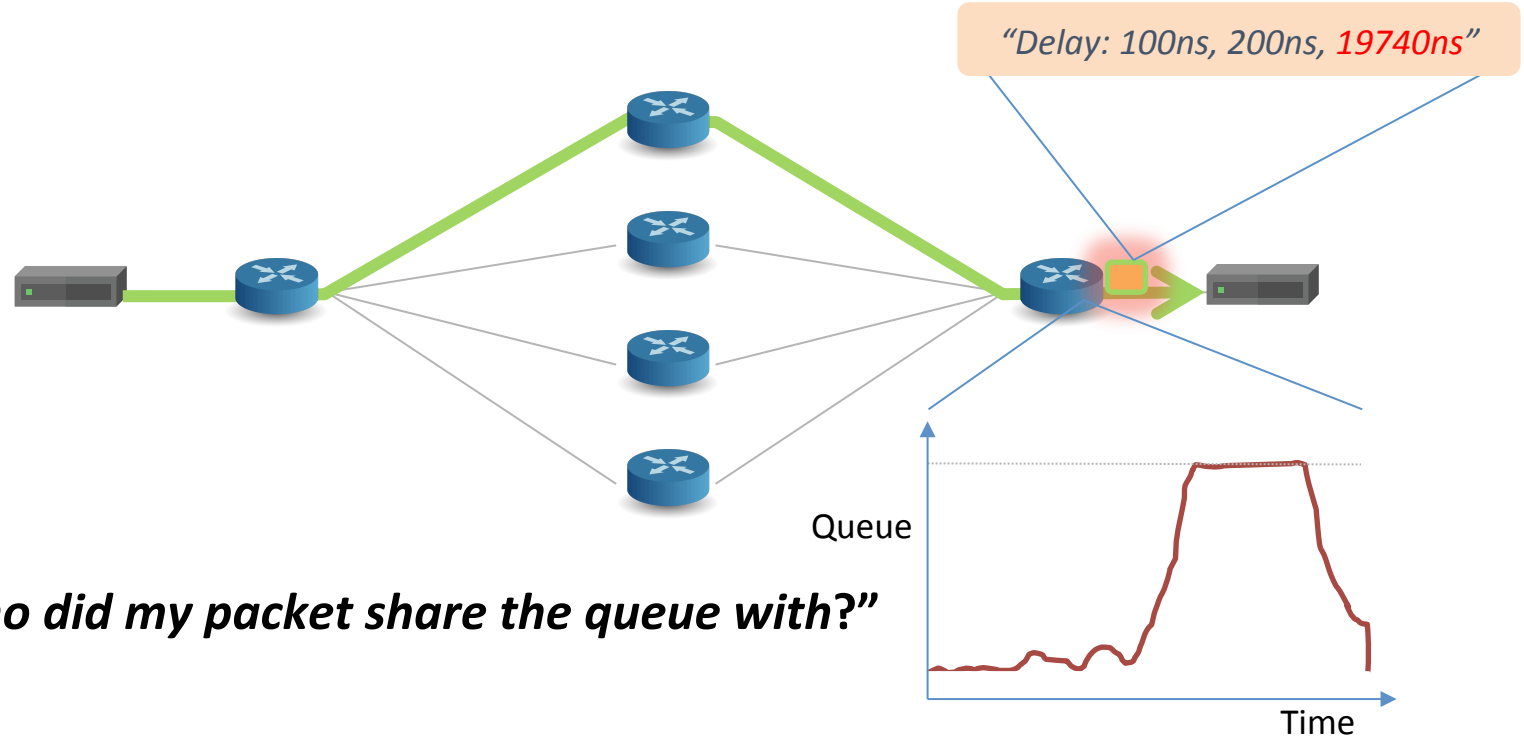
No switches today can answer these **basic** questions.

1 ***"Which path did my packet take?"***



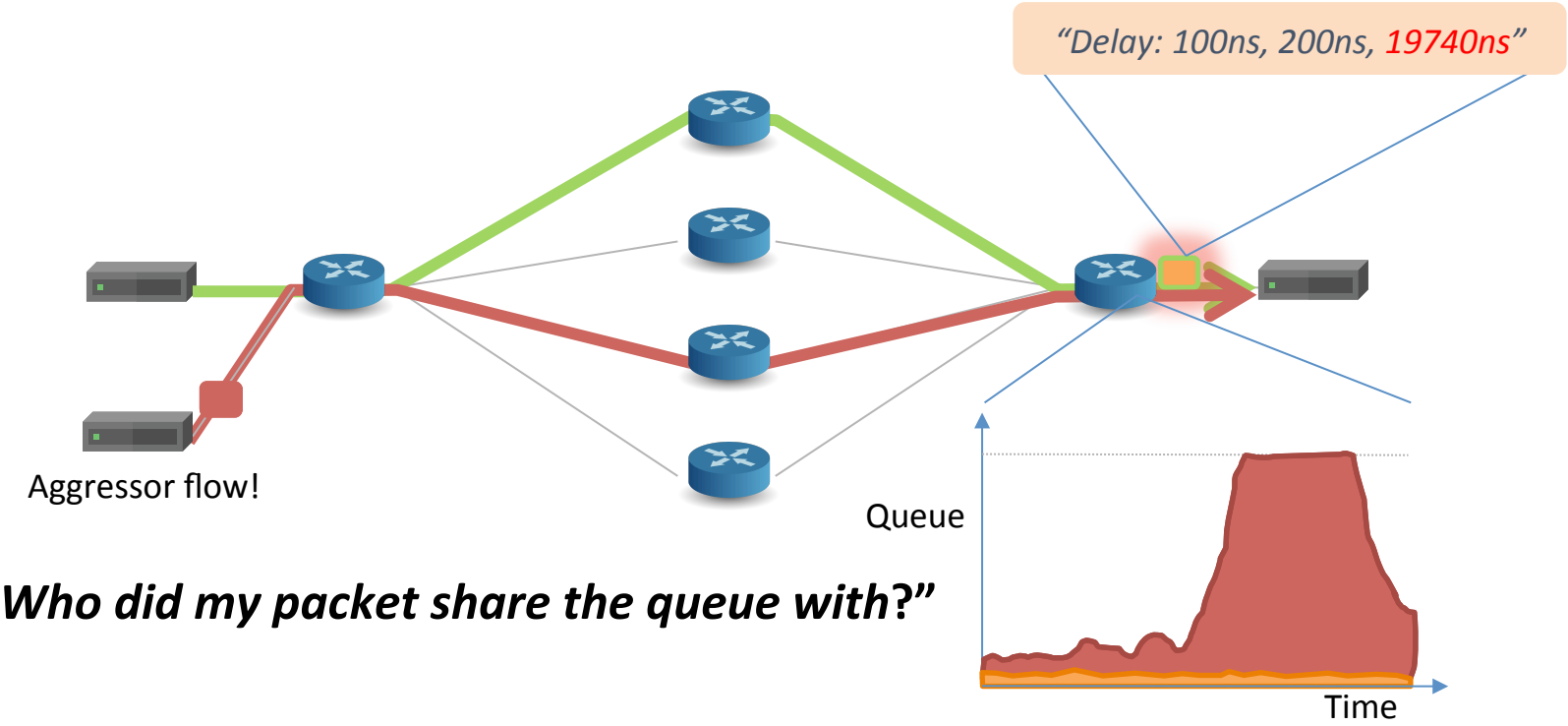
2 ***"Which rules did my packet follow?"***

❸ *"How long did my packet queue at each switch?"*



❹ *"Who did my packet share the queue with?"*

❸ *"How long did my packet queue at each switch?"*



❹ *"Who did my packet share the queue with?"*

The network should answer these questions

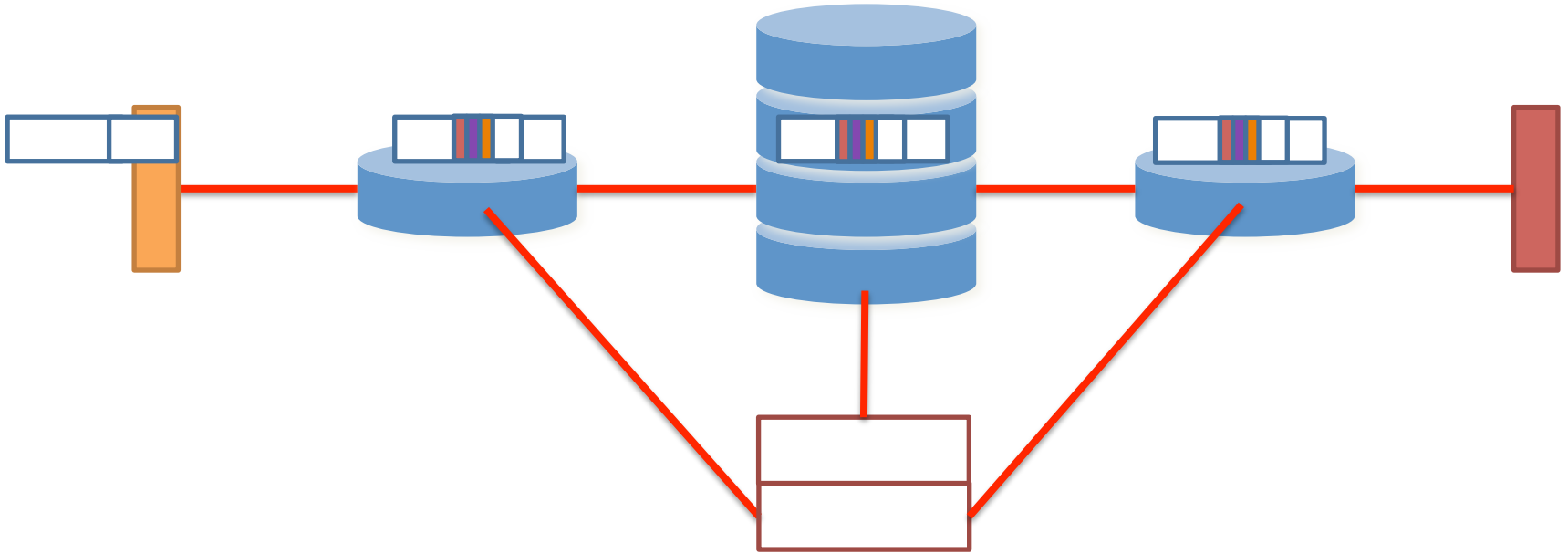
1. “*Which path did my packet take*?”
2. “*Which rules did my packet follow*?”
3. “*How long did it queue at each switch*?”
4. “*Who did it share the queues with*?”

With programmable data plane, we can now answer all these questions, at line rate, without any latency penalty!

Two approaches (each is a P4 program)

1. **Packet postcards**
   - Switch generates a small time-stamped digest for every packet
   - Sends to server(s) for logging and processing

Packet postcards



Two approaches (each is a P4 program)

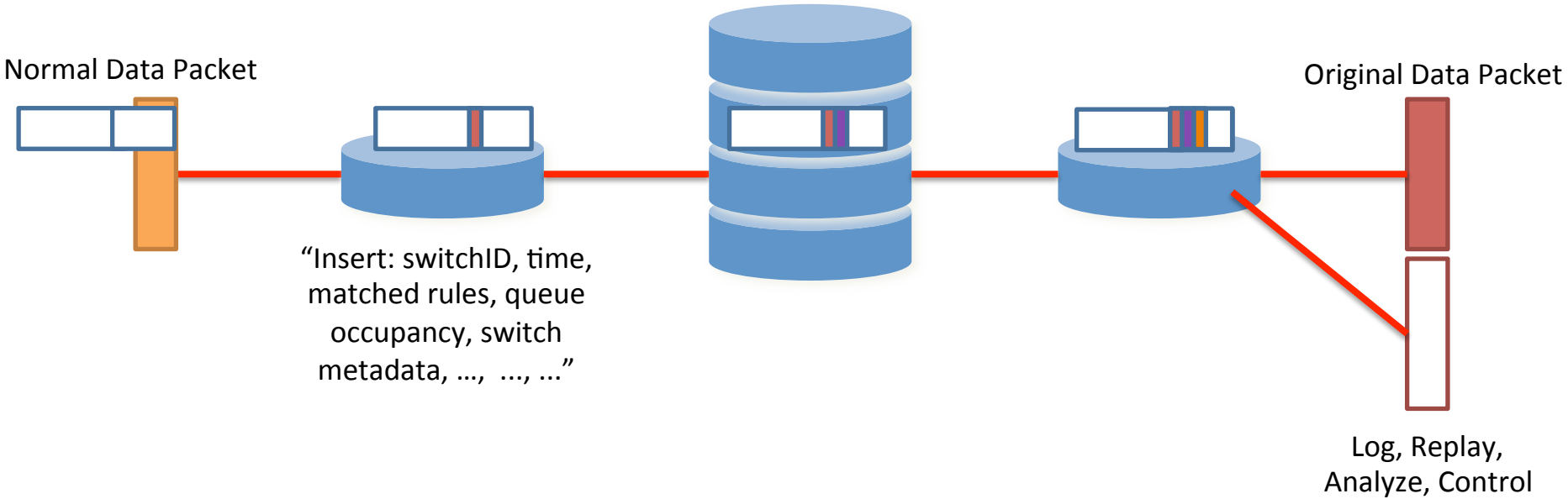
1. **Packet postcards**
   - Switch generates a small time-stamped digest for every packet
   - Sends to server(s) for logging and processing
   - **Pros**: Can replay network history. Packet sizes unchanged.
   - **Cons**: Lots of extra traffic.

Two approaches (each is a P4 program)

1. **Packet postcards**
   - Switch generates a small time-stamped digest for every packet
   - Sends to server(s) for logging and processing
   - **Pros**: Can replay network history. Packet sizes unchanged.
   - **Cons**: Lots of extra traffic.

2. **Inband Network telemetry (INT)**
   - Data packets carry instructions to insert state into packet header

In-band Network Telemetry (INT)



Two approaches (each is a P4 program)

1. **Packet postcards**
   - Switch generates a small time-stamped digest for every packet
   - Sends to server(s) for logging and processing
   - **Pros**: Can replay network history. Packet sizes unchanged.
   - **Cons**: Lots of extra traffic.

2. **Inband Network telemetry (INT)**
   - Data packets carry instructions to insert state into packet header
   - **Pros**: No additional packets. Can replay network history.
   - **Cons**: Packet size increases.

In-band Network Telemetry in P4

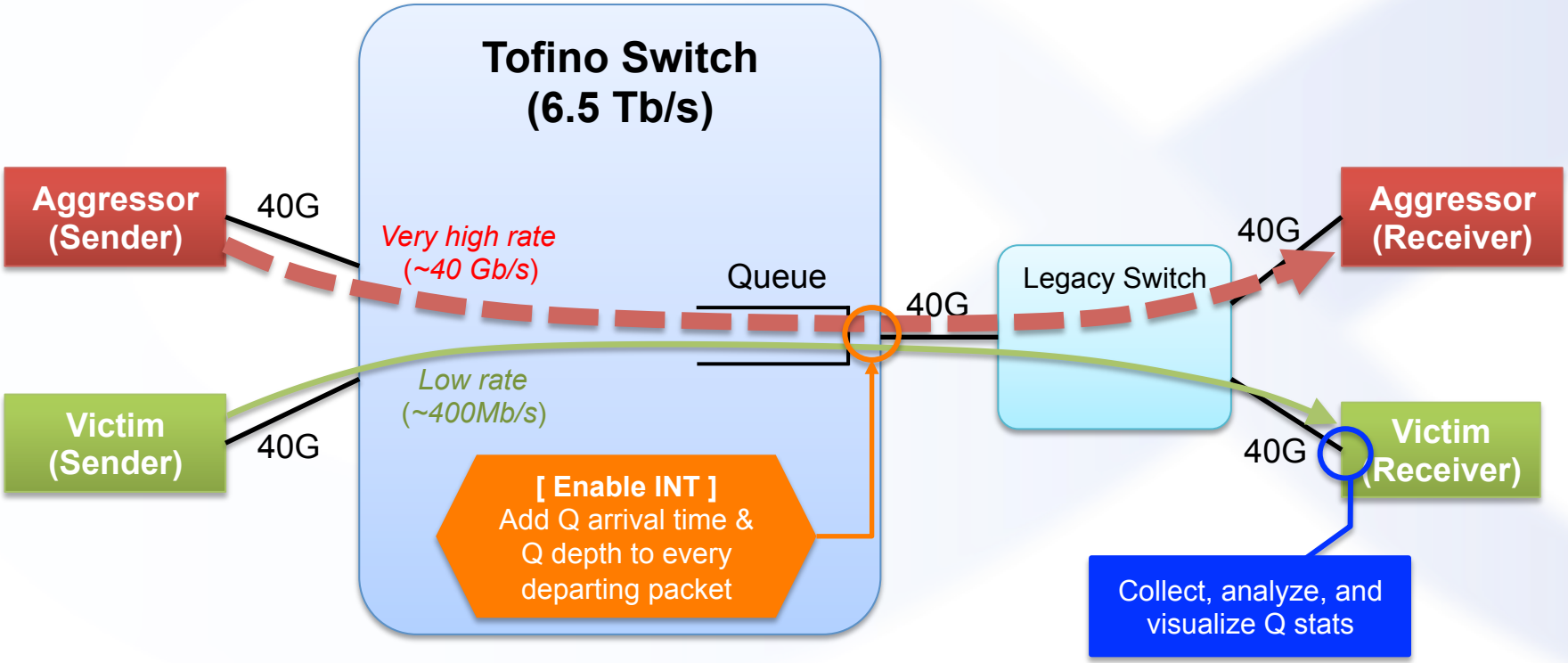
```
table int_table {
  reads {
    ip.protocol;
  }
  actions {
    export_queue_latency;
  }
}
```

```
action export_queue_latency (sw_id) {
  add_header(int_header);
  modify_field(int_header.kind, TCP_OPTION_INT);
  modify_field(int_header.len, TCP_OPTION_INT_LEN);
  modify_field(int_header.sw_id, sw_id);
  modify_field(int_header.q_latency,
               intrinsic_metadata.deq_timedelta);
  add_to_field(tcp.dataOffset, 2);
  add_to_field(ipv4.totalLen, 8);
  subtract_from_field(ingress_metadata.tcpLength,
                      12);
}
```

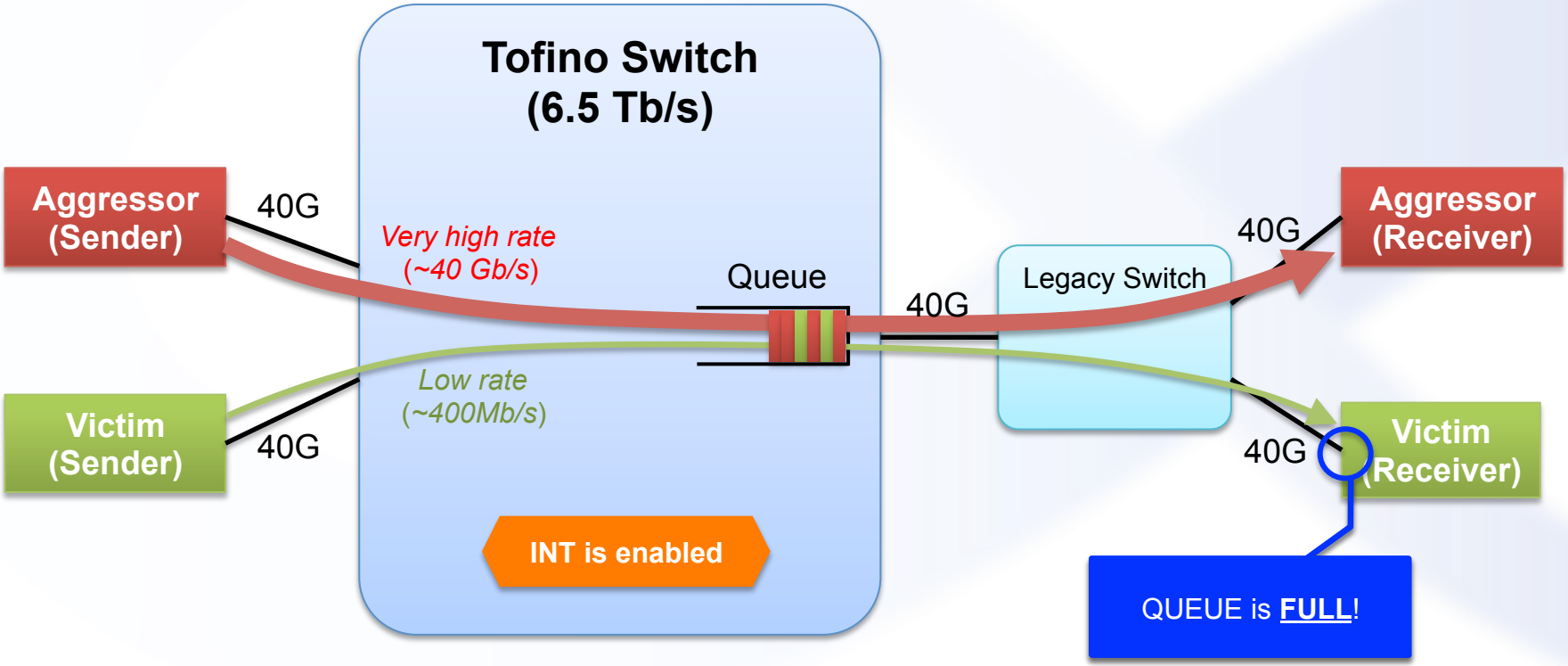
Add TCP Options &
copy switch ID and queue latency
Into the options

Demo!

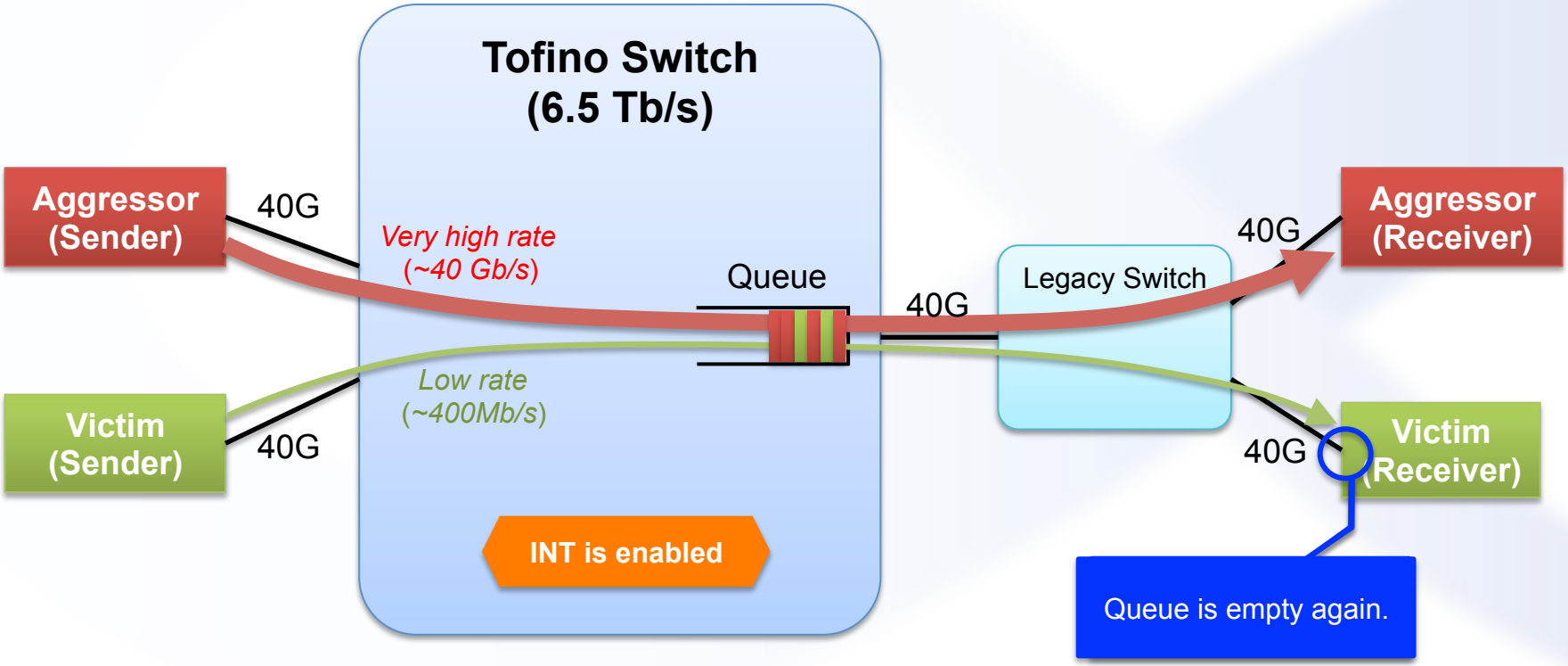
Demo environment



What's going to happen …

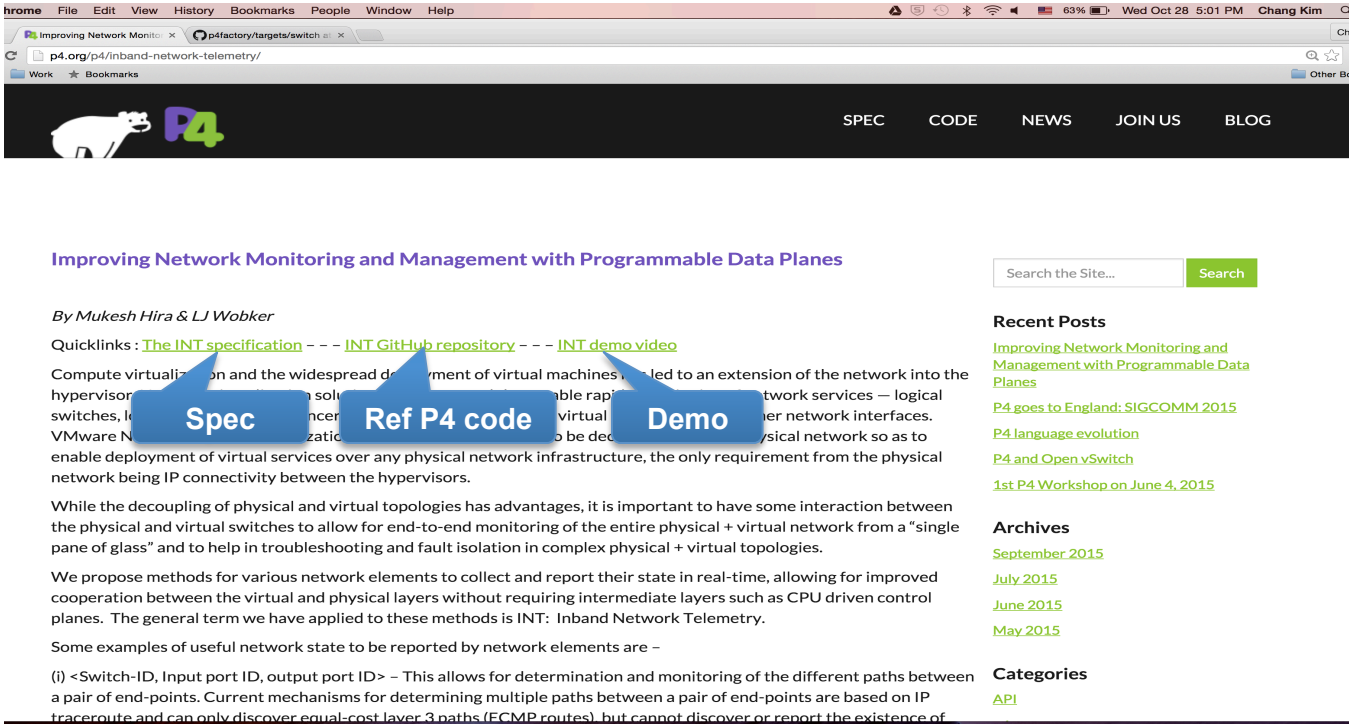


What's going to happen …



INT open-source code and spec

- http://p4.org/p4/inband-network-telemetry/



Recapping: Why is data-plane programmability a big deal?

Key benefits of programmable forwarding

1. **New features**: Add new protocols
2. **Reduce complexity**: Remove unused protocols
3. **Efficient use of resources**: Flexible use of tables
4. **Greater visibility**: New diagnostics, telemetry, OAM etc.
5. **Modularity**: Compose forwarding behavior from libraries
6. **Portability**: Specify forwarding behavior once; compile to many devices
7. **Own your own IP**: No need to tell the chip vendor your features

Closing remark

Network is becoming a programmable platform, *repeating the same evolution pattern that already took place in computing and storage industries*

Join the 4th P4 Workshop and Developer Day, May/16 - 17 at Stanford (more info at http://p4.org)

Thanks!

Q&A

BACKUP SLIDES