adopting software-defined networking: challenges and recent developments

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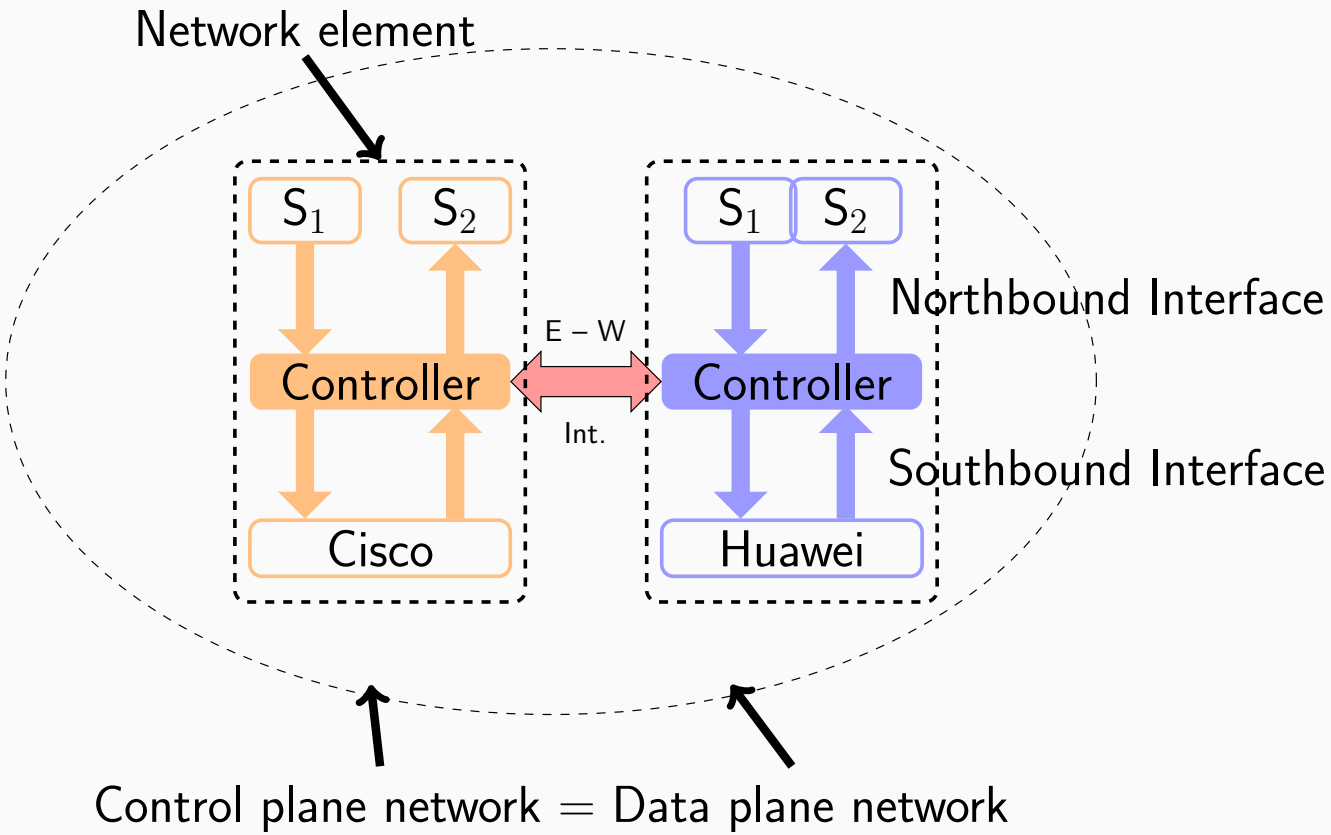
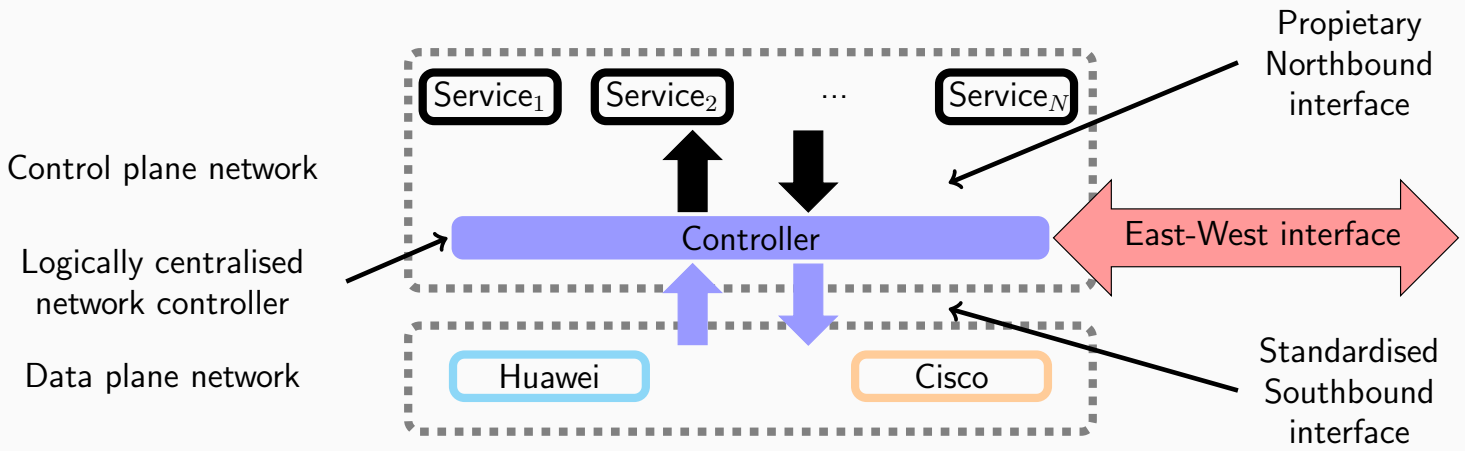
Traditional service interoperation



How should we introduce new services?

Answer: standardization with per service resolution

Traditional service interoperation

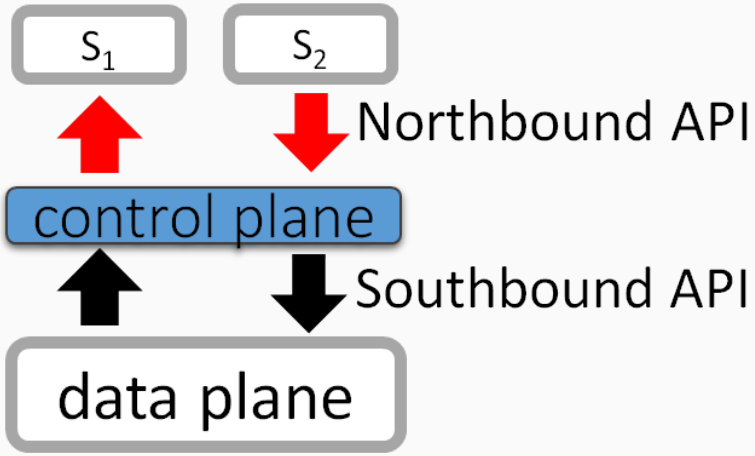


Standardization of southbound API makes possible to manage network elements from heterogeneous vendors.

Logically centralized management can be implemented in distributed manner (some experience from structured p2p networks).

New players, new relations, new abstractions.

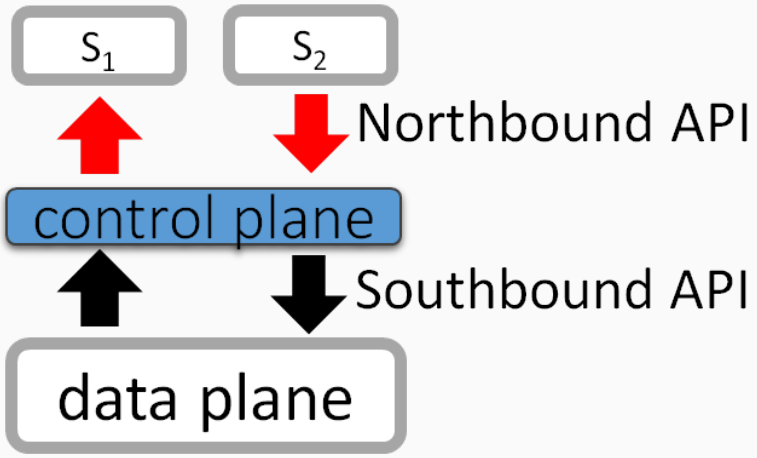
Two questions



What should be flexible to represent desired behaviors in computer networks?

How to represent efficiently these behaviors on control and data planes?

outline



Data plane:

single packet processing (SIGCOMM'14, HOTI'14, ICNP'16-17);

packet stream processing (INFOCOM'15-17, ANCS'16, ICNP'17);

Control plane:

network virtualization (INFOCOM'17).

single packet processing

packet classification

A classifier $\mathcal{K}$ is a prioritized set of rules, where each rule is a pair of a ternary bit string (filter) and an action.

$\mathcal{K}$	#1	#2	#3	#4	*Action*
R_1	0	1	0	0	A_1
R_2	0	$*$	$*$	$*$	A_2
R_3	1	0	1	$*$	A_3
R_4	1	$*$	0	$*$	A_4

A lookup is a process of finding the highest priority rule matched by a given header.

There are two main uses for packet classification:

Traffic forwarding between certain points in a communication network.

Service policies that guarantee desired traffic properties.

Both can be represented as a tuple-match with actions (OpenFlow, P4) but have different invariants.

SW-based vs. TCAM-based solutions

SW-based

$N = 4$ filters, $K = 2$ fields

~~prefixes~~ ~~ranges~~

$$
\begin{array}{lcccc}
R_1 & = & (& \texttt{100*}, & \texttt{001*} &) \\
R_2 & = & (& \texttt{1010}, & \texttt{0001} &) \\
R_3 & = & (& \texttt{000*}, & \texttt{****} &) \\
R_4 & = & (& \texttt{001*}, & \texttt{****} &)
\end{array}
$$

Memory	Lookup time
$O(N)$	$O(log^{k-1}N)$
$O(N^k)$	$O(logN)$

TCAM-based

$N = 3$ filters, $K = 3$ fields

prefixes ~~ranges~~

$$
\begin{aligned}
R_1 &= ([1,3],[4,31],[1,28]) \\
R_2 &= ([4,4],[2,30],[4,27]) \\
R_3 &= ([7,9],[5,21],[3,18])
\end{aligned}
$$

Binary Encoding	SRGE
42+28+50=120	24+8+32=64

Filter-order independence

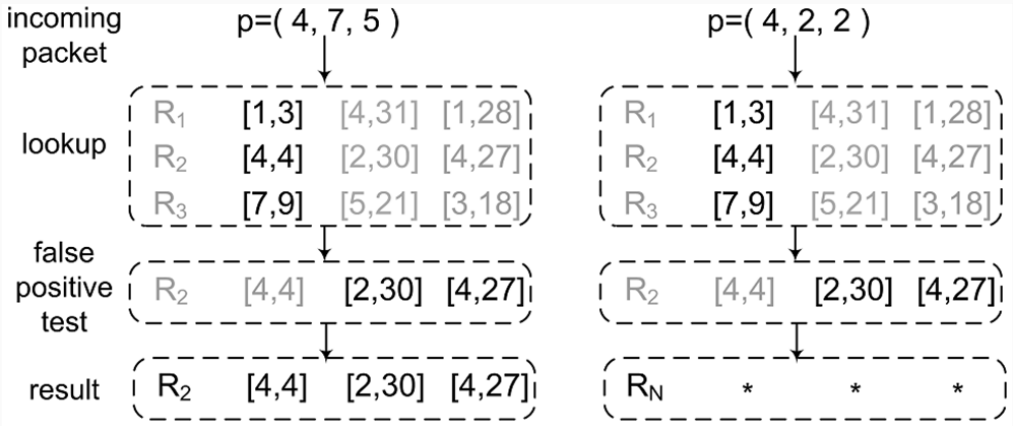
Adding new fields keep order-independence

At most one rule is matched and it can be false-positive.

We can reduce space by skipping new fields

Problem (FSM)

Find a minimal subset of fields that keeps order-independence of a given filter-order independent classifier.



Fields	Binary Encoding	Gray Encoding
{1,2,3}	42+28+50=120	24+8+32=64
{1,2}	6+7+10=23	6+4+8=18
{1}	2+1+2=5	2+1+2=5

$$\begin{array}{lccc} & S_1 & S_2 & S_3 \\ R_1 & = ([1,3], & [4,31], & [1,28]) \\ R_2 & = ([4,4], & [2,30], & [4,27]) \\ R_3 & = ([7,9], & [5,21], & [28,31]) \end{array}$$

$$U = \{(i,j) | i < j, i,j \in [1,N]\} = \{(1,2),(1,3),(2,3)\}$$

$$S_1 = \{(1,2),(1,3),(2,3)\}\ S_2 = \emptyset\ S_3 = \{(2,3)\}$$

FSM is reducible to SetCover in $O(kN^2)$ with approximation factor $2 \ln N + 1$

Classifiers as Boolean Expressions

Classifiers can also be viewed as Boolean expressions.

For example,

$$\begin{aligned} R_1 &= (\ \texttt{100*},\ \texttt{001*}\ ) \\ R_2 &= (\ \texttt{1010},\ \texttt{0001}\ ) \\ R_3 &= (\ \texttt{000*},\ \texttt{****}\ ) \\ R_4 &= (\ \texttt{001*},\ \texttt{****}\ ) \end{aligned}$$

is equivalent to

$$\begin{aligned} f(x_1, \ldots, x_8) = &(x_1 \wedge \bar{x}_2 \wedge \bar{x}_3 \wedge \bar{x}_5 \wedge \bar{x}_6 \wedge x_7) \\ &\vee (x_1 \wedge \bar{x}_2 \wedge x_3 \wedge \bar{x}_4 \wedge \bar{x}_5 \wedge \bar{x}_6 \wedge \bar{x}_7 \wedge x_8) \\ &\vee (\bar{x}_1 \wedge \bar{x}_2 \wedge \bar{x}_3) \\ &\vee (\bar{x}_1 \wedge \bar{x}_2 \wedge x_3). \end{aligned}$$

Classifiers as Boolean Expressions

Classifiers can also be viewed as Boolean expressions.

Hence the MinDNF problem arises.

Problem (MinDNF)

For a given Boolean function, find its minimal size DNF representation.

MinDNF vs. FSM

MinDNF by itself is not as powerful as FSM.

In this example:

$$
\begin{array}{rcl}
R_1 & = & (\ \texttt{100*},\ \texttt{001*}\ ) \\
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R_3 & = & (\ \texttt{000*},\ \texttt{****}\ ) \\
R_4 & = & (\ \texttt{001*},\ \texttt{****}\ )
\end{array}
$$

MinDNF yields

$$
\begin{array}{rcl}
R_1 & = & (\ \texttt{100*},\ \texttt{001*}\ ) \\
R_2 & = & (\ \texttt{1010},\ \texttt{0001}\ ) \\
R_{3,4} & = & (\ \texttt{00**},\ \texttt{****}\ )
\end{array}
$$

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\end{aligned}
$$

FSM with per-bit resolution:

$$
\begin{aligned}
R_1^{-6} &= (\ \texttt{10}\ ) \\
R_2^{-6} &= (\ \texttt{11}\ ) \\
R_3^{-6} &= (\ \texttt{00}\ ) \\
R_4^{-6} &= (\ \texttt{01}\ )
\end{aligned}
$$

Irreducible or Rule-order dependent classifiers

A classifier is rule-order dependent or irreducible:

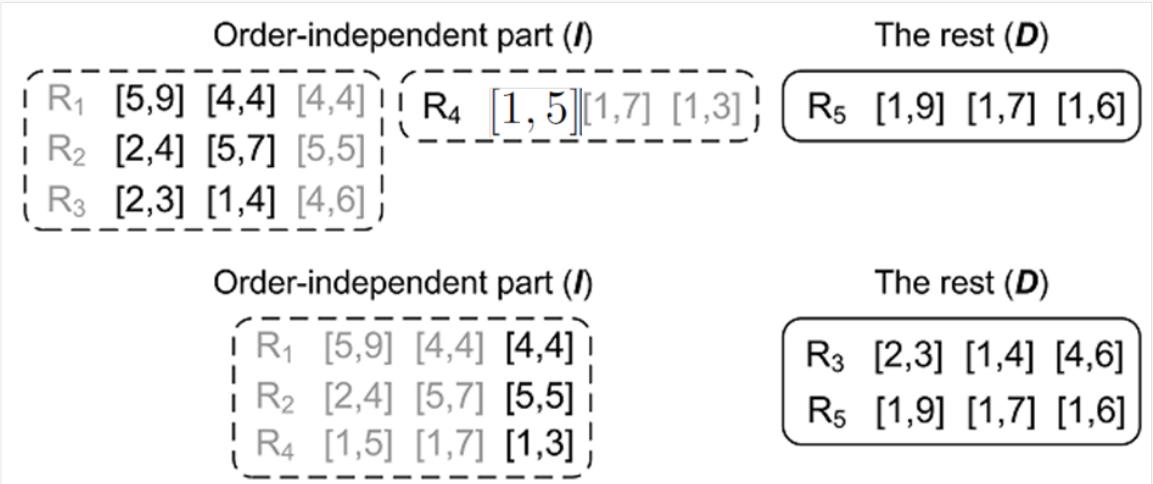
assign a subset of rules;

use the level of pseudo-parallelism β.

Problem

Find an assignment of rules to at most β disjoint groups that keeps order-independence on l fields, minimizing the size of uncovered rules.

$$
\begin{aligned}
R_1 &= ([5,9],[4,4],[4,4]) \\
R_2 &= ([2,4],[5,7],[5,5]) \\
R_3 &= ([2,3],[1,4],[4,6]) \\
R_4 &= ([1,5],[1,7],[1,3]) \\
R_5 &= ([1,9],[1,7],[1,6])
\end{aligned}
$$



Short summary

Semantically equivalent representations on all fields: more fields imply less efficient representation.

Representation with false-positive check: more fields more efficient representation.

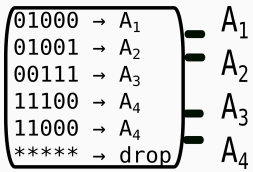
Structural properties can significantly improve time-space trade-off.

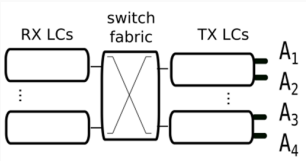
No restrictions on representation of every group (we define only additional abstraction layer).

Additional applications: operation with broken communication channels, optimizations in PLs, lookups in databases.

Impact of scalability and expressiveness

Forwarding tables (FIBs) map addresses to ports in every switch.





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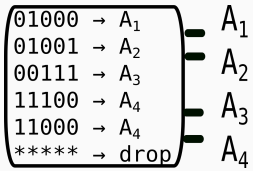
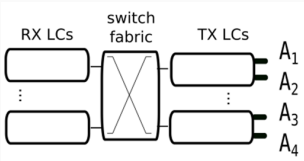
$\left|route(x,y)\right| \leq stretch * dist(x,y)$ to minimize max local table size





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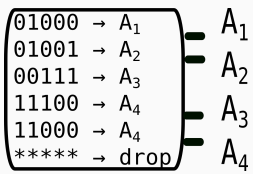
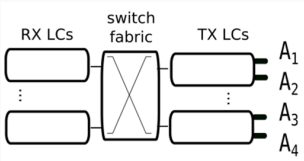


more expressiveness in clean slate solutions - wider tables (IP→ IPv6→ OpenFlow)



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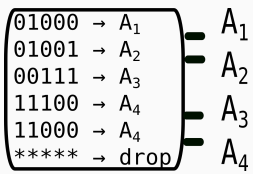

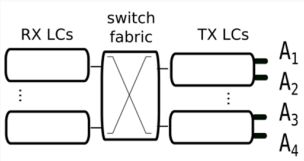

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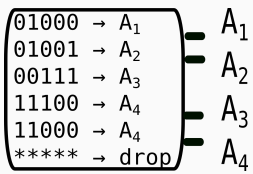

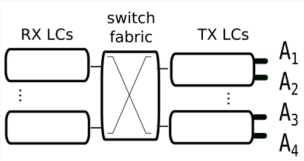

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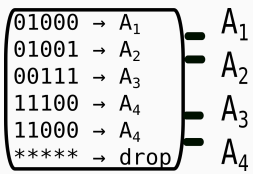

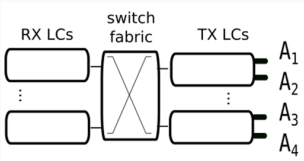

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To address memory vs. performance tradeoff, find abstractions:

- independent from clean slate solutions
- specific platform representations

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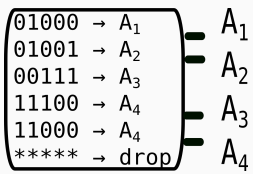

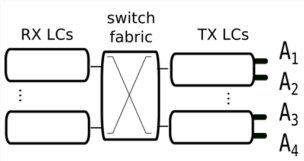

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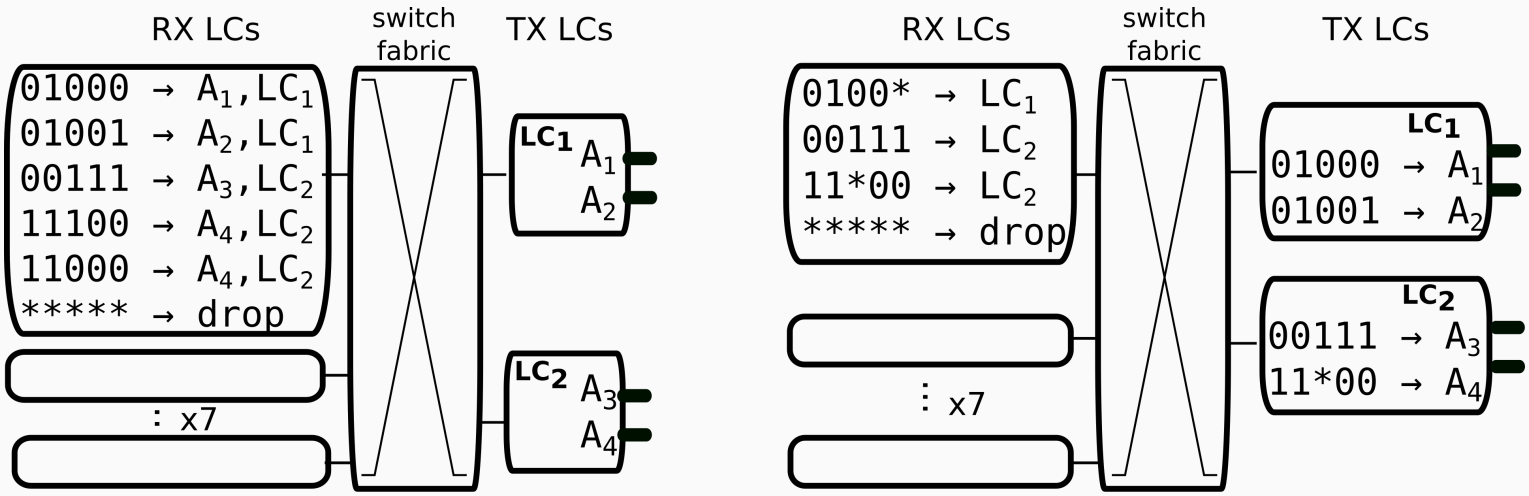
Impact of distributed platforms?

Current FIB implementations in distributed platforms



(*a*) One-stage forwarding

(*b*) Two-stage forwarding

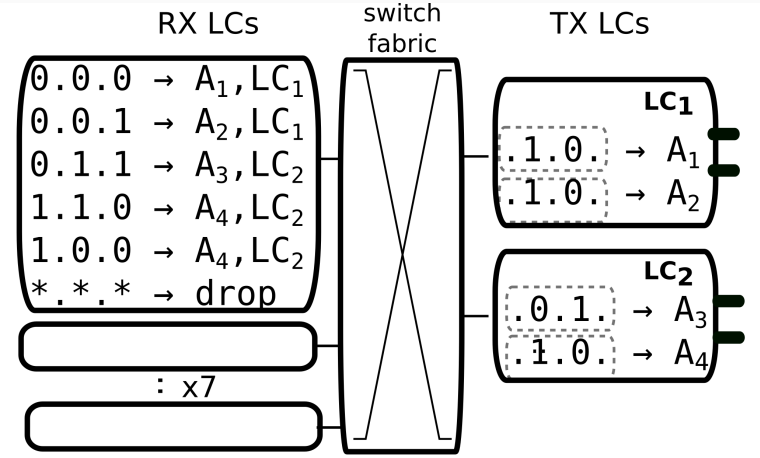
Two classifiers are *equivalent* if both have the same result on any lookup key.

- All address bit identities participate in RX classification
- Both schemes are equivalent on the system level

Can we do it better? Yes, balancing bits beetween RX and TX is required

Filter-order independence

Intuition: if the filters of a classifier do not intersect, their order is not important.



(a) One-stage with RX filter-order independence and false-positive check on TX.

Action-order independence

Idea: a classification result is the *action* of the rule with the highest priority. Two rules with filters F_1^B and F_2^B are *action-order-independent* if either (a) they have the same action or (b) F_1^B and F_2^B are disjoint.

Example

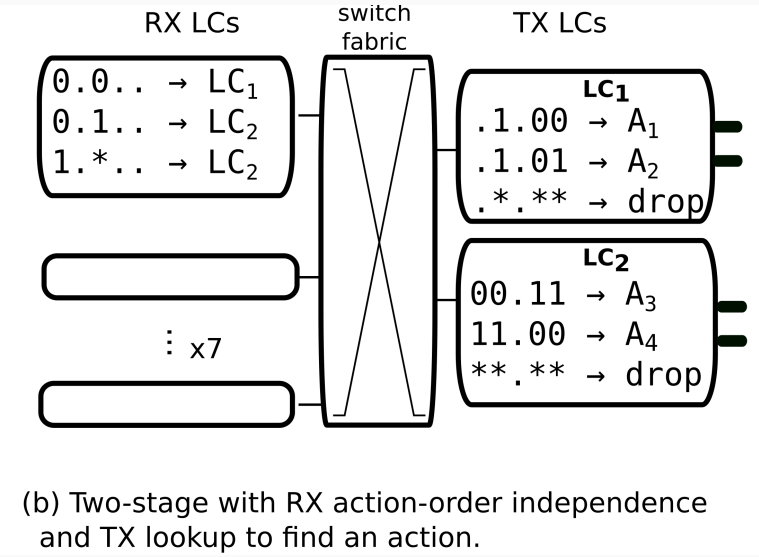
#1	#2	#3	#4	
(0	1	0	0)	$\rightarrow A_1$
(0	1	1	1)	$\rightarrow A_2$
(1	1	1	0)	$\rightarrow A_2$

two bits are required for filter-oi.

#1	#3	
(0	0)	$\rightarrow A_1$
(0	1)	$\rightarrow A_2$
(1	1)	$\rightarrow A_2$

only one bit for action-oi.

#3	
(0)	$\rightarrow A_1$
(1)	$\rightarrow A_2$



(b) Two-stage with RX action-order independence and TX lookup to find an action.

Non-comflicting rules

Definition

Two rules R_1^X and R_2^X with different actions, $R_1^X \prec R_2^X$, are *conflicting* with respect to bit indices $B \subset X$ if there is a header H^X matching R_2^X that is not matched by R_1^X and R_1^B matches H^B.

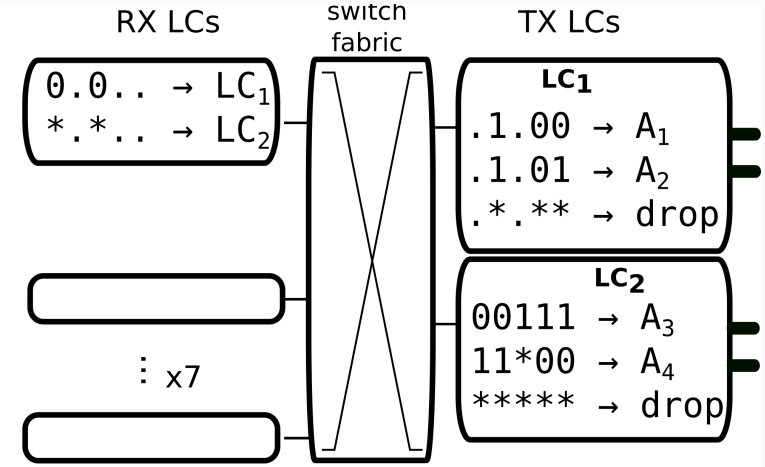
Example

In the following classifier with $|X| = 3$

$$\begin{array}{cccc} & \#1 & \#2 & \#3 & \\ R_1^X & (* & 1 & 0) & \rightarrow A_1 \\ R_2^X & (1 & 1 & *) & \rightarrow A_2 \end{array}$$

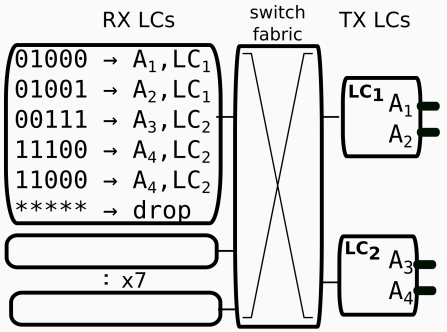
R_1^X and R_2^X are conflicting with respect to $B = \{1, 2\}$ (R_1^B matches $H^B = (1\ 1)$ but R_1^X does not match $H^X = (1\ 1\ 1)$ when R_1^B matches H^B and it matches R_2^X); for $B = \{2, 3\}$, R_1^X and R_2^X are not conflicting with respect to B.

$$\begin{array}{cccc} & \#2 & \#3 & \\ R_1^B & (1 & 0) & \rightarrow A_1 \\ R_2^B & (1 & *) & \rightarrow A_2 \end{array}$$



(c) Two-stage with RX non-conflicting rules and TX lookup to find an action.

Equivalent representations



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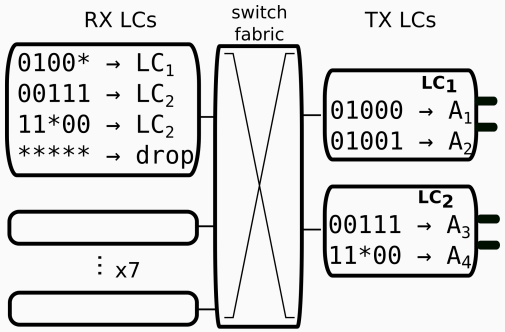

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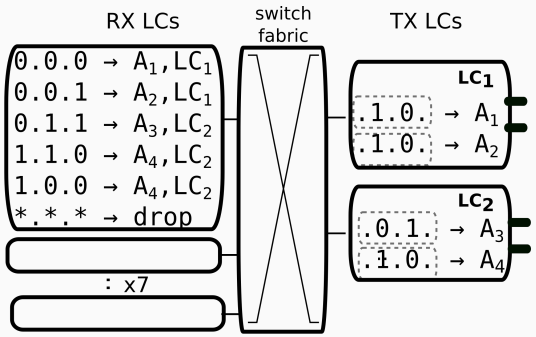

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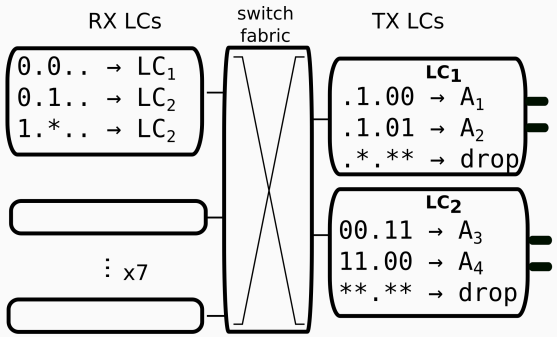

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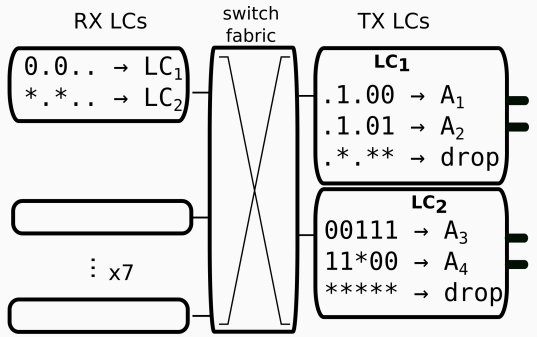

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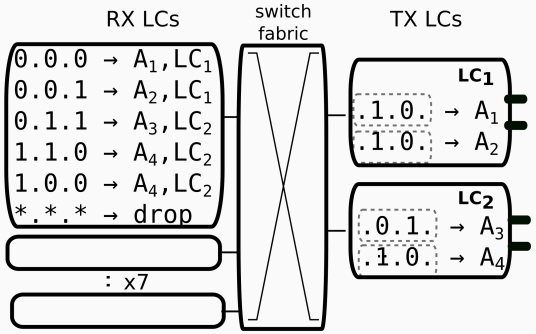
Equivalent vs. non-equivalent representations



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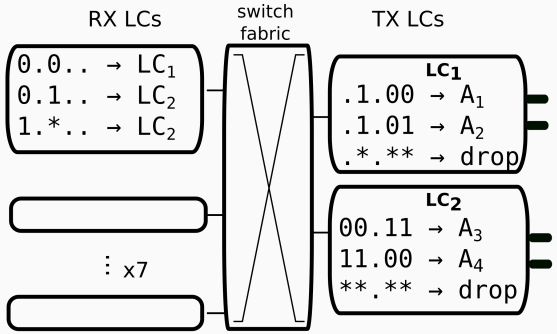
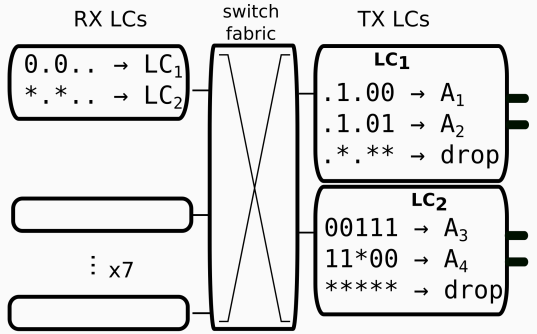
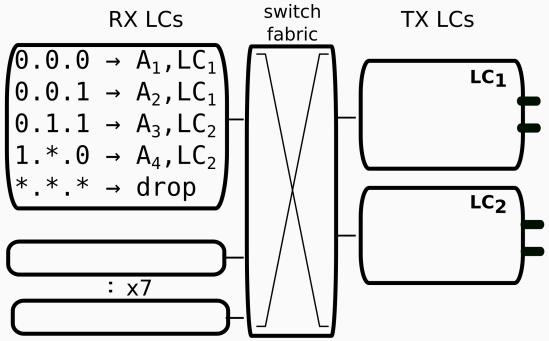


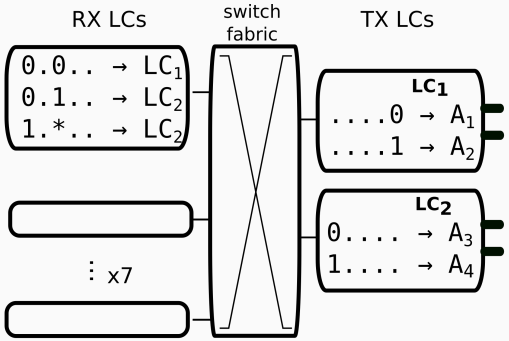
(b) Two-stage with RX action-order independence and TX lookup to find an action.



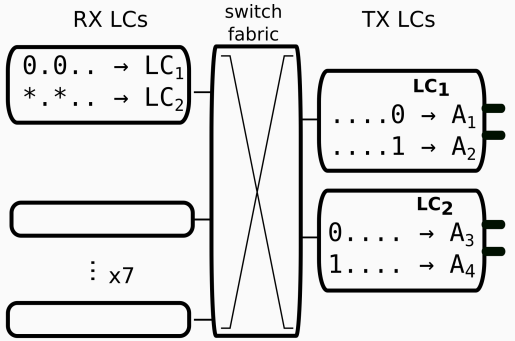
(c) Two-stage with RX non-conflicting rules and TX lookup to find an action.



(a) One-stage with RX action-order independence and no false-positive check on TX.

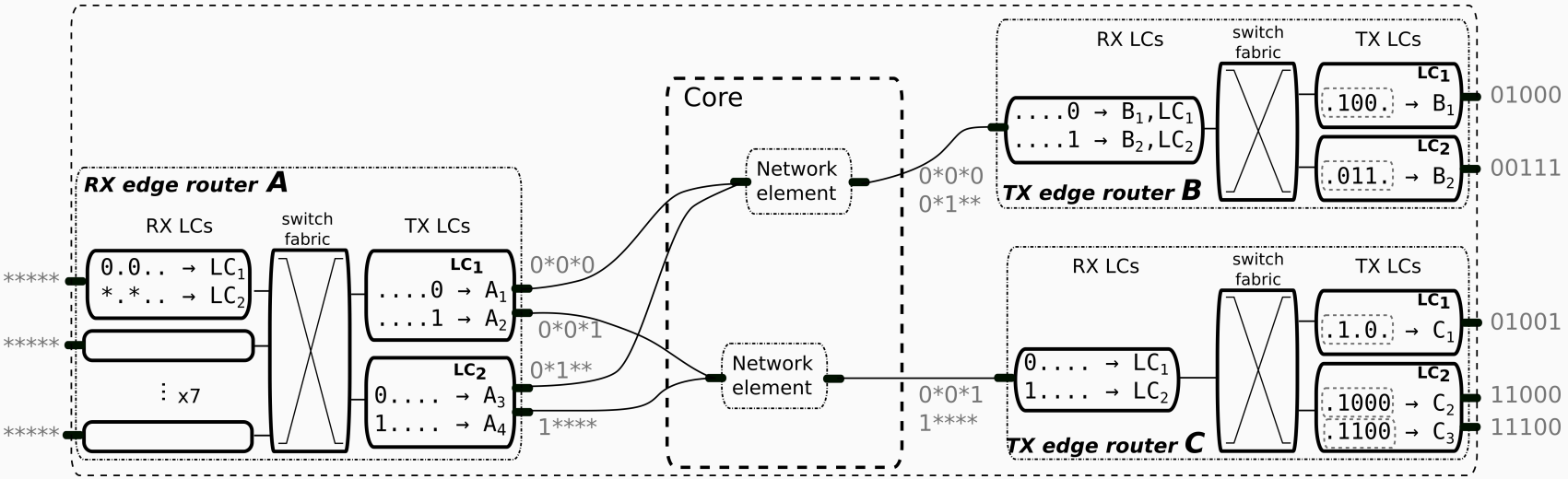


(b) Two-stage with RX action-order independence and TX lookup to distinguish between actions.



(c) Two-stage with RX non-conflicting rules and TX lookup to distinguish between actions.

Network-wide representation



Discussion and further directions

We considered FIB representations on distributed platforms based on various structural properties.

- transparent to PD representations
- no effect on original objective vs. compact routing
- transparent to clean-slate solutions
- improvements in memmory and/or lookup time

Additional directions:

- How to run clean-slate solutions on existing IPv4 infrastracture (ICNP'17)
- Approximate classifiers with controlled errors.

processing multiple packets

Buffering architectures

Buffering architectures define how input and output ports of a network element are connected.

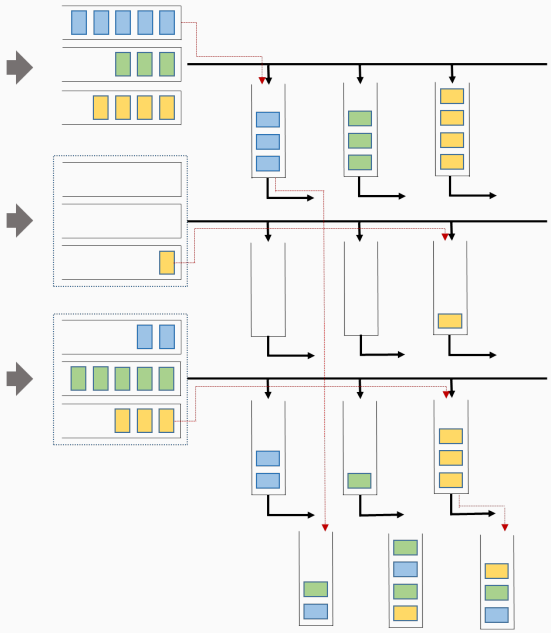
Queue:

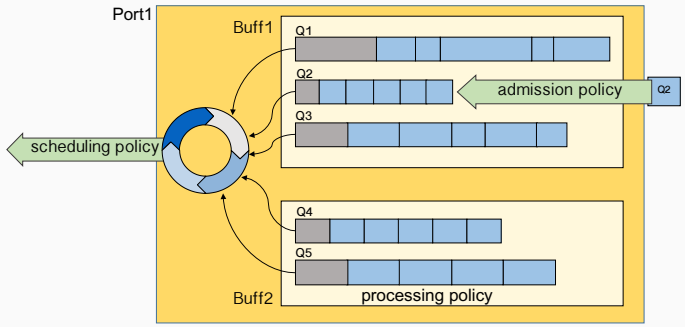
admission policy (tail-drop, RED)

processing policy (FIFO, SRPT)

Port: scheduling policy (DRR, WFQ)

Buffer: admission policy (LQD)





Why is a buffer management important?

Imbalance between incoming and outgoing packet rates.

Overprovisioning of buffer capacity is not viable.

Buffering architecture and management impact performance and cost of network elements.

Traditional buffer management

Traditional networks allow only a predefined set of policies.

Incorporation of new management policies requires CP/DP code changes and respin of implementing hardware.

Objectives beyond fairness and additional traffic properties lead to new challenges (pFabric SIGCOMM14, pHost CoNEXT15).

Traditional approaches and current SDN deal with efficient representation of packet classifiers.

Requirements for Software-Defined buffer management

Expressivity: should be expressive enough

Simplicity: policies should be expressible concisely with a limited set of basic primitives

Performance: implementations of policies should be efficient

Dynamism: specification and provision of new policies should be possible at run-time without any code changes and HW respins

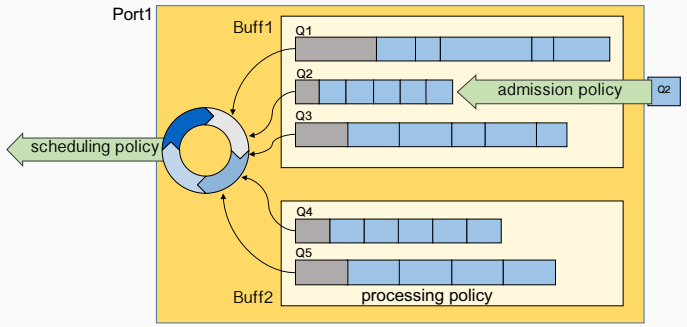
From single packets to packet streams

Primitives:

OF,P4: packets, fields, flows, tables, etc.

$\mathcal{K}$	#1	#2	#3	#4	*Action*
R_1	0	1	0	0	A_1
R_2	0	$*$	$*$	$*$	A_2
R_3	1	0	1	$*$	A_3

OpenQueue: packets, queues, buffer, ports



Problem

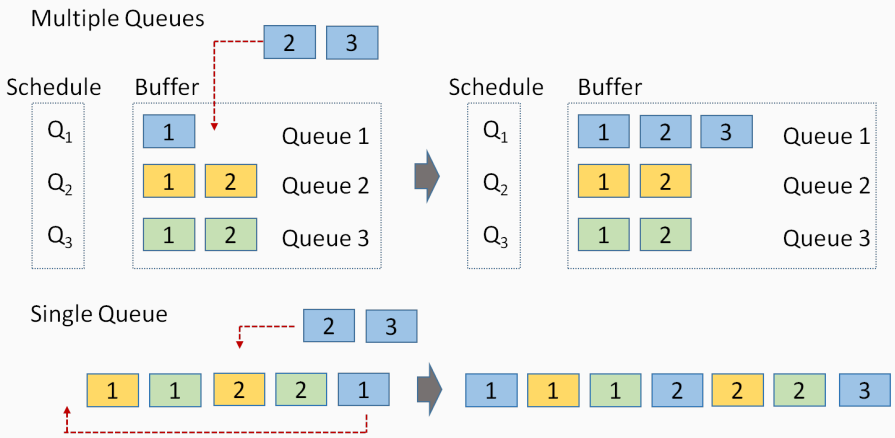
What should be flexible to implement admission, processing, and scheduling?

How to represent this expressiveness?

Queue complexity

How complex should be a queue primitive?

"Towards Programmable Packet Scheduling" HotNets'15



Observation

For any deterministic (or probabilistic) MQ policy ALG, there exists an SQ policy that for any input sequence transmits exactly the same set of packets (or a random set of packets with the same distribution) as ALG.

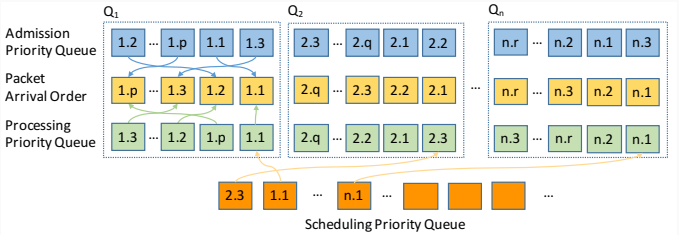
Observation

In the worst case, MQ architecture with m queues has time complexity of operations at least $O(m/\log B)$ times better than SQ simulating the same order.

Expressiveness vs. Simplicity

Buffer management policies mostly deal with extreme cases.

Implementation: priority queues (operating on internal state and packet's info).

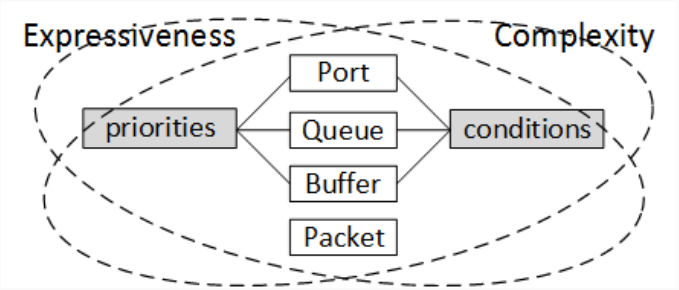


Queue:

admission policy: 1
processing policy: 1

Port: scheduling policy 1

Buffer: admission policy 1



Design considerations:

a single copy of each packet; operations on packet pointers.

user-defined expressions for priorities are immutable.

OpenQueue primitives

Queue primitive

```
Queue {
 // user-specified at declaration
 size                  // size in bytes        [r, cons]
 buffer                // allocating buffer    [r, cons]
 // primitive properties
 currSize              // current size          [r, dyn]
 // admission -- user-specified at decl.
 admPrio(p1, p2)       // pushOut comparat.   [bool fun]
 congestion()          // drop(P) condit.    [drop cond]
 postAdmAct()          // [{mark, notify, modify} comp]
 weightAdm             // adm. priority         [rw, dyn]
 // processing -- user-specified at decl.
 procPrio(p1, p2)      // proc comparat.   [Packet comp]
 getHOL()              // HOL packet         [Packet fun]
 // scheduling -- user-specified at decl.
 weightSched           // scheduling prio.      [rw, dyn]
}
```

```
congestion() = |
   (currSize >= .95*size, drop(1) ) .|
      (currSize >= .9*size, drop(.9) ) .|
         (currSize >= .75*size, drop(.5))|
```

```
procPrio(p1, p2) = (p1.arrival < p2.arrival)
```

Buffer primitive

```
Buffer {
 // primitive properties
 currSize              // current size          [r, dyn]
 getBestQueue()        // on weightAdm        [Queue fun]
 getCurrQueue()        // admitted one        [Queue fun]
 // user-specified at declaration
 size                  // size                  [r, cons]
 // admission -- user-specified at decl.
 congestion()          // drop(P)             [drop cond]
 queuePrio(q1, q2)     // compare q-s          [bool fun]
 postAdmAct()          // [{mark, notify, modify} cond]
}
```

```
queuePrio(q1, q2) = (q1.currSize < q2.currSize)
```

Port and packet primitives

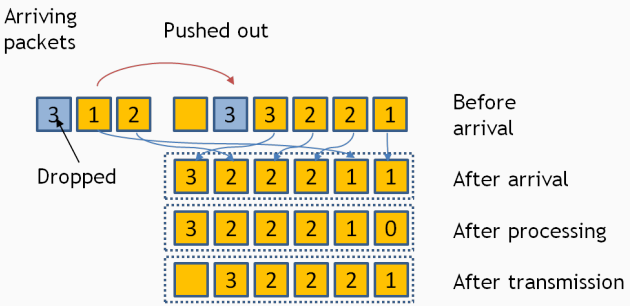
```
Port {
 // primitive properties
 getBestQueue()       // on weightSched     [Queue fun]
 getCurrQueue()       // scheduled one      [Queue fun]
 // scheduling user-specified at decl.
 schedPrio(q1, q2)    // compare q-s          [bool fun]
 postSchedAct()       // [{mark, notify, modify} cond]
}

Packet {
 size                 // size in bytes        [r, cons]
 value                // virtual value        [r, cons]
 processing           // nb of cycles         [r,  dyn]
 arrival              // arrival time         [r, cons]
 slack                // offset in time       [r, cons]
 queue                // target queue id      [r, cons]
 flow                 // flow id              [r, cons]
}
```

Examples in OpenQueue

Example: Single queue

Impact of admission and processing orders



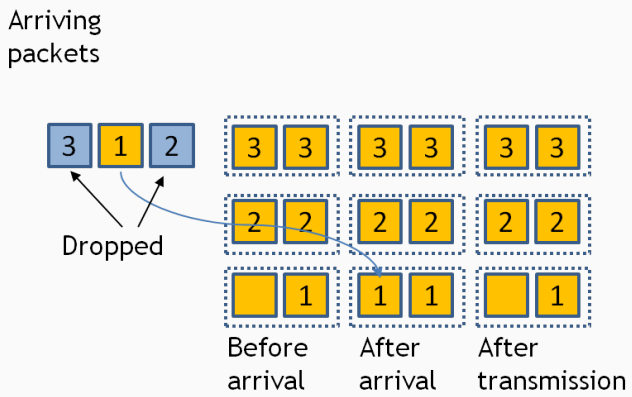
admPrio	procPrio	OPT/ALG
fifo()	fifo()	$O(k)$
rsrpt()	fifo()	$O(\log k)$
rsrpt()	srpt()	1 (optimal)

```
// priorities for admission and processing
fifo(p1, p2) = (p1.arrival < p2.arrival)
srpt(p1, p2) = (p1.processing < p2.processing)
rsrpt(p1, p2) = (p1.processing > p2.processing)
// congestion conds. considered.
// trigger when occupancy exceeds size.
defCongestion() =
  lambda q, (q.currSize >= q.size, drop(1))

// buffering architecture specification
q1 = Queue(B);
out = Port(q1);
// admission control
q1.admPrio(p1, p2) = rsrpt(p1, p2);
q1.congestion = defCongestion(q1);
// processing policy
q1.procPrio(p1, p2) = srpt(p1, p2);
```

Example: Multiple queues

Impact of scheduling.



init. `weightSched`	`postSchedAct`	`schedPrio`	OPT/ALG
unused	unused	`lqf()`	$\Omega(\frac{B}{2})$
unused	unused	`sqf()`	$\Omega(k)$
unused	unused	`maxqf()`	$\Omega(k)$
`qi.weightSched=i`	unused	`minqf()`	upper bound 2
`qi.weightSched=i`	`crrPostSchedAct()`	`crr()`	$\Omega(\frac{k}{\ln k})$
`qi.weightSched=i`	`prrPostSchedAct()`	`prr()`	$\Omega(\frac{3k(k+2)}{4k+16})$

```
// LQF: HOL packet from Longest-Queue-First
lqf(q1,q2) = (q1.currSize > q2.currSize);
// SQF: HOL packet from Shortest-Queue-First
sqf(q1,q2) = (q1.currSize < q2.currSize);
// MAXQF: HOL packet from queue that
// admits max processing
maxqf(q1,q2) = (q1.weightSched > q2.weightSched);
// MINQF: HOL packet from queue that admits
// min processing
minqf(q1,q2) = (q1.weightSched < q2.weightSched);
// CRR: Round-Robin with per cycle resolution
crr(q1,q2) = (q1.weightSched < q2.weightSched);
crrPostSchedAct() =
 lambda port,
  let q = port.getCurrQueue() in
   (true, // condition
     modify(q.weightSched := q.weightSched+k));
// PRR: Round-Robin with per packet resolution
prr(q1,q2) = (q1.weightSched < q2.weightSched);
prrPostSchedAct() =
 lambda port,
  (let q = port.getCurrQueue() in
    (q.getHOL().processing == 0, // condition
      modify(weightSched := weightSched+k*k)));
```

```
// initializing schedWeight for CRR
q1.weightSched = 1; ...; qk.weightSched = k;
// postSchedAct updating schedWeight
out.postSchedAct = crrPostSchedAct(out);
```

short summary

OpenQueue is a concise yet expressive language to define buffer management policies.

new buffer management policies do not require control/data-plane code changes.

Conclusion: OpenQueue can enable and accelerate innovation in buffering architectures and their management, similar to programming abstractions as P4.

network virtualization

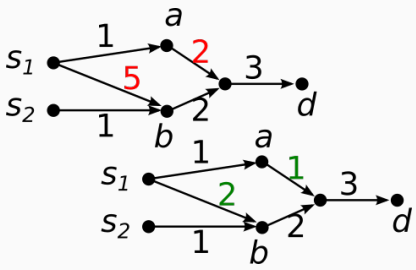
Motivations

Network infrastructure is an expensive resource requiring complex management.

Various bandwidth allocation and routing methods are very complex and time consuming.

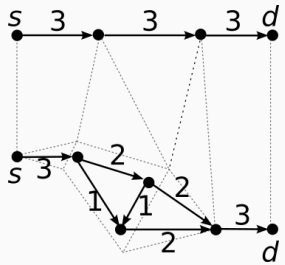
Question: How to operate on **simplified** network without loosing an original network capabilities transparently to bandwidth allocation methods?

Capacity planning: reduce unnecessary link capacity.
Network topology remains unchanged.
(usecase: geo-distributed data centers)



Network topology transformations
Network topology can be changed.

preserves one-to-one mapping of bandwidth allocations;
feasibility of bandwidth allocations (e.g., Fastpath transport);
how to exploit extra capacity to further simplify networks?



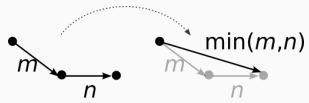
Netw. topology transformations

Routing equivalence

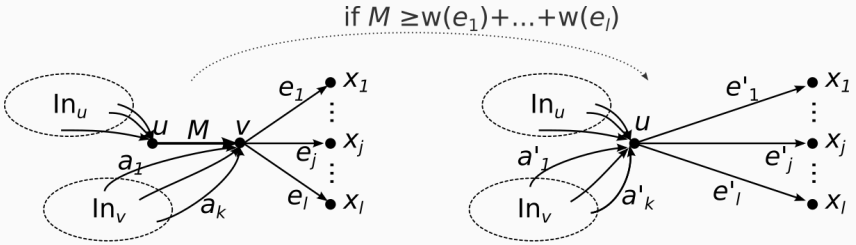
Denote by $\mathrm{Path}_G(A, B)$ the set of paths in network $G = (V, E)$ that begin in $A \subseteq V$ and end in $B \subseteq V$.

Definition

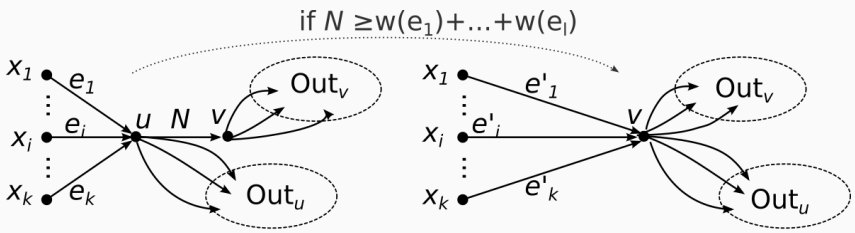
Two networks $G = (V, E, w, S, D)$ and $G' = (V', E', w', S, D)$ are *routing equivalent* if there is a one-to-one mapping $g : \mathrm{Path}_G(S, D) \to \mathrm{Path}_{G'}(S, D)$ between paths from sources to corresponding destinations on G and G' that preserves bandwidth allocations.



Example: Path of length 2



(*a*) Shrinking a non-bottleneck incoming edge



(*b*) Shrinking a non-bottleneck outgoing edge

The transformations (a)-(b) reduce simultaneously the number of edges in the network, the number of vertices in the network, and the total capacity of all edges.

Theorem

Transformations (a)-(b) outputs a routing equivalent network.

Bandwidth Preserving Transformations

For two networks $G = (V, E, w, S, D)$ and $G' = (V', E', w', S, D)$ with the same set of sources and destinations, a *bandwidth-preserving routing transformation* is a function $g : \mathrm{Path}_G(S, D) \to \mathrm{Path}_{G'}(S, D)$ between paths from sources to corresponding destinations on G and G'.

(c) Merge parallel edges (d) Removing self-loops

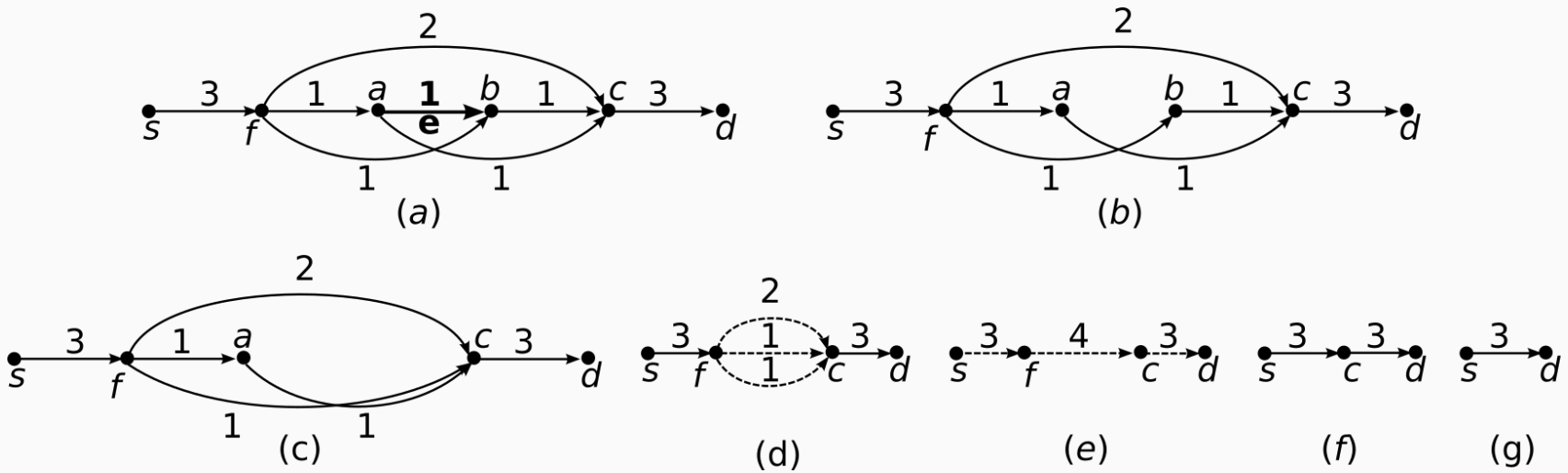
Theorem

Transformations (c)-(d) are bandwidth preserving routing transformation.

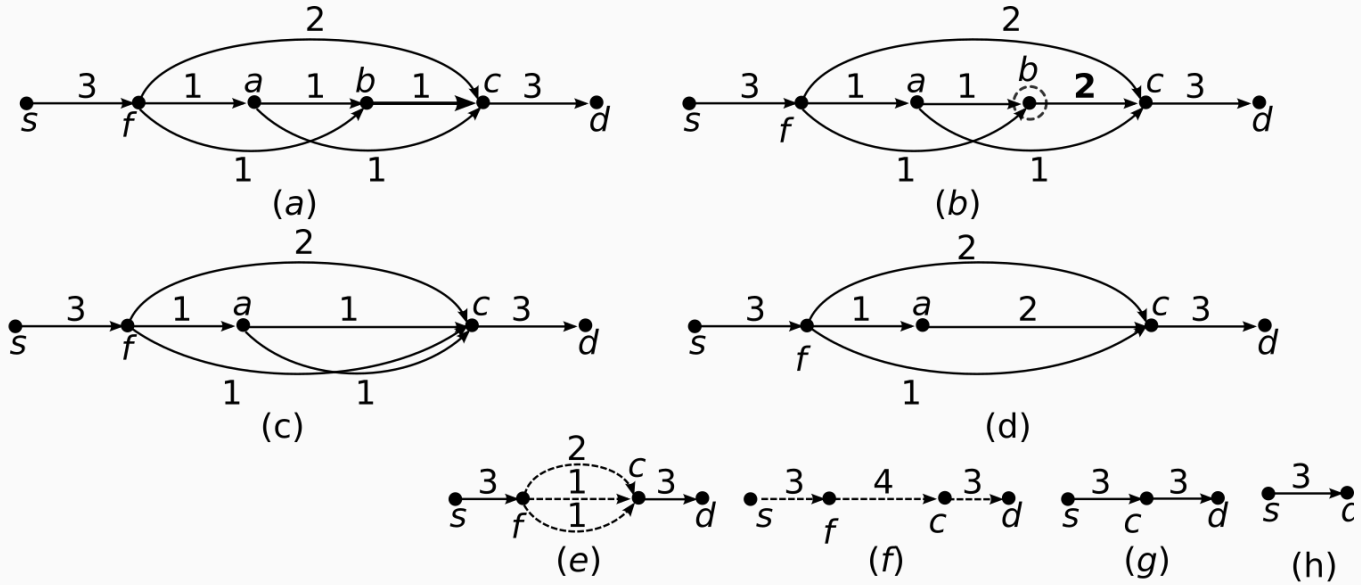
Tradeoff between extra capacity and simplicity

Braess' Paradox

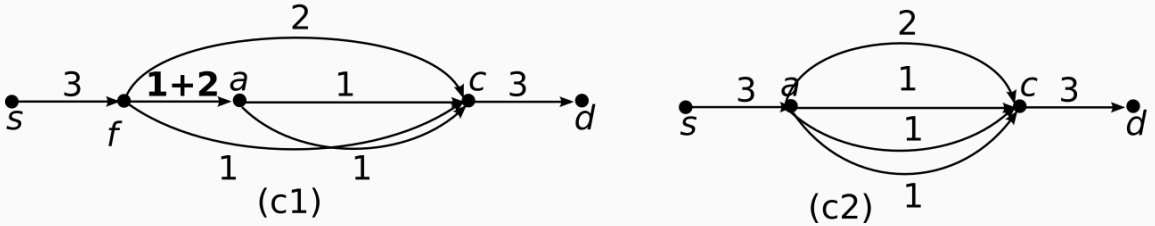
Removing (a, b)-edge leads to the simplest graph.



Using extra capacity to simplify network



extra 2 capacity units to keep routing equivalence



Find the best possible allocation of extra capacity to simplify the resulting graph.

short summary

two types of network topology transformations;

study a tradeoff between extra capacity and simplicity

Our ultimate goal is to understand how to represent a network as a virtual switch and operate on top of it. This work is only the first step towards this goal.

Delayed information and action in on-line algorithms FOCS'98

Current projects

Resource Allocation in Serverless Computing (impact of delaying requests) (Infocom'15,submitted).

Towards in-network processing of data streams (design on FD.io VPP - Cisco grant).

Cost-efficient Infrastructure for Compute-aggregate Problems (taxonomy of aggregation functions vs. Microsoft cam-cube) (ICNP'17,submitted).

Virtualization of heterogeneous computing resources (CPU+FPGA)(ongoing).

Self-adapting buffer-management policies (user defines objectives and traffic properties)(ongoing).

Datacenter transports with provable guarantees (bounded delay vs. average flow compl. time)(ongoing).

Composition of heterogeneous control planes(ONS'14,ICNP'14).

final slide

Questions?

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