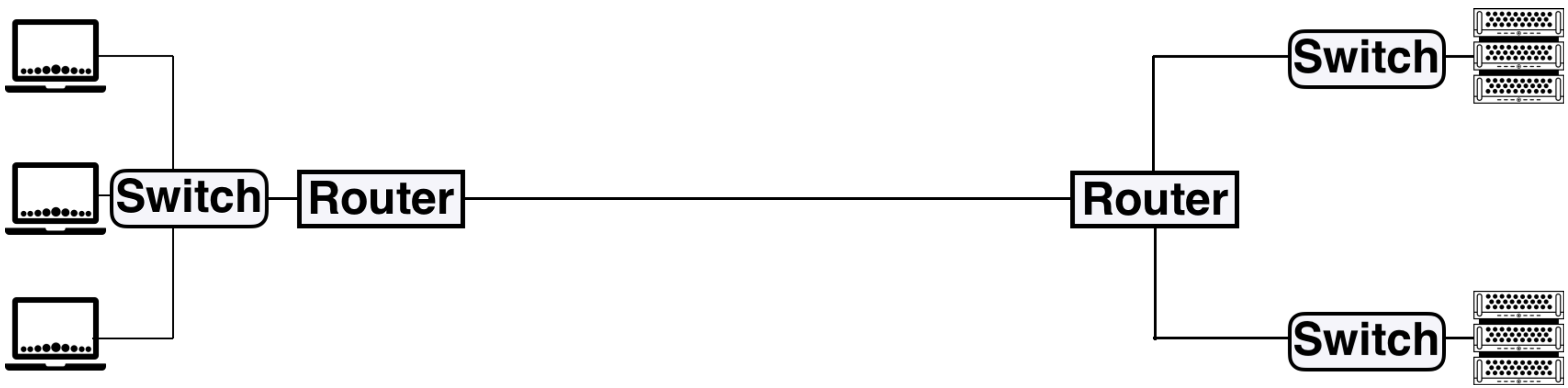
Network Functions

ECE/CS598HPN

Radhika Mittal

Conventional view of networks

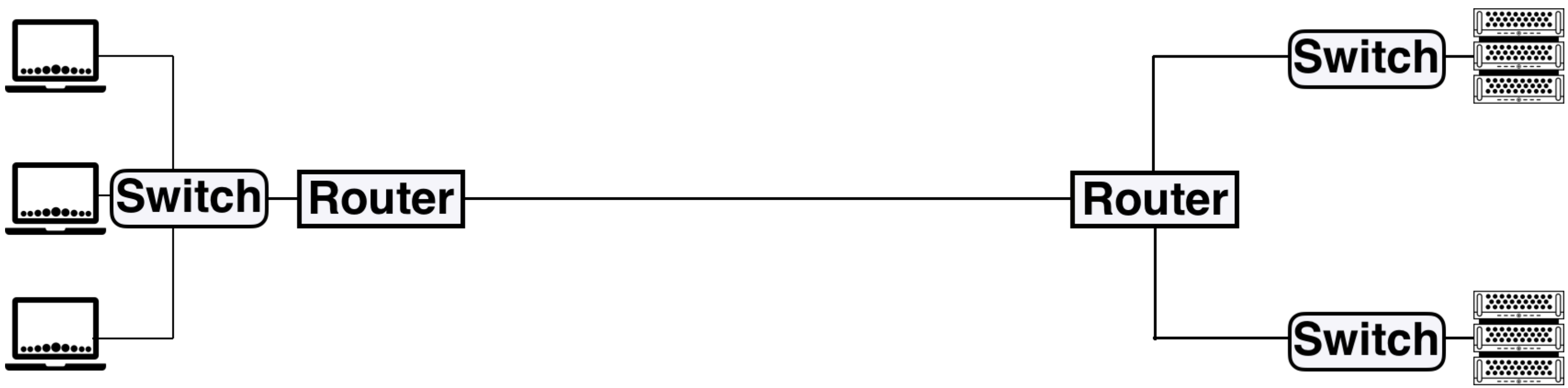


Data delivery is the only functionality provided by such a network.

**contents of the slide borrowed from talks given by Aurojit Panda, NYU*

Conventional view of networks

Data delivery is not the only required functionality.



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Rise of middleboxes

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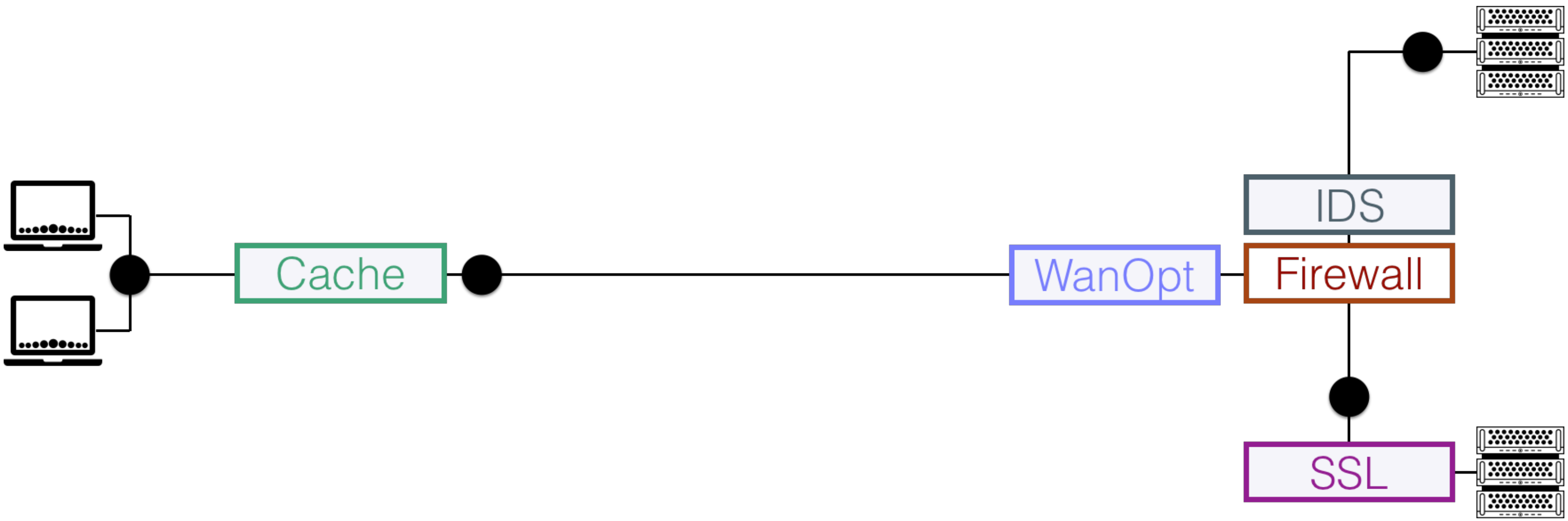

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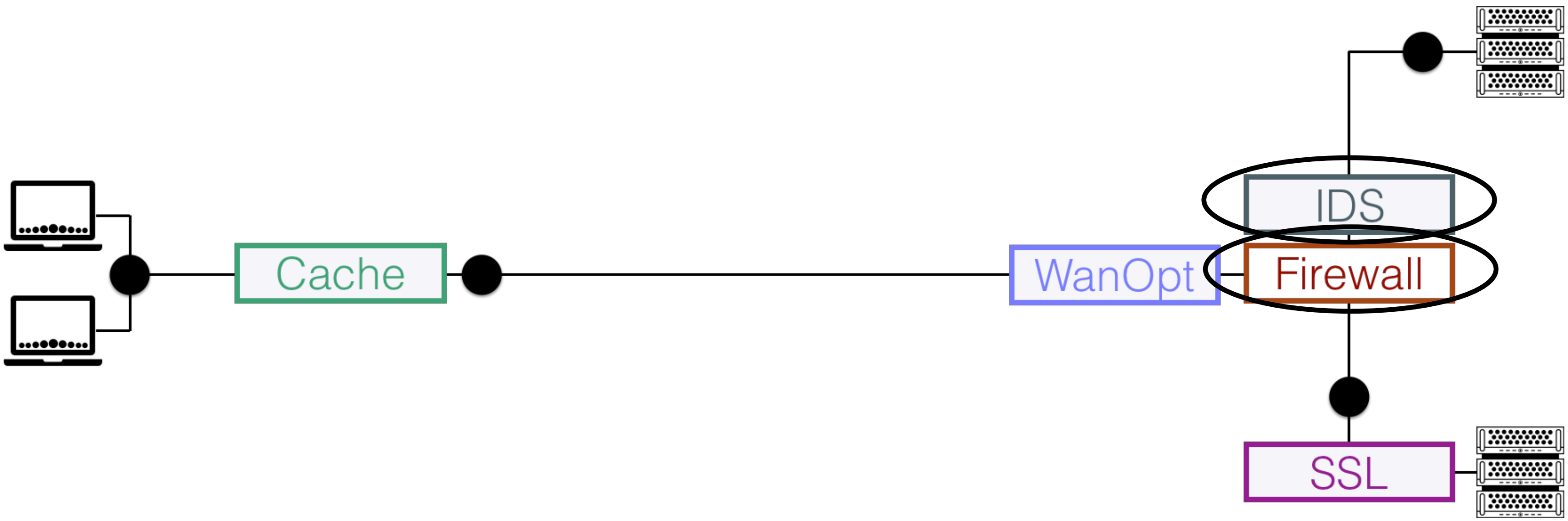

Security: identify and block unwanted traffic.

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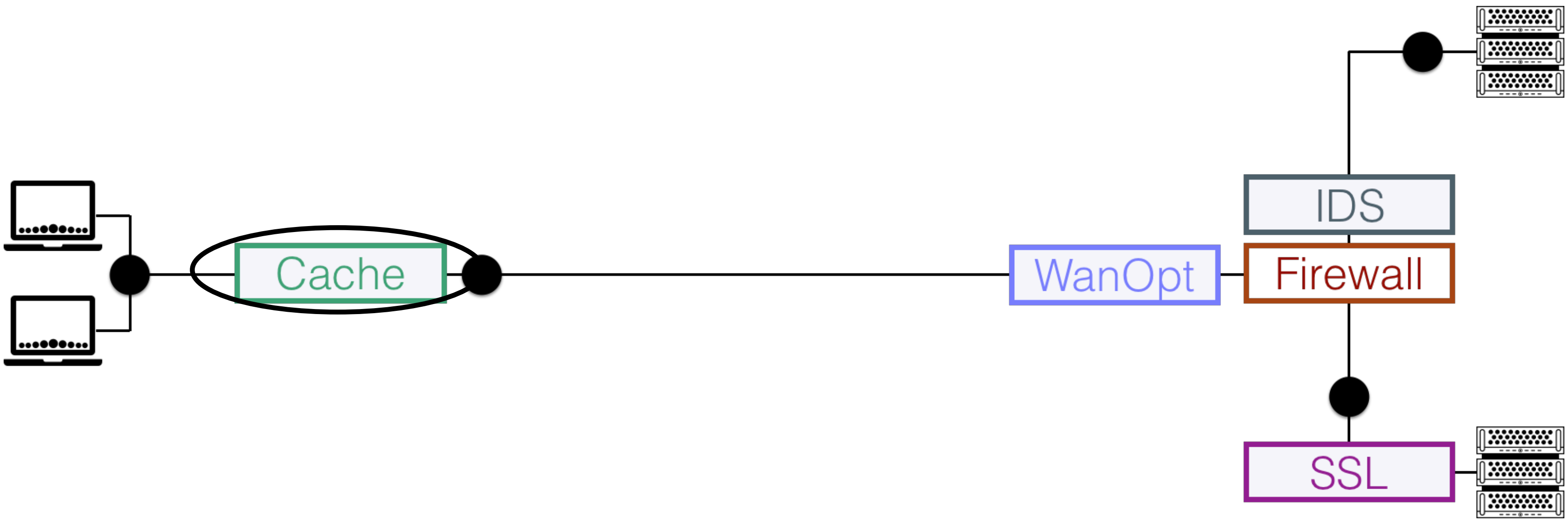

Performance: load content faster.

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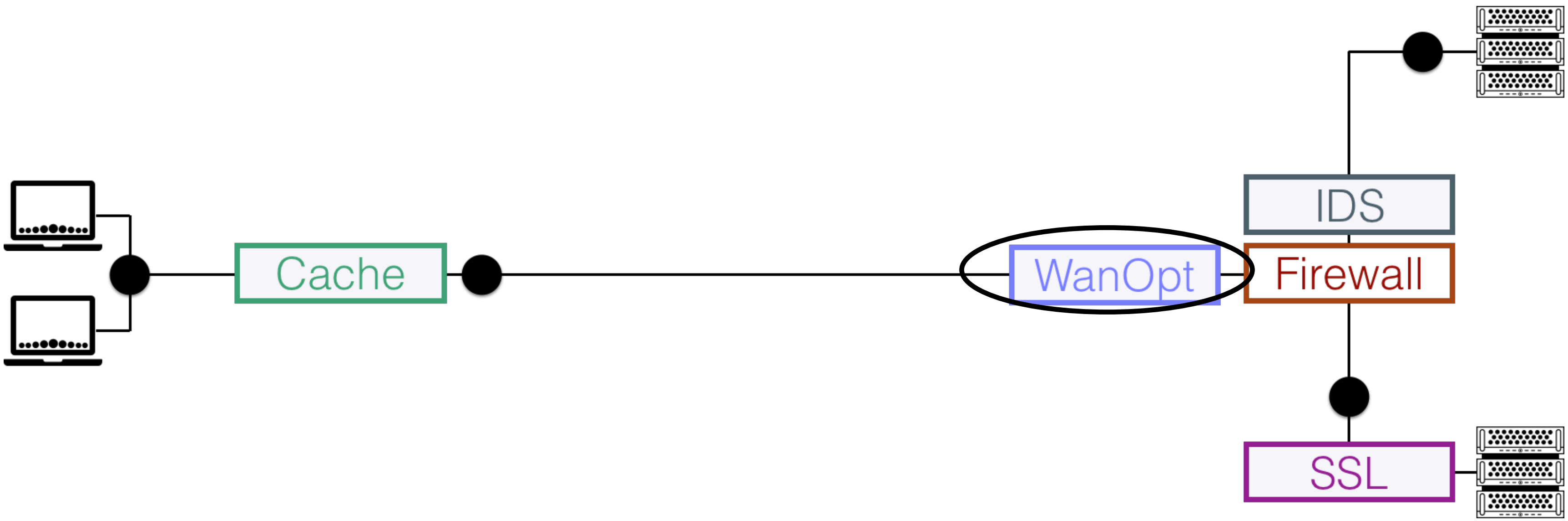

Performance: reduce bandwidth usage.

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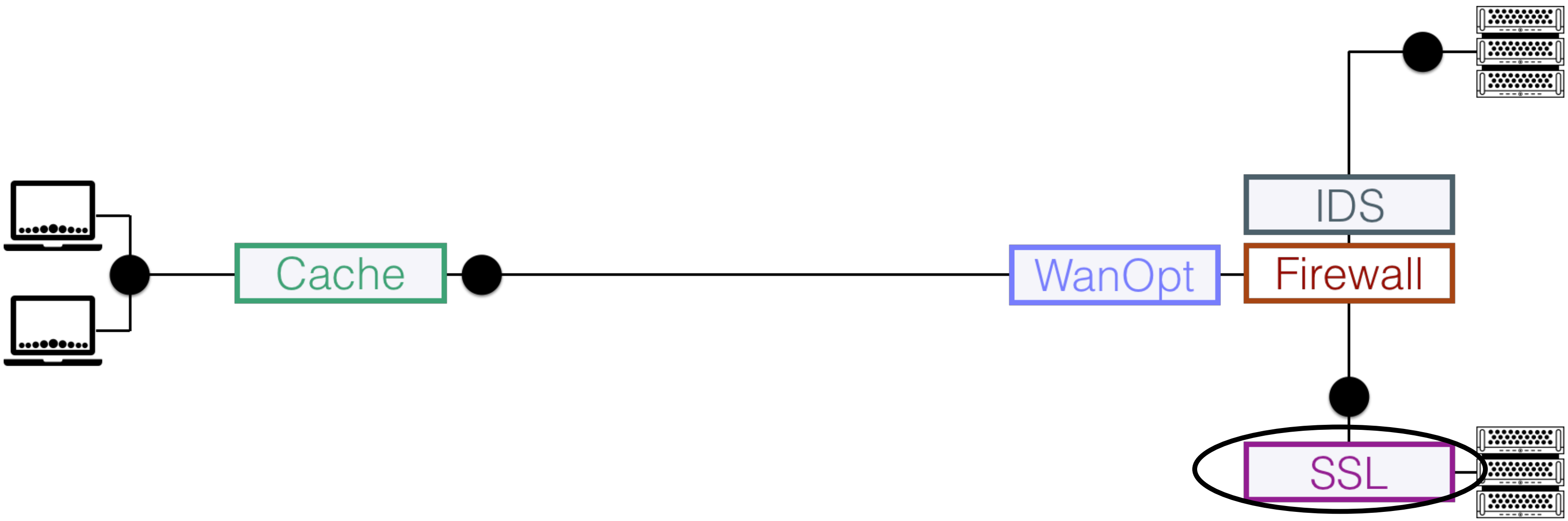

Application support: protocol for legacy application.

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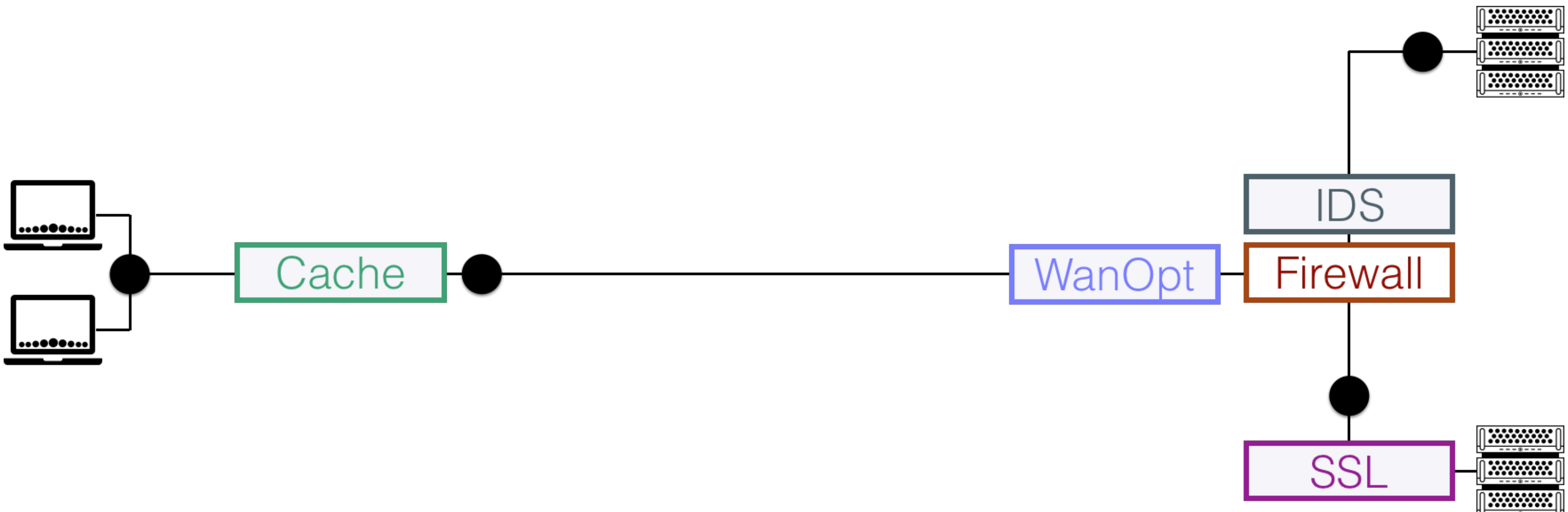

One-third of all network devices in enterprises are middleboxes!

(source: Sherry et. al., SIGCOMM'12)

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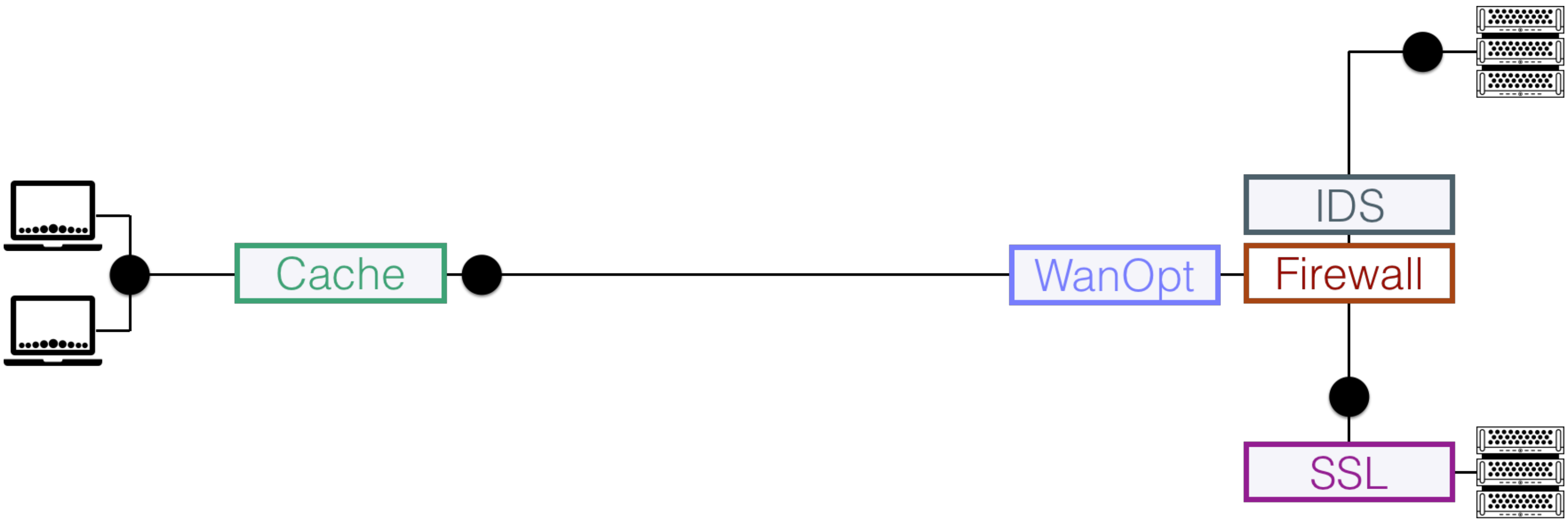
Rise of middleboxes



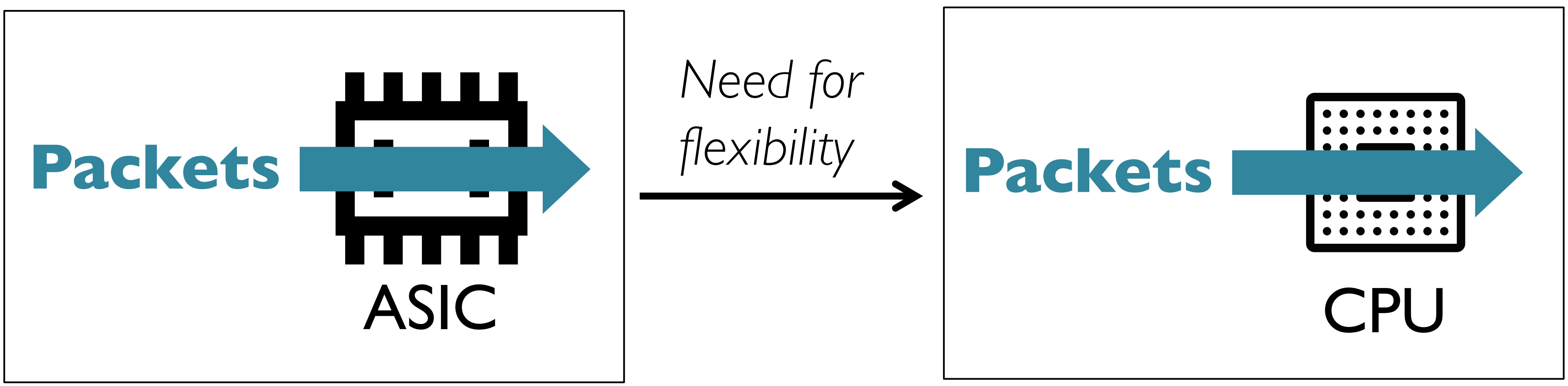
Stringent performance requirements: process packets at line rate with minimal latency overhead.

*contents of the slide borrowed from talks given by Aurojit Panda, NYU

Evolution of middleboxes

Dedicated hardware

Software



Middleboxes

Network functions

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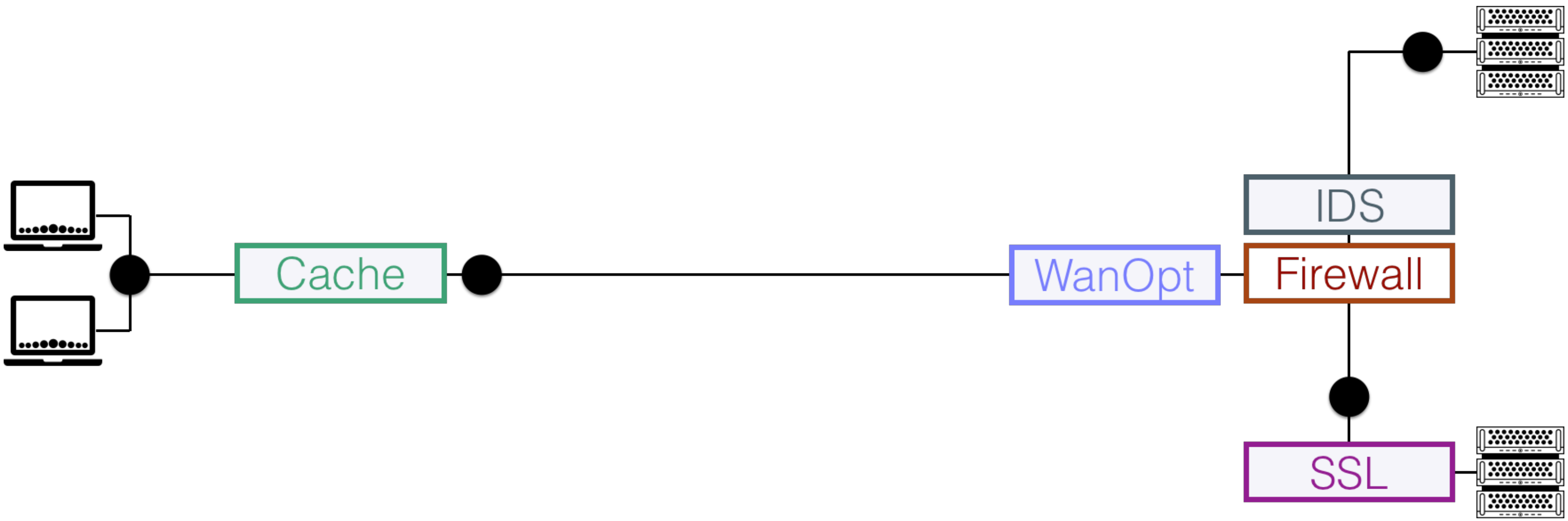
From hardware middleboxes….



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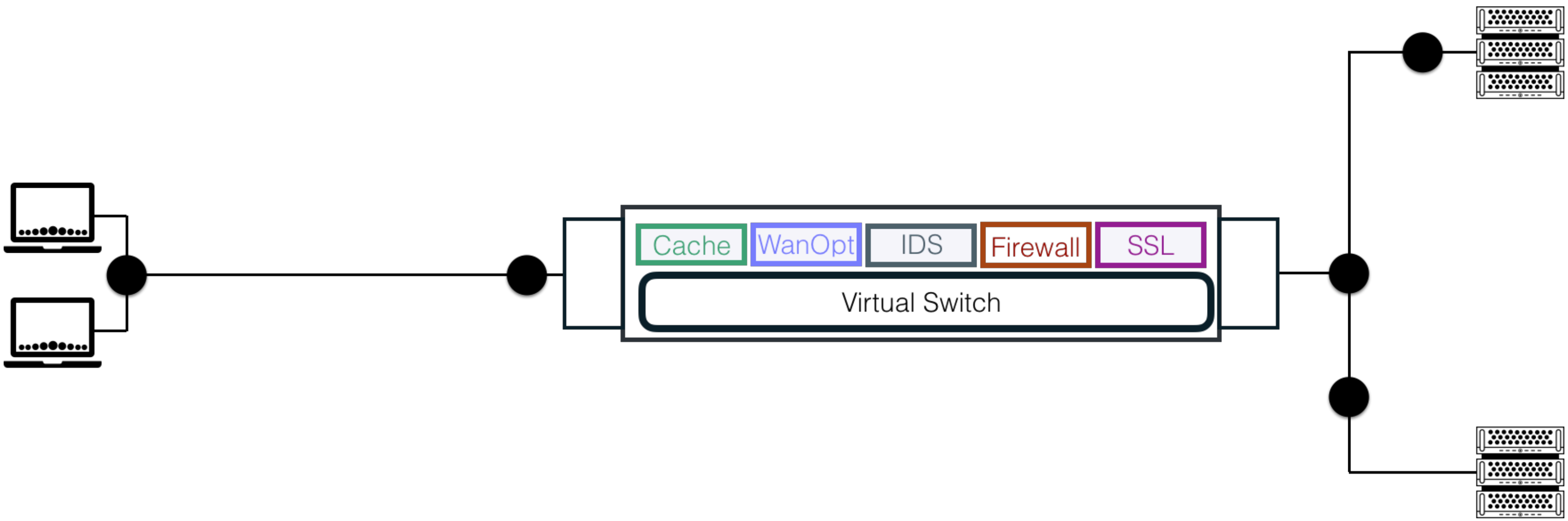
…to software network functions (NFs)



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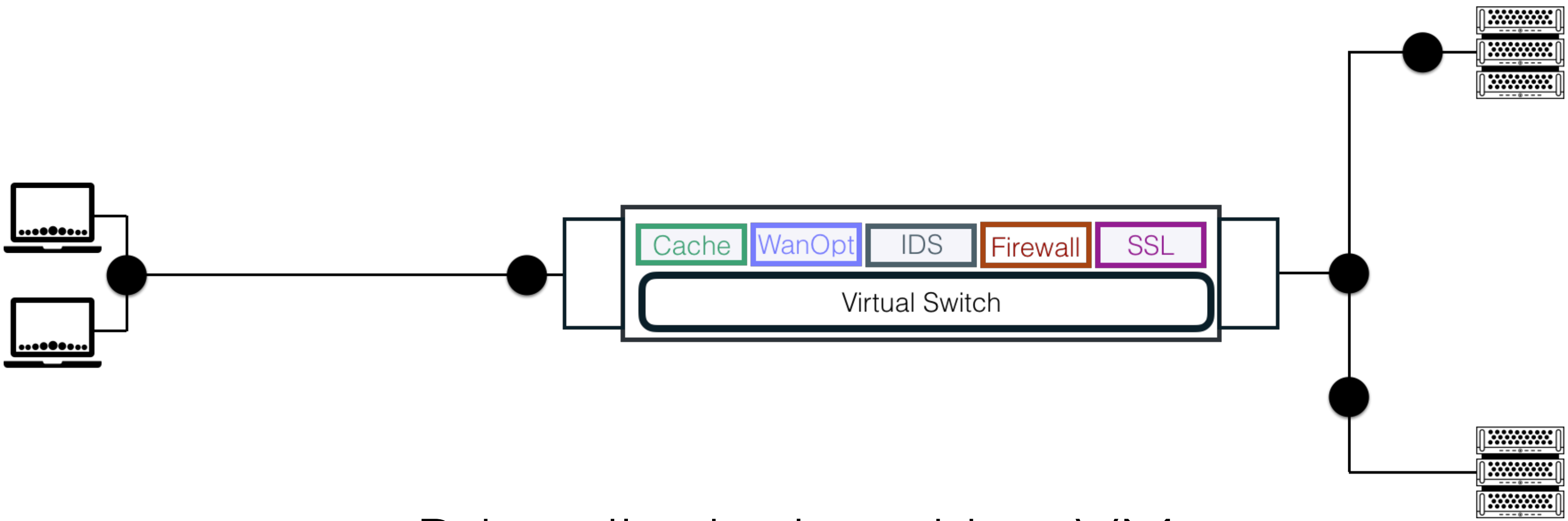

Primarily deployed in a VM

(Network Function Virtualization)

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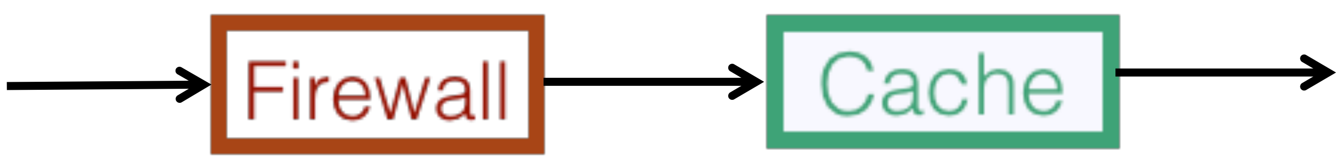
Key benefits of software network functions

- Programmability
  - ability to update and create new NFs.
- Ease of deployment, configuration, and management.



NF Service Chain

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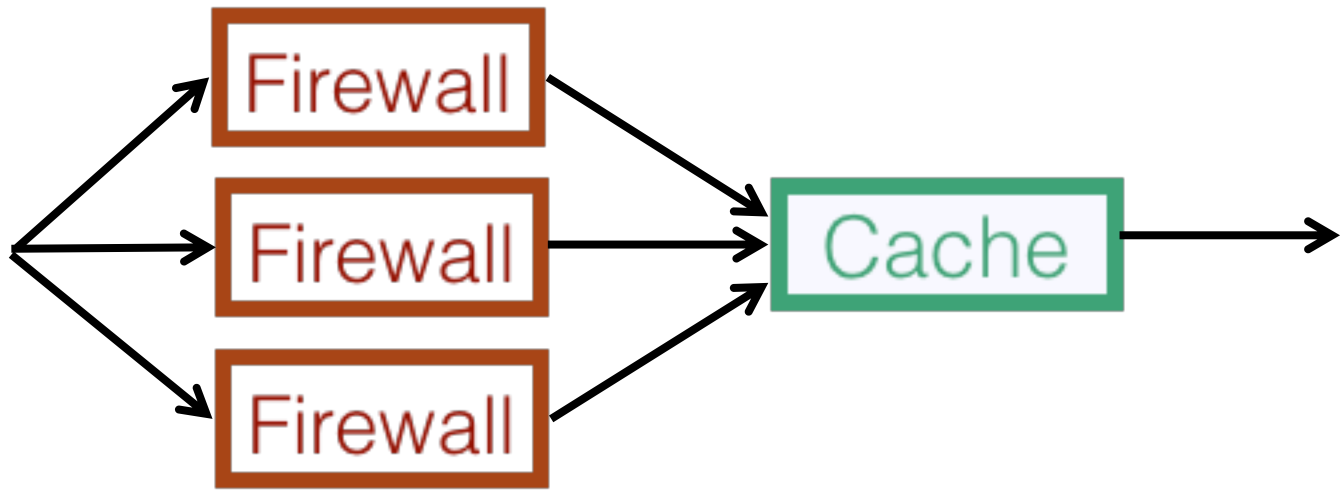


Key benefits of software network functions

- Programmability
  - ability to update and create new NFs.
- Ease of deployment, configuration, and management.

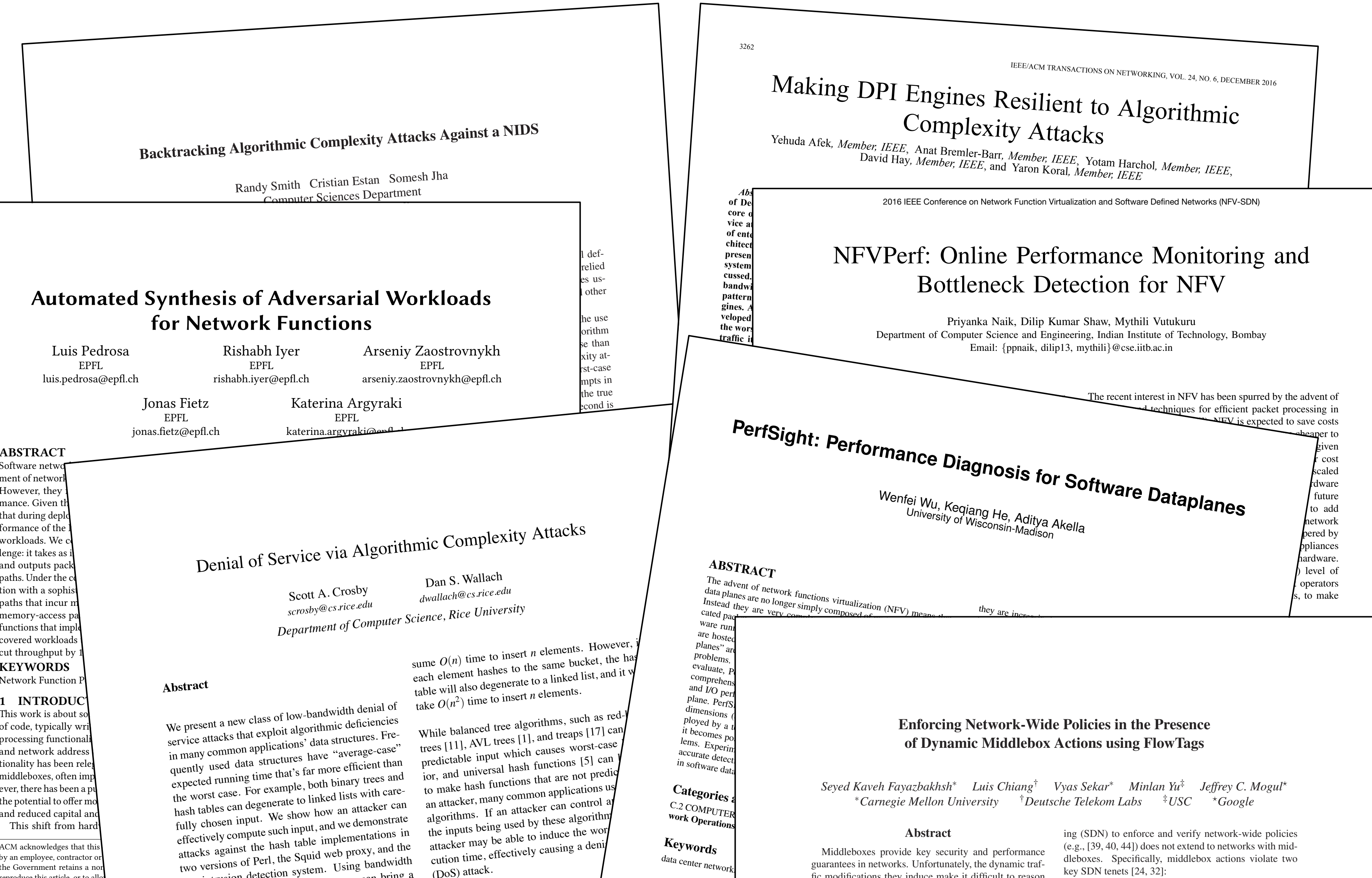
Being adopted by both carriers and cloud providers.

Benefits of software NF come at a cost

- Complex and costly state management.
- Unpredictable performance.
- Performance degradation.

State management during scaling or failover

Understanding NF Performance



Providing guarantees about NF behavior

A Formally Verified NAT

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There exists a lot of prior work on network verification, but,

Verifying Reachability in Networks with Mutable Datapaths

Aurojit Panda* Ori Lahav† Katerina Argyraki‡ Mooly Sagiv◇ Scott Shenker*♠
*UC Berkeley †MPI-SWS ‡EPFL ◇TAU ♠ICSI

Abstract

Recent work has made great progress in verifying the forwarding correctness of networks [26–28, 35]. However, these approaches cannot be used to verify networks containing middleboxes, such as caches and firewalls, whose forwarding behavior depends on previously observed traffic. We explore how to verify reachability properties for networks that include such "mutable datapath" elements, both for the original network and in the presence of fail... The main challenge lies in handling large and... networks. We achieve scaling by d... aging the concept of slices... verification to only re... network.

boxes without changes in the physical infrastructure [13]. Given their complexity and prevalence, middleboxes are the cause of many network failures; for instance, 43% of a network provider's failure incidents i... and between 4% and 15%... result of middlebox...

Software Dataplane Verification

Mihai Dobrescu and Katerina Argyraki
EPFL, Switzerland

Abstract

Software dataplanes are emerging as an alternative to traditional hardware switches and routers, promising programmability and short time to market. These advantages are set against the risk of disrupting the network with bugs, unpredictable performance, or security vulnerabilities. We explore the feasibility of verifying software dataplanes to ensure smooth network operation. For general programs, verifiability and performance are competing goals; we argue that software dataplanes are different—we can write them in a way that enables verification *and* preserves performance. We present a verification tool that takes as input a software dataplane, written in a way that meets a given set of conditions, and (dis)proves that the dataplane satisfies crash-freedom, bounded-execution, and filtering properties. We evaluate our tool on stateless and simple stateful Click pipelines; we perform complete and sound verification of these pipelines within tens of minutes, whereas a state-of-the-art general-purpose tool fails to complete the same task within several hours.

1 Introduction

Software dataplanes are emerging from both research [17,26,27,37] and industry [2,3] backgrounds as a more flexible alternative to traditional hardware switches and routers. They promise to cut network provisioning costs by half, by enabling dynamic allocation of packet-processing tasks to network devices [42]; or to turn the Internet into an evolvable architecture, by enabling continuous functionality update of devices located at strate-

The subject of this work is a verification tool that takes as input the executable binary of a software dataplane and proves that it does (or does not) satisfy a target property; if the target property is not satisfied, the tool should provide counter-examples, i.e., packet sequences that cause the property to be violated. Developers of packet-processing apps could use such a tool to produce software with guarantees, e.g., that never seg-faults or kernel-panics, no matter what traffic it receives. Network operators could use the tool to verify that a new packet-processing app they are considering for deployment will not destabilize their network, e.g., it will not introduce more than some known fixed amount of per-packet latency. One might even envision markets for packet-processing apps—similar to today's smartphone/tablet app markets—where network operators would shop for new code to "drop" into their network devices. The operators of such markets would need a verification tool to certify that their apps will not disrupt their customers' networks.

For general programs, verifiability and performance are competing goals. Proving properties of real programs (unlike searching for bugs) remains an elusive goal for the systems community, at least for programs that consist of more than a few hundred lines of code and are written in a low-level language like C++. A high-level language like Haskell can guarantee certain properties (like the impossibility of buffer overflow) by construction, but typically at the cost of performance.

For software dataplanes, it does not have to be this way: we will argue that we can write them in a way that enables verification and preserves performance. The key question then is: what defines a "software dataplane" and how much more restricted is it than a "general program"?

SymNet: scalable symbolic execution for modern networks

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University Politehnica of Bucharest
Splaiul Independentei 313, Bucharest, Romania
firstname.lastname@cs.pub.ro

Abstract

We present SymNet, a network static analysis tool based on symbolic execution. SymNet injects symbolic packets and tracks their evolution through the network. Our key novelty is SEFL, a language we designed for expressing data plane processing in a symbolic-execution friendly manner.

SymNet statically analyzes an abstract data plane model that consists of the SEFL code for every node and the links between nodes. SymNet can check networks containing routers with hundreds of thousands of prefixes and NATs in seconds, while verifying packet header memory-safety and covering network functionality such as dynamic tunneling, stateful processing and encryption. We used SymNet to debug middlebox interactions from the literature, to check properties of our department's network and the Stanford backbone.

Modeling network functionality is not easy. To aid users we have developed parsers that automatically generate SEFL models from router and switch tables, firewall configurations and arbitrary Click modular router configurations. The parsers rely on prebuilt models that are exact and fast to analyze. Finally, we have built an automated testing tool that combines symbolic execution and testing to check whether the model is an accurate representation of the real code.

or distributed firewall policy compliance is difficult before deploying the network configuration, and deployment can disrupt live traffic. Dynamic testing (packet generation and tracing) can only catch common issues (e.g. lack of connectivity) but does not scale to large networks.

Static analysis of network data planes allows cheap, fast and exhaustive verification of deployed networks for packet reachability, absence of loops, bidirectional forwarding, etc. We do not aim to verify the control plane (e.g. routing protocols, SDN controllers etc.). Control plane verification is a hard problem that includes checking the correctness of the control plane configuration [8, 9, 4], proving convergence after link additions or failures and characterizing the transient behavior until convergence is reached [2, 11]. We assume the control plane configuration is stable and the control plane has converged and analyze the resulting data plane.

All static analysis tools take as input a *model* of the processing performed by each network box, the links between boxes and a snapshot of the forwarding state, and are able to answer queries about the network without resorting to dynamic testing [23, 14, 19, 20, 21]. What is the best modeling language for networks? If possible, we should simply use the implementation of network boxes (e.g. a C program), as this is the most accurate and is easiest to use. If we view packets as variables being passed between different network boxes, static network analysis becomes akin to software testing. This is a problem that has been studied for decades, and the leading approach is to use *symbolic execution* [3].

Symbolic execution is really powerful: it explores all possible paths through the program, providing possible values

High performance NF implementations

Microboxes: High Performance NFV with Customizable, Asynchronous TCP Stacks and Dynamic Subscriptions

Guyue Liu*, Yuxin Ren*, Mykola Yurchenko*,
K.K. Ramakrishnan†, Timothy Wood*
*George Washington University, †University of California, Riverside

mOS: A Reusable Networking Stack for Flow Monitoring Middleboxes

Muhammad Jamshed, YoungGyoun Moon, Donghwi Kim, Dongsu Han, and KyoungSoo Park
School of Electrical Engineering, KAIST

FlowBlaze: Stateful Packet Processing in Hardware

Salvatore Pontarelli[1,2], Roberto Bifulco[3], Marco Bonola[1,2], Carmelo Cascone[4], Marco Spaziani[2,5], Valerio Bruschi[2,5], Davide Sanvito[6], Giuseppe Siracusano[3], Antonio Capone[6], Michio Honda[3], Felipe Huici[3] and Giuseppe Bianchi[2,5]

[1]Axbryd, [2]CNIT, [3]NEC Laboratories Europe, [4]Open Networking Foundation, [5]University of Rome Tor Vergata, [6]Politecnico di Milano

Abstract

While programmab… handle growing net… yet simple abstracti… in hardware remain… problem with Flow… stateful packet pro… straction is based o… troduces the explici… Blaze to leverage f… pressive, supporting… tions, and easy to u… tation issues from t… FlowBlaze on a Ne… tency (in the order… tively little power, … thousands of flows,… for even higher spe… ware and software … licly available.

1 Introductio…

Network infrastruct… network functions t… and server load bala… such as access con… examples. Given … the need to continu… tors have turned to…

ClickNP: Highly Flexible and High Performance Network Processing with Reconfigurable Hardware

Bojie Li§† Kun Tan† Layong (Larry) Luo‡ Yanqing Peng•† Renqian Luo§†
Ningyi Xu† Yongqiang Xiong† Peng Cheng† Enhong Chen§
†Microsoft Research §USTC ‡Microsoft •SJTU

…RACT

…lexible software network functions (NFs) are cru… …ponents to enable multi-tenancy in the clouds. How… …tware packet processing on a commodity server has …capacity and induces high latency. While software …ld scale out using more servers, doing so adds sig… …cost. This paper focuses on accelerating NFs with …mable hardware, *i.e.*, FPGA, which is now a ma… …nology and inexpensive for datacenters. However, … predominately programmed using low-level hard… …cription languages (HDLs), which are hard to code …cult to debug. More importantly, HDLs are almost …ible for most software programmers. This paper presents …, a FPGA-accelerated platform for highly flexible …-performance NFs with commodity servers. ClickNP … flexible as it is completely programmable using …el C-like languages, and exposes a modular program… …straction that resembles Click Modular Router. ClickNP …igh performance. Our prototype NFs show that they …ess traffic at up to 200 million packets per second …a-low latency (< 2μs). Compared to existing soft… …unterparts, with FPGA, ClickNP improves through… …0x, while reducing latency by 10x. To the best of …wledge, ClickNP is the first FPGA-accelerated plat… … NFs, written completely in high-level language and …g 40 Gbps line rate at any packet size.

…Concepts

1. INTRODUCTION

Modern multi-tenant datacenters provide shared infrastructure for hosting many different types of services from different customers (*i.e.*, tenants) at a low cost. To ensure security and performance isolation, each tenant is deployed in a *virtualized network* environment. Flexible network functions (NFs) are required for datacenter operators to enforce isolation while simultaneously guaranteeing Service Level Agreements (SLAs).

Conventional hardware-based network appliances are not flexible, and almost all existing cloud providers, *e.g.*, Microsoft, Amazon and VMWare, have been deploying software-based NFs on servers to maximize the flexibility [23, 30]. However, software NFs have two fundamental limitations – both stem from the nature of software packet processing. First, processing packets in software has limited capacity. Existing software NFs usually require multiple cores to achieve 10 Gbps rate [33, 43]. But the latest network links have scaled up to 40∼100 Gbps [11]. Although one could add more cores in a server, doing so adds significant cost, not only in terms of capital expense, but also more operational expense as they are burning significantly more energy. Second, processing packets in software incurs large, and highly variable latency. This latency may range from tens of microsecond to milliseconds [22,33,39]. For many low latency applications (*e.g.*, stock trading), this inflated latency is unacceptable.

NetBricks: Taking the V out of NFV

Aurojit Panda† Sangjin Han† Keon Jang‡ Melvin Walls† Sylvia Ratnasamy† Scott Shenker†*
† UC Berkeley ‡ Google * ICSI

Abstract

The move from hardware middleboxes to software network functions, as advocated by NFV, has proven more challenging than expected. Developing new NFs remains a tedious process, requiring that developers repeatedly rediscover and reapply the same set of optimizations, while current techniques for providing isolation between NFs (using VMs or containers) incur high performance overheads. In this paper we describe NetBricks, a new NFV framework that tackles both these problems. For building NFs we take inspiration from modern data analytics frameworks (*e.g.*, Spark and Dryad) and build a small set of customizable network processing elements. We also embrace type checking and safe runtimes to provide isolation in software, rather than rely on hardware isolation. NetBricks provides the same memory isolation as containers and VMs, without incurring the same performance penalties. To improve I/O…

standard tools for managing VMs; (c) faster development, which now requires writing software that runs on commodity hardware; and (d) reduced costs by consolidating several NFs on a single machine. However, despite these promised advances, there has been little progress towards large-scale NF deployments. Our discussions with three major carriers revealed that they are only just beginning small scale test deployments (with 10-100s of customers) using simple NFs *e.g.*, firewalls and NATs.

The move from hardware middleboxes to software NFs was supposed to speed innovation, so why has progress been so slow? We believe this delay is because traditional approaches for both *building* and *running* NFs are a poor match for carrier networks, which have the following requirements: *performance*, NF deployments should be able to provide per-packet latencies on the order of 10s of μs, and throughput on the order of 10s of Gbps; *efficiency*, it should be possible to consolidate several NFs on a sin…

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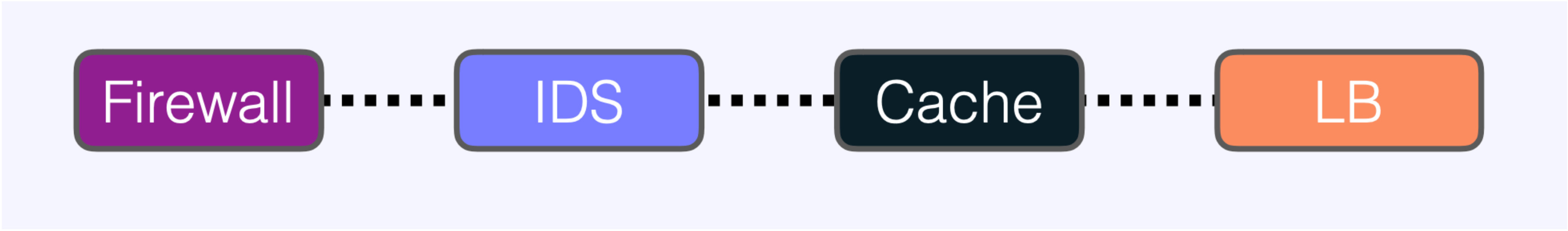
NetBricks: Taking the V out of NFV

OSDI'16

Slides borrowed from the OSDI talk

NFV Requirements

- **High Packet Rates:** Must keep up with line rate which is >10MPPS
- **Low Latency:** Used for applications like VoIP and video conferencing
- **Support NF Chaining:** Packets go through sequence of NFs



Challenges for NFV

- **Running NFs:**
  – Isolation and Performance

- **Building NFs:**
  – High-level Programming and Performance

Challenges for NFV

- Running NFs:
  - Isolation and Performance

- Building NFs:
  - High-level Programming and Performance

Isolation

- **Memory Isolation:**
  - Each NF's memory cannot be accessed by other NFs.
- **Packet Isolation:**
  - When chained, each NF processes packets in isolation.
- **Performance Isolation:**
  - One NF does not affect another's performance.

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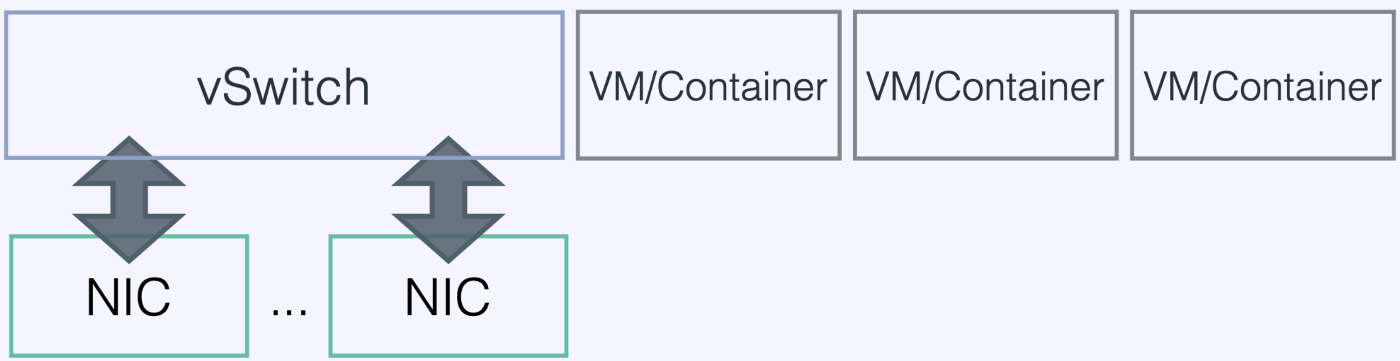
Current Solution

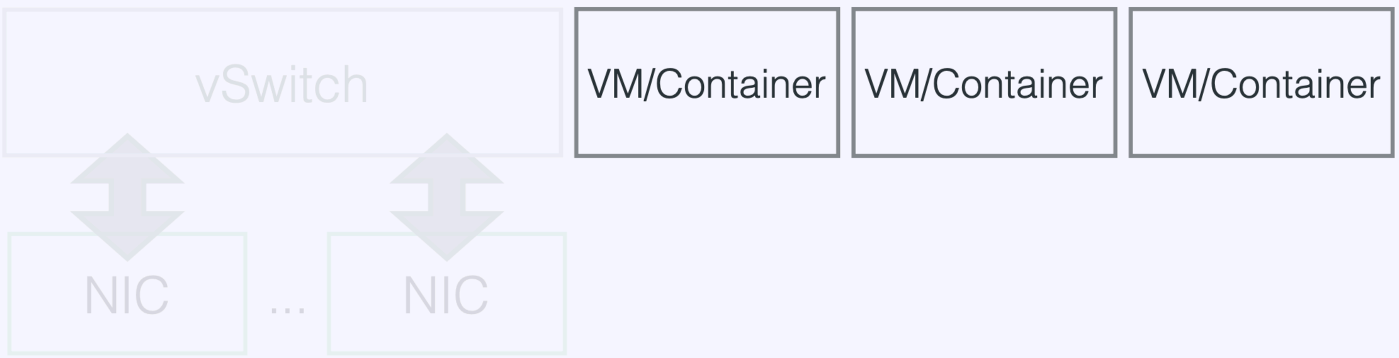


Memory Isolation

Packet Isolation

Performance

Current Solution

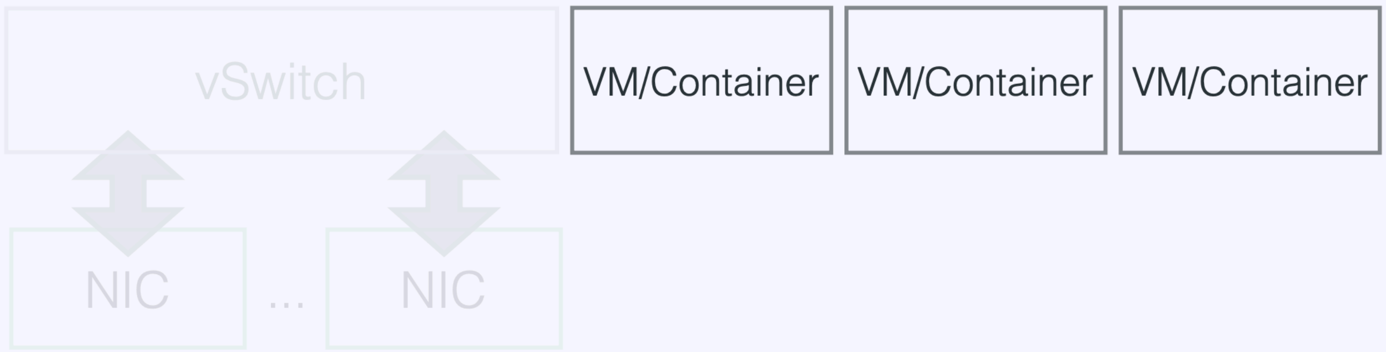


Memory Isolation

Packet Isolation

Performance

Current Solution



✔ Memory Isolation

Packet Isolation

Performance

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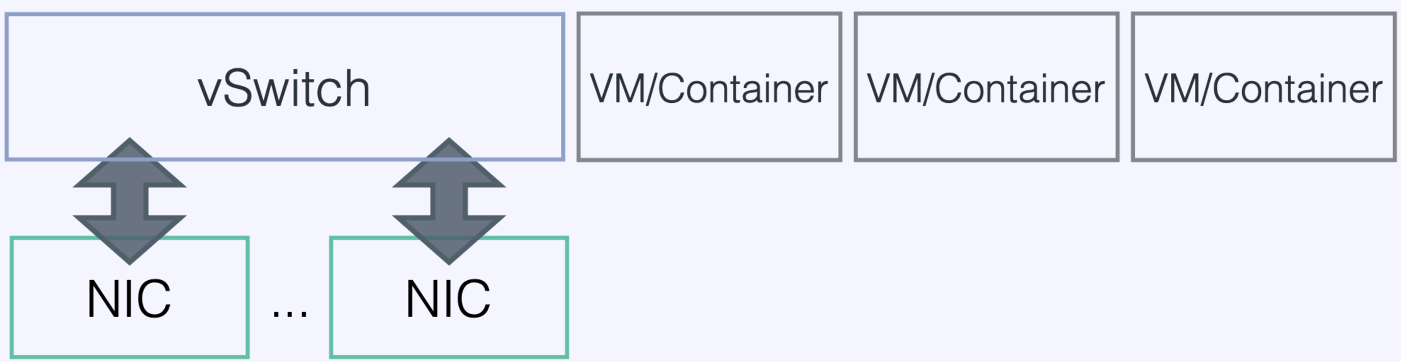

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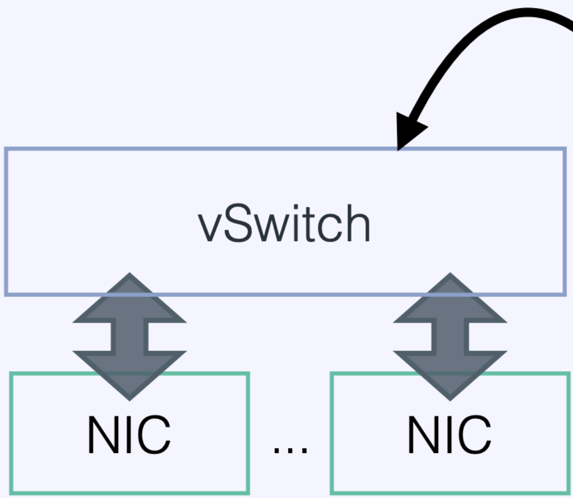

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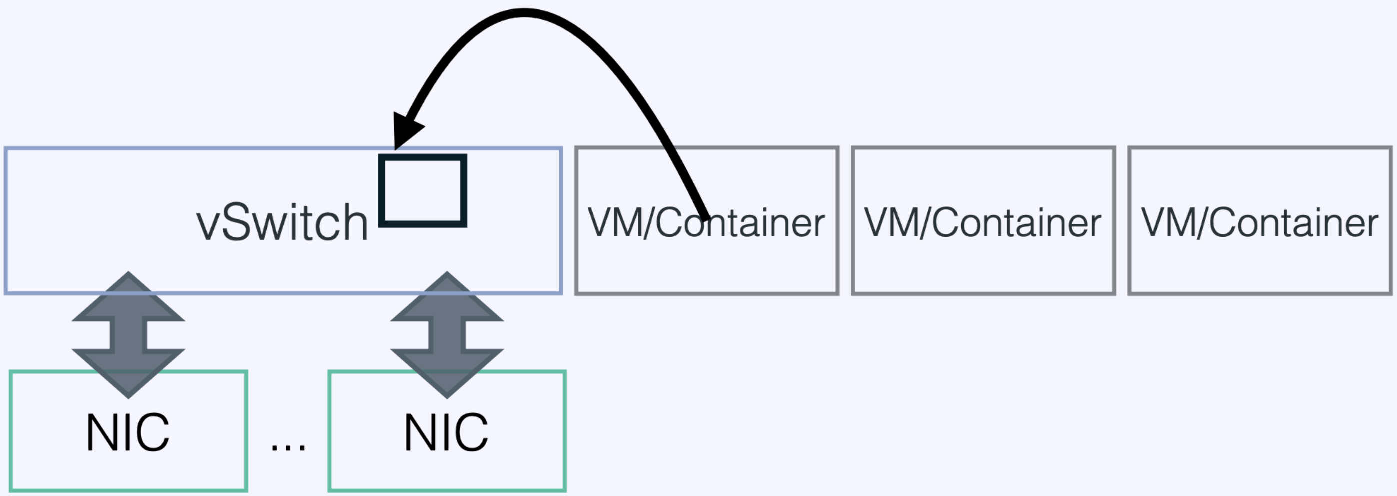

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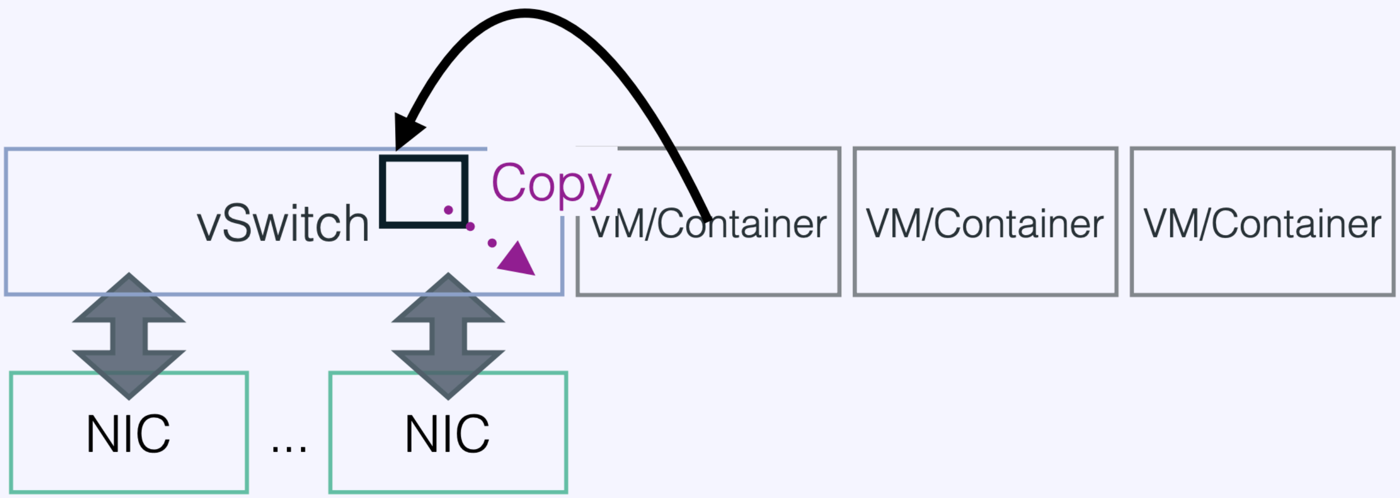

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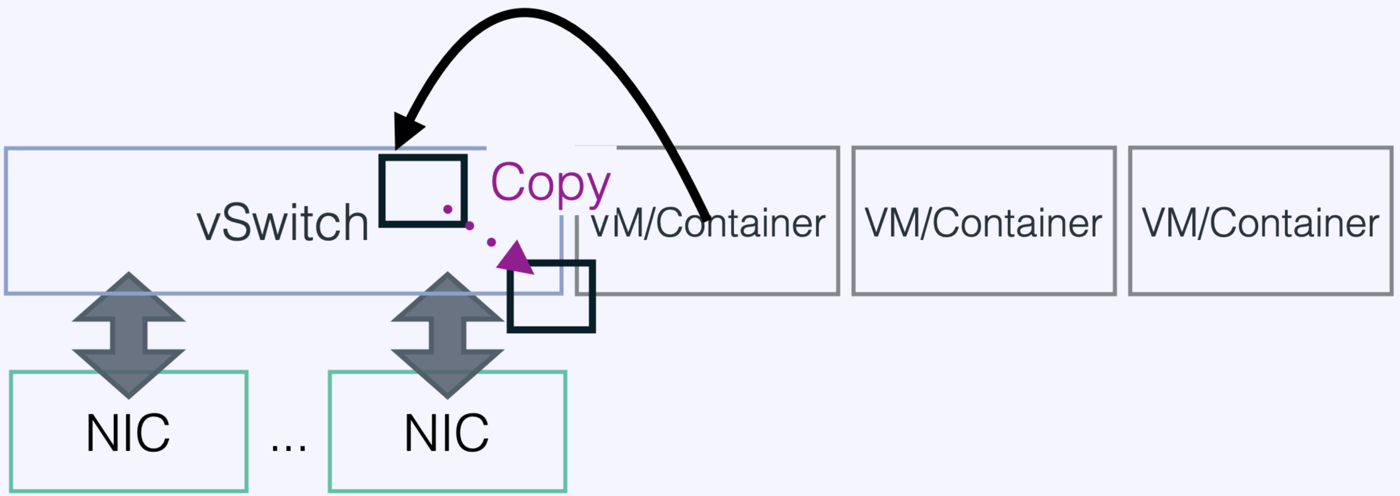

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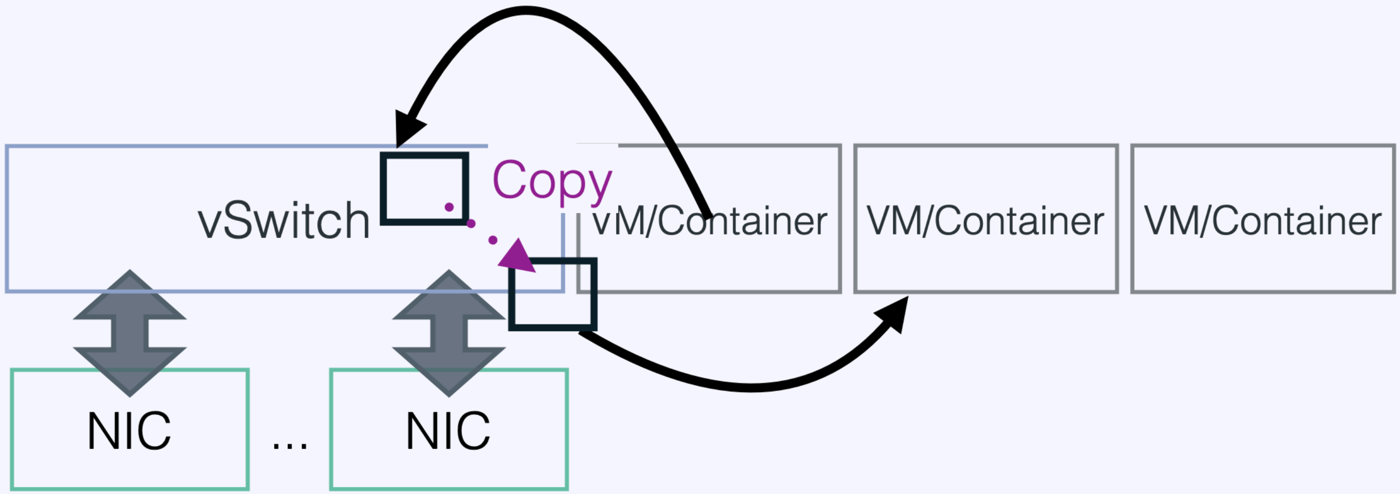

✔Memory Isolation

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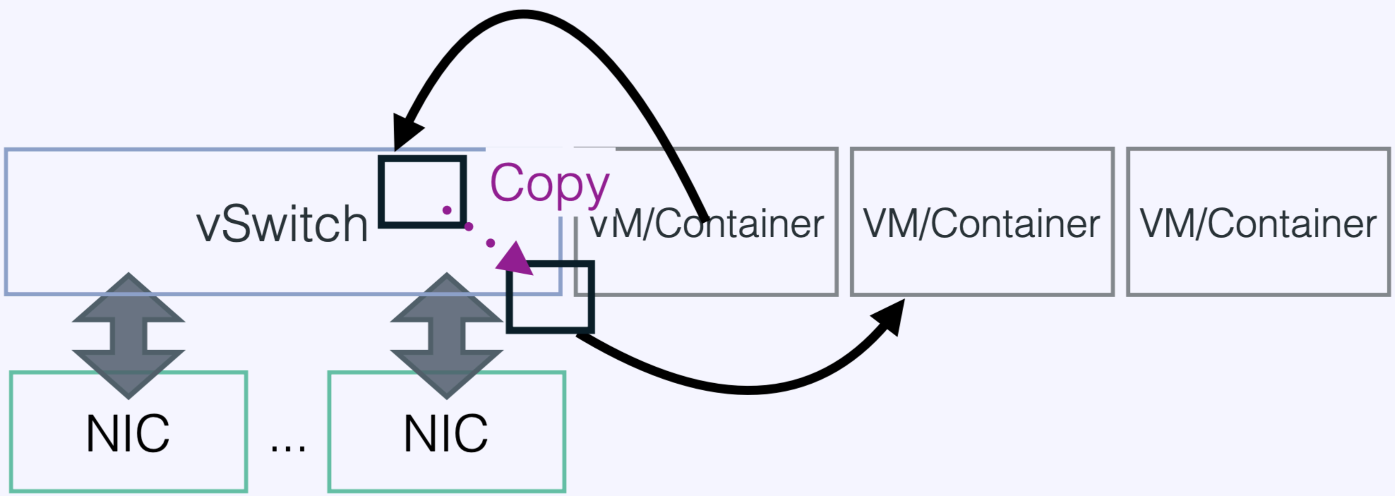
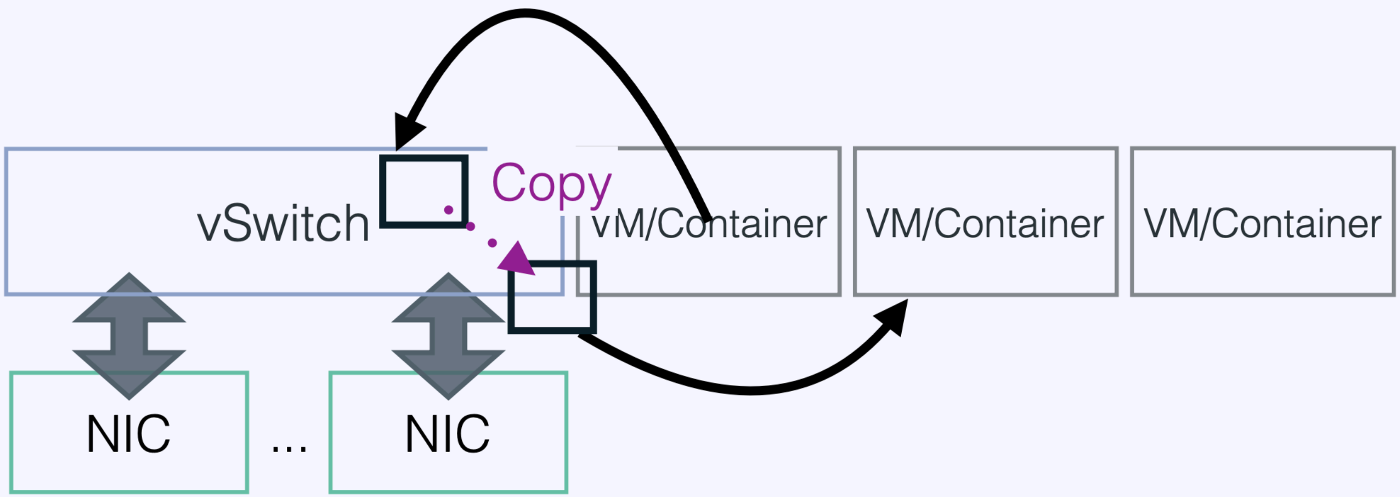


✔ Memory Isolation

✔ Packet Isolation

Performance

Current Solution

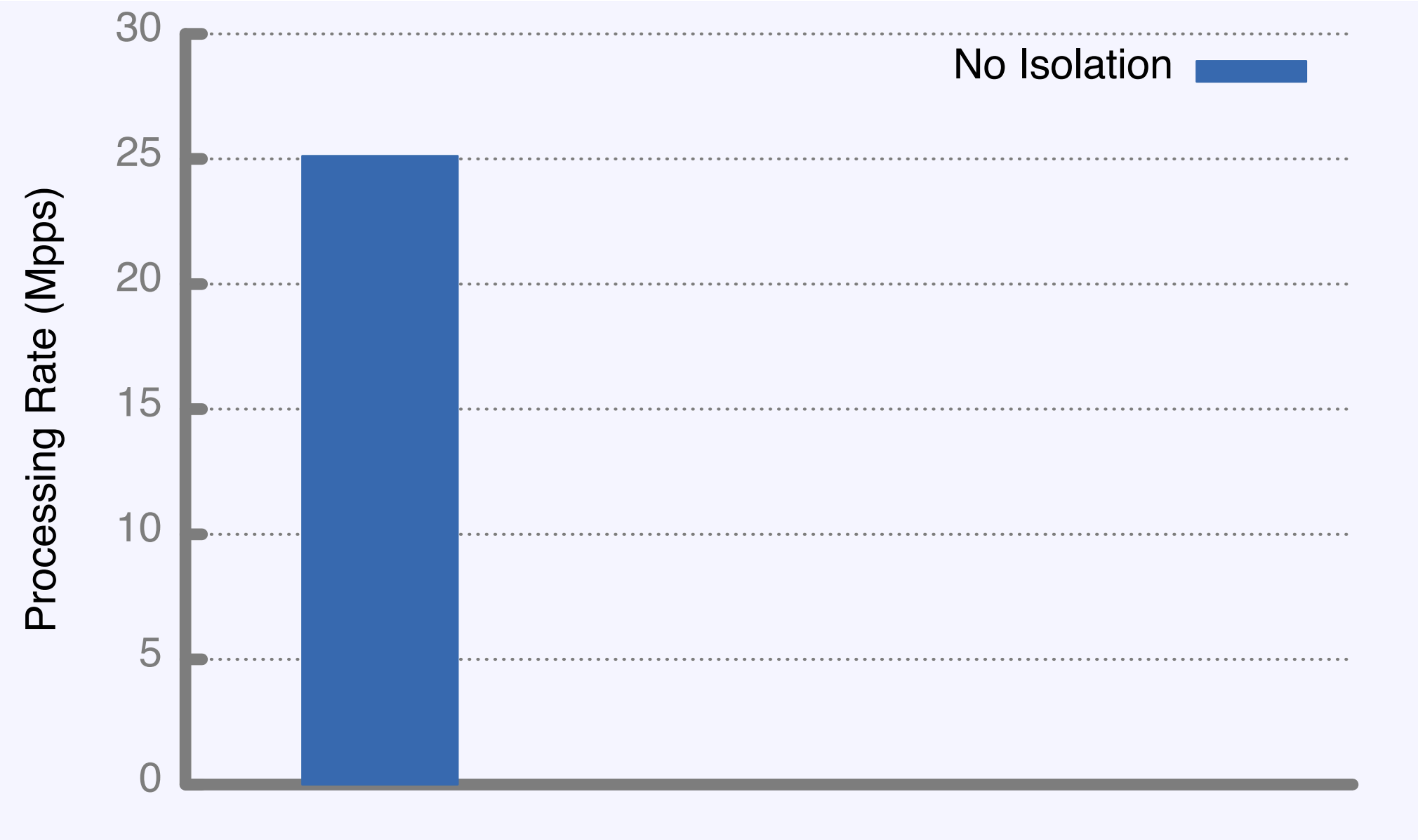


✔ Memory Isolation

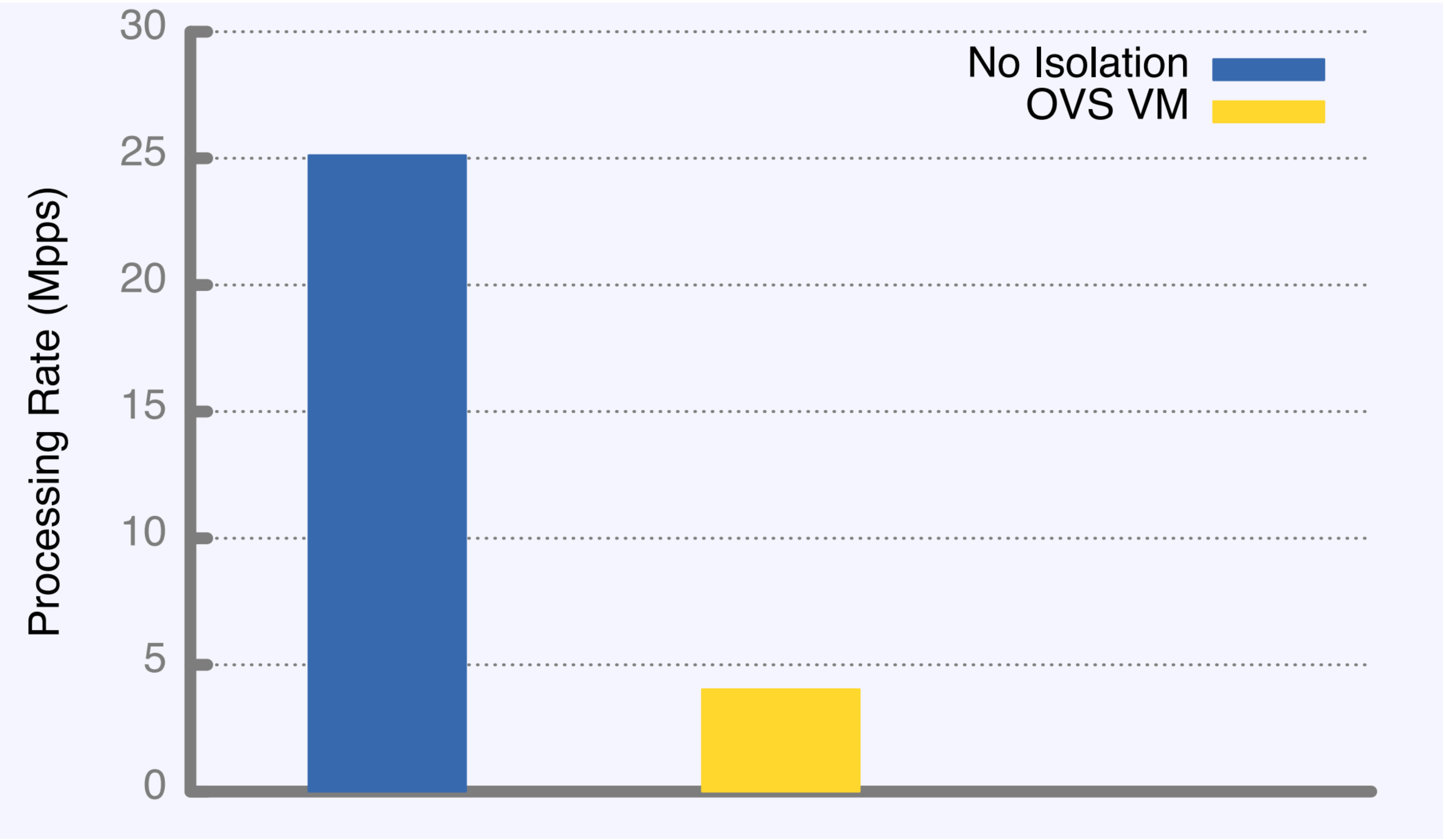
✔ Packet Isolation

✗ Performance

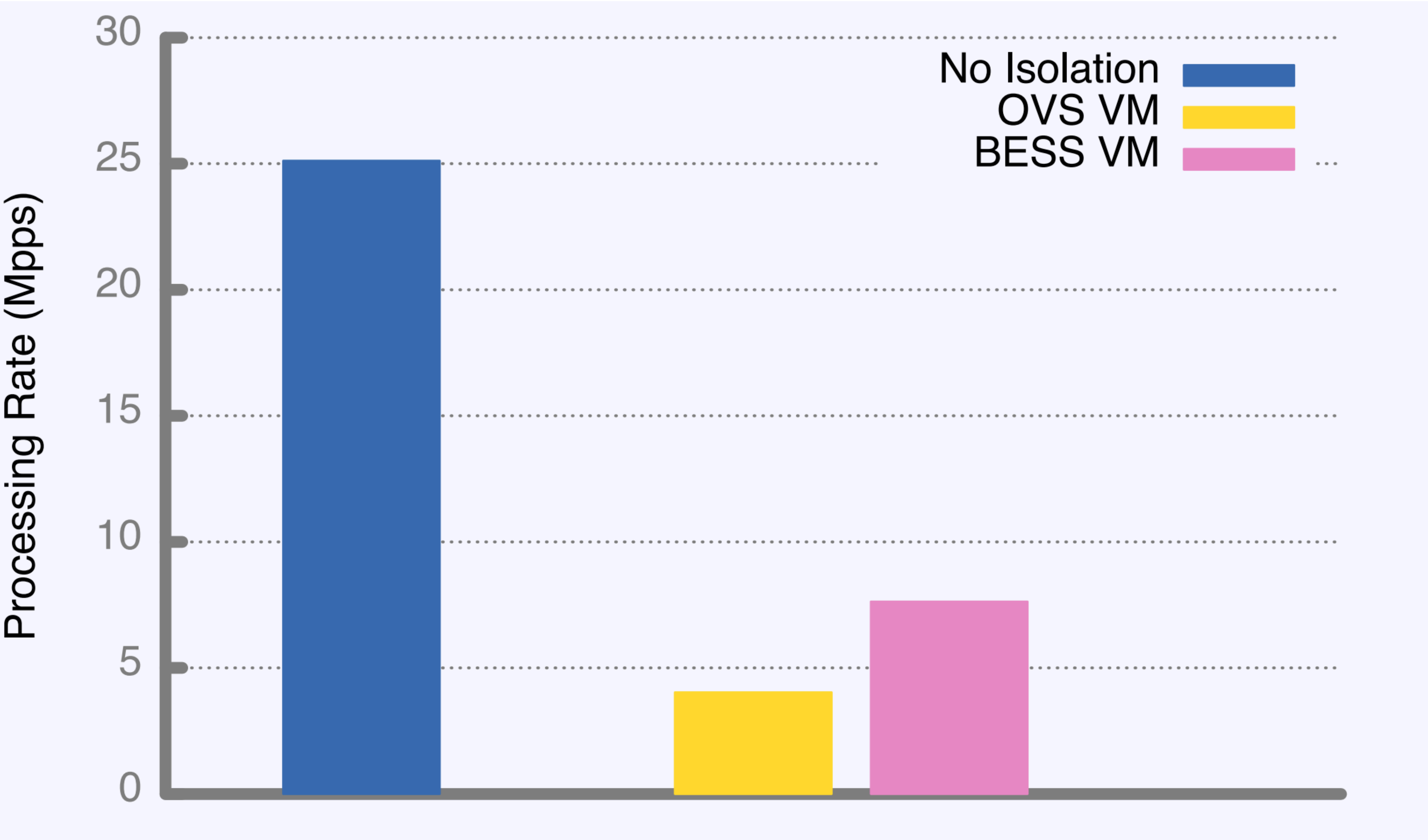
Isolation costs Performance



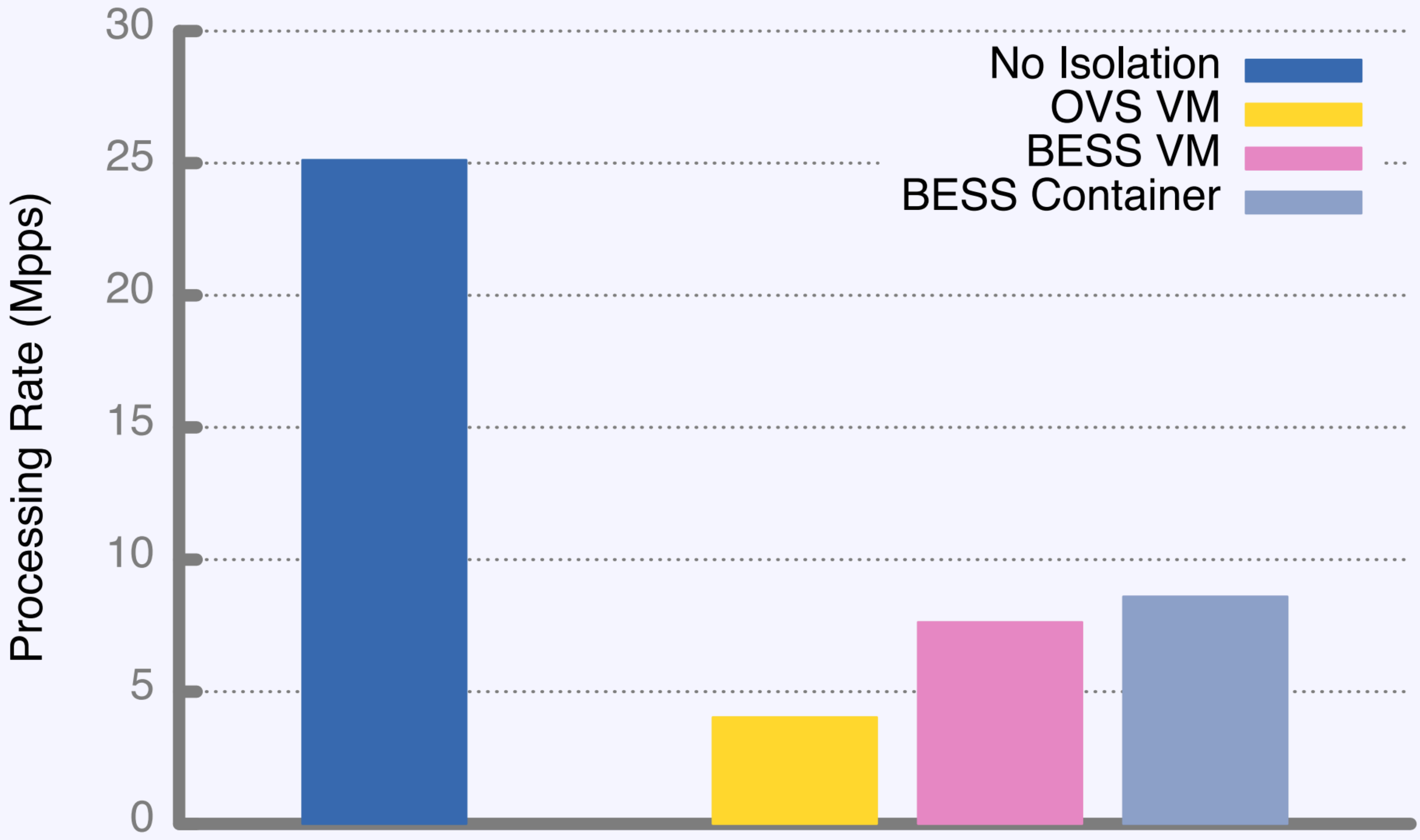
Isolation costs Performance



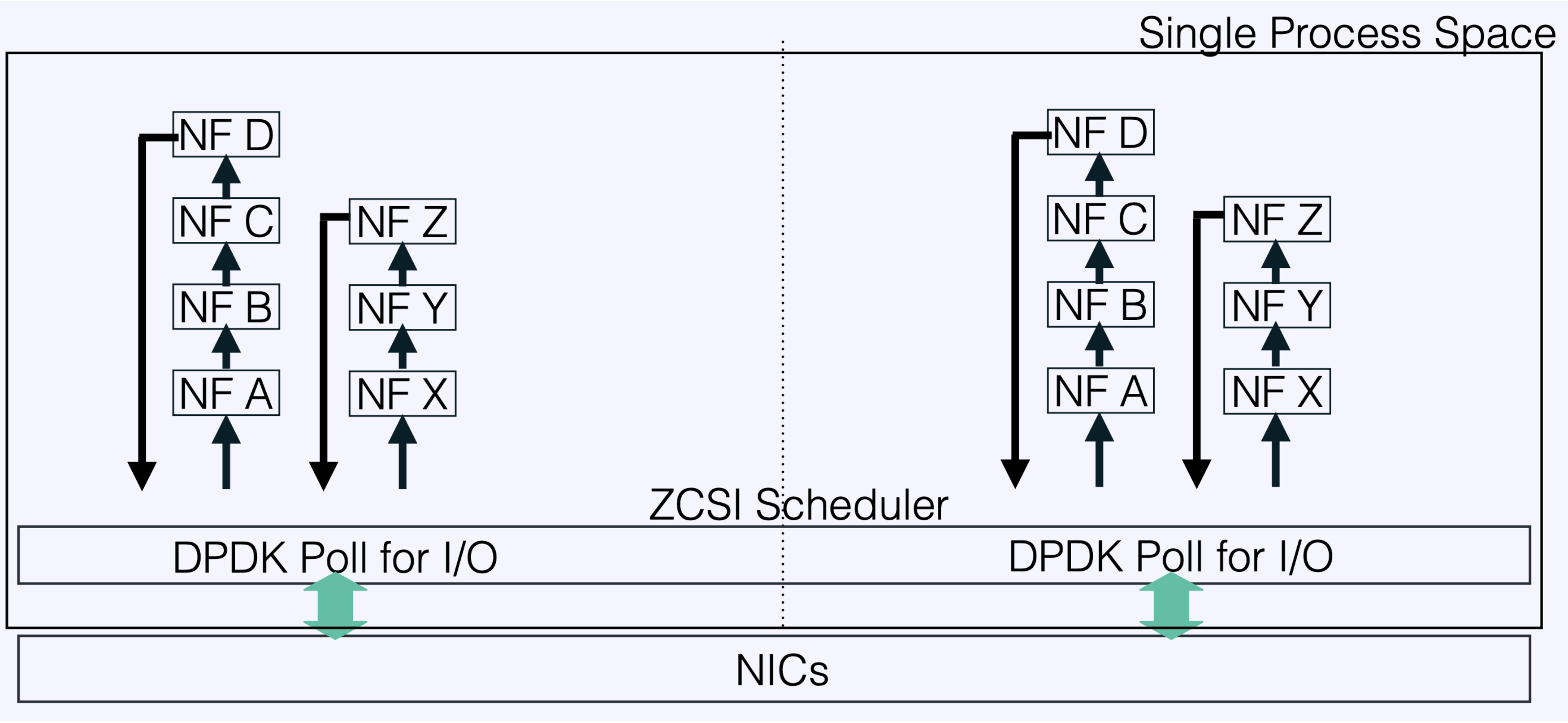
Isolation costs Performance



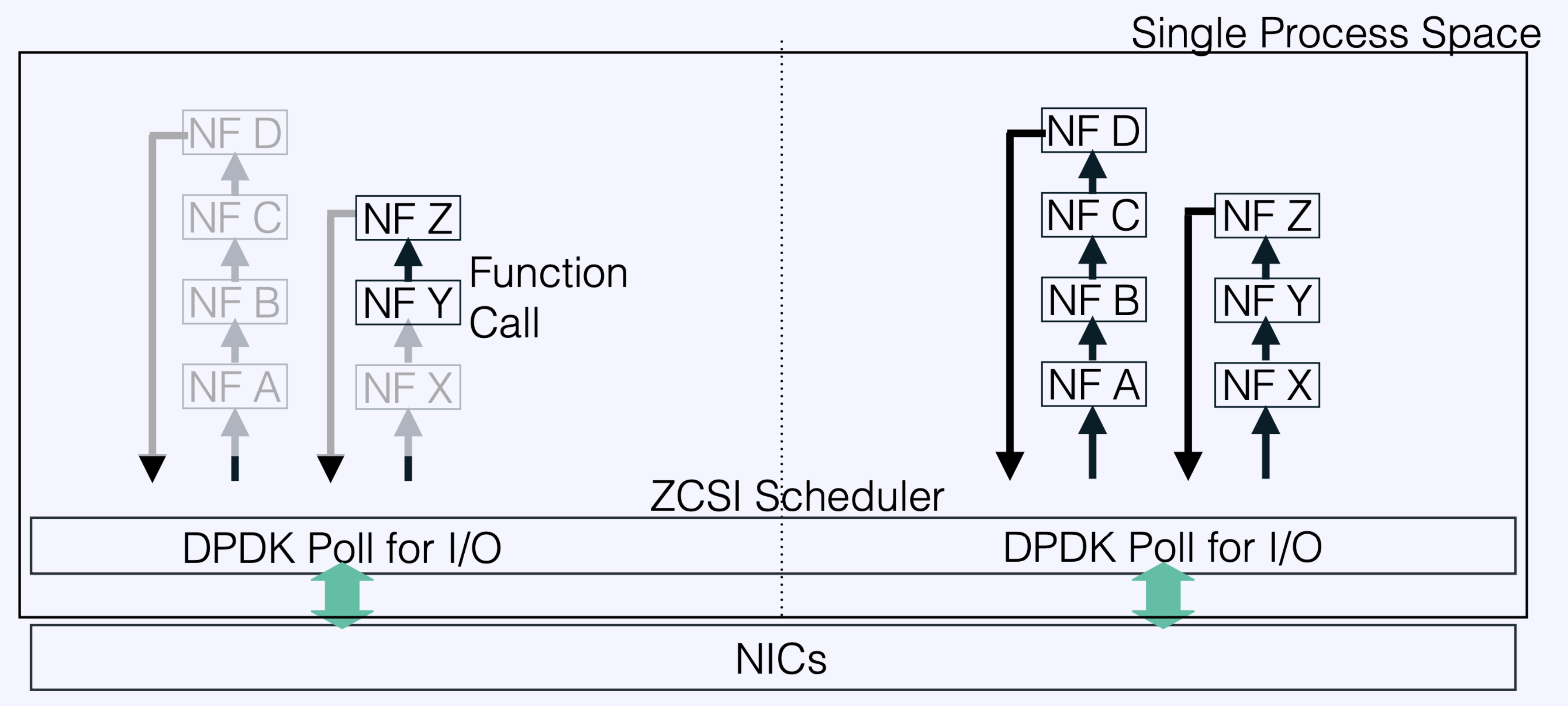
Isolation costs Performance



NetBricks Runtime Architecture



NetBricks Runtime Architecture



ZCSI: Zero Copy Soft Isolation

- VMs and containers impose cost on packets crossing isolation boundaries.
- Insight: Use type checking (compile time) and runtime checks for isolation.
- Isolation costs largely paid at compile time (small runtime costs).

NetBricks Approach

- Disallow pointer arithmetic in NF code: use safe subset of languages.
- Type checks + array bounds checking provide memory isolation.
- Build on unique types for packet isolation.
  - Unique types ensure references destroyed after certain calls.
  - Ensure only one NF has a reference to a packet.
  - Enables zero copy packet I/O.
- All of these features implemented on top of **Rust**.

Software Isolation

- Provides memory and packet isolation.
- Improved consolidation: multiple NFs can share a core.
  - Function call to NF (~ few cycles) vs context switch (~1 μs).
- Reduce memory and cache pressure.
  - Zero copy I/O => do not need to copy packets around.

Challenges for NFV

- Running NFs:
  - Isolation and Performance
- Building NFs:
  - High-level Programming and Performance

How to write NFs?

- **Current:** NF writers concerned about meeting performance targets
  - Low level abstractions (I/O, cache aware data structures) and low level code.
- Spend lots of time optimizing how abstractions are used to get performance.
- **Observation:** NFs exhibit common patterns: abstract and optimize these.
- Analogous to what happened in other areas.
  - MPI to Map Reduce, etc.

Abstractions

Packet Processing
- Parse/Deparse
- Transform
- Filter

Control Flow
- Group By
- Shuffle
- Merge

Byte Stream
- Window
- Packetize

State
- Bounded Consistency

Behavior of these abstractions dictated by user-defined functions (UDFs)

Example NF

- Maglev: Load balancer from Google (NSDI'16).
- NetBricks implementation: 105 lines, 2 hours of time.
- Comparable performance to optimized code

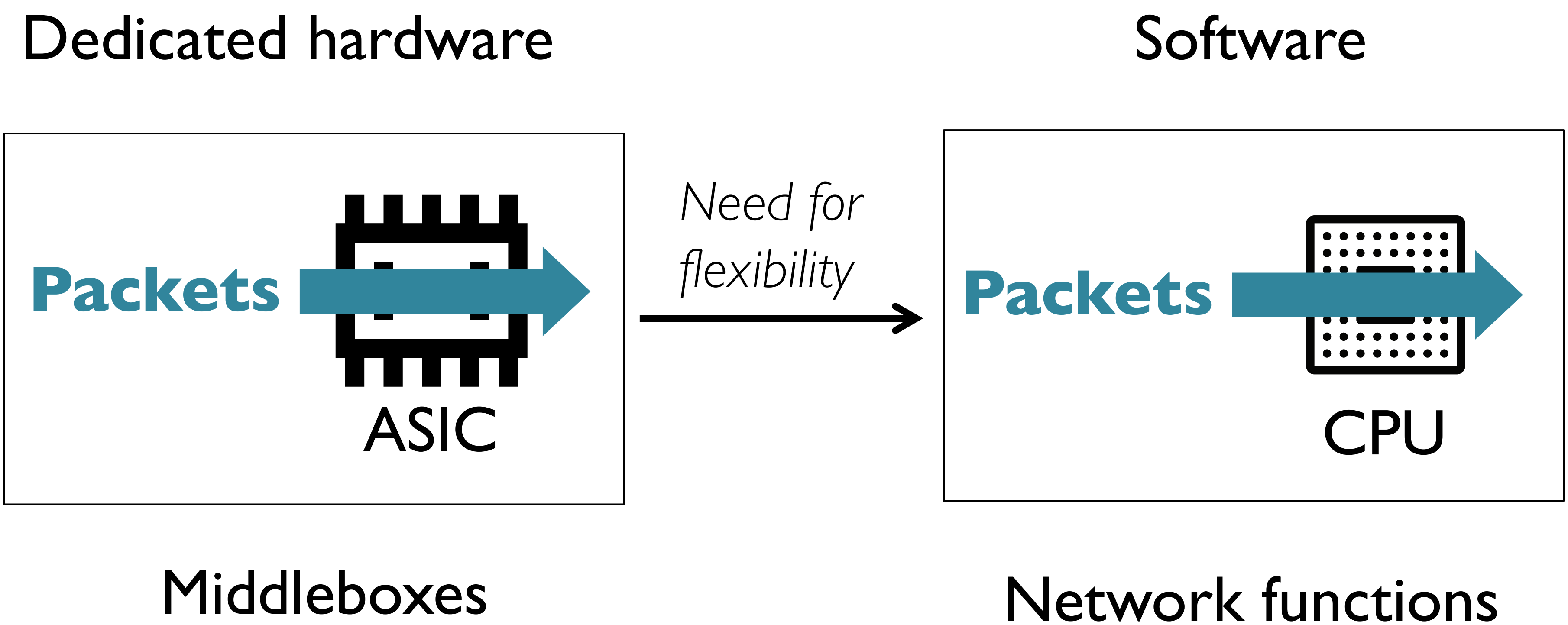
Conclusion

- Software isolation is necessary for high performance NFV.
  - Type checking + bound checking + unique types.
- Performance is not anathema to high-level programming
  - Abstract operators + UDF simplify development.

Your thoughts?

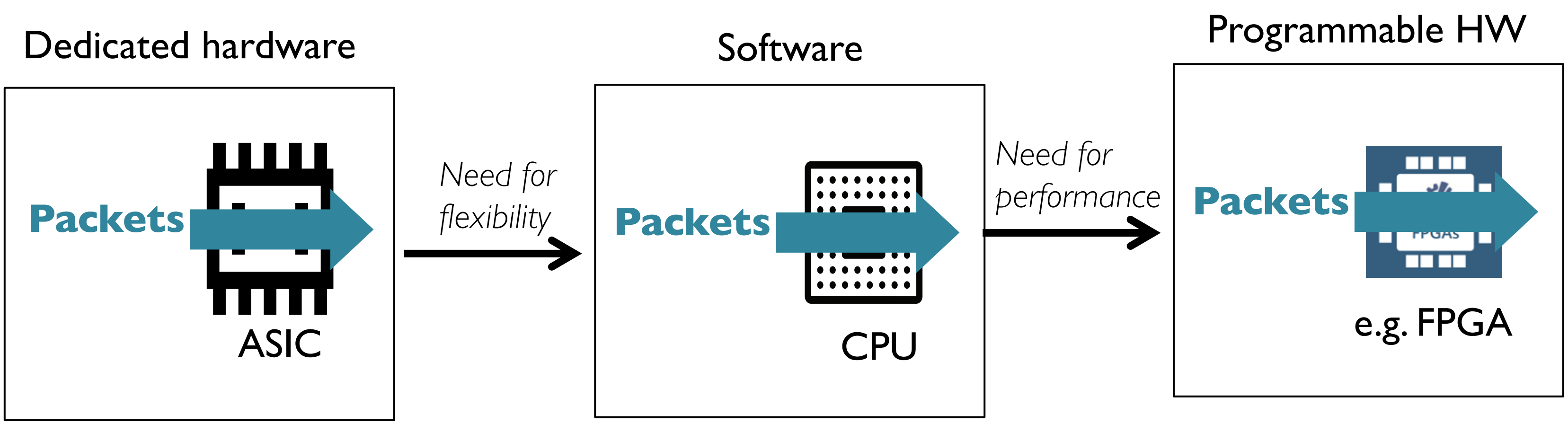
- What did you like about the paper?
- What are its limitations?

Evolution of middleboxes



**contents of the slide borrowed from talks given by Aurojit Panda, NYU*

Evolution of middleboxes

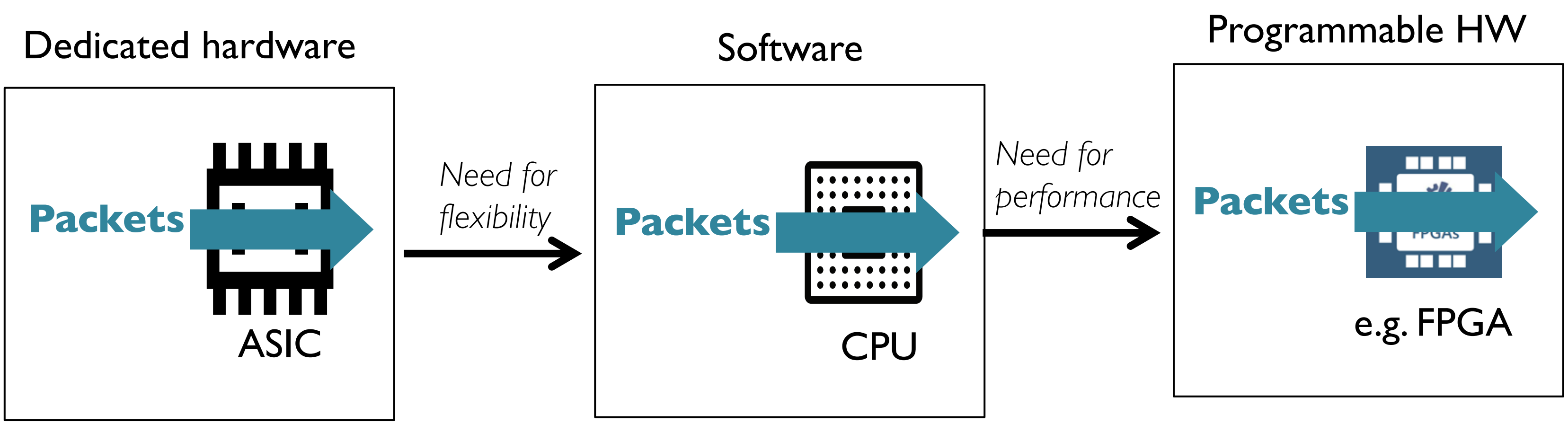


Middleboxes

Network functions

ClickNP, SIGCOMM'16
FlowBlaze, NSDI'19
TEA, SIGCOMM'20

Evolution of middleboxes



Middleboxes

Network functions

ClickNP, SIGCOMM'16
FlowBlaze, NSDI'19
TEA, SIGCOMM'20

Upcoming classes

- No class on Nov 16th.
  - Optional reading on network edge.
  - 5G systems microbook is a useful resource (linked on the webpage).
- Nov 18 and Nov 30: your presentations (each up to 6mins long).
- Fiday, Dec 2nd:
  - Wrapping up
  - Quiz for *<u>bonus</u>* class participation scores.
- Monday, Dec 5th: Final projects due (will update on course website).
- Dec 7th: Final project presentation. Details TBA.