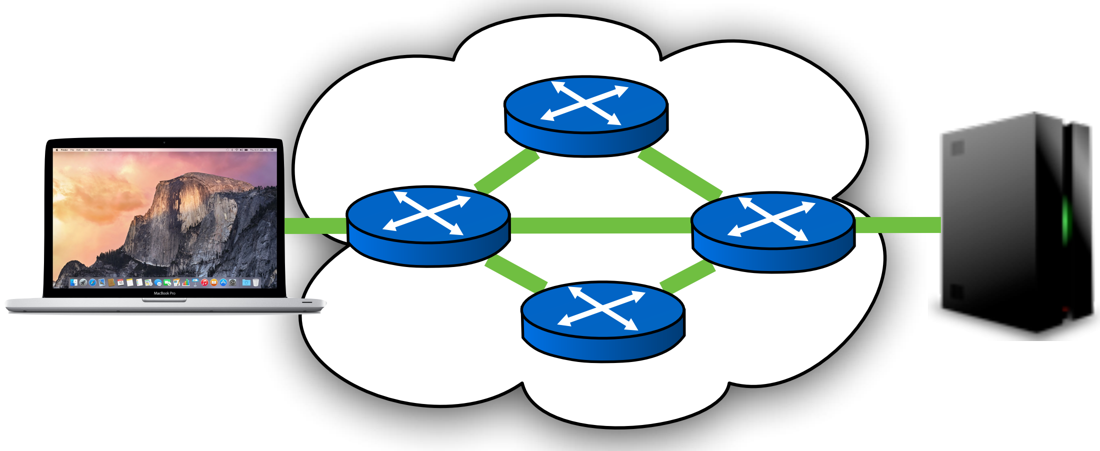
Verifying Network Data Planes

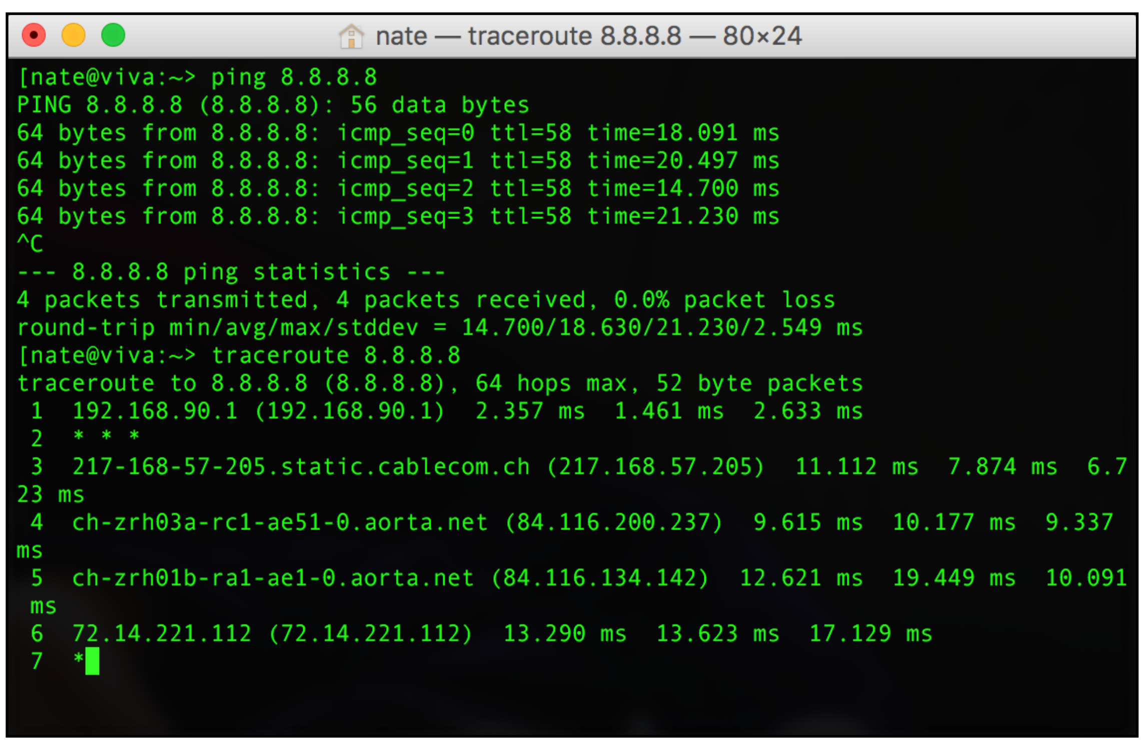
Nate Foster
Cornell / Barefoot


LINKSYS
Wireless-G
Cisco Systems
Secure Easy Setup
Wireless-G
Ethernet
Power
DMZ
WLAN
1
2
3
4
Internet
Wireless-G Broadband Router
With SpeedBooster
Model WRT54GS
LINKSYS

Can you help me fix my WiFi?

Network Management

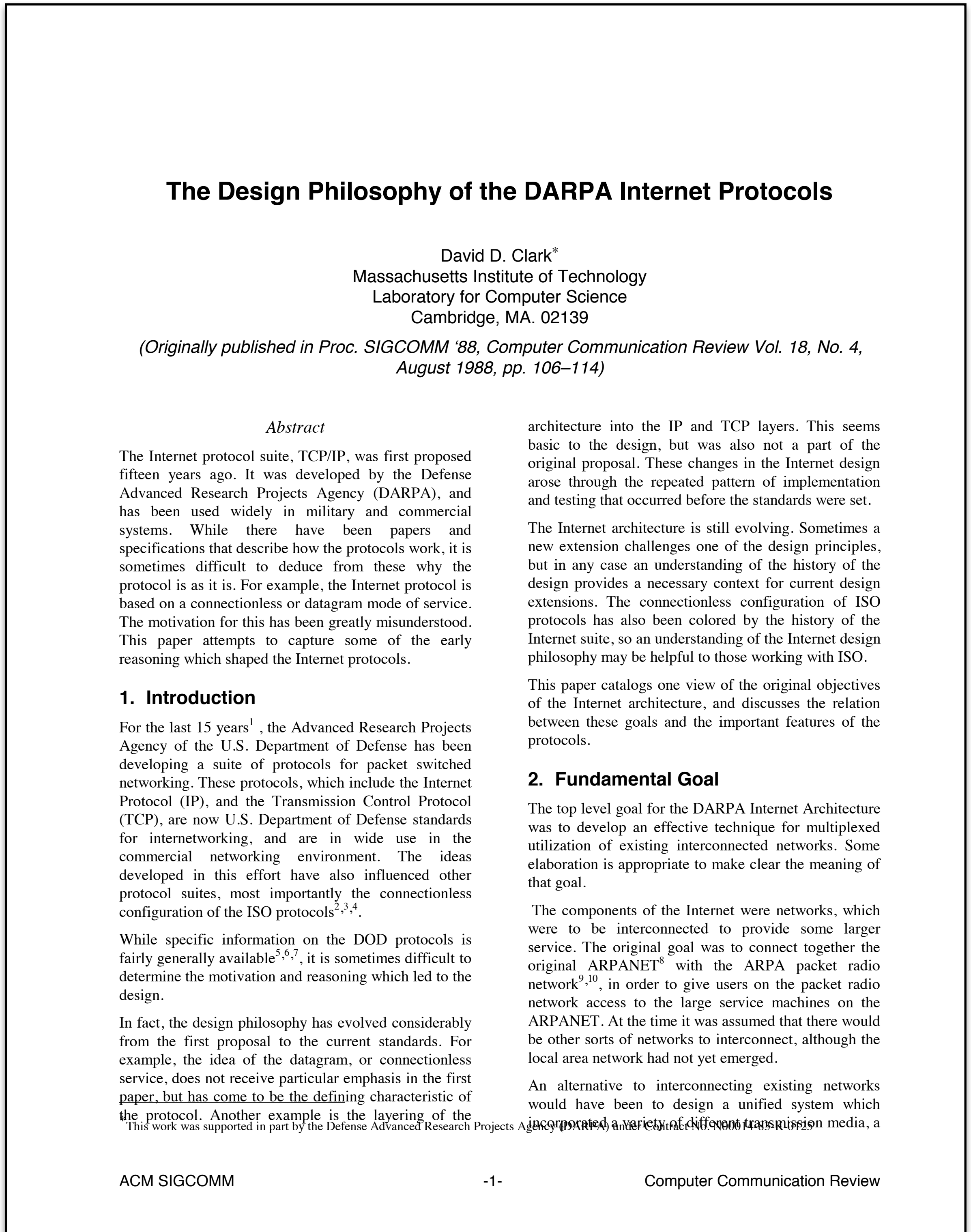




Network operators use a variety of techniques to keep things running including:

- Generating configurations from high-level policies
- Scraping configurations using command-line tools
- Diagnosing errors with `ping` and `traceroute`

Internet Principles



The Design Philosophy of the DARPA Internet Protocols

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Abstract

The Internet protocol suite, TCP/IP, was first proposed fifteen years ago. It was developed by the Defense Advanced Research Projects Agency (DARPA), and has been used widely in military and commercial systems. While there have been papers and specifications that describe how the protocols work, it is sometimes difficult to deduce from these why the protocol is as it is. For example, the Internet protocol is based on a connectionless or datagram mode of service. The motivation for this has been greatly misunderstood. This paper attempts to capture some of the early reasoning which shaped the Internet protocols.

1. Introduction

For the last 15 years[1] , the Advanced Research Projects Agency of the U.S. Department of Defense has been developing a suite of protocols for packet switched networking. These protocols, which include the Internet Protocol (IP), and the Transmission Control Protocol (TCP), are now U.S. Department of Defense standards for internetworking, and are in wide use in the commercial networking environment. The ideas developed in this effort have also influenced other protocol suites, most importantly the connectionless configuration of the ISO protocols[2,3,4].

While specific information on the DOD protocols is fairly generally available[5,6,7], it is sometimes difficult to determine the motivation and reasoning which led to the design.

In fact, the design philosophy has evolved considerably from the first proposal to the current standards. For example, the idea of the datagram, or connectionless service, does not receive particular emphasis in the first paper, but has come to be the defining characteristic of the protocol. Another example is the layering of the architecture into the IP and TCP layers. This seems basic to the design, but was also not a part of the original proposal. These changes in the Internet design arose through the repeated pattern of implementation and testing that occurred before the standards were set.

The Internet architecture is still evolving. Sometimes a new extension challenges one of the design principles, but in any case an understanding of the history of the design provides a necessary context for current design extensions. The connectionless configuration of ISO protocols has also been colored by the history of the Internet suite, so an understanding of the Internet design philosophy may be helpful to those working with ISO.

This paper catalogs one view of the original objectives of the Internet architecture, and discusses the relation between these goals and the important features of the protocols.

2. Fundamental Goal

The top level goal for the DARPA Internet Architecture was to develop an effective technique for multiplexed utilization of existing interconnected networks. Some elaboration is appropriate to make clear the meaning of that goal.

The components of the Internet were networks, which were to be interconnected to provide some larger service. The original goal was to connect together the original ARPANET[8] with the ARPA packet radio network[9,10], in order to give users on the packet radio network access to the large service machines on the ARPANET. At the time it was assumed that there would be other sorts of networks to interconnect, although the local area network had not yet emerged.

An alternative to interconnecting existing networks would have been to design a unified system which incorporated a variety of different transmission media, a

*This work was supported in part by the Defense Advanced Research Projects Agency (DARPA) under Contract No. N00014-83-K-0125

Designed to be robust even when some nodes misbehave or even experience outright failures...

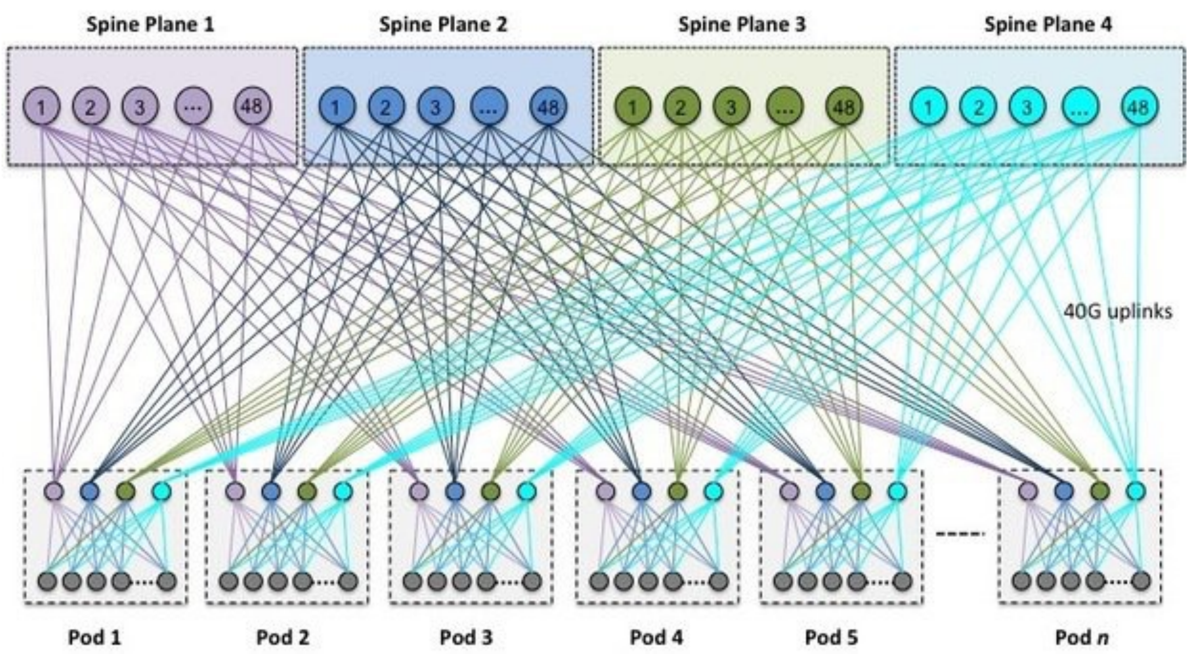
...defers many important issues such as performance, security, accountability, etc.

Modern Challenges

Networks have truly become a critical part of our infrastructure...

...they have grown dramatically in size and complexity...

...and they are becoming unwieldy for operators to manage correctly!



Desired Properties

- Connectivity
- Fault-Tolerance
- Isolation
- Loop Freedom
- Blackhole Freedom
- Service Chaining
- Load Balancing

This Talk

Two (mostly) automated approaches for verifying formal properties of network data planes

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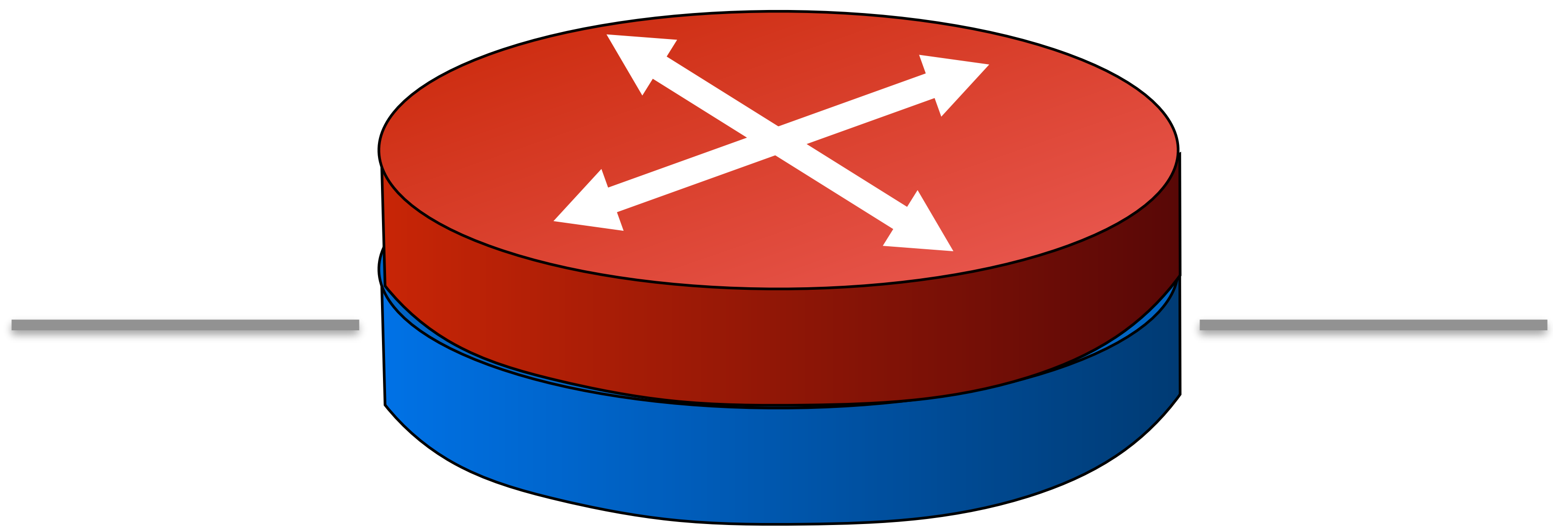
Plan:

- Network-wide properties in NetKAT
- Single-device properties in P4

Network-Wide Verification in NetKAT

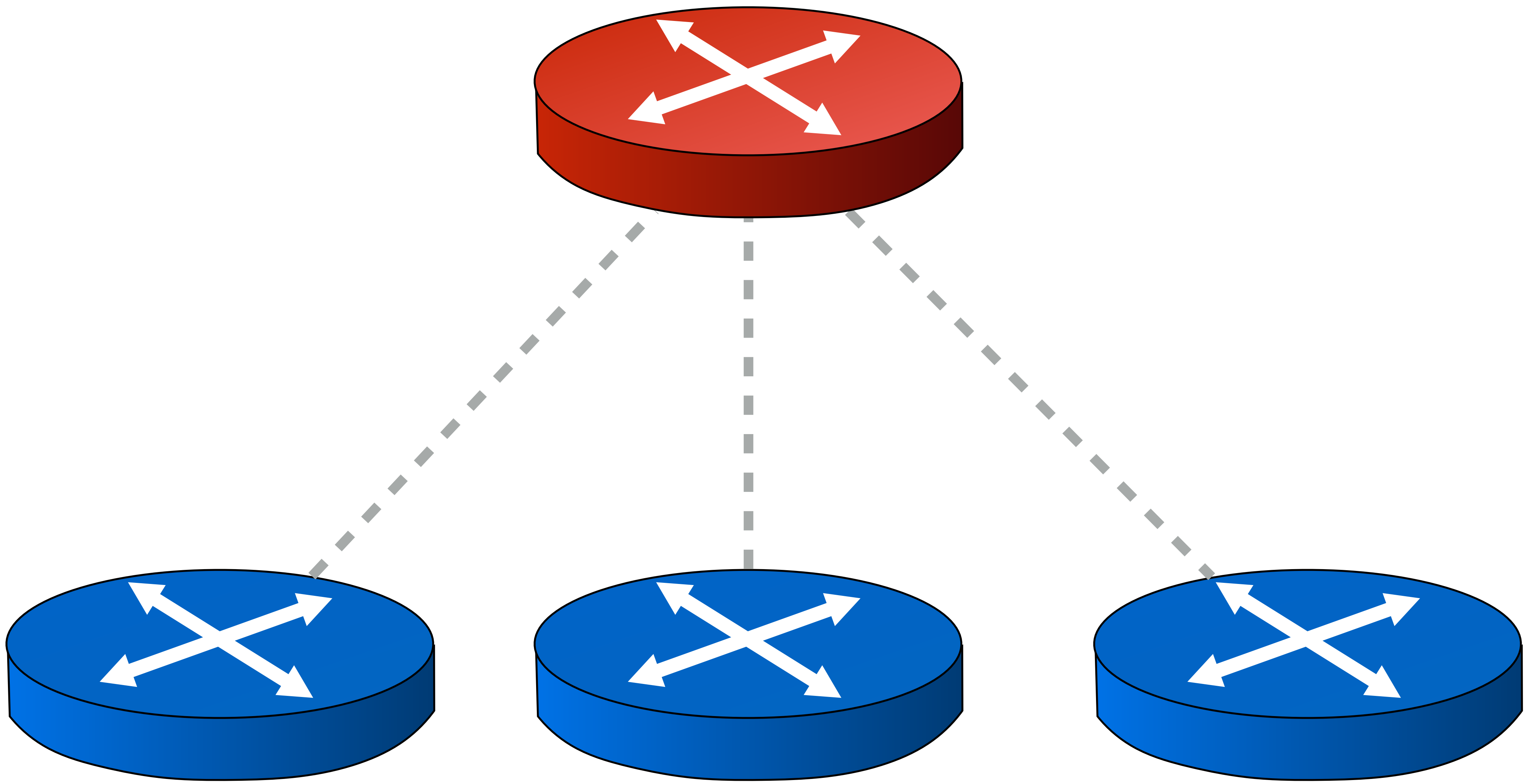
Conventional Networking

Control Plane: discovers topology, computes routes, manages policy, etc.

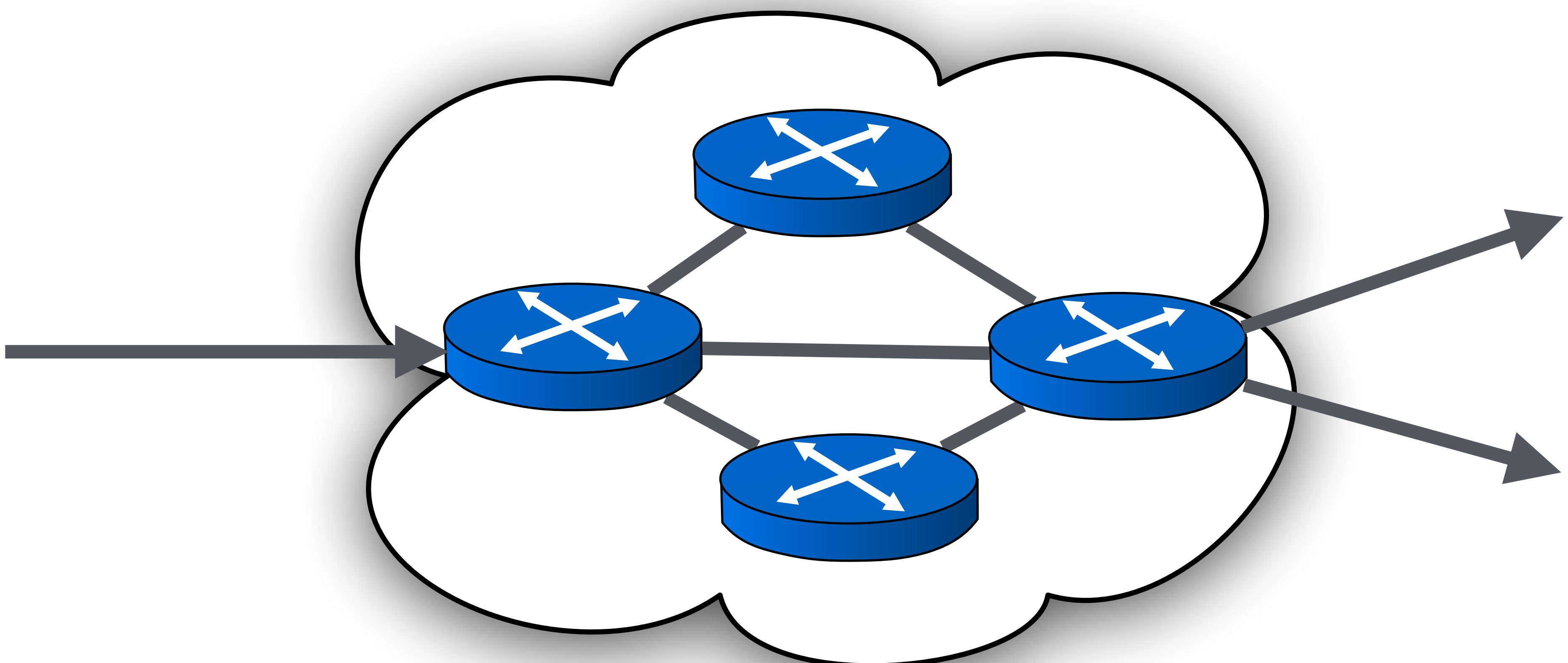


Data plane: forwards packets, enforces access control, monitors flows, etc.

Software-Defined Networking

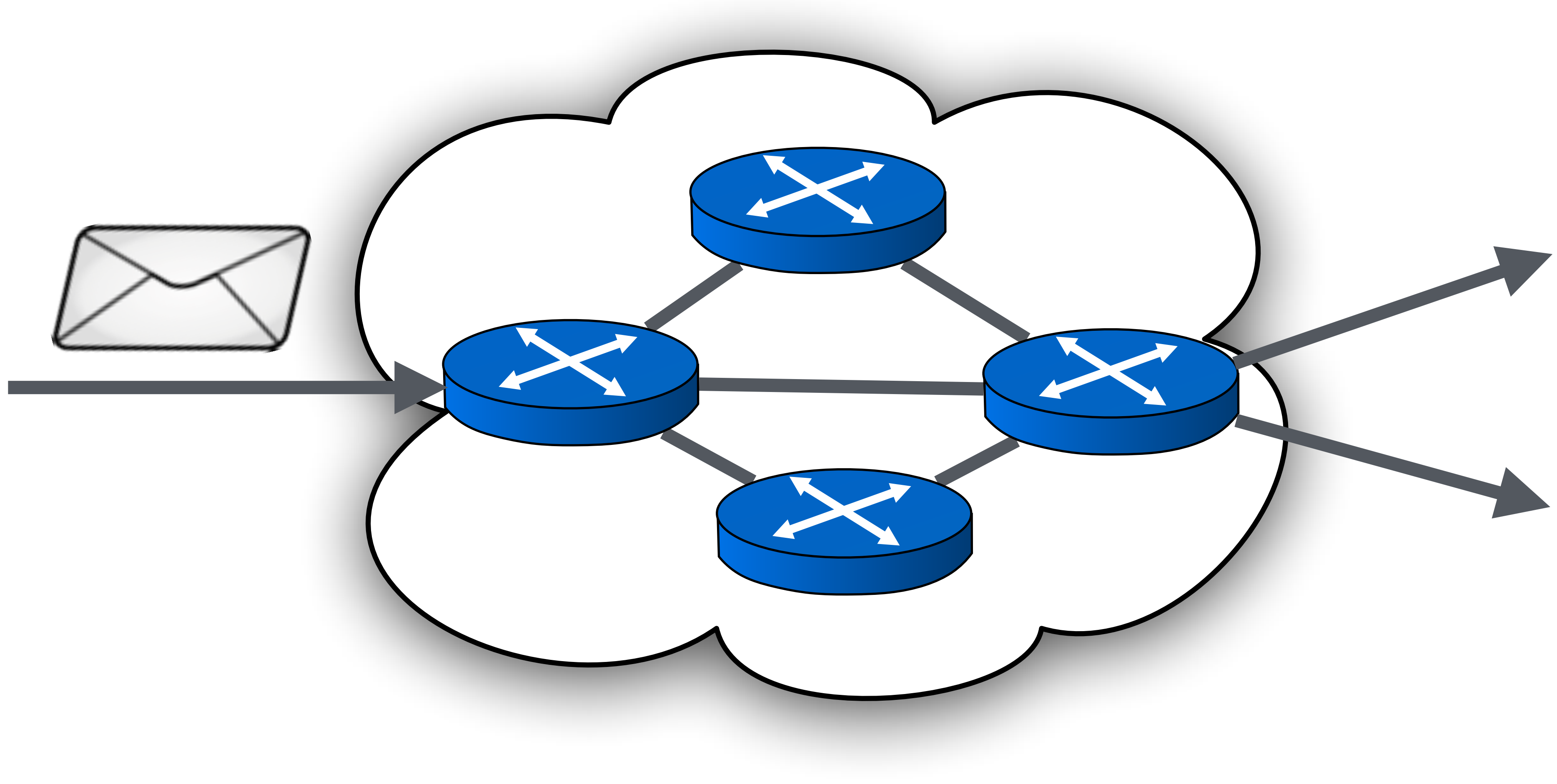


Model



Packets → Packets

Model



Packets → Packets

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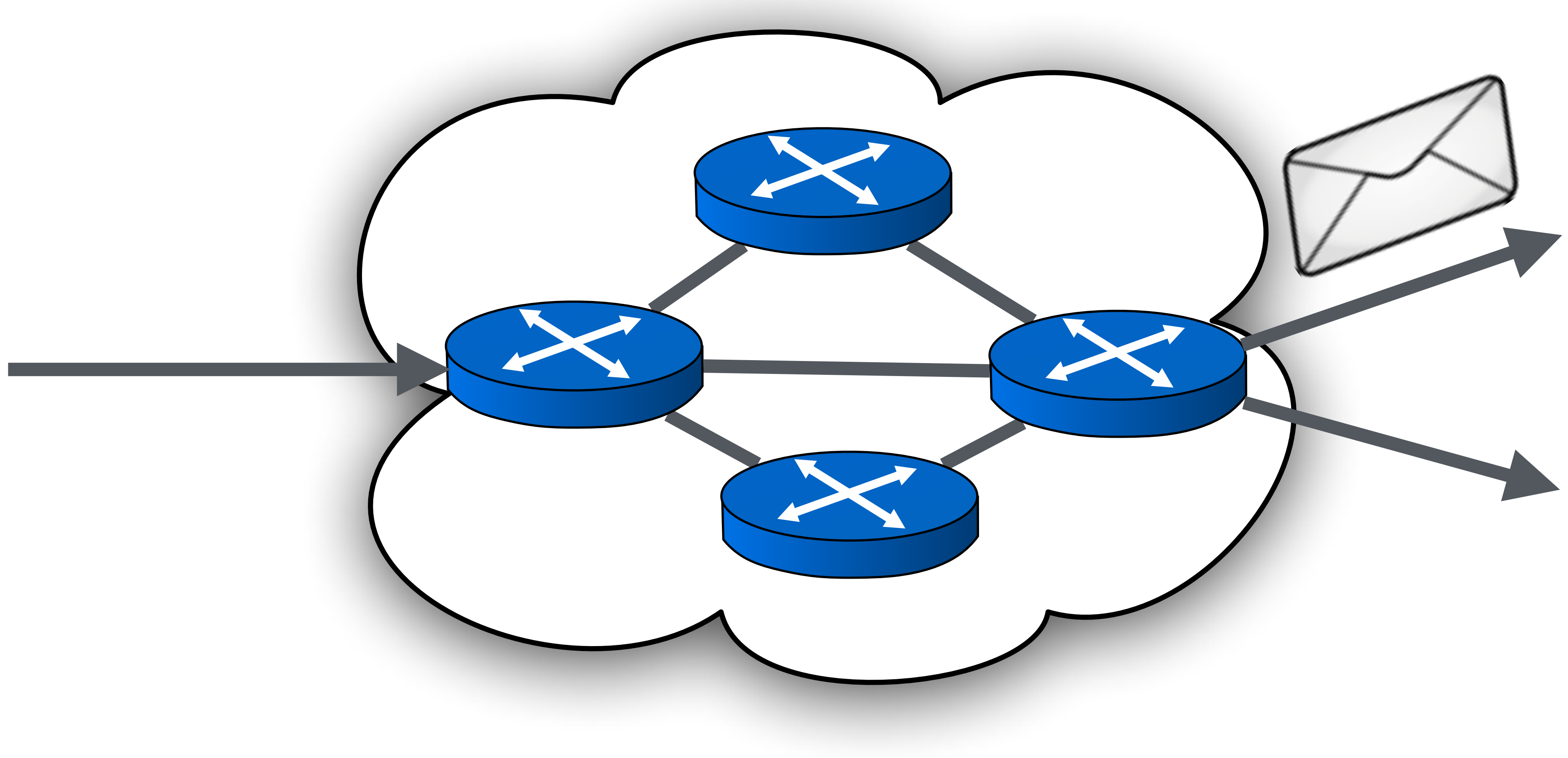

Packets → Packets

NetKAT Syntax

$$
\begin{aligned}
\text{pol} ::= \; & \textbf{false} \\
\mid \; & \textbf{true} \\
\mid \; & f = n \\
\mid \; & f := n \\
\mid \; & \text{pol}_1 + \text{pol}_2 \\
\mid \; & \text{pol}_1 \bullet \text{pol}_2 \\
\mid \; & !\text{pol} \\
\mid \; & \text{pol}^* \\
\mid \; & \textbf{dup}
\end{aligned}
$$

NetKAT Syntax

pol ::= **false**
| **true**
| f **=** n
| f **:=** n
| pol_1 **+** pol_2
| pol_1 • pol_2
| !pol
| pol*
| **dup**

Boolean Predicates

+

Regular Expressions

+

Packet Primitives

Negation may only be applied to B*oolean predicates:*
true, **false**, f **=** n, closed under +, **•**, and **!**

NetKAT Syntax

pol ::=	**false**
	| **true**
	| f **=** n
	| f **:=** n
	| pol_1 **+** pol_2
	| pol_1 • pol_2
	| !pol
	| pol*
	| **dup**

$$\left.\begin{array}{c}\text{Boolean Predicates} \\ + \\ \text{Regular Expressions}\end{array}\right\}\ \text{KAT}$$

\+

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Boolean Predicates

\+

Regular Expressions

KAT

\+

Packet Primitives

NetKAT

Negation may only be applied to B*oolean predicates:*

true, **false**, f = n, closed under +, •, and **!**

NetKAT Syntax

pol ::= **false**
| **true**

Boolean
Predicates

$$\textbf{if } b \textbf{ then } p_1 \textbf{ else } p_2 \triangleq (b \bullet p_1) + (!b \bullet p_2)$$

$$\textbf{while } b \textbf{ do } p \triangleq (b \bullet p)^* \bullet !b$$

$$S \rightarrow S' \triangleq sw = S \bullet \textbf{dup} \bullet sw := S' \bullet \textbf{dup}$$

| pol
| **dup**

Primitives

Negation may only be applied to B*oolean predicates:*
true, **false**, f = n, closed under +, •, and **!**

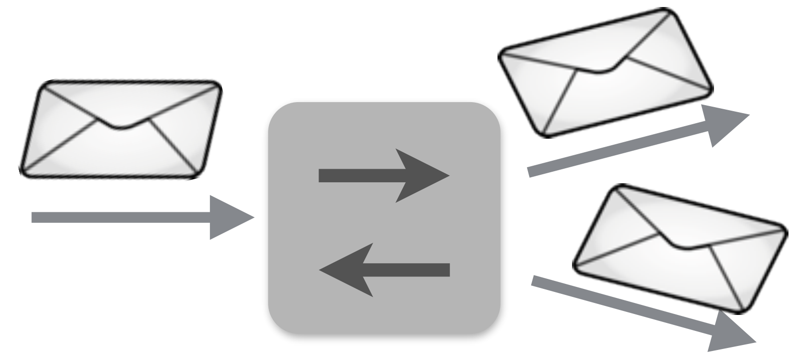
Semantics

pol ::=
  | **false**
  | **true**
  | field **=** val
  | field **:=** val
  | pol_1 **+** pol_2
  | pol_1 **•** pol_2
  | !pol
  | pol*
  | **dup**

Semantics

pol ::=
| **false**
| **true**
| field = val
| field **:=** val
| $pol_1 + pol_2$
| $pol_1 \bullet pol_2$
| !pol
| pol*
| ~~**dup**~~

Local: input-output behavior of switches



$$[\![\Phi(pol)]\!] \in \text{Packets} \rightarrow \text{Packets}$$

Semantics

pol ::=
| **false**
| **true**
| field **=** val
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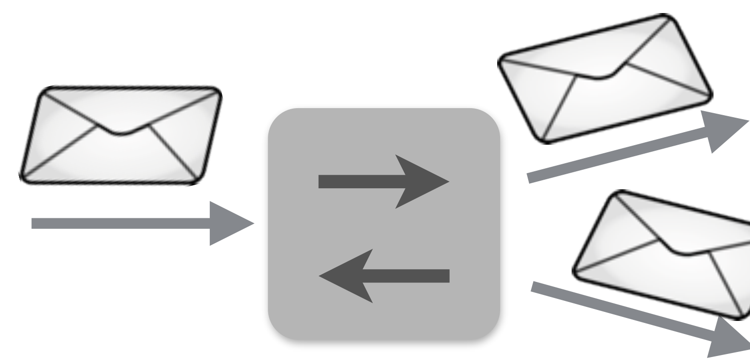
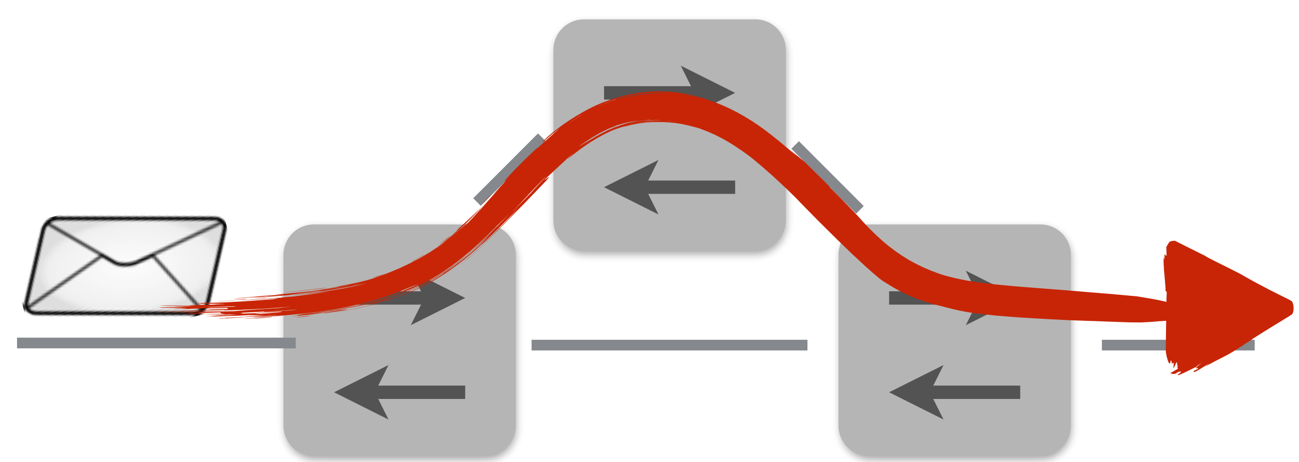
| pol_1 **+** pol_2
| pol_1 **•** pol_2
| !pol
| pol*
| **dup**

Local: input-output behavior of switches



$[\![\Phi(\text{pol})]\!] \in$ Packets → Packets

Global: network-wide paths



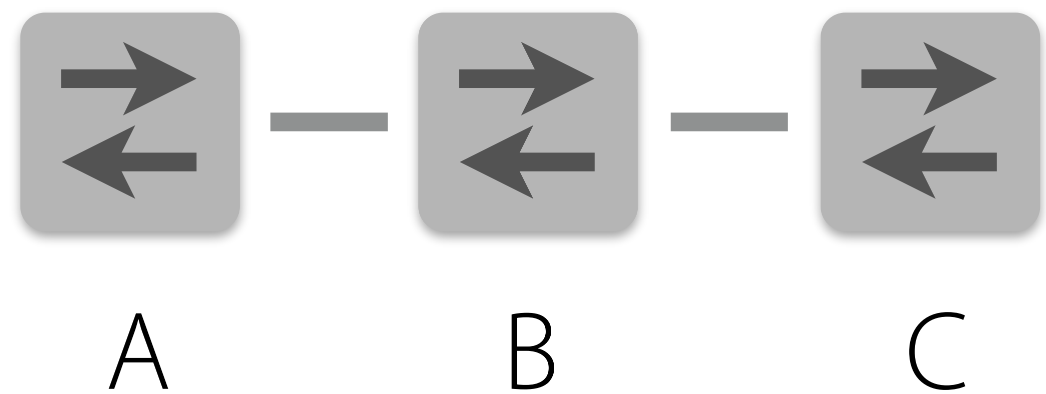
$[\![\text{pol}]\!] \in$ Histories → Histories

Encoding Tables and Links

Switch routing tables and network topologies can be represented in NetKAT using straightforward encodings

Match	Actions
dstport=22	Drop
srcip=10.0.0.1	Forward 1
*	Forward 2

if dstport=22 **then false**
elsif srcip=10.0.0.1 **then** port := 1
else port := 2



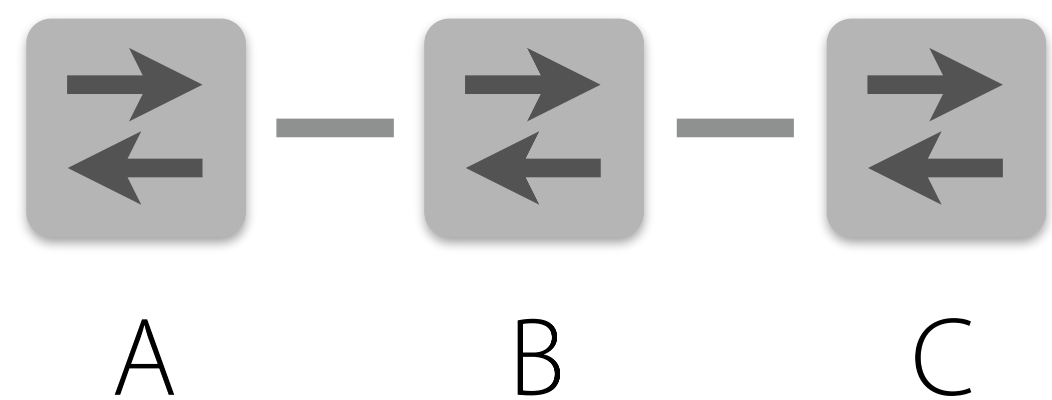
$A \rightarrow B + B \rightarrow A + B \rightarrow C + C \rightarrow B$

Encoding Tables and Links

Switch routing tables and network topologies can be represented in NetKAT using straightforward encodings

Match	Actions
`dstport=22`	`Drop`
`srcip=10.0.0.1`	`Forward 1`
`*`	`Forward 2`

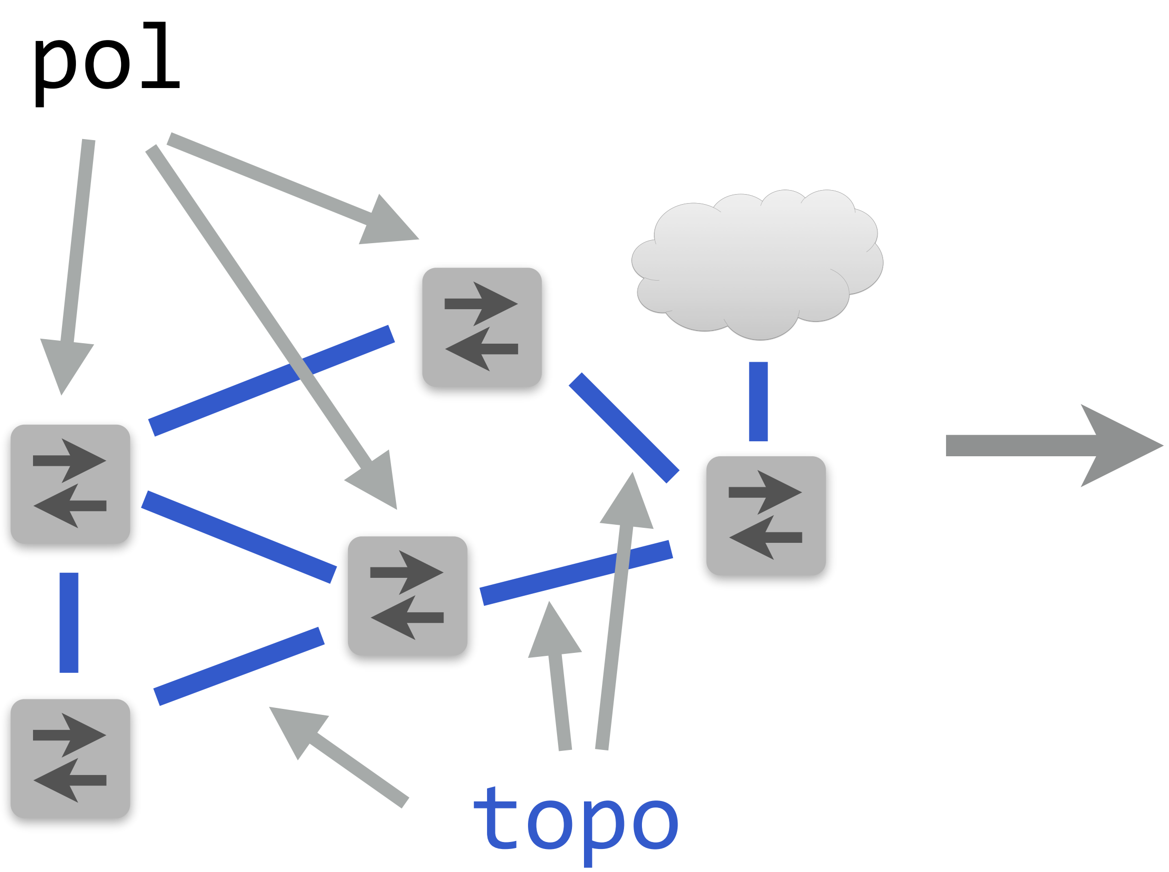
if dstport=22 **then false**
elsif srcip=10.0.0.1 **then** port := 1
else port := 2



$A \rightarrow B + B \rightarrow A + B \rightarrow C + C \rightarrow B$

Encoding Networks

A network can be encoded in NetKAT by interleaving steps of processing by switches and topology



(pol • topo)*

Decision Procedure

Can check whether programs are equivalent automatically!

Theoretical Insight: NetKAT programs ↔ NetKAT automata

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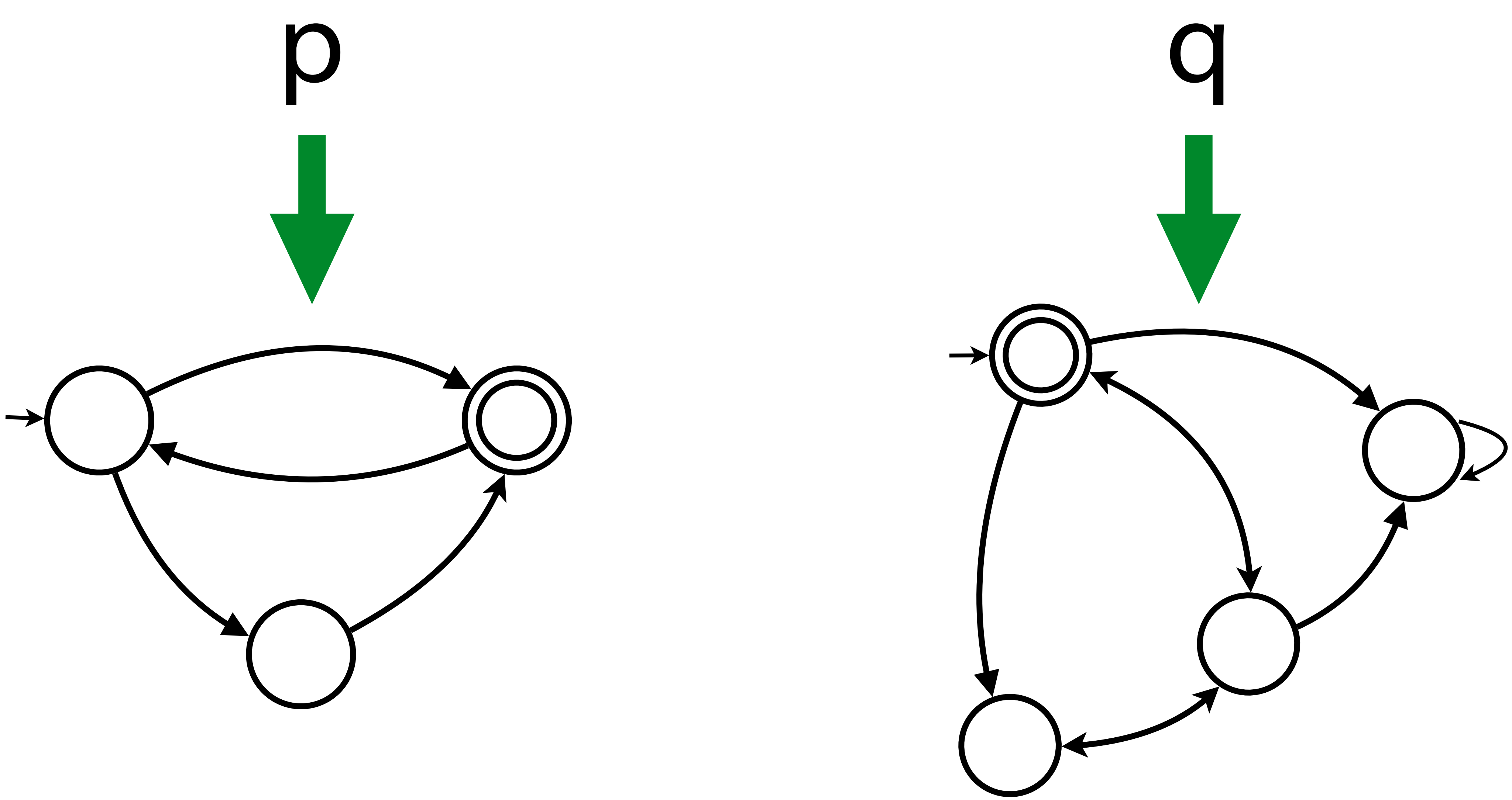
Can check whether programs are equivalent automatically!

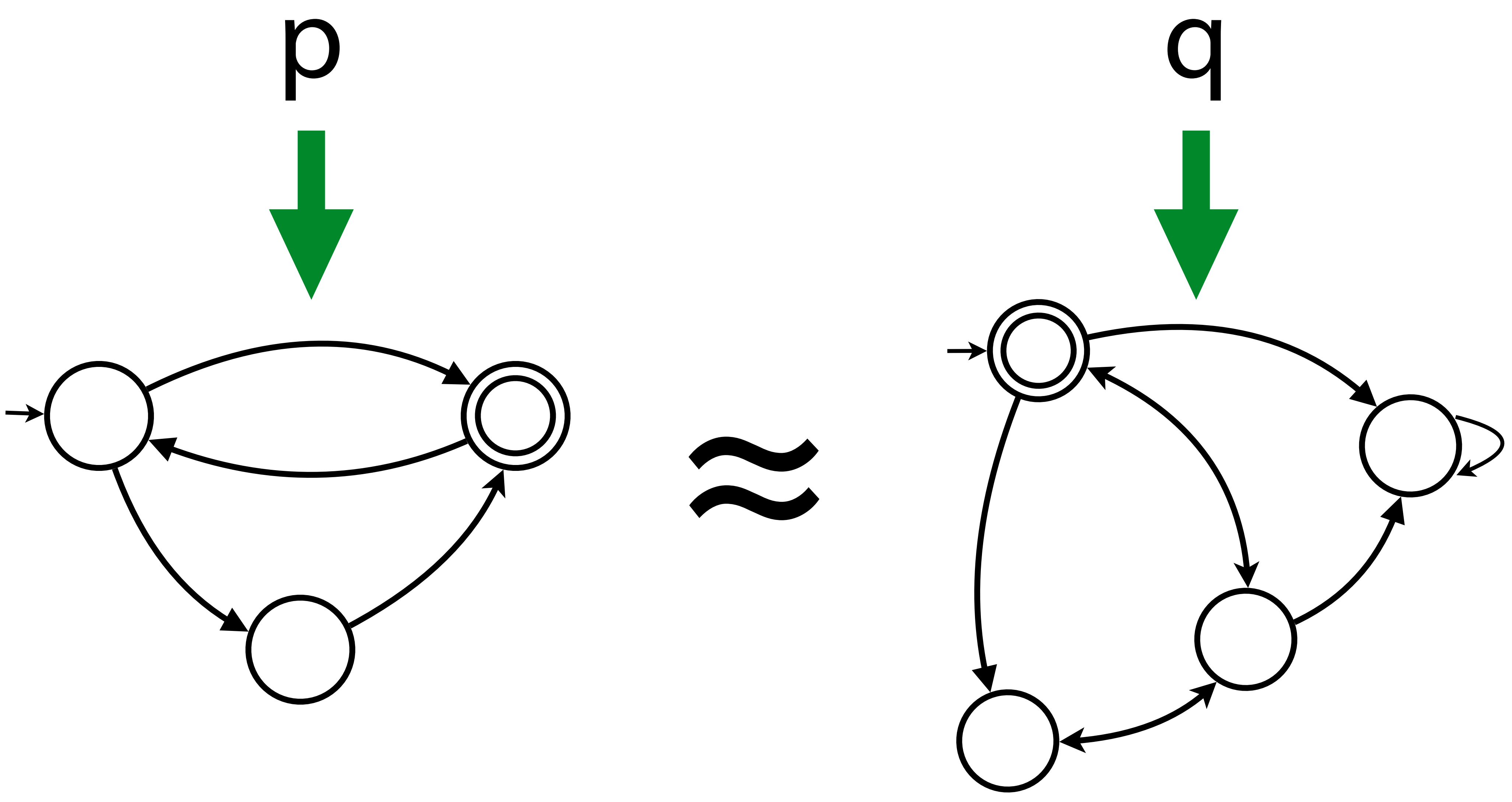
Theoretical Insight: NetKAT programs ↔ NetKAT automata



Decision Procedure

Can check whether programs are equivalent automatically!

Theoretical Insight: NetKAT programs ↔ NetKAT automata



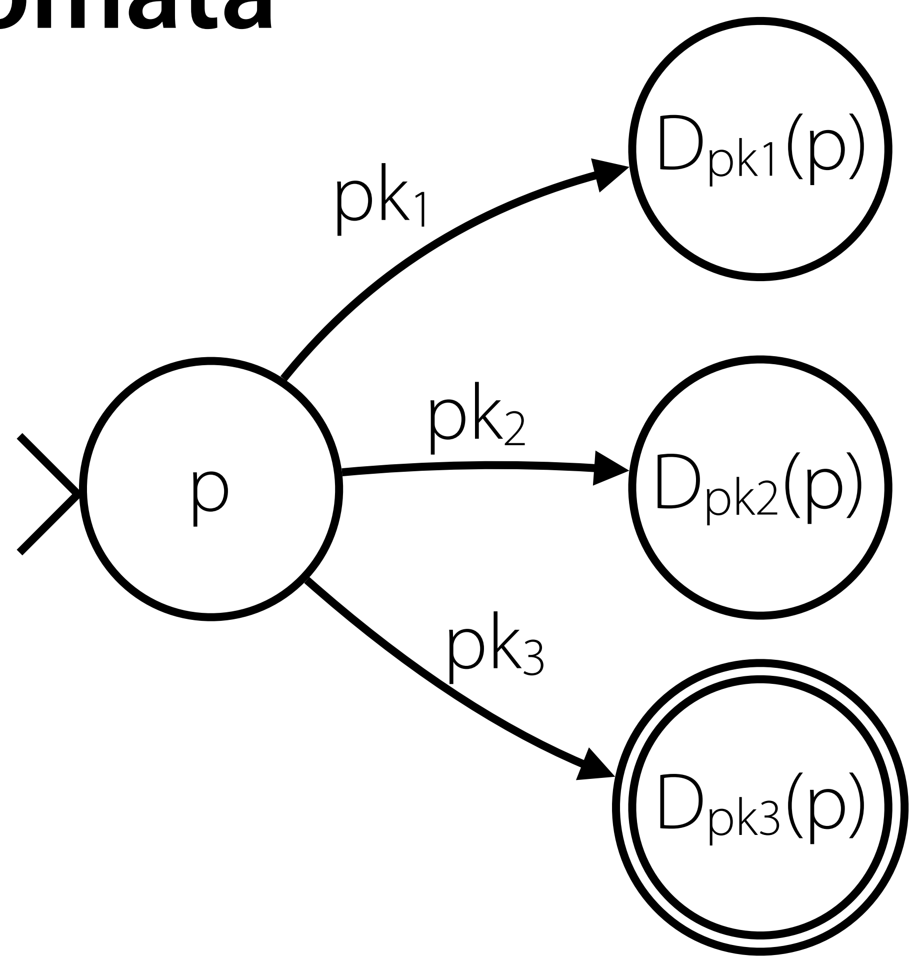
Algorithm checks whether automata are bisimilar

From Programs to Automata

Derivatives

$$D_c\, L = \{\, w \mid c \cdot w \in L \,\}$$

Automata



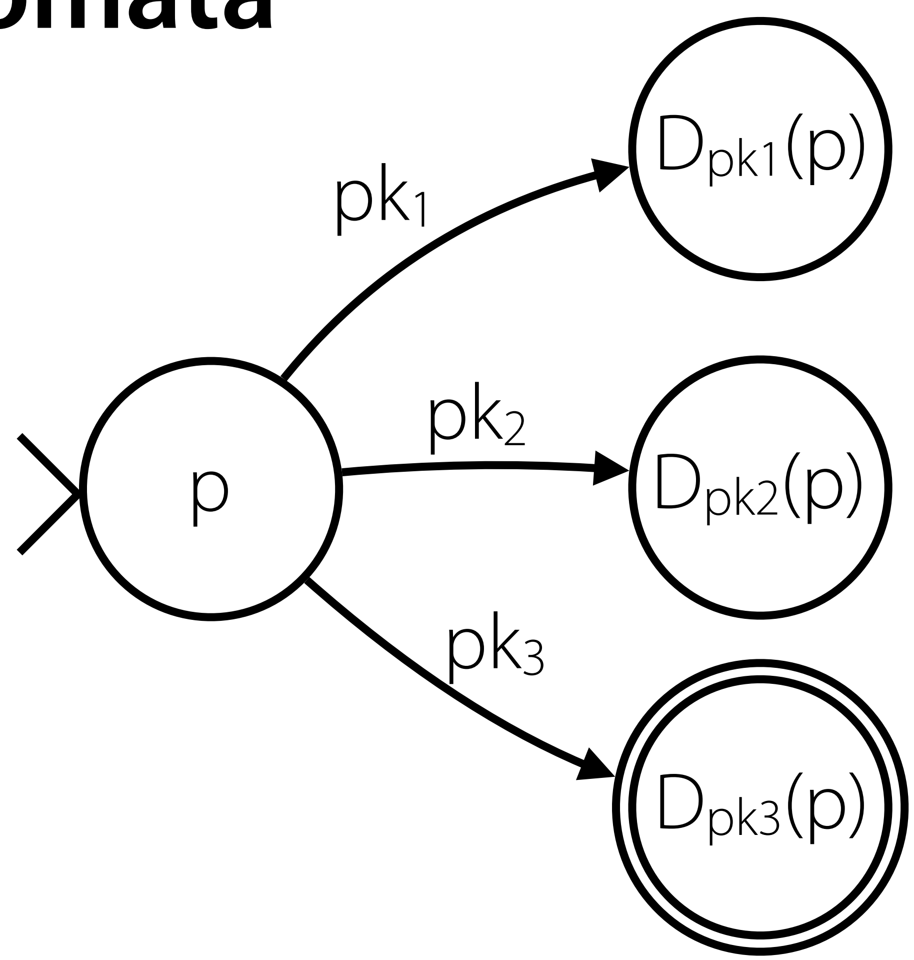
From Programs to Automata

Derivatives

$$\boxed{D_c L = \{ w \mid c \cdot w \in L \}}$$

Can be defined syntactically via a simple recursive definition

Automata



From Programs to Automata

Derivatives

$$\boxed{D_c\, L = \{\, w \mid c \cdot w \in L \,\}}$$

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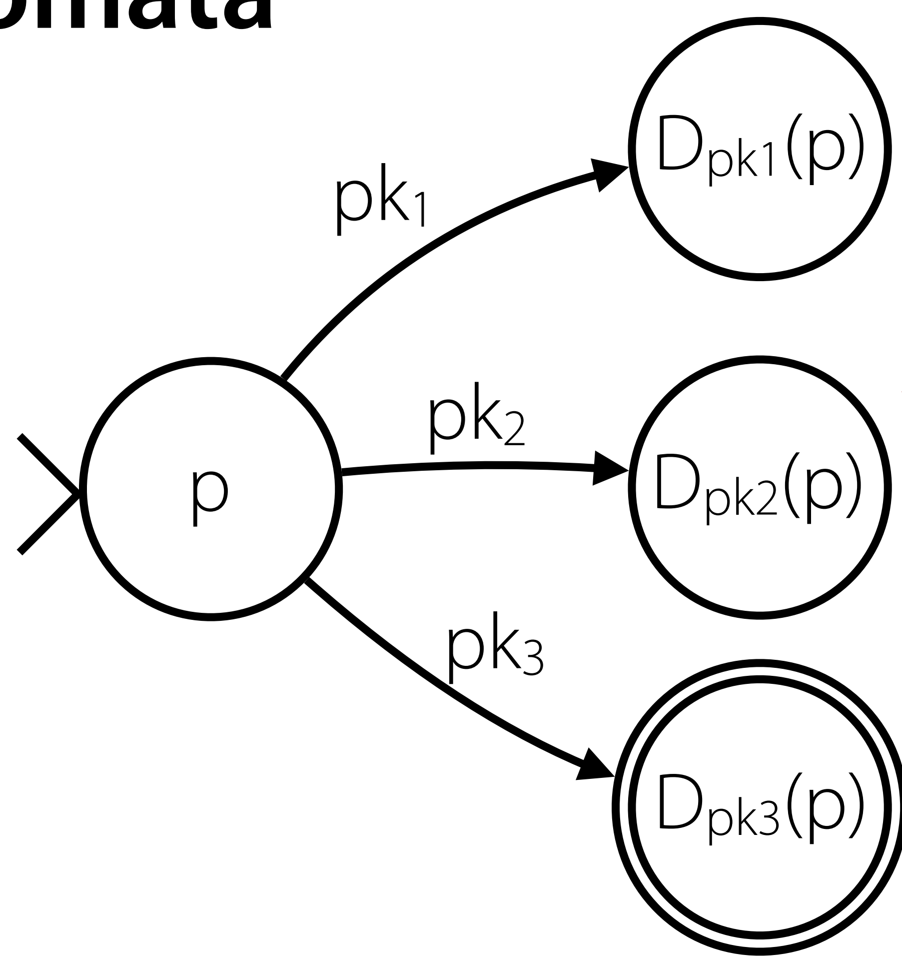
Automata



Terminates since every program has a finite number of distinct derivatives

NetKAT Automata

NetKAT automata recognize the histories generated by packets as they traverse the network:

$\mathrm{pkt}_{in} \cdot \mathrm{pkt}_{1} \cdot \textbf{dup} \cdot \ldots \cdot \textbf{dup} \cdot \mathrm{pkt}_{n}\ \textbf{dup} \cdot \mathrm{put}_{out}$

Similar to standard automata, but generalized to packets

NetKAT Automata

NetKAT automata recognize the histories generated by packets as they traverse the network:

$\mathrm{pkt}_{in} \cdot \mathrm{pkt}_1 \cdot \textbf{dup} \cdot \ldots \cdot \textbf{dup} \cdot \mathrm{pkt}_n\ \textbf{dup} \cdot \mathrm{put}_{out}$

Similar to standard automata, but generalized to packets

A *NetKAT automaton* $M = (S, s_0, \varepsilon, \delta)$ is a tuple where:

- S is a finite set of states,
- $s_0 \in S$ is the start state,
- $\varepsilon \in S \to \text{Packet} \to \text{Packet Set}$ is the "acceptance" function
- $\delta \in S \to \text{Packet} \to (\text{State} * \text{Packet})\ \text{Set}$ is the "transition" function

Syntactic Derivatives

$\boxed{E(pol) \in Pol}$

$E(\boldsymbol{\mathit{false}}) = \boldsymbol{\mathit{false}}$

$E(\textbf{true}) = \textbf{true}$

$E(f \mathbin{\textbf{=}} n) = f \mathbin{\textbf{=}} n$

$E(f \mathbin{\textbf{:=}} n) = f \mathbin{\textbf{:=}} n$

$E(\textbf{!}pol) = \textbf{!}pol$

$E(dup^l) = \textbf{false}$

$E(pol_1 \mathbin{\textbf{+}} pol_2) = E(pol_1) \mathbin{\textbf{+}} E(pol_2)$

$E(pol_1 \bullet pol_2) = E(pol_1) \bullet E(pol_2)$

$E(pol^*) = E(pol)^*$

$\boxed{D(pol) \in (Pol * L * Pol)\ Set}$

$D(\textbf{false}) = \{\}$

$D(\textbf{true}) = \{\}$

$D(f\textbf{=}n) = \{\}$

$D(f\textbf{:=}n) = \{\}$

$D(\textbf{!}pol) = \{\}$

$D(dup^l) = \{\ (\textbf{true}, l, \textbf{true})\ \}$

$D(pol_1 \mathbin{\textbf{+}} pol_2) = D(pol_1) \mathbin{\textbf{+}} D(pol_2)$

$D(pol_1 \bullet pol_2) = D(pol_1) \bullet pol_2 + E(pol_1) \bullet D(pol_2)$

$D(pol^*) = E(pol)^* \bullet D(pol) \bullet pol^*$

NetKAT Automaton

- S is the set of **dup**s, plus a fresh start state
- $\varepsilon\ l\ pkt = \{\ pkt' \mid pkt' \in [\![E(k_l)]\!]\ pkt\ \}$
- $\delta\ l\ pkt = \{\ (pkt', l') \mid (d, l', k) \in [\![D(k_l)]\!] \wedge pkt' \in [\![d]\!]\ pkt\ \}$

where k_l is the "continuation" of dup^l

Syntactic Derivatives

dup *labels*

$\boxed{\text{E(pol)} \in \text{Pol}}$

*E(**false**) = **false***
E(**true**) = **true**
E(f **=** n) = f **=** n
E(f **:=** n) = f **:=** n
E(**!**pol) = **!**pol
E(dup^l) = **false**
E(pol_1 **+** pol_2) = E(pol_1) **+** E(pol_2)
E(pol_1 • pol_2) = E(pol_1) • E(pol_2)
E(pol*) = E(pol)*

$\boxed{\text{D(pol)} \in \text{(Pol * L * Pol) Set}}$

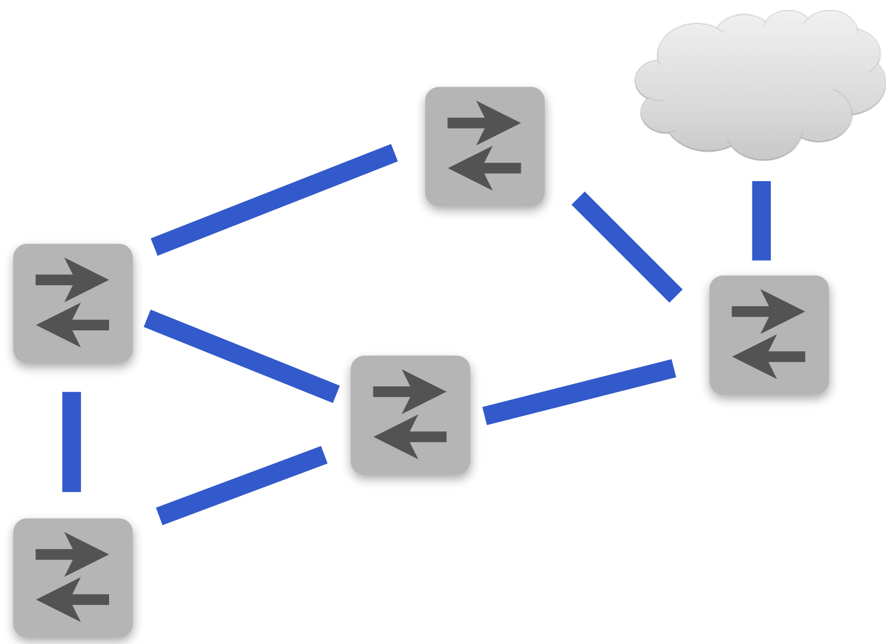
D(**false**) = {}
D(**true**) = {}
D(f**=**n) = {}
D(f**:=**n) = {}
D(**!**pol) = {}
D(dup^l) = { (**true**, l, **true**) }
D(pol_1 **+** pol_2) = D(pol_1) **+** D(pol_2)
D(pol_1 • pol_2) = D(pol_1) • pol_2 + E(pol_1) • D(pol_2)
D(pol*) = E(pol)* • D(pol) • pol*

NetKAT Automaton

- S is the set of **dup**s, plus a fresh start state
- ε l pkt = { pkt' | pkt' $\in$ $[\![E(k_l)]\!]$ pkt }
- δ l pkt = { (pkt', l') | (d, l', k) $\in$ $[\![D(k_l)]\!]$ $\wedge$ pkt' $\in$ $[\![d]\!]$ pkt }

where k_l is the "continuation" of dup^l

Application: Traffic Isolation



$$\models \quad \phi$$

We'd like to be able to answer questions like:

"Does the network isolate A and B?"

Can reduce this question to equivalence!

$$A \bullet (pol \bullet topo)^{*} \bullet B \equiv \textbf{false}$$

Application: Loop Freedom

Can exploit automata representations to *efficiently* check whether a network is free of forwarding loops...

Intuitively,

$$\forall \alpha.\ (p \bullet t)^+ \bullet \alpha \bullet (p \bullet t)^+ \bullet \alpha \equiv \textbf{false}$$

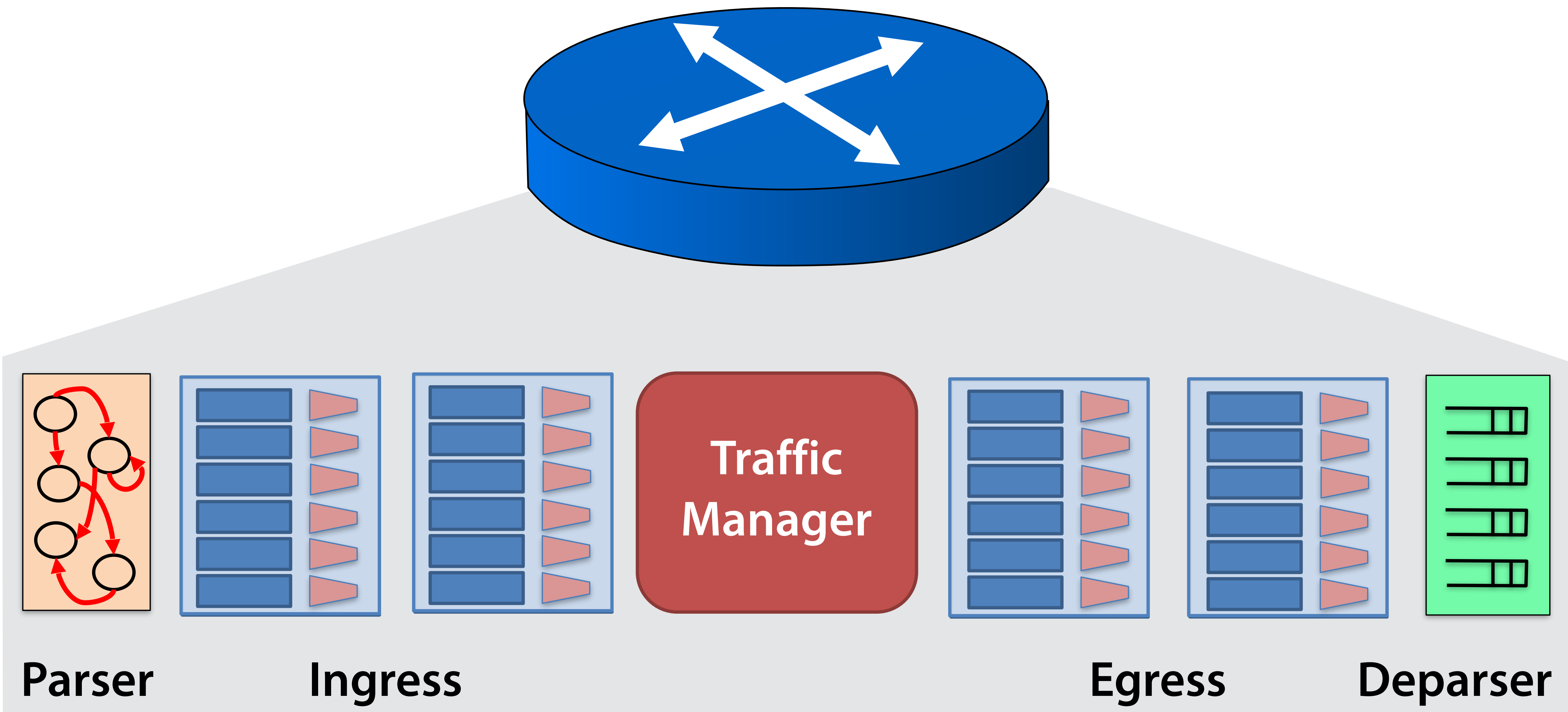
Formally:

- $\forall$ pkt, pkt'. pkt' $\in [\![E(\Phi(in \bullet (p \bullet t)^+))]\!]$ pkt
- Check whether pkt' $\in [\![E(\Phi(p \bullet t)^+))]\!]$ pkt'

Can be made fast using sparse matrix representation

Single-Device Verification in P4

P4/RMT [SIGCOMM '13]



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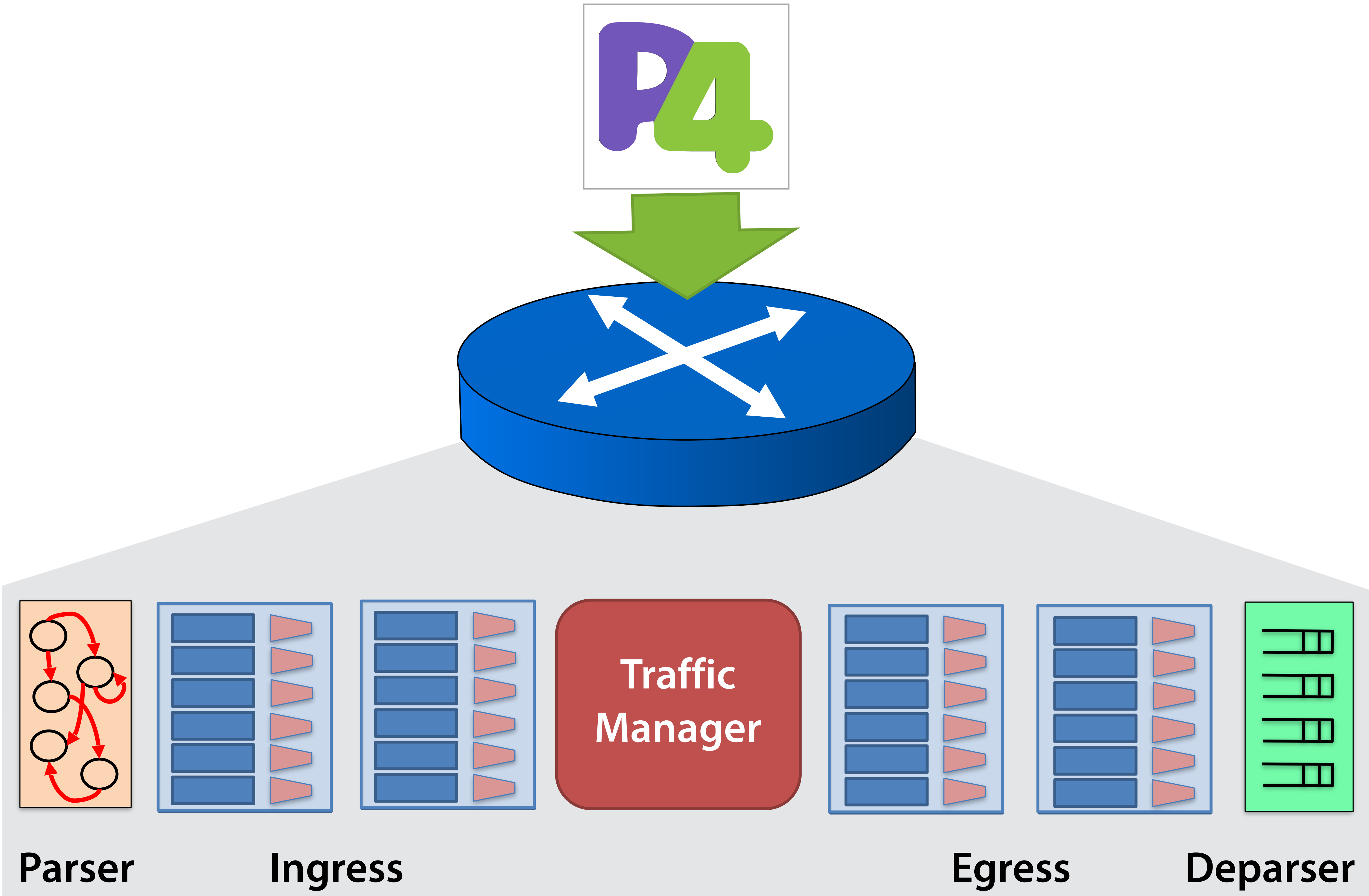

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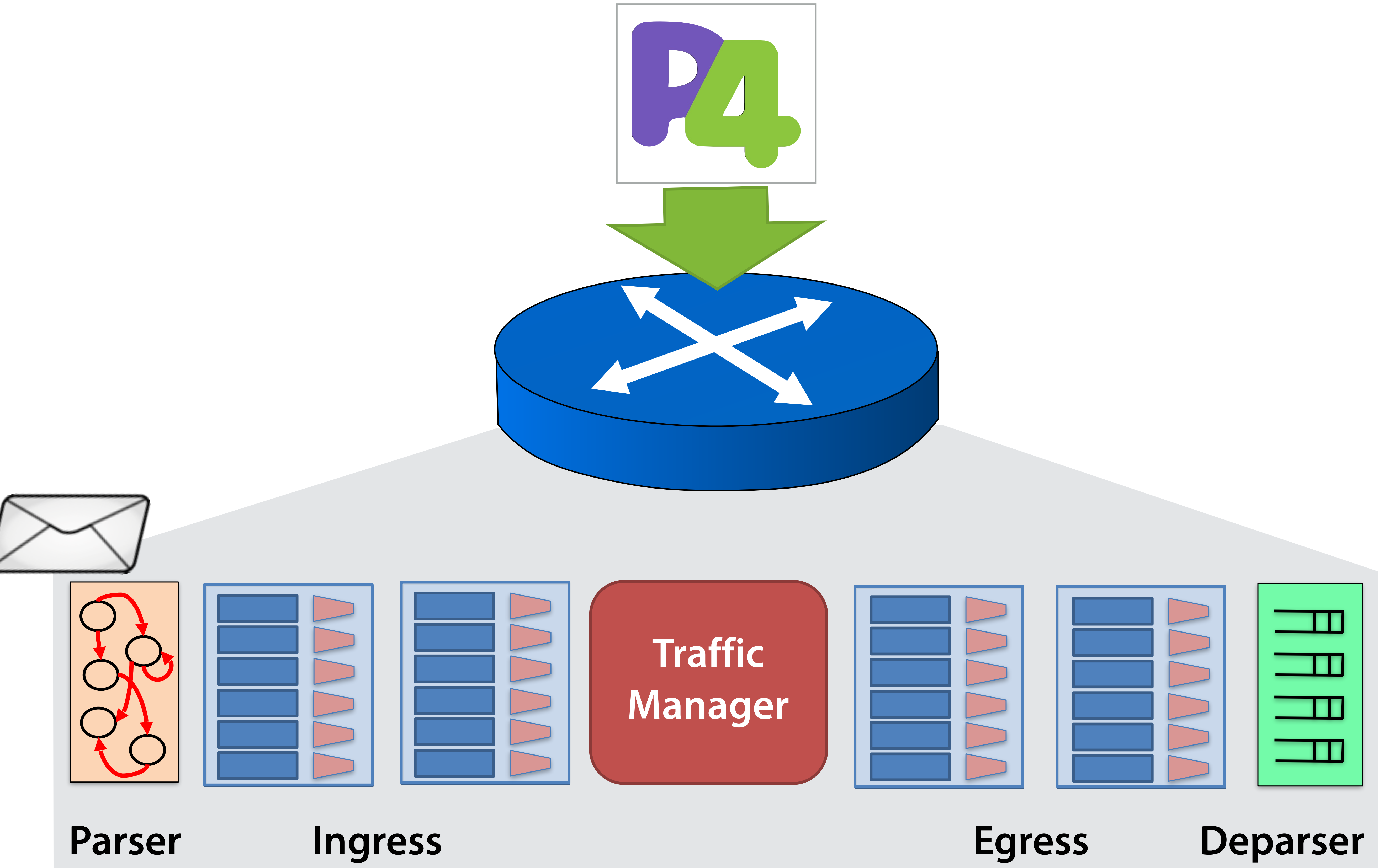

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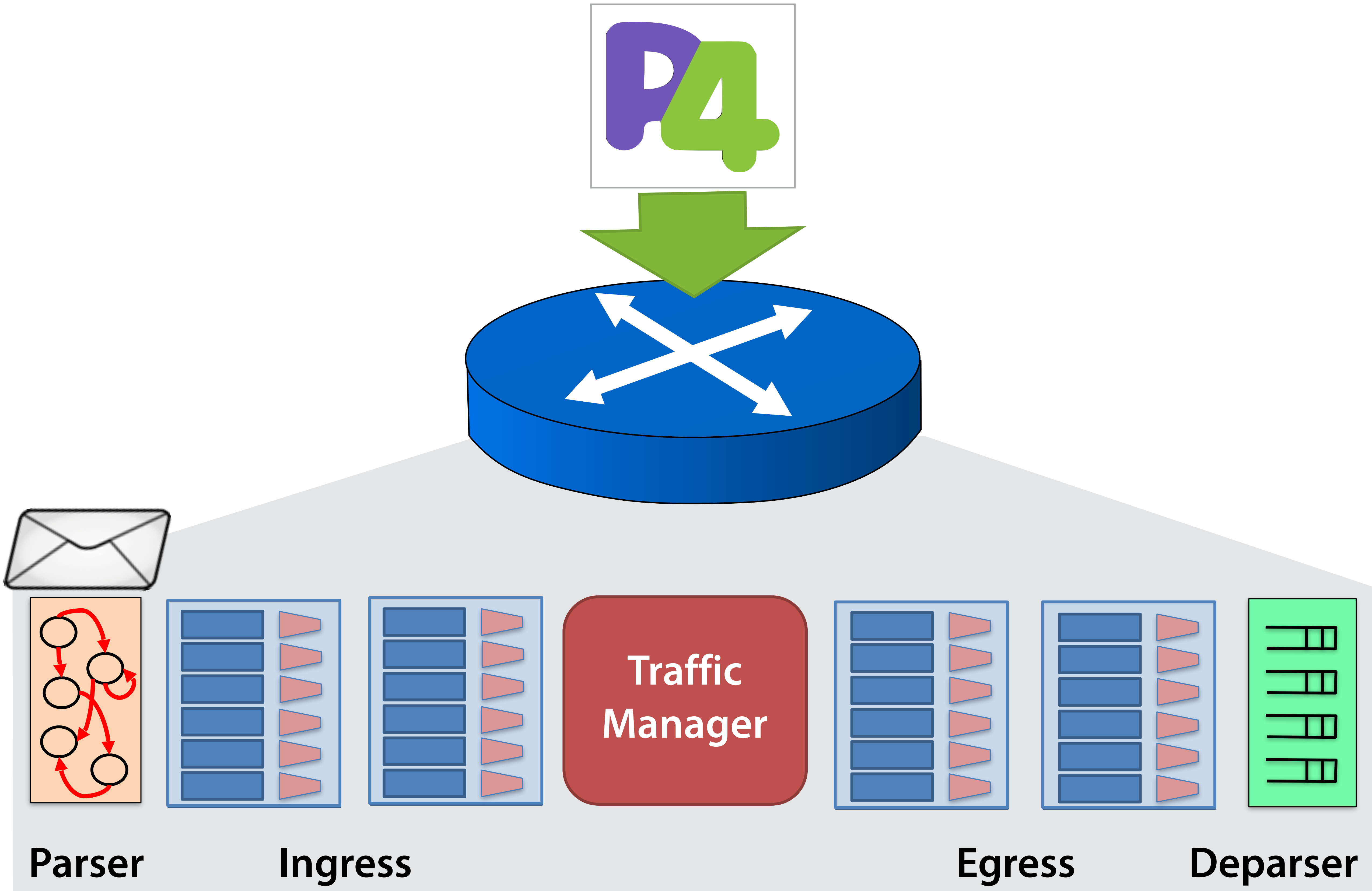

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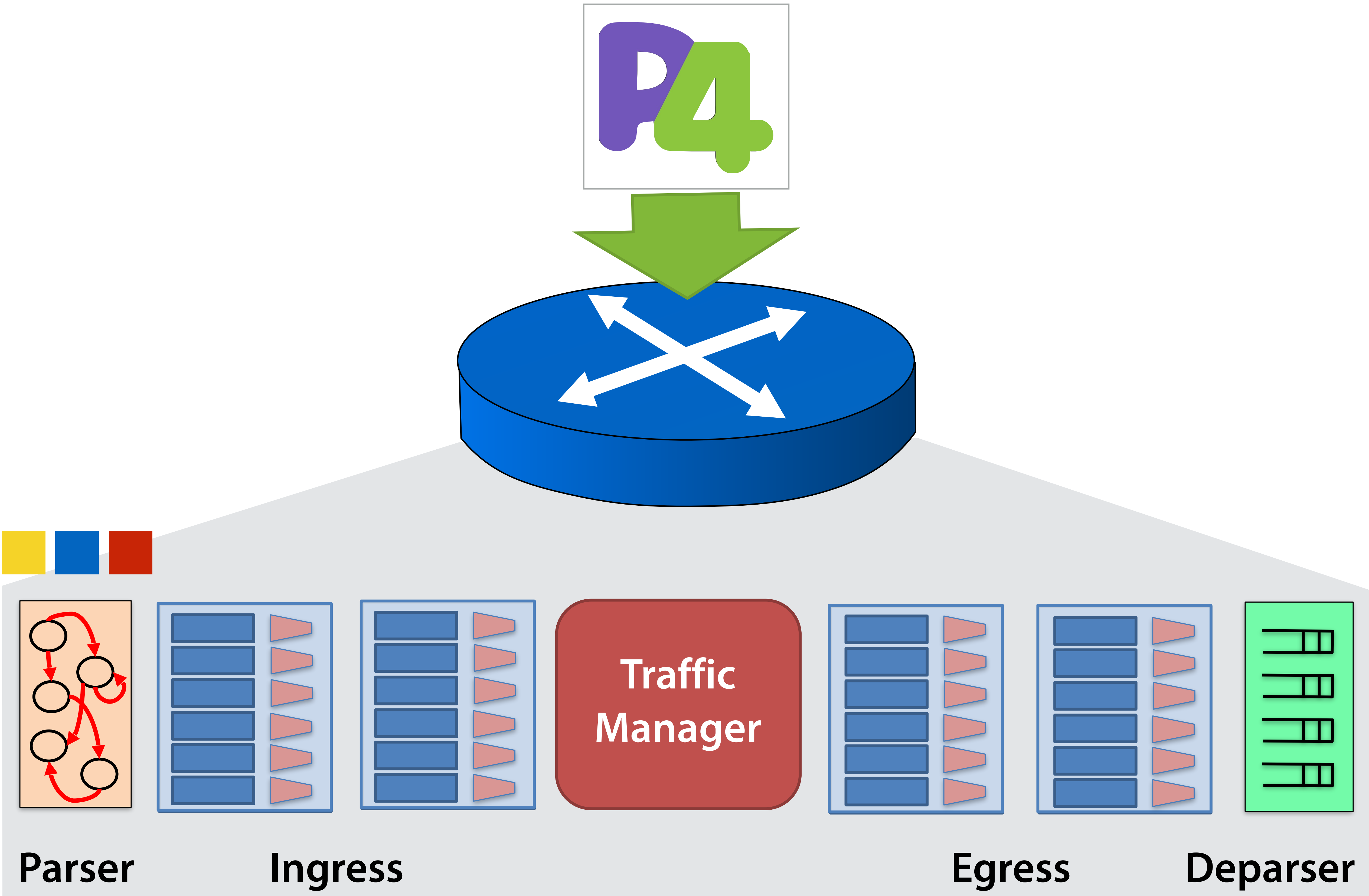

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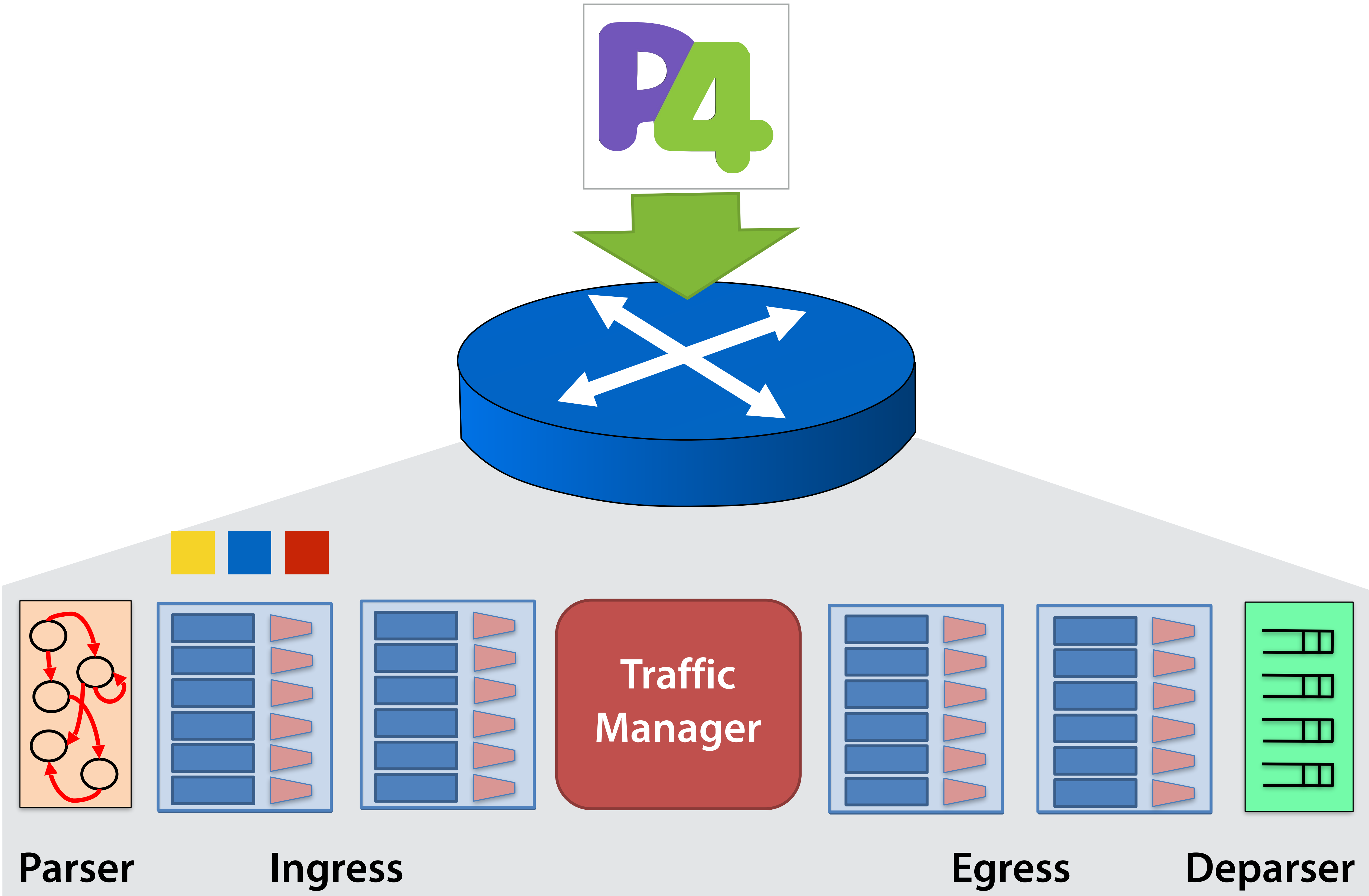

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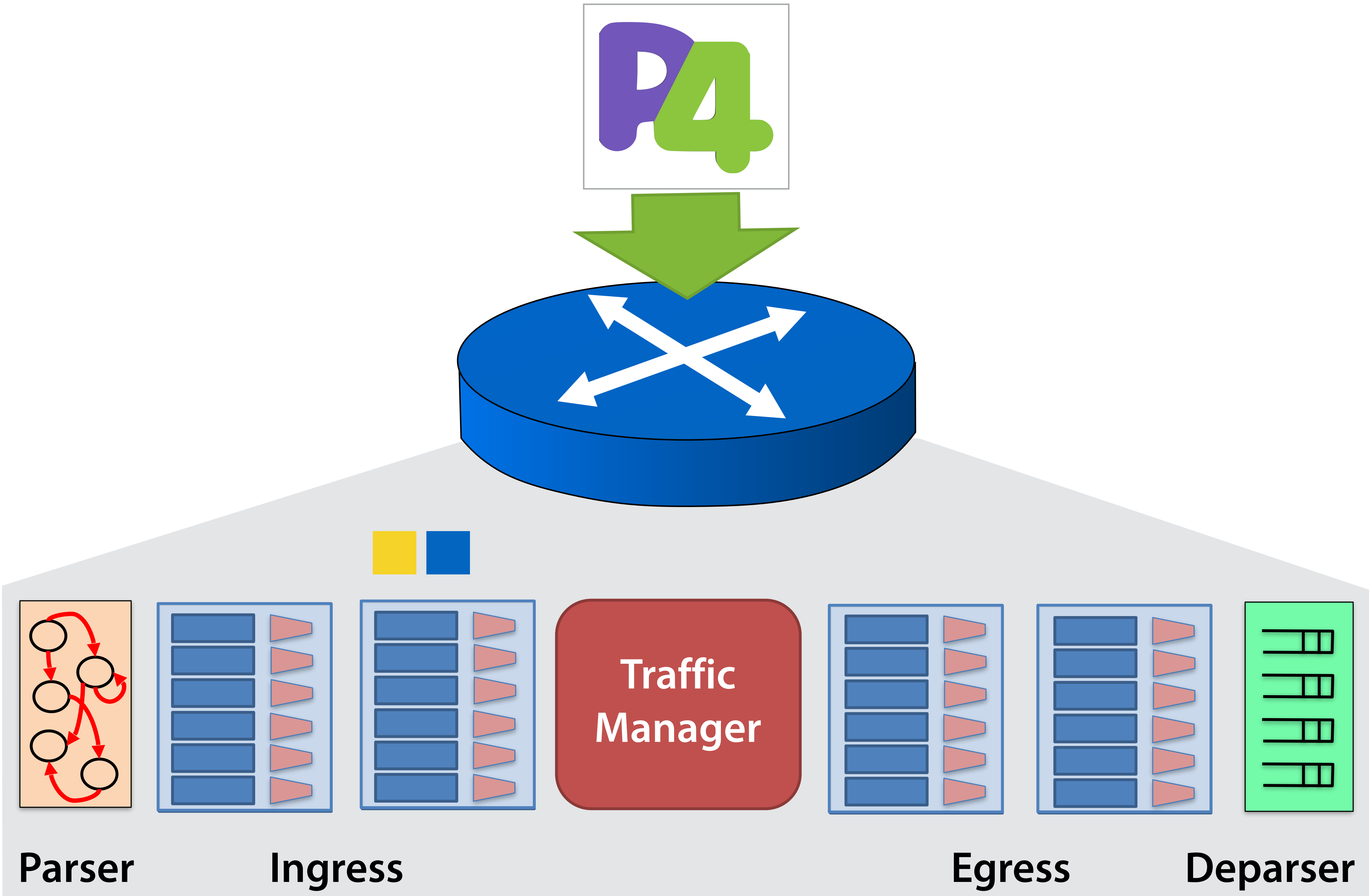

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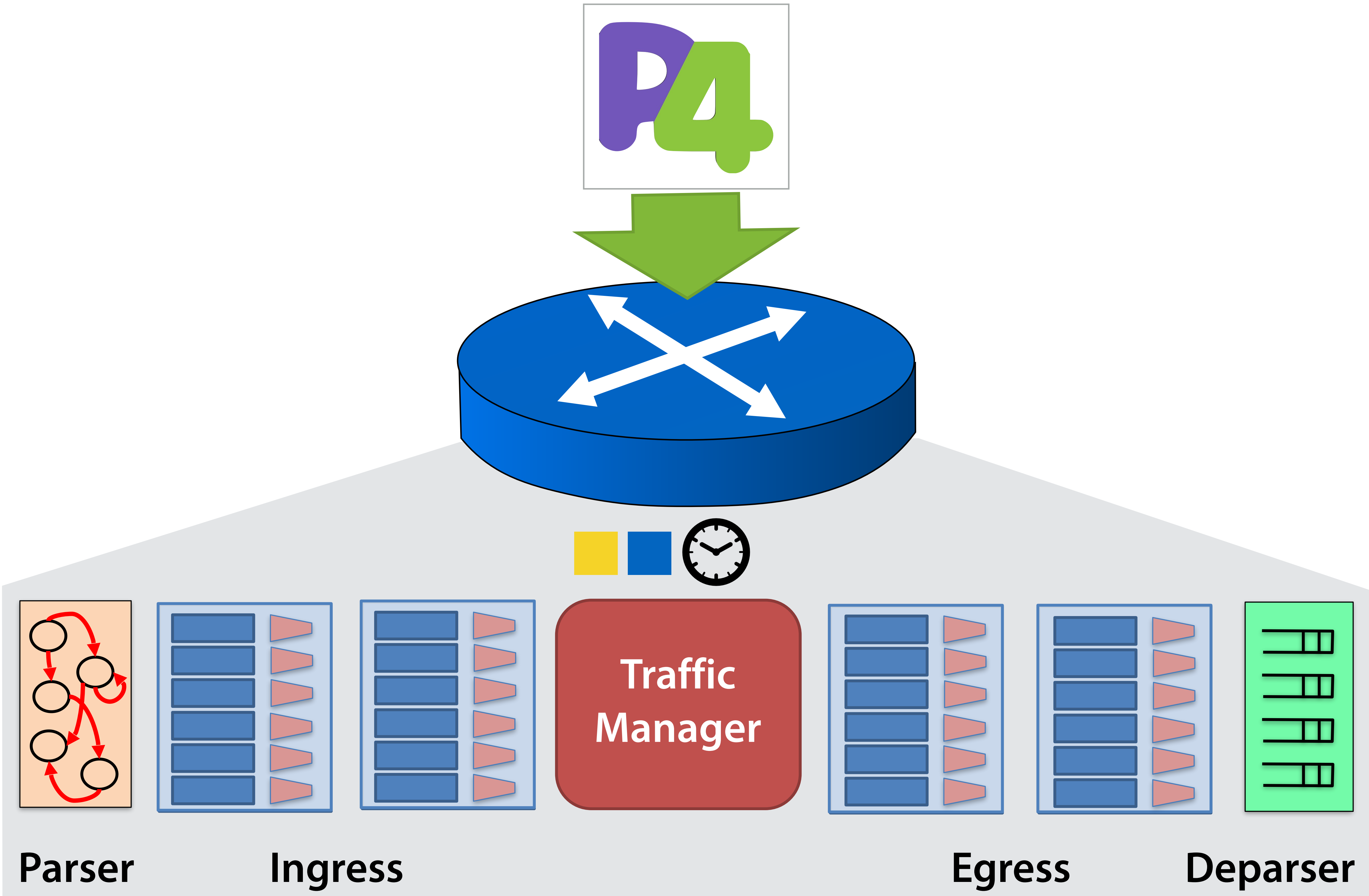
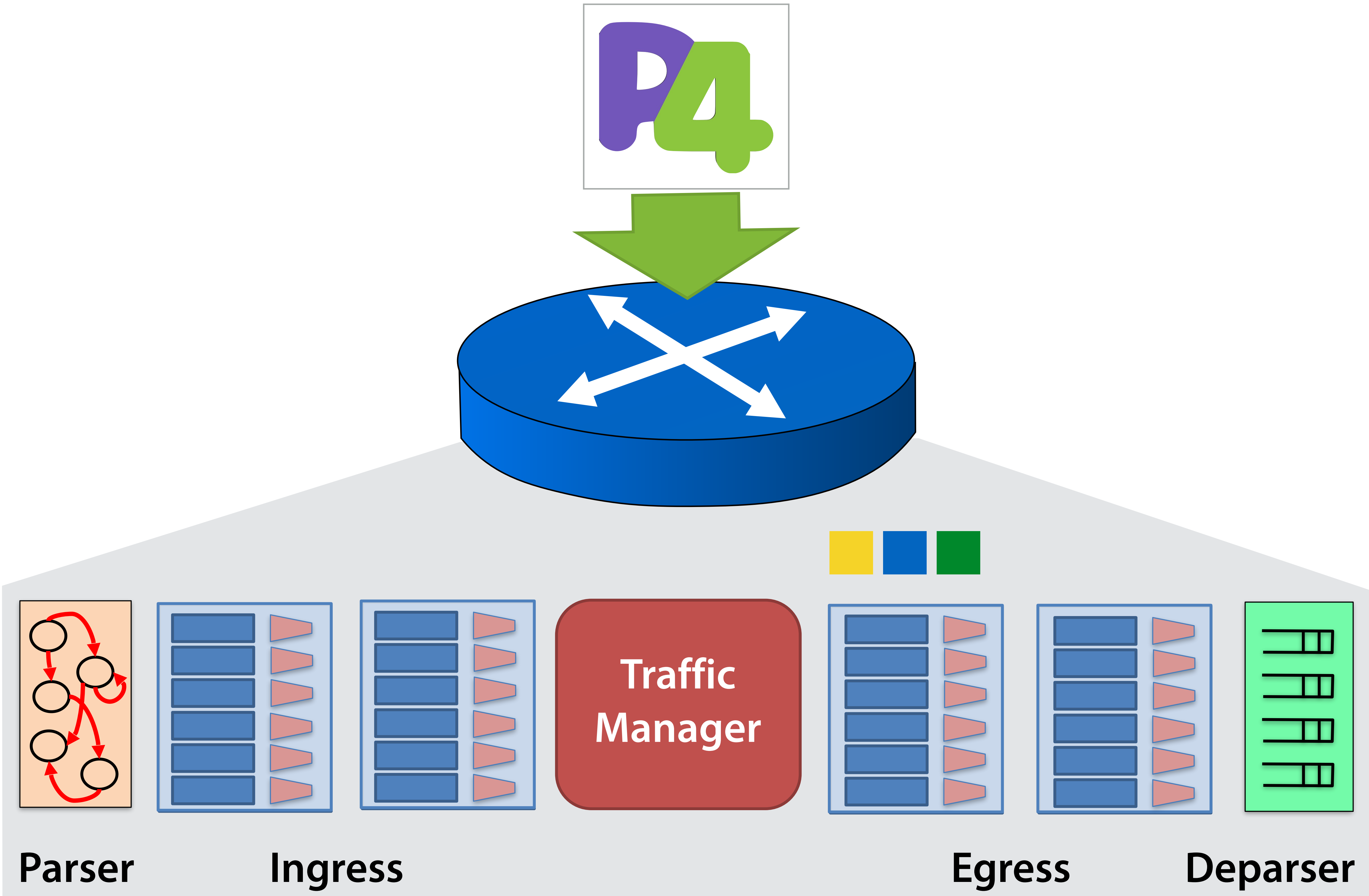


P4/RMT [SIGCOMM '13]



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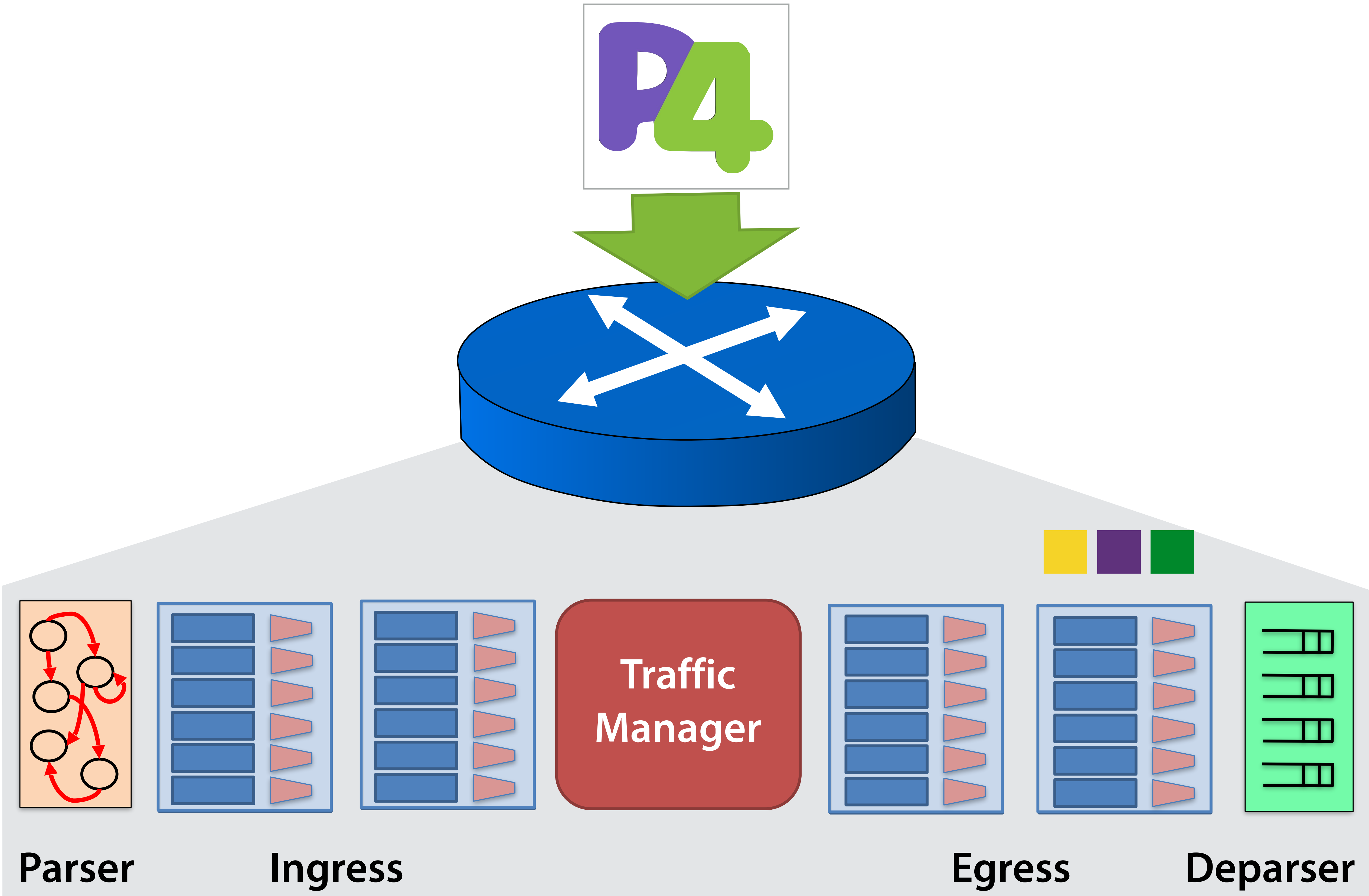

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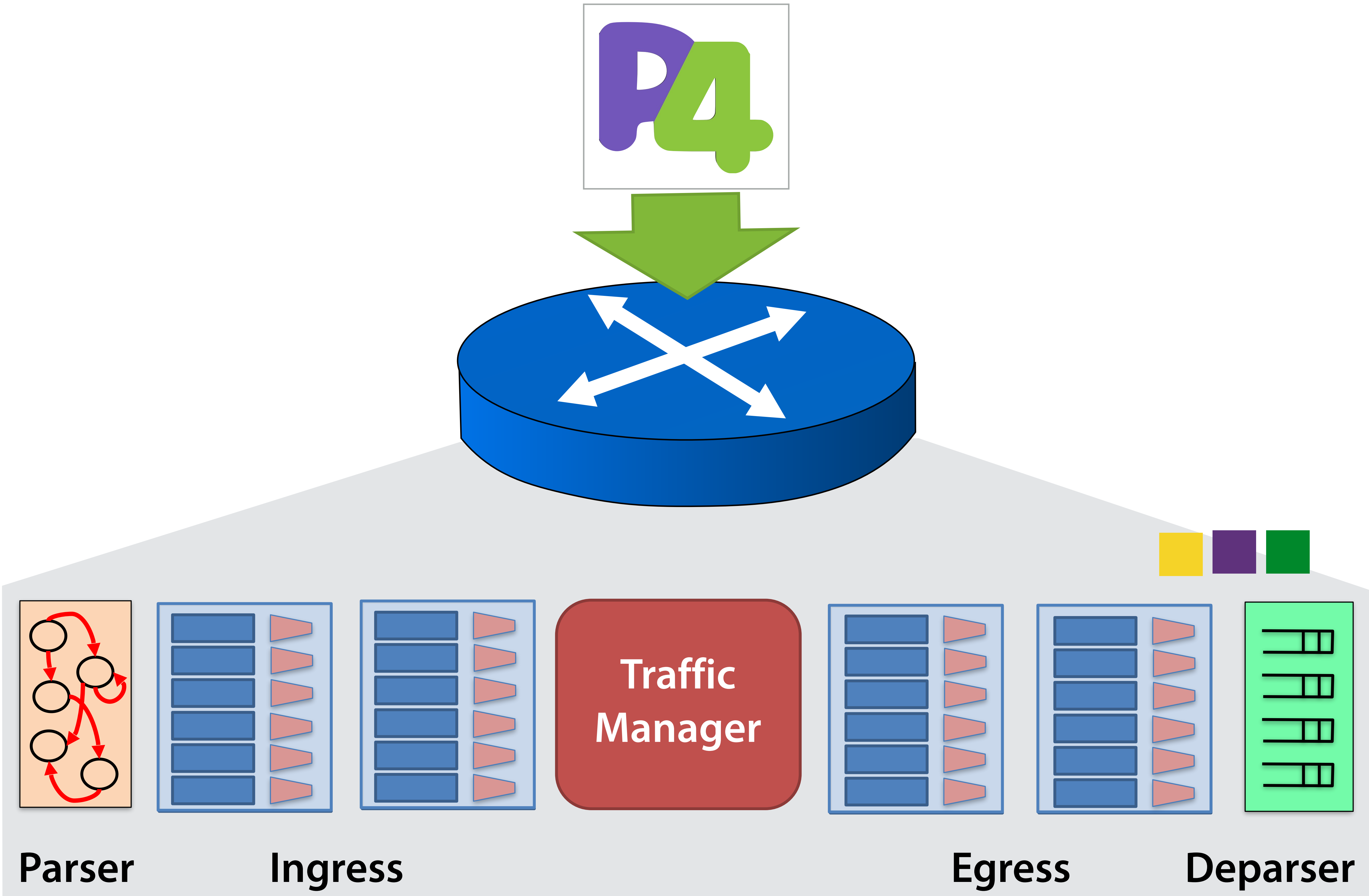
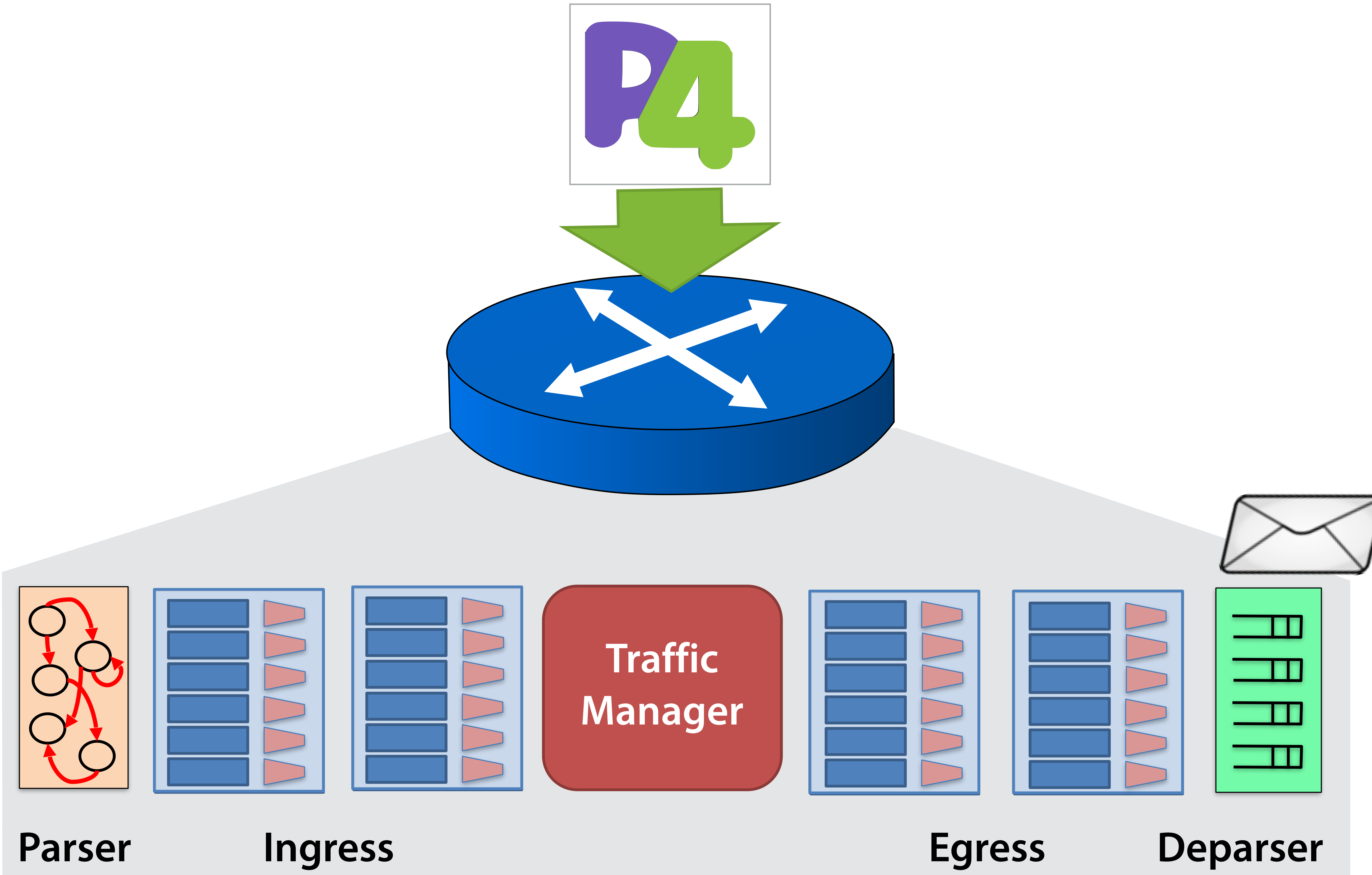


P4/RMT [SIGCOMM '13]



P4 Language

- Slogan: "constant work in constant time"
  - No pointers or complex data types
  - Bounded state
  - No loops
- Key construct is a match-action table

```
action learn() {
  generate_digest(RECV, learn_digest);
}

table smac {
  reads { ethernet.srcAddr : exact; }
  actions { learn; nop; }
  default_action: nop;
}
```

Match	Action
00:00:00:00:00:01	learn
00:00:00:00:00:02	learn
*	nop

Example: Ethernet Switch

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

header_type intrinsic_metadata_t {
  fields {
    mcast_grp : 4;
    egress_rid : 4;
    mcast_hash : 16;
    lf_field_list: 32;
  }
}

header ethernet_t ethernet;
metadata intrinsic_metadata_t intrinsic_metadata;

parser start {
  return parse_ethernet;
}

parser parse_ethernet {
  extract(ethernet);
  return ingress;
}

field_list mac_learn_digest {
  ethernet.srcAddr;
  standard_metadata.ingress_port;
}

action mac_learn() {
  generate_digest(MAC_LEARN_RECEIVER, mac_learn_digest);
}

action forward(port) {
  modify_field(standard_metadata.egress_spec, port);
}

action broadcast() {
  modify_field(intrinsic_metadata.mcast_grp, 1);
}
```

```
table smac {
  reads {
    ethernet.srcAddr : exact;
  }
  actions {
    mac_learn;
    nop;
  }
  size : 512;
}

table dmac {
  reads {
    ethernet.dstAddr : exact;
  }
  actions {
    forward;
    broadcast;
  }
  size : 512;
}

table mcast_src_pruning {
  reads {
    standard_metadata.instance_type : exact;
  }
  actions {_
    nop;
    drop;
  }
  size : 1;
}

control ingress {
  apply(smac);
  apply(dmac);
}

control egress {
  (if(standard_metadata.ingress_port ==
      standard_metadata.egress_port) {
    apply(mcast_src_pruning);
  }
}
```

Example: Ethernet Switch

Types

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

header_type intrinsic_metadata_t {
  fields {
    mcast_grp : 4;
    egress_rid : 4;
    mcast_hash : 16;
    lf_field_list: 32;
  }
}

header ethernet_t ethernet;
metadata intrinsic_metadata_t intrinsic_metadata;
```

Parsers

```
parser start {
  return parse_ethernet;
}

parser parse_ethernet {
  extract(ethernet);
  return ingress;
}
```

Actions

```
field_list mac_learn_digest {
  ethernet.srcAddr;
  standard_metadata.ingress_port;
}

action mac_learn() {
  generate_digest(MAC_LEARN_RECEIVER, mac_learn_digest);
}

action forward(port) {
  modify_field(standard_metadata.egress_spec, port);
}

action broadcast() {
  modify_field(intrinsic_metadata.mcast_grp, 1);
}
```

Tables

```
table smac {
  reads {
    ethernet.srcAddr : exact;
  }
  actions {
    mac_learn;
    nop;
  }
  size : 512;
}

table dmac {
  reads {
    ethernet.dstAddr : exact;
  }
  actions {
    forward;
    broadcast;
  }
  size : 512;
}

table mcast_src_pruning {
  reads {
    standard_metadata.instance_type : exact;
  }
  actions {_
    nop;
    drop;
  }
  size : 1;
}
```

Controls

```
control ingress {
  apply(smac);
  apply(dmac);
}

control egress {
  (if(standard_metadata.ingress_port ==
      standard_metadata.egress_port) {
    apply(mcast_src_pruning);
  }
}
```

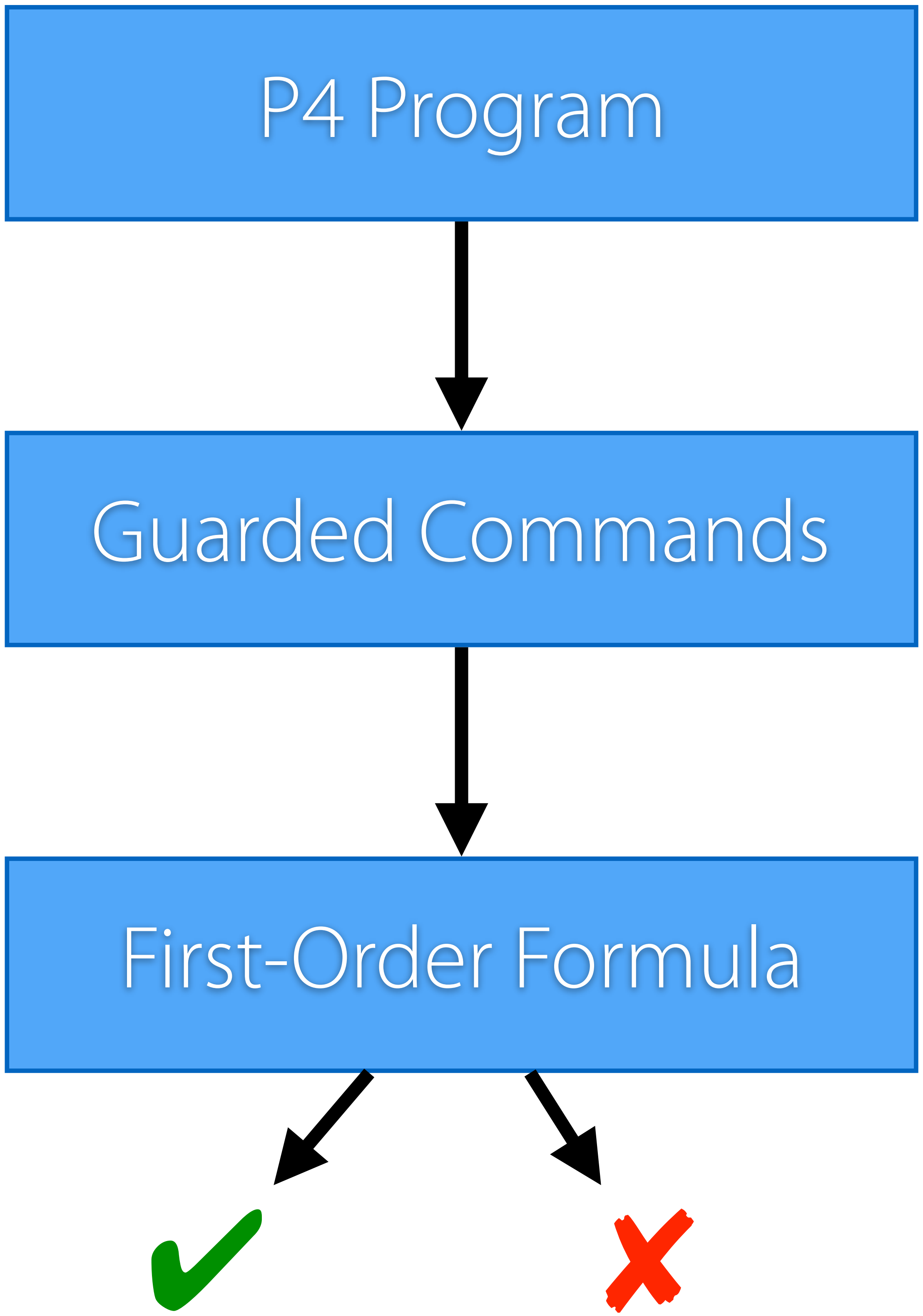
Data Plane Errors

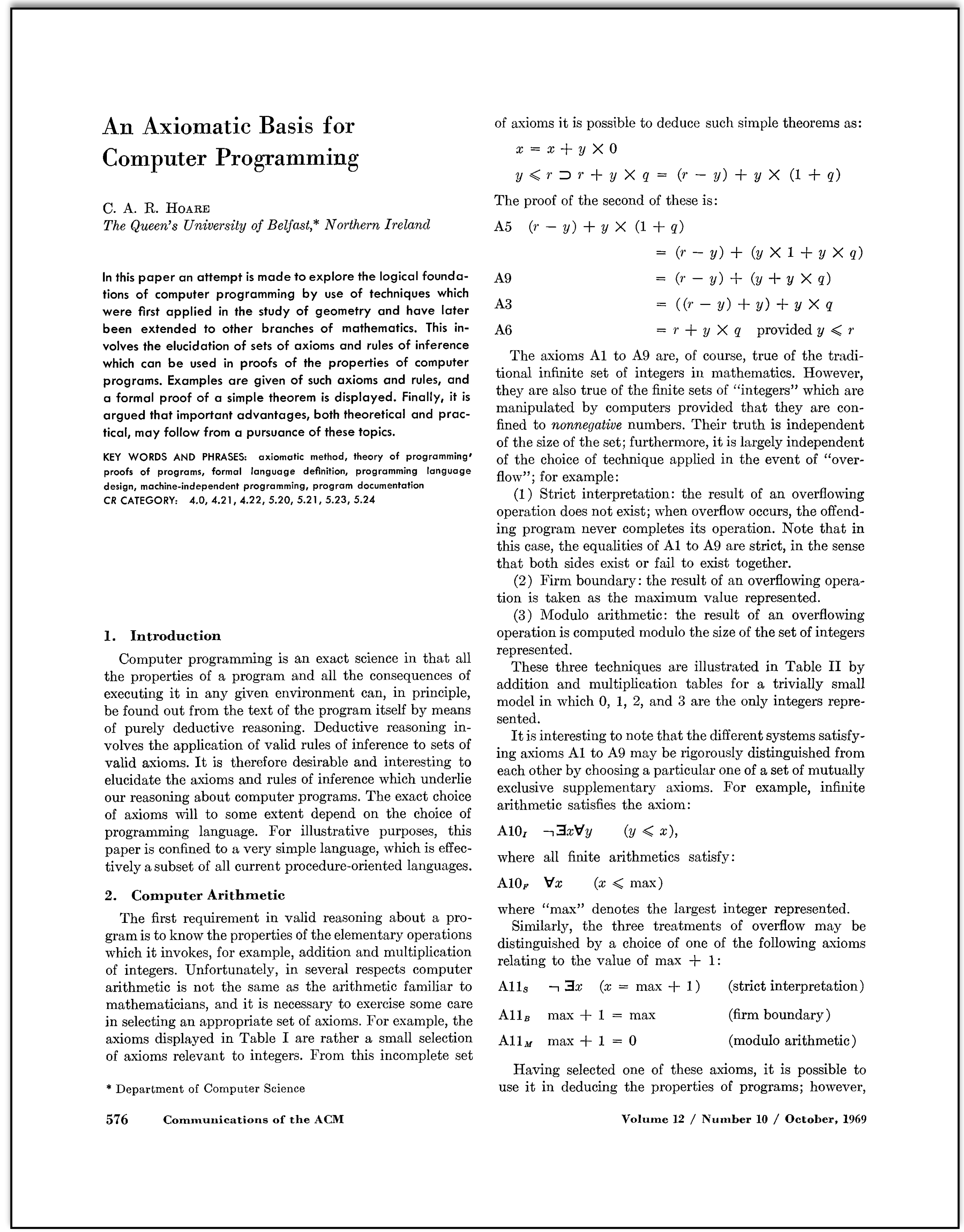
Making switches more programmable increases flexibility…

…but also opens up possibilities for new kinds of errors:

- Reading/writing invalid headers
- Unhanded exceptions
- Incorrect use of packet metadata
- Malformed parsers/deparsers
- Unintended control flows

Approach





An Axiomatic Basis for Computer Programming

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The Queen's University of Belfast, Northern Ireland*

In this paper an attempt is made to explore the logical foundations of computer programming by use of techniques which were first applied in the study of geometry and have later been extended to other branches of mathematics. This involves the elucidation of sets of axioms and rules of inference which can be used in proofs of the properties of computer programs. Examples are given of such axioms and rules, and a formal proof of a simple theorem is displayed. Finally, it is argued that important advantages, both theoretical and practical, may follow from a pursuance of these topics.

KEY WORDS AND PHRASES: axiomatic method, theory of programming' proofs of programs, formal language definition, programming language design, machine-independent programming, program documentation
CR CATEGORY: 4.0, 4.21, 4.22, 5.20, 5.21, 5.23, 5.24

1. Introduction

Computer programming is an exact science in that all the properties of a program and all the consequences of executing it in any given environment can, in principle, be found out from the text of the program itself by means of purely deductive reasoning. Deductive reasoning involves the application of valid rules of inference to sets of valid axioms. It is therefore desirable and interesting to elucidate the axioms and rules of inference which underlie our reasoning about computer programs. The exact choice of axioms will to some extent depend on the choice of programming language. For illustrative purposes, this paper is confined to a very simple language, which is effectively a subset of all current procedure-oriented languages.

2. Computer Arithmetic

The first requirement in valid reasoning about a program is to know the properties of the elementary operations which it invokes, for example, addition and multiplication of integers. Unfortunately, in several respects computer arithmetic is not the same as the arithmetic familiar to mathematicians, and it is necessary to exercise some care in selecting an appropriate set of axioms. For example, the axioms displayed in Table I are rather a small selection of axioms relevant to integers. From this incomplete set of axioms it is possible to deduce such simple theorems as:

$$x = x + y \times 0$$

$$y \leqslant r \supset r + y \times q = (r - y) + y \times (1 + q)$$

The proof of the second of these is:

A5	$(r - y) + y \times (1 + q)$
	$= (r - y) + (y \times 1 + y \times q)$
A9	$= (r - y) + (y + y \times q)$
A3	$= ((r - y) + y) + y \times q$
A6	$= r + y \times q$ provided $y \leqslant r$

The axioms A1 to A9 are, of course, true of the traditional infinite set of integers in mathematics. However, they are also true of the finite sets of "integers" which are manipulated by computers provided that they are confined to *nonnegative* numbers. Their truth is independent of the size of the set; furthermore, it is largely independent of the choice of technique applied in the event of "overflow"; for example:

(1) Strict interpretation: the result of an overflowing operation does not exist; when overflow occurs, the offending program never completes its operation. Note that in this case, the equalities of A1 to A9 are strict, in the sense that both sides exist or fail to exist together.

(2) Firm boundary: the result of an overflowing operation is taken as the maximum value represented.

(3) Modulo arithmetic: the result of an overflowing operation is computed modulo the size of the set of integers represented.

These three techniques are illustrated in Table II by addition and multiplication tables for a trivially small model in which 0, 1, 2, and 3 are the only integers represented.

It is interesting to note that the different systems satisfying axioms A1 to A9 may be rigorously distinguished from each other by choosing a particular one of a set of mutually exclusive supplementary axioms. For example, infinite arithmetic satisfies the axiom:

$$\text{A10}_I \quad \neg\exists x \forall y \quad (y \leqslant x),$$

where all finite arithmetics satisfy:

$$\text{A10}_F \quad \forall x \quad (x \leqslant \max)$$

where "max" denotes the largest integer represented.

Similarly, the three treatments of overflow may be distinguished by a choice of one of the following axioms relating to the value of max + 1:

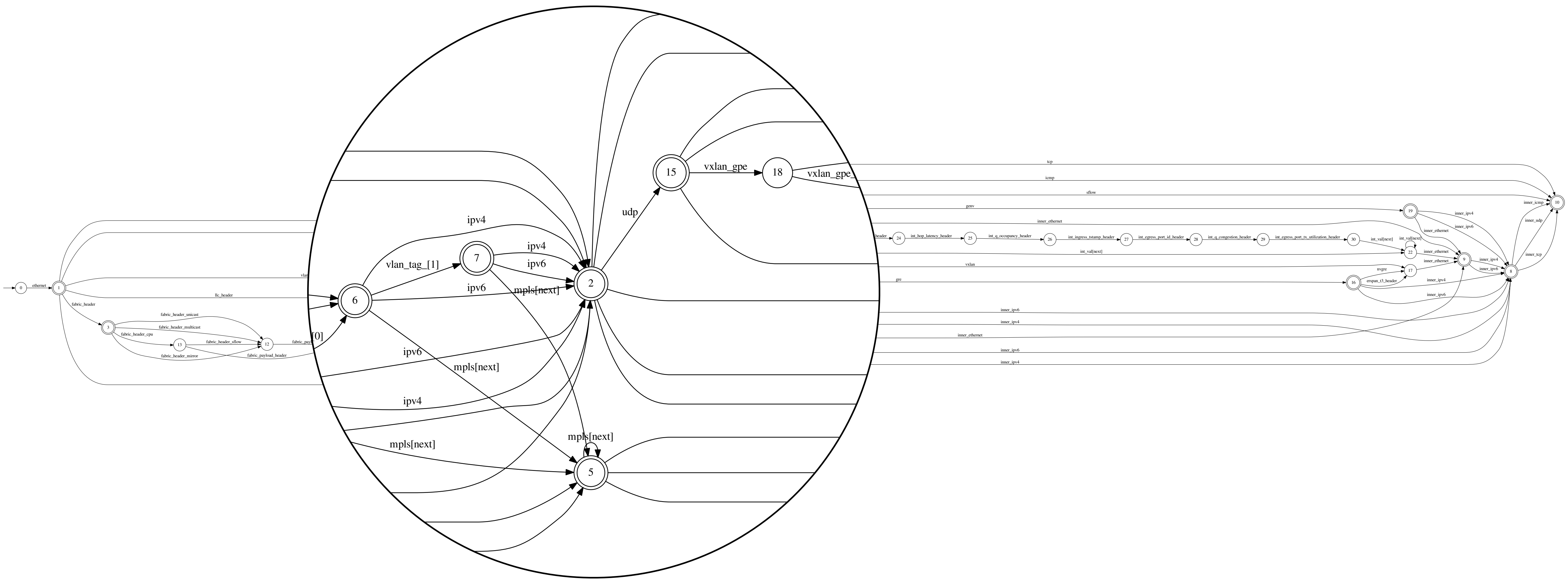
A11_S	$\neg\exists x \ (x = \max + 1)$	(strict interpretation)
A11_B	$\max + 1 = \max$	(firm boundary)
A11_M	$\max + 1 = 0$	(modulo arithmetic)

Having selected one of these axioms, it is possible to use it in deducing the properties of programs; however,

* Department of Computer Science

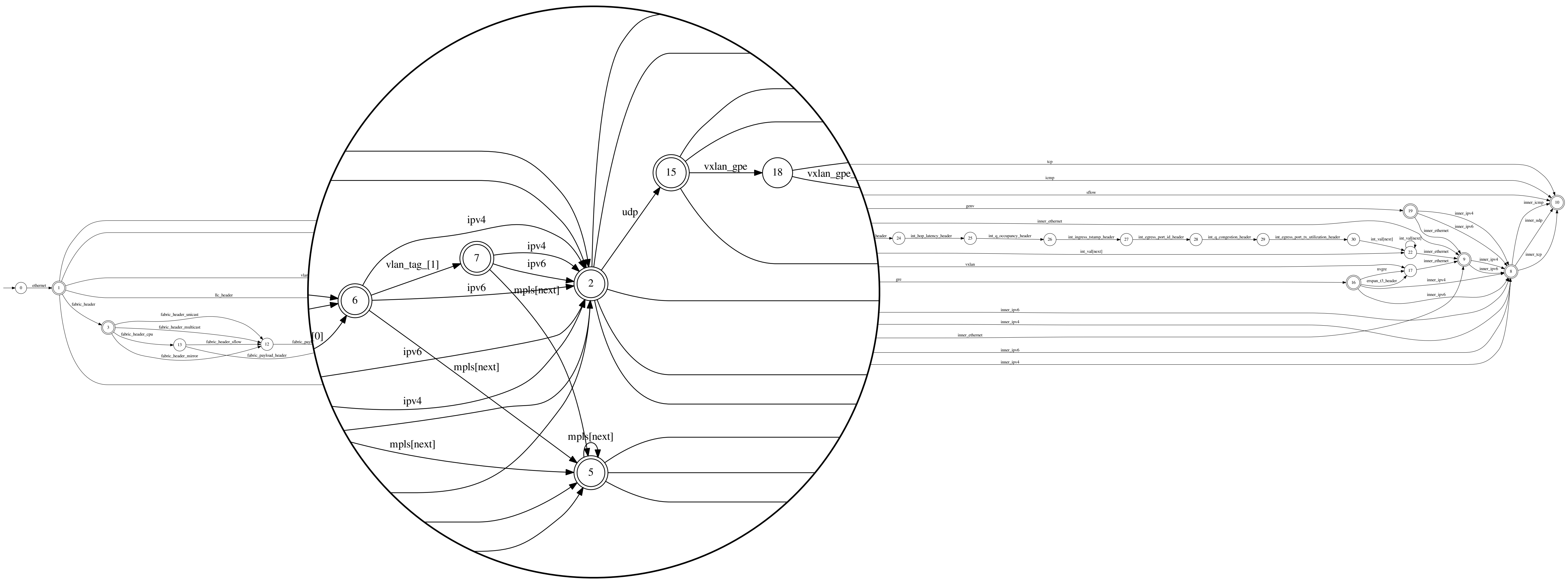
Example: Header Validity

Reading or writing an invalid header yields an undefined value (!) but packet headers have complex dependencies



Example: Header Validity

Reading or writing an invalid header yields an undefined value (!) but packet headers have complex dependencies



Worse, P4's type system does not offer good constructs for precisely documenting which headers are valid!

Demo

Example: Correct Decapsulation

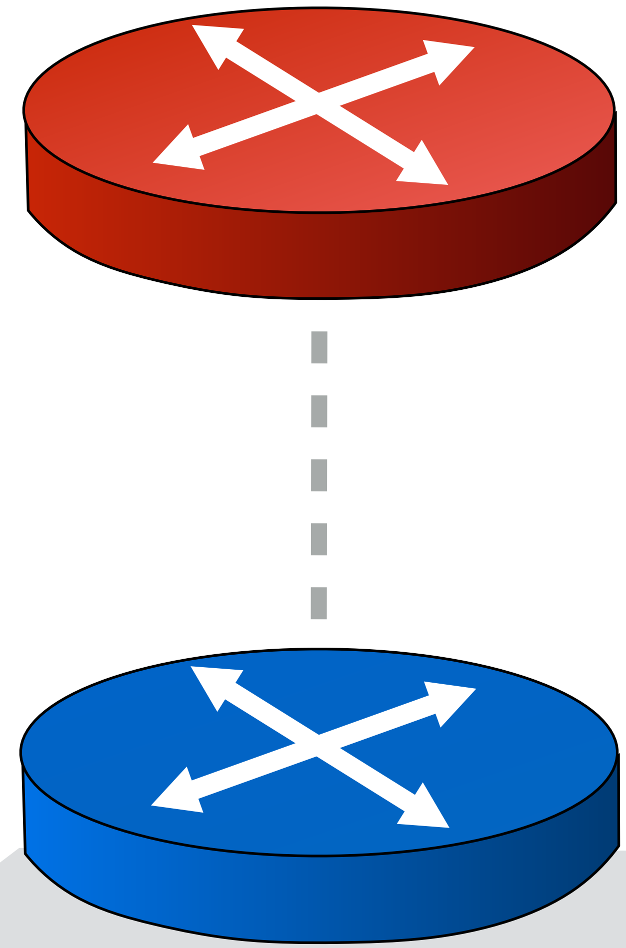
```
action remove_vlan_single_tagged() {
    modify_field(ethernet.etherType, vlan_tag_[0].etherType);
    remove_header(vlan_tag_[0]);
}
action remove_vlan_double_tagged() {
    modify_field(ethernet.etherType, vlan_tag_[1].etherType);
    remove_header(vlan_tag_[0]);
    remove_header(vlan_tag_[1]);
}
table vlan_decap {
    reads {
        vlan_tag_[0]: valid;
        vlan_tag_[1]: valid;
    }
    actions {
        nop;
        remove_vlan_single_tagged;
        remove_vlan_double_tagged;
    }
}

@pragma assert not(valid(vlan[0]) or valid(vlan[1]))
```

Challenge

A P4 program is really only half of a program

The match-action tables are populated by the control plane which is unknown!

Need a way to document assumptions about the control plane



Match	Action
00:00:00:00:00:01	learn
00:00:00:00:00:02	learn
*	nop

Ghost State

Idea: instrument program with ghost state

```
header_type _p4v_zombie_t {
  fields {
    ...
    decap_order : 2;
    decap_hit : 1;
    decap_action : 2;
    decap_reads_0 : 1;
 }
}
action decap_nop() {
  modify_field(_p4v_zombie.decap_hit, 1);
  modify_field(_p4v_zombie.decap_reads_0, valid(vlan[0]));
  modify_field(_p4v_zombie.decap_action, 1);
}
```

Can then formulate control-plane assumptions

```
@pragma assume hit(decap)
```

Wrapping up...

Conclusions

The intersection between formal methods and networking has gotten *very* interesting in recent years

The emergence of SDN/P4 offers a unique opportunity to shape how networks are built and operated for decades to come

Many challenging problems remain:

- Stateful verification
- Quantitative properties
- Usability by non-experts

Thank you!

http://frenetic-lang.org/

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- Steffen Smolka (Cornell)
- Laure Thompson (Cornell)
- David Walker (Princeton)
- Han Wang (Barefoot Networks)


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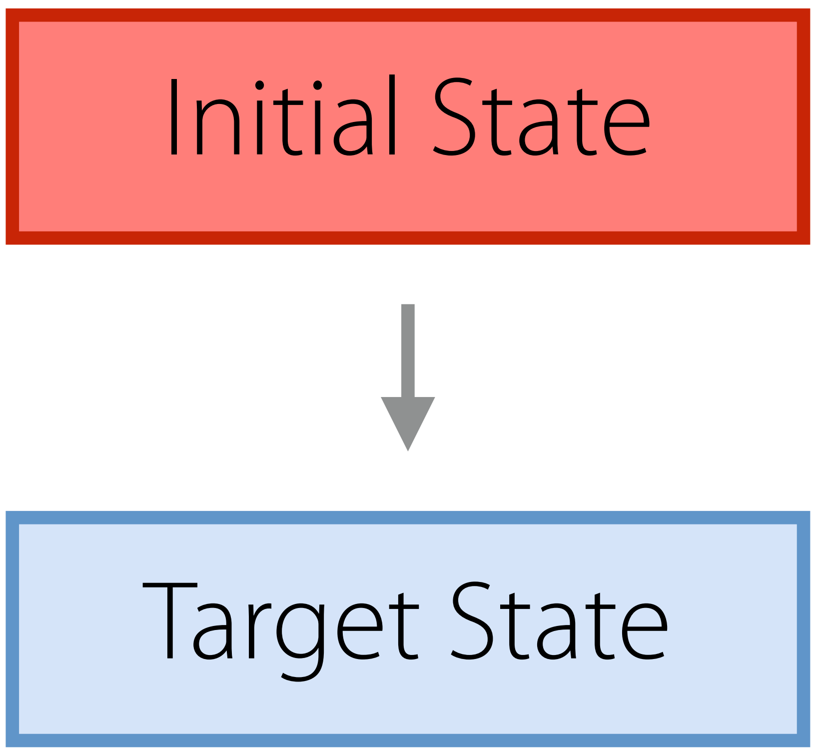
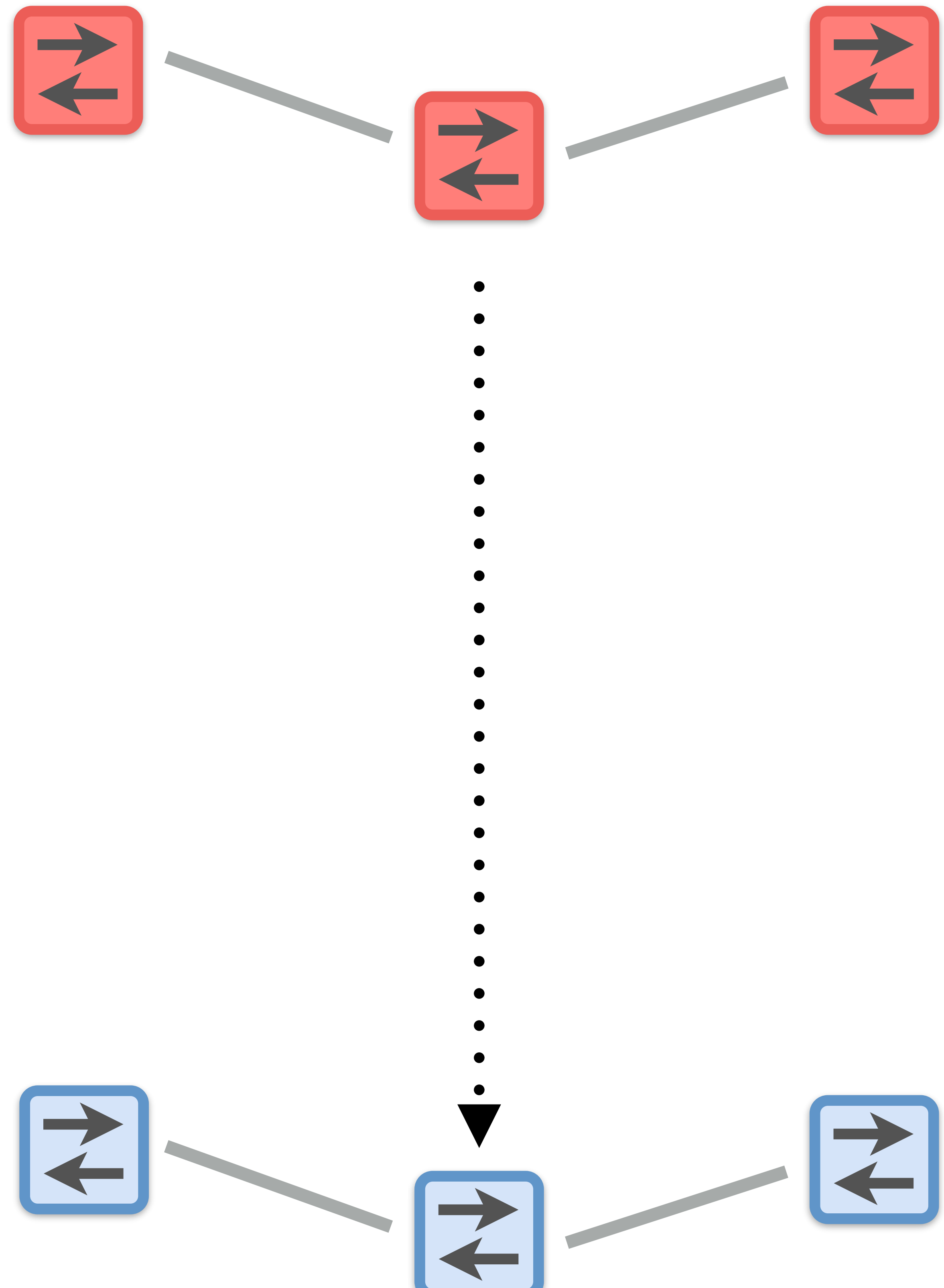
Backup Slides

Network Updates

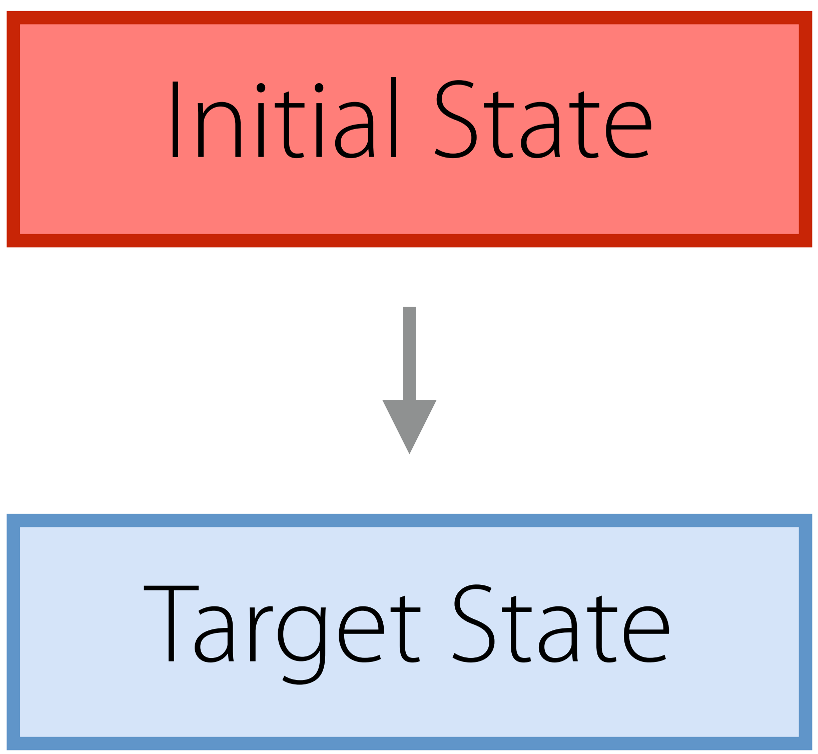
How can we transition between global states?

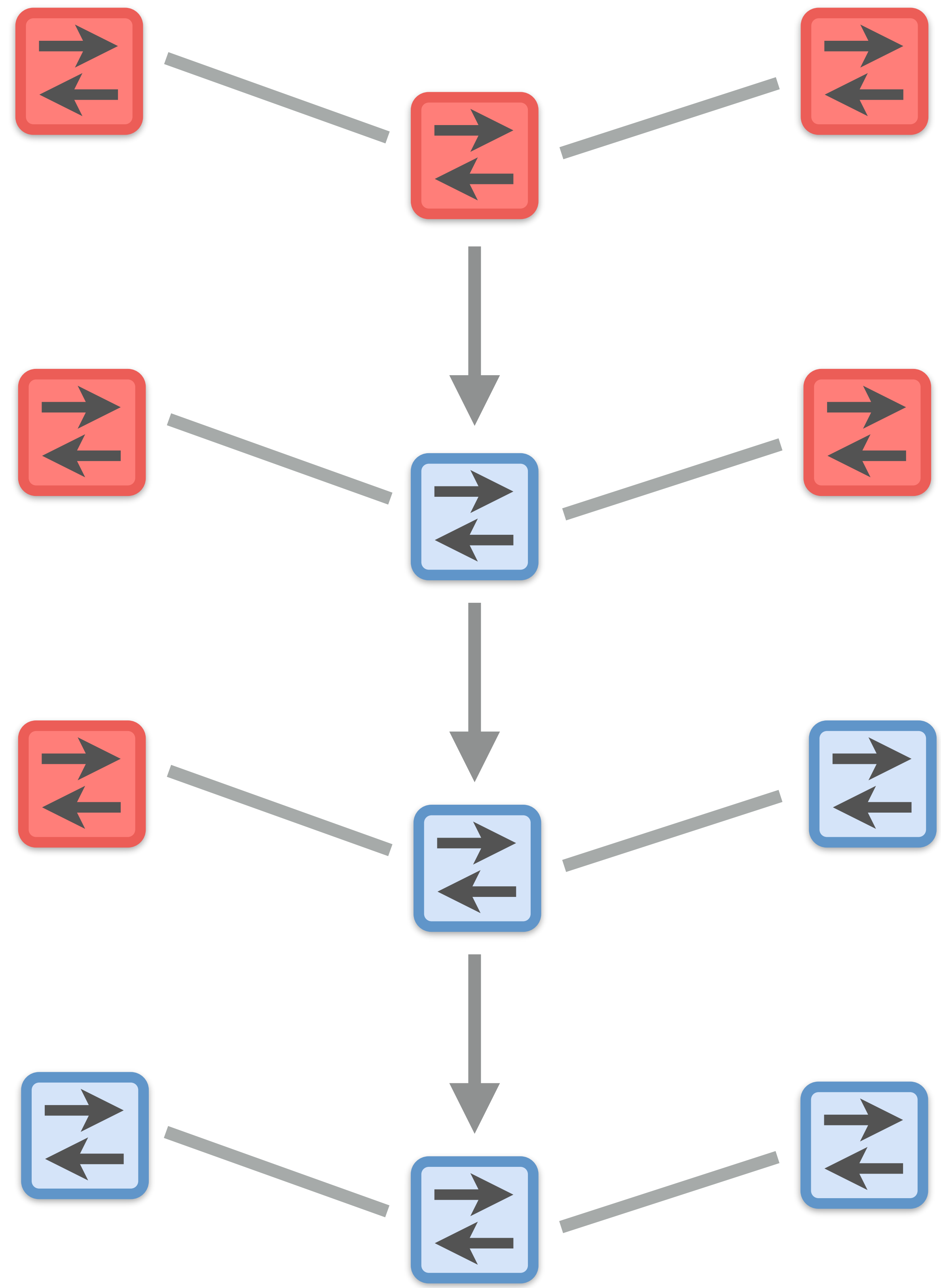




Network Updates

How can we transition between global states?





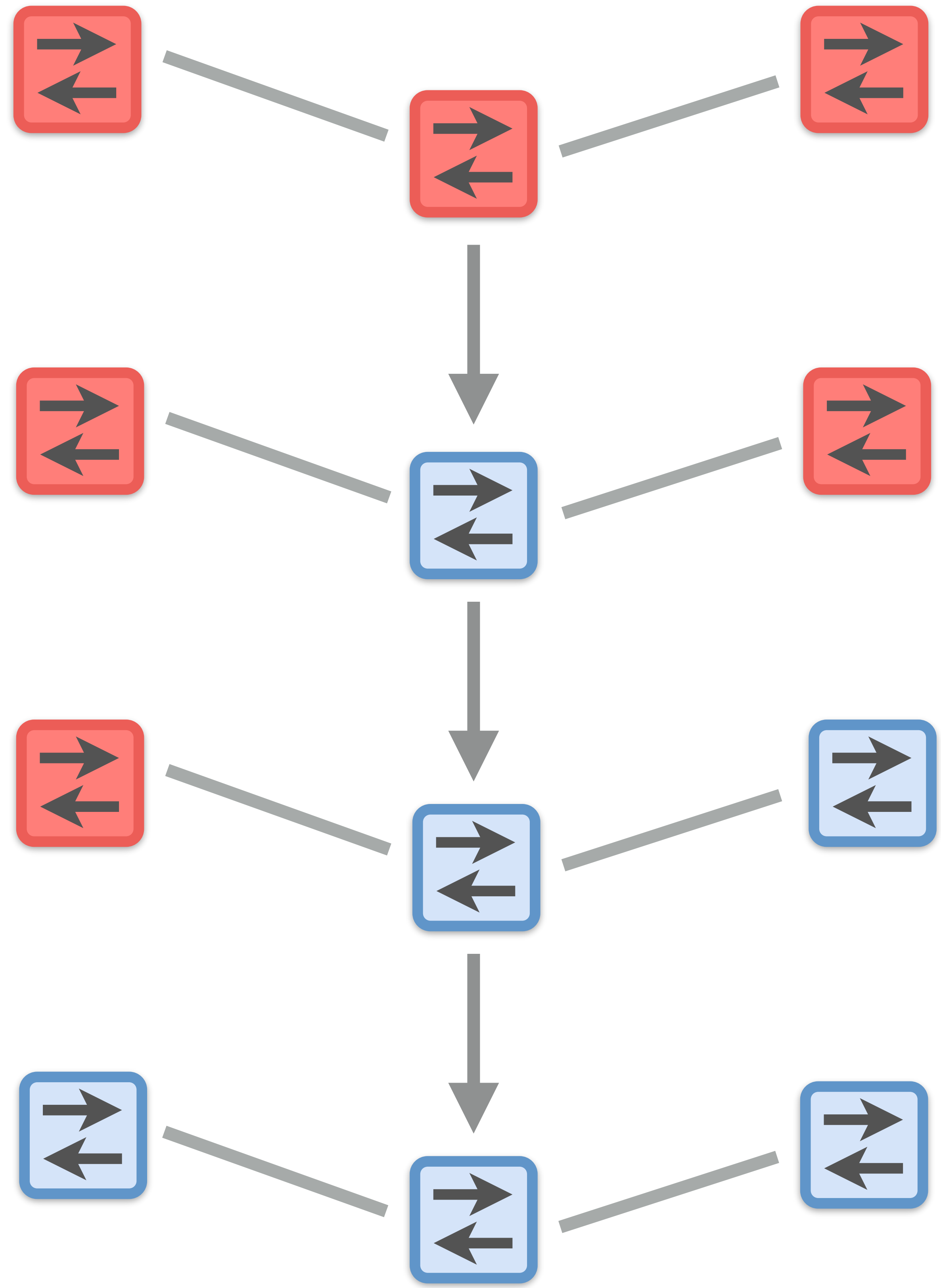
Network Updates

How can we transition between global states?

Initial State

Target State

Problem: naive updates can break important invariants!



Consistent Updates [SIGCOMM '12]

Consistency Guarantee:
every packet (or flow) will be processed by a single version of the network-wide configuration

Implementations:
- Two-Phase Update
- One-Touch Update
- Order Update