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Mantis: Reactive Programmable Switches

Liangcheng Yu, John Sonchack, Vincent Liu

Penn
University of Pennsylvania

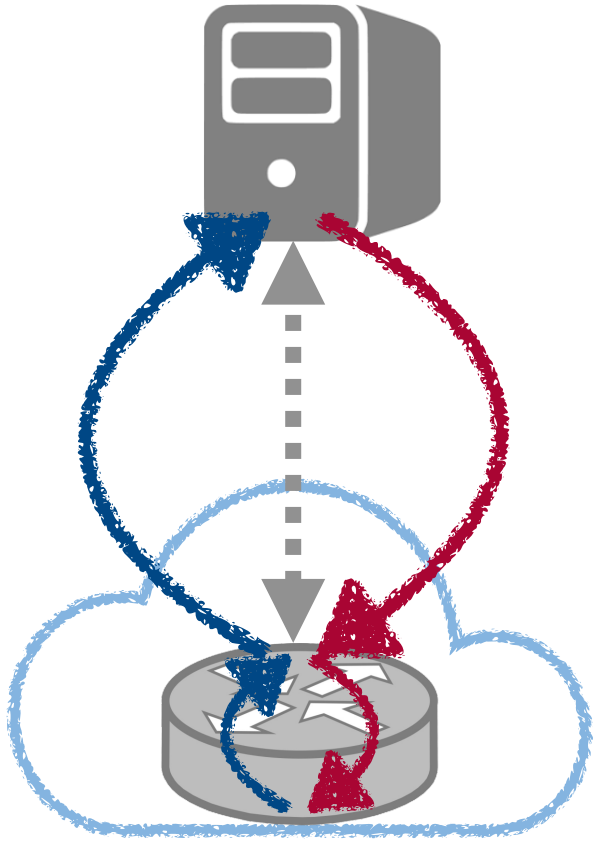
Princeton University

Today's Networks React

- A common task: ***reacting*** to current network conditions
  - Detecting failures and then rerouting
  - Identifying malicious flows and then filtering
  - Recognizing load imbalance and then adjusting

- In data centers, reactions need be fast

Today's Primitives for Reaction



SDNs or conventional control loops

Flexible but slow

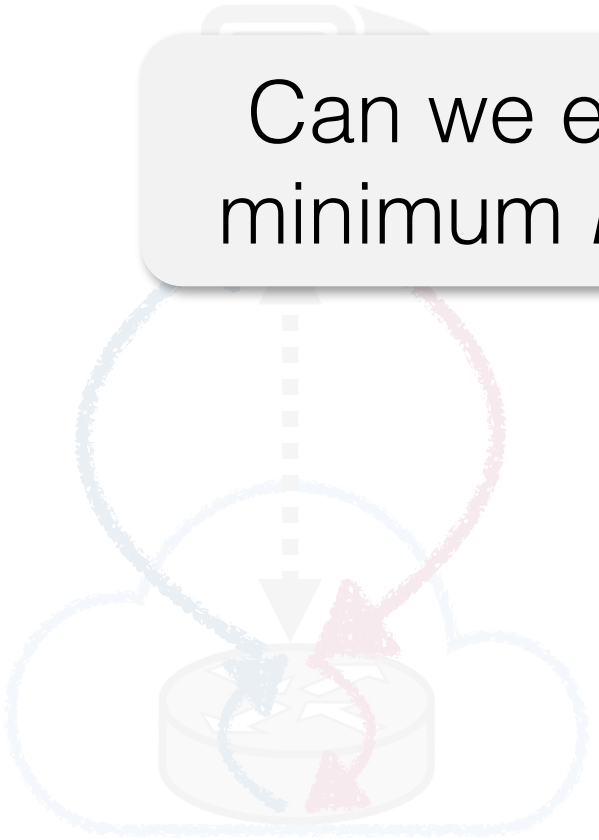
Built-in data plane primitives

Fast but restrictive

Programmable switches?

Constraints on operations in actions, number of stages, SRAM accesses, egress/ingress communication, in-band match-action updates…

Today's Primitives for Reaction



Can we enable fine-grained reactions with minimum ***latency*** and maximum ***flexibility***?

Built-in data plane primitives

Fast but restrictive

Programmable switches?

Constraints on operations in actions, number of stages, SRAM accesses, egress/ingress communication, in-band match-action updates…

Approach

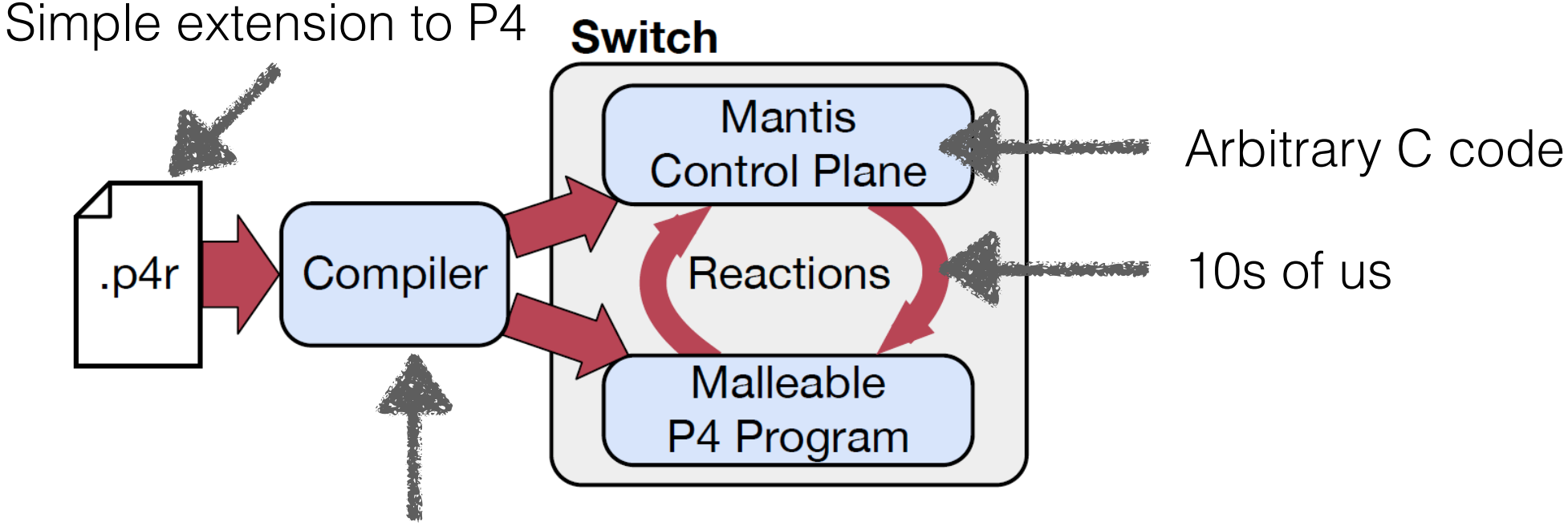
Can we enable fine-grained reactions with minimum ***latency*** and maximum ***flexibility***?

1. Push the reactions as close to the switch ASIC as possible

2. Co-design the data plane program for fine-grained malleability and ease of use

Mantis Overview

Usable, fast, and expressive in-network reactions on today's RMT switches



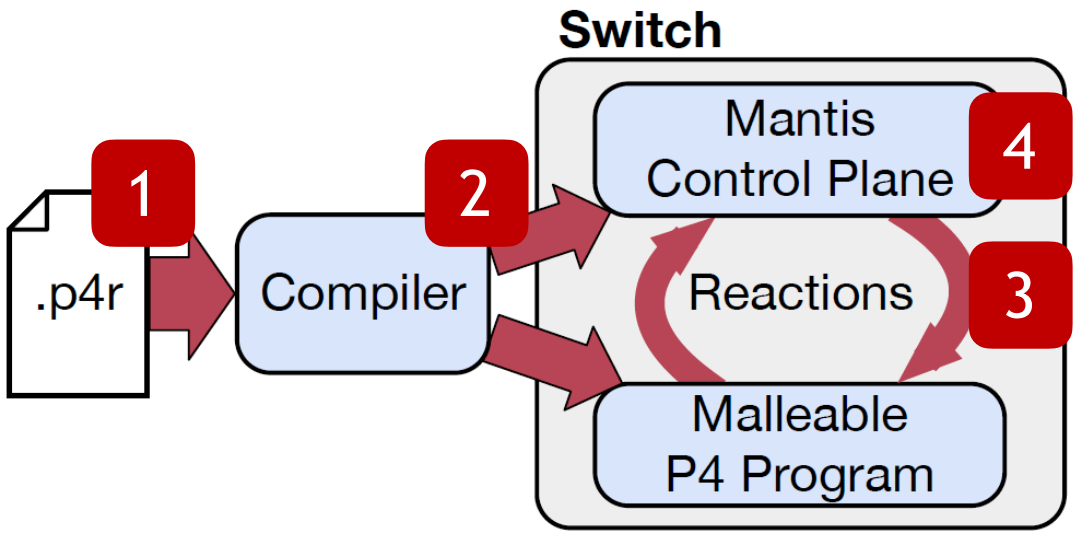
Generates code for dynamic reconfigurability/serializability

Abstraction

1. Malleable entities
   - Amenable to fine-grained reconfiguration at runtime

2. Reactions
   - Package reaction logic into a C-like function

Anatomy of Mantis



M1 Language

M2 Translation

M3 Isolation

M4 Execution

M1: Start with P4 Code

foo.p4

```
table my_table {
  reads { ipv4.dst : ternary; }
  actions { my_action; drop; }
}
action my_action() {
  modify_field(priority, 1);
}
```

How to make it run time reconfigurable?

M1: P4R Example

foo.p4r

```
table my_table {
  reads { ipv4.dst : ternary; }
  actions { my_action; drop; }
}
action my_action() {
  modify_field(priority, 1);
}
```

M1: P4R Example

foo.p4r

```
malleable value prio_var {
  width : 16; init : 1;
}
```

Declaring malleable entities

```
table my_table {
  reads { ipv4.dst : ternary; }
  actions { my_action; drop; }
}
action my_action() {
  modify_field(priority, ${prio_var});
}
```

Previous P4 code with references to malleable entities

M1: P4R Example

foo.p4r

```
malleable value prio_var {
  width : 16; init : 1;
}
```

Declaring malleable entities

```
table my_table {
  reads { ipv4.dst : ternary; }
  actions { my_action; drop; }
}
action my_action() {
  modify_field(priority, ${prio_var});
}
```

Previous P4 code with references to malleable entities

```
reaction my_reaction(reg re_qdepths[1:10]){
  uint16_t cur_max = 0;
  for (int i = 1; i <= 10; ++i)
    if (re_qdepths[i] > cur_max) {
      cur_max = re_qdepths[i];
    }
  }
  if (cur_max > THRESHOLD) {
    ${prio_var} = 5;
  }
}
```

Specifying reaction arguments

Reaction with arbitrary C

Reconfiguration

M1: P4R Example

foo.p4r

```
malleable value prio_var {
  width : 16; init :
}

table my_table {
  reads { ipv4.dst :
  actions { my_actio
}
action my_action() {
  modify_field(prior
}

reaction my_reaction
  uint16_t cur_max =
  for (int i = 1; i
    if (re_qdepths[i] > cur_max) {
      cur_max = re_qdepths[i];
    }
  }
  if (cur_max > THRESHOLD) {
    ${prio_var} = 5;
  }
}
```

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ces to malleable entities

ing reaction arguments

Reaction with arbitrary C

Reconfiguration

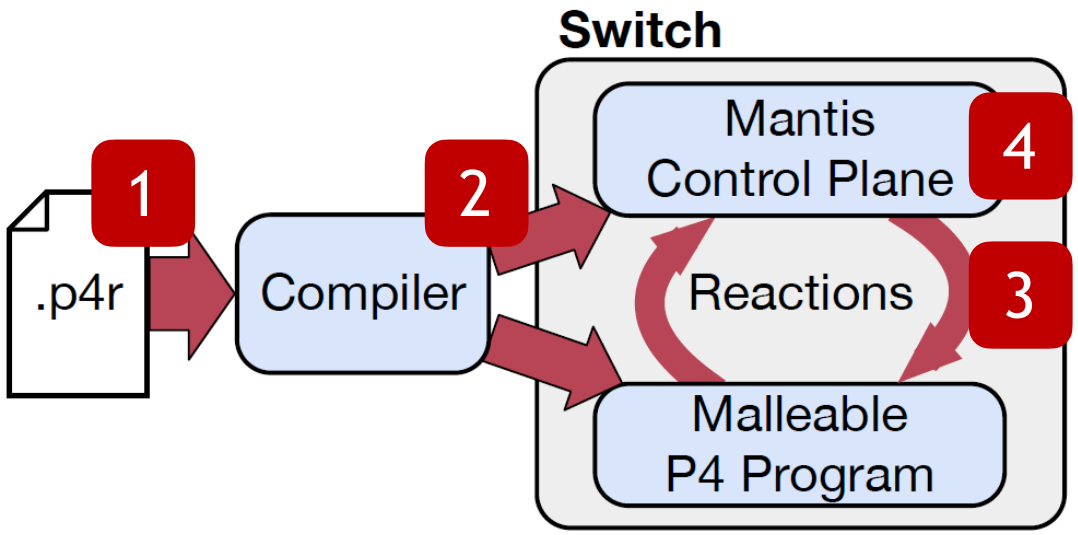
Malleable entities

- Malleable value
- Malleable field (table match, action…)
- Malleable table

Reaction function arguments

- Register
- Field
- Malleable field

Anatomy of Mantis



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M2: P4R Transformation

foo.p4r

```
malleable value prio_var {
  width : 16; init : 1;
}
table my_table {
  reads { ipv4.dst : ternary; }
  actions { my_action; drop; }
}
action my_action() {
  modify_field(priority, ${prio_var});
}
```

Generalize user-specified knobs for **“hitless” reconfiguration**

M2: P4R Transformation

foo.p4r

```
malleable value prio_var {
  width : 16; init : 1;
}
table my_table {
  reads { ipv4.dst : ternary; }
  actions { my_action; drop; }
}
action my_action() {
  modify_field(priority, ${prio_var}p4r_meta_.prio_var);
}
header_type p4r_meta_t_ {
  field {prio_var : 16;}
}
metadata p4r_meta_t_ p4r_meta_;
```

Replace the malleable value

M2: P4R Transformation

foo.p4r

```
malleable value prio_var {
  width : 16; init : 1;
}
table my_table {
  reads { ipv4.dst : ternary; }
  actions { my_action; drop; }
}
action my_action() {
  modify_field(priority, ${prio_var}p4r_meta_.prio_var);
}
```

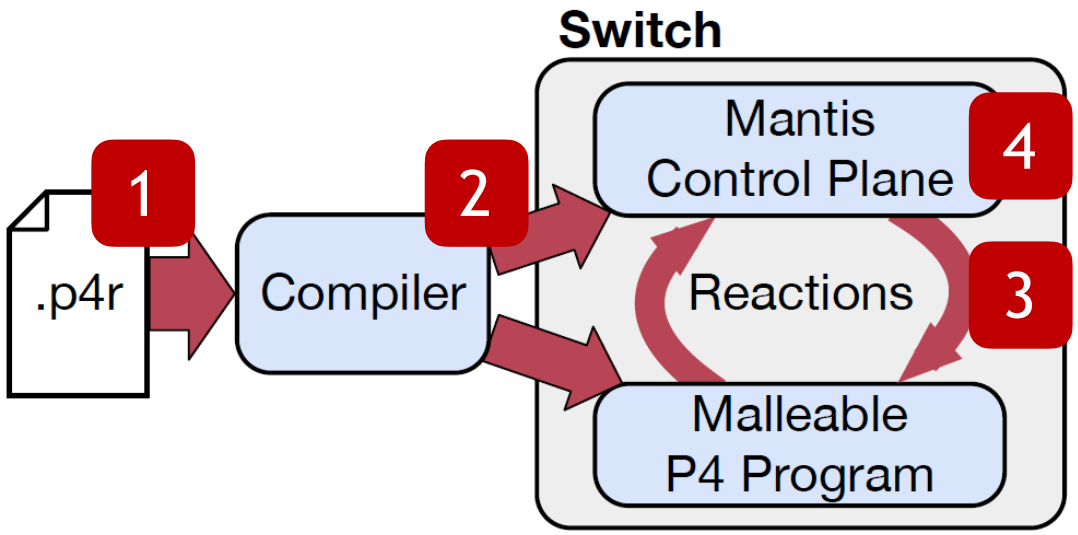
```
header_type p4r_meta_t_ {
  field {prio_var : 16;}
}
metadata p4r_meta_t_ p4r_meta_;
```

Replace the malleable value

```
table p4r_init_ {
  actions {p4r_init_action_;}
  size : 1;
}
action p4r_init_action_(prio_var) {
  modify_field(p4r_meta_.prio_var, prio_var);
}
```

Multi-purpose initialization table

Anatomy of Mantis



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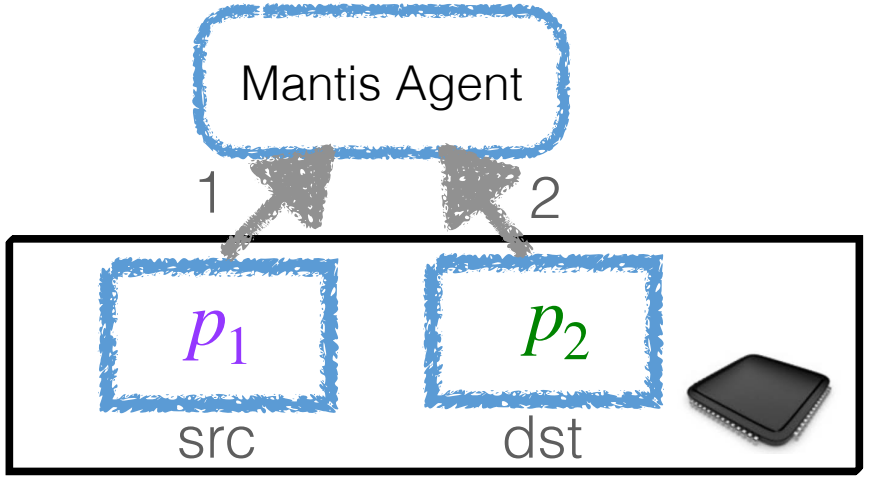
M3: Isolation (ACID)

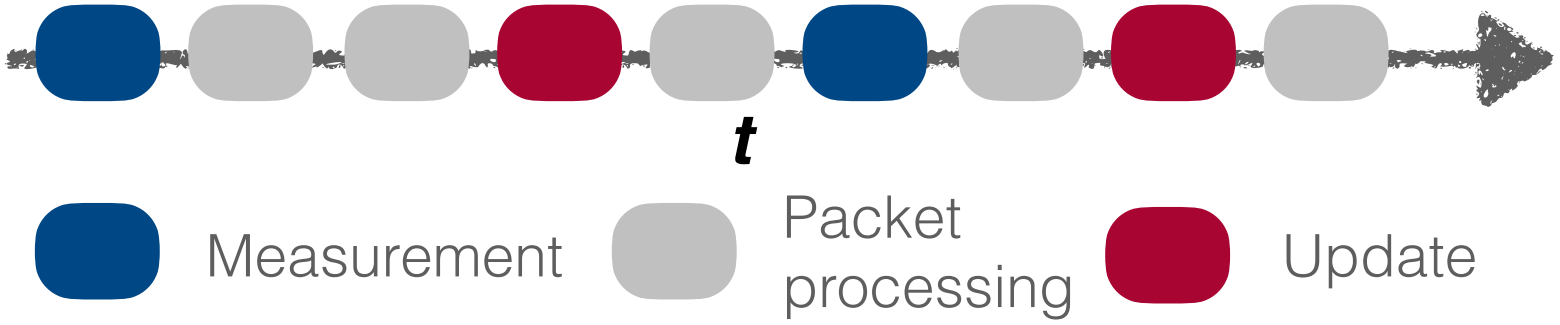
Isolation ***matters***, consider

```
reaction my_reaction(reg src, reg dst){}
```

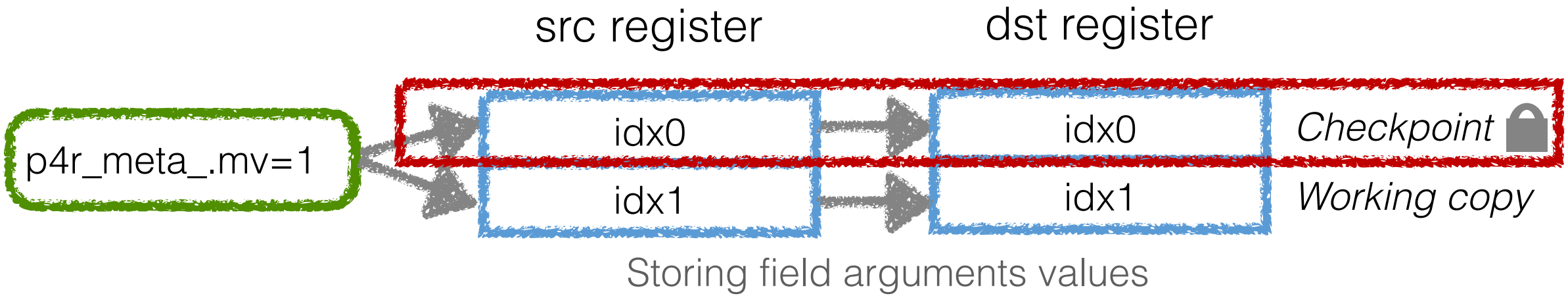
- Expectation: $src \leftarrow p_1, dst \leftarrow p_1$
- Without isolation: $src \leftarrow p_1, dst \leftarrow p_2$



Mantis enforces *per-pipeline, per-reaction* serializable isolation



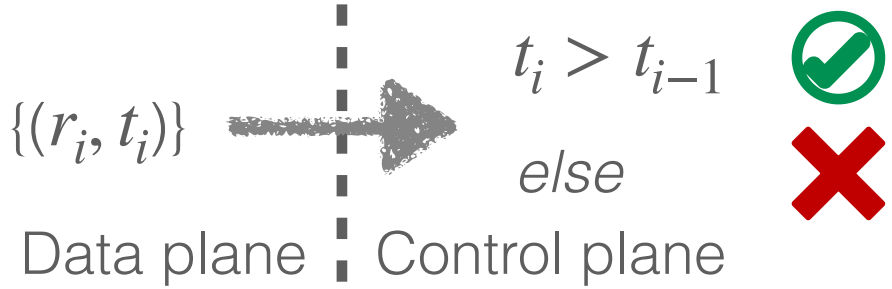
M3: Isolating Measurement



For a register, ***at most*** one element will be updated on a packet thread

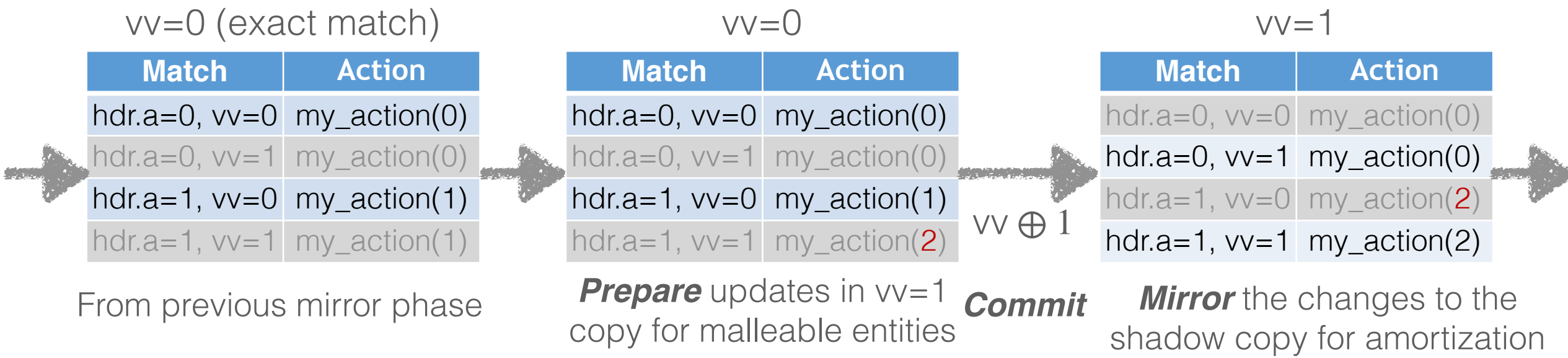
Stale values may appear in the current checkpoint for register arguments

Timestamps t_i appended to the duplicate buffer



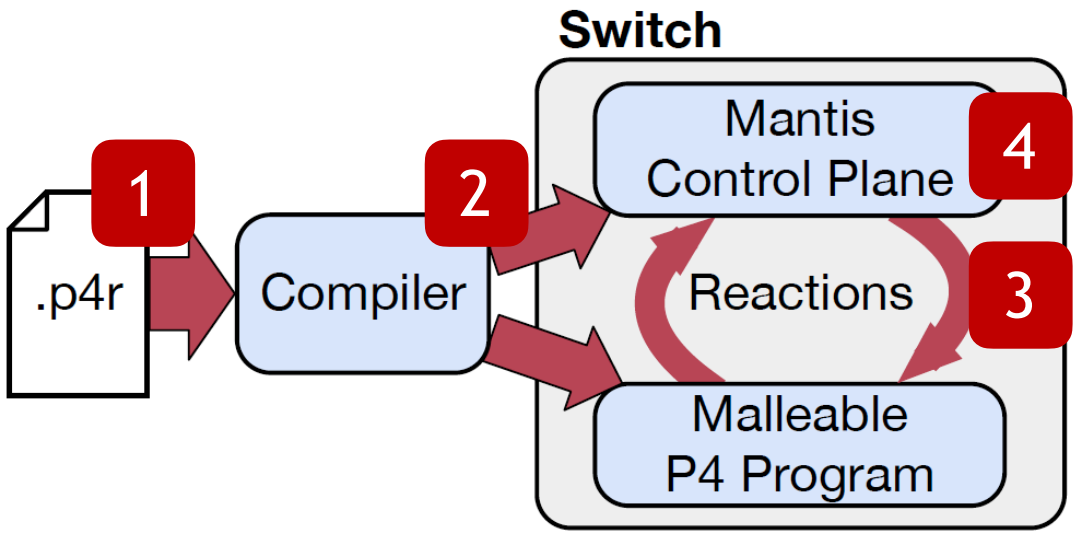
M3: Isolating Updates

Three-phase updates for isolating *fast, repeated, partial* updates



Bounded memory overhead and *predictable* latency

Anatomy of Mantis



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M4: Mantis Control Plane

Traditionally data/control plane interactions are treated as *one-off, isolated* events, i.e., assumed to be *"on the slow path"*

Mantis control plane is instead ***reaction-centric***

```
helper_state = precompute_metadata();
memo = setup_cache(helper_state);
run_user_initialization(helper_state, memo);
```

Prologue

```
while(!stopped) {
  updateTable(memo, "p4r_init_", {measure_ver : mv ^ 1});
  read_measurements(memo, mv); mv ^= 1;
  run_user_reaction(memo, helper_state, vv ^ 1);
  updateTable(memo, "p4r_init_", {config_ver : vv ^ 1});
  fill_shadow_tables(memo, vv); vv ^= 1;
}
```

Dialogue

~PCIe latency of the underlying system

Implementation and Evaluation

Prototype implementation on a Wedge100BF-32X Tofino switch

- P4R frontend: Flex/Bison based, ~5000 lines of C++ and grammar
- Mantis agent: dynamic (re)loading of user reaction (.so object)

https://github.com/eniac/Mantis

D e m o

Implementation and Evaluation

Prototype implementation on a Wedge100BF-32X Tofino switch

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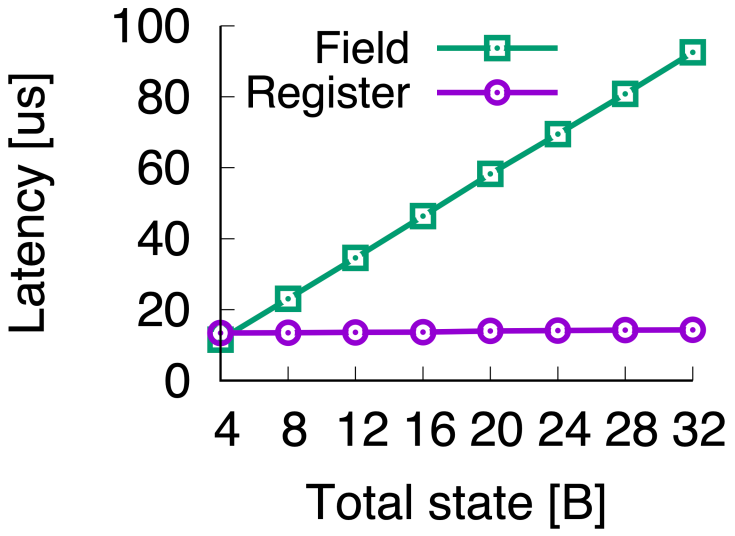
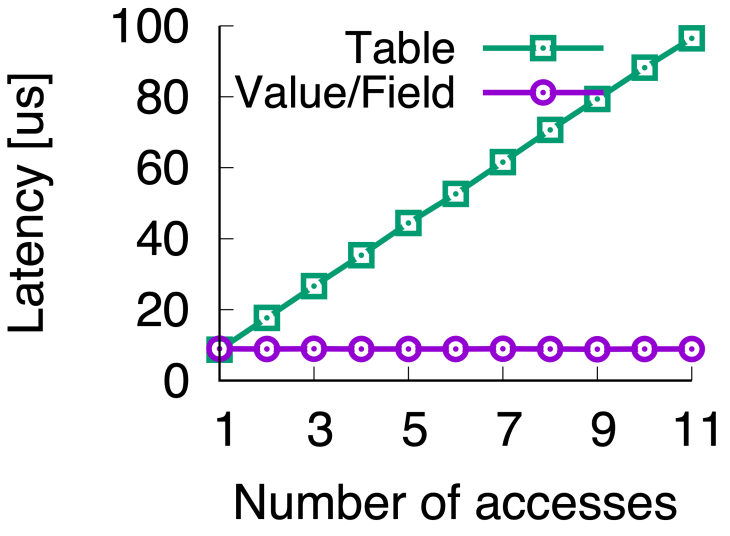
Evaluation

- How fast is Mantis's reaction time?
- What is the overhead?
- What are the applications of Mantis?
- How does Mantis compare to existing alternatives?

Mantis Achieves Fast Reaction Times



a: Reaction argument



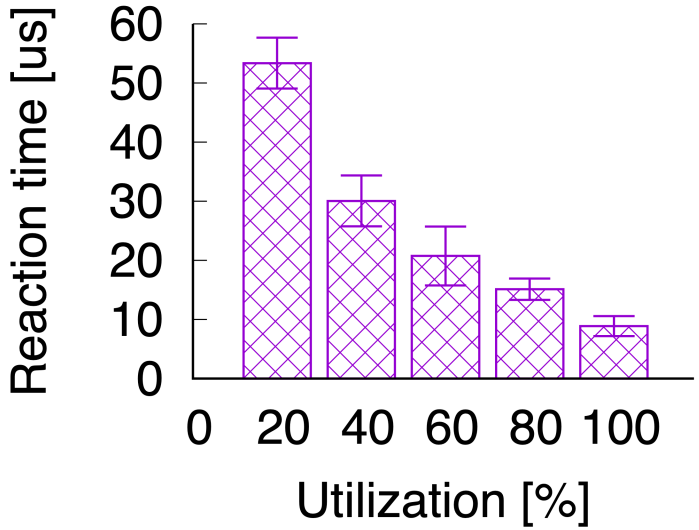
b: Malleable entity update

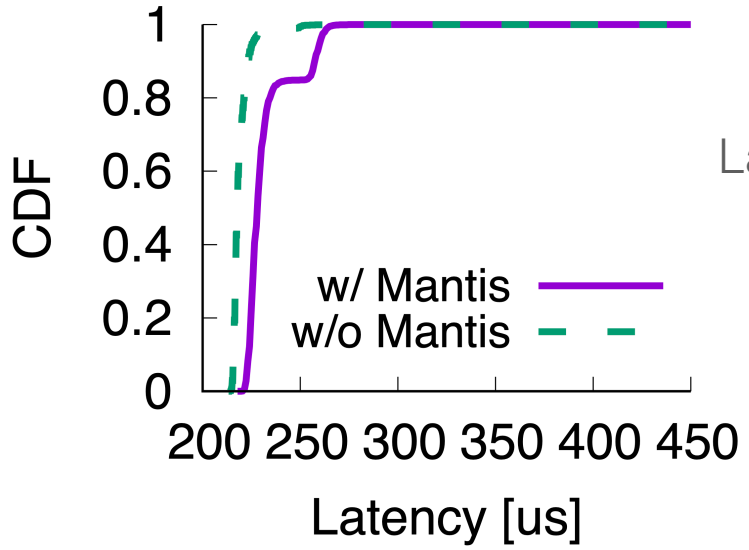
$$F_{\text{b}}(1\ \text{tblMod}) + \sum_{a \in \text{args}} \left(F_{\text{a}}(a) \right) + C + \sum_{t \in \text{tblMods}} \left(2F_{\text{b}}(t) \right) + 2F_{\text{b}}(N_{\text{init}} - 1) + F_{\text{b}}(1\ \text{tblMod})$$

End-to-end reaction time: ***10s of us***

Mantis CPU Overhead

A dialogue loop occupies up to a single core but can be throttled





Latency penalty
median: ~4.64%
p99: ~6.45%

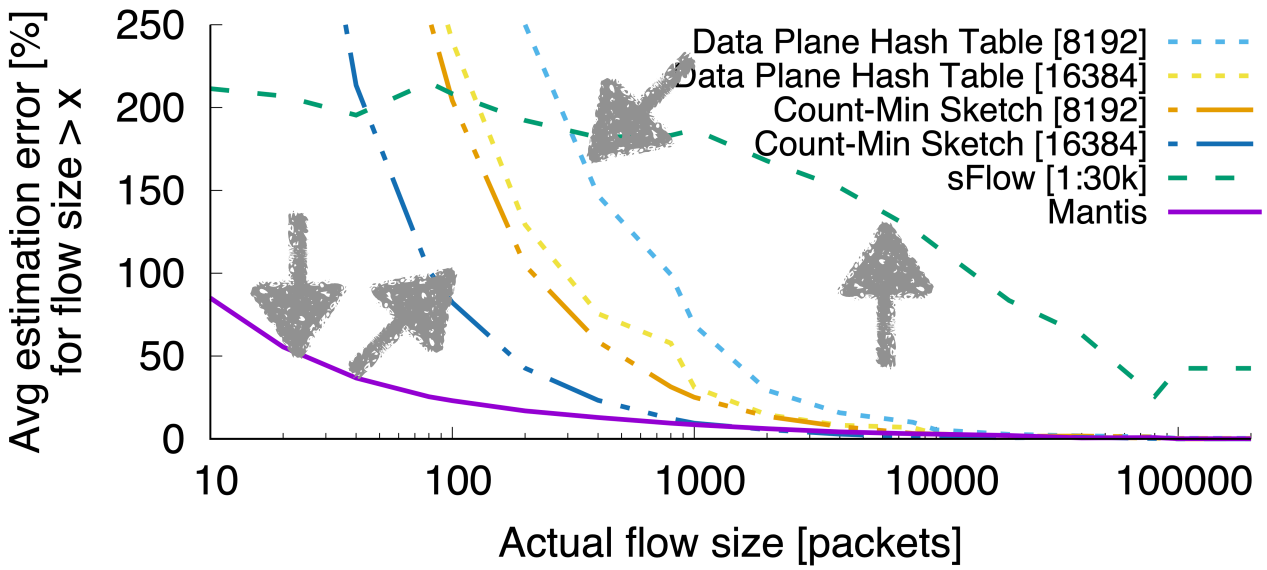
Overall, Mantis can ***co-exist*** with other functionalities

Use Cases

	DoS mitigation	*Route Recomputation*	*Hash polarization mitigation*	*Reinforcement Learning*
 *Measurement*	Flow signature, packet count	Heartbeat counts, timestamp	Queue depths of ECMP ports	Packet counts and queue depths
 *Control logic*	Block the sender if the estimated flow size exceeds a threshold	Mark the failed link if received heartbeat number is small than expected after consecutive K confirmations	Change ECMP hashing input to another permutation if found a persistent imbalance of port utilization	Use a Q-learning algorithm to calculate the optimal ECN threshold based on rewards
 *Reconfiguration*	Drop the malicious traffic for the blocked senders	Reroute traffic towards the affected link	Reconfigure the malleable fields for another 5-tuple permutation	Change ECN malleable value

Flow Size Estimation

- Evaluation setting
  - CAIDA traces, 20s chunk, 10Gbps link of ISP backbone
- Arguments
  - packet source IP and packet counter
- Algorithm
  - Estimation formula $\frac{\hat{f}_t - \hat{f}_{t_0}}{t - t_0}$
  - t_0: timestamp when first observe the flow
- Mantis sampling rate: every 10us, ~1 in 5 packet

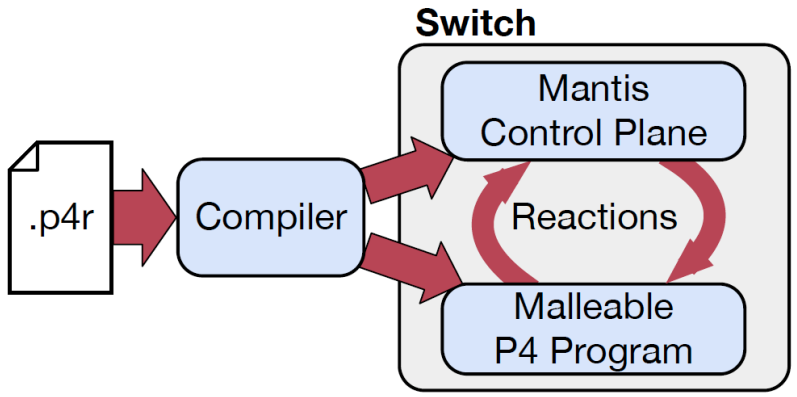


Summary

- Fine-grained reaction to network statistics as first class citizen
- P4R interface to simplify the encoding of serializable reaction
- Generic support of sub-RTT reactive behaviors

Mantis can be used for…

- Encoding flexible control logic
- Workarounds of current limitations
- Reducing memory overhead via offloading
- Data/control plane co-design



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Thank you for your attention!

Live Q&A