Lucid: A Language for Control in the Data Plane

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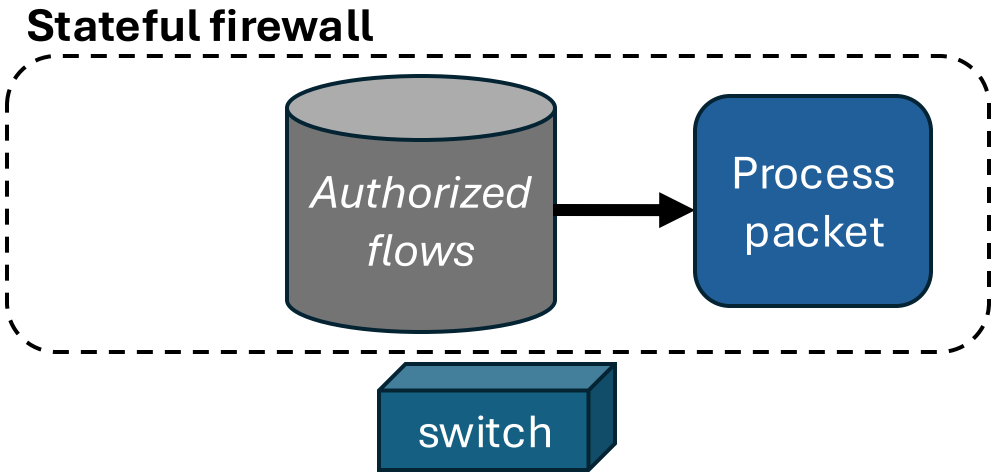
Future Internet

Control in the data plane



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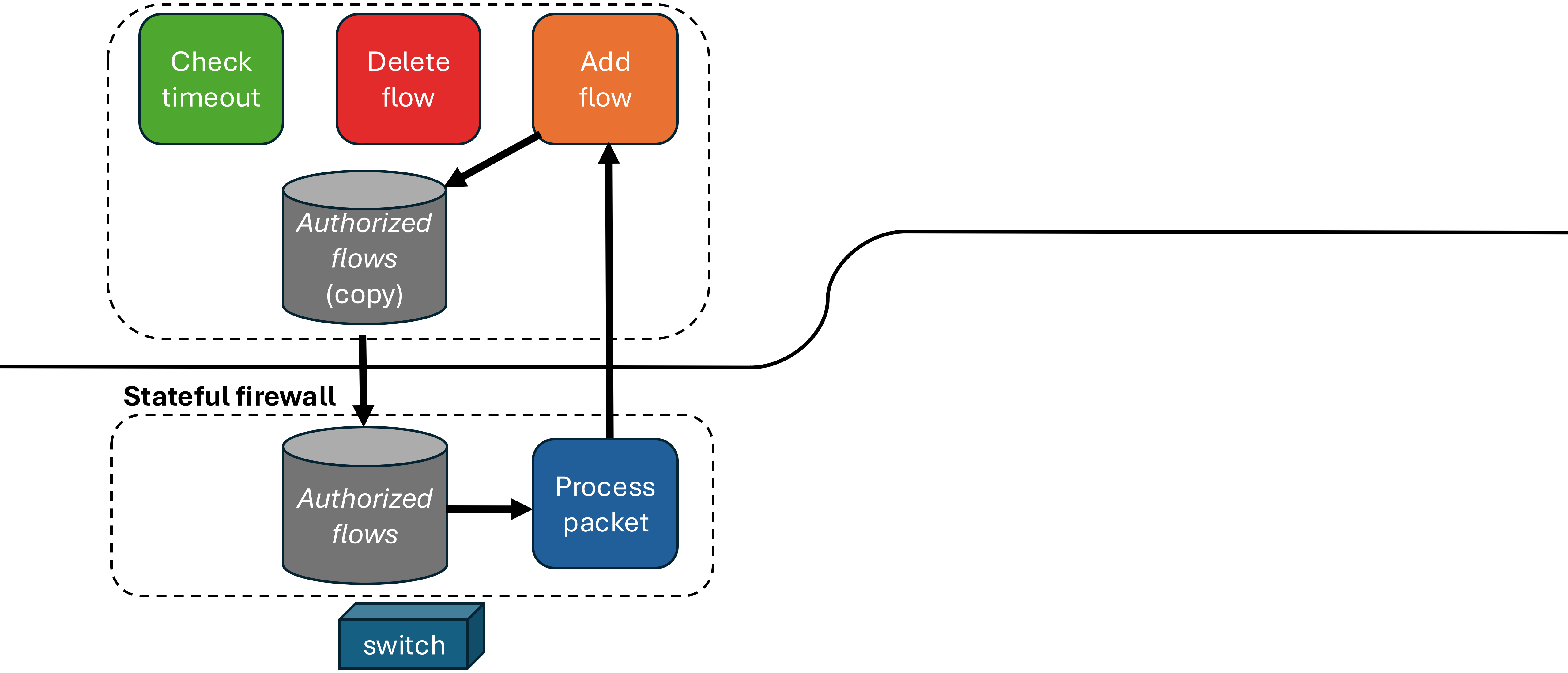

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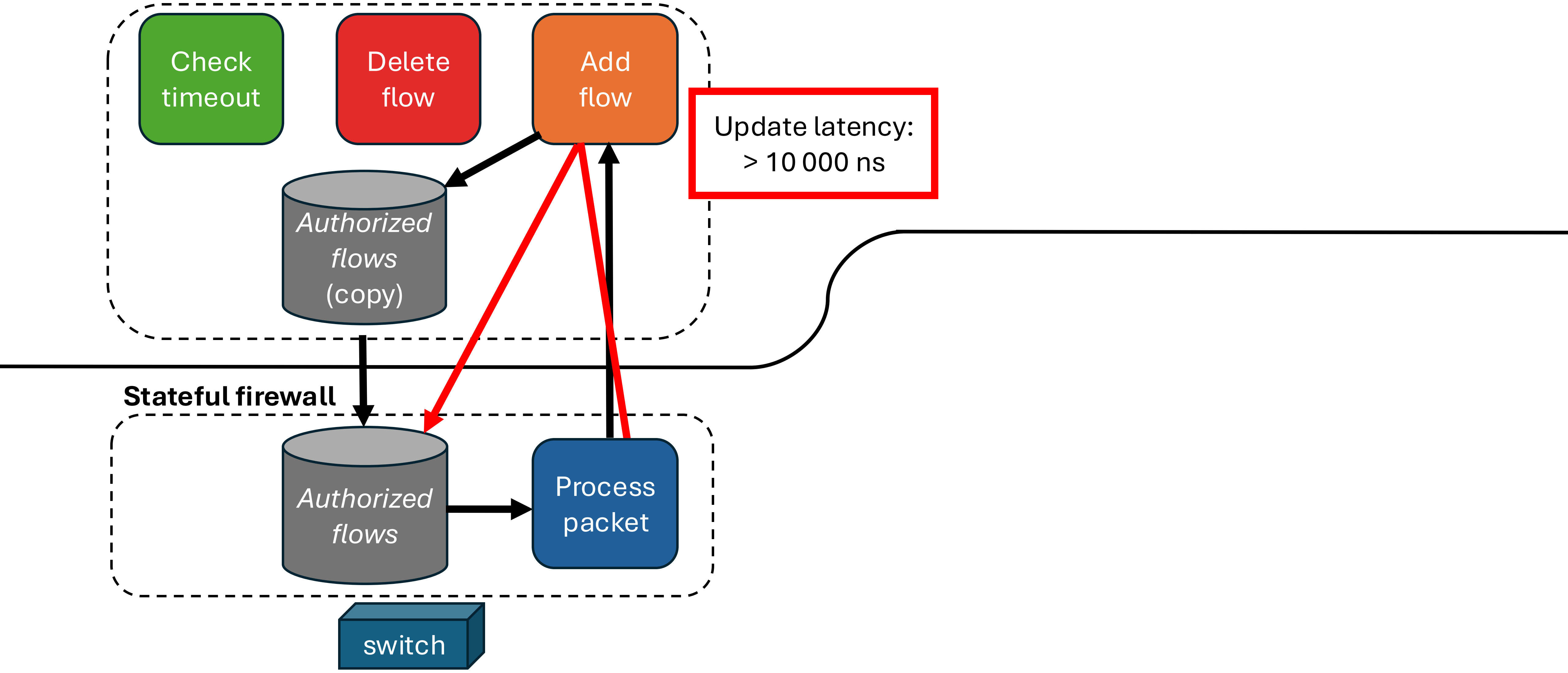

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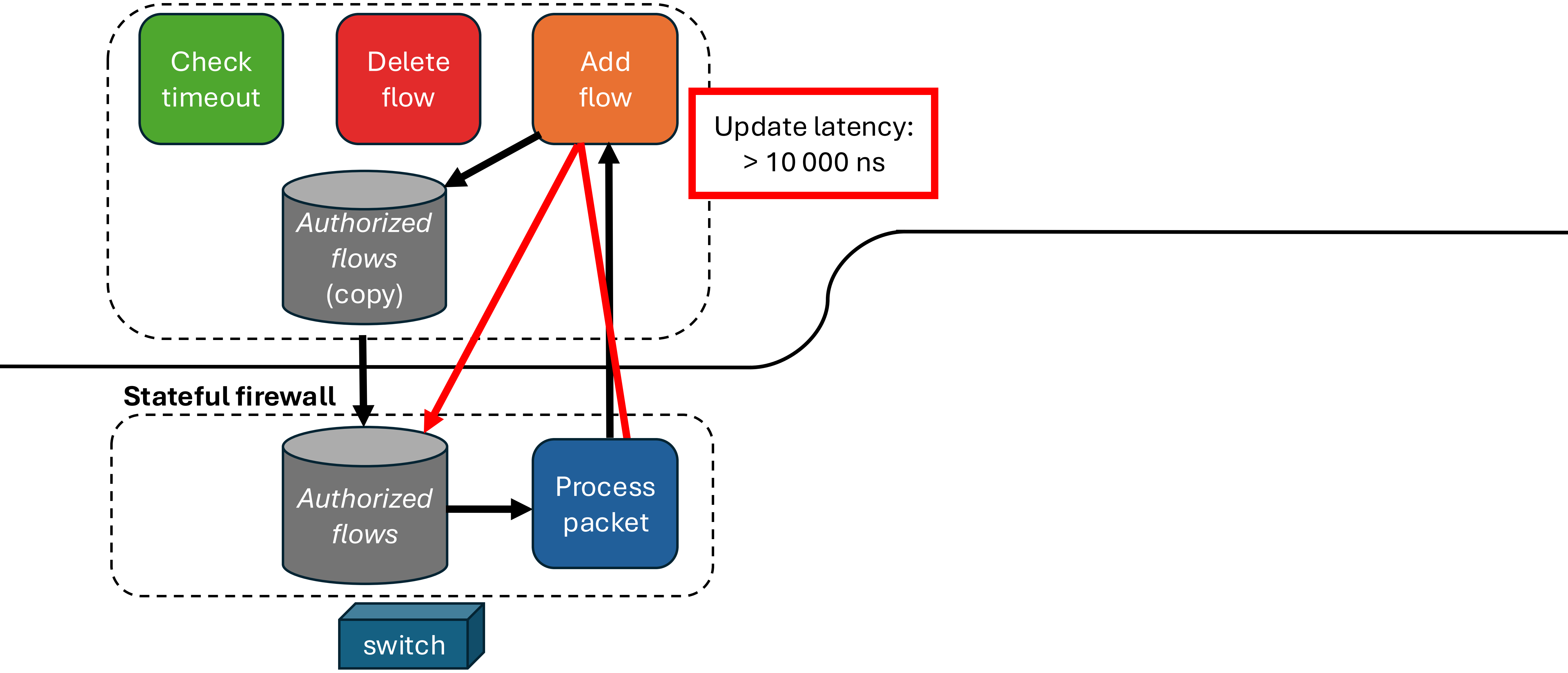

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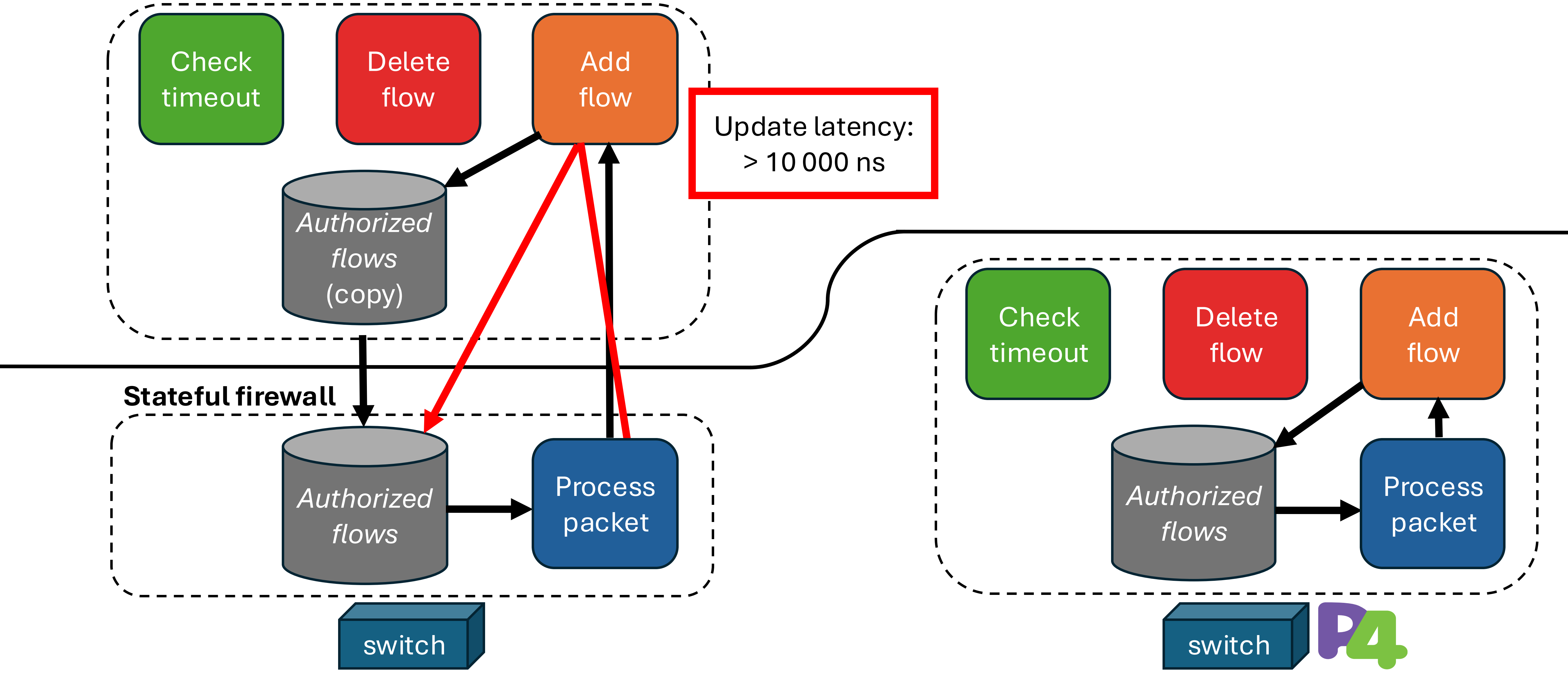

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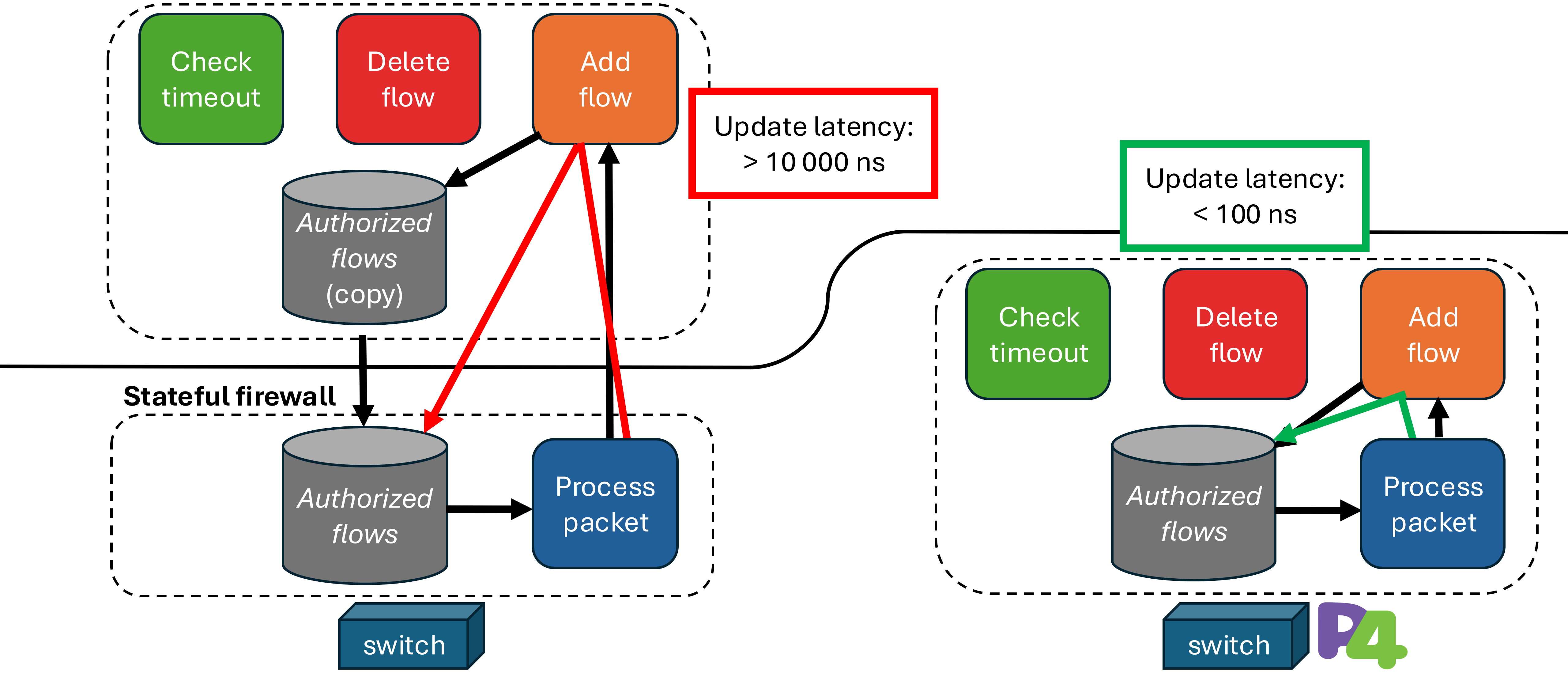

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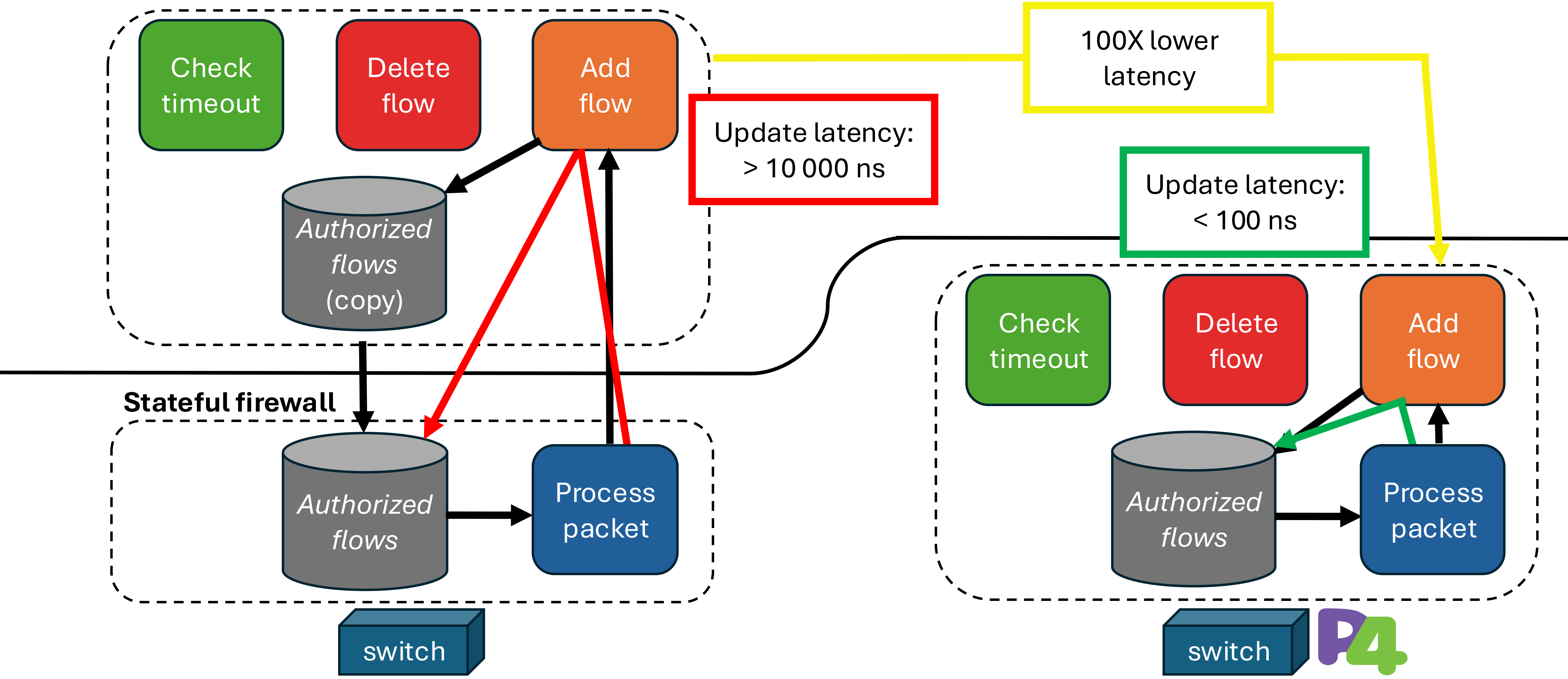


Control in the data plane

- Low latency for performance-critical tasks
- Scalability under high traffic loads
- Reduced communication overhead
- Enhanced reliability
- Enabling new applications

Problem: Control programs are not trivial

Low-level primitives

- Focussed on processing streams of packet headers

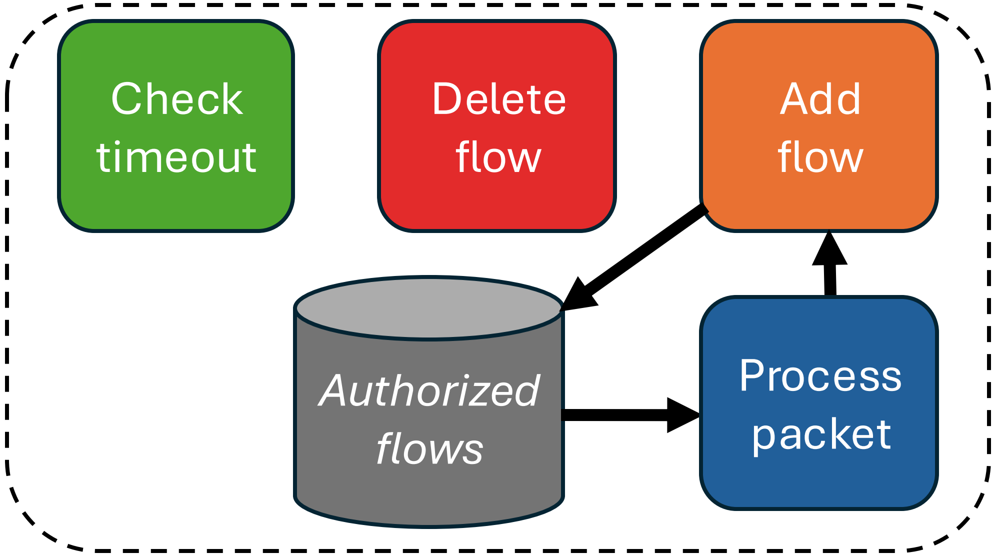
Problem

Low-level primitives

- Focussed on processing streams of packet headers

Stateful firewall

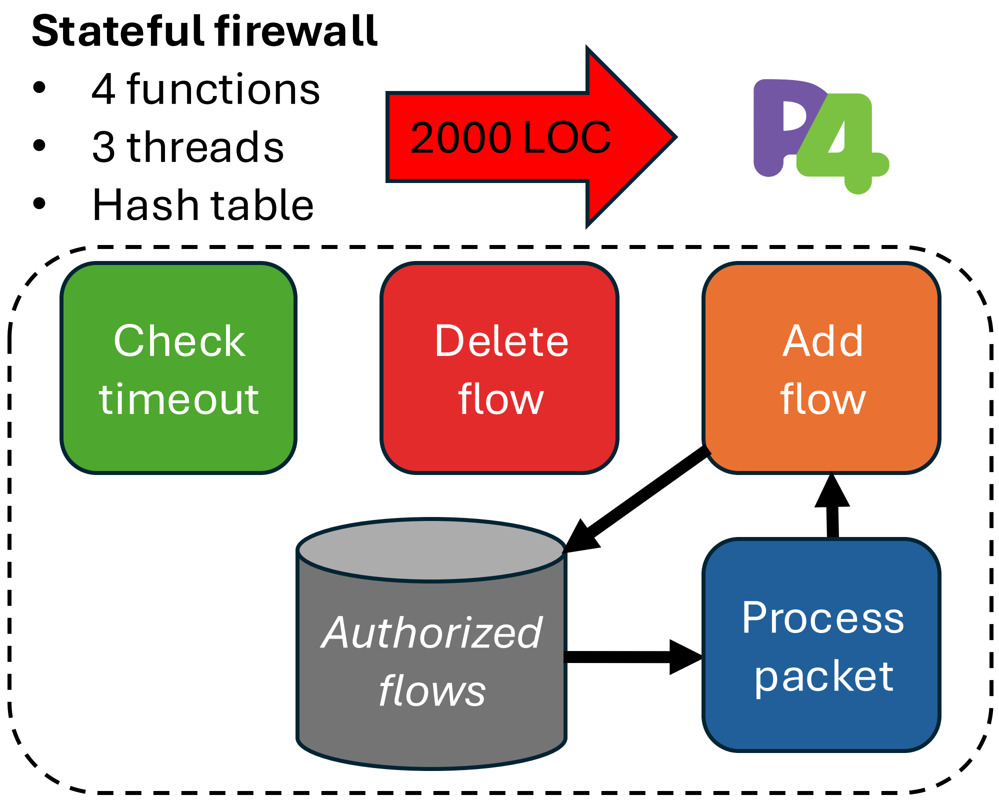
- 4 functions
- 3 threads
- Hash table



Problem

Low-level primitives

- Focussed on processing streams of packet headers
- Stateful firewall example takes 2000 LOC in P4
  - Not modular, hard to maintain, hard to understand



Problem

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Low-level constraints

- Hardware constraints not enforced by language
- Operations on persistent state common in control programs
- P4 compiler does *not* handle hardware constraint violations

Lucid abstractions

High-level general purpose primitives

- Events
- Handlers
- Arrays

→ Write ~10x fewer lines of code than in P4

Simple syntax rules

- Ordered arrays
- Memory operation restrictions

→ Build compiling prototypes without hardware expertise

Lucid abstractions

High-level general purpose primitives

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Simple syntax rules

- Ordered arrays
- Memory operation restrictions

→ *Build compiling prototypes without hardware expertise*

Stateful firewall example ≈ 200 LOC:
https://github.com/PrincetonUniversity/lucid/blob/main/examples/tofino_apps/src/simple_cuckoo_firewall.dpt

Lucid Language Cheat Sheet

Events

```
// declare a kind of event
event foo(type1 id1, type2 id2, ...);

// create an event value
event x = foo(arg1, arg2, ..., argN);

// pack arguments directly into packet
packet event foo(type1 id1, ...);

// send event to port n
generate_port(n, x);

// send event to switches in group g
generate_port(g, x);

// queue event for recirculation
generate(x);
```

Parser Declarations

```
// example parser implementation
parser main(bitstring pkt) {
  int<48> d = read(pkt);
  int<48> s = read(pkt);
  int<16> t = read(pkt);
  match t with
    | LUCID_ETHERTY -> {do_lucid_parsing(
   pkt);}
    | _ -> {
      skip(32, pkt);
      int<16> csum = hash<16>(checksum, d,
    s, t);
      generate(eth_with_csum(csum, d, s, t
   , Payload.parse(pkt))); }
}
```

Parser Actions

```
// read from bitstring
read(pkt);

// pop n bits off bitstring
skip(n, pkt);

// computes the n-bit checksum
hash<n>(checksum, a1, a2, ..., an);
```

Parser Steps

```
// generate event
generate(foo(a1, a2, ..., an));

// call to previously declared parser
my_parser(a1, a2, ..., an);

// drop the packet
drop;

// branch to parse blocks
match proto with
  | 0x800 -> {parse_ipv4(pkt);}
  | _ -> {...}
```

Handlers

```
// define handler for corresponding event
handle foo(type1 id1, type2 id2, ...) {
  ...
}
```

Arrays

```
// array with n entries of sz-bit ints
global Array.t<<sz>> arr = Array.create(n)

// return the value at index
Array.get(arr, idx);

// store the value at index
Array.set(arr, idx, v);

// apply memop setop to v using getarg
Array.getm(arr, idx, getop, getarg);

// apply memop setop to v using setarg
Array.setm(arr, idx, setop, setarg);

// return getop(v, getarg) and replace
    with setop(v, setarg)
Array.update(arr, idx, getop, getarg,
    setop, setarg);

// update for three-argument memop
Array.update_complex(arr, idx, memop, arg1
    , arg2, default)
```

Tables

```
// create a table
global Table.t<<key_ty, data_ty, arg_ty,
    ret_ty>> t = Table.create(sz, actions,
    default_action, default_data);

// table lookup
ret_ty result = Table.lookup(t, key, arg);

// install table entry; vendor dependent
Table.install(t, key, acn, data);
```

Memops

```
// two arguments: two forms

// single return
memop foo(int mem, int local) {
    return <e>;
}

// single if with single return per branch
memop foo(int mem, int local) {
    if (<e>) then { return <e>; } else {
    return <e>; }
}


// four arguments, structured like
memop foo(int mem1, int mem2, int local1,
    int local2) {
  bool b1 = <boolexp>; // May be omitted
  bool b2 = <boolexp>; // May be omitted

  // Omitted entirely, or just else branch
    if (<cond>) { cell1 = <ret_exp> } else
  { if (<cond>) { cell1 = <ret_exp> }

  // Omitted entirely, or just else branch
    if (<cond>) { cell2 = <ret_exp> } else
  { if (<cond>) { cell2 = <ret_exp> }

  // May be omitted. No else permitted
  if (<cond>) { return <local_exp> }
}

// three arguments; no mem2
memop foo(int mem, int loc1, int loc2)
```

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}
```

```
type eth_t = {
    int<48> dmac;
    int<48> smac;
    int<16> etype;
}
type ip_t = {
    int src;
    int dst;
    int<16> len;
}

event eth_ip(eth_t eth, ip_t ip);

event prepare_report(eth_t eth, ip_t ip);

event report(int src, int dst, int<16> len) {skip;}

handle eth_ip(eth_t eth, ip_t ip) {
    // 1. forward an event representing the packet out of port 1.
    generate_port(OUT_PORT, eth_ip(eth, ip));
    // 2. prepare a report to send to the monitoring server.
    generate(prepare_report(eth, ip));
}

handle prepare_report(eth_t eth, ip_t ip) {
    printf("sending report about packet {src=%d; dst=%d; len=%d} to monitor on port %d", ip#src,
ip#dst, ip#len, SERVER_PORT);
    // make an report event and send it to the monitoring server.
    event r = report(ip#src, ip#dst, ip#len);
    generate_port(SERVER_PORT, r);
}
```

Implementation

(Demo)

Try it yourself

- Project Repository (us): https://github.com/ythienpont/lucid
    - Cheatsheet
    - Demo code
- Lucid Repository: https://github.com/PrincetonUniversity/lucid
    - Lucid interpreter
    - Open source compiler, optimized for Intel Tofino
    - Example programs, including programs for Tofino

Summary

- Writing **control programs** in existing data-plane languages (e.g., P4) is **complex** and **error-prone**
- **Lucid** introduces **event-driven** programming with **high-level abstractions** to interleave control and packet processing seamlessly
- Guarantees programs fit hardware constraints via "**correct-by-construction**" checks
- **Simplifies programming**, enabling fast prototyping even for newcomers

References

- https://www.cs.princeton.edu/~dpw/papers/lucid-SIGCOMM-2021.pdf
- https://dl.acm.org/doi/10.1145/3452296.3472903
- https://github.com/PrincetonUniversity/lucid