EN.601.414/614
Computer Networks

Programmable Networks

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Fall 2020 (TuTh 1:30-2:45pm on Zoom)

https://github.com/xinjin/course-net

Today, we will take a peek at the forefront of contemporary computer networking research…

- **An exciting journey**
  - One of the hottest topic in today's networking research
- **Yet, might be a little overwhelming**
  - Don't worry if you do not fully understand it
  - Raise your hand and ask questions

Agenda

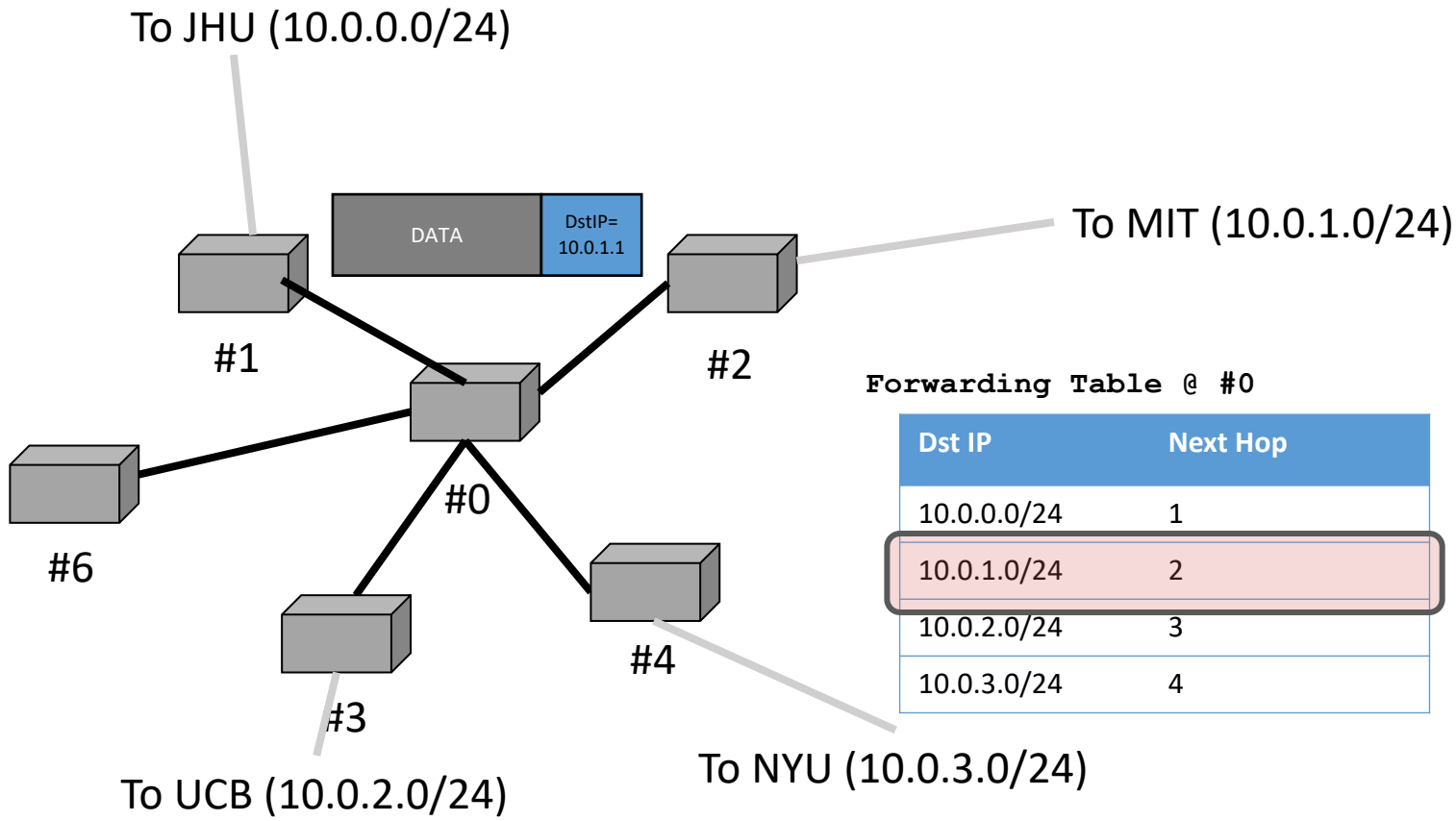
- **Programmable Networks**
- **Tutorial on Assignment 4**

Recap: Forwarding vs. routing

- **Forwarding: "data plane"**
  - Directing one data packet
  - Each router using local routing state
- **Routing: "control plane"**
  - Computing the forwarding tables that guide packets
  - Jointly computed by routers using a distributed algorithm

- **Very different timescales!**

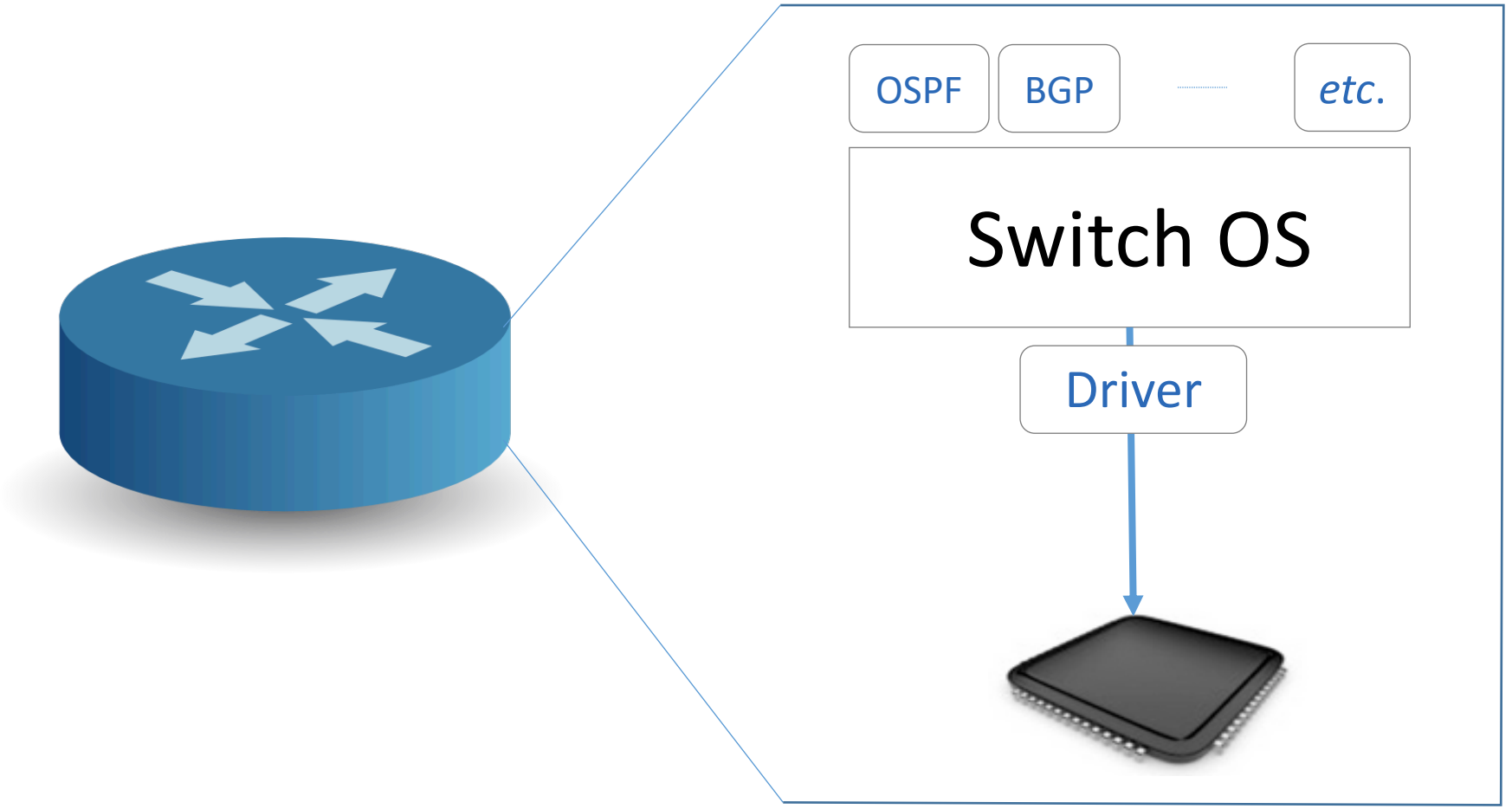
Recap: Forwarding

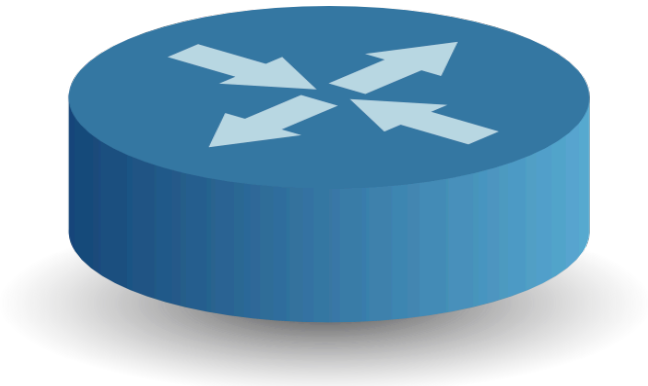


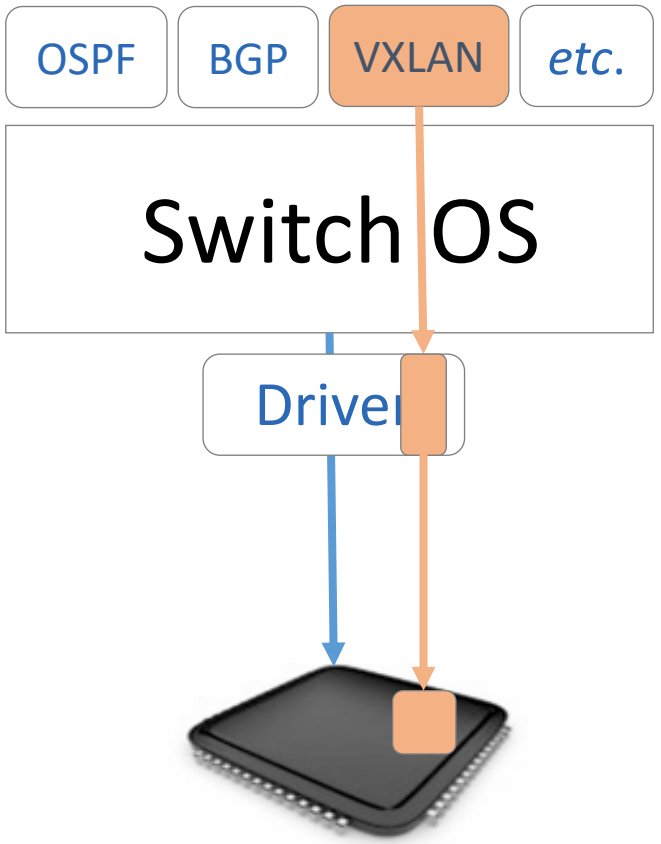
Forwarding Table @ #0

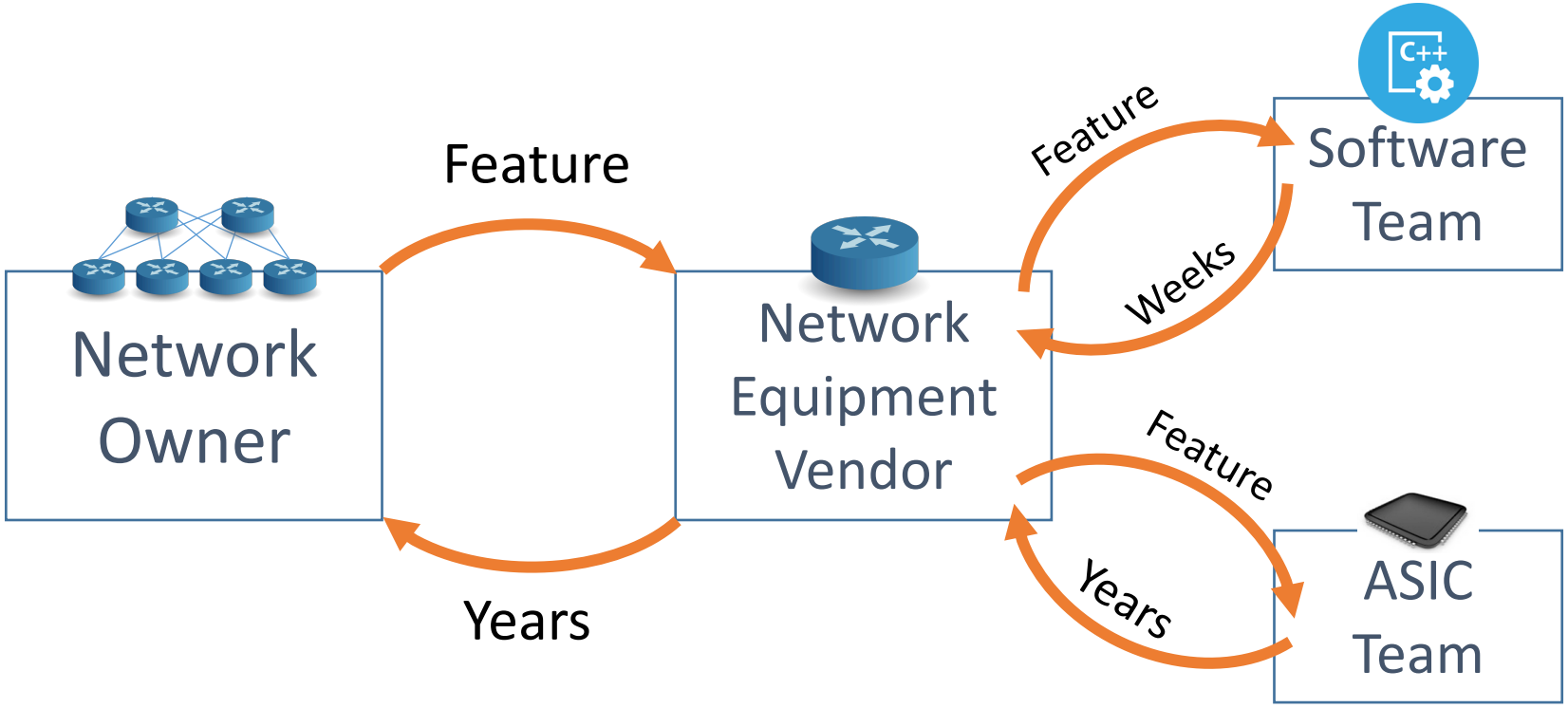
Dst IP	Next Hop
10.0.0.0/24	1
10.0.1.0/24	2
10.0.2.0/24	3
10.0.3.0/24	4

Many functionalities in the data plane


OSPF
BGP
etc.
Switch OS
Driver




OSPF
BGP
VXLAN
etc.
Switch OS
Driver

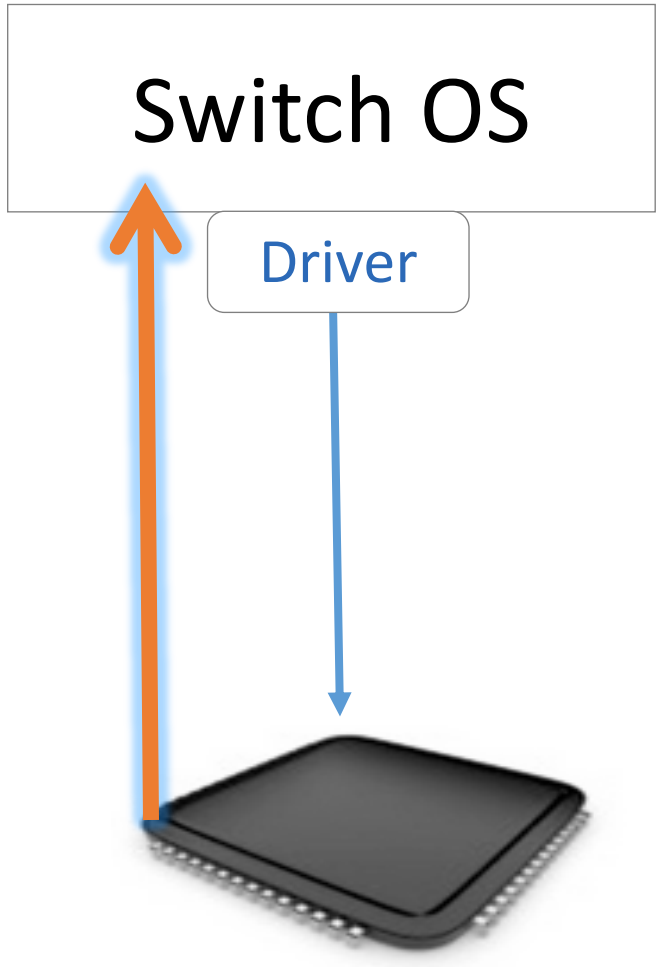

Feature
Network
Owner
Years
Network
Equipment
Vendor
Feature
Weeks
Software
Team
Feature
Years
ASIC
Team

When you need a new feature…

1. Equipment vendor can’t just send you a software upgrade
2. New forwarding features take years to develop
3. By then, you’ve figured out a kludge to work around it
4. Your network gets more complicated, more brittle
5. Eventually, when the upgrade is available, it either
   - No longer solves your problem, or
   - You need a fork-lift upgrade, at huge expense.

Network systems are built “bottoms-up”

“This is how I process packets …”



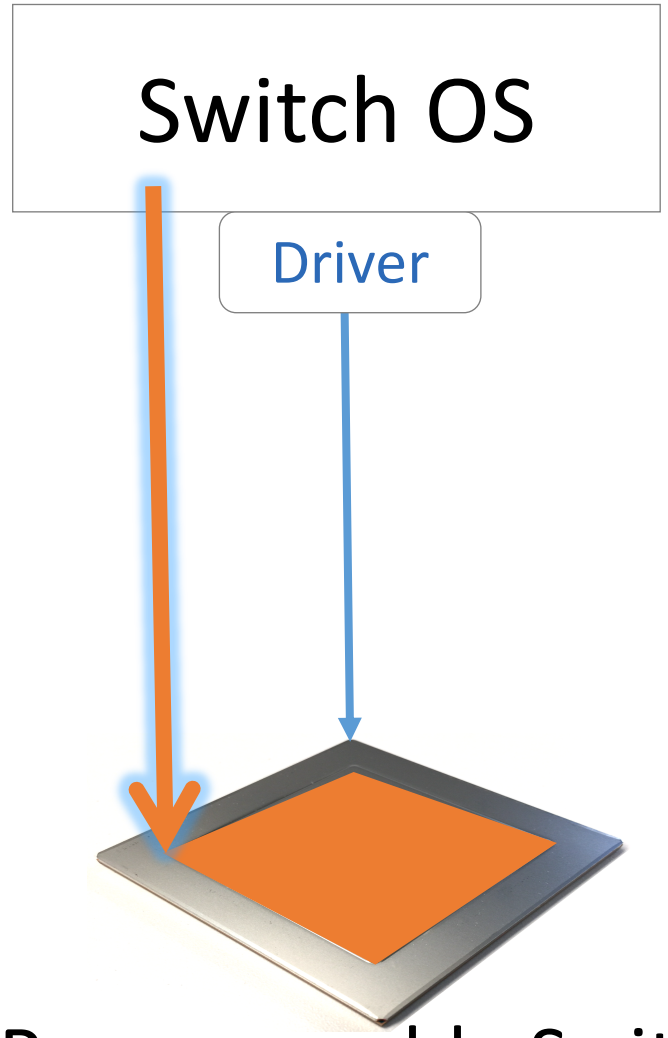
Fixed-function switch

Network systems are starting to be programmed “top-down”

“This is precisely how you must process packets”

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

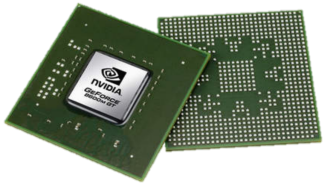
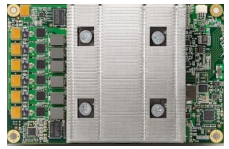
```
action export_queue_latency (sw_id) {
  add_header(int_header);
  modify_field(int_header.kind, TCP_OPTION_INT);
  modify_field(int_header.len, TCP_OPTION_INT_LEN);
  modify_field(int_header.sw_id, sw_id);
  modify_field(int_header.q_latency,
               intrinsic_metadata.deq_timedelta);
  add_to_field(tcp.dataOffset,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



Outline

1. Why programmability is happening now
2. How programmability is being used
   - Subtract features: Reducing complexity
   - Add proprietary features: Invent, differentiate, own
   - Silicon independence: Breaking a lock-in
   - Telemetry and measurement
3. Why programmability now from an ASIC technology viewpoint

Domain Specific Processors

Computers	Graphics	Signal Processing	Machine Learning		Networking
Java	OpenCL	Matlab	TensorFlow	>>>	Language
Compiler	Compiler	Compiler	Compiler		Compiler
↓	↓	↓	↓		↓
					?
CPU	GPU	DSP	TPU		

Domain Specific Processors

Computers

Java

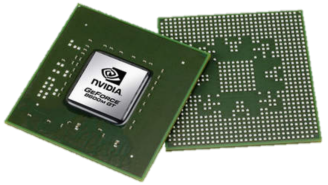
Compiler

CPU

Graphics

OpenCL

Compiler



GPU

Signal Processing

Matlab

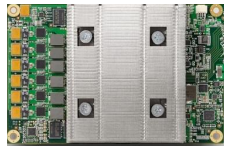
Compiler

DSP

Machine Learning

TensorFlow

Compiler

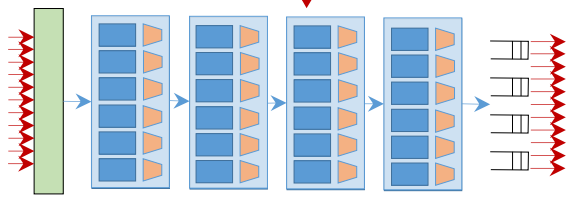


TPU

Networking

P4

Compiler



PISA

Many functionalities in the data plane

Data plane functionalities have a common style: match-action packet processing

IP Prefix Forwarding

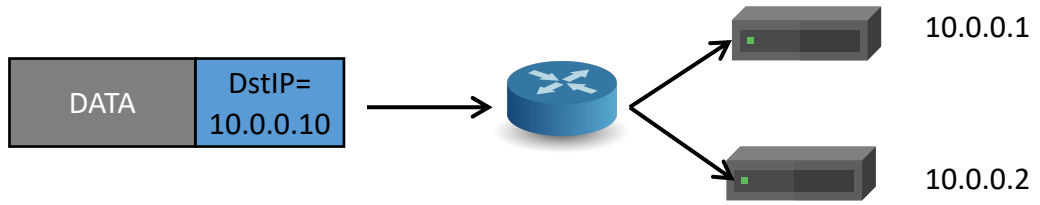
Match	Action
DstIP = 10.0.0.0/24	fwd(1)
DstIP = 10.0.1.0/24	fwd(2)
DstIP = 10.0.2.0/24	fwd(3)
DstIP = 10.0.3.0/24	fwd(4)

Access Control

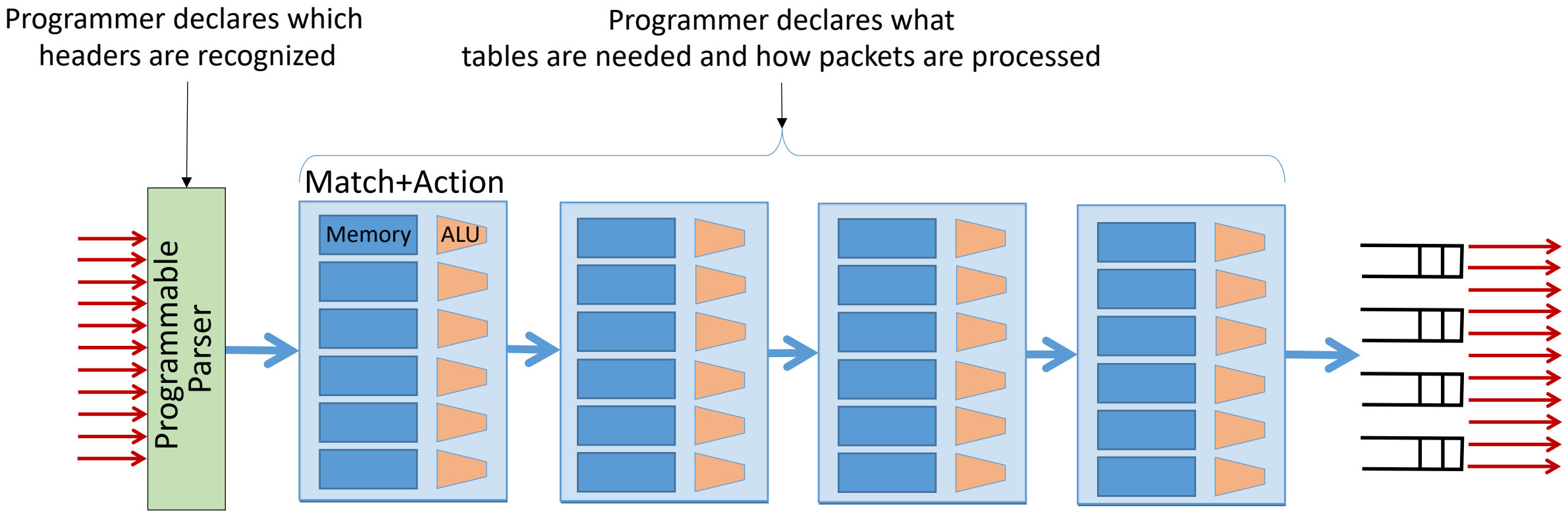
Match	Action
DstPort = 80	drop
DstIP = 10.0.0.1	drop
DstIP = 10.0.0.0/24	pass
DstIP = 10.0.0.0/16	drop

Load Balancing

Match	Action
DstIP = 10.0.0.10	DstIP = random(10.0.0.1, 10.0.0.2)
DstIP = 10.0.1.10	DstIP = random(10.0.1.1, 10.0.1.2)

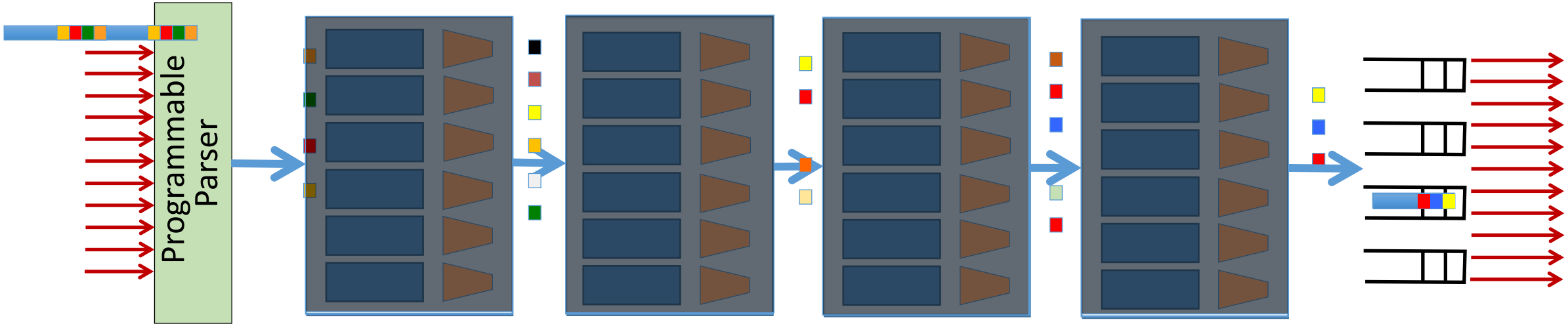


PISA: Protocol Independent Switch Architecture



All stages are identical – makes PISA a good “compiler target”

PISA: Protocol Independent Switch Architecture



Tofino 6.5Tb/s Switch

December 2016

65 x 100GE (or 260 x 25GE)

Same power and cost as fixed-function switches.

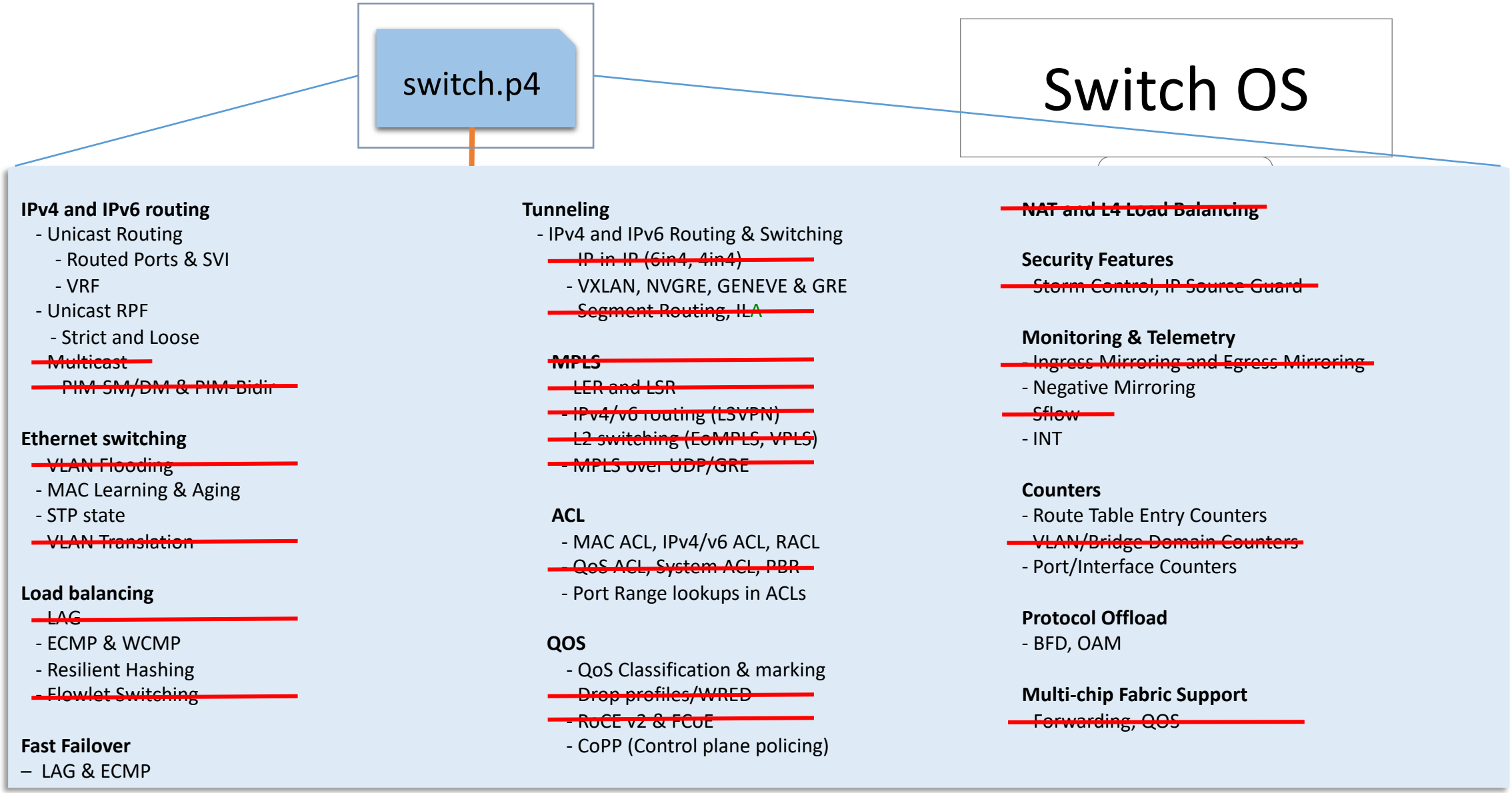
Outline

1. Why programmability is happening now
2. How programmability is being used
   - Subtract features: Reducing complexity
   - Add proprietary features: Invent, differentiate, own
   - Silicon independence: Breaking a lock-in
   - Telemetry and measurement
3. Why programmability now from an ASIC technology viewpoint

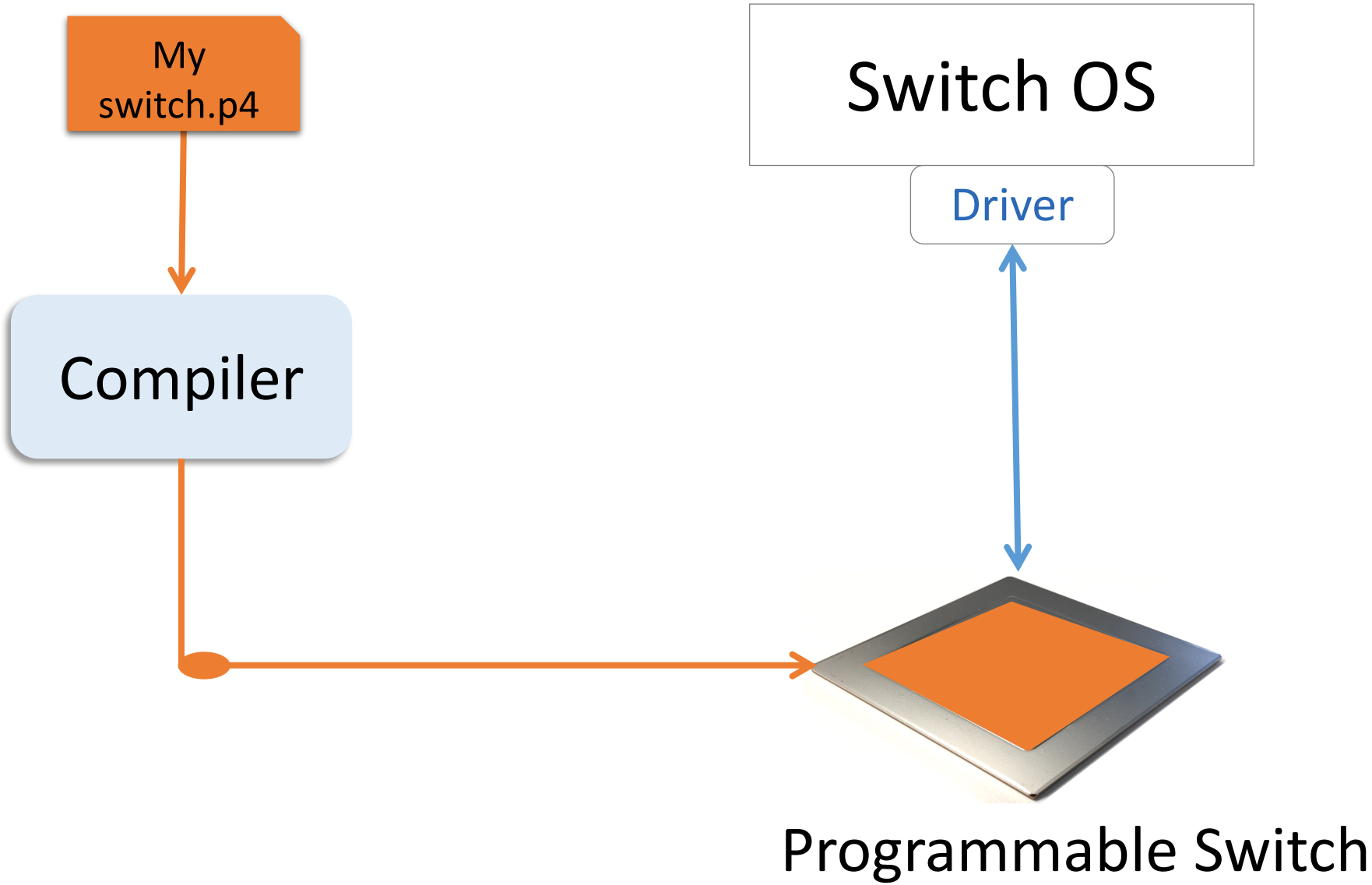
How programmability is being used

❶ Reducing complexity

Reducing complexity



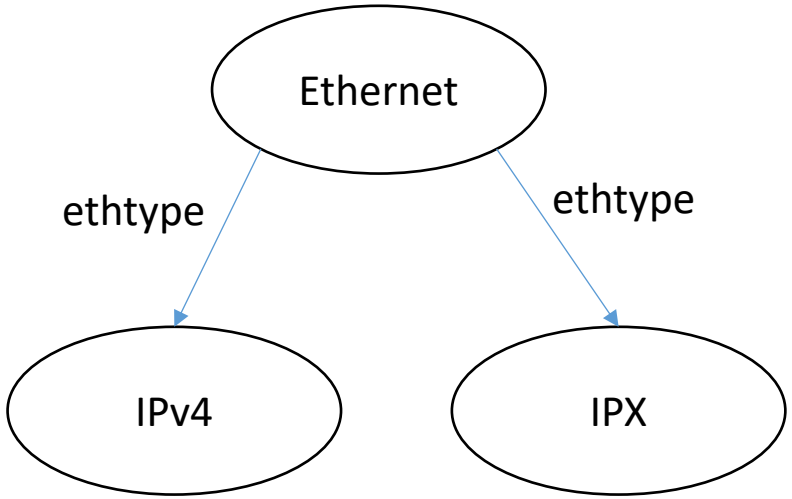
Reducing complexity



How programmability is being used

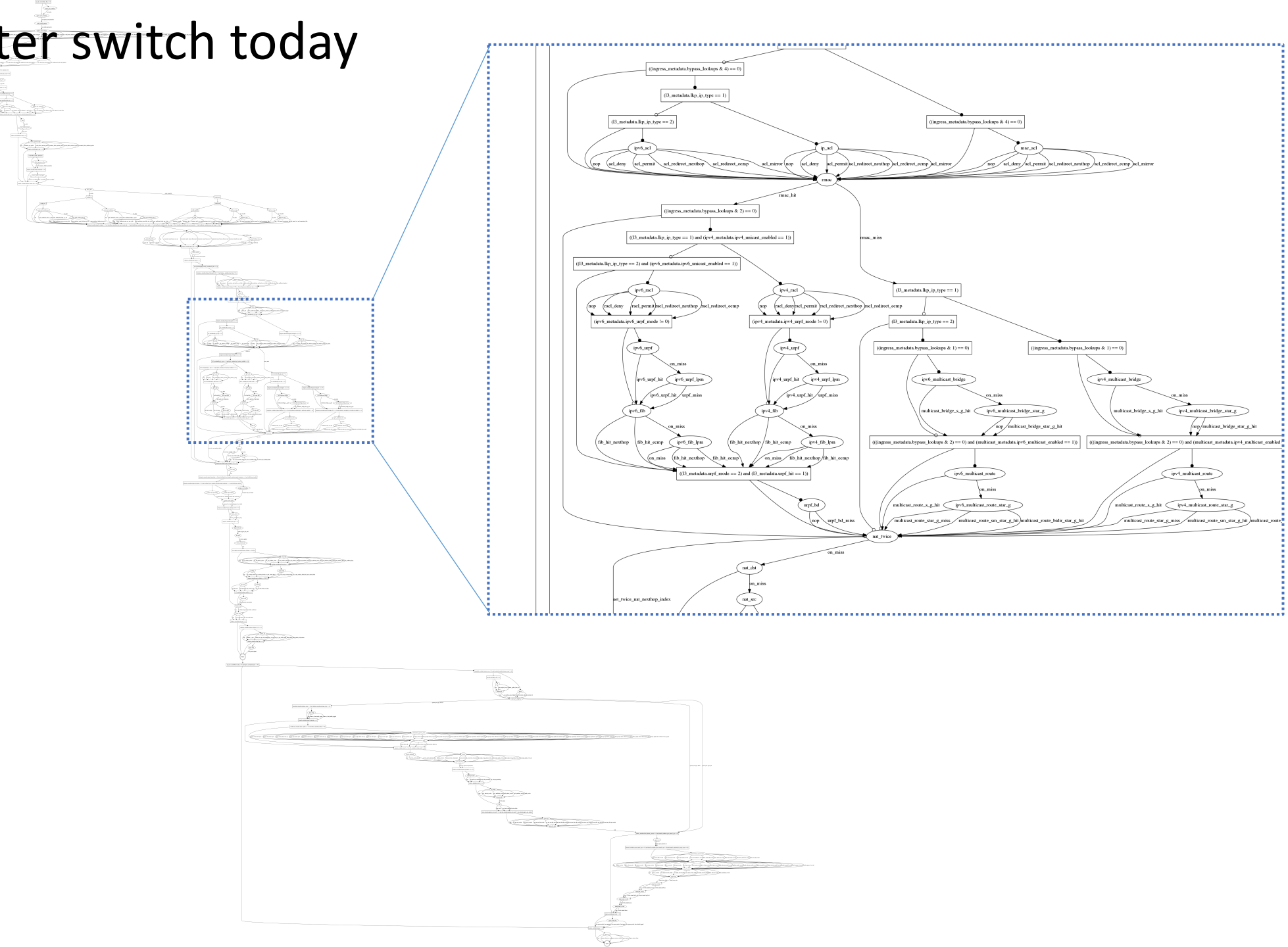
❷ Adding proprietary features

Protocol complexity 20 years ago



Datacenter switch today

switch.p4



Adding features: Some examples so far

1. New encapsulations and tunnels
2. New ways to tag packets for special treatment
3. New approaches to routing: e.g. source routing in MSDCs
4. New approaches to congestion control
5. New ways to process packets: e.g. processing ticker-symbols

New applications: Some examples so far

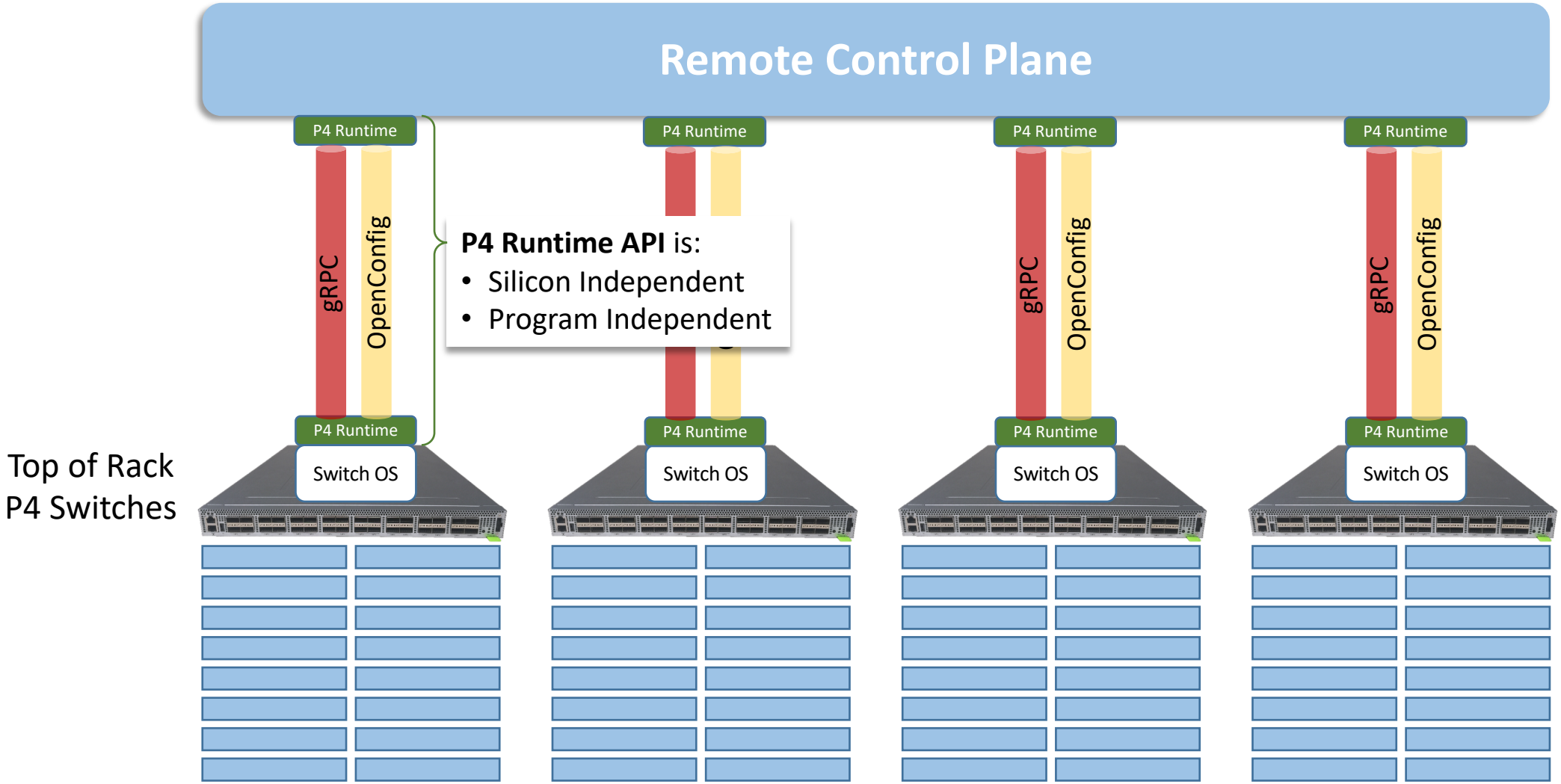
1. Layer-4 Load Balancer[1]
   - Replace 100 servers or 10 dedicated boxes with one programmable switch
   - Track and maintain mapping for 5-10 million http flows
2. Fast stateless firewall
   - Add/delete and track 100s of thousands of new connections per second
3. Cache for Key-value store[2]
   - Memcache in-network cache for 100 servers
   - 1-2 billion operations per second

[1] “SilkRoad: Making Stateful Layer-4 Load Balancing Fast and Cheap Using Switching ASICs.” Rui Miao et al. Sigcomm 2017.
[2] “NetCache: Balancing Key-Value Stores with Fast In-Network Caching”, Xin Jin et al. To appear at SOSP 2017

How programmability is being used

❸ Silicon independence

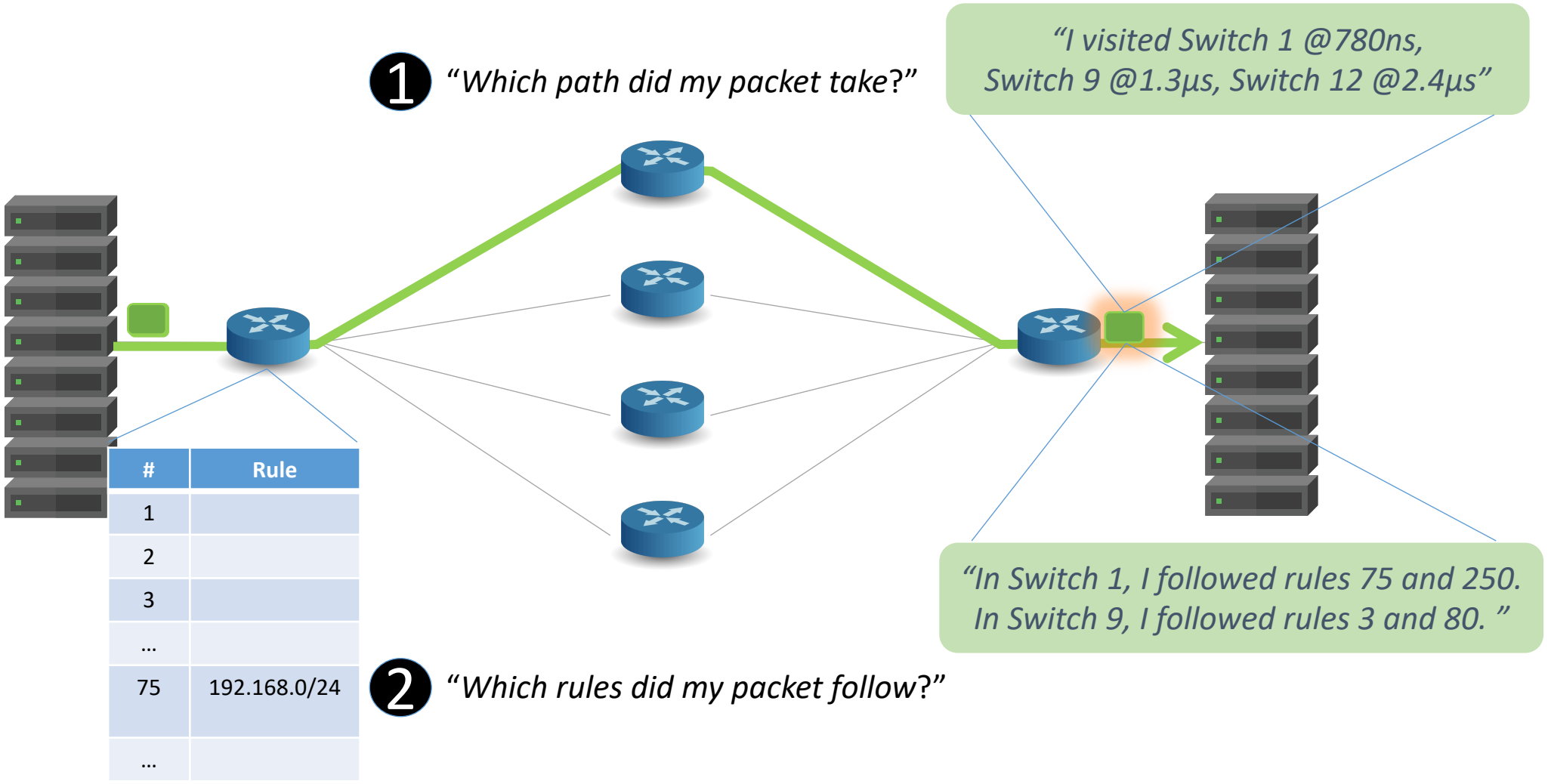
P4 Runtime Open-source project to remotely control P4 switches[1]



[1] “P4 Program-dependent Controller Interface for SDN Applications”, Samar Abdi et al (Google), P4 Workshop 2017

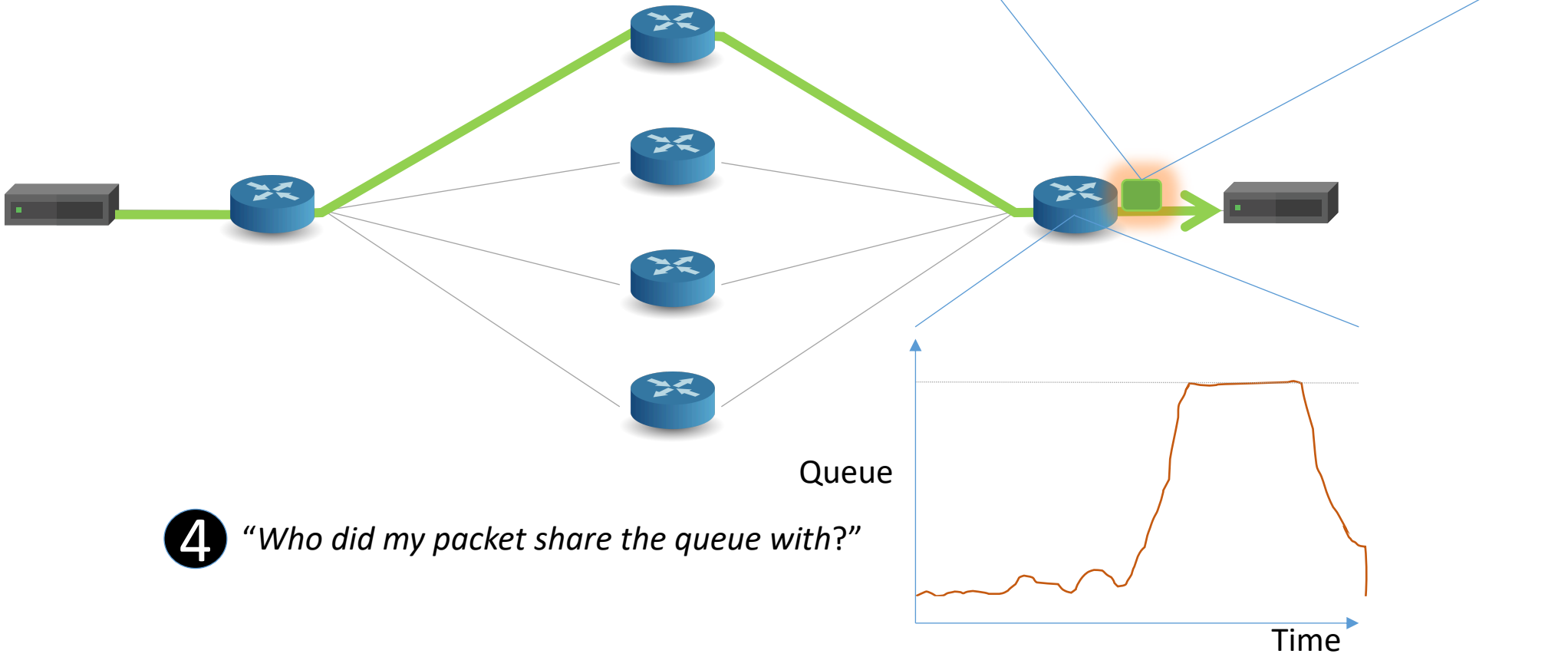
How programmability is being used

❹ Network telemetry


1
"Which path did my packet take?"
"I visited Switch 1 @780ns,
Switch 9 @1.3µs, Switch 12 @2.4µs"
Rule
1
2
3
...
75 192.168.0/24
...
2
"Which rules did my packet follow?"
"In Switch 1, I followed rules 75 and 250.
In Switch 9, I followed rules 3 and 80. "

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

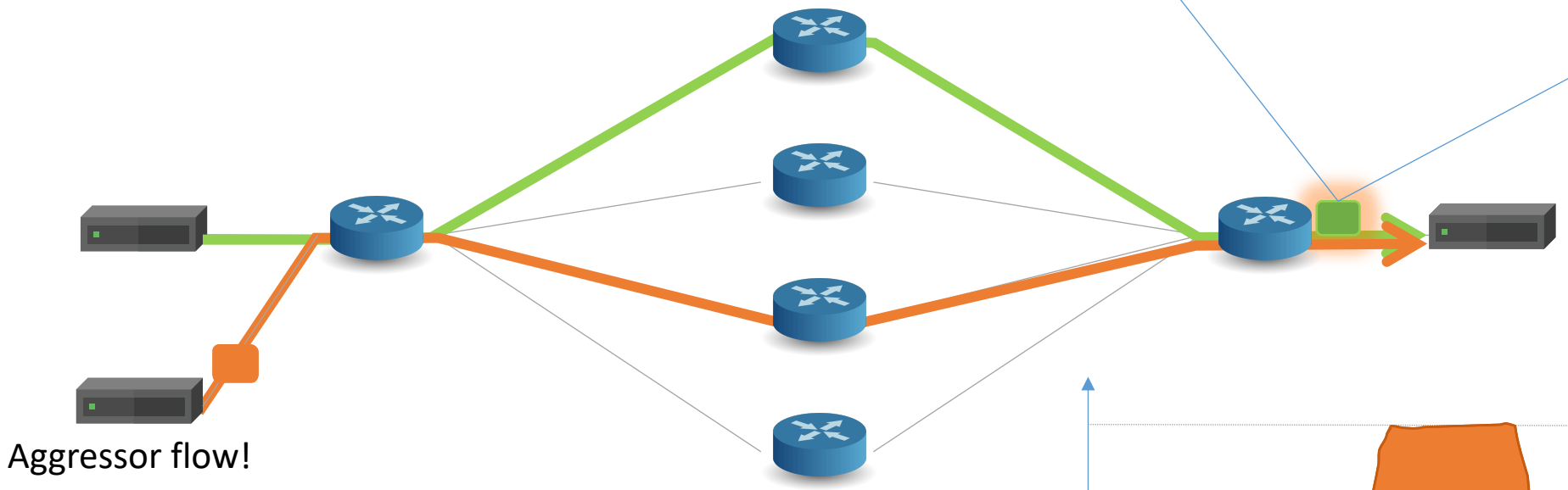
"Delay: 100ns, 200ns, 19740ns"

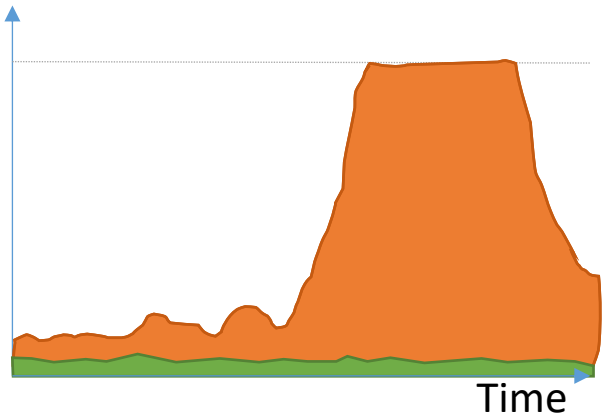


4 *"Who did my packet share the queue with?"*

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

"Delay: 100ns, 200ns, 19740ns"





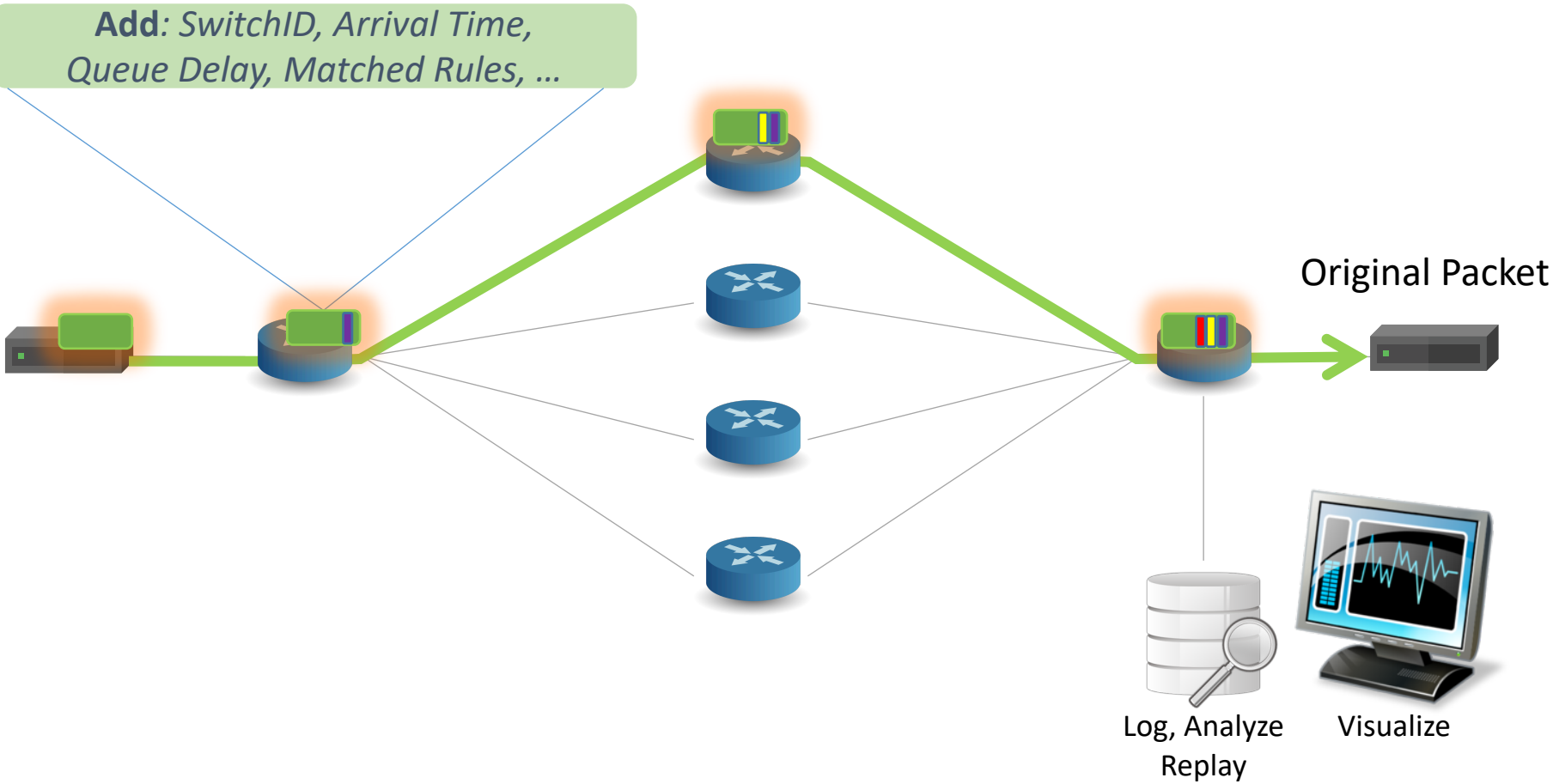
4 *"Who did my packet share the queue with?"*

We’d like the network to 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?”*

A programmable device can potentially answer all four questions at line rate.

INT: Inband Network Telemetry

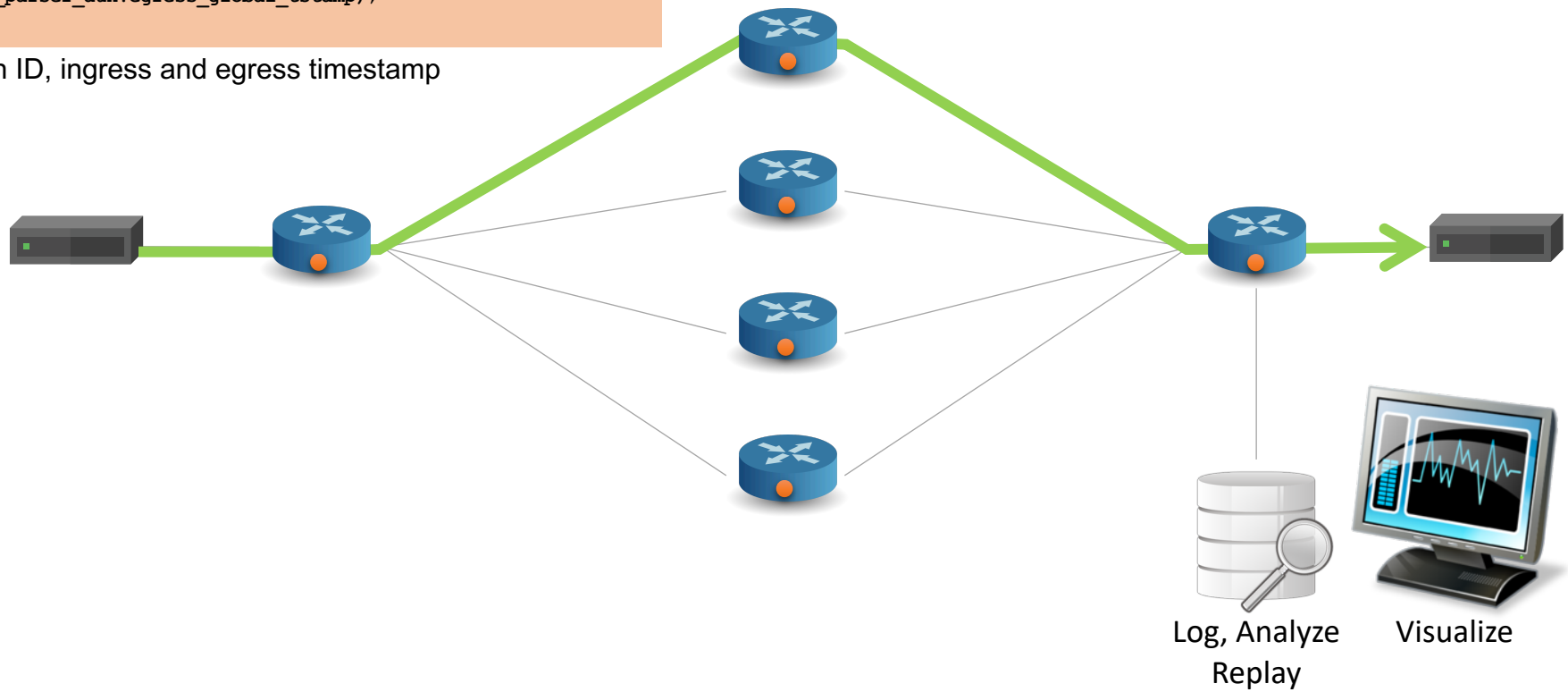


```
/* INT: add switch id */
action int_set_header_0() {
  add_header(int_switch_id_header);
  modify_field(int_switch_id_header.switch_id,
               global_config_metadata.switch_id);
}

/* INT: add ingress timestamp */
action int_set_header_1() {
  add_header(int_ingress_tstamp_header);
  modify_field(int_ingress_tstamp_header.ingress_tstamp, i2e_metadata.ingress_tstamp);
}

/* INT: add egress timestamp */
action int_set_header_2() {
  add_header(int_egress_tstamp_header);
  modify_field(int_egress_tstamp_header.egress_tstamp,
                eg_intr_md_from_parser_aux.egress_global_tstamp);
}
```

P4 code snippet: Insert switch ID, ingress and egress timestamp



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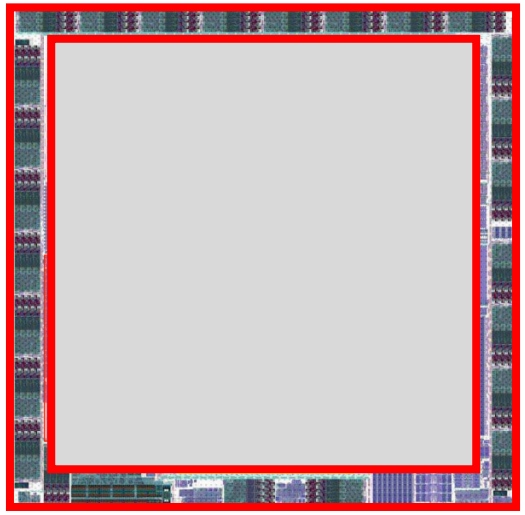
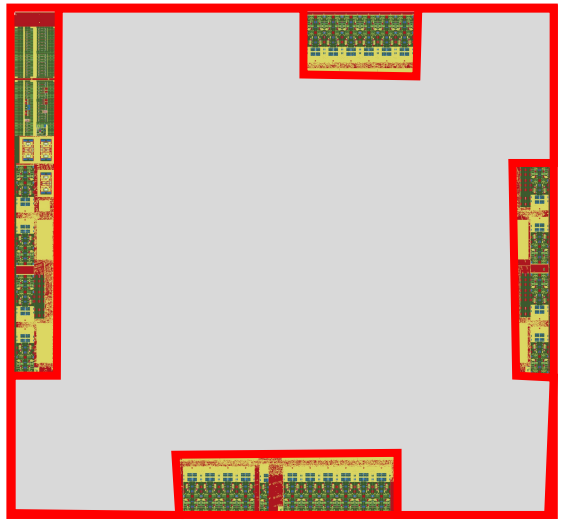
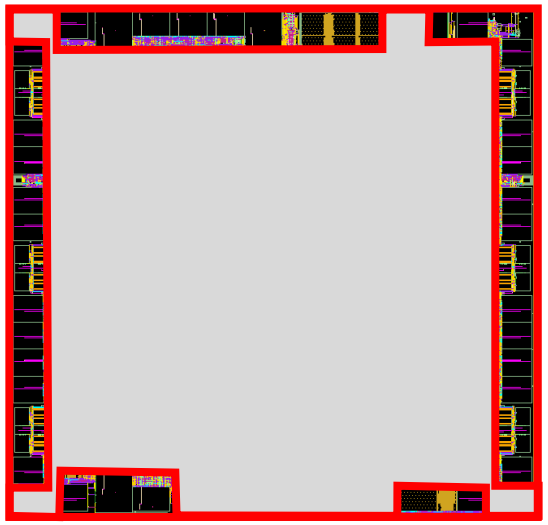
Serial I/O: About 30% of switch chip area



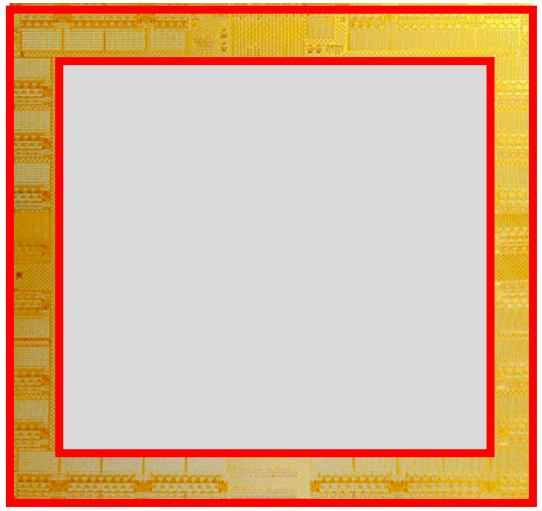
Intel Alta (2011)



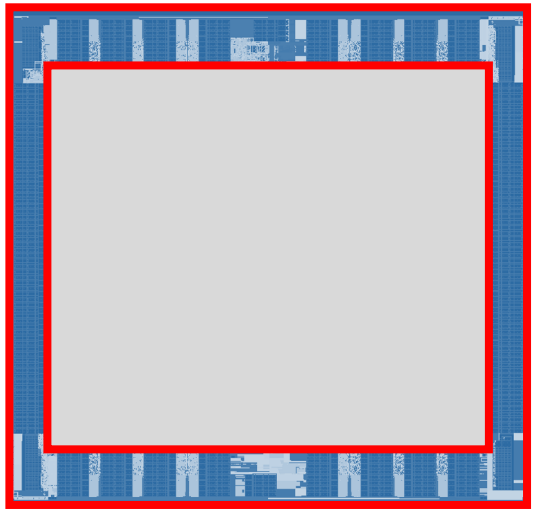
Cisco (2011)



Ericsson Spider (2011)

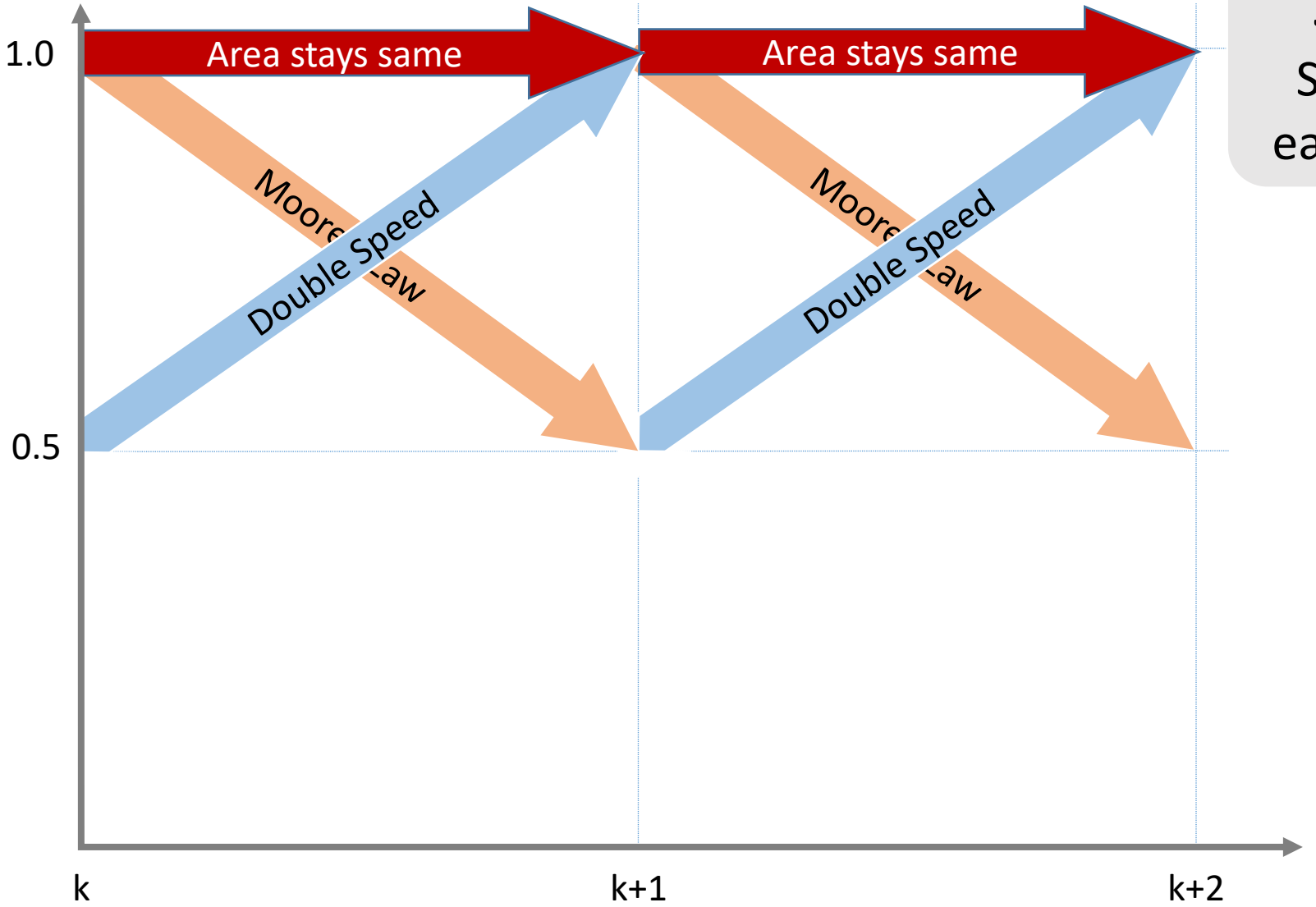


Broadcom Tomahawk (2014)



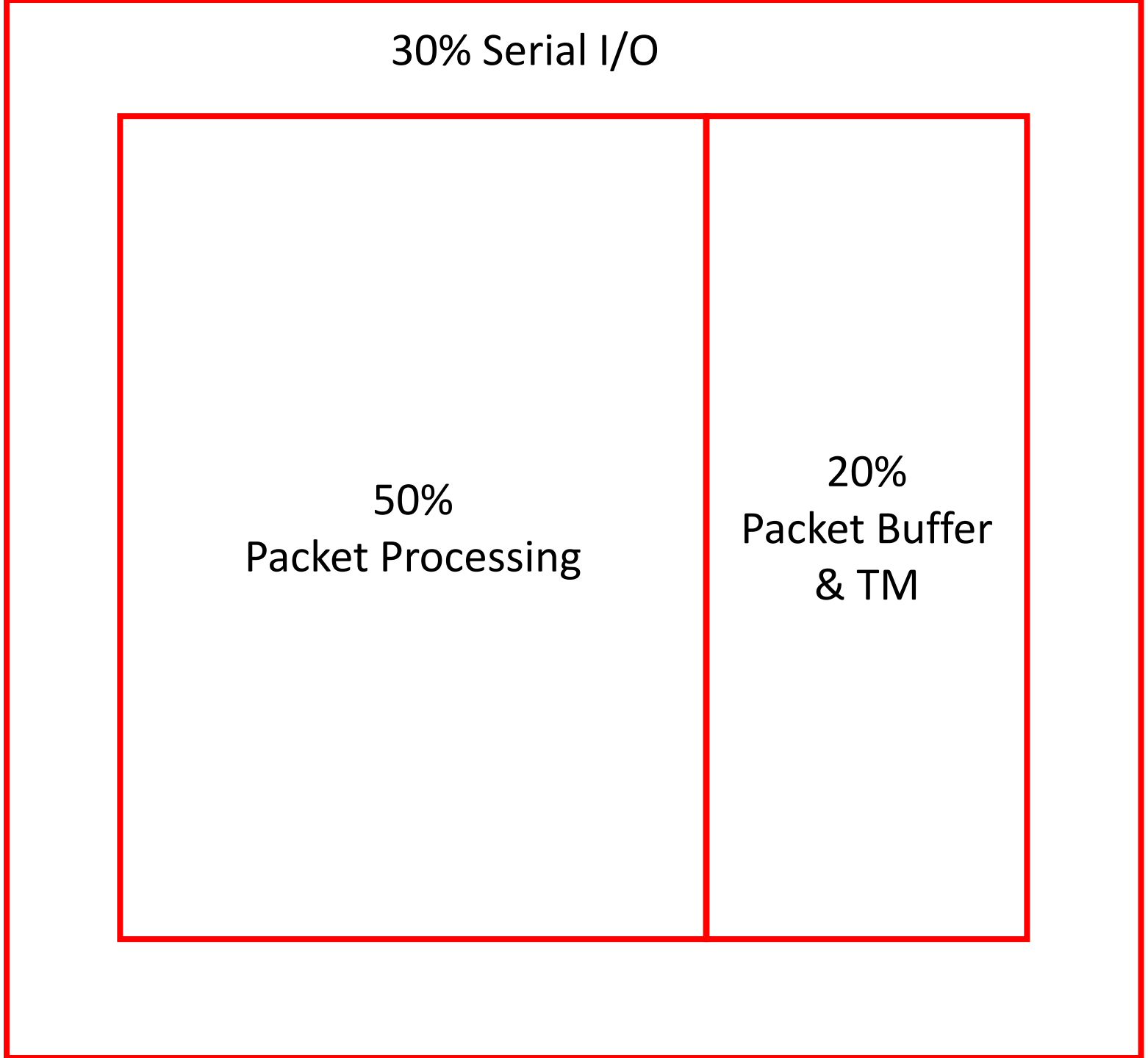
Barefoot Tofino (2016)

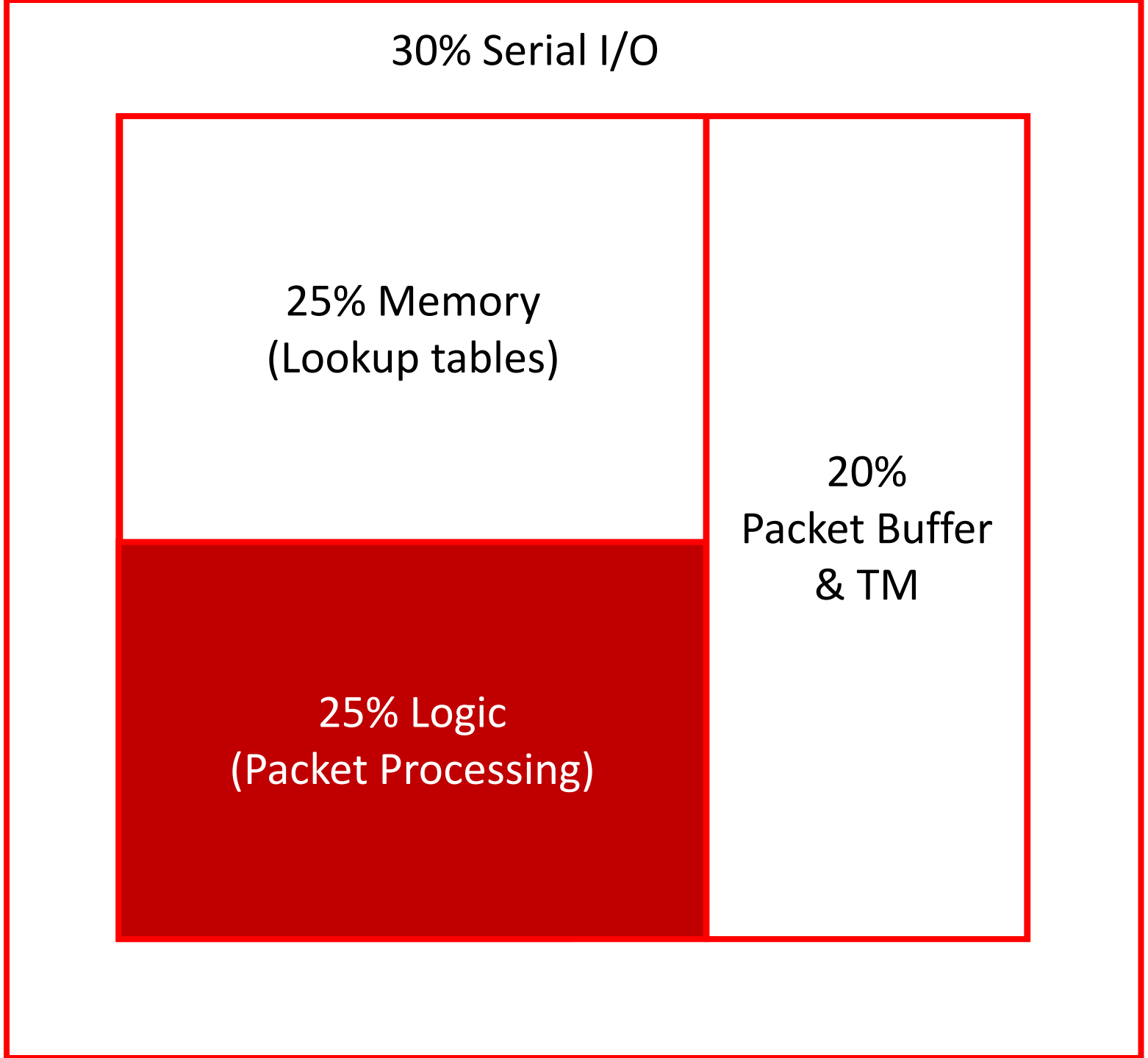
Switch chip area: Serial I/O



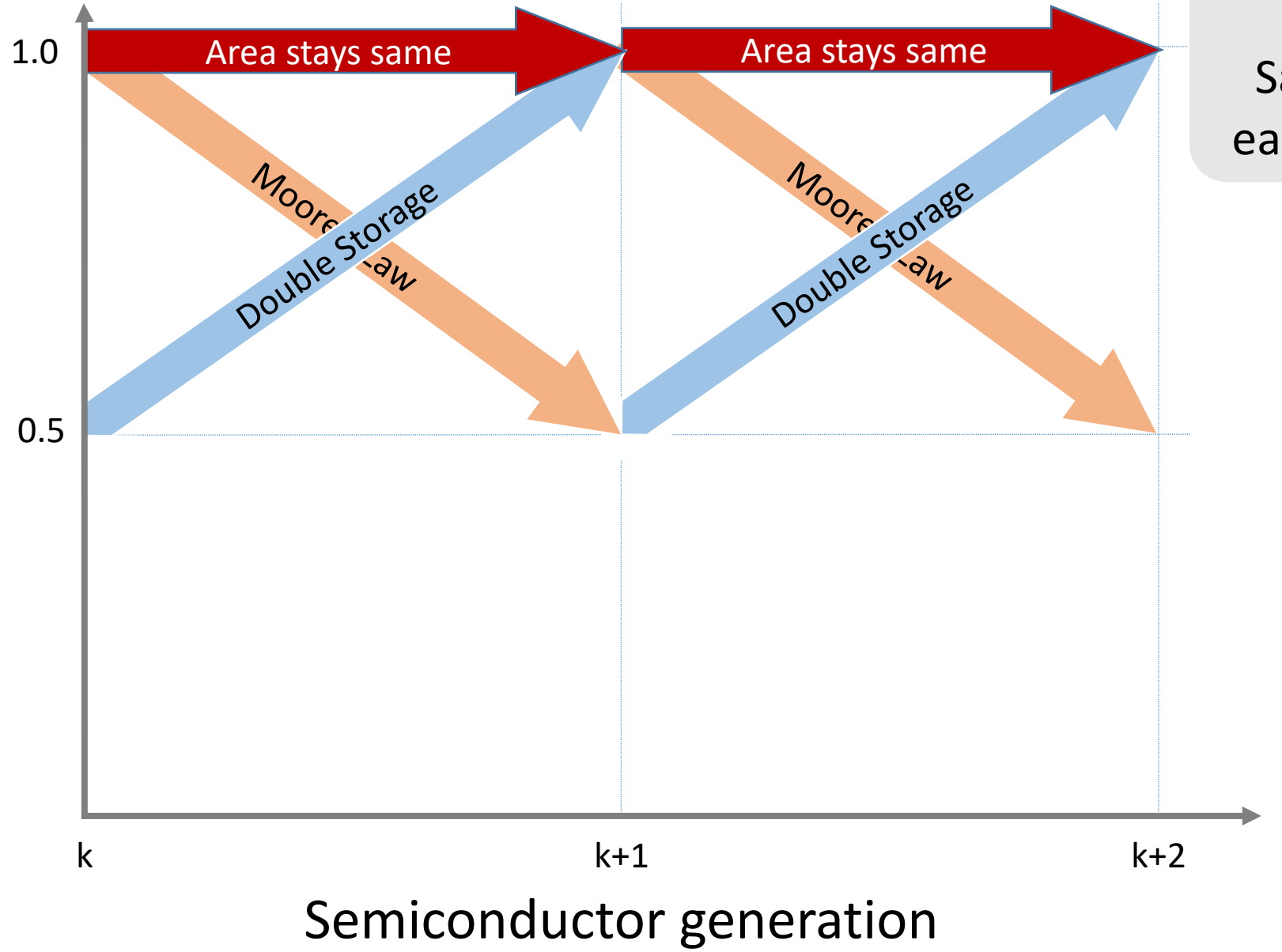
Serial I/O

Same area for each generation


30% Serial I/O
50%
Packet Processing
20%
Packet Buffer
& TM

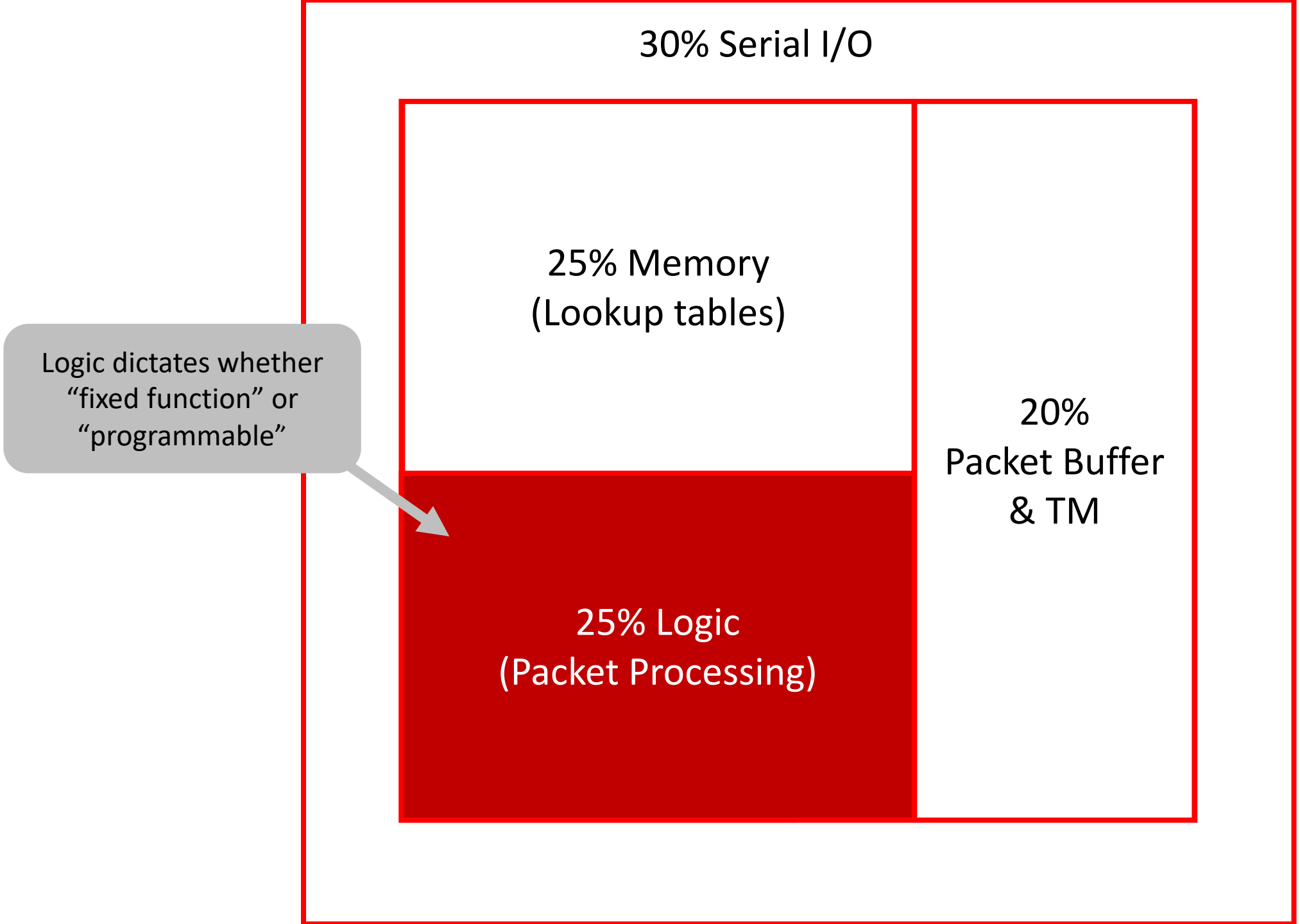

30% Serial I/O
25% Memory
(Lookup tables)
25% Logic
(Packet Processing)
20%
Packet Buffer
& TM

Switch chip area: Memory (Tables and Buffer)

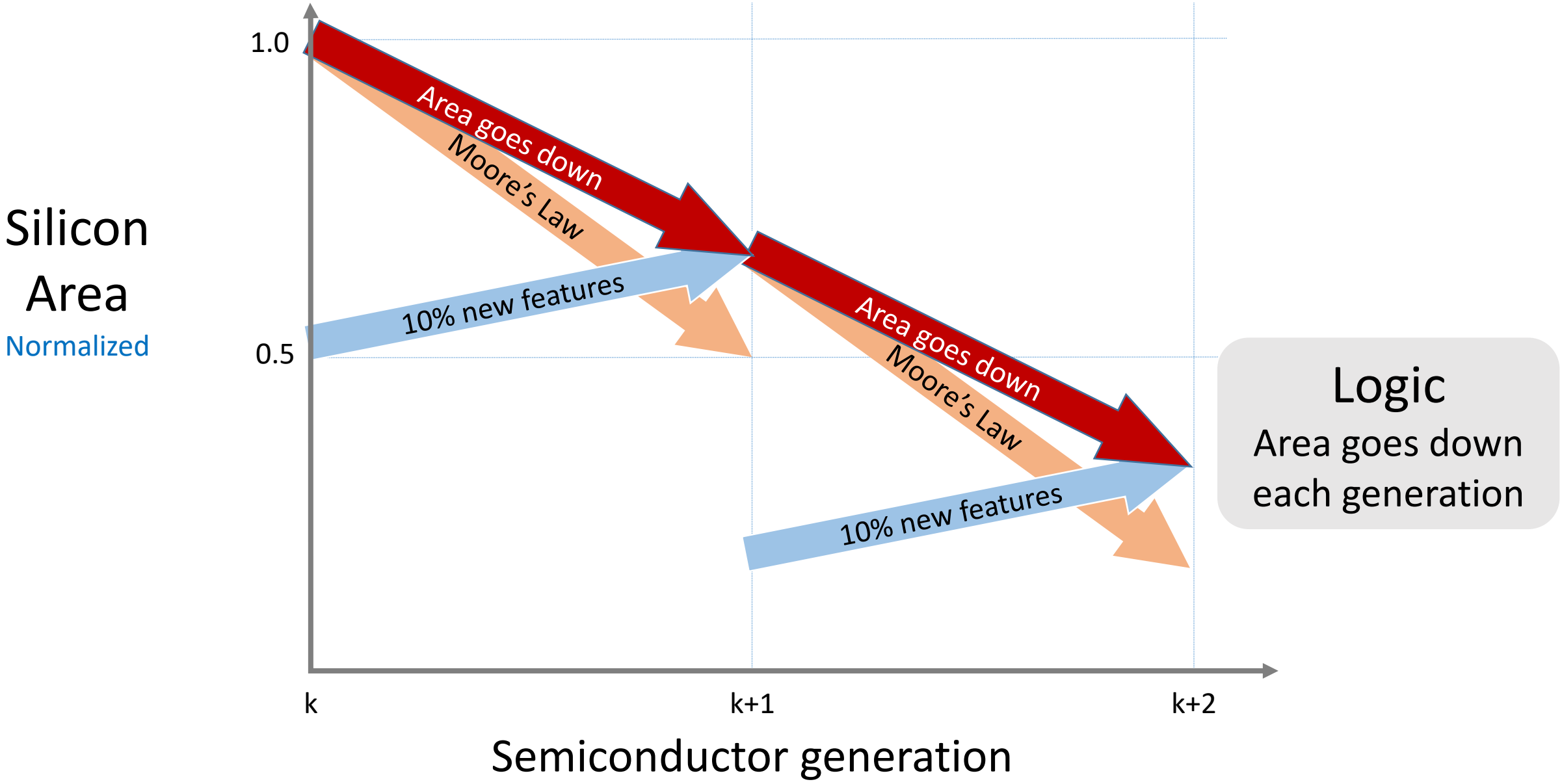


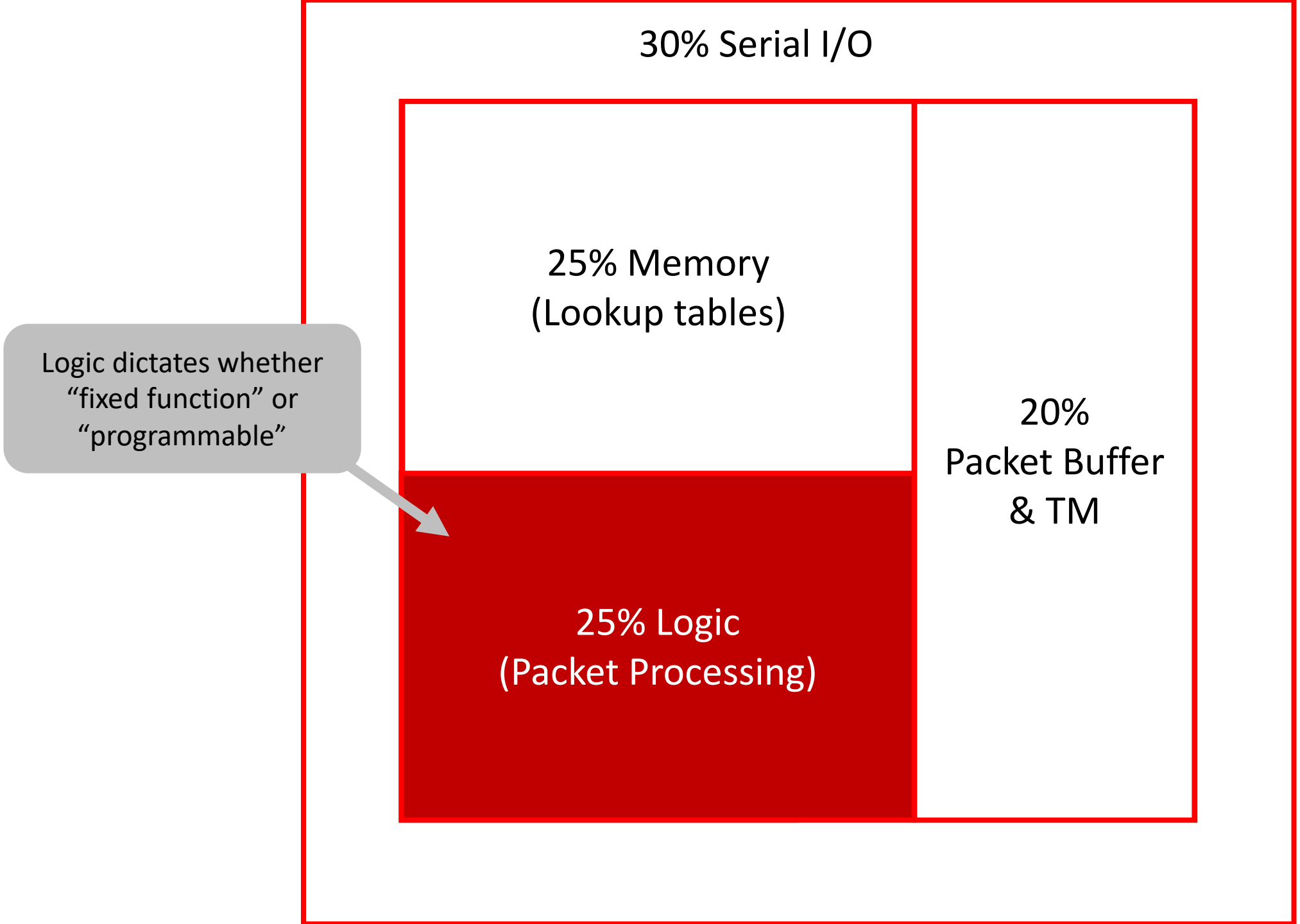
Memory

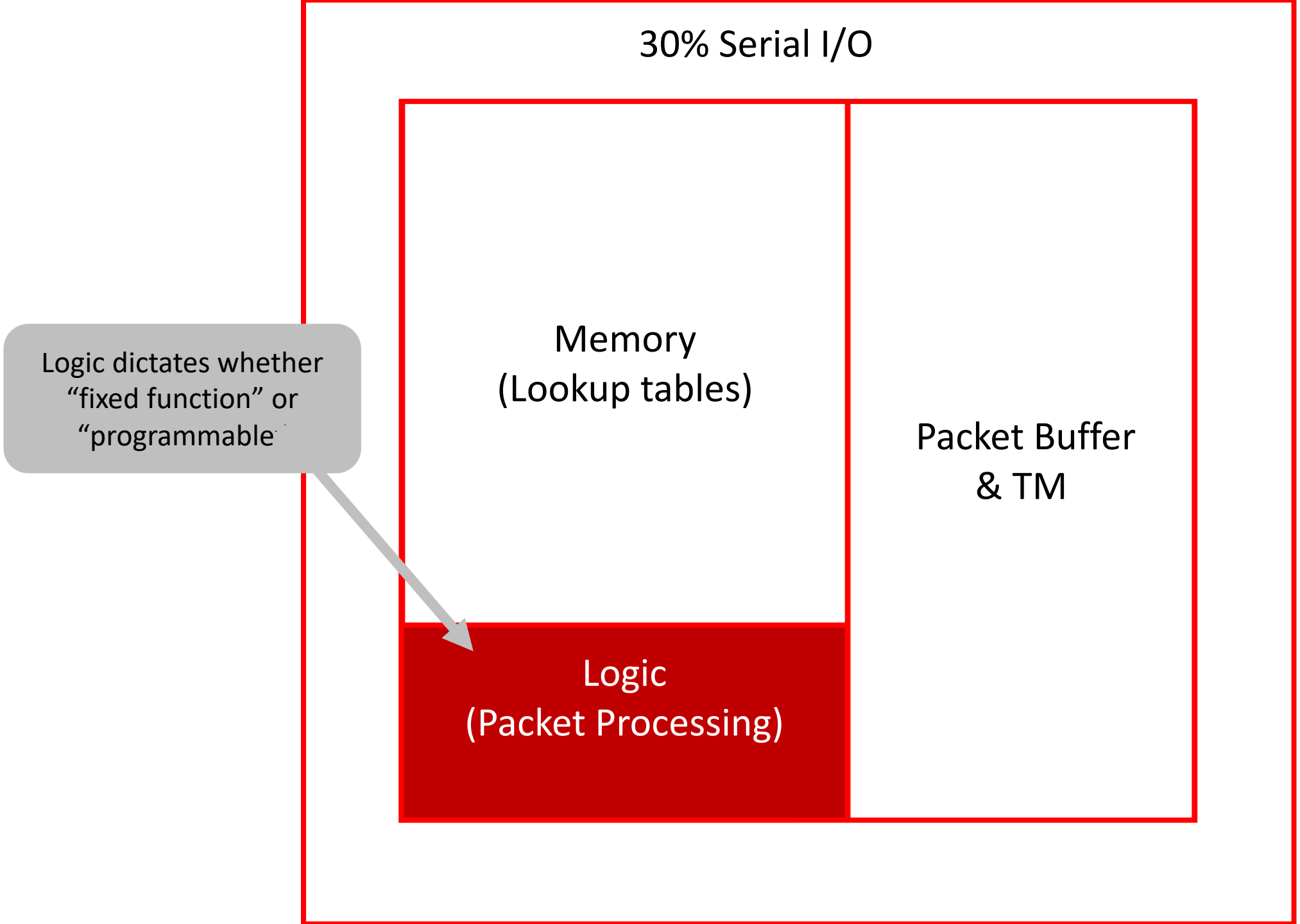
Same area for each generation


30% Serial I/O
25% Memory
(Lookup tables)
20%
Packet Buffer
& TM
25% Logic
(Packet Processing)
Logic dictates whether
“fixed function” or
“programmable”

Switch chip area: Packet Processing Logic




30% Serial I/O
25% Memory
(Lookup tables)
20%
Packet Buffer
& TM
25% Logic
(Packet Processing)
Logic dictates whether
“fixed function” or
“programmable”


30% Serial I/O
Memory
(Lookup tables)
Packet Buffer
& TM
Logic
(Packet Processing)
Logic dictates whether
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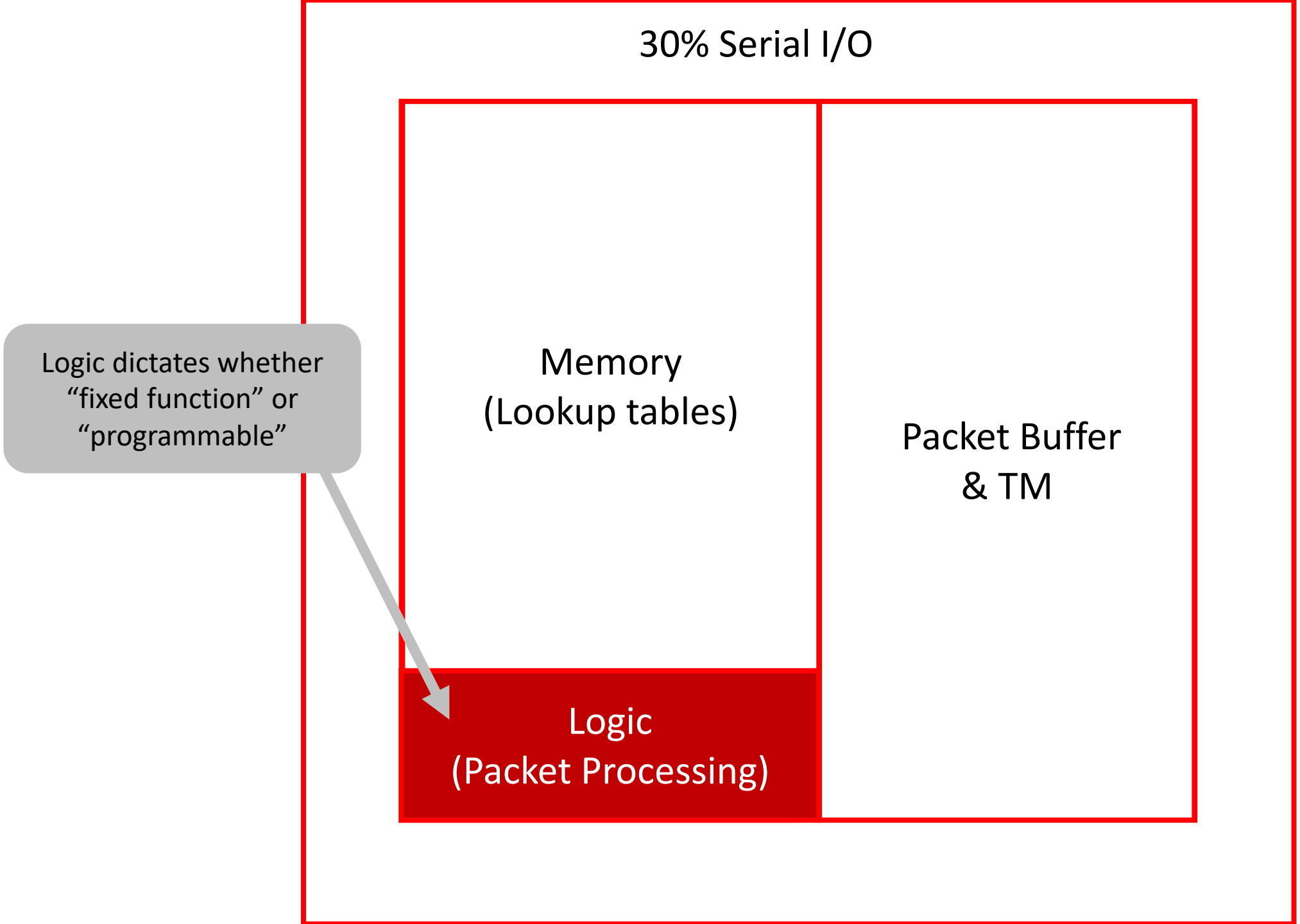
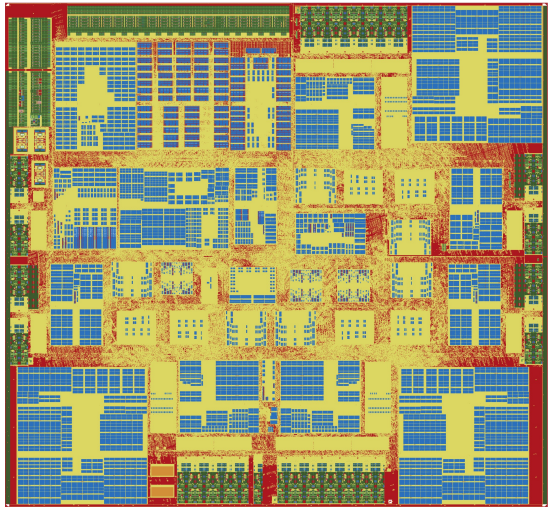
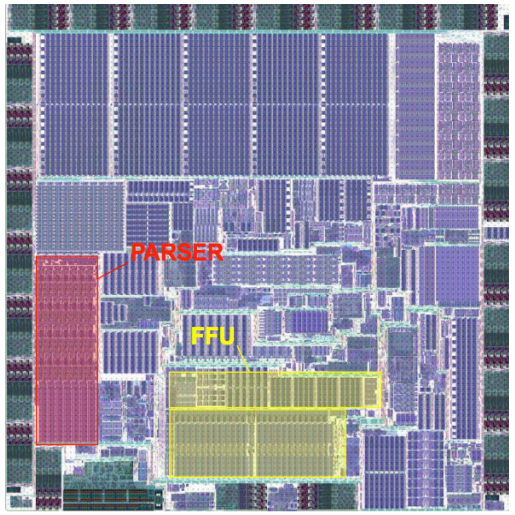

30% Serial I/O
Logic dictates whether "fixed function" or "programmable"
Memory (Lookup tables)
Packet Buffer & TM
Logic (Packet Processing)

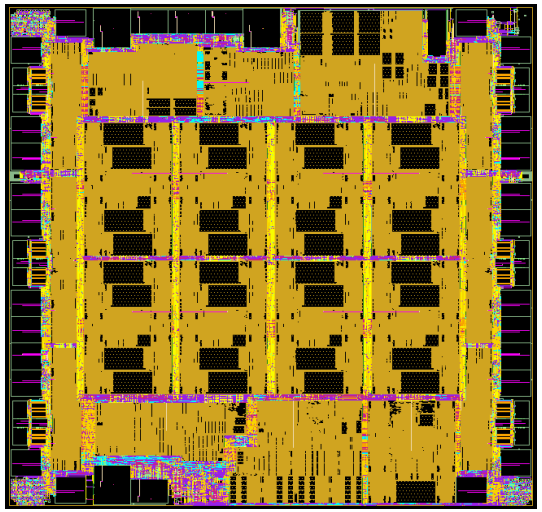
Programmable switch chips are more uniform



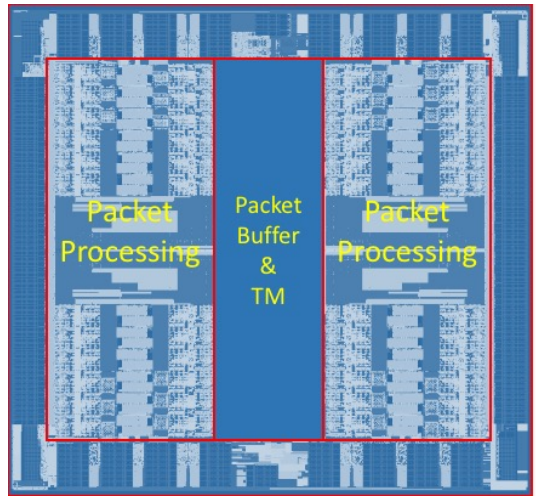
Cisco



Intel Alta



Ericsson Spider



Barefoot Tofino

More programmable

In summary

1. **Chip speed**: We can now make programmable switch chips as fast as fixed ones.
2. **Chip technology**: The difference in chip area and power between “programmable” and “fixed function” is going away.
3. **Chip complexity**: There are now too many protocols to correctly hard-code in silicon.
4. **New ideas**: Beautiful new ideas are owned by the programmer, not the chip designer.
5. **Level playing field**: Lets us create a solid platform, an abstraction layer, upon which more will be built

To learn more, visit P4.org

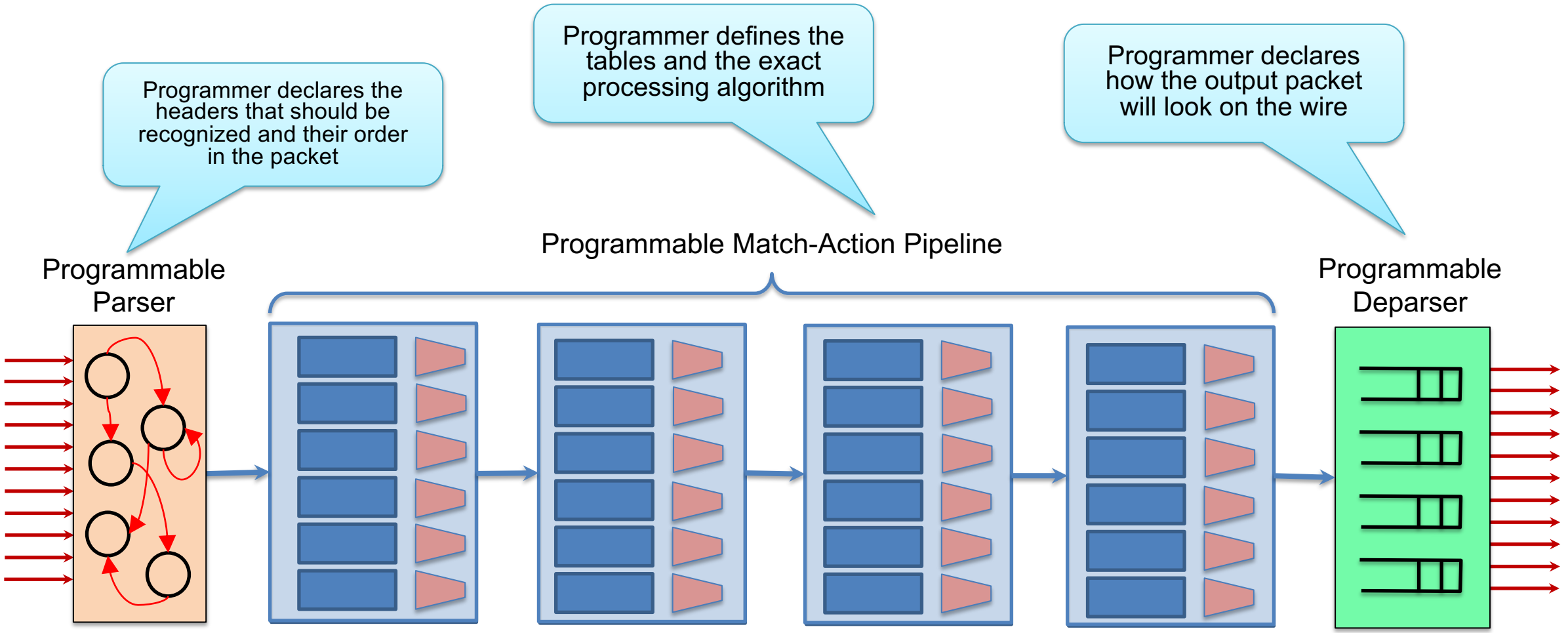
Agenda

- **Programmable Networks**
- **Tutorial on Assignment 4**

Tutorial on Assignment 4

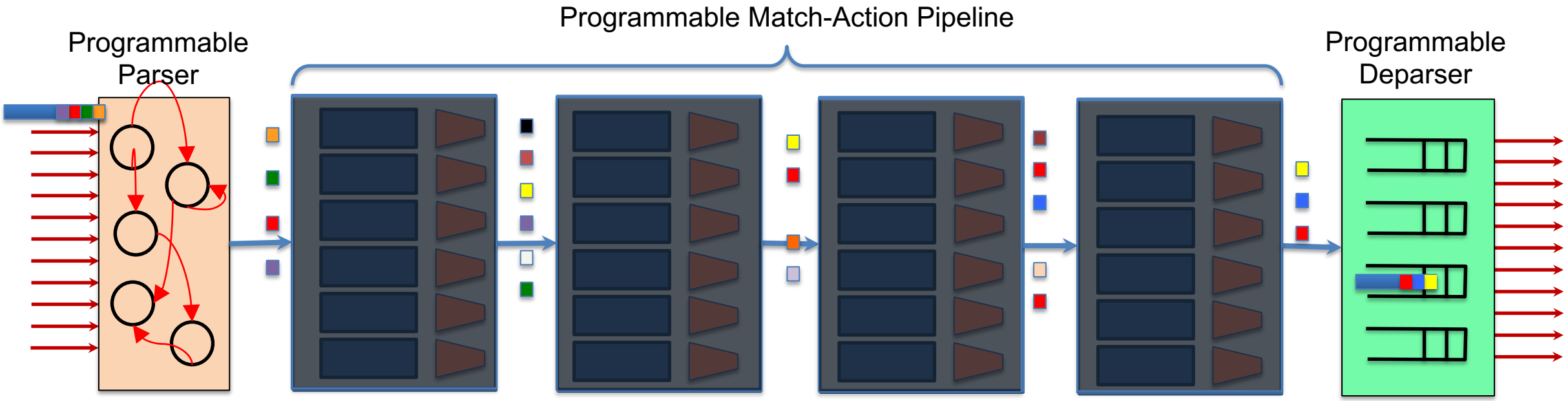
- Exercise 1: Access control list (ACL)
  - Write P4 code to implement access control list (acl.p4)
  - Add rules to your table to block certain destination port and IP (s1-acl.json)
- Exercise 2: Load balancing
  - Write P4 code to implement load balancing (lb.p4)
  - Add rules to your table to block certain destination port and IP (s1-lb.json)

PISA: Protocol-Independent Switch Architecture



PISA in Action

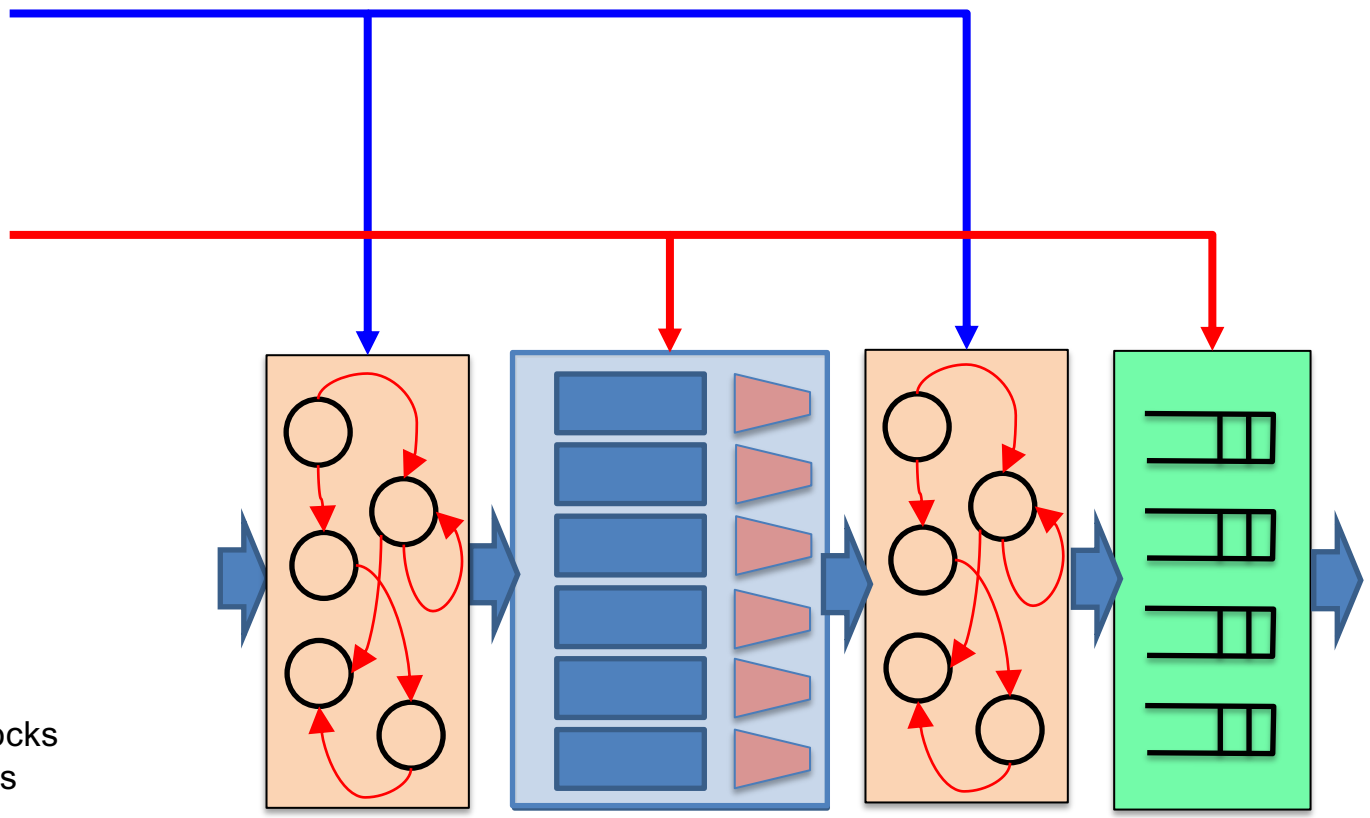
- Packet is parsed into individual headers (parsed representation)
- Headers and intermediate results can be used for matching and actions
- Headers can be modified, added or removed
- Packet is deparsed (serialized)



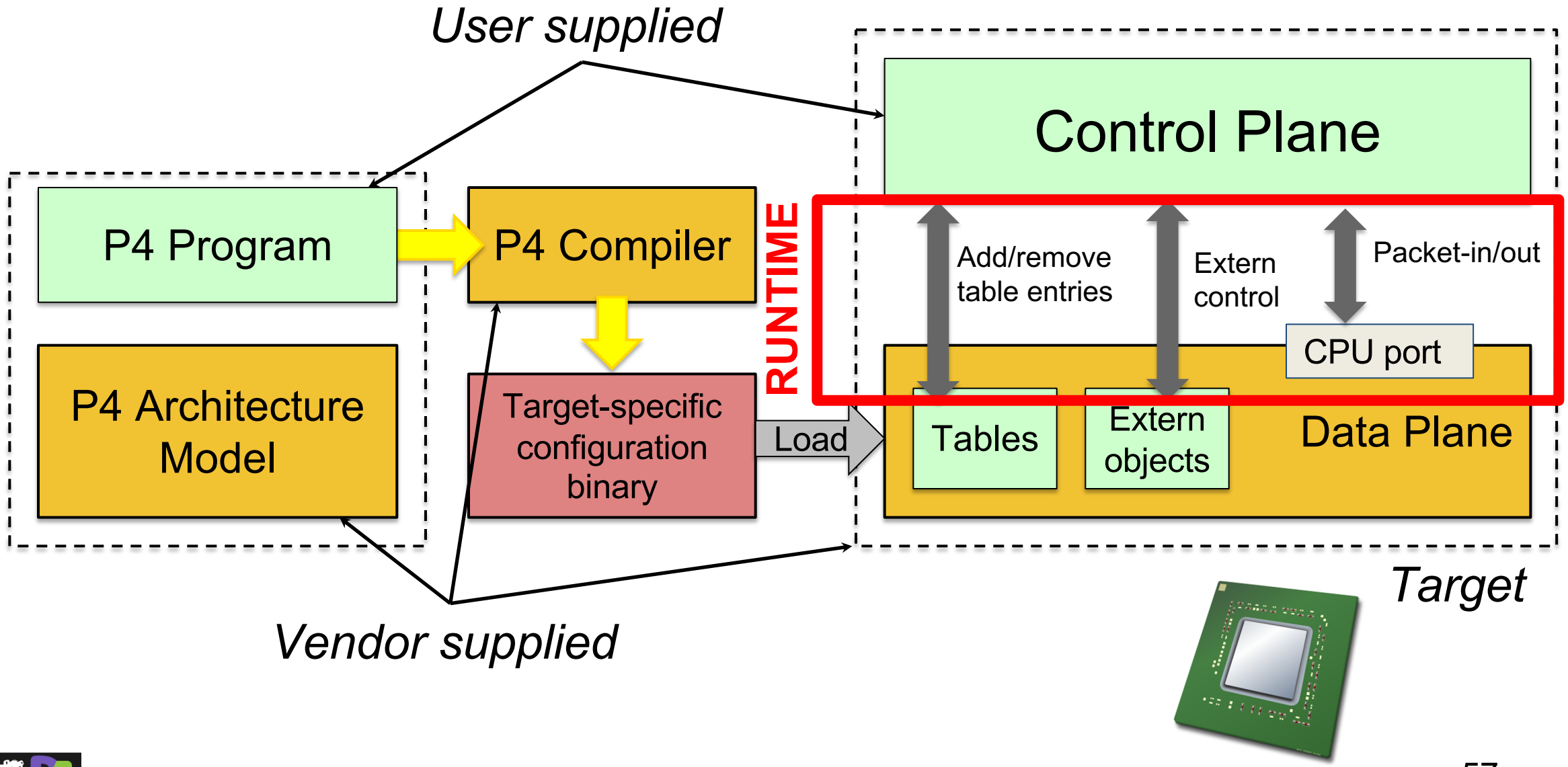
P4$_{16}$ Language Elements

- **Parsers** — State machine, bitfield extraction
- **Controls** — Tables, Actions, control flow statements
- **Expressions** — Basic operations and operators
- **Data Types** — Bistrings, headers, structures, arrays

- **Architecture Description** — Programmable blocks and their interfaces
- **Extern Libraries** — Support for specialized components

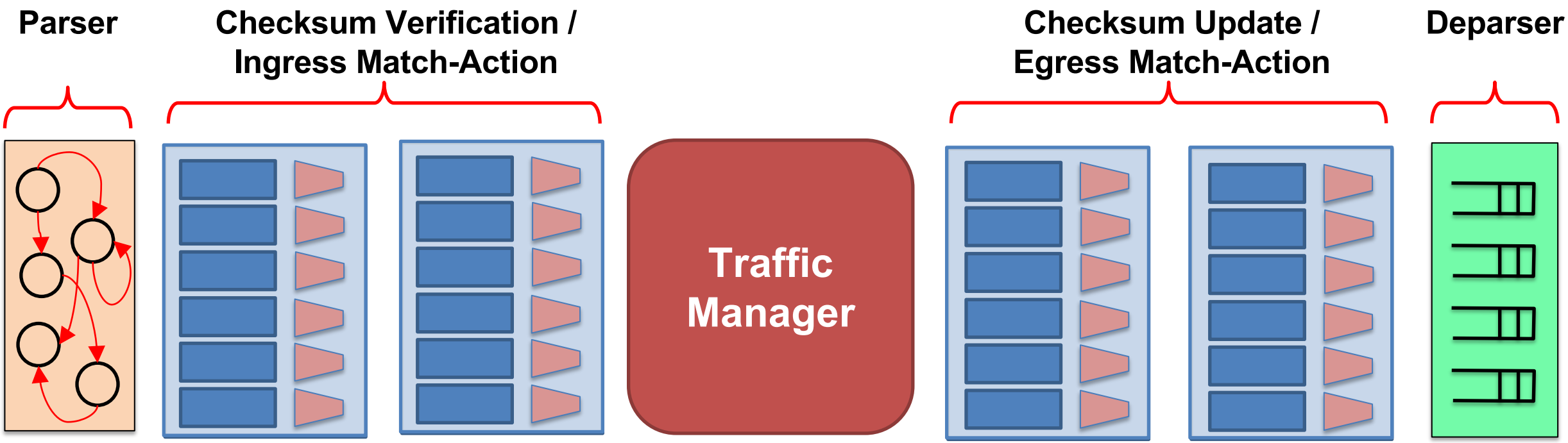


Programming a P4 Target



V1Model Architecture

- **Implemented on top of Bmv2's `simple_switch` target**
- **Bmv2 is a software switch that can run on your laptop**



$P4_{16}$ Program Template (V1Model)

```
#include <core.p4>
#include <v1model.p4>
/* HEADERS */
struct metadata { ... }
struct headers {
  ethernet_t   ethernet;
  ipv4_t       ipv4;
}
/* PARSER */
parser MyParser(packet_in packet,
                out headers hdr,
                inout metadata meta,
                inout standard_metadata_t smeta) {
  ...
}
/* CHECKSUM VERIFICATION */
control MyVerifyChecksum(in headers hdr,
                         inout metadata meta) {


  ...
}
/* INGRESS PROCESSING */
control MyIngress(inout headers hdr,
                  inout metadata meta,
                  inout standard_metadata_t std_meta) {
  ...
}
```

```
/* EGRESS PROCESSING */
control MyEgress(inout headers hdr,
                 inout metadata meta,
                 inout standard_metadata_t std_meta) {
  ...
}
/* CHECKSUM UPDATE */
control MyComputeChecksum(inout headers hdr,
                          inout metadata meta) {
  ...
}
/* DEPARSER */
control MyDeparser(inout headers hdr,
                   inout metadata meta) {
  ...
}
/* SWITCH */
V1Switch(
  MyParser(),
  MyVerifyChecksum(),
  MyIngress(),
  MyEgress(),
  MyComputeChecksum(),
  MyDeparser()
) main;
```

$P4_{16}$ Hello World (V1Model)

```
#include <core.p4>
#include <v1model.p4>
struct metadata {}
struct headers {}

parser MyParser(packet_in packet,
   out headers hdr,
   inout metadata meta,
   inout standard_metadata_t standard_metadata) {

    state start { transition accept; }
}

control MyVerifyChecksum(inout headers hdr, inout
metadata meta) {   apply {  }   }

control MyIngress(inout headers hdr,
   inout metadata meta,
   inout standard_metadata_t standard_metadata) {
apply {
        if (standard_metadata.ingress_port == 1) {
            standard_metadata.egress_spec = 2;
        } else if (standard_metadata.ingress_port == 2) {
            standard_metadata.egress_spec = 1;
        }
    }
}
```

```
control MyEgress(inout headers hdr,
   inout metadata meta,
   inout standard_metadata_t standard_metadata) {
    apply {  }
}

control MyComputeChecksum(inout headers hdr, inout metadata
meta) {
     apply { }
}

control MyDeparser(packet_out packet, in headers hdr) {
    apply { }
}

V1Switch(
   MyParser(),
   MyVerifyChecksum(),
   MyIngress(),
   MyEgress(),
   MyComputeChecksum(),
   MyDeparser()
) main;
```

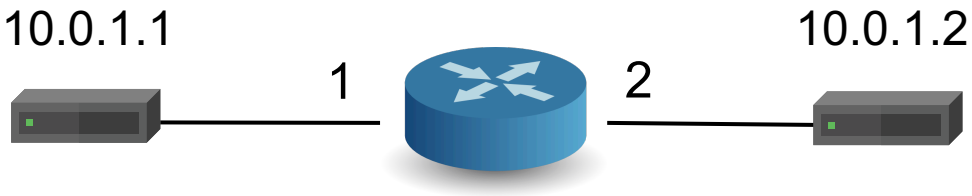
P4$_{16}$ Hello World (V1Model)

```
#include <core.p4>
#include <v1model.p4>
struct metadata {}
struct headers {}

parser MyParser(packet_in packet, out headers hdr,
   inout metadata meta,
   inout standard_metadata_t standard_metadata) {
    state start { transition accept; }
}

control MyIngress(inout headers hdr, inout metadata meta,
   inout standard_metadata_t standard_metadata) {
    action set_egress_spec(bit<9> port) {
        standard_metadata.egress_spec = port;
    }
    table forward {
        key = { standard_metadata.ingress_port: exact; }
        actions = {
            set_egress_spec;
            NoAction;
        }
        size = 1024;
        default_action = NoAction();
    }
    apply {   forward.apply();   }
}
```

```
control MyEgress(inout headers hdr,
   inout metadata meta,
   inout standard_metadata_t standard_metadata) {
    apply {  }
}

control MyVerifyChecksum(inout headers hdr, inout metadata
meta) {   apply { }   }

control MyComputeChecksum(inout headers hdr, inout metadata
meta) {   apply { }   }

control MyDeparser(packet_out packet, in headers hdr) {
    apply { }
}

V1Switch( MyParser(), MyVerifyChecksum(), MyIngress(),
MyEgress(), MyComputeChecksum(), MyDeparser() ) main;
```

Key	Action ID	Action Data
1	set_egress_spec ID	2
2	set_egress_spec ID	1

Example: IPv4_LPM Table



Key	Action	Action Data
10.0.1.1/32	ipv4_forward	port=1
10.0.1.2/32	ipv4_forward	port=2
*	drop	

- **Data Plane (P4) Program**
  - Defines the format of the table
    - Key Fields
    - Actions
    - Action Data
  - Performs the lookup
  - Executes the chosen action
- **Control Plane (IP stack, Routing protocols)**
  - Populates table entries with specific information
    - Based on the configuration
    - Based on automatic discovery
    - Based on protocol calculations

Example: IPv4_LPM Table

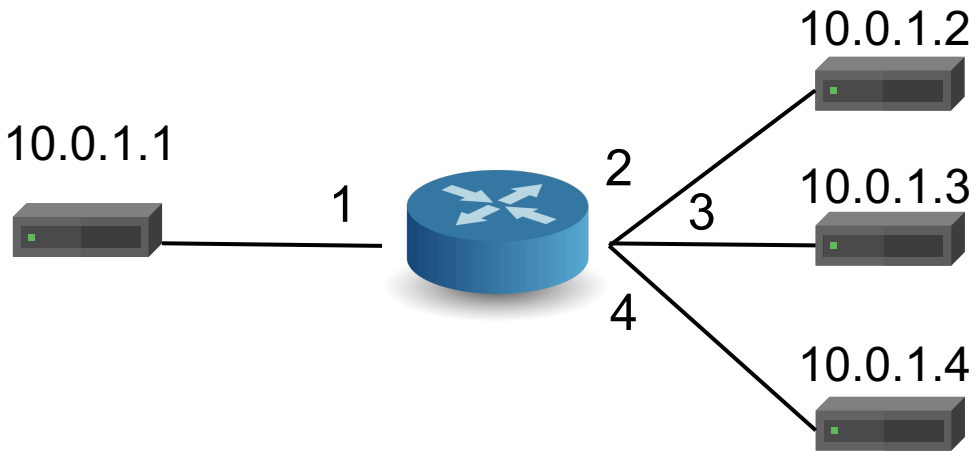
```
control MyIngress(inout headers hdr, inout metadata meta,
   inout standard_metadata_t standard_metadata) {

    action drop() {
        mark_to_drop();
    }
    action ipv4_forward(egressSpec_t port) {
        standard_metadata.egress_spec = port;
    }
    table ipv4_lpm{
        key = {
            hdr.ipv4.dstAddr: lpm;
        }
        actions = {
            ipv4_forward;
            drop;
        }
        size = 1024;
        default_action = drop();
    }

    apply {
        if (hdr.ipv4.isValid()) {
            ipv4_lpm.apply();
        }
}
```

Key	Action	Action Data
10.0.1.1/32	ipv4_forward	port=1
10.0.1.2/32	ipv4_forward	port=2
*	drop	

Specify rules in a JSON file

```
{
  "target": "bmv2",
  "p4info": "build/acl.p4info",
  "bmv2_json": "build/acl.json",
  "table_entries": [
    {
      "table": "MyIngress.ipv4_lpm",
      "match": {
        "hdr.ipv4.dstAddr": ["10.0.1.1", 32]},
      "action_name": "MyIngress.ipv4_forward",
      "action_params": {
        "port": 1}
    },
    ……
  ]
}
```

Exercise 1: Access Control List for UDP Traffic



Key	Action	Action Data
dstIP = *, dstPort = 80	drop	
dstIP = 10.0.1.4, dstPort = *	drop	
*	NoAction	

- **Data Plane (P4) Program**
  - Defines the format of the table
    - Key Fields:
      - hdr.ipv4.dstAddr: ternary
      - hdr.udp.dstPort: ternary
    - Actions:
      - drop
      - NoAction
    - Action Data: None

- **Control Plane**
  - Populates table entries with specific information
    - Use the two rules in the example

Exercise 1: Access Control List for UDP Traffic

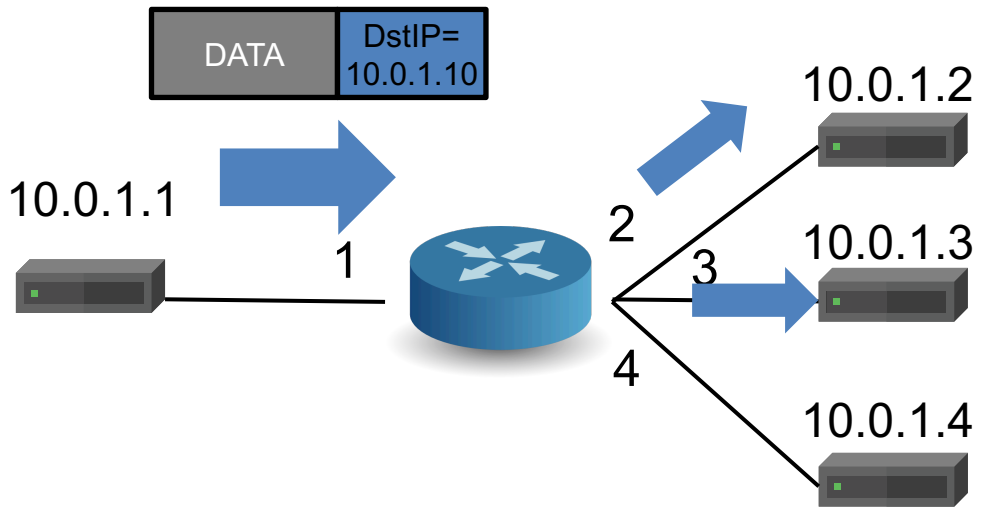
```
control MyIngress(inout headers hdr, inout metadata meta,
   inout standard_metadata_t standard_metadata) {

   table udp_acl {
        key = {
            hdr.ipv4.dstAddr: ternary;
            hdr.udp.dstPort: ternary;
        }
        actions = {
            drop;
            NoAction;
        }
        size = 1024;
        default_action = NoAction();
    }

    apply {
        if (hdr.ipv4.isValid()) {
            ipv4_lpm.apply();
        if (hdr.udp.isValid()) {
            udp_acl.apply();
        }
    }
}
```

Key	Action	Action Data
dstIP = *, dstPort = 80	drop	
dstIP = 10.0.1.4, dstPort = *	drop	
*	NoAction	

Specify rules in a JSON file

```
{
  "target": "bmv2",
  "p4info": "build/acl.p4info",
  "bmv2_json": "build/acl.json",
  "table_entries": [
    {
      "table": "MyIngress.udp_acl",
      "match": {
        "hdr.udp.dstPort": [80, 65535]},
      "action_name": "MyIngress.drop",
      "action_params": {}
    },
    ……
  ]
}
```

Exercise 2: Load Balancing



Key	Action	Action Data
dstIP = 10.0.1.10	select_nhop	0, 2
*	NoAction	

Key	Action	Action Data
meta.nhop = 0	set_ip_egress	10.0.1.2, 2
meta.nhop = 1	set_ip_egress	10.0.1.3, 3
*	NoAction	

- **Data Plane (P4) Program**
  - The first table picks one server
  - The second table updates the destination IP address and egress port
- **Control Plane**
  - Populates table entries with specific information
    - Use the rules in the example

Exercise 2: Load Balancing

```
control MyIngress(inout headers hdr, inout metadata meta,
   inout standard_metadata_t standard_metadata) {

   action set_nhop(bit<16> base, bit<16> count) {
       hash(meta.nhop, HashAlgorithm.crc16, base,
           {hdr.ipv4.srcAddr, hdr.ipv4.dstAddr,
            hdr.ipv4.protocol, hdr.udp.srcPort,
            hdr.udp.dstPort}, count);
    }

   table lb_select {
        key = {
            hdr.ipv4.dstAddr: exact;
        }
        actions = {
            set_nhop;
            NoAction;
        }
        size = 1024;
        default_action = NoAction();
    }

}
```

Key	Action	Action Data
dstIP = 10.0.1.10	select_nhop	0, 2
*	NoAction	

Specify rules in a JSON file

```
{
  "target": "bmv2",
  "p4info": "build/load_balance.p4info",
  "bmv2_json": "build/load_balance.json",
  "table_entries": [
    {
      "table": "MyIngress.lb_select",
      "match": {
        "hdr.ipv4.dstAddr": ["10.0.1.10", 32]},
      "action_name": "MyIngress.set_nhop",
      "action_params": {
        "base": 0,
        "count": 2}
    },
    ……
  ]
}
```

Exercise 2: Load Balancing

```
control MyIngress(inout headers hdr, inout metadata meta,
   inout standard_metadata_t standard_metadata) {

   action set_ip_egress(bit<32> ip, egressSpec_t port) {
        hdr.ipv4.dstAddr = ip;
        standard_metadata.egress_spec = port;
    }

   table lb_set {
        key = {
            meta.nhop: exact;
        }
        actions = {
            set_ip_egress;
            NoAction;
        }
        size = 2;
        default_action = NoAction();
    }

   apply {
        if (hdr.udp.isValid()) {
            lb_select.apply();
            lb_set.apply();
        }
    }
}
```

Key	Action	Action Data
meta.nhop = 0	set_ip_egress	10.0.1.2, 2
meta.nhop = 1	set_ip_egress	10.0.1.3, 3
*	NoAction	

Specify rules in a JSON file

```
{
  "target": "bmv2",
  "p4info": "build/load_balance.p4info",
  "bmv2_json": "build/load_balance.json",
  "table_entries": [
    {
      "table": "MyIngress.ecmp_set",
      "match": {
        "meta.nhop": 0},
      "action_name": "MyIngress.set_ip_egress",
      "action_params": {
        "ip": "10.0.1.2"
        "Count": 2}
    },
    ……
  ]
}
```

Group Discussion

- Topic: programmable networks
  - What are the differences between traditional fixed-function switches and new-generation programmable switches? Can you come up with some new applications enabled by programmable switches?

- Discuss in groups, and each group chooses a leader to summarize the discussion
  - **Everyone should speak.**
  - **Turn on your audio and video. Do not mute.**

Summary

- **Programmable networks: programmable switches enable fast development and deployment of new data plane functionalities**

- **Next lecture: link layer**

Thanks!
Q&A

V1Model Standard Metadata

```
struct standard_metadata_t {
    bit<9>  ingress_port;
    bit<9>  egress_spec;
    bit<9>  egress_port;
    bit<32> clone_spec;
    bit<32> instance_type;
    bit<1>  drop;
    bit<16> recirculate_port;
    bit<32> packet_length;
    bit<32> enq_timestamp;
    bit<19> enq_qdepth;
    bit<32> deq_timedelta;
    bit<19> deq_qdepth;
    bit<48> ingress_global_timestamp;
    bit<32> lf_field_list;
    bit<16> mcast_grp;
    bit<1>  resubmit_flag;
    bit<16> egress_rid;
    bit<1>  checksum_error;
}
```

- **`ingress_port`** - the port on which the packet arrived
- **`egress_spec`** - the port to which the packet should be sent to
- **`egress_port`** - the port that the packet will be sent out of (read only in egress pipeline)

$P4_{16}$ Types (Basic and Header Types)

```
typedef bit<48> macAddr_t;
typedef bit<32> ip4Addr_t;
header ethernet_t {
  macAddr_t dstAddr;
  macAddr_t srcAddr;
  bit<16>   etherType;
}
header ipv4_t {
  bit<4>    version;
  bit<4>    ihl;
  bit<8>    diffserv;
  bit<16>   totalLen;
  bit<16>   identification;
  bit<3>    flags;
  bit<13>   fragOffset;
  bit<8>    ttl;
  bit<8>    protocol;
  bit<16>   hdrChecksum;
  ip4Addr_t srcAddr;
  ip4Addr_t dstAddr;
}
```

Basic Types

- **bit<n>**: Unsigned integer (bitstring) of size n
- **bit** is the same as **bit<1>**
- **int<n>**: Signed integer of size n (>=2)
- **varbit<n>**: Variable-length bitstring

Header Types: Ordered collection of members

- Can contain **bit<n>**, **int<n>**, and **varbit<n>**
- Byte-aligned
- Can be valid or invalid
- Provides several operations to test and set validity bit: **isValid()**, **setValid()**, and **setInvalid()**

Typedef: Alternative name for a type

P4$_{16}$ Types (Other Types)

```
/* Architecture */
struct standard_metadata_t {
  bit<9>  ingress_port;
  bit<9>  egress_spec;
  bit<9>  egress_port;
  bit<32> clone_spec;
  bit<32> instance_type;
  bit<1>  drop;
  bit<16> recirculate_port;
  bit<32> packet_length;
  ...
}

/* User program */
struct metadata {
  ...
}
struct headers {
  ethernet_t   ethernet;
  ipv4_t       ipv4;
}
```

Other useful types

- **Struct**: Unordered collection of members (with no alignment restrictions)
- **Header Stack:** array of headers
- **Header Union:** one of several headers

$P4_{16}$ Controls

- **Similar to C functions (without loops)**
- **Can declare variables, create tables, instantiate externs, etc.**
- **Functionality specified by code in `apply` statement**
- **Represent all kinds of processing that are expressible as DAG:**
  - Match-Action Pipelines
  - Deparsers
  - Additional forms of packet processing (updating checksums)
- **Interfaces with other blocks are governed by user- and architecture-specified types (typically headers and metadata)**

$P4_{16}$ Tables

- **The fundamental unit of a Match-Action Pipeline**
  - Specifies what data to match on and match kind
  - Specifies a list of *possible* actions
  - Optionally specifies a number of table **properties**
    - Size
    - Default action
    - Static entries
    - etc.
- **Each table contains one or more entries (rules)**
- **An entry contains:**
  - A specific key to match on
  - A **single** action that is executed when a packet matches the entry
  - Action data (possibly empty)

Example: Simple Actions

```
control MyIngress(inout headers hdr,
                  inout metadata meta,
                  inout standard_metadata_t std_meta) {

  action swap_mac(inout bit<48> src,
                  inout bit<48> dst) {
    bit<48> tmp = src;
    src = dst;
    dst = tmp;
  }

  apply {
    swap_mac(hdr.ethernet.srcAddr,
             hdr.ethernet.dstAddr);
    std_meta.egress_spec = std_meta.ingress_port;
  }
}
```

- **Very similar to C functions**
- **Can be declared inside a control or globally**
- **Parameters have type and direction**
- **Variables can be instantiated inside**
- **Many standard arithmetic and logical operations are supported**
  - +, -, *
  - ~, &, |, ^, >>, <<
  - ==, !=, >, >=, <, <=
  - No division/modulo
- **Non-standard operations:**
  - Bit-slicing: [m:l] (works as l-value too)
  - Bit Concatenation: ++

IPv4_LPM Table

```
table ipv4_lpm {
    key = {
      hdr.ipv4.dstAddr: lpm;
    }
    actions = {
      ipv4_forward;
      drop;
      NoAction;
    }
    size = 1024;
    default_action = NoAction();
}
```

Match Kinds

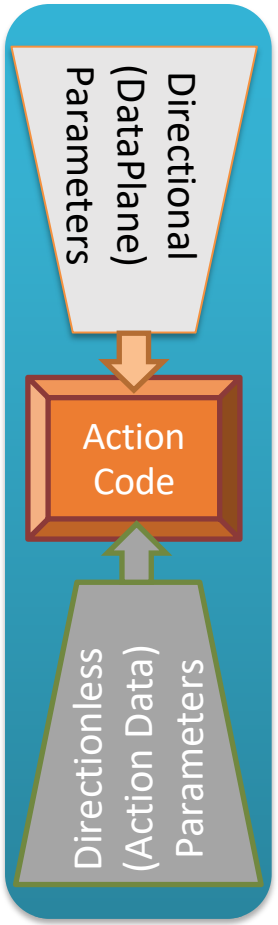
```
/* core.p4 */
match_kind {
    exact,
    ternary,
    lpm
}

/* v1model.p4 */
match_kind {
    range,
    selector
}

/* Some other architecture */
match_kind {
    regexp,
    fuzzy
}
```

- **The type `match_kind` is special in P4**
- **The standard library (`core.p4`) defines three standard match kinds**
  - Exact match
  - Ternary match
  - LPM match
- **The architecture (`v1model.p4`) defines two additional match kinds:**
  - range
  - selector
- **Other architectures may define (and provide implementation for) additional match kinds**

Defining Actions for L3 forwarding

```
/* core.p4 */
action NoAction() {
}

/* basic.p4 */
action drop() {
  mark_to_drop();
}

/* basic.p4 */
action ipv4_forward(macAddr_t dstAddr,
                    bit<9> port) {
  ...
}
```

- **Actions can have two different types of parameters**
  - Directional (from the Data Plane)
  - Directionless (from the Control Plane)
- **Actions that are called directly:**
  - Only use directional parameters
- **Actions used in tables:**
  - Typically use directionless parameters
  - May sometimes use directional parameters too



Action Execution

Applying Tables in Controls

```
control MyIngress(inout headers hdr,
                  inout metadata meta,
                  inout standard_metadata_t standard_metadata) {
  table ipv4_lpm {
    ...
  }
  apply {
     ...
     ipv4_lpm.apply();
     ...
  }
}
```

FAQs

- **Can I apply a table multiple times in my P4 Program?**
  - No (except via resubmit / recirculate)
- **Can I modify table entries from my P4 Program?**
  - No (except for direct counters)
- **What happens upon reaching the `reject` state of the parser?**
  - Architecture dependent
- **How much of the packet can I parse?**
  - Architecture dependent