CS5412 / LECTURE 27
PROGRAMMING THE NETWORK

Ken Birman
Spring, 2020

WE DON'T OFTEN THINK ABOUT THE NETWORK AS A "COMPUTING DEVICE"

For most of us, the network is just the Internet, or perhaps a virtually private cloud (VPC).

But modern networks are actually programmable.

How does this work, and what are cloud companies like Amazon and Microsoft using this for?

OLD FASHIONED NETWORK PROGRAMMING

Network devices include

- Network interface cards (NICs)
- Switches (they support a 1:1 form of packet movement, very rigid)
- Routers (they look at the destination and send the packet on a good path to reach that destination. Very flexible because the routing table can be updated at runtime).

We are already "programming" a network if we configure a switch or load a routing table into a router.

HOW IT "WORKS"

Network administrator or the superuser has special ways to

- Connect to the device
- Send it commands via command line
- The GUI will update a set of devices if you ask it to.

There are also "routing protocols" you can enable. The routers talk to each other continuously and dynamically discover and adapt routing paths.

OTHER INTERESTING NETWORK-LAYER DEVICES

Firewalls: They use “rules” to block attacks like DDoS traffic or spam.

Network address translation devices (NAT boxes): They map from one network address range to a different one, and might also map port numbers or even byte ranges.

VLAN boxes: They create and manage VPNs and VPCs.

Cryptography “pass-through” devices: They encrypt and decrypt “on the wire”

MONITORING A NETWORK

An important form of programmability involves watching for conditions important to the operator, such as individual applications grabbing too big a share of the network.

The enabler is a feature for configuring devices to count traffic on links.

These tools often can issue program-triggered alarms: "Warning, network overload on segment T:5-3.B. Packet drop rate spiking!" They can also automatically modify routing to bypass broken hardware or mask issues.

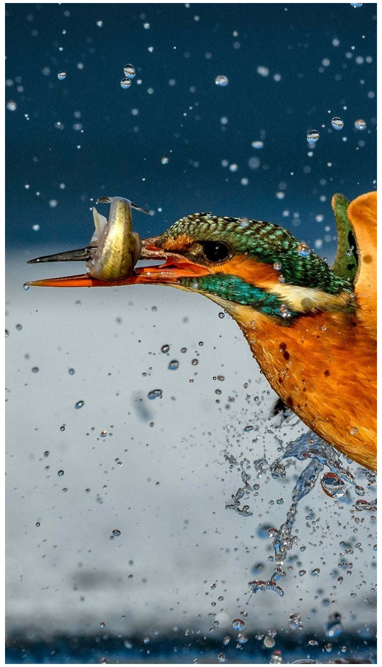
… BUT THEY CAN'T DO FANCIER KINDS OF PROGRAMS

Suppose that I wanted to do fine-grained monitoring of just the traffic to a specific VLAN, or even to some single microservice within my network.

Or I might want to move part of a MapReduce task right into the network itself and have it compute the "reduce" functions with no help from the host

Or we might want to create a very flexible new form of routing that dynamically selects specific packets and sends them to particular machines

WHY NOT?



These examples all require some form of filtering.

To filter and count, you need to “parse” the packet, then break out certain fields and compare against a specific value or pattern, etc. Then count only the packets that match your criteria (and you might make a histogram using some other field as the “index” to decide which bin)

But this is way beyond what a standard router can do today.

A NUMBER OF PROPOSALS HAVE BEEN MADE

OpenFlow: A router-control API that can support fancier network behavior

P4: A new language for writing programs that run directly on the routers

WE WILL LOOK AT SLIDES ON THE P4 LANGUAGE

Mihai Budiu was a Cornell PhD student, but he moved with a faculty member who went to CMU and finished up there.

He helped create the Microsoft LINQ technology we learned about. Then when Microsoft Research Silicon Valley closed, he moved to VMWare.

At VMWare he leads a P4 research group.

P4: specifying data planes

http://P4.org

VMware Techtalk
March 30, 2017

Mihai Budiu

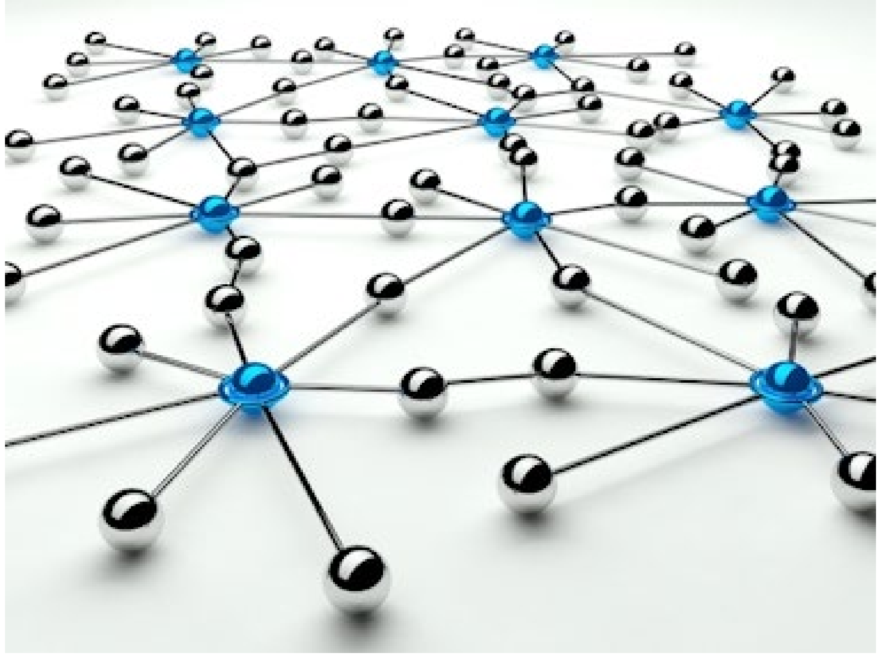
VMware Research Group

About Myself

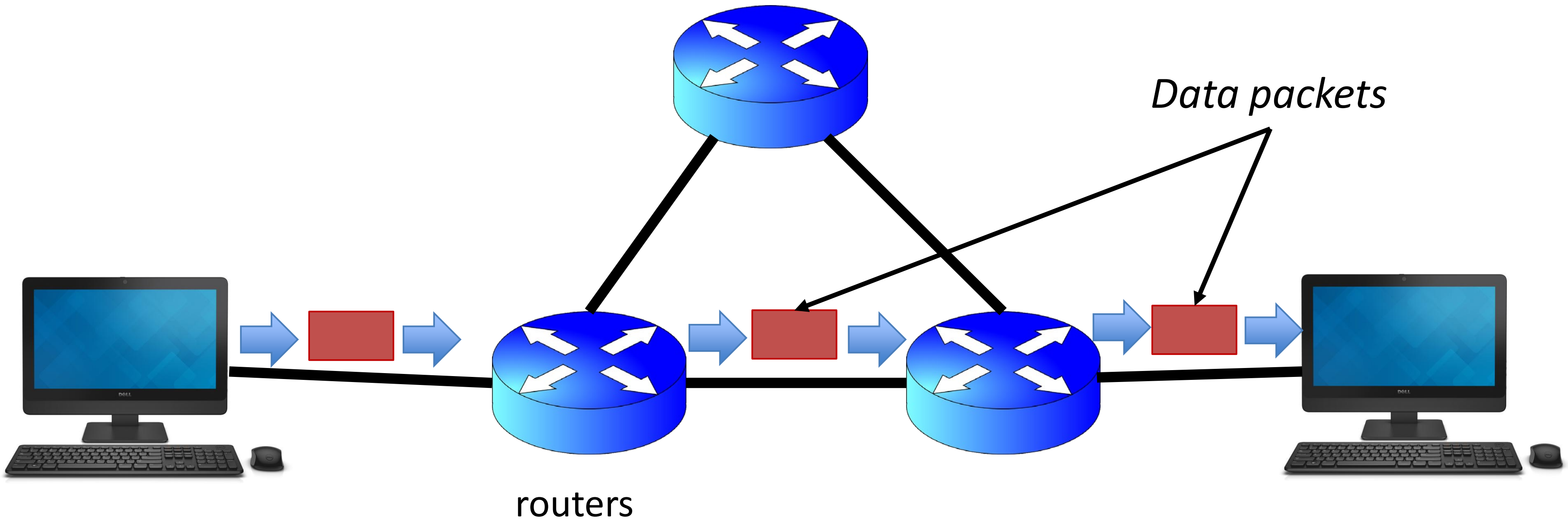
- Ph.D. from Carnegie Mellon
- Researcher at Microsoft Research, Silicon Valley
  - Distributed systems, security, compilers, cloud platforms, machine learning, visualization
- Software engineer at Barefoot Networks
  - Design and implementation of P4
- Researcher at VMware Research Group
  - Big data, P4

Presentation outline

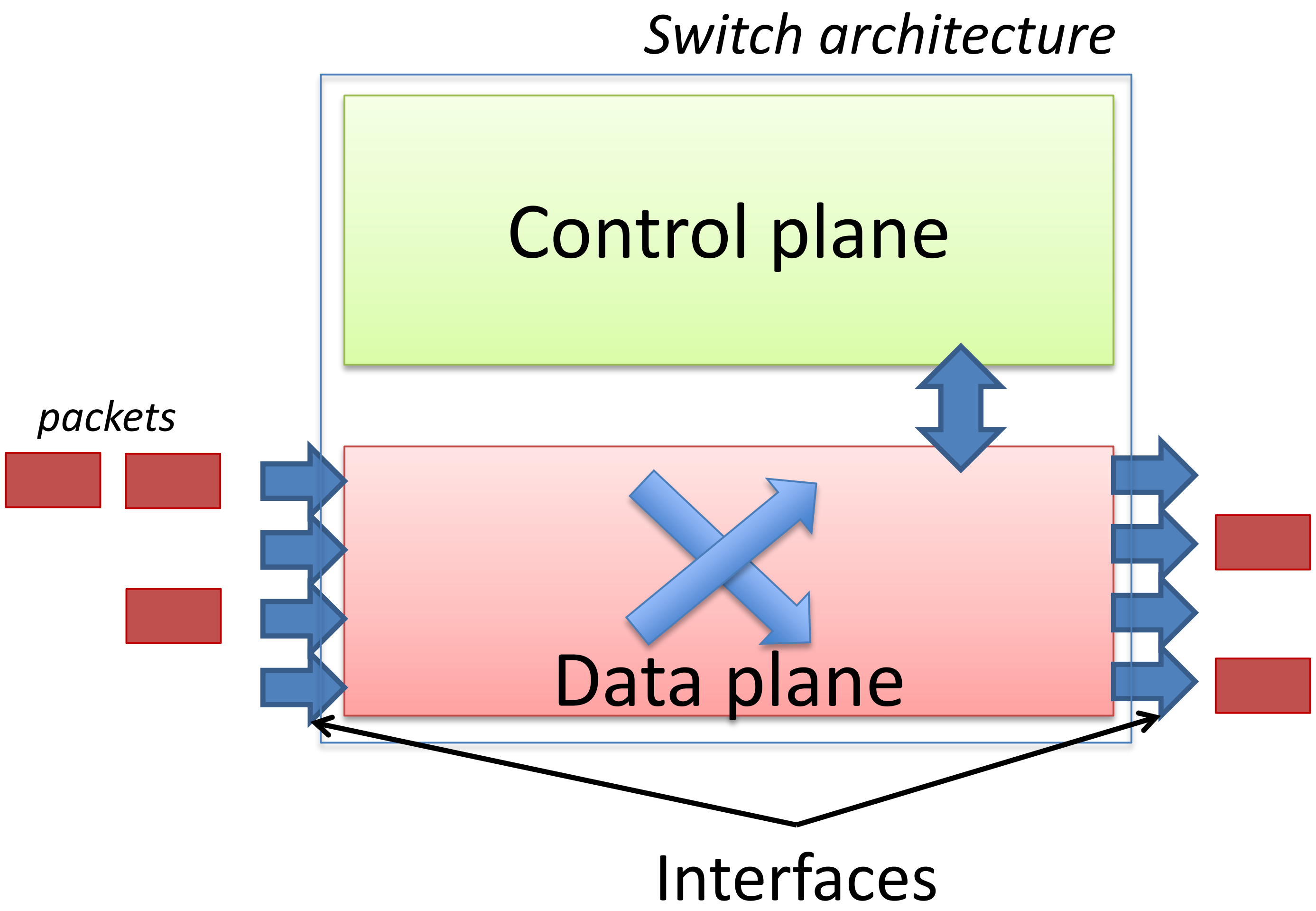
- P4 & Programmable networks
  - Why should you care?
- An introduction to $P4_{16}$
  - P4 limitations
- Conclusions



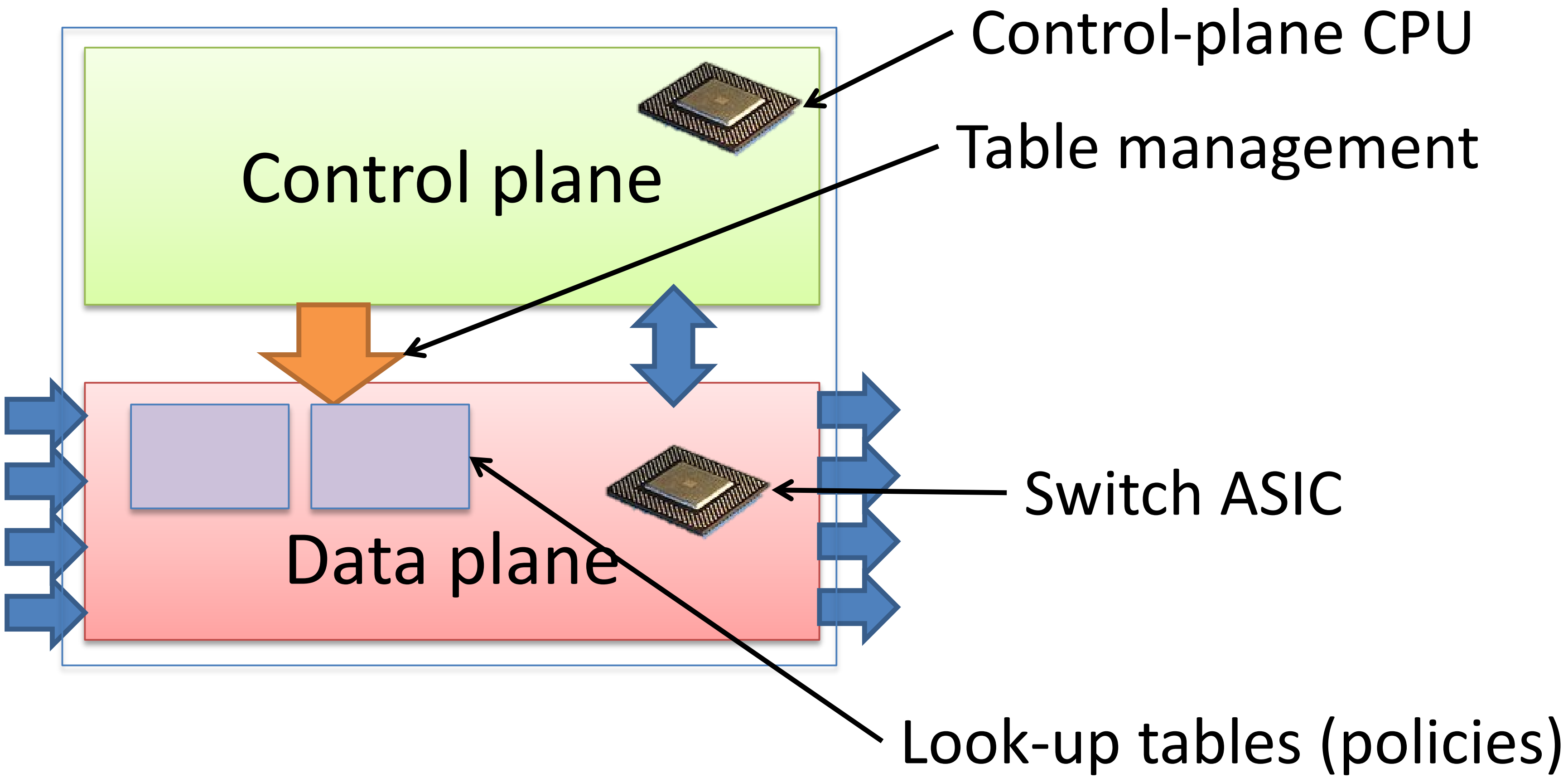
Networking 101



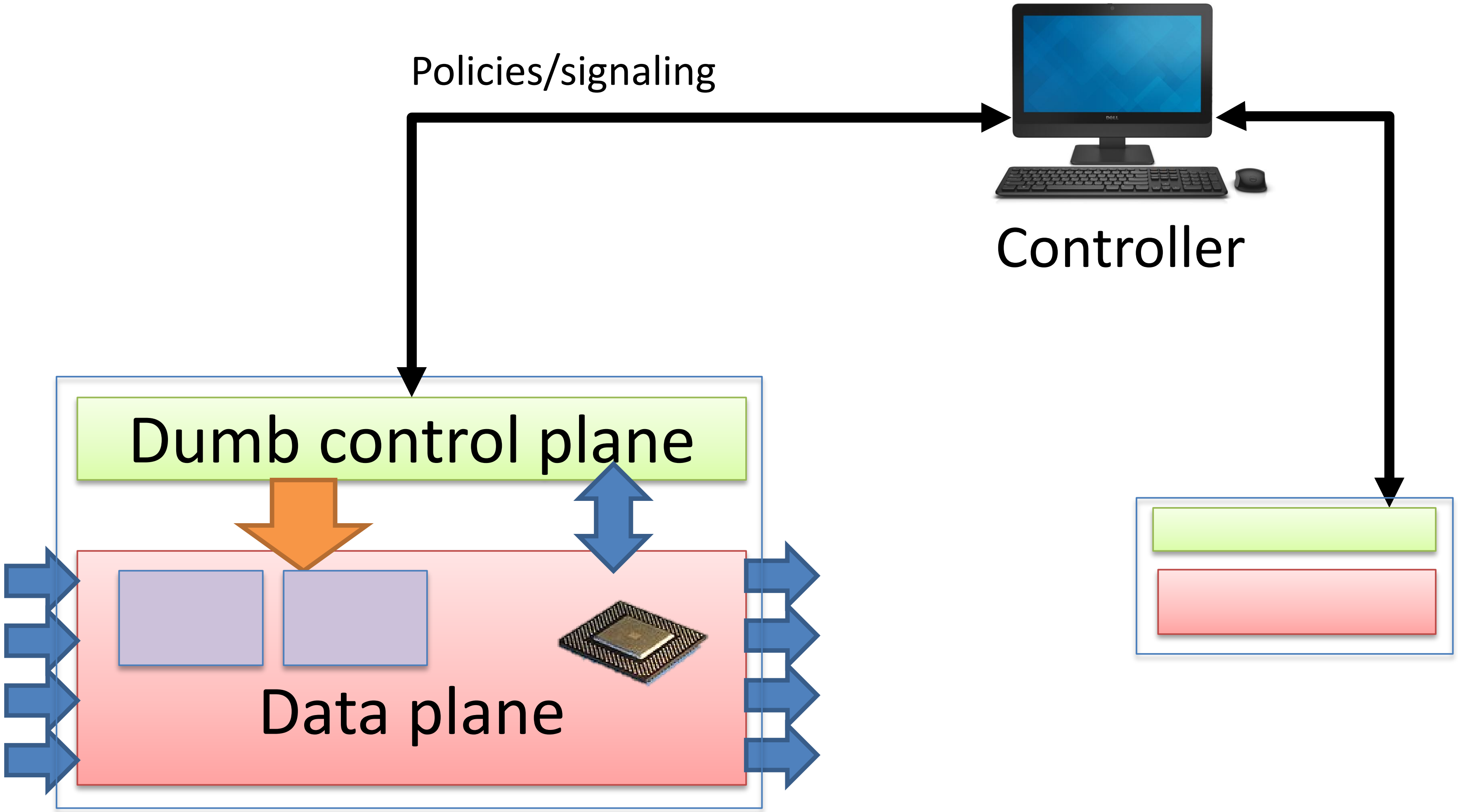
Control and Data Planes



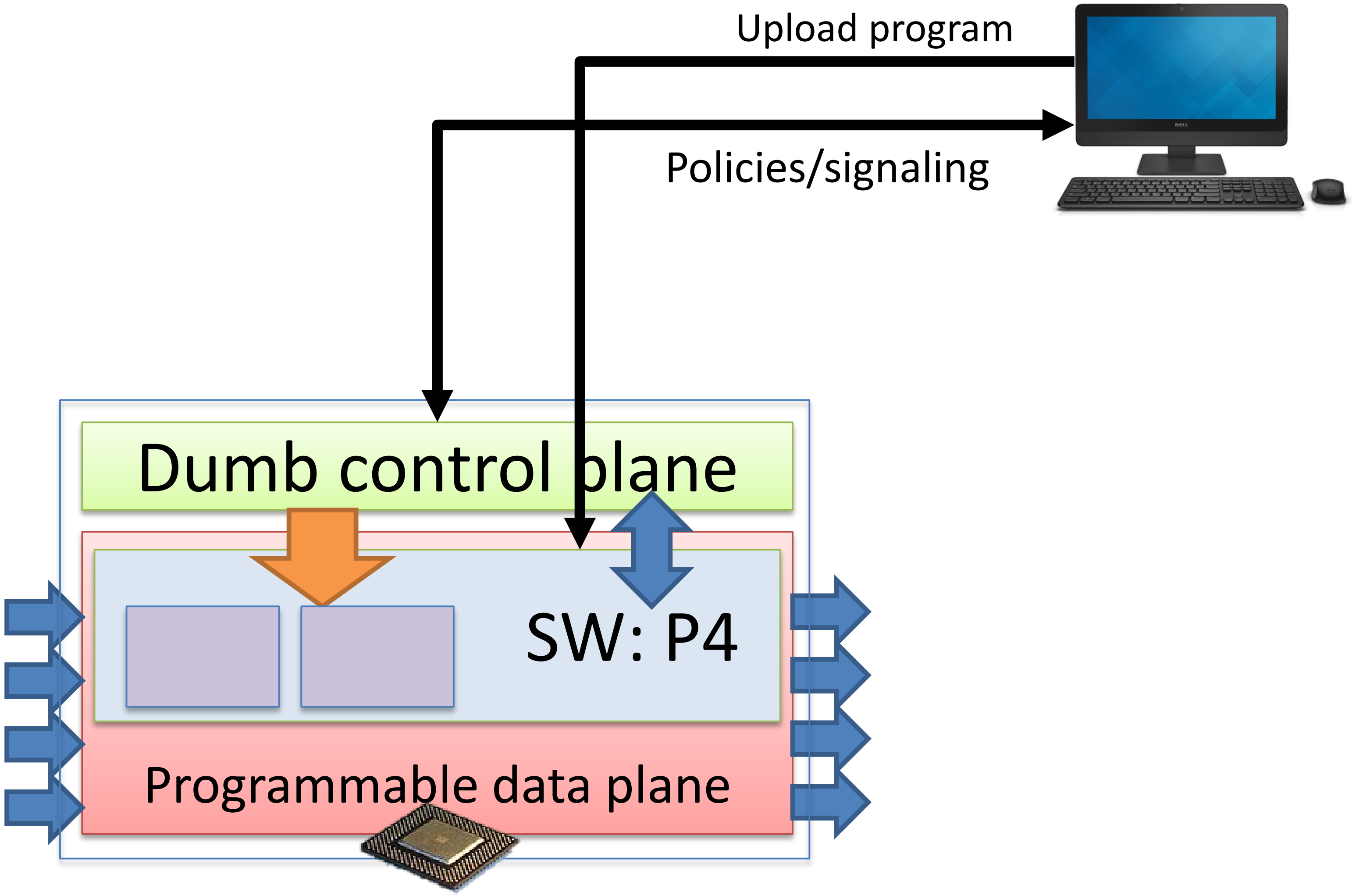
Traditional switch architecture



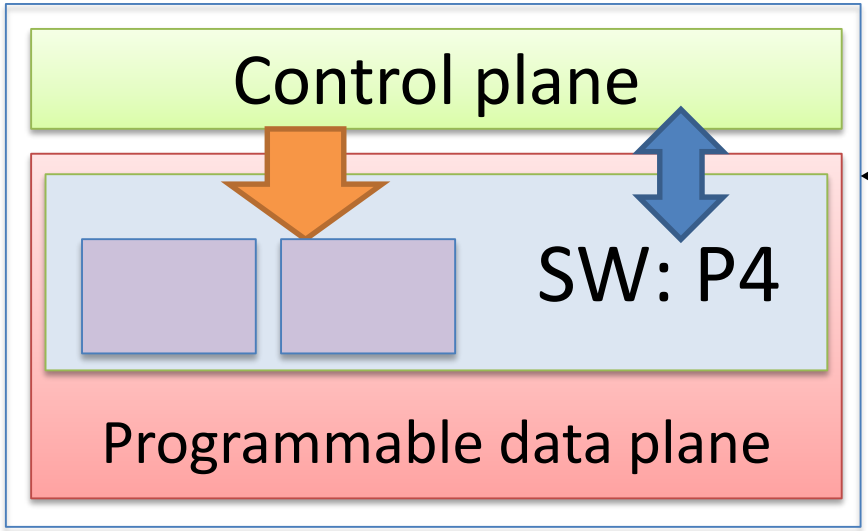
Software-Defined Networking



The P4 world

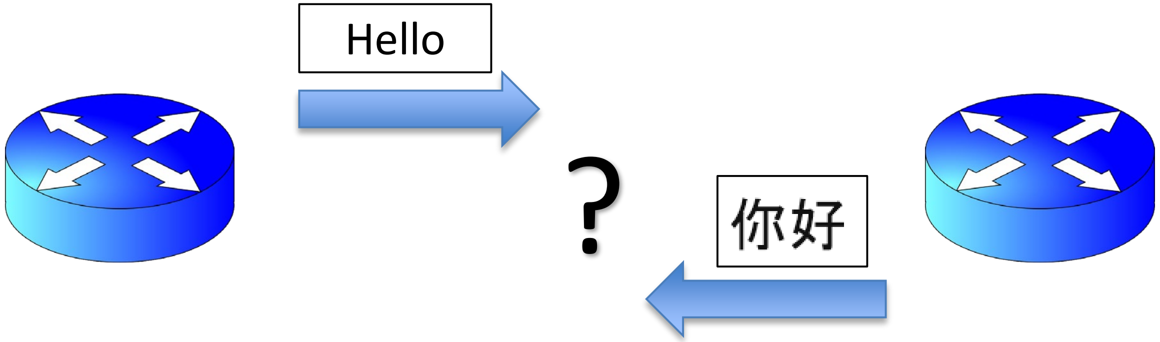

Upload program
Policies/signaling
Dumb control plane
SW: P4
Programmable data plane

Not just for switches!

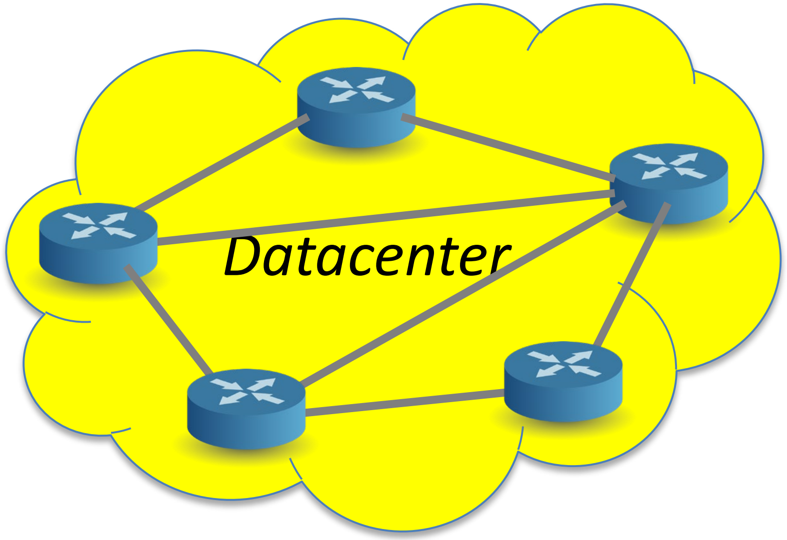


- Programmable switches
- FPGA switches
- Programmable network cards
- Software switches
- Hypervisor switches
- You name it…

How is this possible?

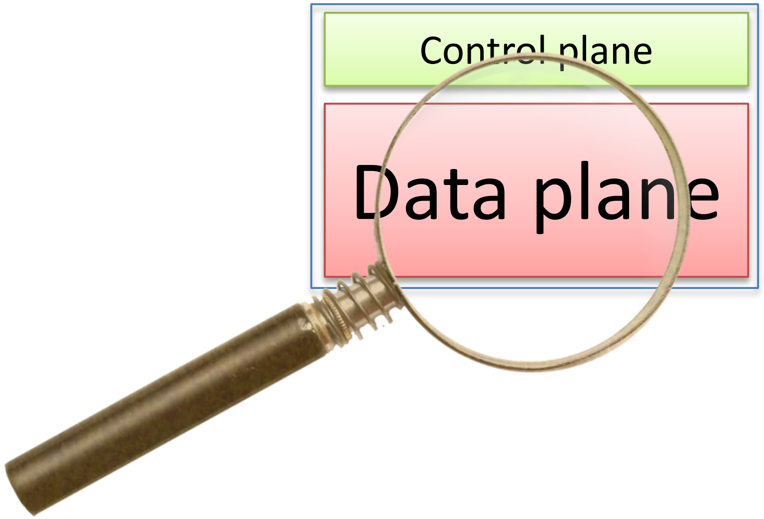


Most useful if you have
your own network playground



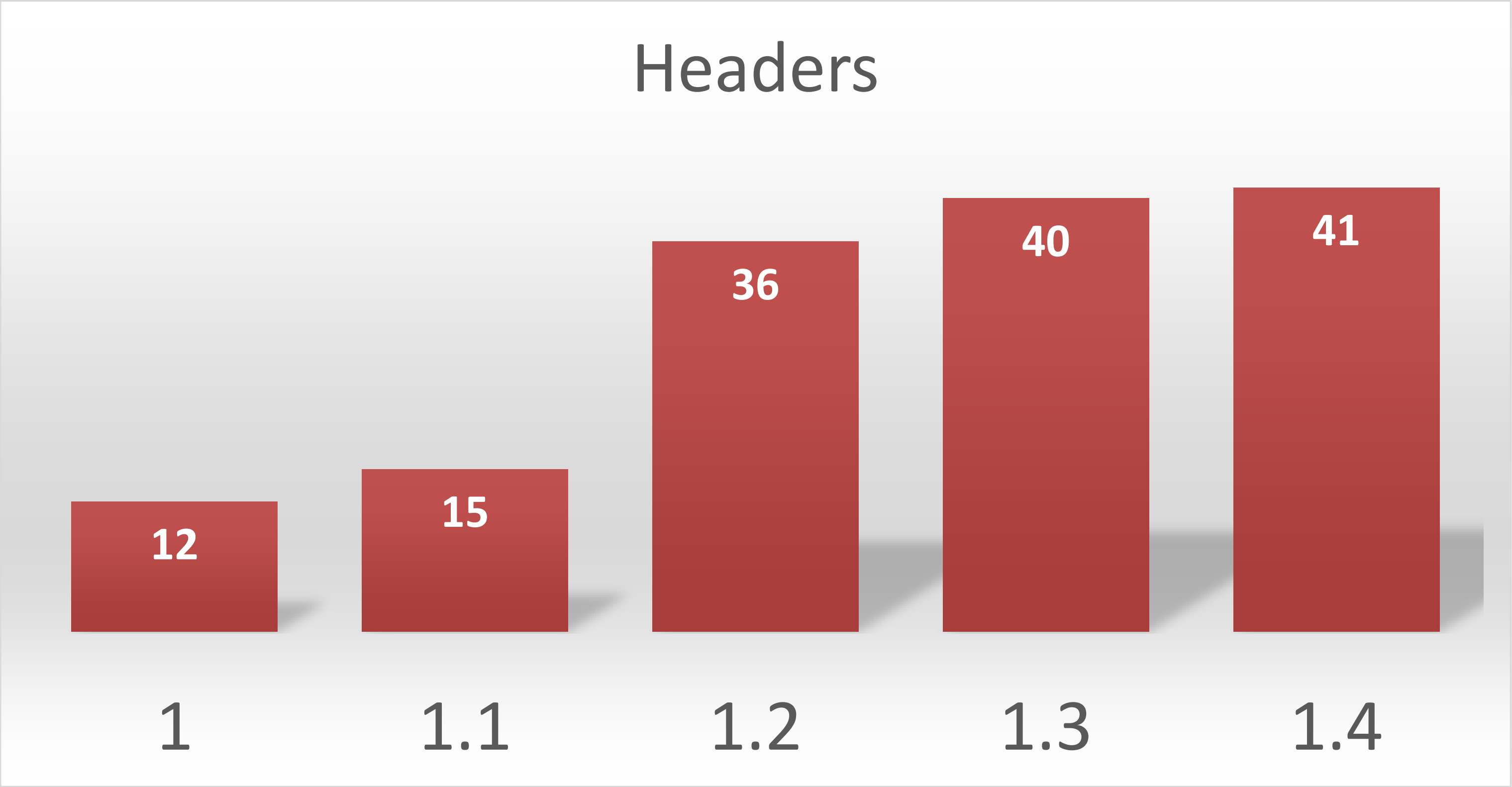
Data-planes

- From now on in this presentation we only talk about the data-plane
- We expect that SDN will continue to evolve the control-plane



WHY SHOULD YOU CARE?

Isn’t Open-Flow Enough?



Open-Flow version

Open-flow has *never* been enough: it keeps changing to describe new protocols

vmware has lots at stake

- NSX is about programmable networks
  - Flexibility in networking
  - We are an industry leader
- P4 will change the dynamics in the industry
  - Device manufacturer ≠ device programmer
  - Many network capabilities exposed to software

Protocols = programs

- VxLAN: 175 lines of P4
  - Took 4 years from proposal to wide availability
- NVGRE: 183 lines of P4

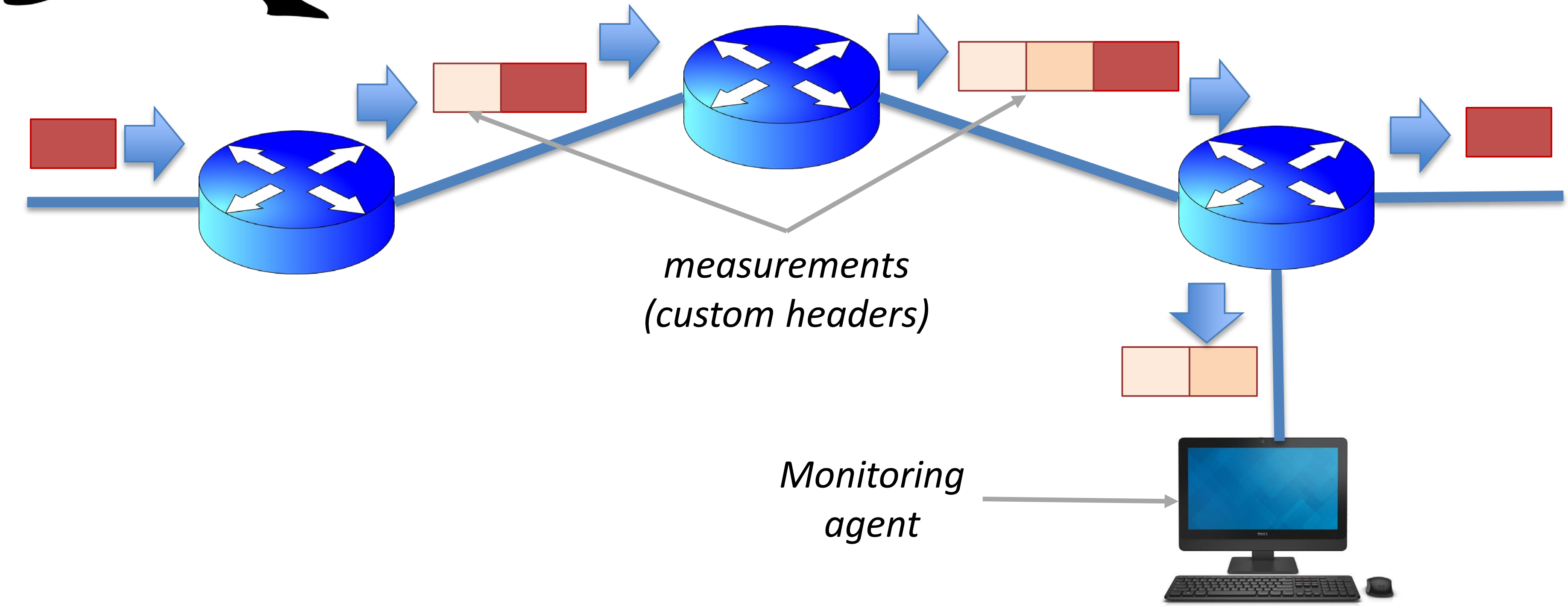
M. Shahbaz, S. Choi, B. Pfaff, C. Kim, N. Feamster, N. McKeown, J. Rexford, PISCES: A Programmable, Protocol-Independent Software Switch
SIGCOMM 2016

- 40 times reduction in the size of the OvS parser
- Much easier to add new protocols
- Same performance

Use only what you need

- IETF has issued thousands of RFCs
- Switch RAM and CPU is very expensive
- Network operators can *remove* protocols
- Simpler troubleshooting

Network monitoring



In-Band Network Telemetry (INT)

Improving Network Monitoring and Management with Programmable Data Planes

By Mukesh Hira & LJ Wobker

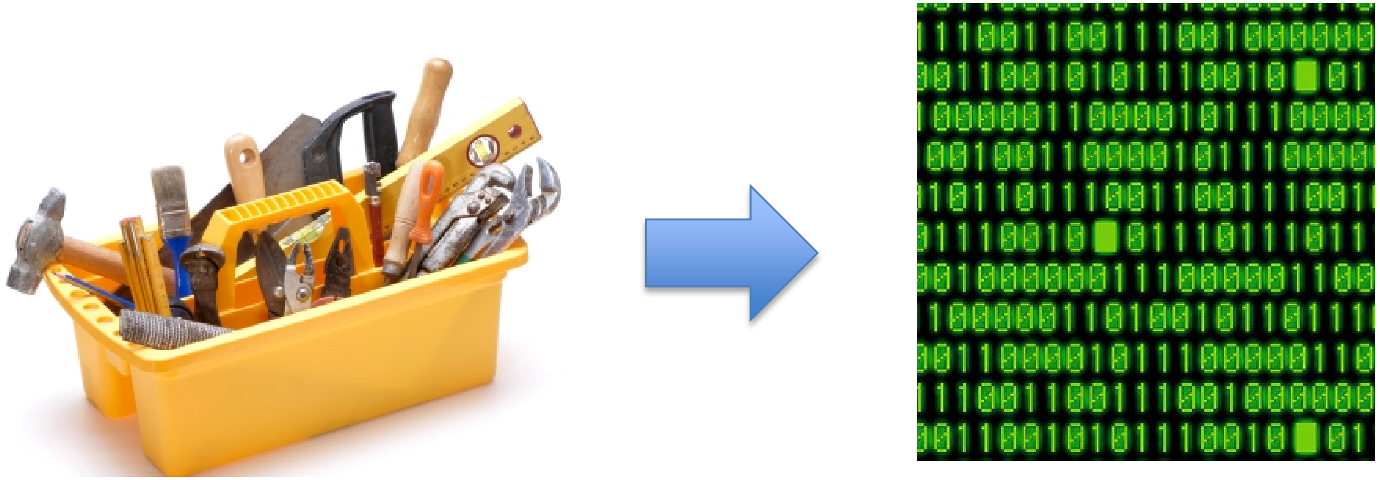
Optimize your network

- Push application functionality in the network
- High speed

Paxos Made Switch-y
Huynh Tu Dang, Marco Canini, Fernando Pedone, Robert Soulé
CCR April 2016

Network = software

- Use ***software*** engineering principles and tools
- Upgrade your network at any time
- Protocols = intellectual property



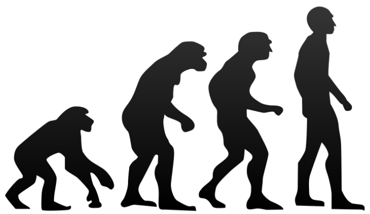
P4.org Consortium

UNIVERSITY MEMBERS

Carriers, cloud operators, chip co.s, networking, systems, universities, start-ups

AN INTRODUCTION TO $P4_{16}$

Language evolution



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 *ACM SIGCOMM Computer Communications Review (CCR). Volume 44, Issue #3 (July 2014)*

P4 v1.0 spec, reference implementation and tools released in Spring 2015 (mostly by Barefoot Networks), Apache 2 license, http://github.com/p4lang.

$P4_{16}$ spec, reference implementation and tools released in December 2016.

P4 Community

- http://github.com/p4lang
- http://p4.org

- Mailing lists
- Workshops
- P4 developer days

- Academic papers (SIGCOMM, SOSR)

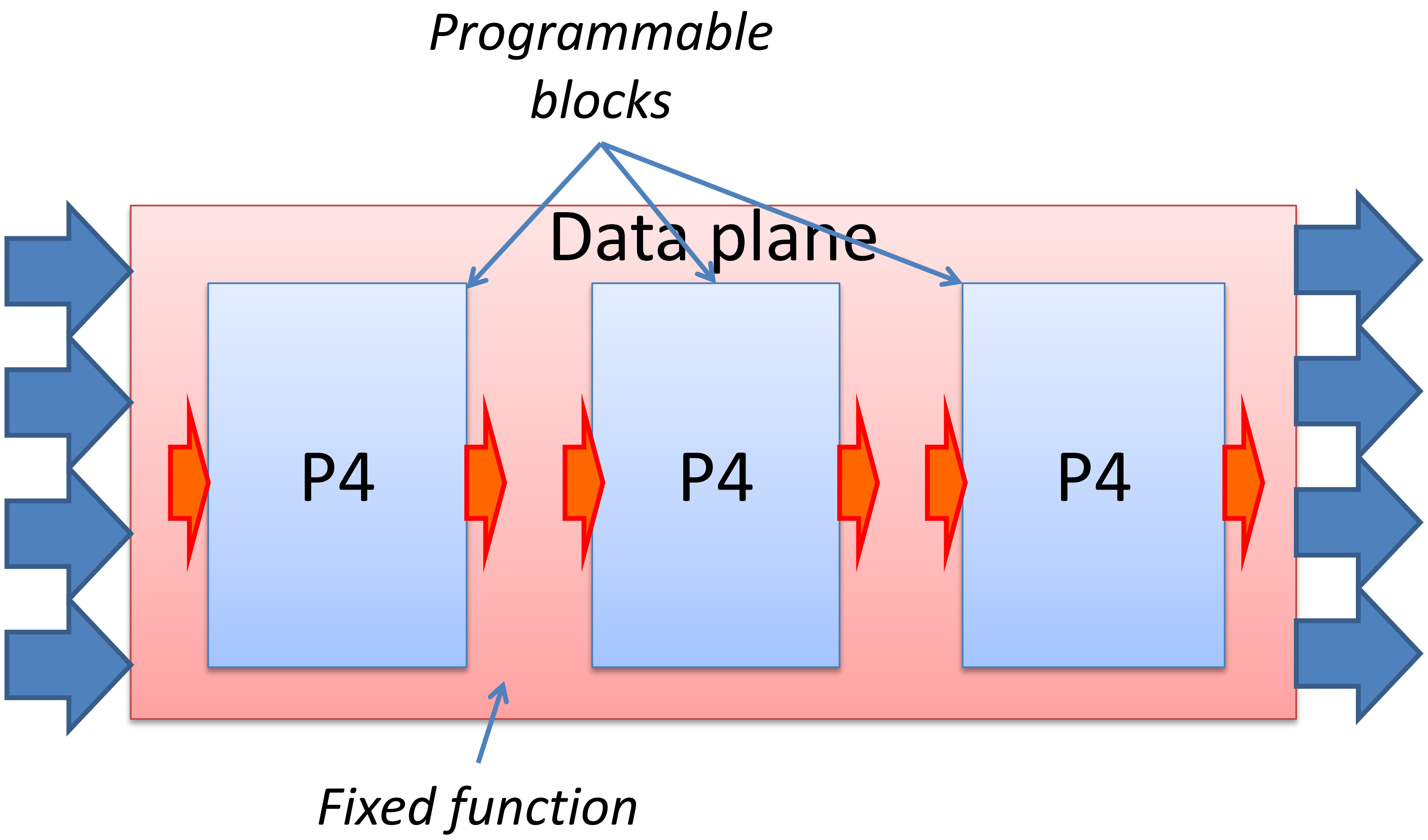
Available Software Tools

- Compilers for various back-ends
  - Netronome chip, Barefoot chip, eBPF, Xilinx FPGA
  (open-source and proprietary)
- Multiple control-plane implementations
  - SAI, OpenFlow
- Simulators
- Testing tools
- Sample P4 programs
- Tutorials

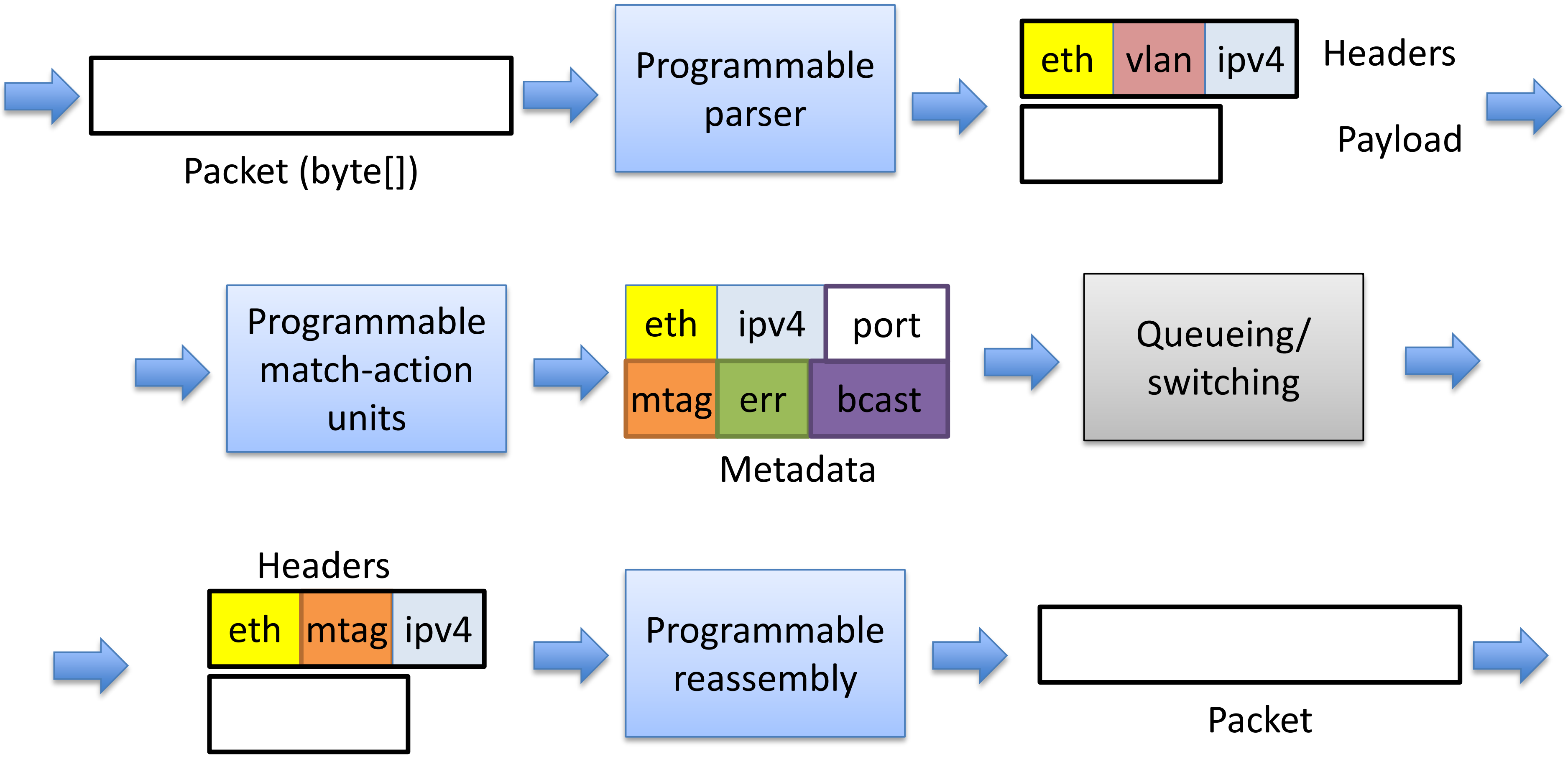
$P4_{16}$

- Most recent revision of P4
- Similar to C; strongly typed
- Currently in draft form
- Spec: http://p4.org/wp-content/uploads/2016/12/P4_16-prerelease-Dec_16.pdf
- Reference compiler implementation (Apache 2 license): http://github.com/p4lang/p4c

$P4_{16}$ data plane model



Example packet processing pipeline



Language elements

Programmable parser	State-machine; bitfield extraction
Programmable match-action units	Table lookup; bitfield manipulation; control flow
Programmable reassembly	Bitfield reassembly
Data-types	Bitstrings, headers, structures, arrays

user

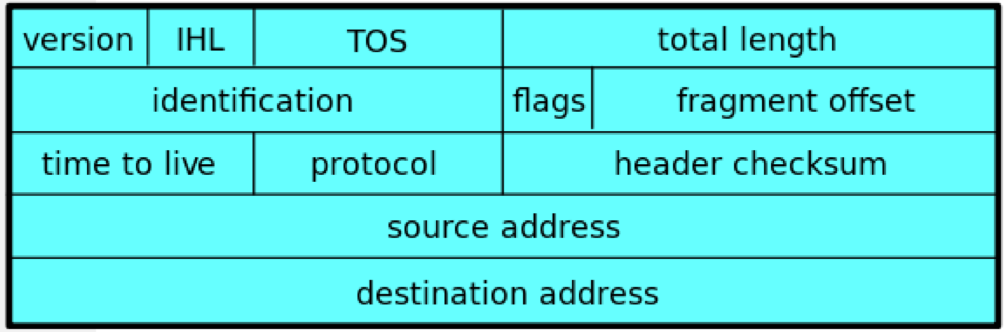
---

target

Target description	Interfaces of programmable blocks
External libraries	Support for custom accelerators

Data Types

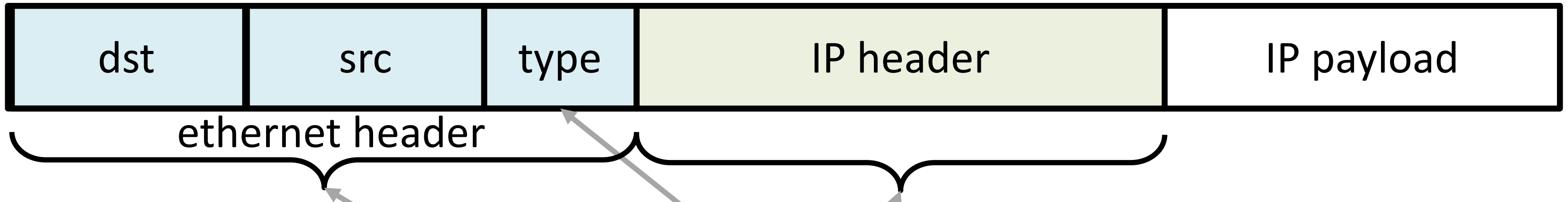
```
typedef bit<32>  IPv4Address;

header IPv4_h {
    bit<4>       version;
    bit<4>       ihl;
    bit<8>       tos;
    bit<16>      totalLen;
    bit<16>      identification;
    bit<3>       flags;
    bit<13>      fragOffset;
    bit<8>       ttl;
    bit<8>       protocol;
    bit<16>      hdrChecksum;
    IPv4Address  srcAddr;
    IPv4Address  dstAddr;
}
// List of all recognized headers
struct Parsed_packet {
    Ethernet_h ethernet;
    IPv4_h     ip;
}
```



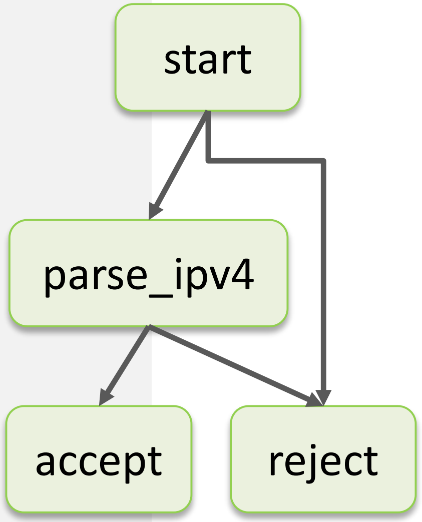
header = struct + valid bit

Other types: array of headers, error, boolean, enum

Parsing = State machines




```
parser Parser(packet_in b, out Parsed_packet p) {
    state start {
        b.extract(p.ethernet);
        transition select(p.ethernet.type) {
            0x0800: parse_ipv4;
            default: reject;
        }
    }
    state parse_ipv4 {
        b.extract(p.ip);
        transition accept;
    }
}
```



Actions

- ~ Objects with a single method.
- Straight-line code.
- Reside in tables; invoked automatically on table match.

Action data; from control plane

```
action Set_nhop(IPv4Address ipv4_dest, PortId port) {
      nextHop = ipv4_dest;
      outCtrl.outputPort = port;
}
```

```
class Set_nhop {
     IPv4Address ipv4_dest;
     PortId      port;
     void run() {
         nextHop = ipv4_dest;
         outCtrl.outputPort = port
     }
}
```

Java/C++ equivalent code.

Tables

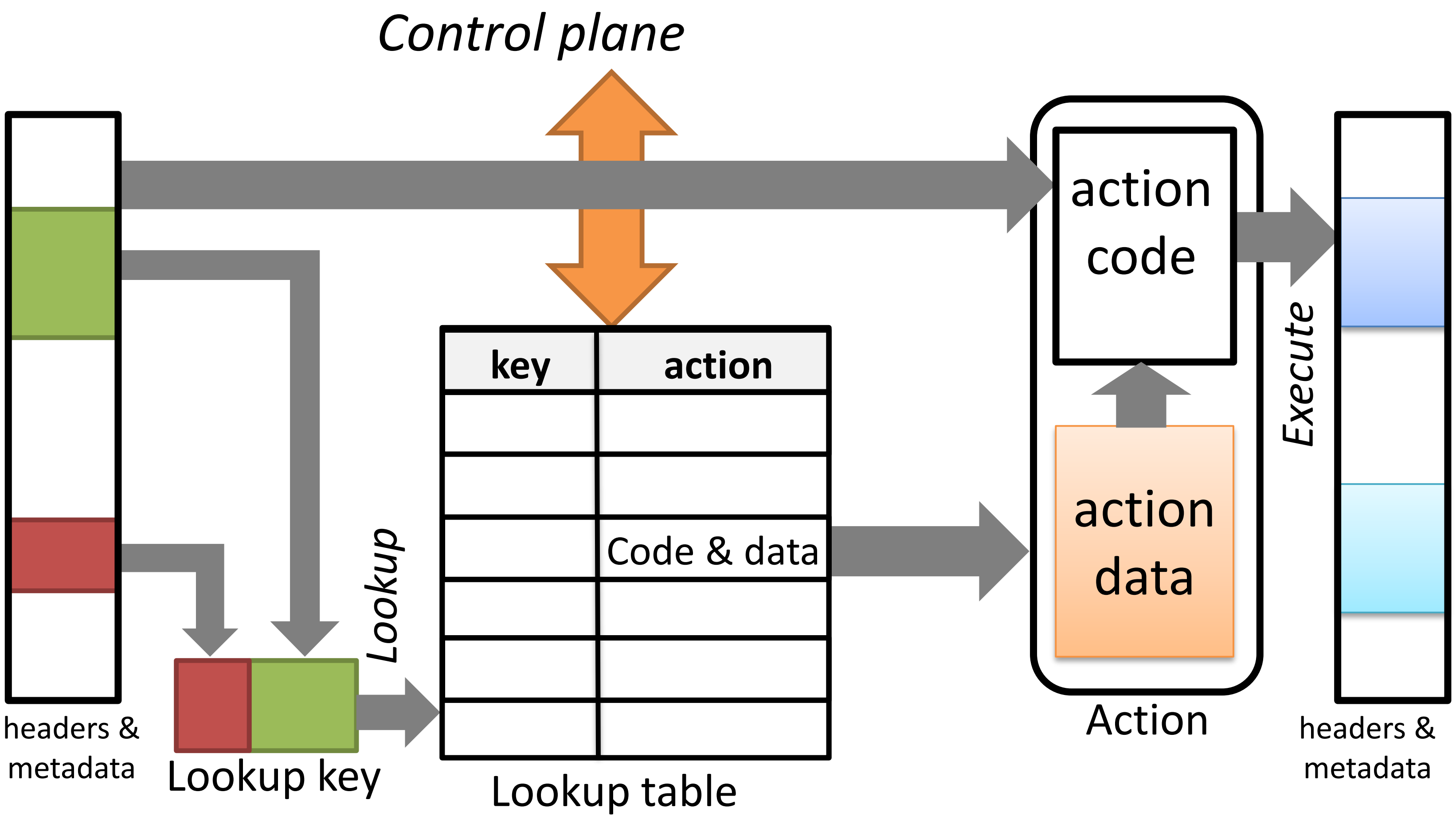
- HashMap<K, Action>

```
table ipv4_match() {
   key = { headers.ip.dstAddr: exact; }
   actions = { Drop_action; Set_nhop; }
   default_action = Drop_action;
}
```

Populated by
the control plane

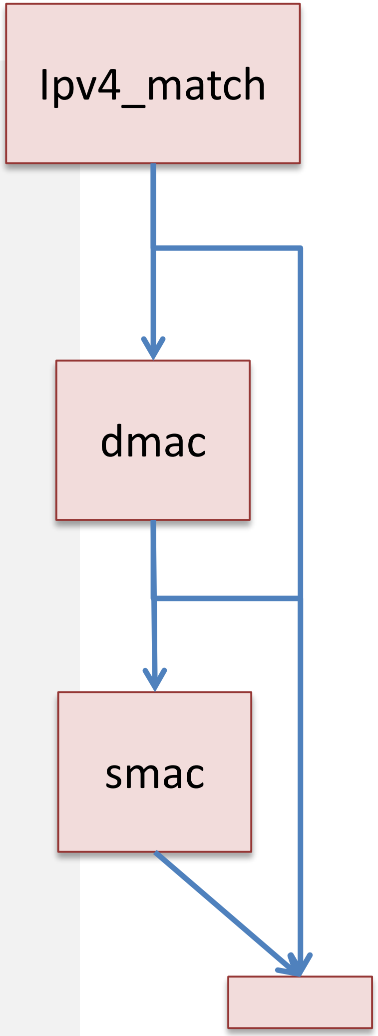
dstAddr	action
0.0.0.0	drop
10.0.0.1	Set_nhop(10.4.3.4, 4)
224.0.0.2	drop
192.168.1.100	drop
10.0.1.10	Set_nhop(10.4.2.1, 6)

Match-Action Processing



Control-Flow

```
control Pipe(inout Parsed_packet headers,
             in InControl inCtrl,// input port
             out OutControl outCtrl) { // output port
      IPv4Address nextHop; // local variable

      action Drop_action() { … }
      action Set_nhop(…) { … }
      table ipv4_match() { … }
      …

      apply {  // body of the pipeline
          ipv4_match.apply();
          if (outCtrl.outputPort == DROP_PORT) return;
          dmac.apply(nextHop);
          if (outCtrl.outputPort == DROP_PORT) return;
          smac.apply();
     }
}
```



Packet Reassembly

Convert headers back into a byte stream.
Only valid headers are emitted.

```
control Deparser(in Parsed_packet p, packet_out b) {
    apply {
        b.emit(p.ethernet);
        b.emit(p.ip);
    }
}
```

P4 Program structure

```
#include <core.p4> // core library
#include <target.p4> // target description
#include "library.p4" // library functions
#include "user.p4" // user program
```

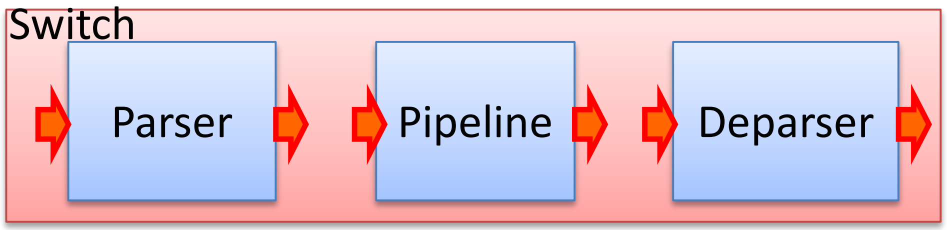
Architecture declaration

Provided by the target manufacturer

```
struct input_metadata { bit<12> inputPort; }
struct output_metadata { bit<12> outputPort; }

parser Parser<H>(packet_in b, out H headers);
```

H = user-specified header type

```
control Pipeline<H>(inout H headers,
                    in input_metadata input,
                    out output_metadata output);

control Deparser<H>(in H headers, packet_out p);

package Switch<H>(Parser<H> p, Pipeline<H> p, Deparser<H> d);
```



Support for custom “accelerators”

```
extern bit<32> random();
```

External function

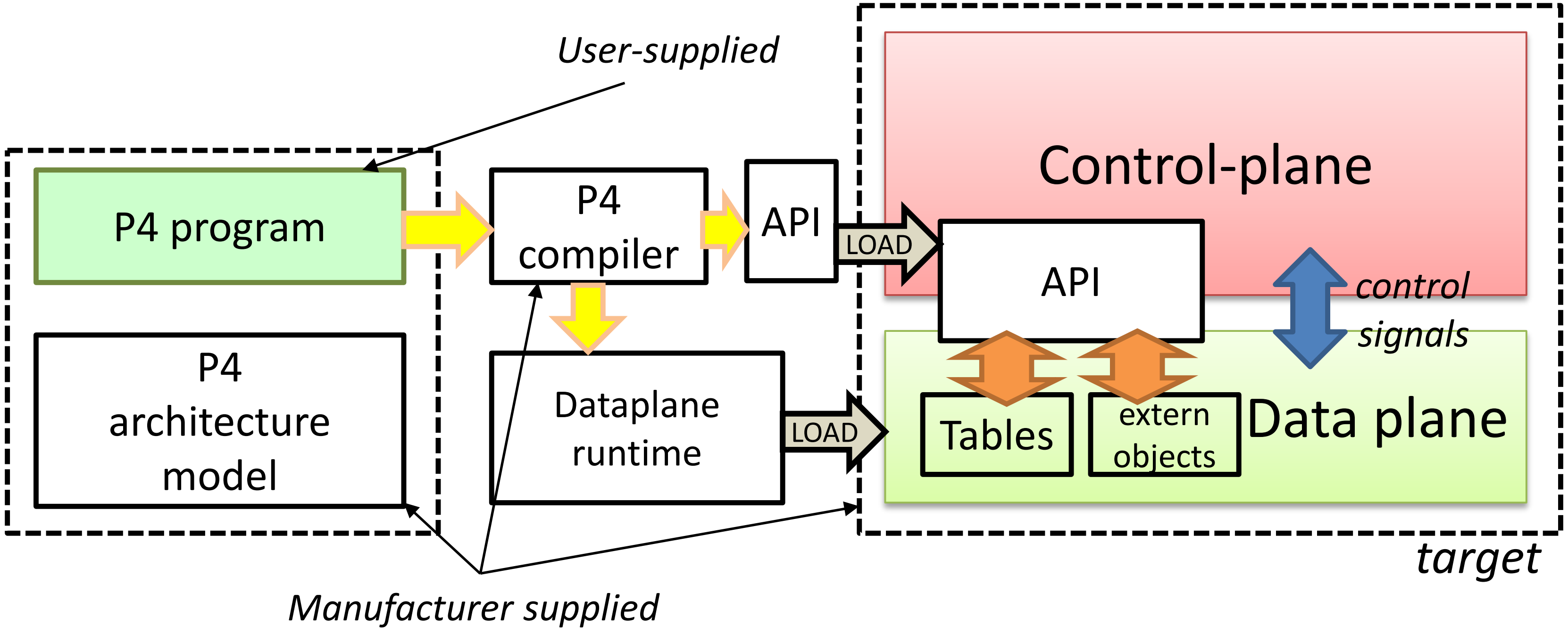
```
extern Checksum16 {
    void clear();                // prepare unit for computation
    void update<T>(in T data);  // add data to checksum
    void remove<T>(in T data);  // remove data from checksum
    bit<16> get();              // get the checksum for data added
}
```

External object with methods. Methods can be invoked like functions.
Some external objects can be accessed from the control-plane.

Execution model

- When a block is invoked (parser, control) it executes to completion on a separate thread
  - All local variables are thread-local
  - Only inter-thread communication possible through extern objects and functions
- Execution triggered by outside event (e.g., packet arrival)
- Actions execute atomically
  - @atomic annotation for futher user-level control

P4 software workflow



P4 LIMITATIONS

Limitations of $P4_{16}$

- The core P4 language is very small
  - Highly portable among many targets
  - But very limited in expressivity
- Accelerators can provide additional functionality
  - May not be portable between different targets
  - Under construction: library of standard accelerators

What is missing

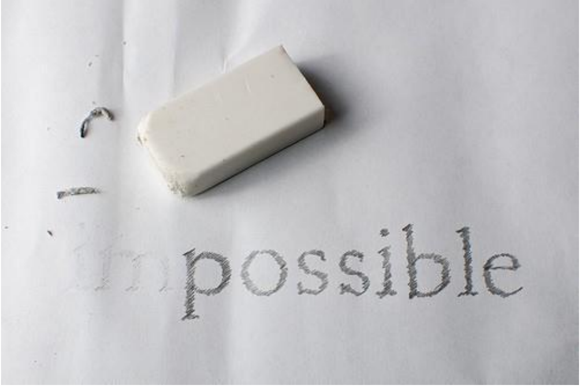
- Floating point
- Pointers, references
- Data structures, recursive data types
- Dynamic memory management
- Loops, iterators (except the parser state-machine)
- Recursion
- Threads

- => Constant work/byte of header

What cannot be done in (pure) P4

- Multicast or broadcast
- Queueing, scheduling, multiplexing
- Payload processing: e.g., encryption
- Packet trailers
- Persistent state across packets
- Communication to control-plane
- Inter-packet operations (fragmentation and reassembly)
- Packet generation
- Timers

How are these done?



- Multicast, broadcast, queueing, scheduling, multiplexing
  - By target device, controlled by P4 metadata
- Persistent state across packets (e.g. per-flow state)
  - External objects: registers, counters, meters
- Communication to control-plane
  - External objects: learning providers
- Packet generation
  - Control-plane, or external objects
- Reassembly, trailers:
  - Not currently done

P4 is not…

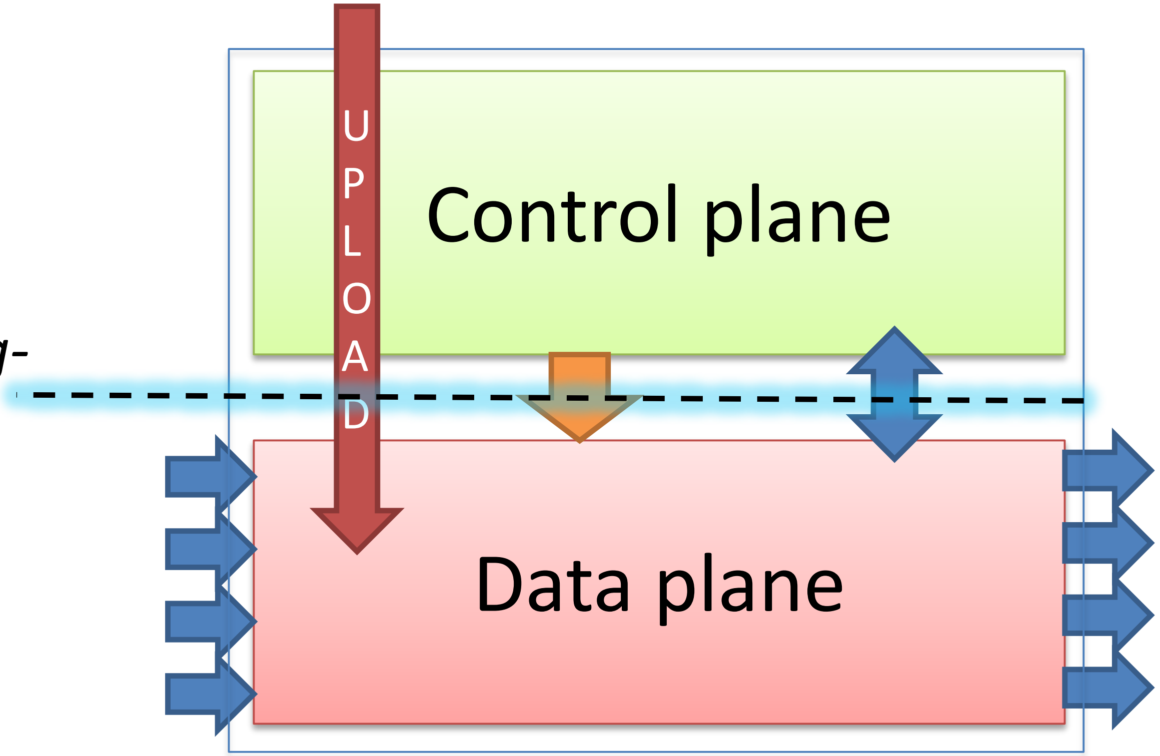
- Active networking:
  a way for packets to inject new code
- Programming the control plane:
  that is Software-Defined Networking
- A tool for third parties to program the network
- A language for:
  - distributed computations
  - network middleboxes (NFV)
  - network operating systems

Why use P4?

- **It is a language:**
  you can specify the data-plane precisely
- **Expressive**:
  express many packet-forwarding policies
- **High-level, type-safe**:
  compiler-managed abstract resources
- **Software**:
  treat network devices like software
- **Killer app:**
  network monitoring

Creating a Programming Language Interface in a place where there wasn't one.

The P4 Programming-Language Interface



USE CASES IN CLOUD SETTINGS

(back on topic)

P4 GENERATED A LOT OF EXCITEMENT AT FIRST

The idea of a fully programmable network thrilled the data center operators, who find it hard to "adapt" the data center to prioritize some flows while treating others as second class.

But P4 is like the assembler language for packet process. What's the HLL?

HIGH LEVEL LANGUAGES (HLLs) FOR NETWORKS

This is a big, tough topic! Nate Foster is a world expert

Goal: we would like to write sophisticated programs that compile into code that runs "everywhere" and carries out policies that were described "somewhere", with sound semantic foundations.

The code could compile to a mix of P4 + host logic on router coprocessors. The P4 steps are blindingly fast, but very limited…

THE HLL SIDE HAS BEEN THE BARRIER

P4 was remarkably quick to hit the market and for a while, pushed the prior programmability tool (OpenFlow SDNs) to the side.

Yet neither has really become the mainstream story because the HLL options remain complex and their semantics are hard to work with.

Until someone finds an HLL that would be easy to use but also easy to compile into P4, we won't see P4 (or successors) in their full power.

WHAT'S THE REAL BARRIER?

The core problem is that a network has lots of moving parts, at many places. But the HLL interaction with the P4 layer is slow and asynchronous

A program normally has a kind of sequentiality. But this doesn't map easily to updating the P4 network and switching from one control pattern to a different one "transparently".

As a result, HLLs tend to lock the whole network, update the P4, then unlock it… and this is not really viable.

CONCLUSIONS?

Network programmability is one of those ideas that feels as if it will always be 10 years in the future!

But IoT was like that… until now, when suddenly IoT is a real thing.

Don’t bet against network programming “coming soon”!