# A PROGRAM LOGIC FOR

# AUTOMATED P4 VERIFICATION

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General P4 safety properties

Program-specific properties

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- If an IP packet is not dropped, the TTL is decremented by one

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- Avoid unexpected arithmetic overflow/truncation
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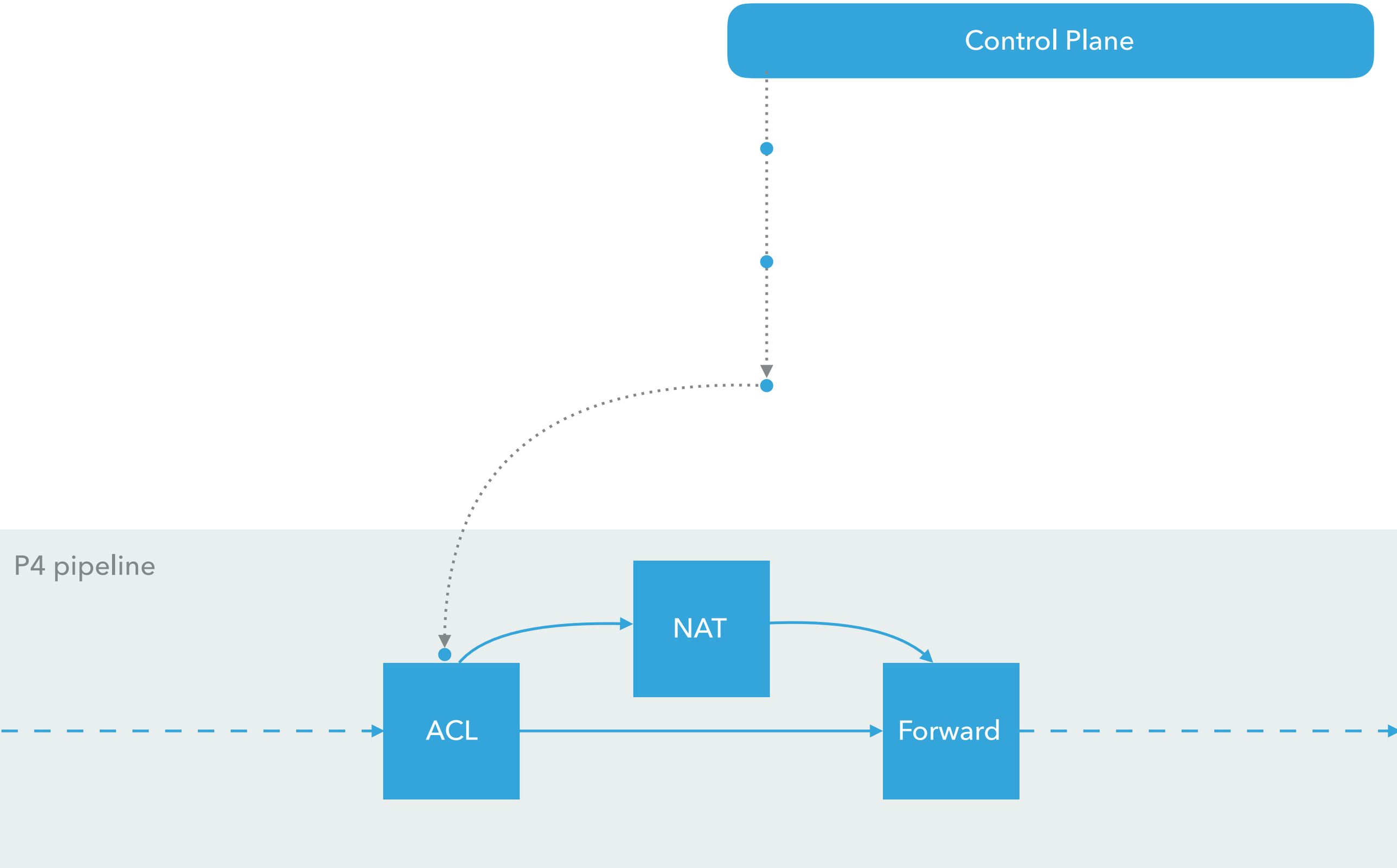
- Always explicitly handle every packet

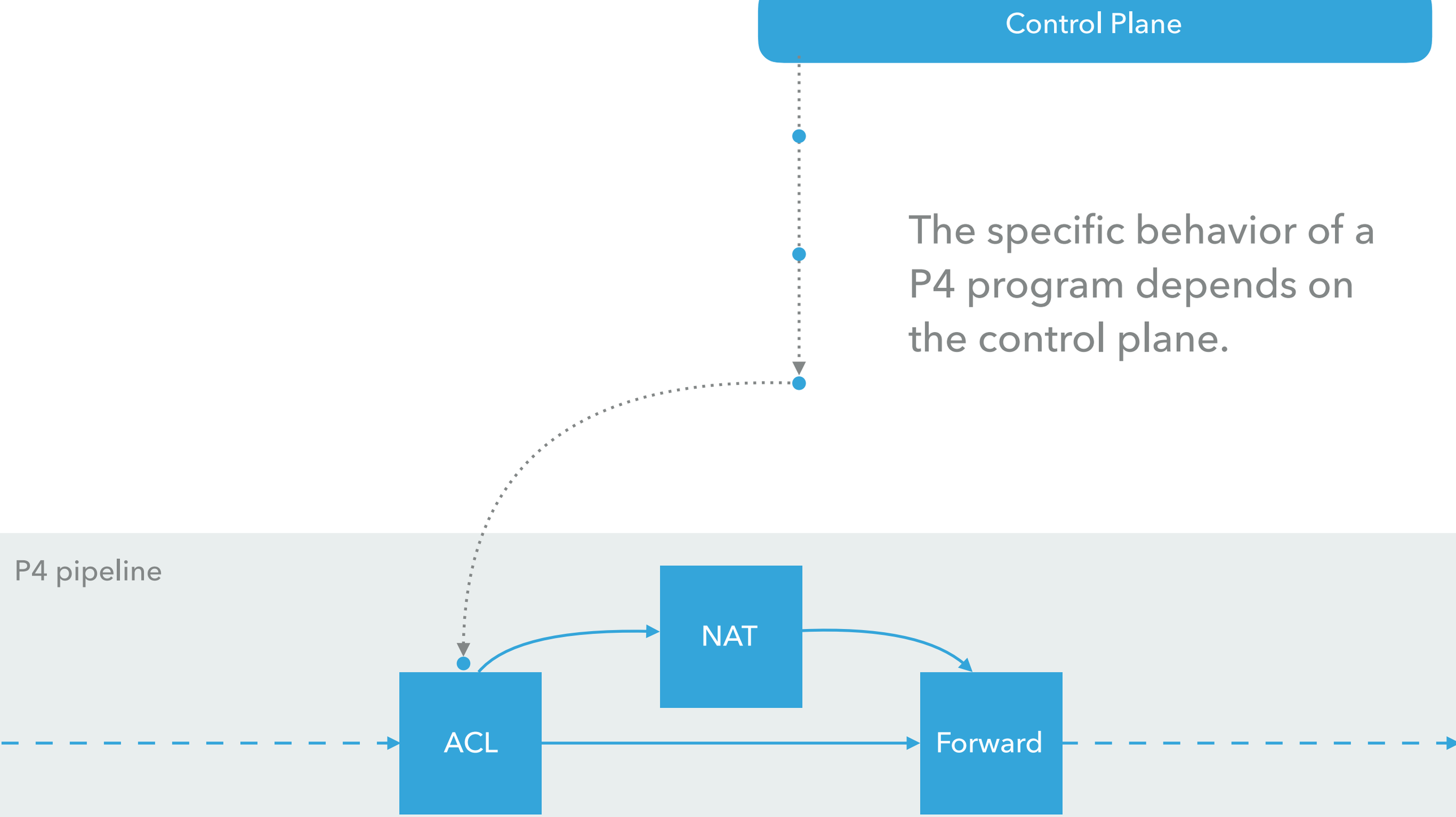
## Program-specific properties

- The ACL blocks SSH traffic
- If an IP packet is not dropped, the TTL is decremented by one
- NAT and multicast are never applied to the same packet


Control Plane
P4 pipeline
NAT
ACL
Forward

Control Plane

The specific behavior of a P4 program depends on the control plane.



```
action forward(p) { … }
table T {
reads {
  tcp.dstPort;
  eth.src;}
actions {
  drop;
  forward; } }
```

Packet-processing pipeline

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action forward(p) { … }
table T {
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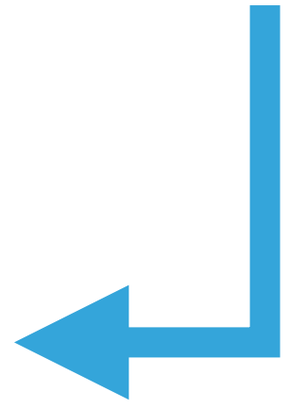
```

**Desired property:**

*If tcp.dstPort is 22, packet has been dropped.*



Packet-processing pipeline

Under what condition is the desired property **guaranteed** to be true?

*If the packet has already been dropped.*

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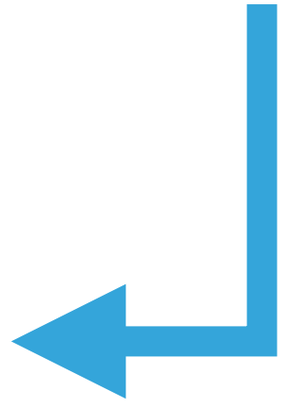

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"table constraint"

```
action forward(p) { … }
table T {
  reads {
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actions {
  @pragma(true)
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  @pragma(tcp.dstPort != 22)
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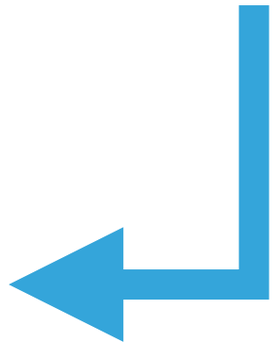

Packet-processing pipeline

Under what condition is the desired property **guaranteed** to be true?

~~*If the packet has already been dropped.*~~

*Always.*

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Packet-processing pipeline

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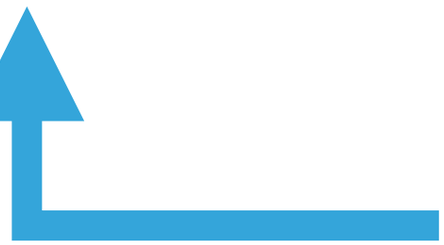
*???*



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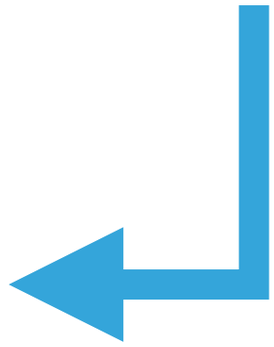
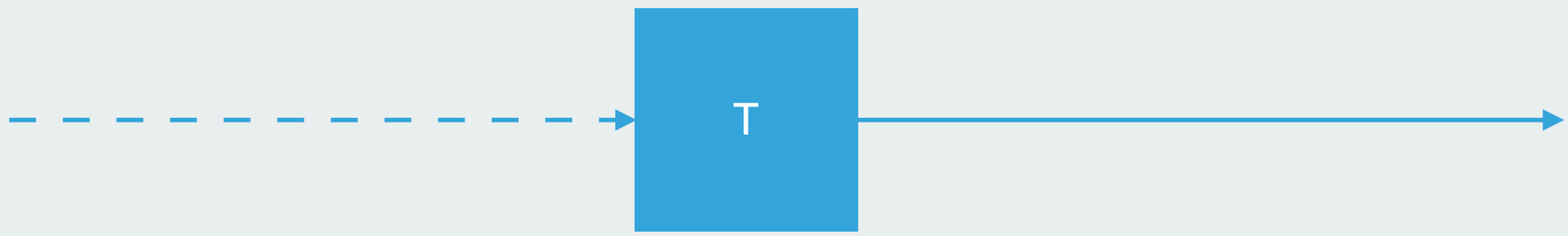
**Desired property:**

*No packet is sent to the control port (say, 512).*



Packet-processing pipeline



Under what condition is the desired property **guaranteed** to be true?

*Always.*

```
action forward(p) { … }
table T {
  reads {
    tcp.dstPort;
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  actions {
    @pragma(true)
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           (0 <= p < 48)
    forward; } }
```

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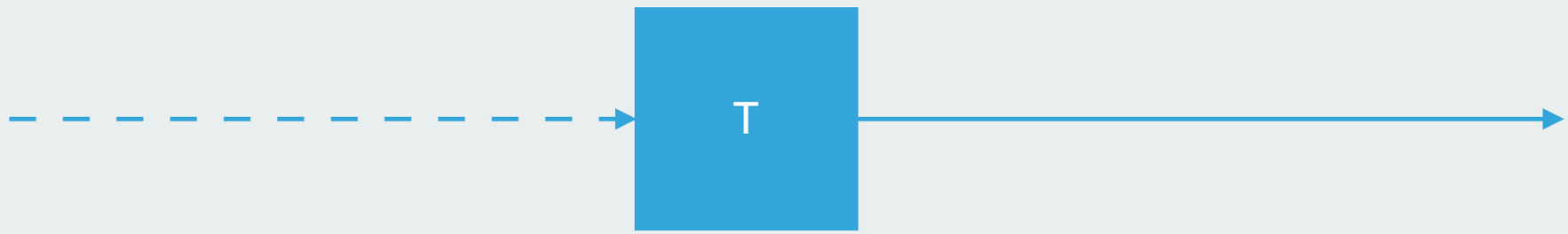
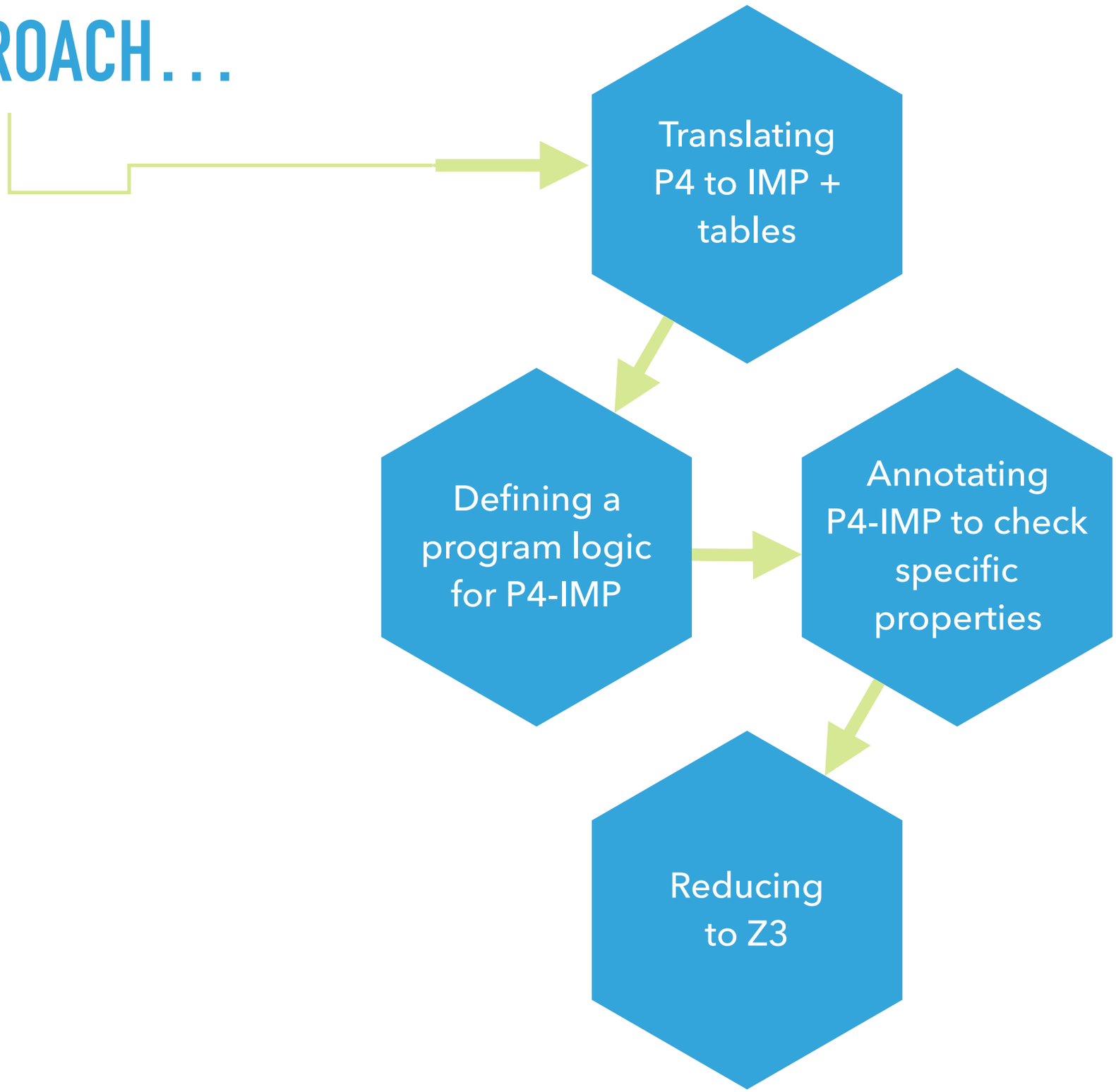
*No packet is sent to the control port (say, 512).*

Packet-processing pipeline



# OUR APPROACH...



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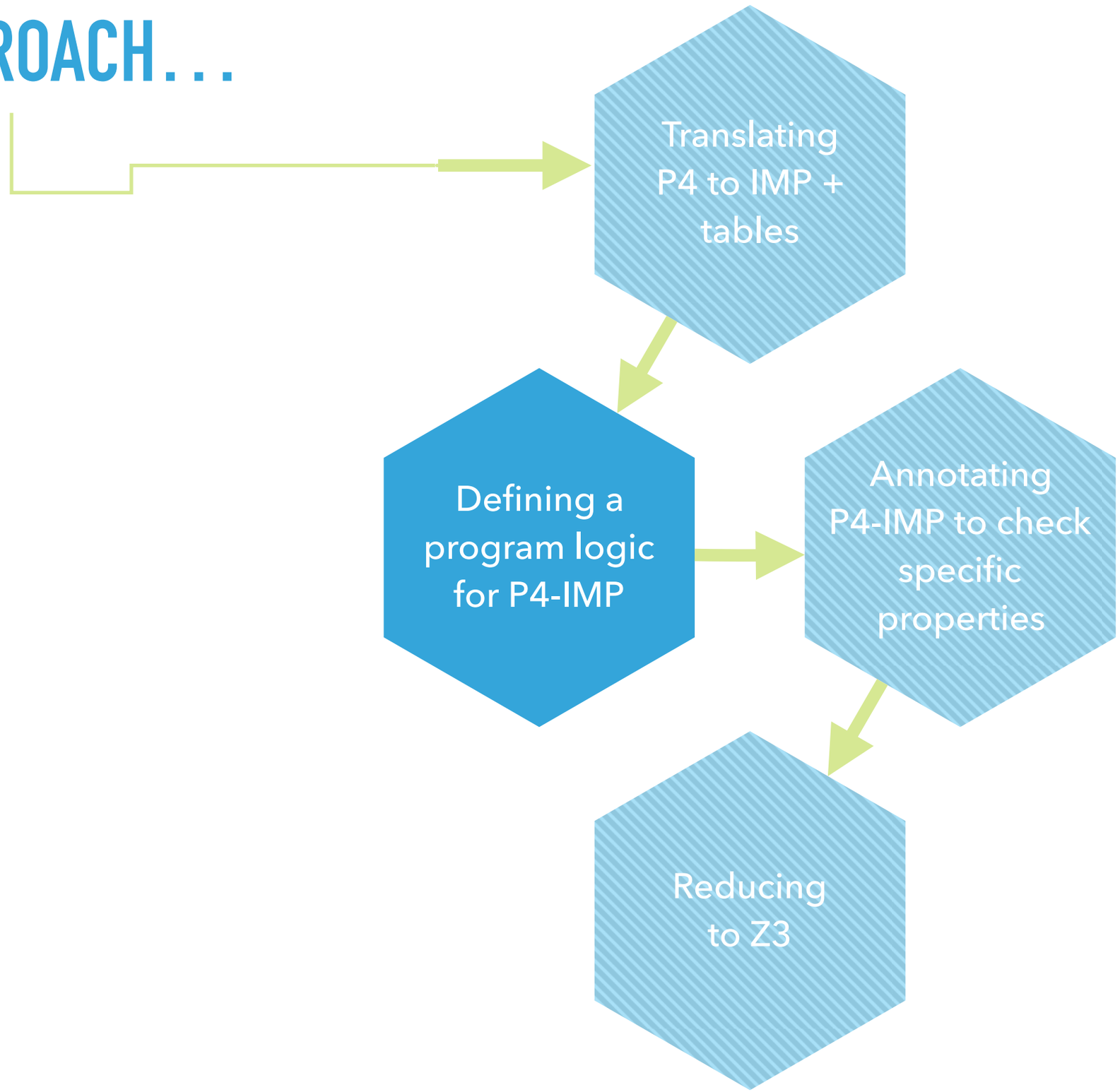

# IMP + HOARE LOGIC

Assignments, if statements, and ~~table applications~~

Axioms describing what is true before and after a command executes.

$$\vdash \{P\}\ c\ \{Q\}$$

*If P holds and c executes, then Q holds.*

IF $\vdash \{P \wedge b\}\ c1\ \{Q\}$

AND $\vdash \{P \wedge \neg b\}\ c2\ \{Q\}$

THEN $\vdash \{P\}$ `if b then c1 else c2` $\{Q\}$

# P4 PROGRAM LOGIC

Hoare logic + table constraints

Given a table T:

```
table T {
  reads { … }
  actions {
    @pragma(true)
    drop;
    @pragma(tcp.dstPort != 22)
           (0 <= p < 48)
    forward; } }
```

$$\vdash \{ P \wedge true \wedge true \} \quad \texttt{drop} \quad \{ Q \}$$

$$\vdash \left\{ \begin{array}{c} P \wedge \\ tcp.dstPort \mathrel{!}= 22 \wedge \\ 0 <= p < 48 \end{array} \right\} \quad \texttt{forward(p)} \quad \{ Q \}$$

$$\models \quad R1 \vee \ldots \vee Rn$$

---

Then P (plus the table constraints) is sufficient to establish that Q holds after applying T, written

$$\vdash \{ P \} \quad \texttt{T()} \quad \{ Q \}$$

# P4 PROGRAM LOGIC

Hoare logic + table constraints

Given a table T:

```
table T {
  reads { … }
  actions {
    @pragma(R1)
            (S1)
    a1;
    @pragma(R2)
            (S2)
    a2; } }
```

If for all actions `ai`,

$\vdash \{ P \wedge Ri \wedge Si(xi) \}$ `ai(xi)` $\{ Q \}$

And

$\models R1 \vee \ldots \vee Rn$

---

Then P (plus the table constraints) is sufficient to establish that Q holds after applying T, written

$\vdash \{P\}$ `T()` $\{Q\}$

# P4 PROGRAM LOGIC

Hoare logic + table constraints

Given a command c and a post-condition Q,

**wp**(c, Q) = P  such that  |- { P } c { Q }

P4 PROGRAM

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P4 PROGRAM

**wp**(IMP PROGRAM, **Q**)

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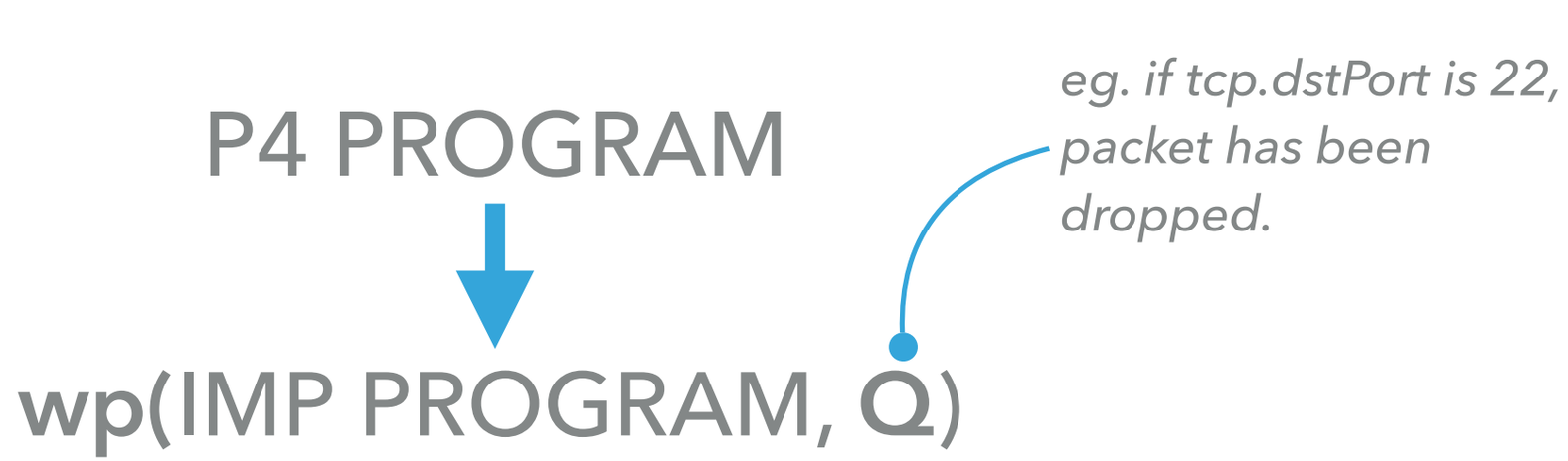

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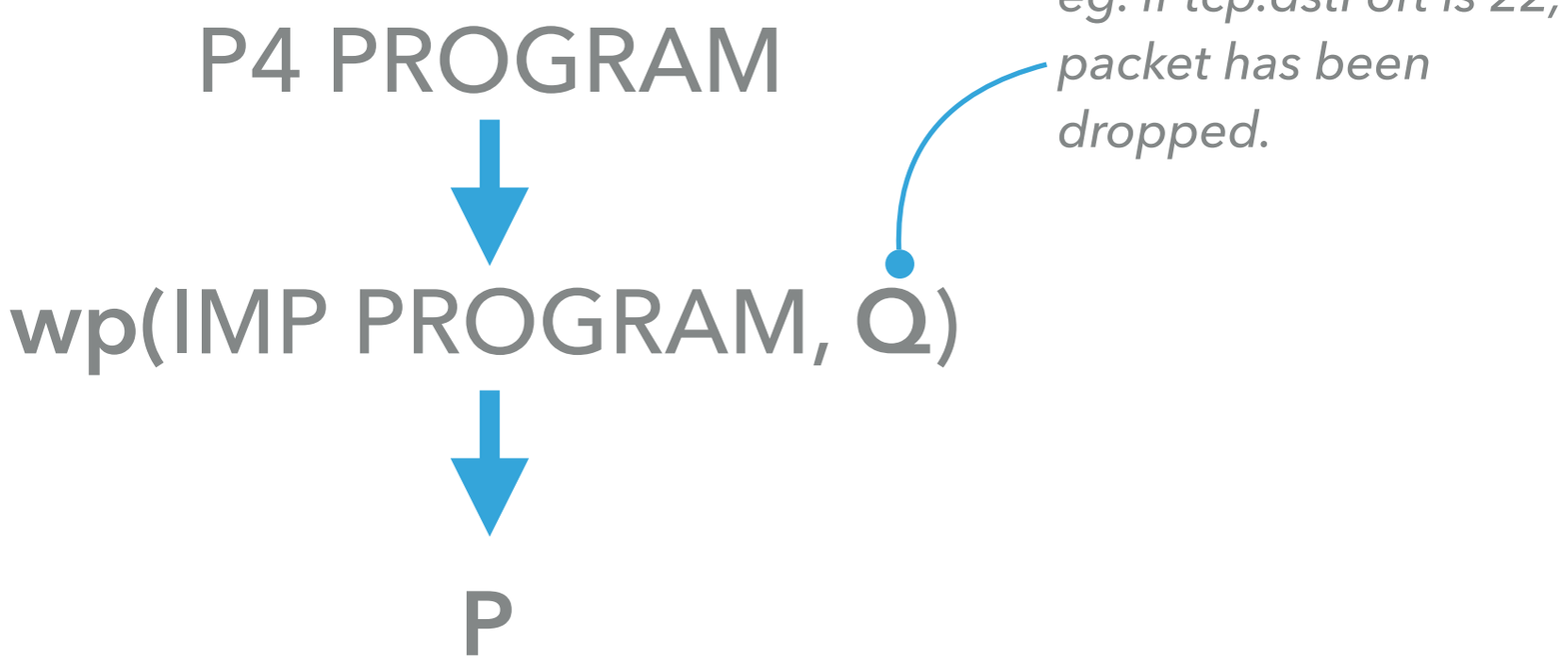

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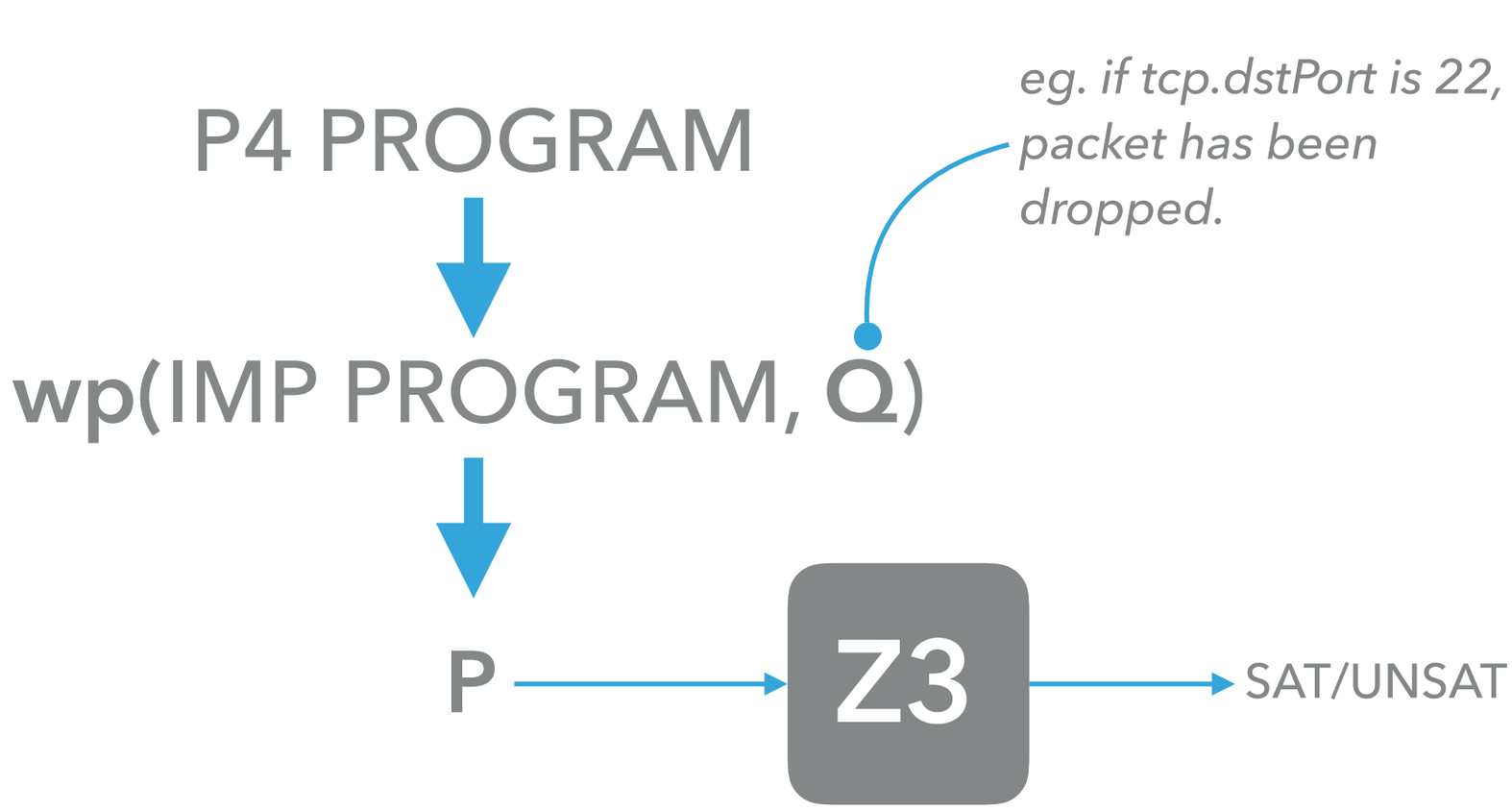
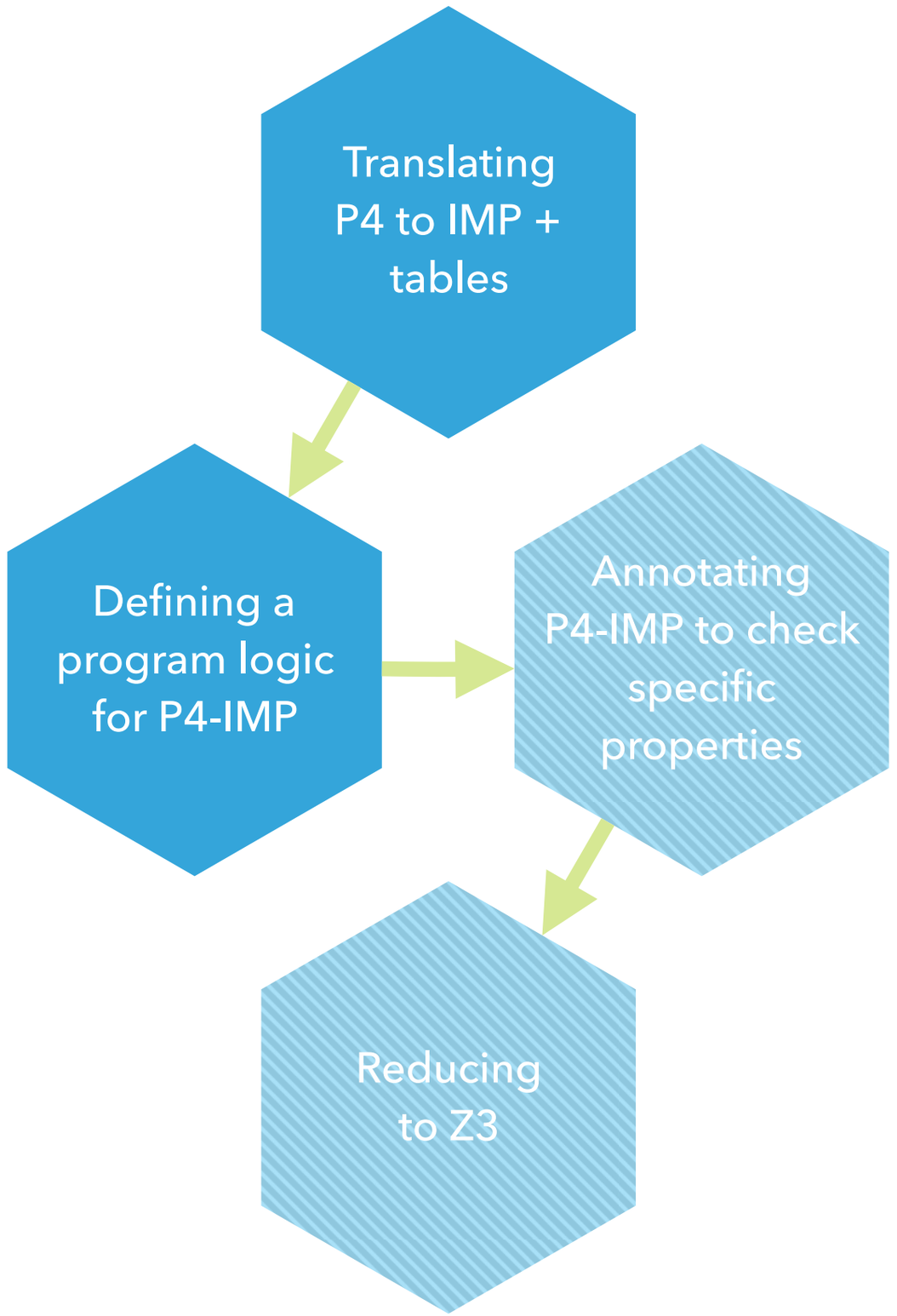


# NEXT STEPS

1. Automatically annotate P4-IMP programs to check safety properties.
2. Explore table constraints that hold across multiple tables.
3. Build a control plane run-time monitor.
4. Use table constraints to drive compiler optimizations.



THANK YOU

# QUESTIONS?

X

# IMP + HOARE LOGIC

Assignments, if statements, and ~~table applications~~

Axioms describing what is true before and after a command executes.

Predicates P, Q ::=

- true
- false
- equals expr expr
- less expr expr
- not P
- P /\ Q
- P \/ Q
- P ==> Q
- forall X. P
- exists X. P

*First order logic with comparisons over program expressions.*

Standard Hoare logic axioms for commands:

```
commands c ::=
  skip
  c1; c2                      (sequence)
  e1 := e2                    (assignment)
  if b then c1 else c2        (if)
```

## How to handle tables?

# P4 → IMP

Assignments, if statements,
and table applications

```
parser start {
  return parse_ethernet; }

parser parse_ethernet {
  extract(ethernet);
  return select(ethernet.typ) {
    ETH_IPV4 : parse_ipv4;
    default: ingress; } }

parser parse_ipv4 {
  extract(ipv4);
  return ingress; }

control ingress {
  if(valid(ipv4) and ipv4.ttl > 0) {
    apply(ipv4_lpm);
    apply(forward); } }
```

# P4 → IMP

Assignments, if statements, and table applications

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    apply(ipv4_lpm);
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```

# P4 → IMP

Assignments, if statements, and table applications

```
parser start {
  return parse_ethernet; }

parser parse_ethernet {
  extract(ethernet);                          extract(ethernet);
  return select(ethernet.typ) {               if(ethernet.typ == ETH_IPV4)
    ETH_IPV4 : parse_ipv4;
    default: ingress; } }

parser parse_ipv4 {
  extract(ipv4);                                extract(ipv4);
  return ingress; }

control ingress {
  if(valid(ipv4) and ipv4.ttl > 0) {          if(valid(ipv4) and ipv4.ttl > 0)
    apply(ipv4_lpm);                            apply(ipv4_lpm);
    apply(forward); } }                         apply(forward);
```

# P4 → IMP

Assignments, if statements, and table applications

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control ingress {
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    apply(forward); } }
```

```
ethernet.valid := 1;
ethernet.src := havoc;
ethernet.dst := havoc;
ethernet.typ := havoc;

if(ethernet.typ == ETH_IPV4)

ipv4.valid := 1;
ipv4.src := havoc;
ipv4.dst := havoc;
ipv4.ttl := havoc;

if(valid(ipv4) and ipv4.ttl > 0)
  apply(ipv4_lpm);
  apply(forward);
```

## GOAL 1

Automatically detect violations of generic safety properties, including:

- reads of uninitialized values
- unsafe arithmetic operations
- unhandled parser exceptions
- and so on…

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Automatically detect violations of generic safety properties, including:

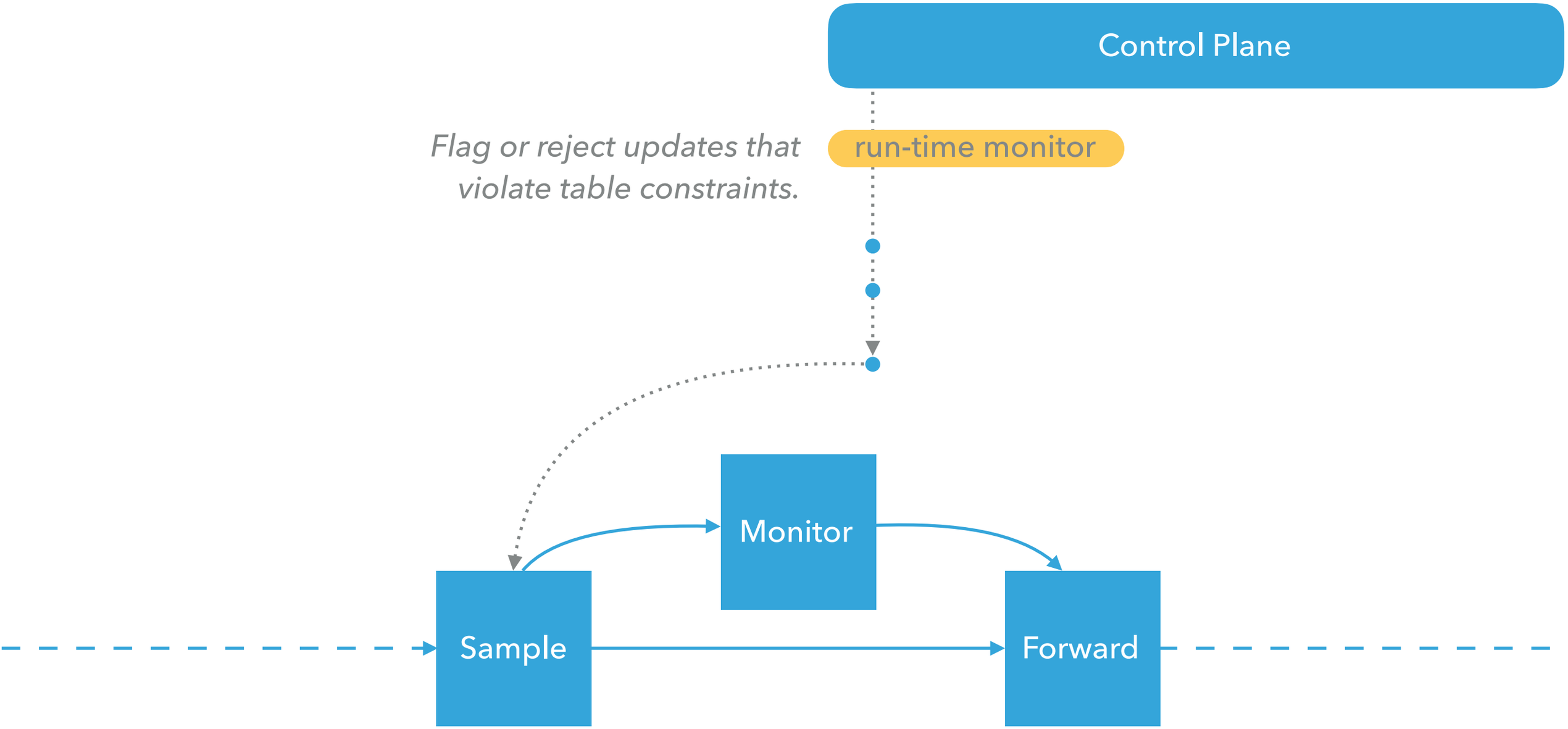
- **reads of uninitialized values**
- **unsafe arithmetic operations**
- **unhandled parser exceptions**
- **and so on…**

And enable programmers to describe expected control plane behavior with **table constraints**.

## GOAL 2

# Check table constraints in the control plane with **run-time monitoring**.

*Flag or reject updates that violate table constraints.*



# MORE GOALS

- Automatically generate table constraints necessary to ensure correct behavior.

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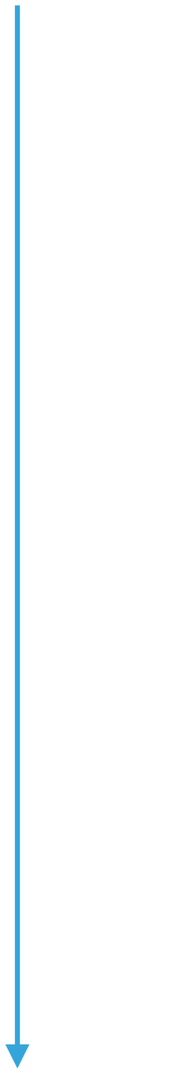
- Automatically generate table constraints necessary to ensure correct behavior.
- Use table constraints to drive compiler optimizations.

Observation: P4 programs are loop-free* table graphs.



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**P4**

Convert parsers/
controls to functions
with imperative bodies

**IMP**

Assignments, if statements,
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Convert parsers/ controls to functions with imperative bodies

Unroll parser loops and inline function bodies

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Define primitive actions as reads/writes of metadata fields

**IMP**

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# Observation: P4 programs are loop-free* table graphs.

**P4**

Convert parsers/ controls to functions with imperative bodies

Unroll parser loops and inline function bodies

Define primitive actions as reads/writes of metadata fields

Treat tables and externs as uninterpreted functions

**IMP**

Assignments, if statements, and table applications

# TRANSLATING PARSERS/CONTROLS



```
parser start {
  extract(eth);
  return ingress; }

control ingress {
  if valid(eth) {
    apply(acl);
    apply(forward); } }
```

**P4**

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Assignments, if statements,
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# TRANSLATING PARSERS/CONTROLS



```
parser start {
  extract(eth);
  return ingress; }

control ingress {
  if valid(eth) {
    apply(acl);
    apply(forward); } }
```

```
def start() =
  extract(eth);
  ingress();

def ingress() =
  if valid(eth) then
    acl();
    forward();

start();
```

**P4**

Convert parsers/ controls to functions with imperative bodies

**IMP**

Assignments, if statements, and table applications

# TRANSLATING PARSERS/CONTROLS



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    forward();

start();
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```
extract(eth);
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**P4**

Convert parsers/ controls to functions with imperative bodies

Unroll parser loops and inline function bodies

**IMP**

Assignments, if statements, and table applications

# TRANSLATING PRIMITIVE ACTIONS

```
def extract(eth) =
  eth.valid = 1;
  eth.srcaddr = havoc;
  eth.dstaddr = havoc;
  eth.ethTyp = havoc;


def valid(h) = h.valid == 1


extract(eth);
if valid(eth) then
  acl();
  forward();
```

**P4**

Encode primitive actions as bit manipulation

**IMP**

Assignments, if statements, and table applications

```
def extract(eth) =
  eth.valid = 1;
  eth.srcaddr = havoc;
  eth.dstaddr = havoc;
  eth.ethTyp = havoc;

def valid(h) = h.valid == 1

extract(eth);
if valid(eth) then
  acl();
  forward();
```

```
eth.valid = 1;
eth.srcaddr = havoc;
eth.dstaddr = havoc;
eth.ethTyp = havoc;
if eth.valid == 1 then
  acl();
  forward();
```

**P4**

Encode primitive actions as bit manipulation

Inline the encoding

**IMP**

Assignments, if statements, and table applications

# ADDING ASSERTIONS AND ASSUMPTIONS



```
parser start {
  @pragma assert(X == egress_spec);
  extract(eth);
  @pragma assume(eth.ethTyp == 0x806)
  return ingress; }
control ingress {
  if valid(eth) {
    apply(acl);
    apply(forward);
    @pragma assert(egress_spec != X) } }
```

Assertion/assumption annotations
are passed through to IMP

```
assert(X == egress_spec);
extract(eth);
assume(eth.ethTyp == 0x806);
if valid(eth) then
  acl();
  forward();
  assert(egress_spec != havoc);
```

**P4**

**IMP**

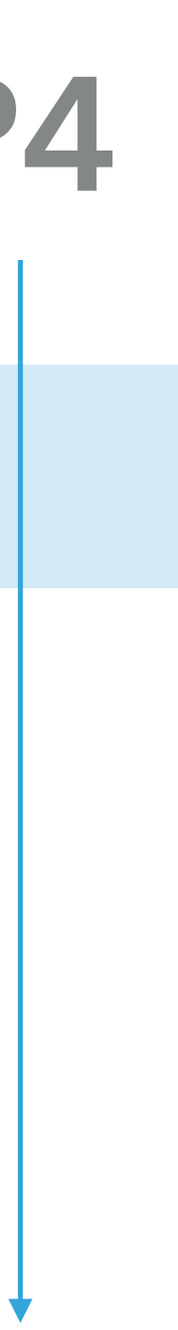
Assignments, if statements,
and table applications

```
table acl { reads = { eth.ethTyp; }
            actions = { drop; nop; } }

control ingress {
  if valid(eth) {

    apply(acl);
    @pragma assert(eth.ethTyp == 0x86DD ==> egress_spec == DROP)

    apply(forward); } }
```



# COMPILE TIME



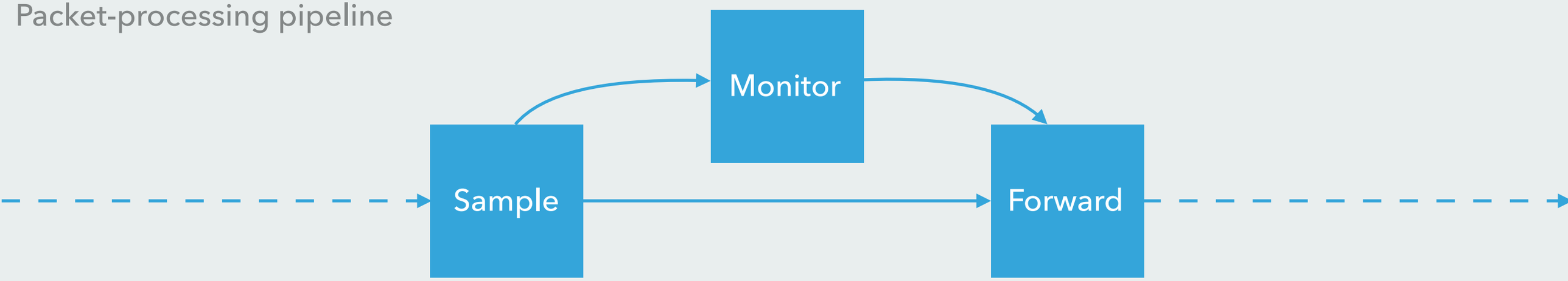
```
bit<1> do_monitoring;
table Sample {
    reads = { … }
    actions = { nop; } }
table Monitor { … }
table Forward { … }
control ingress {
    Sample.apply();
    if (do_monitoring) Monitor.apply();
    Forward.apply(); }
```

Metadata for flow sampling

Decides whether Monitor is applied

But is never set...

Packet-processing pipeline



# COMPILE TIME



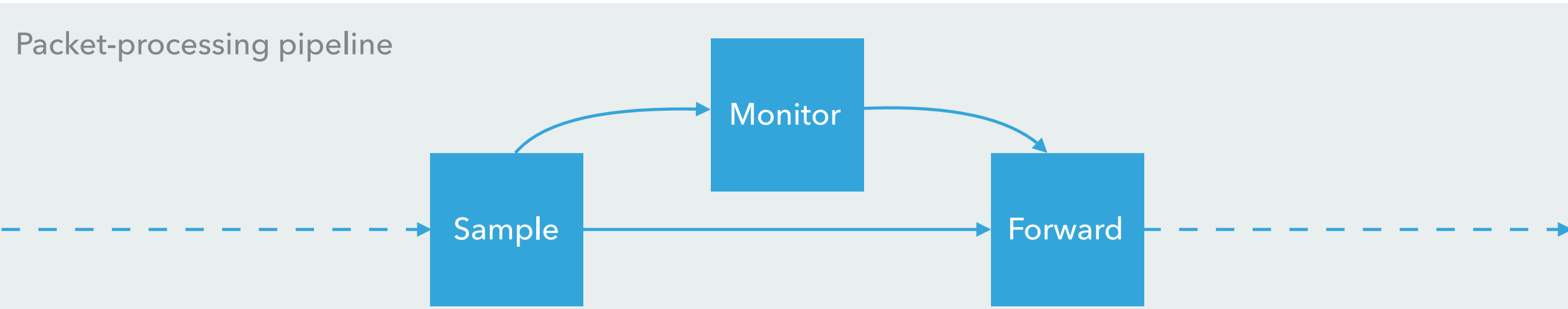
```
bit<1> do_monitoring;
table Sample {
    reads = { … }
    actions = { sampling; set; nop; } }
table Monitor { … }
table Forward { … }
control ingress {
    Sample.apply();
    if (do_monitoring) Monitor.apply();
    Forward.apply(); }
```

Metadata for flow sampling

Decides whether Monitor is applied

`sample()` randomly sets `do_monitoring`

`set()` explicitly sets `do_monitoring`



# RUN TIME

X

# Problems:

1. **nop**() leaves
   do_monitoring **uninitialized**

2. Table “miss” is **nop**()

Control Plane

Add:

```
if ipv4_src == 10.12/16 then set(1)
```

Add:

```
if ipv4_src == 10/24 then sample()
```

Add:

```
if ipv4_src == 192/24 then nop()
```