Runtime Verification of P4 Switches with Reinforcement Learning

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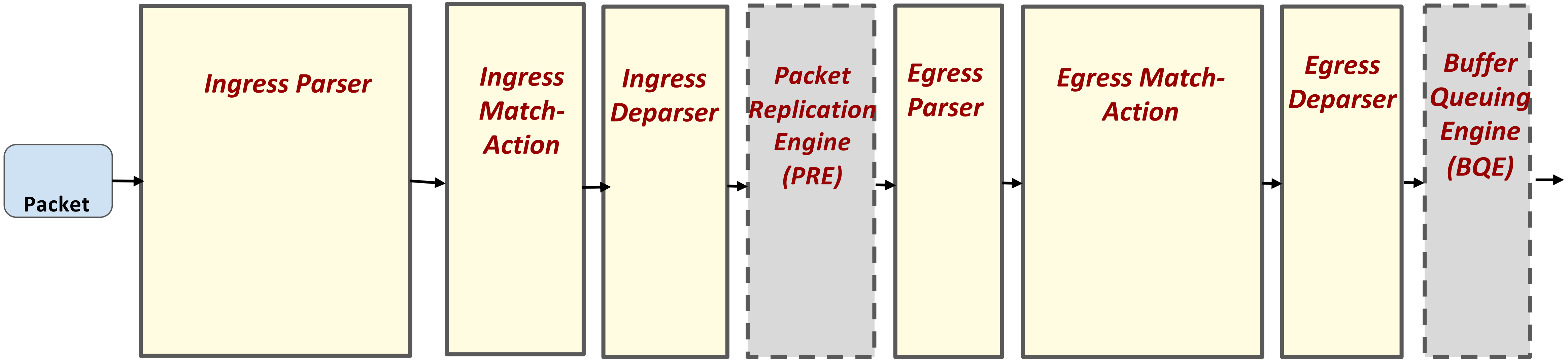
P4[1]: Data plane Programming Language

- Domain-specific high-level language for data plane programming
- Support for user-defined custom protocols, target independence, etc.

[1] P. Bosshart, D. Daly, G. Gibby, M. Izzardy, N. McKeown, J. Rexford, C. Schlesinger, D. Talaycoy, A. Vahdat, G. Varghese, D. Walker. P4: Programming Protocol-Independent Packet Processors. SIGCOMM' 14.

P4 Pipeline: Complex



PSA Architecture with programmable (yellow) and non-programmable blocks (grey)

P4: Multiple versions and platforms

- Versions: $P4_{14}$ & $P4_{16}$
- Platforms: bmv2, Tofino, eBPF, XDP
- Platform-specific implementations

Interplay between programmable and non-programmable blocks gets complex!

Bugs happen

- Bugs related to memory safety: buffer overflow, invalid memory accesses (detectable by static analysis)

- Runtime bugs related to checksum, ECMP/hash-calculation, platform-dependent, etc.

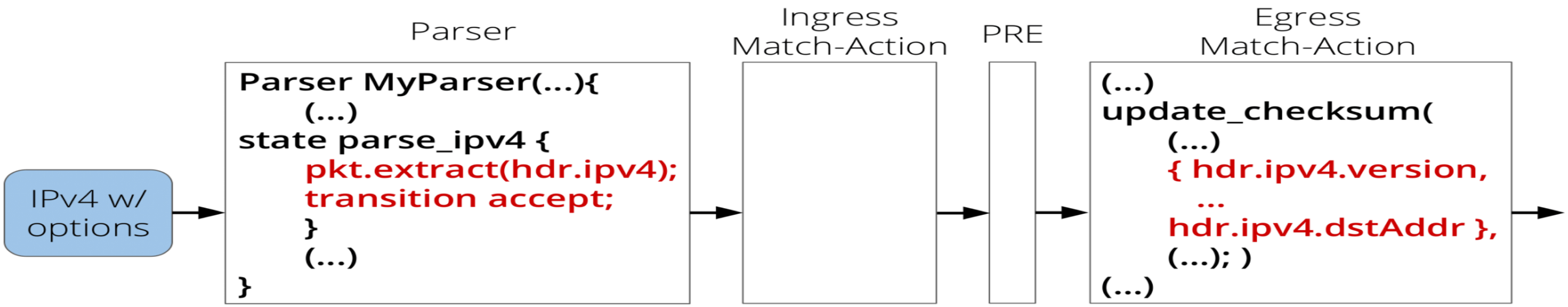
Runtime bug detection is hard

- P4 is half a program; forwarding rules populated at runtime
- Static Analysis prone to false positives: insufficient
- Switch does not throw any runtime exceptions: hard to catch

This talk: P4 Runtime bug Detection!

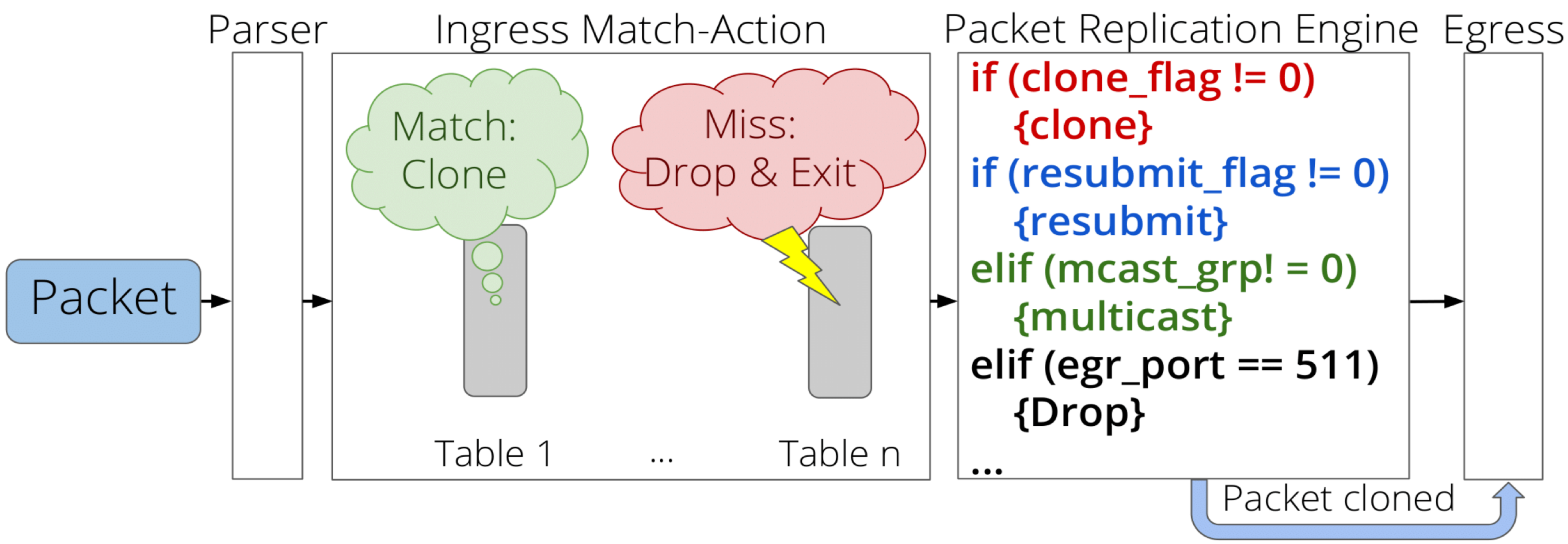
Example: Platform-Independent Bug

- L3 switch parser of P4 language tutorials does not validate IPv4 ihl
- Packets with IP options are forwarded with wrong checksum



Motivating Example: Platform-Dependent Bug

- Conflicting forwarding decisions can lead to unexpected behavior
- Dependent on implementation of packet replication engine (PRE)



More bug examples in the paper!

Problem Statement

Is it possible to automatically detect runtime bugs in P4 switches?

Goal

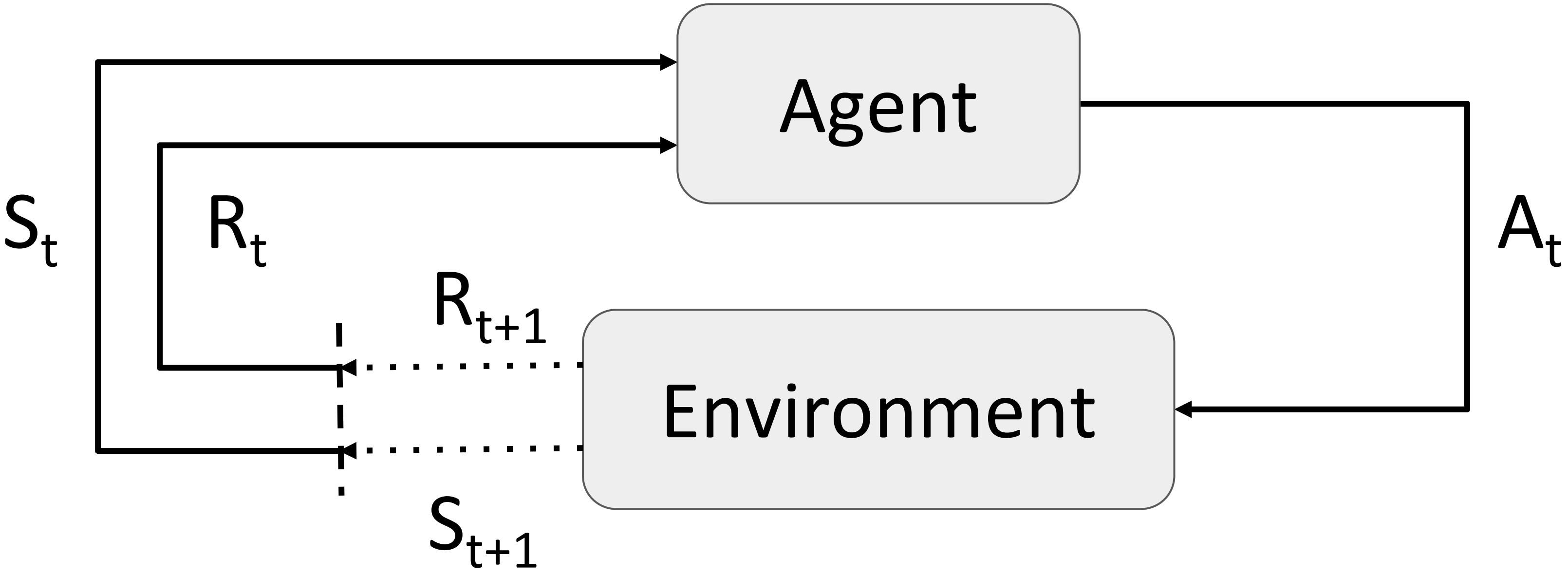
- Design a system which automatically detects runtime bugs
- Detects both: platform-dependent and –independent bugs
- Is non-intrusive: no changes to the P4 program or switch

Approach in a nutshell

- Use fuzzing, and guide it through reinforcement learning agent
- Generate +ve rewards if an anomaly is detected in the feedback
- Feedback also guides the agent further

P4RL

- P4RL Agent – Guides Fuzzing
- p4q – Query Language for expressivity, reducing input search space



Credit: https://www.kdnuggets.com/2018/03/5-things-reinforcement-learning.html

P4RL Reinforcement Learning

- States: Sequence of bytes forming the packet header
- Actions: Add/modify/delete bytes at position X
- Rewards: $\begin{cases} 1, \text{ if the packet triggered a bug} \\ 0, \text{ otherwise} \end{cases}$

Reducing Input Search Space for Fuzzing

- Pre-generated dictionary created using control plane configuration, compiled P4 program and p4q queries
- Compiled P4 program in JSON format aids in knowing accepted header layouts
- Check boundary values first for header fields by queries

Query Language: p4q

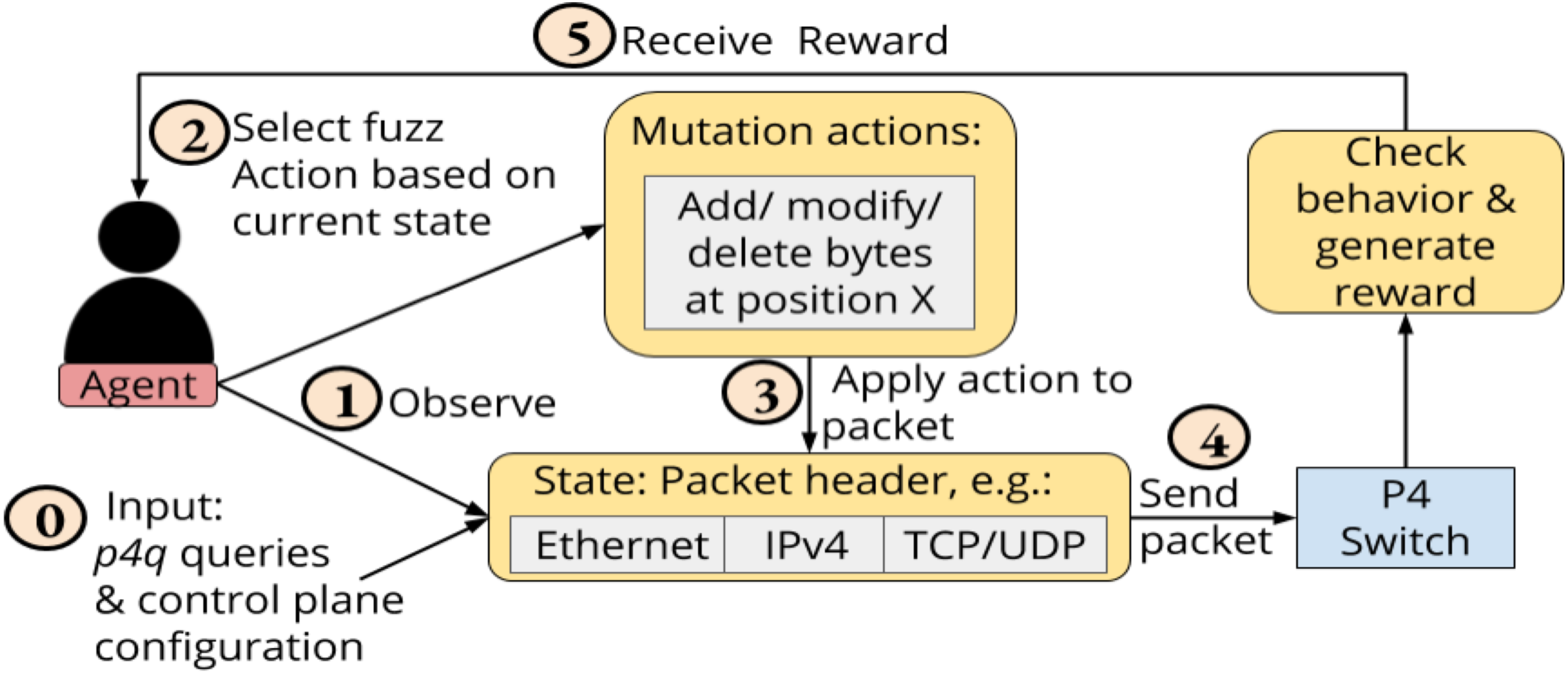
- Goal: Specify expected P4 switch behavior

- If-then-else conditional statements

- Common boolean expressions & relational operators

  (ing.hdr.ipv4 & ing.hdr.ipv4.version !=4,
  egr.egress_port == False,)

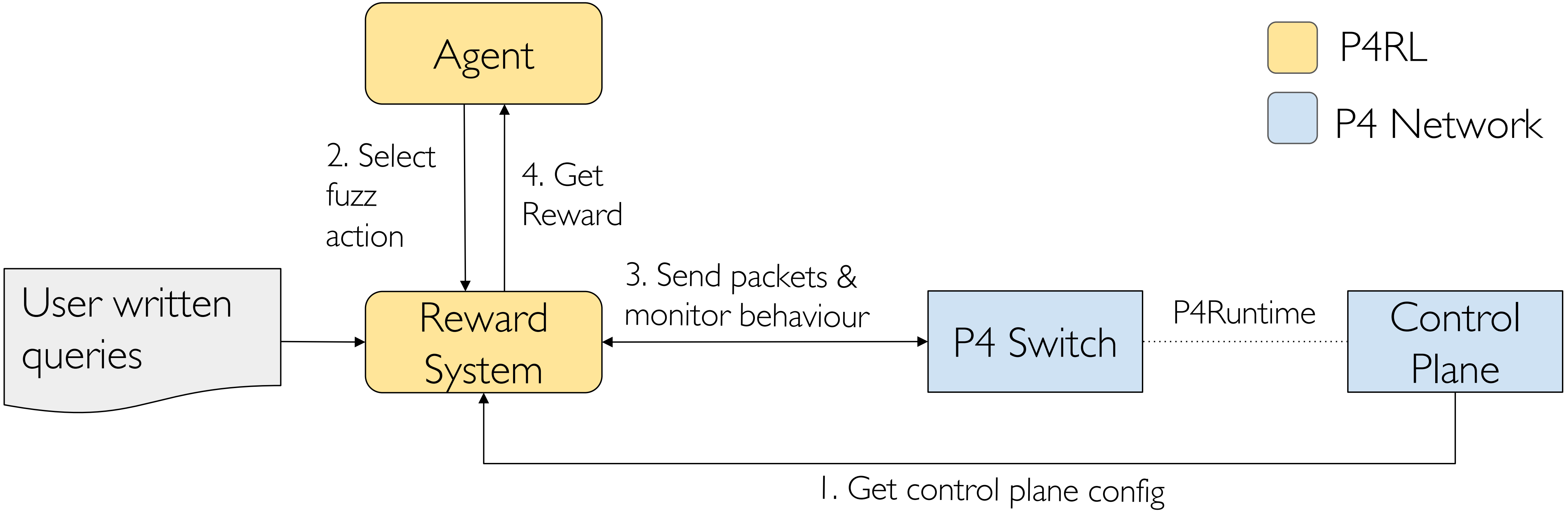
P4RL Agent-guided Fuzzing



P4RL DDQN

- Combination of double Q-learning and deep Q networks with a simple form of prioritized experience replay
- Select next action based upon the result of feeding current environment state to neural network
- Two separate neural networks for action selection and evaluation

P4RL Workflow



Evaluation Strategy

- Target: Publicly available L3 (basic.p4) switch (simple_switch_grpc) implementation
- Baseline: Simple Agent relying on random action selection
- Metrics:
  - Mean Cumulative Reward (MCR) over 10 runs
  - Bug Detection Time

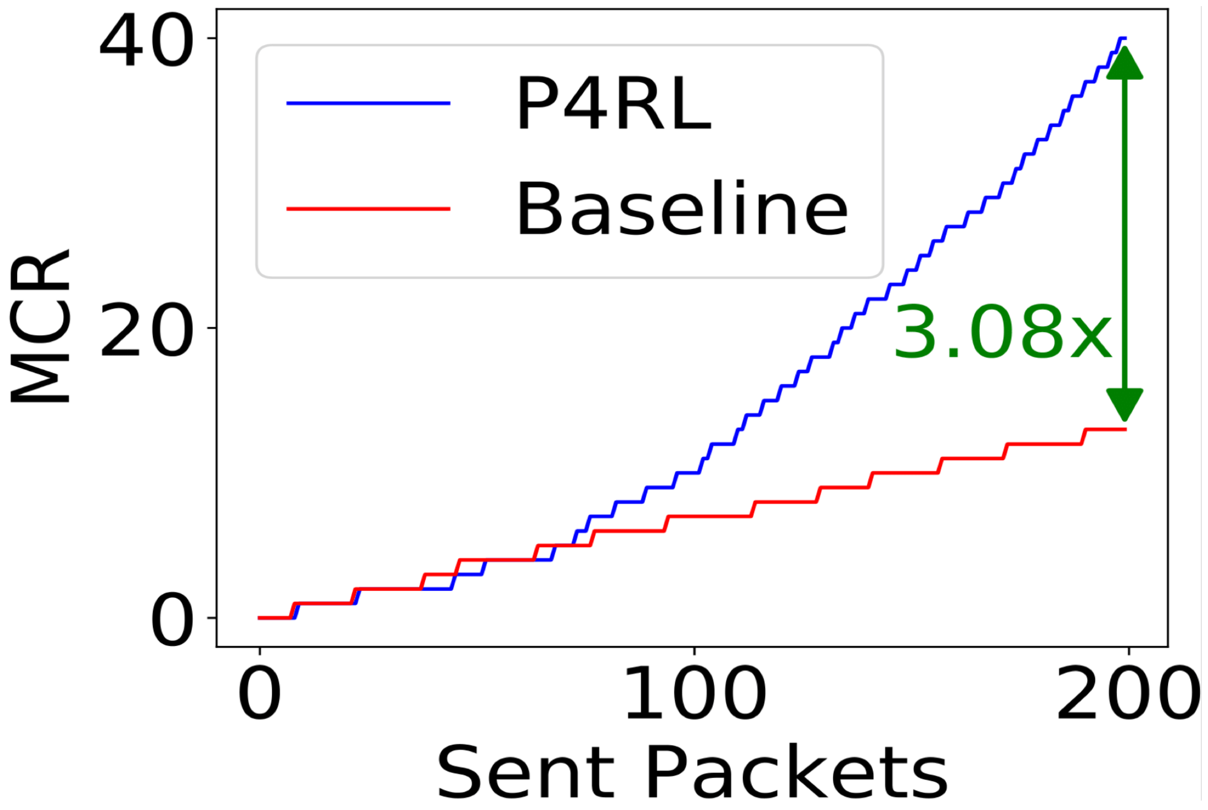
Bugs found by P4RL in publicly available programs

Bug IDs	Bugs
1	Accepted wrong checksum (PI)
2	Generated wrong checksum (PI)
3	Incorrect IP version (PI)
4	IP IHL value out of bounds (PI)
5	IP TotalLen value is too small (PI)
6	TTL 0 or 1 is accepted (PI)
7	TTL not decremented (PI)
8	Clone not dropped (PD)

PI – Platform-independent

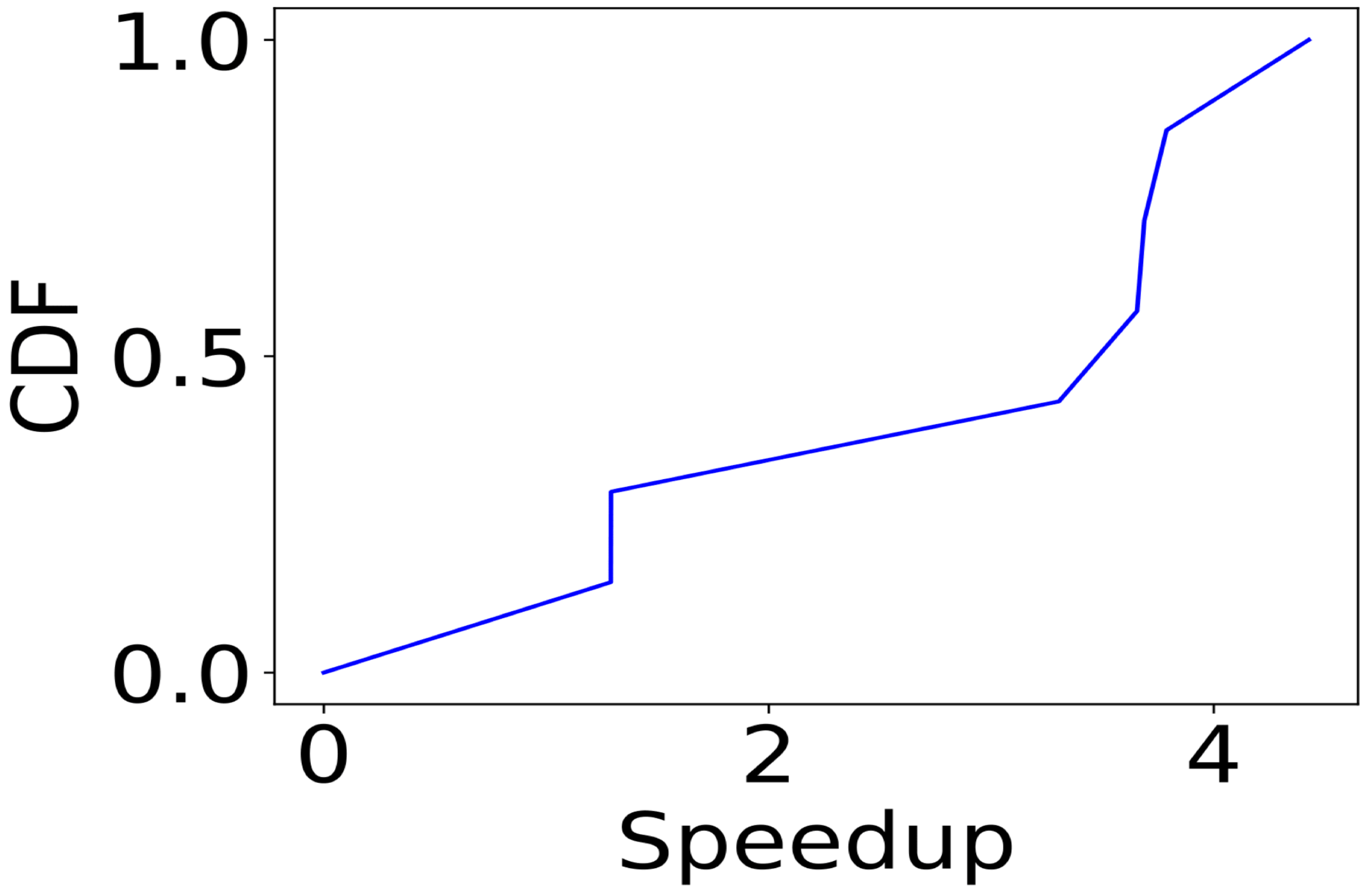
PD – Platform-dependent

Learning Performance: P4RL Agent vs. Baseline



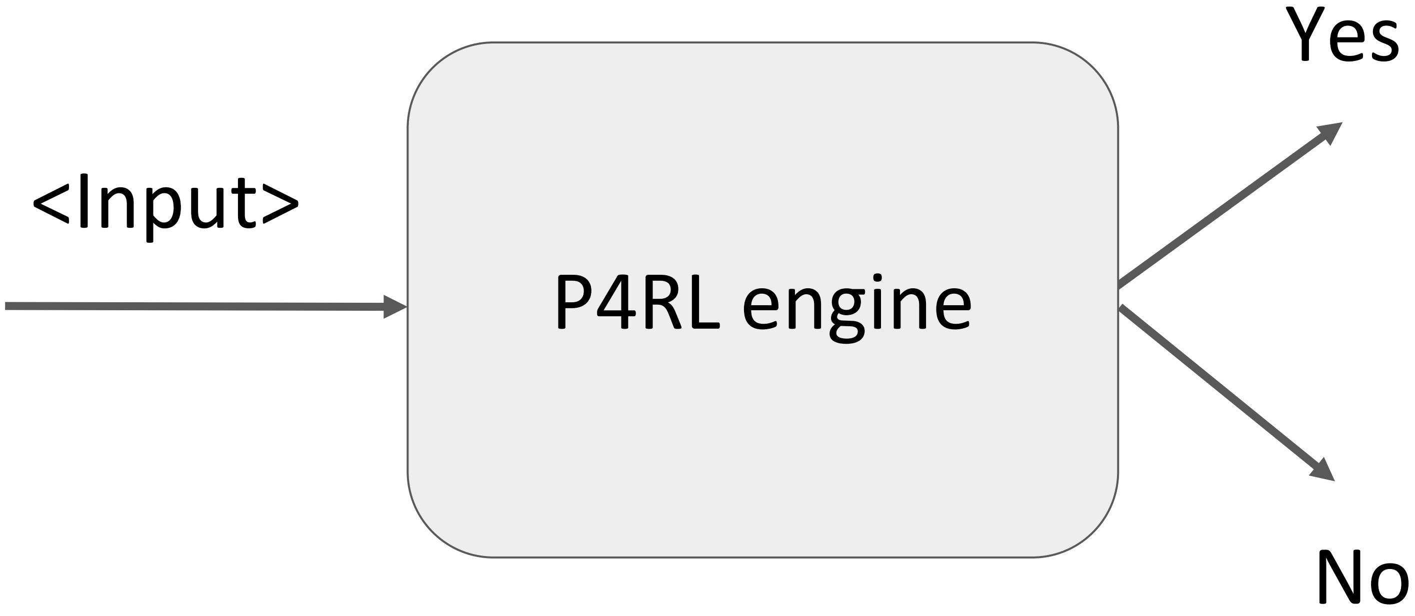
➔ P4RL generates ~3× rewards

Detection Time Speedup: P4RL Agent vs. Baseline



➔ P4RL up to 4.42× faster

Limitations: Undecidability



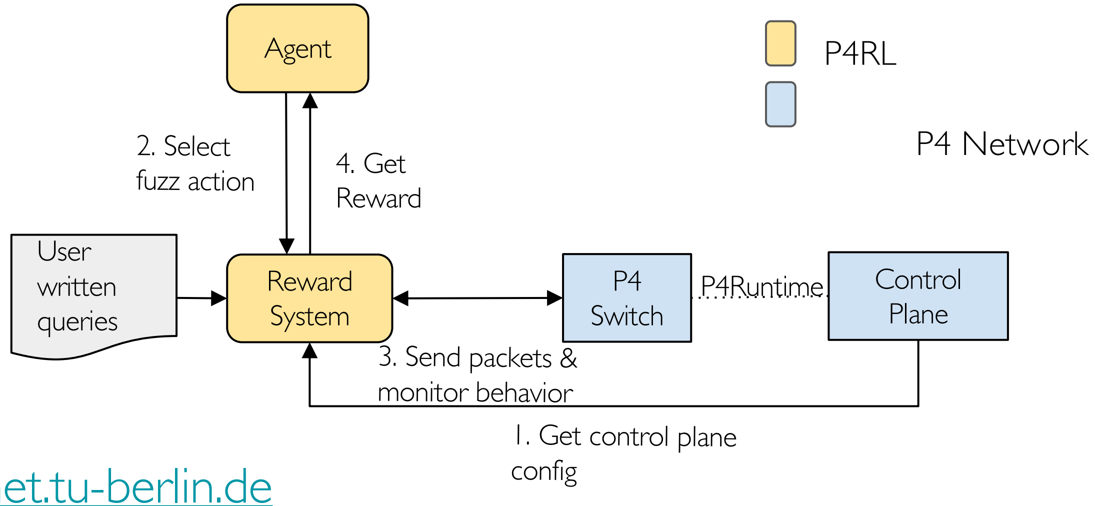
Alan designed the perfect computer

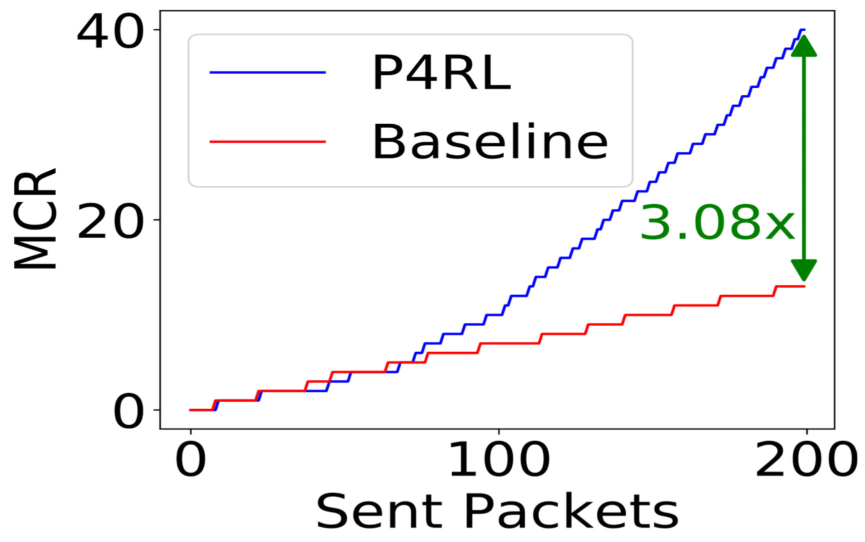
Credit: https://www.coopertoons.com/education/haltingproblem/haltingproblem.html

Conclusion

- P4RL's machine learning-guided fuzzing enables detection of complex runtime bugs (non-intrusively)
- Identifies platform-dependent and -independent bugs
- Ensure correctness in P4 deployments

Summary





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