High Level Management of Firewall Configurations

Mauriana Pesaresi Seminar

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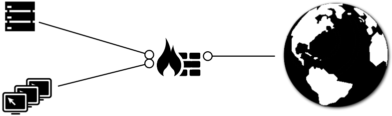
Presentation Outline

- **Introduction and Motivation**
  - What is a **Firewall**
  - Their **configuration** are **difficult** to manage
- **Transcompilation Pipeline**
  - A language-based **Solution**
  - FireWall Synthesizer (**FWS**)
- **Function-Based Redefinition** (Master Thesis)
  - **from Firewalls to Functions and Back**
  - **Composition**
  - **Function Representation**
- **Ongoing and Future Work**
  - **Tag System**
  - **Networks of Firewalls**

What is a Firewall?



Inspects the traffic: for each packet

- **accepts or drops** it
- possibly **modifying** it (NAT)

Based on a **configuration**

- **List of rules**
- Possibly using **tags**
- **Control-flow** constructs
- **Complex Interaction** among rules (Shadowing)
- **Different** configuration languages
- **Low level** details

Difficult and **error** prone:

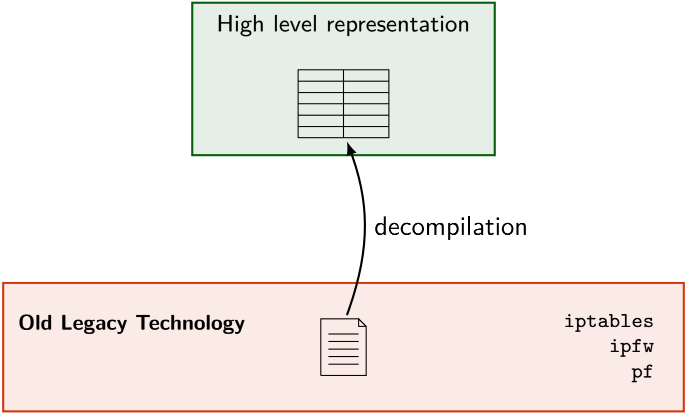
- Configuration
- Cross-system porting
- Test
- Verification

Our Goal

Old Legacy Technology

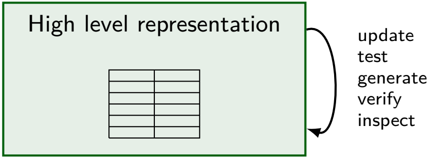
`iptables`
`ipfw`
`pf`

Our Goal



High level representation
decompilation
Old Legacy Technology
iptables
ipfw
pf

Our Goal



Old Legacy Technology

`iptables`
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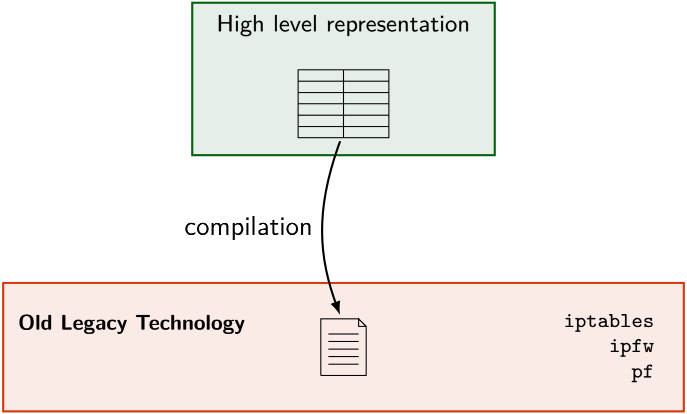
Our Goal


High level representation
compilation
Old Legacy Technology
iptables
ipfw
pf

Transcompiltation Pipeline

Transcompilation Pipeline between firewall languages

- Supports `iptables`, `pf`, `ipfw` and (partially) `CISCO`-*ios*
- General approach
- Supports NAT
- Formal semantics
- tool: **FireWall Synthesizer**

IFCL — Intermediate Firewall Configuration Language

Each firewall system

- Has **its own** configuration **language**
- Makes **different evaluation steps** to process packets
- Lots of **low level** details
  - First do the NAT, than filtering or vice-versa?
  - How to express complex conditions (disjunction and negation)?

IFCL — Intermediate Firewall Configuration Language

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$\Downarrow$ General Model

Firewall = set of rules + the evaluating procedure

IFCL — Intermediate Firewall Configuration Language

Firewall = set of rules + the evaluating procedure

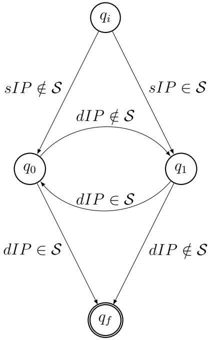
Configuration

Assigns a rulesets to each node

Ruleset : list of **rules** $r = (\phi, a)$

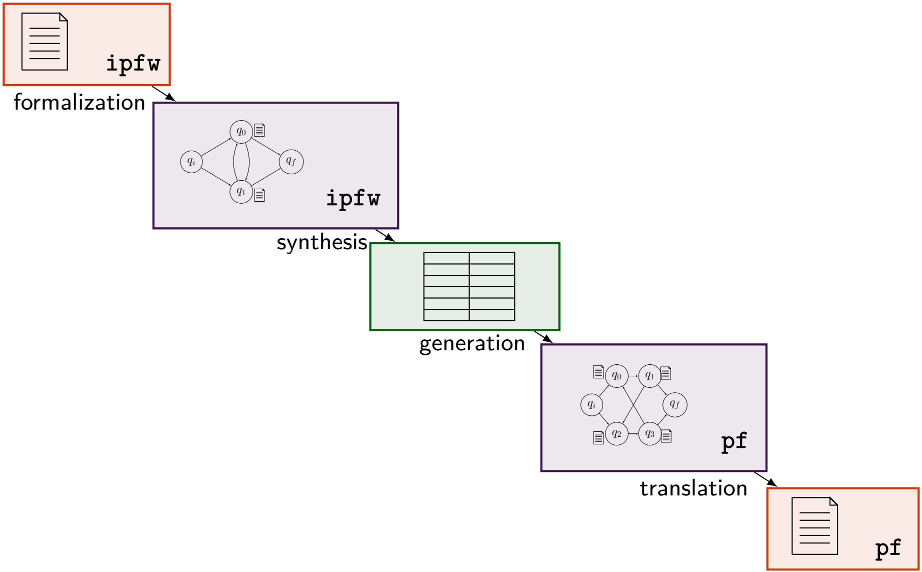
- $\phi(p)$: **condition**
- a : **action**
  - ACCEPT
  - DROP
  - NAT(d_n, s_n)
  - MARK(m)
  - ~~GOTO(R)~~
  - ~~CALL(R)~~
  - ~~RETURN~~

Control Diagram

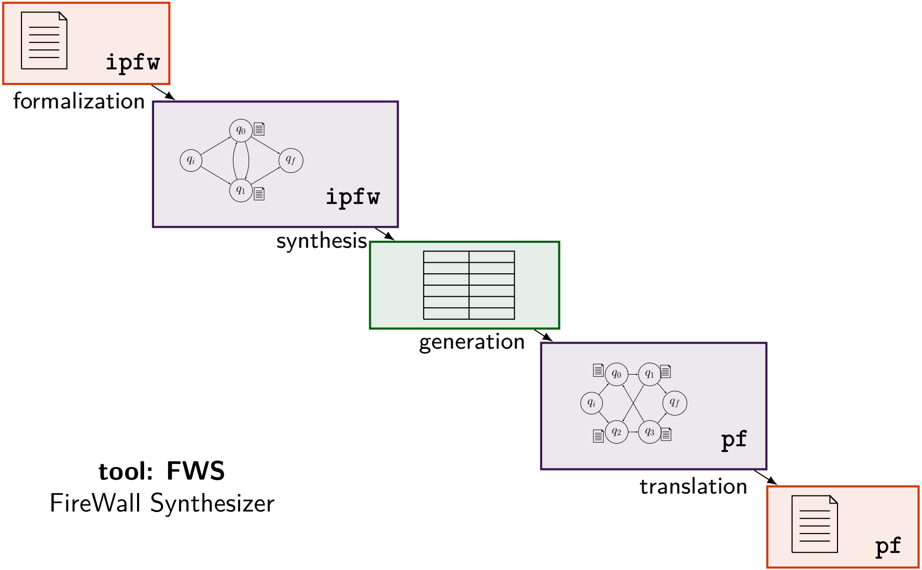


$\mathcal{S}$ are the addresses of the firewall

Transcompilation Pipeline



Transcompilation Pipeline



tool: FWS
FireWall Synthesizer

From Firewalls to Functions and Back: The Idea

Previous implementation of the pipeline synthesis:

- **Associate two predicates with a configuration: its meaning**
  on pairs p, p' when p is accepted as p' or on discarded p
- **Compute the models of a predicate (SAT-solver)**
  Black-box approach (no fine tuning)

Change of domain:

Function-based redefinition of the pipeline

(Firewalls $\multimap$ Functions) :

source configuration $\mapsto$ function representing **its meaning**

(Firewalls $\multimapinv$ Functions) :

functional representation $\mapsto$ target configuration

Rulesets and Firewalls as Functions

$$\tau : \mathbb{P} \to \mathcal{T}(\mathbb{P}) \cup \{\bot\}$$ where

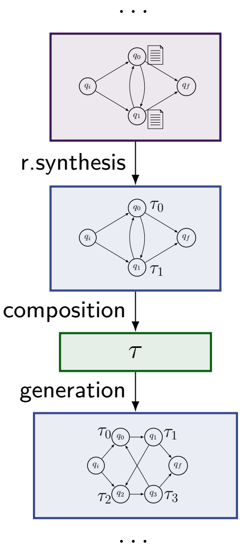
- $\mathbb{P}$ network packets
- $\mathcal{T}(\mathbb{P})$ transformations possibly applied to packets
- $\bot$ discard of a packet

New pipeline stages:

- **ruleset synthesis:** rulesets became functions
- **composition:** computes the semantics of the firewall
- **generation:** assign functions to the target nodes

Why:

- **Parametric** w.r.t. IFCL specification
- Support **minimal control diagrams** and `MARK`
- Translation from IFCL **to target language** is trivial

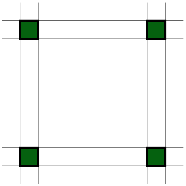


Function Representation

Functions $\tau : \mathbb{P} \to \mathcal{T}(\mathbb{P}) \cup \{\perp\}$ as **sets of pairs** (P, t)

t is a transformation

P is a multi-cube of packets

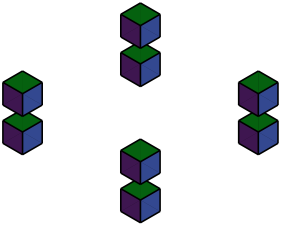


Cube :

Cartesian product of one segment for each dimension

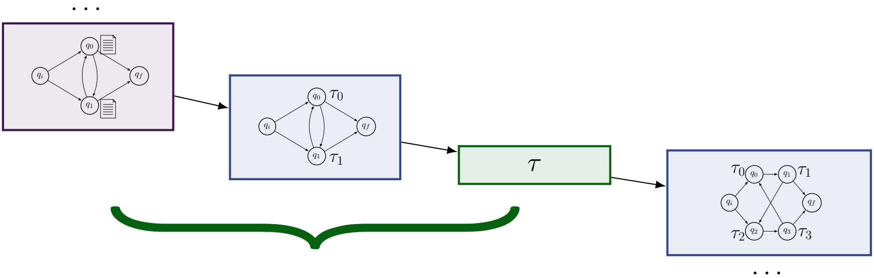
Multi-cube :

Cartesian product of one **union of segments** for each dimension



- **succinct** representation
- sets of packets verifying **rule conditions**
- sets of packets verifying **arc conditions**
- closed under **transformations**

Synthesis



q_0
q_i
q_f
q_1
q_0 τ_0
q_i
q_f
q_1 τ_1
τ
τ_0 q_0
q_1 τ_1
q_i
q_f
τ_2 q_2
q_3 τ_3

Ruleset Synthesis: from ruleset to pairs (P, t)

We **scan** the ruleset rule-by-rule, **keeping track** of

P packets still to process

t transformation assigned to P

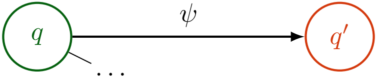
$$P = \begin{cases} P_s & \text{packets that verifiy the rule condition} \\ P_n & \text{packets that do not – managed by the } \textbf{other rules} \end{cases}$$

if the action accept/rejects the packet **then** (P_s, t'), where t' updates t

else processing continues with the other rules on P_s (updating t to t')

Composition

τ	
P_1	t_1
P_2	t_2
P_3	t_3



Globally $p \mapsto t$ updated with t'

τ'	
P'_1	t'_1
P'_2	t'_2
P'_3	t'_3

Ideally, for each $p \in \mathbb{P}$

- compute t in the first node
- compute p':
  (how p is when exits node q)
- check $\psi(p')$ ... if it does then
  - compute t' in the second node
  - **Overall**: $p \mapsto t$ updated by t'

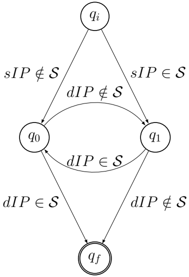
Composition Algorithm:

The same,
but with Multi-cubes ...

(... with additional details)

Example from `ipfw` to `pf`: formalization

```
ipfw -q nat 1 config ip 151.15.185.183
ipfw -q nat 2 config redirect_port tcp 9.9.8.8:17 17
ipfw -q add 0010 nat 1 tcp from 192.168.0.0/24 to not 192.168.0.0/24
ipfw -q add 0020 nat 2 tcp from 151.15.185.183 to not 192.168.0.0/24 17
ipfw -q add 0030 allow tcp from 151.15.185.183 to not 192.168.0.0/24 out
ipfw -q add 0040 deny all from any to any
```



$$
\begin{aligned}
R_0 : &(\texttt{sIP} \in 192.168.0.0/24 \wedge \texttt{dIP} \notin 192.168.0.0/24,\\
&\qquad \texttt{NAT}(\star : \star, 151.15.15.183 : \star));\\
&(\texttt{sIP} = 151.15.185.183 \wedge \texttt{dIP} \notin 192.168.0.0/24 \wedge \texttt{dPort} = 17,\\
&\qquad \texttt{NAT}(9.9.8.8 : \star, \star : \star));\\
&(true,\ \texttt{DROP})
\end{aligned}
$$

$$R_1 : \ \ldots$$

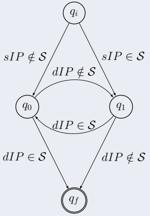
Example from `ipfw` to `pf`: ruleset synthesis

$$
\begin{aligned}
R_0 : &(\texttt{sIP} \in 192.168.0.0/24 \wedge \texttt{dIP} \notin 192.168.0.0/24, \texttt{NAT}(\star : \star, 151.15.15.183 : \star));\\
&(\texttt{sIP} = 151.15.185.183 \wedge \texttt{dIP} \notin 192.168.0.0/24 \wedge \texttt{dPort} = 17, \texttt{NAT}(9.9.8.8 : \star, \star : \star));\\
&(\mathit{true},\ \texttt{DROP})
\end{aligned}
$$

τ_0

Received packets				**Accepted packets**			
source		**destination**		**source**		**destination**	
192.168.0.0/24	*	* \{ 192.168.0.0/24 }	*	151.15.185.183	-	-	-
151.15.185.183	*	* \{ 192.168.0.0/24 }	17	-	-	9.9.8.8	-

Example from `ipfw` to `pf`: composition



τ_0

Received packets				Accepted packets			
source		destination		source		destination	
192.168.0.0/24	*	* \{ 192.168.0.0/24 }	*	151.15.185.183	-	-	-
151.15.185.183	*	* \{ 192.168.0.0/24 }	17	-	-	9.9.8.8	-

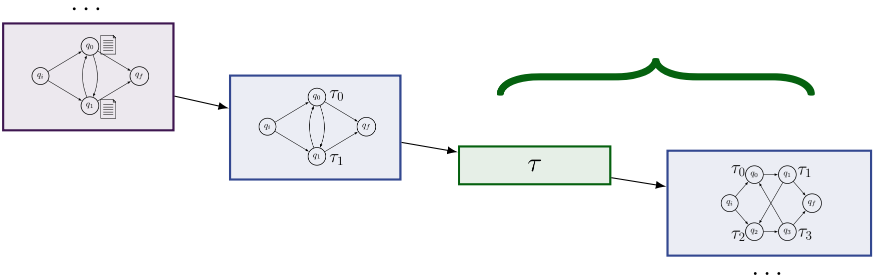
τ_1

Received packets				Accepted packets			
source		destination		source		destination	
192.168.0.0/24	*	* \{ 192.168.0.0/24 }	*	151.15.185.183	-	-	-
151.15.185.183	*	* \{ 192.168.0.0/24 }	17	-	-	9.9.8.8	-
151.15.185.183	*	* \{ 192.168.0.0/24 }	* \{ 17 }	-	-	9.9.8.8	-

⬇

Received packets				Accepted packets			
source		destination		source		destination	
151.15.185.183	*	* \{ 151.15.185.183 192.168.0.0/24 }	* \{17}	-	-	-	-
192.168.0.0/24 \{192.168.0.1}	*	127.0.0.1 151.15.185.183	*	151.15.185.183	-	-	-
192.168.0.0/24 \{192.168.0.1}	*	* \{ 127.0.0.1 151.15.185.183 192.168.0.0/24 }	* \{17}	151.15.185.183	-	-	-
192.168.0.0/24 \{192.168.0.1}	*	* \{ 127.0.0.1 151.15.185.183 192.168.0.0/24 }	17	151.15.185.183	-	9.9.8.8	-
192.168.0.1	*	* \{ 127.0.0.1 151.15.185.183 192.168.0.0/24 }	*	151.15.185.183	-	-	-
151.15.185.183	*	* \{ 192.168.0.0/24 }	17	-	-	9.9.8.8	-

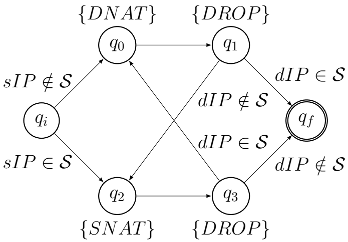
Generation


...
q_0
q_i
q_f
q_1
q_0 $\mathcal{T}_0$
q_i
q_f
q_1 $\mathcal{T}_1$
$\mathcal{T}$
$\mathcal{T}_0$ q_0
q_1 $\mathcal{T}_1$
q_i
q_f
$\mathcal{T}_2$ q_2
q_3 $\mathcal{T}_3$
...

How to generate functions

Problem: not every ruleset can be assigned to each node!

- Assign **Labels** to nodes
  - `DROP`
  - `SNAT`
  - `DNAT`
- **Different expressive power**



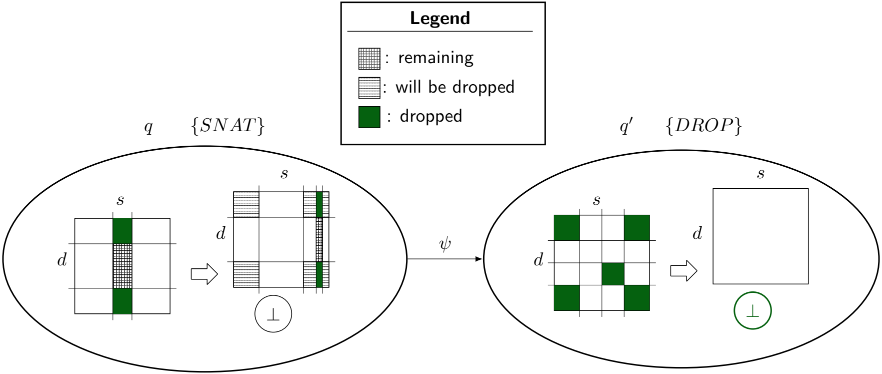
Algorithm

- **For each** pair (P, t) with $t \neq \perp$
  - Find the **path**
  - **For each** node q
    - Preceding nodes $\rightarrow \mathbf{P_q}$
    - Labels in $q \rightarrow \mathbf{t_q}$
- Special management for `DROP` pairs $(P, \perp)$

Management of DROP pairs

Special management for DROP pairs $(P, \perp)$

- For each node: packets **still not managed**
- **Drop as many as possible**



Recap

This transcompilation approach

- Is **parametric** w.r.t. the IFCL specification
- Supports the use of **tags** in IFCL
- Supports firewalls with **minimal control diagram**
- Preserves the **NAT**
- Reveals **different expressive power** of firewall languages

Ongoing and Future Work

Objectives

- Preserve the structure of the original configuration: **Refactoring**
- Reduce the **gap** between real languages and IFCL
- Fully support of **tag** system in real languages
- Handle **networks** with many firewalls
- Port configurations to **Software Defined Networks**

Problem with tags: *pf*

PF:

- Rules **read top-down**
- **Last matching** rule is applied
- **Tag** is applied **immediately** (evaluation continues)
- **Quick rules** are applied immediately (evaluation stops)

IFCL:

- Rules read top-down and **applied immediately**
- Tags never stop the evaluation

Basic solution

Just rewrite **bottom-up** the same list of rules (prepending quick rules)

Example:

$$(true,\ \text{DROP})$$
$$(src = 1.2.3.4,\ \text{ACCEPT})$$
$$(dst = 5.6.7.8,\ \text{NAT}(1.6.3.8, \star))\ \lightning$$
$$(src = 8.8.8.8,\ \text{DROP})$$

Basic solution

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$$(true,\ \texttt{DROP})$$
$$(src = 1.2.3.4,\ \texttt{ACCEPT})$$
$$(dst = 5.6.7.8,\ \texttt{NAT}(1.6.3.8, \star))\ ⚡$$
$$(src = 8.8.8.8,\ \texttt{DROP})$$

become

$$(dst = 5.6.7.8,\ \texttt{NAT}(1.6.3.8, \star))$$
$$(src = 8.8.8.8,\ \texttt{DROP})$$
$$(src = 1.2.3.4,\ \texttt{ACCEPT})$$
$$(true,\ \texttt{DROP})$$

Basic solution: tag

Divide each rule r into

quick part : r' ($\lightning$ + tag)

slow part : r'' (everything else)

Example:

$$R = \begin{cases} (r_1) \\ (r_2) \\ \dots \\ (r_n) \end{cases}$$

Basic solution: tag

Divide each rule r into

quick part : r' ($\lightning$ + tag)

slow part : r'' (everything else)

Example:

$$R = \begin{cases} (r_1) \\ (r_2) \\ \dots \\ (r_n) \end{cases} \quad \Rightarrow \quad R' = \begin{cases} (r'_1) \\ (r'_2) \\ \dots \\ (r'_n) \end{cases}$$

$$reverse(R'') = \begin{cases} (r''_n) \\ \dots \\ (r''_2) \\ (r''_1) \end{cases}$$

Basic solution: tag

Divide each rule r into

- quick part : r' (↯ $+$ tag)
- slow part : r'' (everything else)

Example:

$$R = \begin{cases} (r_1) \\ (r_2) \\ \ldots \\ (r_n) \end{cases} \quad \Rightarrow \quad R' = \begin{cases} (r'_1) \\ (r'_2) \\ \ldots \\ (r'_n) \end{cases} \qquad reverse(R'') = \begin{cases} (r''_n) \\ \ldots \\ (r''_2) \\ (r''_1) \end{cases}$$

The devil is in the detail

Problem with tags: Example

$$(true,\ \texttt{DROP})$$
$$(src = 1.2.3.4 \wedge tag = a,\ \ tag \leftarrow b;\ \texttt{ACCEPT})$$
$$(dst = 5.6.7.8 \wedge tag = b,\ \ \texttt{NAT}(1.6.3.8, \star))$$

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$$\Downarrow$$

$$(src = 1.2.3.4 \wedge tag = a,\ tag \leftarrow b)$$
$$(dst = 5.6.7.8 \wedge tag = b,\ \text{NAT}(1.6.3.8, \star))$$
$$(src = 1.2.3.4 \wedge tag = a,\ \text{ACCEPT})$$
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$$(src = 1.2.3.4 \wedge tag = a,\ \ tag \leftarrow b)$$
$$(dst = 5.6.7.8 \wedge tag = b,\ \ \texttt{NAT}(1.6.3.8, \star))$$
$$(src = 1.2.3.4 \wedge tag = \underline{b},\ \ \texttt{ACCEPT})$$
$$(true,\ \texttt{DROP})$$

Problem with tags: Example

$(true,\ \texttt{DROP})$

$(src = 1.2.3.4 \wedge tag = a,\ tag \leftarrow b;\ \texttt{ACCEPT})$

$(src = 1.2.3.4 \wedge tag = c,\ tag \leftarrow b;\ \texttt{NAT}(\star, 5.2.7.4))$

$(dst = 5.6.7.8 \wedge tag = b,\ \texttt{NAT}(1.6.3.8, \star))$

Problem with tags: Example

$(true,\ \texttt{DROP})$
$(src = 1.2.3.4 \wedge tag = a,\ tag \leftarrow b;\ \texttt{ACCEPT})$
$(src = 1.2.3.4 \wedge tag = c,\ tag \leftarrow b;\ \texttt{NAT}(\star, 5.2.7.4))$
$(dst = 5.6.7.8 \wedge tag = b,\ \texttt{NAT}(1.6.3.8, \star))$

$\Downarrow$

$(src = 1.2.3.4 \wedge tag = a,\ tag \leftarrow b)$
$(src = 1.2.3.4 \wedge tag = c,\ tag \leftarrow b)$
$(dst = 5.6.7.8 \wedge tag = b,\ \texttt{NAT}(1.6.3.8, \star))$
$(src = 1.2.3.4 \wedge tag = b,\ \texttt{NAT}(\star, 5.2.7.4))$
$(src = 1.2.3.4 \wedge tag = b,\ \texttt{ACCEPT})$
$(true,\ \texttt{DROP})$

Problem with tags: Example

$(true,\ \text{DROP})$

$(src = 1.2.3.4 \land tag = a,\ \ tag \leftarrow b;\ \text{ACCEPT})$

$(src = 1.2.3.4 \land tag = c,\ \ tag \leftarrow b;\ \text{NAT}(\star, 5.2.7.4))$

$(dst = 5.6.7.8 \land tag = b,\ \ \text{NAT}(1.6.3.8, \star))$

$$\Downarrow$$

$(src = 1.2.3.4 \land tag = a,\ \ tag \leftarrow b1)$

$(src = 1.2.3.4 \land tag = c,\ \ tag \leftarrow b2)$

$(dst = 5.6.7.8 \land tag = b1,\ \ tag \leftarrow b;\ \text{NAT}(1.6.3.8, \star))$

$(dst = 5.6.7.8 \land tag = b2,\ \ tag \leftarrow b;\ \text{NAT}(1.6.3.8, \star))$

$(src = 1.2.3.4 \land tag = b2,\ \ tag \leftarrow b;\ \text{NAT}(\star, 5.2.7.4))$

$(src = 1.2.3.4 \land tag = b1,\ \ tag \leftarrow b;\ \text{ACCEPT})$

$(true,\ \text{DROP})$

Programming network behaviour at high level

NetKAT: Kleene Algebra with Tests for Networks

Kleene Algebra for reasoning about network structure

Boolean Algebra for reasoning about switch behaviour

Packet Algebra for reasoning about packets

	$+$	$\cdot$	$\neg$	0	1
action (policy)	choice	composition		fail	skip
test (predicate)	disjunction	conjunction	negation	false	true

$f = n$ (test on a packet field) $f \leftarrow n$ (modification of a packet field)

Programming network behaviour at high level

Network topology : a NetKAT formula

Each Firewall configuration : NetKAT formula

Code Motion & Refactoring : Equational theory

Security property : NetKAT formula

Property verification : Equational theory

Compilation from real firewall languages to NetKAT

From IFCL to NetKAT is quite simple:

Ruleset : a NetKAT formula (a syntactic translation)

Control Diagram : as Network topology

Non-propagation of Tags : explicitly set to empty in ruleset

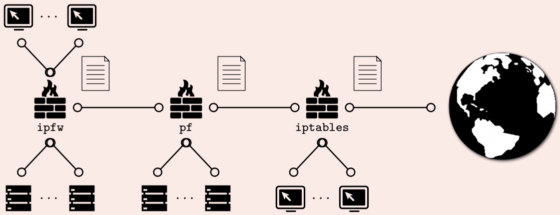
$$
[\![(\phi, t); R]\!] = \begin{cases}
(\!|\phi|\!) \cdot (\!|t|\!) + (\!|\neg\phi|\!) \cdot [\![\mathtt{R}]\!] & \text{if } t \in \{\texttt{ACCEPT}, \texttt{NAT}\} \\
(\!|\neg\phi|\!) \cdot [\![\mathtt{R}]\!] & \text{if } t = \texttt{DROP} \\
(\!|\phi|\!) \cdot (\!|t|\!) \cdot [\![\mathtt{R}]\!] + (\!|\neg\phi|\!) \cdot [\![\mathtt{R}]\!] & \text{if } t = \texttt{MARK}(m) \\
(\!|\phi|\!) \cdot [\![\mathtt{R'}]\!] + (\!|\neg\phi|\!) \cdot [\![\mathtt{R}]\!] & \text{if } t = \texttt{GOTO(R')} \\
(\!|\phi|\!) \cdot [\![\mathtt{R'}]\!] \cdot [\![\mathtt{R}]\!] + (\!|\neg\phi|\!) \cdot [\![\mathtt{R}]\!] & \text{if } t = \texttt{CALL(R')} \\
(\!|\phi|\!) + (\!|\neg\phi|\!) \cdot [\![\mathtt{R}]\!] & \text{if } t = \texttt{RETURN}
\end{cases}
$$

Compilation from NetKAT to real firewall languages

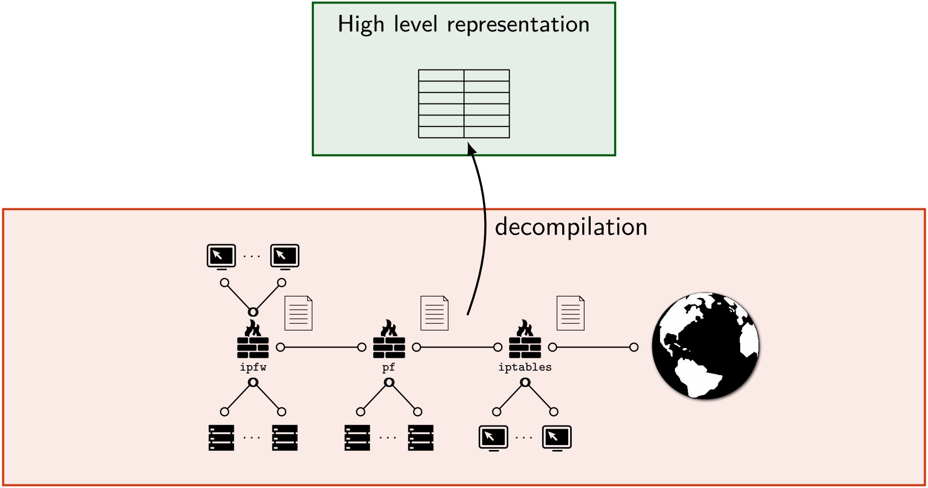
NetKAT for configuring traditional firewalls: NetKAT $\rightarrow$ specific language

- Each language corresponds to a **normal form**
- Equational **reduction** to the specific normal form
- **Compilation** from normal form of NetKAT to target language
- **Preserve the structure** of the original configuration **for free**

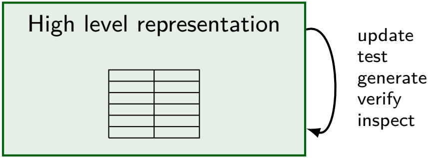
Our NEW Goal

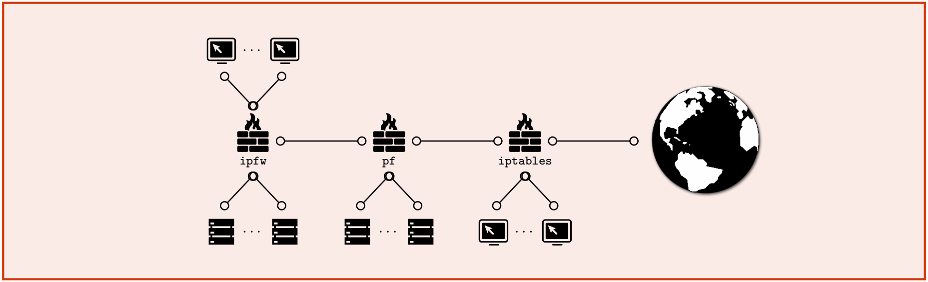


Our NEW Goal


High level representation
decompilation
ipfw
pf
iptables
...

Our NEW Goal


High level representation
update
test
generate
verify
inspect


ipfw
pf
iptables

Our NEW Goal