On Kirill's Contribution to Packet Classification and an Example Why It Matters

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MŰEGYETEM 1782

ERICSSON

universität wien

Motivation

- A joint presentation by Gabor and Stefan: two friends and colleagues of Kirill

- We have a joint national project inspired by and building upon Kirill's work
  - Dependable Network Data Plane for the Cloud (DELTA)
  - Funded by NKFIH and FWF

- Emerging programmable data plane: new opportunities for innovative algorithms as the ones devised by Kirill

Agenda

- Algorithms in the data plane and example: Tuple Space Search
- Why designing good algorithms matters: a case study
- One solution by Kirill and Gabor

Packet Classification: Basics

Given an ordered list of wildcard (ternary) rules, find the first rule that matches a given packet header

Exact-match and longest-prefix-match (LPM) are simpler subproblems

Indispensable in packet processing: IP packet forwarding (only LPM), firewalls/ACLs, QoS shapers/rate-limiters/classifiers, OpenFlow/P4 match-action processing & policy routing, accounting & billing, etc. [Gupta, 2001]

Example: allow HTTP and DNS traffic from select networks, deny everything else

Src	**Dst**	**Proto**	**Dst port**	**Action**
10.10.0.0/16	192.168.1.100	6 (TCP)	80 (HTTP)	Allow
10.0.0.0/8	192.168.1.53	17 (UDP)	53 (DNS)	Allow
*	*	*	*	Deny

Packet Classification: Algorithms

“Easy” in hardware (TCAMs), **notoriously difficult in software**: "a packet classifier with *n* rules and $k>1$ fields uses either $O(n^k)$ bits space and $O(\log n)$ time, or $O(n)$ space and $O((\log n)^k)$ time" [Feldman 2000, Gupta, 2001, Kogan 2014]

Difficulty stems from that (1) rules can have **wildcard bit** (“don’t care” bit *) and so (2) **may overlap**, but (3) we need to find the **first matching rule**

Software implementations typically use **heuristics**: linear search, hierarchical tries, tuple space search & decision trees (see later), geometric/cut-based algorithms (HiCuts/Efficuts), etc.

Kirill was highly active in this area [Kogan 2013, Kogan 2014, Nikolenko 2016, Demianiuk 2021]

Tuple Space Search (TSS): Idea

Hash-tables work for exact-match but a generic packet classifier has wildcards in the rules: we need something more clever

TSS: decompose a *w* bit wide ruleset into at most 2^w exact-match instances

1. Find all combinations of wildcard bit positions in the rules (called **tuples**)
2. For each tuple, create a hash on the **non-wildcard bit positions** (“mask”)
3. Mask & match each each incoming packet **against all hashes/tuples**
4. Return the **highest priority match** (if any)

Heuristic “prerequisite”: $O(2^w)$ hash lookups in the worst case, but typically much fewer

Tuple Space Search (TSS): Example

An **IPv6 forwarding table:** rather wide (*w=128*), but only prefix rules

Prefix	Next-hop
0x80::/4	a
0x40::/2	b
0xc0::/2	c
0x80::/1	d

filter	#0	#1	#2	#3
F_1	1	0	0	0
F_2	0	1	*	*
F_3	1	1	*	*
F_4	1	*	*	*

3 tuples, a separate hash table for each one

filter	#0	#1	#2	#3
F_1	1	0	0	0

filter	#0	#1
F_2	0	1
F_3	1	1

filter	#0
F_4	1

Input `0111` matches only the 2nd hash only, `1100` matches both 2nd and 3rd, F_3 “wins”

Good news: the number of tuples (3) is much smaller than the worst case (2^4=16)

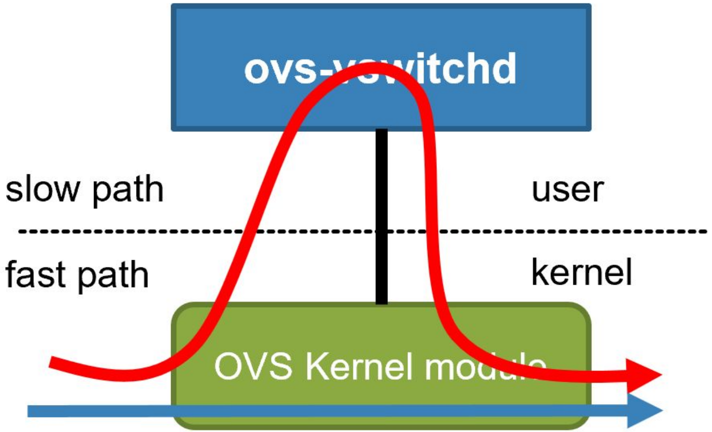
Observe that (1) **each rule maps to a single tuple**, and (2) rules per each tuple admit an exact-match lookup (i.e., be **order-independent**, [Kogan 2014])

A Threat: Algorithmic Complexity Attacks

- In general, algorithmic complexity attacks exploit known cases in which an algorithm will exhibit worst-case behavior
  - E.g., *Billion Laughs*: attack on XML parsers, exponentially expanding itself (“lol”)
  - E.g., *Zip bomb*: attack on virus scanner unpacking an archive (resource explosion)
- Algorithmic complexity attacks are also a threat for network algorithms
- We have recently shown that Tuple Space Search (TSS) has such an issue
  - TSS for example used in the Open vSwitch (OvS) MegaFlow Cache (MFC)
  - OvS is the “de facto” software switch in data centers
- Simple flow table: “allow some but drop others”

Denial-of-Service Attack on OVS Packet Processing

- OVS uses a MegaFlow cache: first packet subject to full-table processing, then flow-specific rules and actions cached
- Entries matching on the same headers are collected into a hash
  - Masked packet headers can be found fast
  - However, masks and associated hashes are searched sequentially



Can be a costly linear search in case of lots of masks!

A Denial-of-Service Attack on TSS

- KEY FINDING: More masks -> slower packet processing
- Strategy: for each packet for the allow rule, add a packet with the relevant bits inverted
    - Each packet gives one mask
- Multiple allow rules on multiple header fields -> Exponential growth
- Matching on either 1) and 2) -> 512 masks

With less than 1 Mbps specially crafted packet sequence we get a full Denial-of-Service (OVS performance drops close to 0%).

TSS on steroids: Kirill’s beautiful idea

TSS is extremely simple but slow if the number of hashes grows huge

How to decrease the number of tuples/hashes?

Recall the “invariants” of TSS: (1) each rule must map to a single hash, (2) rules per each hash must be order-independent

Kirill’s observation: rules that belong to different tuples can be assigned into a single hash as long as the above two prerequisites hold

This may allow to map rules that belong to different tuples to a single hash

Reduced order-independent decompositions: Idea

Strong reduced order-independent decompositions [Nikolenko 2016]:

1) partition the rules into the smallest number of groups, where each group is associated with a bitmask, so that
2) the rules in each group masked with the group's bit positions are order-independent

But we may lose "valuable" bits in each group due to applying the mask

Perform a **false positive (FP) check** after each hash-lookup (cf. [Kogan 2014])

TSS is the worst-case order-independent reduction, so we may only get fewer hash lookups, this may be worth the additional false-positive check

Simulations show that usually only 20-30 hashes ($w=16$) is enough, instead of 128

Reduced order-independent decompositions: Example

Recall the previous IPv6 forwarding table: TSS needed 3 hash lookups

filter	#0	#1	#2	#3
F_1	1	0	0	0
F_2	0	1	*	*
F_3	1	1	*	*
F_4	1	*	*	*

A reduced order-independent decomposition with just 2 hash lookups + 1 FP check

filter	#0	#1	#2	#3
F_1	1	0	0	0
F_2	0	1	*	*
F_3	1	1	*	*
false-positive check				

filter	#0	#1	#2	#3
F_4	1	*	*	*

Kirill’s crazy optimal solution: 1 bit per hash (FP checks not shown)

filter	#1
F_1	0
F_3	1

filter	#0
F_2	0
F_4	1

Closing thoughts

SW packet classification is an actively researched area

Kirill made cornerstone contributions to the field

His ideas will always be an inspiration to the community

SAX-PAC (Scalable And eXpressive PAcket Classification)

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