Verified Firewall Ruleset Verification

with Isabelle/HOL

Cornelius Diekmann

December 17, 2015

Introduction to Firewalls

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Chain INPUT (policy ACCEPT)
target      prot source          destination
DOS_PROTECT all  0.0.0.0/0       0.0.0.0/0
ACCEPT      all  0.0.0.0/0       0.0.0.0/0   state RELATED,ESTABLISHED
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DROP        tcp  0.0.0.0/0       0.0.0.0/0   multiport dports 21,873,5005,5006,80,548,...
DROP        udp  0.0.0.0/0       0.0.0.0/0   multiport dports 123,111,2049,892,5353
ACCEPT      all  192.168.0.0/16  0.0.0.0/0
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"*firewalls are (still) poorly configured*"

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"*firewalls are (still) poorly configured*"

"*tools do not understand real-world firewall rules*"

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C. Diekmann, L. Hupel, and G. Carle, Semantics-Preserving Simplification of Real-World Firewall Rule Sets, in Formal Methods (FM). Springer, pp. 195–212. Jun. 2015

A Tool for Ruleset Verification

Specification

- Documentation

Implementation

- Code, tool
- Performance

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- *What is a correct ruleset?*

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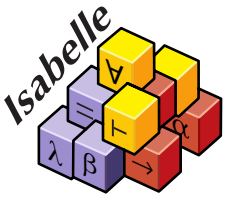

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`http://isabelle.in.tum.de/`

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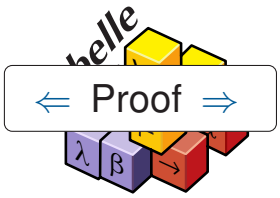

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Match Expressions: Syntax and Semantics

Syntax

- How to represent match expressions?

datatype *'a mexpr* = Match *'a* | MatchAny
| MatchNot *'a mexpr* | MatchAnd *'a mexpr* *'a mexpr*

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Polymorphic: arbitrary type *'a*

datatype *'a mexpr* = Match *'a* | MatchAny
| MatchNot *'a mexpr* | MatchAnd *'a mexpr* *'a mexpr*

Match Expressions: Syntax and Semantics

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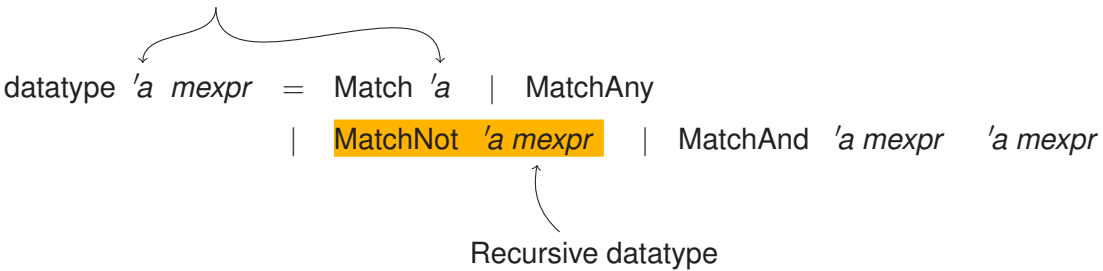

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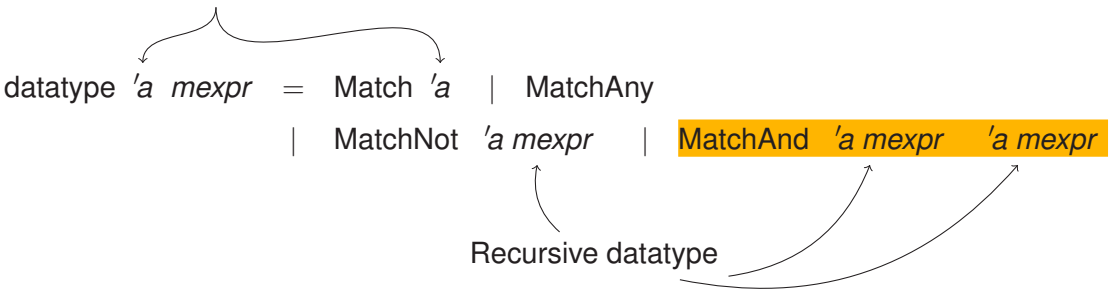

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Example:

MatchAnd (Match (DstIP 8.8.8.8)) (Match (Protocol TCP))

Match Expressions: Syntax and Semantics

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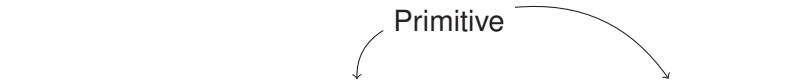

Match Expressions: Syntax and Semantics

Semantics

- What do match expressions mean?

$$matches :: \left('a \Rightarrow 'p \Rightarrow \mathbb{B}\right) \Rightarrow 'a\ mexpr \Rightarrow 'p \Rightarrow \mathbb{B}$$

$$\begin{aligned}
&\text{matches } \gamma \text{ (Match } a\text{) } p && \longleftrightarrow \gamma\ a\ p \\
&\text{matches } _ \text{ MatchAny } _ && \longleftrightarrow \text{True} \\
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$$matches :: (\text{'}a \Rightarrow \text{'}p \Rightarrow \mathbb{B}) \Rightarrow \text{'}a\ mexpr \Rightarrow \text{'}p \Rightarrow \mathbb{B}$$

matches γ (Match a) p $\longleftrightarrow \gamma\ a\ p$

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Iptables Semantics: Filtering Behavior

$$\textsc{Skip}\ \frac{}{\gamma, p \vdash \langle [],\ t\rangle \Rightarrow t} \qquad \textsc{Accept}\ \frac{\text{matches}\ \gamma\ m\ p}{\gamma, p \vdash \langle [(m,\ \texttt{Accept})],\ ?\rangle \Rightarrow \checkmark} \qquad \textsc{Drop}\ \frac{\text{matches}\ \gamma\ m\ p}{\gamma, p \vdash \langle [(m,\ \texttt{Drop})],\ ?\rangle \Rightarrow \times}$$

$$\textsc{Reject}\ \frac{\text{matches}\ \gamma\ m\ p}{\gamma, p \vdash \langle [(m,\ \texttt{Reject})],\ ?\rangle \Rightarrow \times} \qquad \textsc{NoMatch}\ \frac{\neg\ \text{matches}\ \gamma\ m\ p}{\gamma, p \vdash \langle [(m,\ a)],\ ?\rangle \Rightarrow ?} \qquad \textsc{Decision}\ \frac{t \neq ?}{\gamma, p \vdash \langle rs,\ t\rangle \Rightarrow t}$$

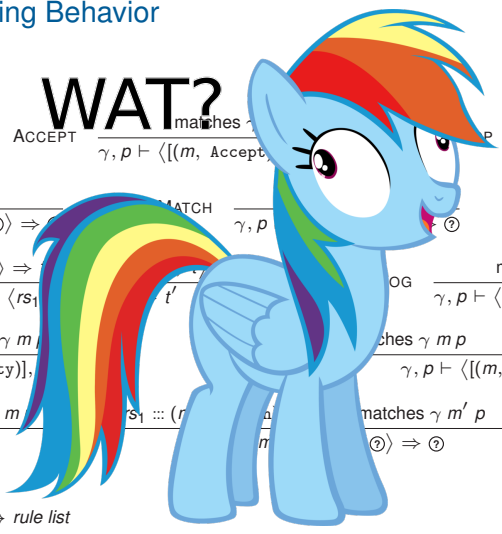
$$\textsc{Seq}\ \frac{\gamma, p \vdash \langle rs_1,\ ?\rangle \Rightarrow t \qquad \gamma, p \vdash \langle rs_2,\ t\rangle \Rightarrow t'}{\gamma, p \vdash \langle rs_1 :::: rs_2,\ ?\rangle \Rightarrow t'} \qquad \textsc{Log}\ \frac{\text{matches}\ \gamma\ m\ p}{\gamma, p \vdash \langle [(m,\ \texttt{Log})],\ ?\rangle \Rightarrow ?}$$

$$\textsc{Empty}\ \frac{\text{matches}\ \gamma\ m\ p}{\gamma, p \vdash \langle [(m,\ \texttt{Empty})],\ ?\rangle \Rightarrow ?} \qquad \textsc{CallResult}\ \frac{\text{matches}\ \gamma\ m\ p \qquad \gamma, p \vdash \langle \Gamma\ c,\ ?\rangle \Rightarrow t}{\gamma, p \vdash \langle [(m,\ \texttt{Call}\ c)],\ ?\rangle \Rightarrow t}$$

$$\textsc{CallReturn}\ \frac{\text{matches}\ \gamma\ m\ p \qquad \Gamma\ c = rs_1 :::: (m',\ \texttt{Return}) :: rs_2 \qquad \text{matches}\ \gamma\ m'\ p \qquad \gamma, p \vdash \langle rs_1,\ ?\rangle \Rightarrow ?}{\gamma, p \vdash \langle [(m,\ \texttt{Call}\ c)],\ ?\rangle \Rightarrow ?}$$

Background ruleset Γ : *chain name* $\rightarrow$ *rule list*

Iptables Semantics: Filtering Behavior



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$$\textsc{Drop}\ \frac{\text{matches } \gamma\ m\ p}{\gamma, p \vdash \langle [(m,\ \texttt{Drop})],\ \textcircled{?}\rangle \Rightarrow \text{✗}}$$

$$\textsc{Reject}\ \frac{\text{matches } \gamma\ m\ p}{\gamma, p \vdash \langle [(m,\ \texttt{Reject})],\ \textcircled{?}\rangle \Rightarrow \text{✗}}$$

$$\textsc{Match}\ \frac{\gamma, p \vdash \langle rs,\ \textcircled{?}\rangle \Rightarrow \textcircled{?}}{\gamma, p \vdash \langle [(m,\ \texttt{Match}\ ms)] @ rs,\ \textcircled{?}\rangle \Rightarrow \textcircled{?}}$$

$$\textsc{Decision}\ \frac{t \neq \textcircled{?}}{\gamma, p \vdash \langle rs,\ t\rangle \Rightarrow t}$$

$$\textsc{Seq}\ \frac{\gamma, p \vdash \langle rs_1,\ \textcircled{?}\rangle \Rightarrow t' \qquad t' \neq \textcircled{?}}{\gamma, p \vdash \langle rs_1 @ rs_2,\ \textcircled{?}\rangle \Rightarrow t'}$$

$$\textsc{Log}\ \frac{\text{matches } \gamma\ m\ p}{\gamma, p \vdash \langle [(m,\ \texttt{Log})],\ \textcircled{?}\rangle \Rightarrow \textcircled{?}}$$

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$$\textsc{Call}\ \frac{\text{matches } \gamma\ m\ p \qquad \gamma, p \vdash \langle \Gamma\ c,\ \textcircled{?}\rangle \Rightarrow t}{\gamma, p \vdash \langle [(m,\ \texttt{Call}\ c)],\ \textcircled{?}\rangle \Rightarrow t}$$

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Background ruleset Γ : *chain name* $\rightarrow$ *rule list*

Semantics Explained

$$\gamma\ ,\quad p \vdash \left\langle rs\ ,\quad s \right\rangle \Rightarrow\ t$$

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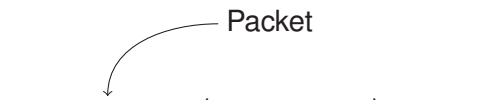

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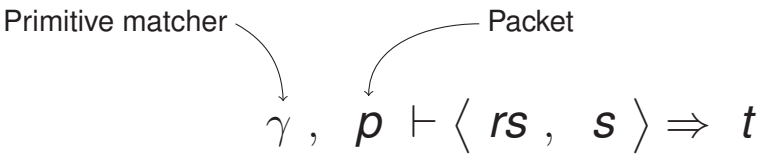

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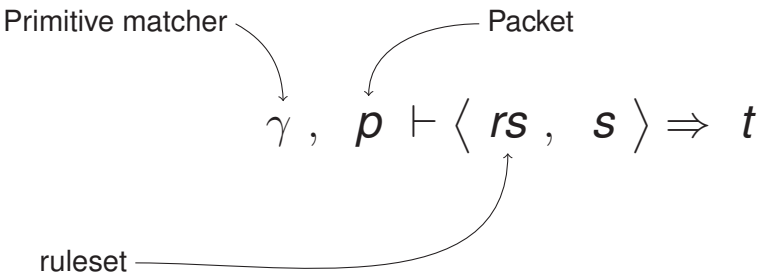

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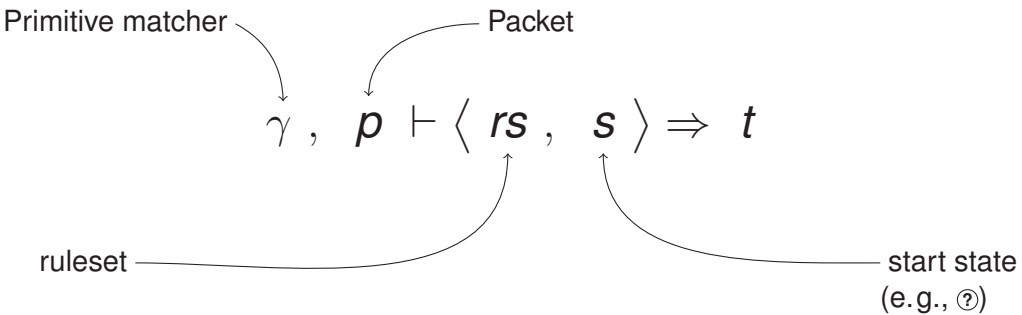

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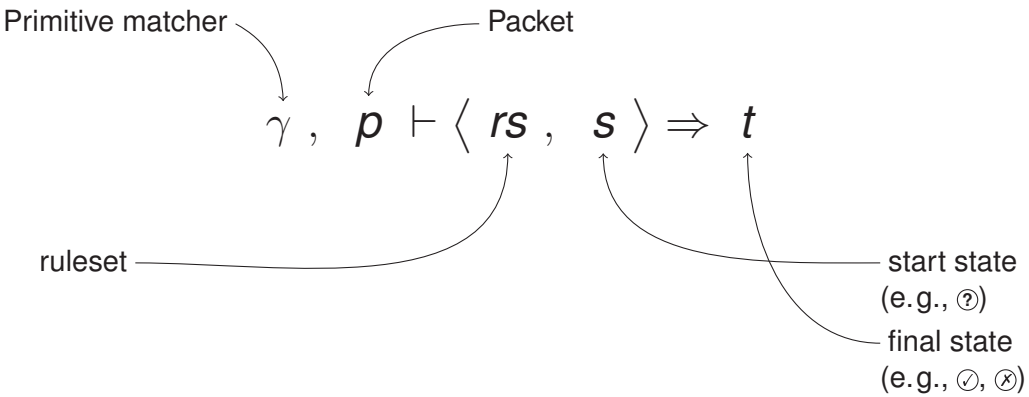

Semantics Explained: SKIP

$$\frac{}{\gamma, p \vdash \langle [],\ t \rangle \Rightarrow t}$$

Semantics Explained: SKIP

Precondition

$$\frac{}{\gamma, p \vdash \langle [],\ t \rangle \Rightarrow t}$$

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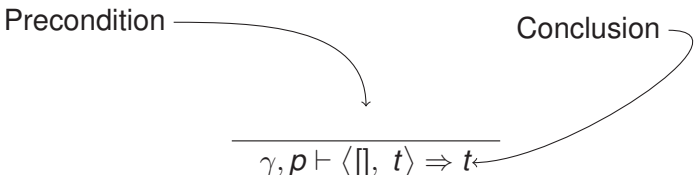

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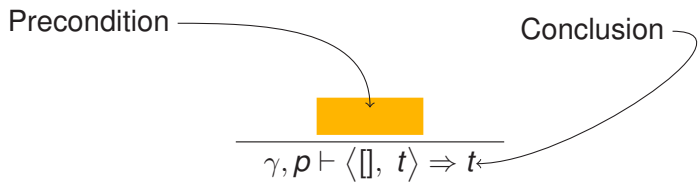

- no precondition
  - Holds unconditionally

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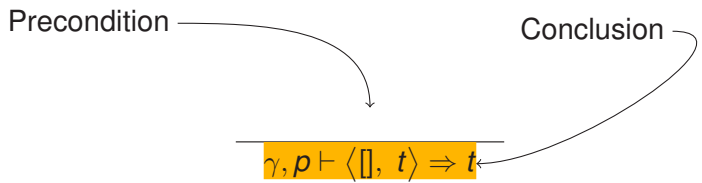

- no precondition
  - Holds unconditionally
  - IF TRUE then $\gamma, p \vdash \langle [],\ t \rangle \Rightarrow t$

Semantics Explained: SKIP

$$\frac{}{\gamma, p \vdash \langle [],\ t \rangle \Rightarrow t}$$

Semantics Explained: SKIP

$$\gamma, p \vdash \langle [], t \rangle \Rightarrow t$$

- Empty Ruleset

Semantics Explained: SKIP

$$\frac{}{\gamma, p \vdash \langle [],\ t \rangle \Rightarrow t}$$

- Empty Ruleset
- Start state equals final state

Semantics Explained: SKIP

$$\frac{}{\gamma, p \vdash \langle [],\ t \rangle \Rightarrow t}$$

- Empty Ruleset
- Start state equals final state
- For the empty ruleset, the firewall does nothing

Semantics Explained: ACCEPT

$$\frac{\text{matches } \gamma\ m\ p}{\gamma, p \vdash \langle [(m,\ \texttt{Accept})],\ ? \rangle \Rightarrow \checkmark}$$

Semantics Explained: ACCEPT

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- Ruleset: single rule

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$$\frac{\text{matches } \gamma\ m\ p}{\gamma, p \vdash \langle [(m,\ \texttt{Accept})],\ ?\rangle \Rightarrow \checkmark}$$

- Ruleset: single rule
- matches

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- Ruleset: single rule
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- The action of the rule is `Accept` rule

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- Ruleset: single rule
- matches
- The action of the rule is `Accept` rule
- The firewall does not have a decision yet
- It will accept the packet
- A matching `Accept` rule accepts packets

Semantics Explained: CallReturn

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- The called chain c in the background ruleset Γ is defined as $rs_1 :::: (m',\ \texttt{Return}) :: rs_2$

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- First part rs_1 is processed without result

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- The called chain c in the background ruleset Γ is defined as $rs_1 ::: (m',\ \texttt{Return}) :: rs_2$
- First part rs_1 is processed without result
- Then there is a matching `Return`
- Calling to user-defined chain and return without result

Semantics Explained: CallReturn

$$\frac{\text{matches } \gamma\ m\ p \qquad \Gamma\ c = rs_1 :::\ (\ldots) :: rs_2 \qquad \text{matches } \gamma\ m'\ p \qquad \gamma, p \vdash \langle rs_1,\ ⑦\rangle \Rightarrow ⑦}{\ldots\ \texttt{all}\ c)],\ ⑦\rangle \Rightarrow ⑦}$$

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- Calling to user-defined chai… ut result

Semantics-Preserving Simplification

$$\gamma, p \vdash \langle rs,\ s \rangle \Rightarrow t \quad \textit{iff} \quad \gamma, p \vdash \langle \mathrm{f}\ rs,\ s \rangle \Rightarrow t$$

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- Removing `Log` rules

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- Removing `Log` rules
- Unfolding of user-defined chains

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- f does not change filtering behavior of firewall

- Removing `Log` rules
- Unfolding of user-defined chains
- Normalizing match expressions, ...

Embedding in Ternary Logic

$\mathbb{B} = \{\mathit{True}, \mathit{False}\}$ $\quad$ $\mathit{Ternary} = \{\mathit{True}, \mathit{False}, \mathit{Unknown}\}$

$$\Big\{p \mid \text{approx\_firewall } \gamma \text{ stricter } \mathit{rs} = \text{✓}\Big\}$$
$$\subseteq$$
$$\{p \mid \gamma, p \vdash \langle \mathit{rs}, \text{?} \rangle \Rightarrow \text{✓}\}$$
$$\subseteq$$
$$\Big\{p \mid \text{approx\_firewall } \gamma \text{ permissive } \mathit{rs} = \text{✓}\Big\}$$

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- Set of packets accepted by the firewall

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$$\subseteq$$
$$\{p \mid \gamma, p \vdash \langle rs,\ \text{?}\rangle \Rightarrow \text{✓}\} \longleftarrow \text{not executable}$$
$$\subseteq$$
$$\Big\{p \mid \text{approx\_firewall } \gamma \text{ permissive } rs = \text{✓}\Big\}$$

- Set of packets accepted by the firewall
- We can specify a lot . . .

Embedding in Ternary Logic

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executable

$$\Big\{p \mid \text{approx\_firewall } \gamma \text{ stricter } rs = \textcircled{✓}\Big\}$$

$$\subseteq$$

$$\{p \mid \gamma, p \vdash \langle rs,\ \textcircled{?}\rangle \Rightarrow \textcircled{✓}\}$$ not executable

$$\subseteq$$

$$\Big\{p \mid \text{approx\_firewall } \gamma \text{ permissive } rs = \textcircled{✓}\Big\}$$

executable

- Set of packets accepted by the firewall
- We can specify a lot . . . but we also believe in running code

Spoofing Protection

ipassmt :: *interface* $\Rightarrow$ *IP set*
Example:

$$ipassmt = [\texttt{eth0} \mapsto 192.168.0.0/24]$$

Spoofing Protection:

$$\{p.\text{src\_ip} \mid p.\text{in\_iface} = \texttt{eth0} \wedge \gamma, p \vdash \langle rs, ⍰ \rangle \Rightarrow ✓\} \subseteq 192.168.0.0/24$$

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Example:

$$\mathit{ipassmt} = [\texttt{eth0} \mapsto 192.168.0.0/24]$$

Spoofing Protection:

$$\forall \texttt{eth} \in \mathit{ipassmt}.\text{keys}$$
$$\{p.\text{src\_ip} \mid p.\text{in\_iface} = \texttt{eth} \wedge \gamma, p \vdash \langle \mathit{rs},\ ⍰ \rangle \Rightarrow ✓\} \subseteq \mathit{ipassmt}.\text{get}(\texttt{eth})$$

Spoofing Protection

ipassmt :: *interface* $\Rightarrow$ *IP set*
Example:

$$ipassmt = [\texttt{eth0} \mapsto 192.168.0.0/24]$$

Spoofing Protection:

check_spoofing_protection *ipassmt rs* $\longrightarrow$

$$\forall \texttt{eth} \in ipassmt.\text{keys}$$
$$\{p.\text{src\_ip} \mid p.\text{in\_iface} = \texttt{eth} \wedge \gamma, p \vdash \langle rs,\ ? \rangle \Rightarrow \checkmark\} \subseteq ipassmt.\text{get}(\texttt{eth})$$

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Example:

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$$\text{check\_spoofing\_protection } ipassmt\ rs \longrightarrow$$
$$\forall \texttt{eth} \in ipassmt.\text{keys}$$
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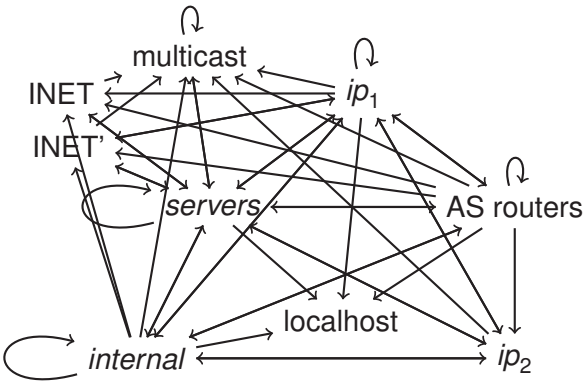
diekmann@xps12: ~/git/Iptables_Semantics/beta_haskell_tool

```
$ iptables-save | ./check_spoofing_protection ipassmt_tumi8
loading ipassmt from `ipassmt_tumi8'
Parsed IpAssmt
sanity_wf_ruleset passed
Parsed 90 chains in table filter, a total of 4813 rules
Table `nat' : `Reading ruleset failed! sanity_wf_ruleset check failed.'.
Table `raw' : `Reading ruleset failed! sanity_wf_ruleset check failed.'.
sanity_wf_ruleset passed
(eth0,True)
(foo,False)
(eth1.96,True)
(eth1.108,True)
(eth1.109,True)
(eth1.110,False)
(eth1.116,True)
(eth1.152,True)
(eth1.171,True)
(eth1.173,True)
(eth1.1010,True)
(eth1.1011,True)
```

Service Matrix



- Partitions complete IPv4 space
- All IP addresses in each group have same access rights
- Cannot be compressed any further

Sources

Firewall Rulesets ← plz contribute

`https://github.com/diekmann/net-network`

Isabelle Theories + Haskell Tool:

`https://github.com/diekmann/Iptables_Semantics`