Building Extensible Networks with Rule-Based Forwarding

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Making Internet forwarding flexible

- A network's core functionality is to forward packets
  - "Power" of a network ⇔ flexibility of its forwarding plane

- A long-held goal: ***flexible*** forwarding

Making Internet forwarding flexible

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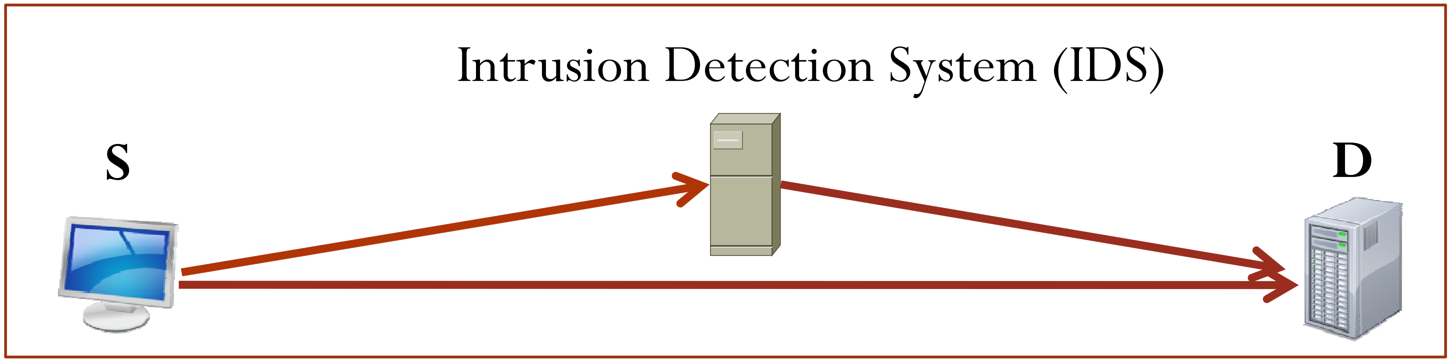
- Example: Middlebox-aware forwarding



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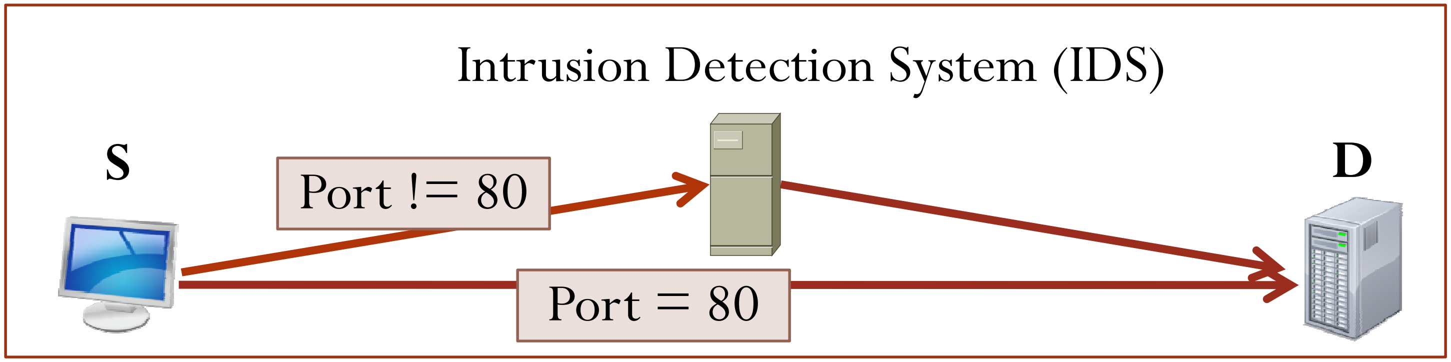

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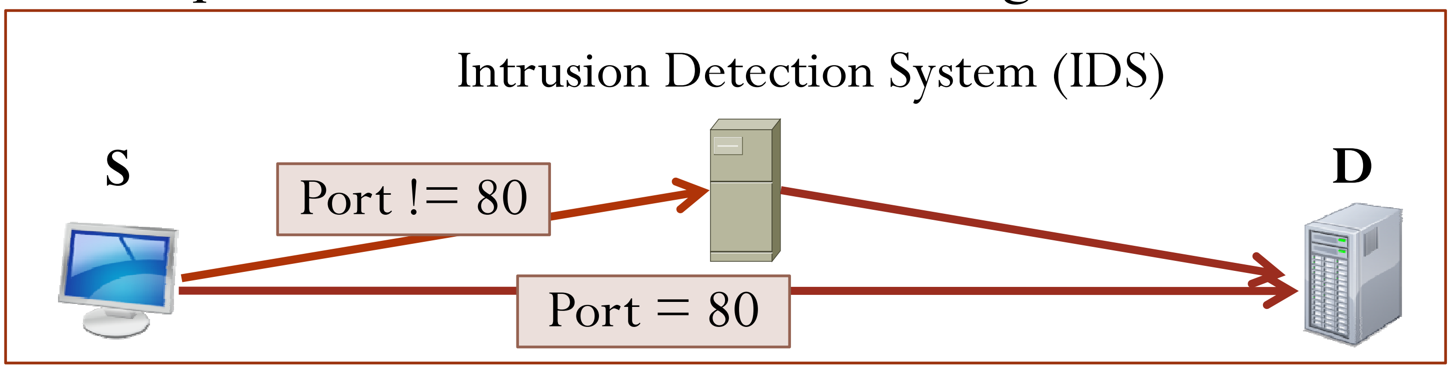

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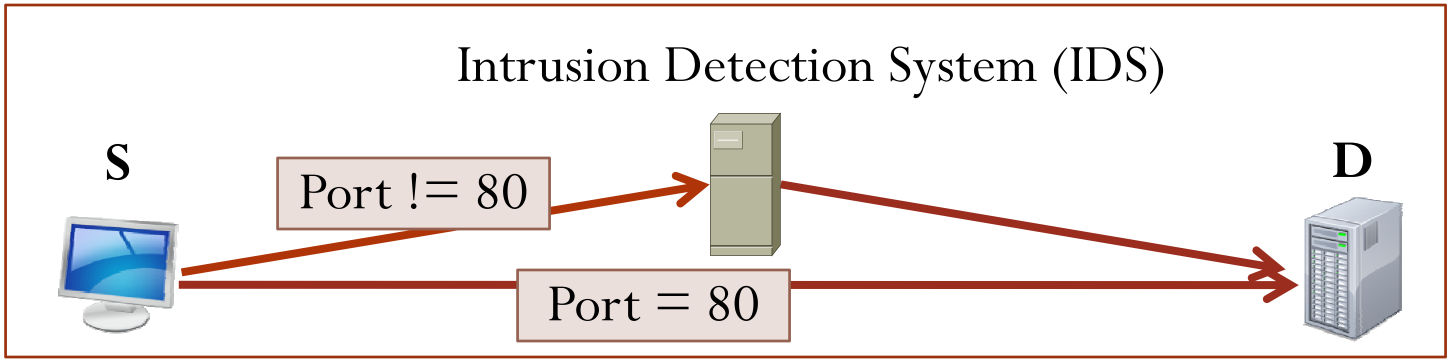

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- Using general *forwarding directives* – instructions to the network on how to forward packets

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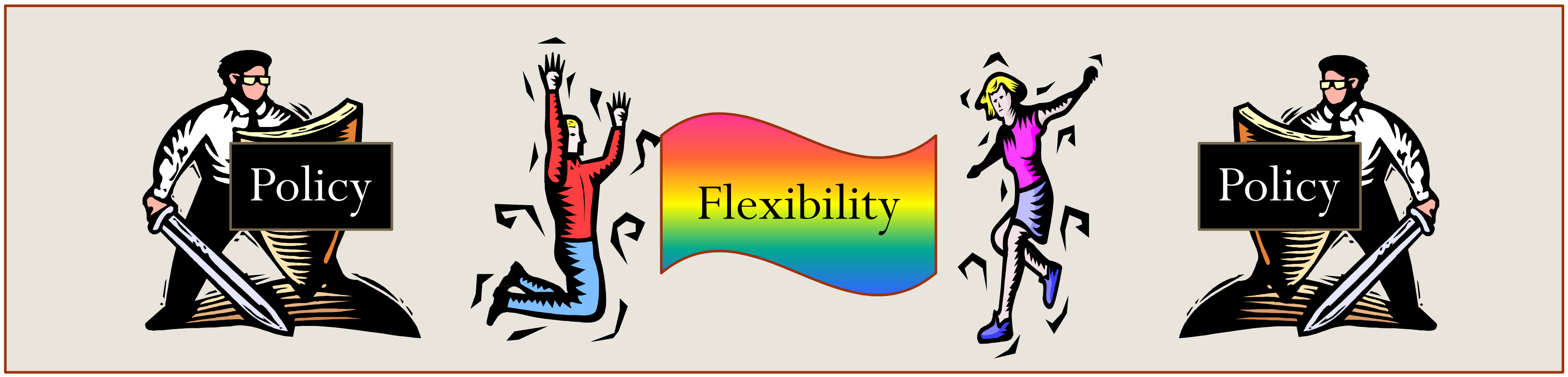

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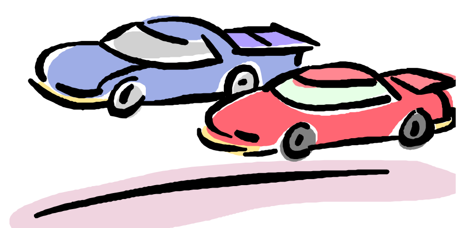

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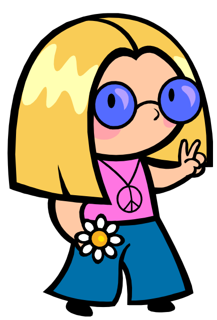

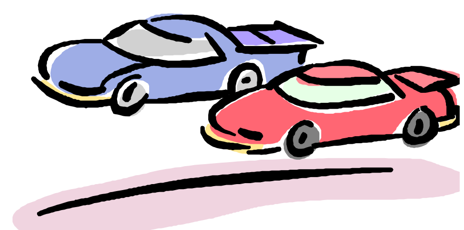

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  1. A car can be driven only by its owner
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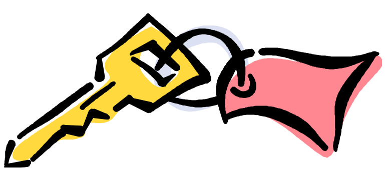
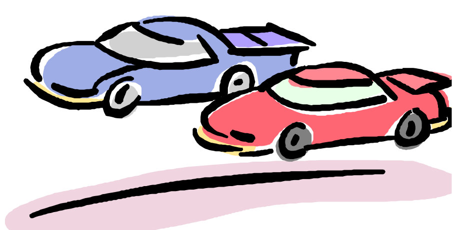
  3. Can only drive a car with the *approval* of its owner





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Constrain forwarding directives

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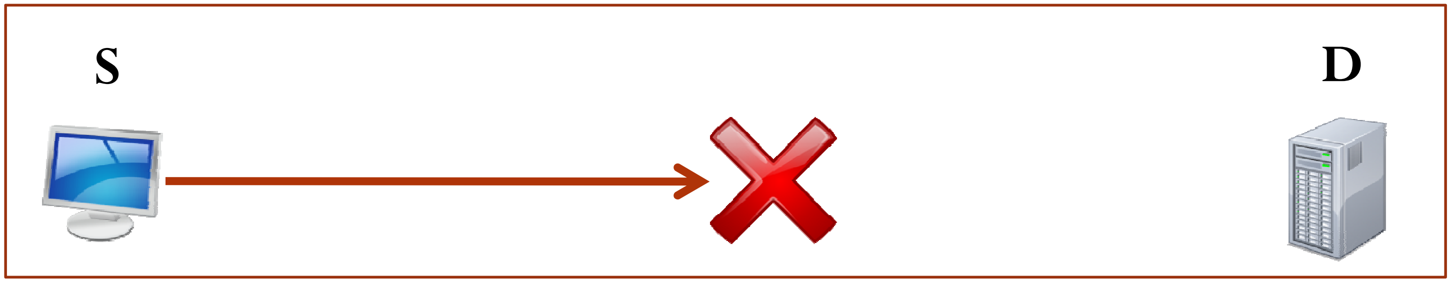
- Example: apply thesis to current Internet
  - Forwarding directive = Send to destination **D**
  - Policy of **D** = No packets from **S**
  - Not respected in the current Internet



Constrain forwarding directives

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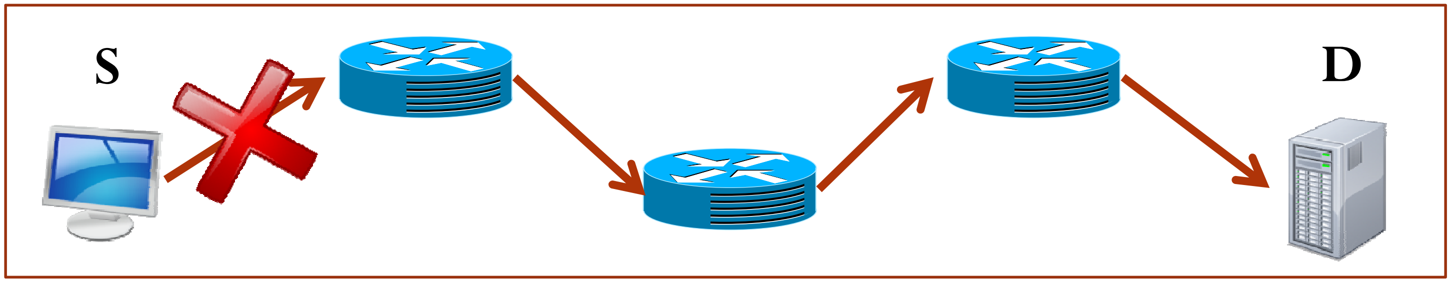
- Example: IP source routing
  - Option available with current IP spec
  - Not supported by ISPs since there is no way to constrain it
  - Desirable: ISPs get to approve source routes



Constrain forwarding directives

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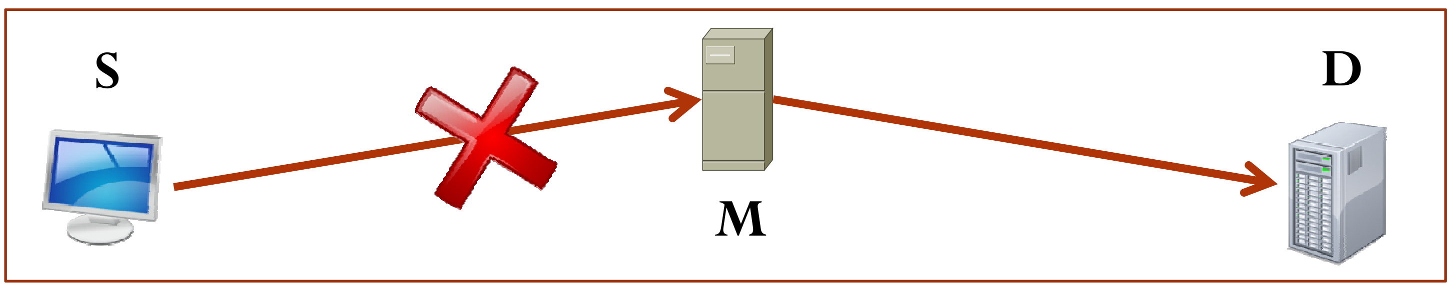
- Example: Middlebox-aware forwarding
  - Allows use of in-network processing
  - Policy of **M**: only process S-D traffic



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Policy-compliance

Goal

- ***Flexible and*** P***olicy-Compliant*** architecture
  - Flexible: path control, use in-network functionality and state
  - Policy-compliant: all stakeholders' policies are respected

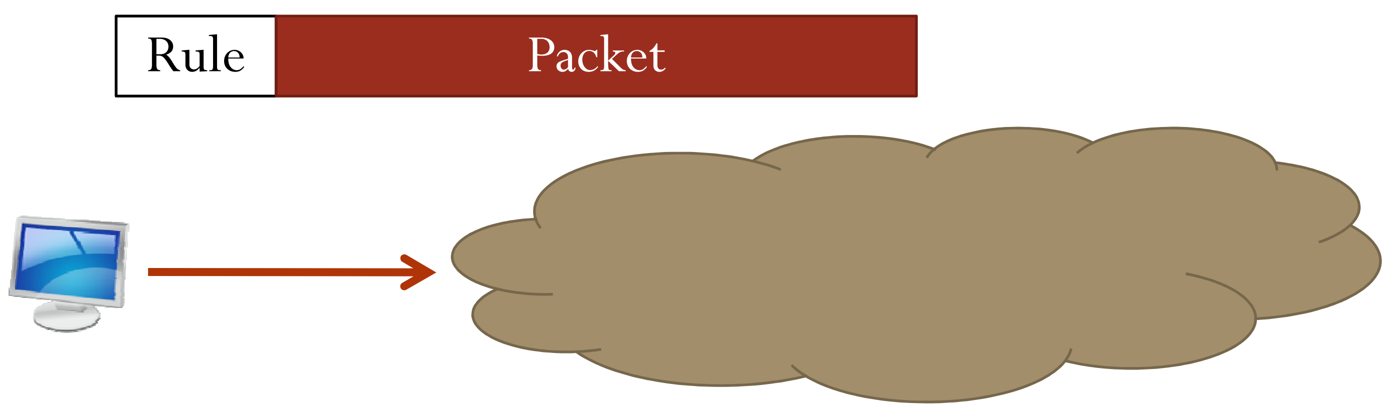
Flexibility

Policy Compliance

Idea: Packet Rule

- Forwarding directives carried *in packet*

- Current Internet – packet sent to destination
- Rule Based Forwarding – packet sent to rule



Idea: Packet Rule

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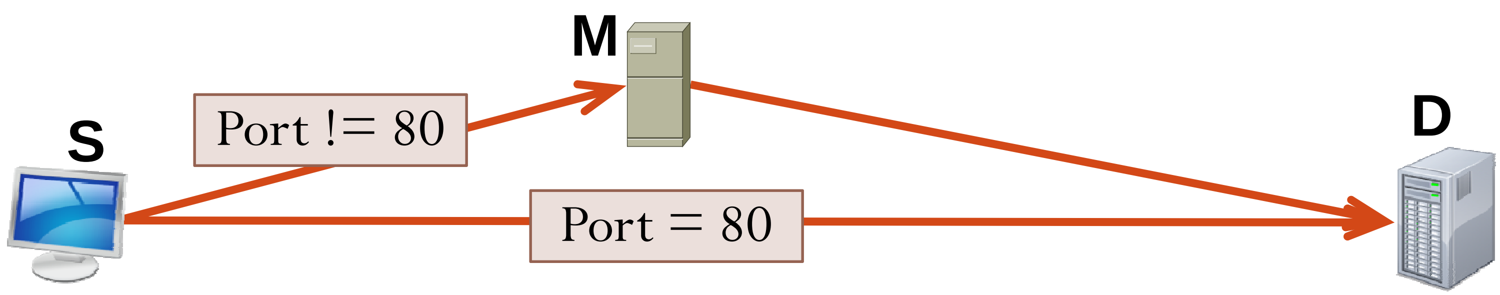
```
Rule:
  if(packet.dest_port == 80)
    sendto D
  else
    sendto M
…
```



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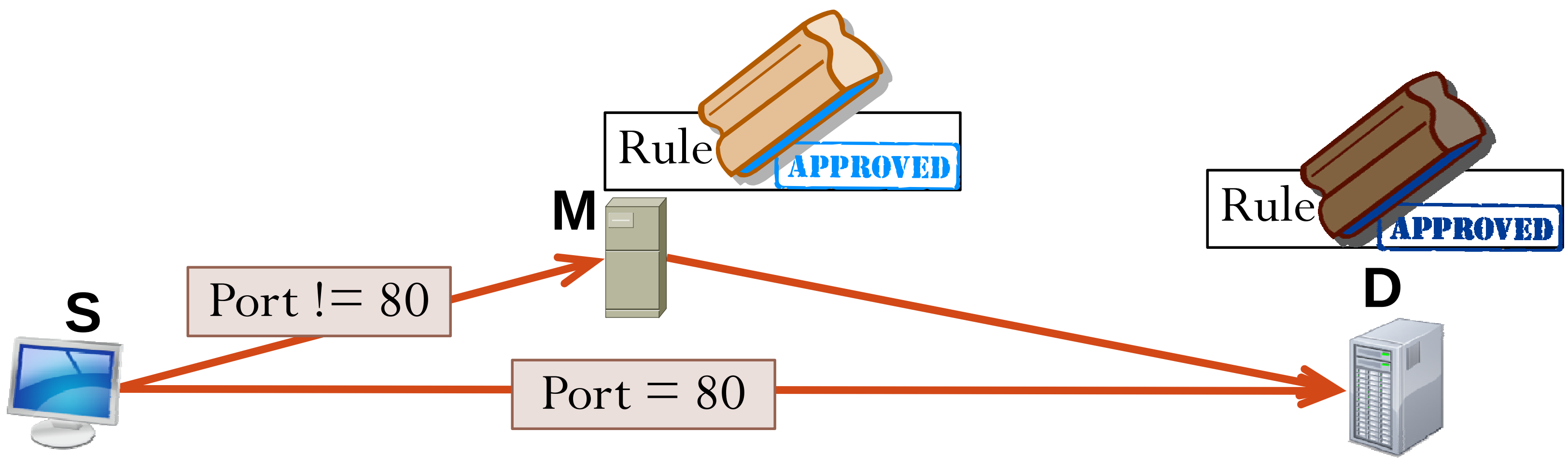

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Encapsulates proof of policy-compliance

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Idea: Packet Rule

- ***Rules naturally tie in flexibility and policy-compliance***

Specifies flexible directives

Rule

Encapsulates proof of policy-compliance

Policies approve/disapprove rule

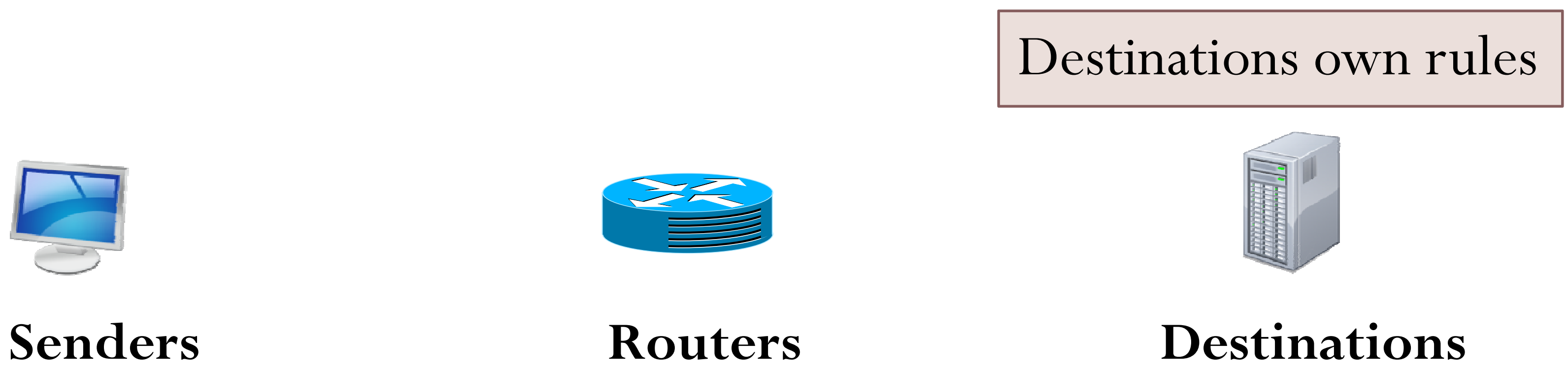
Routers only need information in packet (rule) to:

- Forward the packet
- Verify that it complies with policies of all parties

Outline

- Motivation & Solution Overview
- Rule-Based Forwarding Architecture – Overview
- Rule Forwarding Mechanism & Examples
- Evaluation

Rule-Based Forwarding (RBF) Architecture



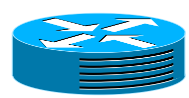
Rule-Based Forwarding (RBF) Architecture

RCE

For policy-compliance, rules are *certified* by trusted entities – **Rule Certification Entities** (RCEs)

D

Senders

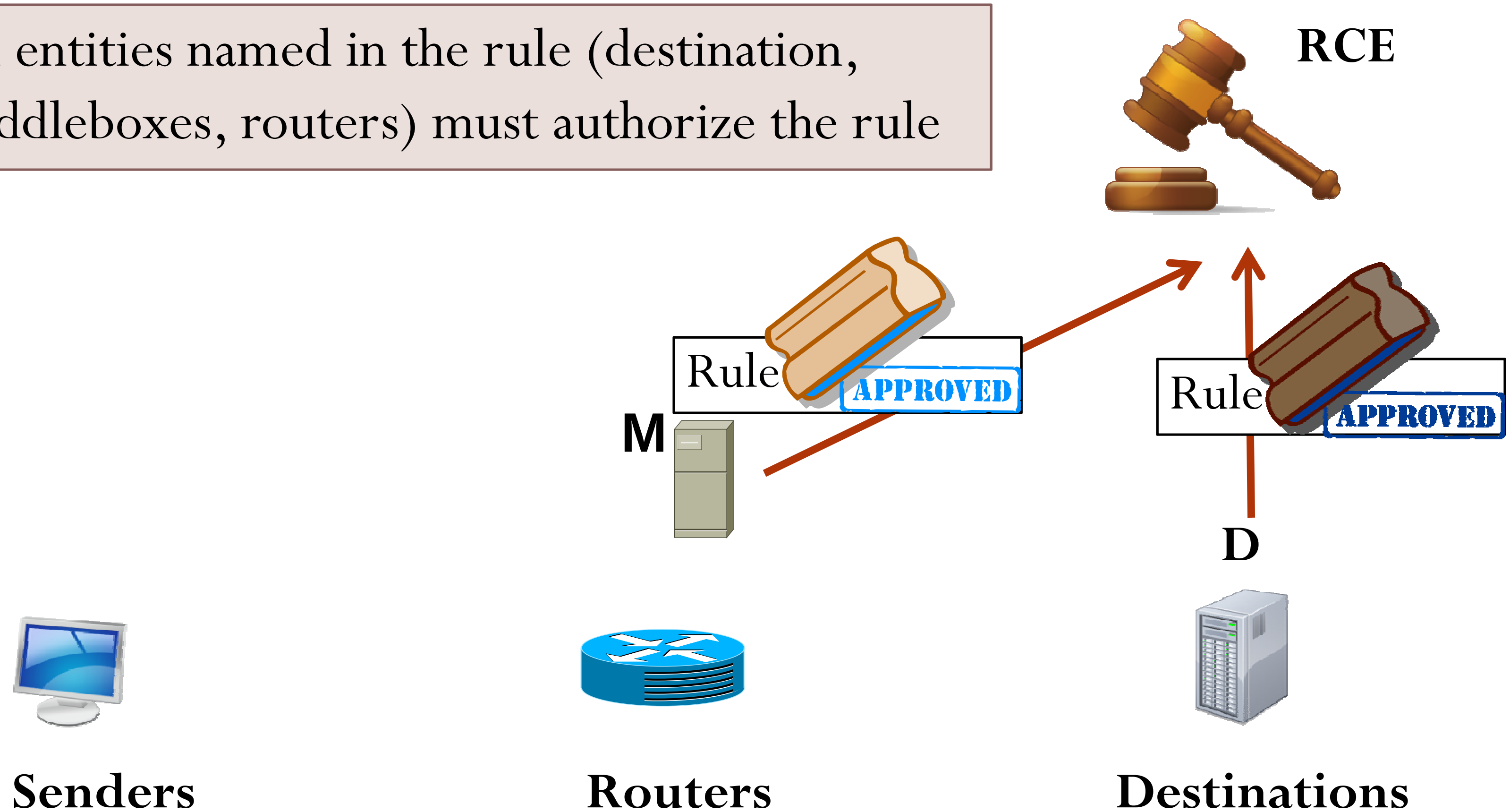


Routers

Destinations

Rule-Based Forwarding (RBF) Architecture

All entities named in the rule (destination, middleboxes, routers) must authorize the rule



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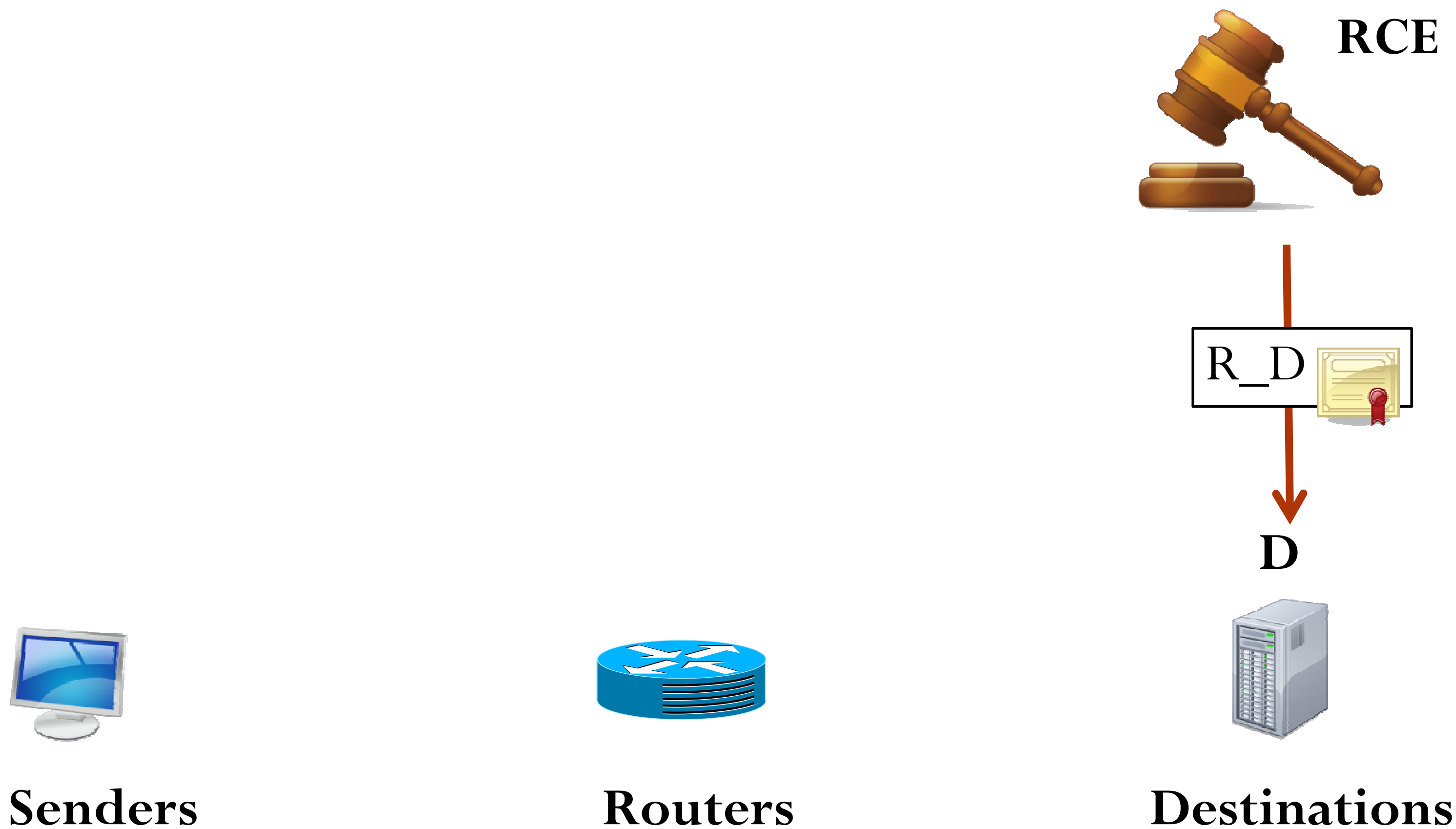

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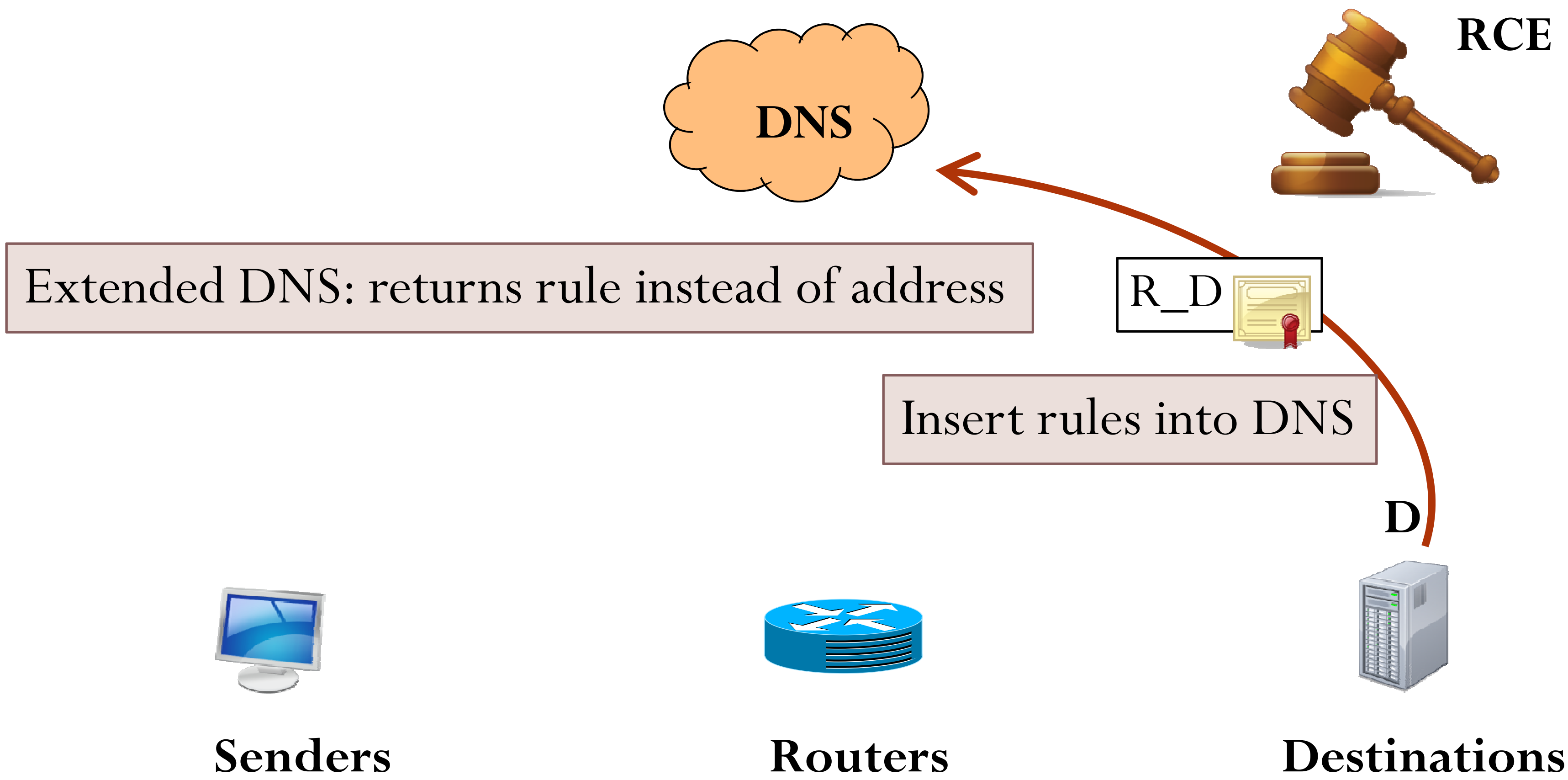

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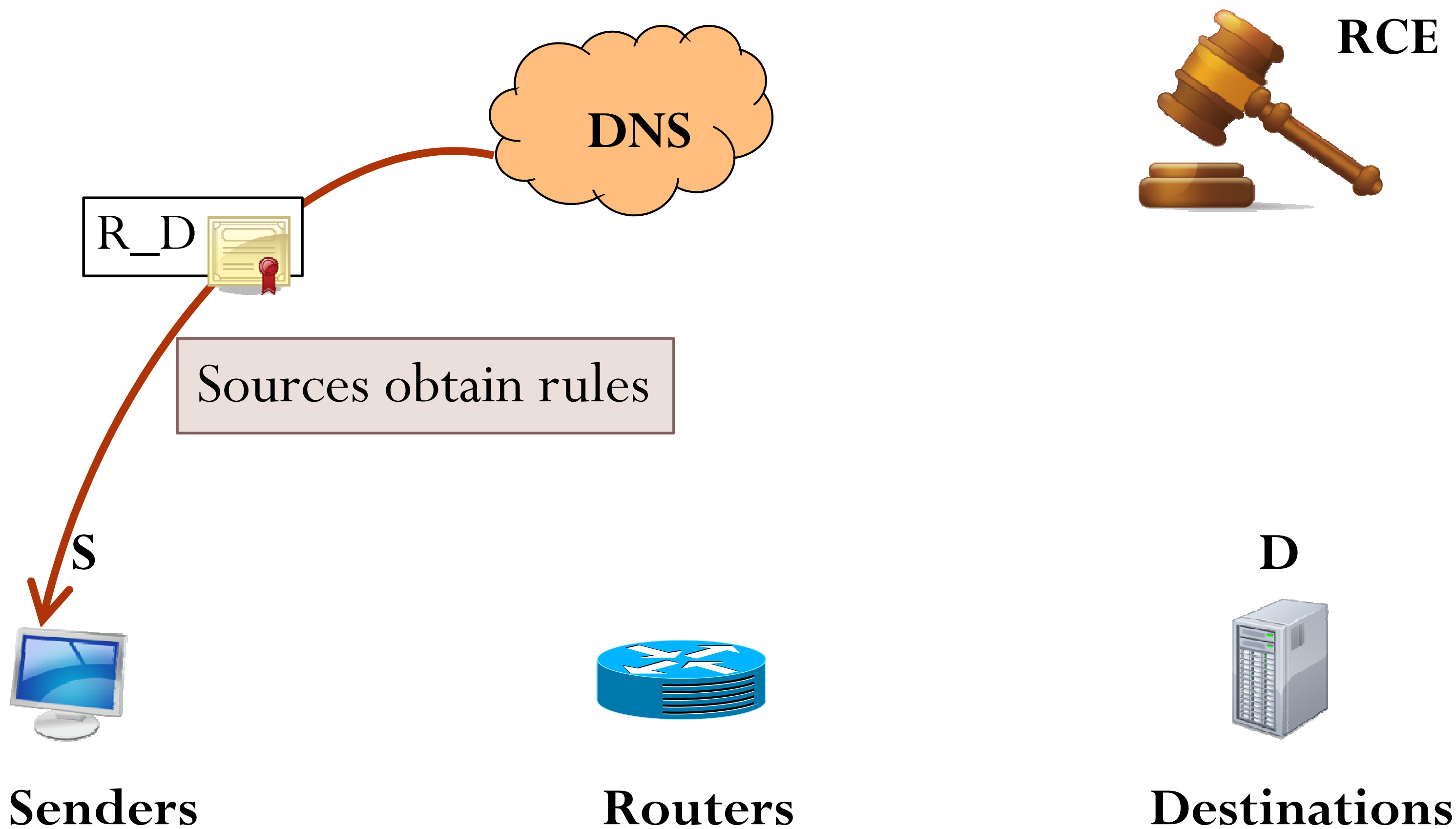

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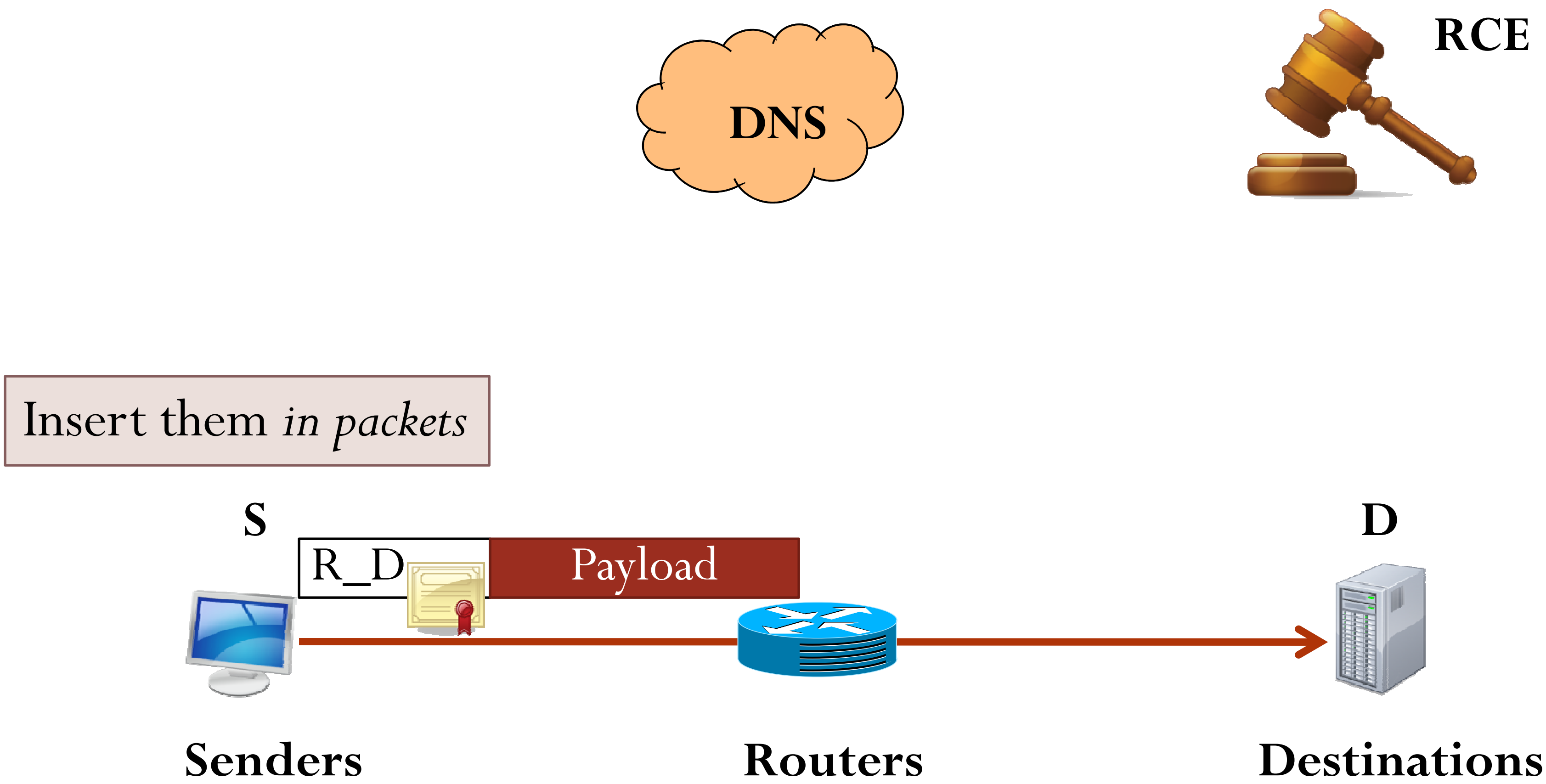

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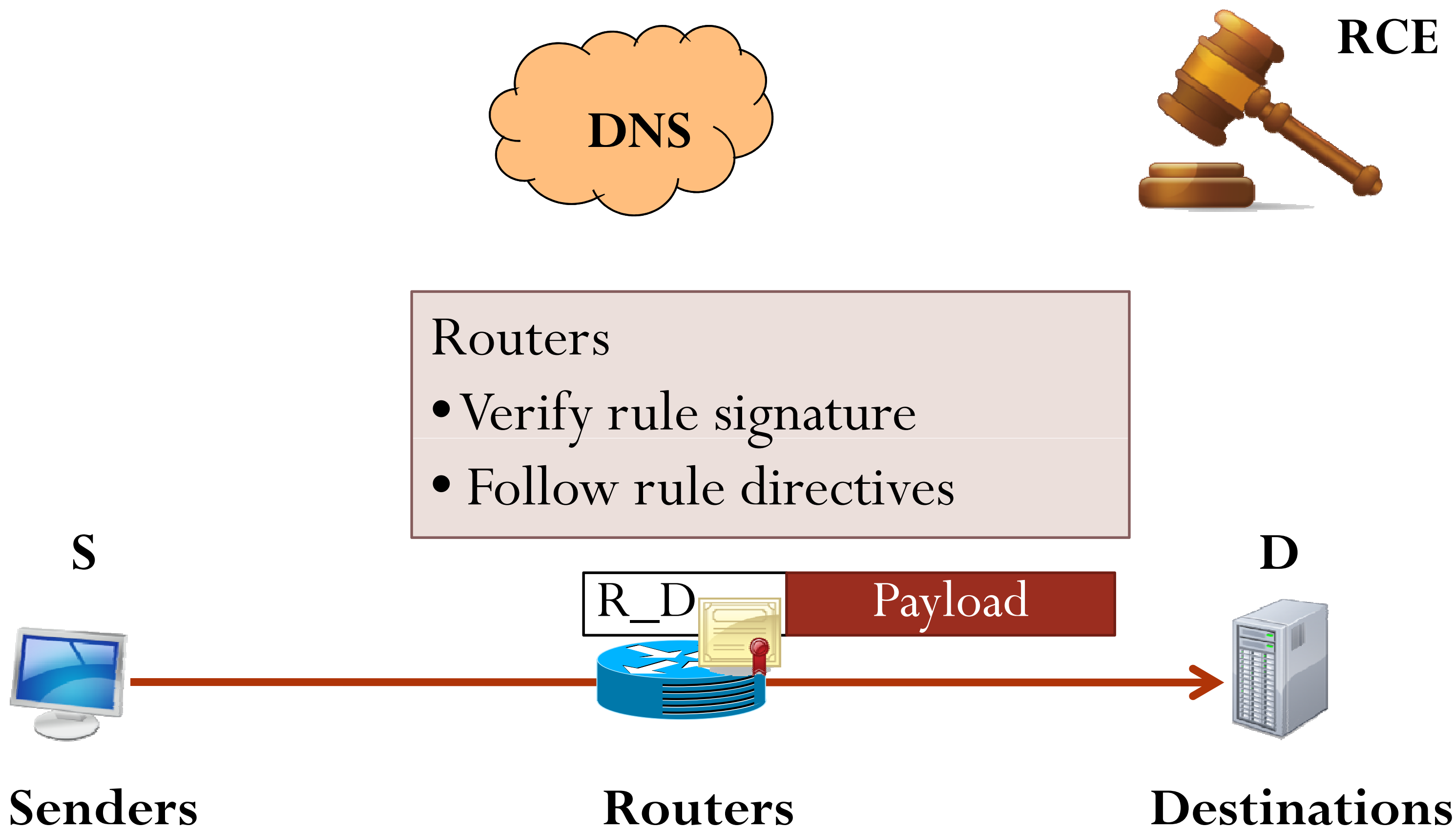

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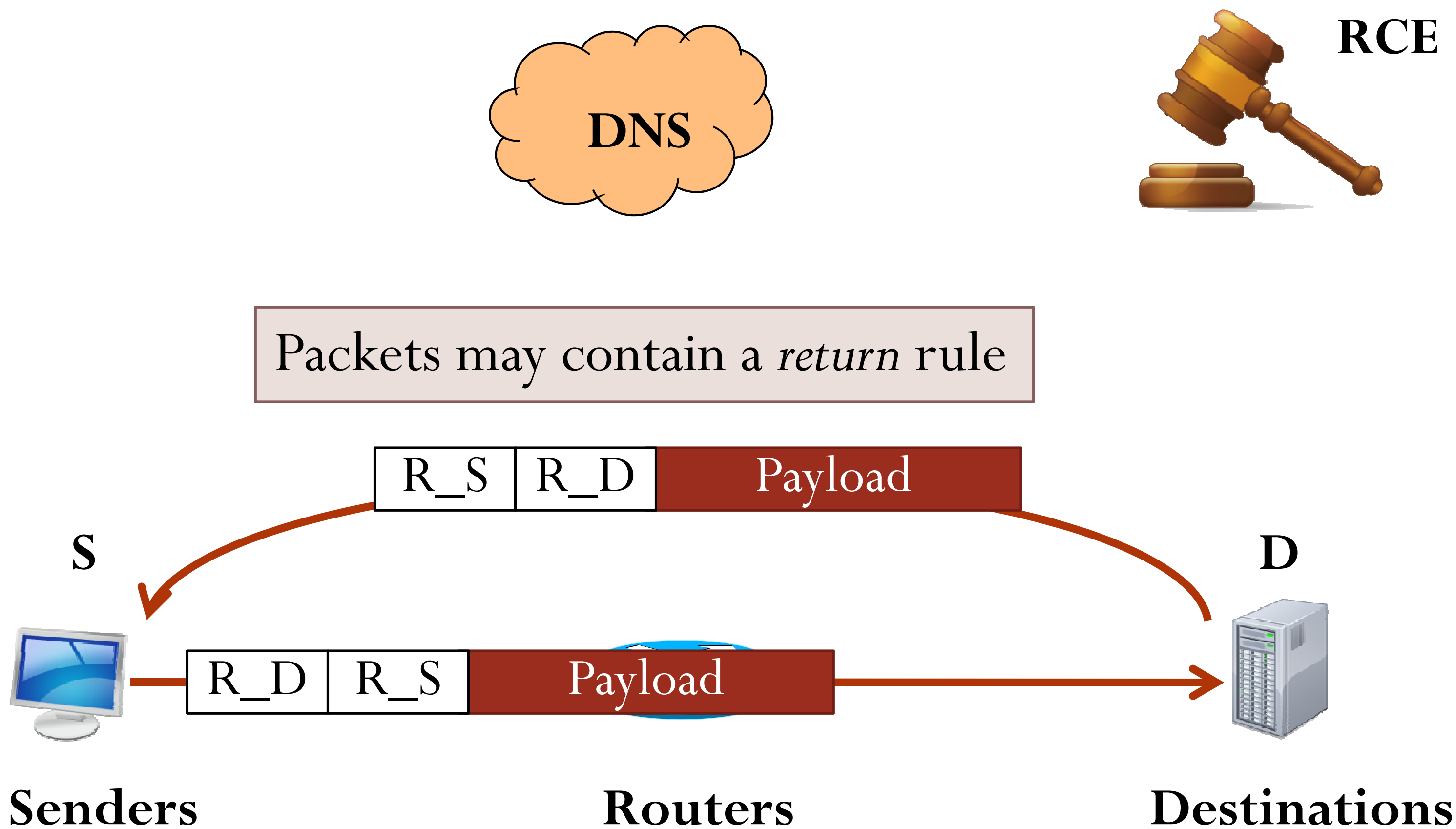

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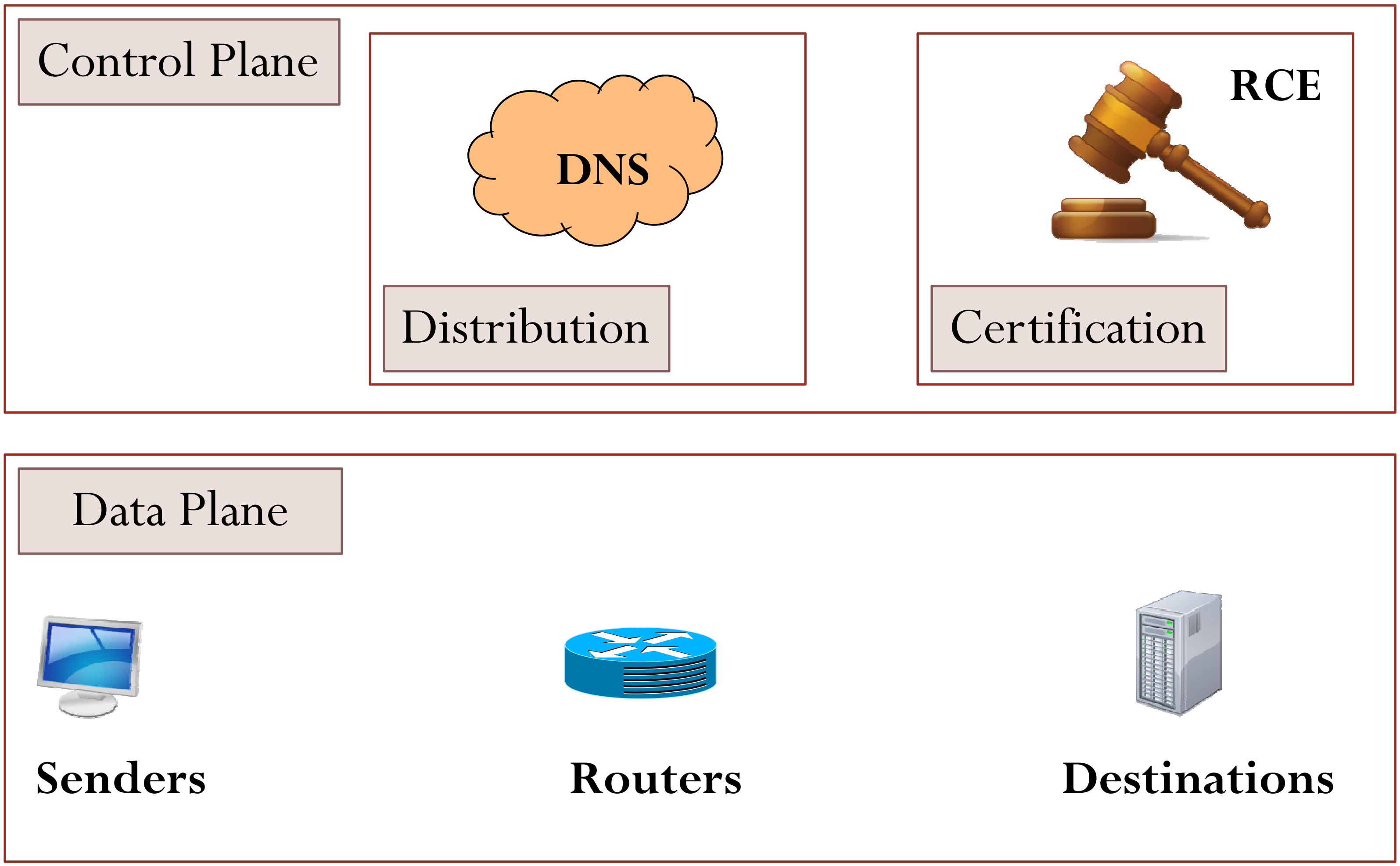

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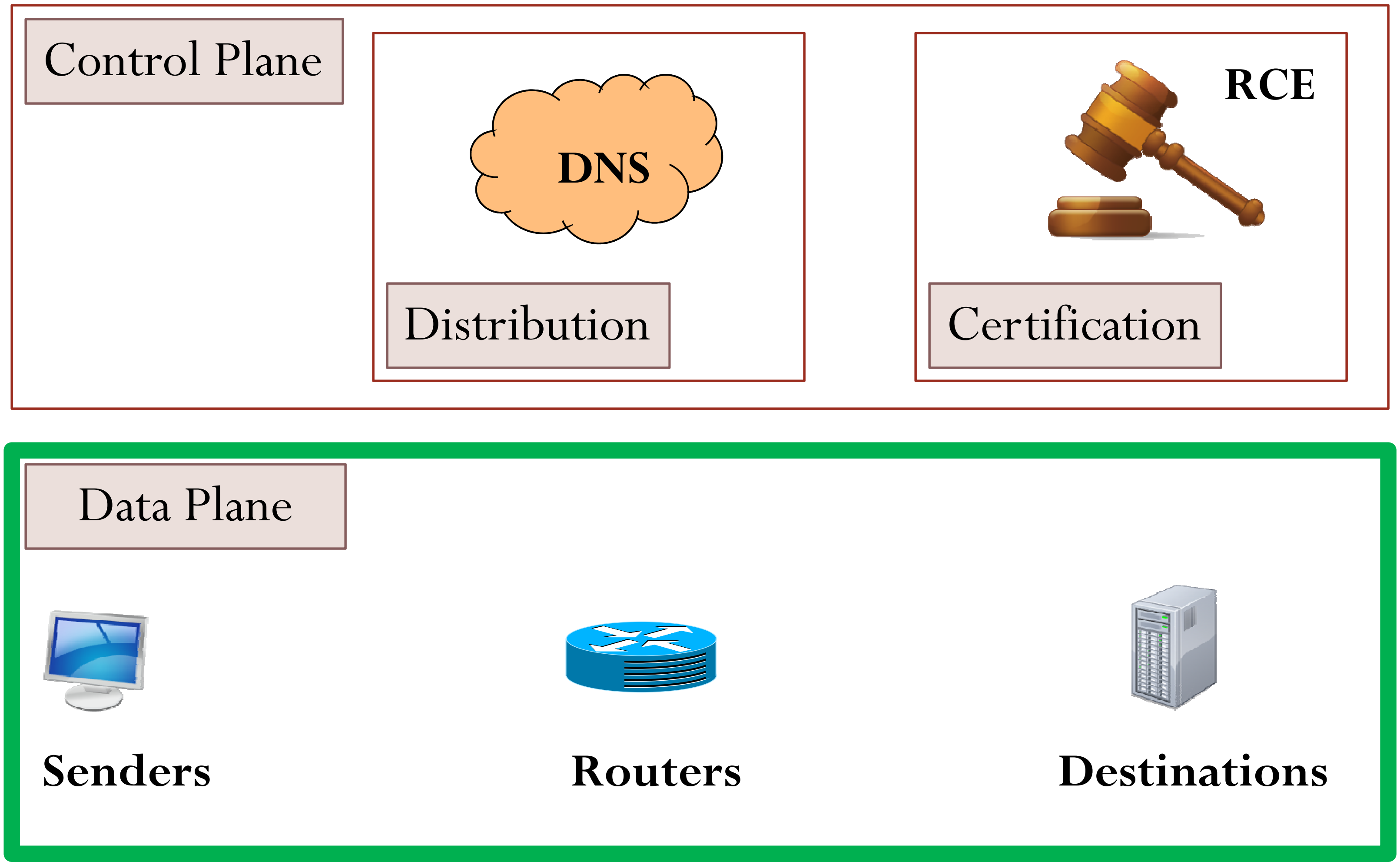

RBF Assumptions

- Anti-spoofing mechanism
  - Ingress filtering
- Existence of Rule Certifying Entities and distribution of RCE keys to routers
  - RCEs few large Verisign-like entities or AS based
- Rule distribution (DNS) well provisioned against DDoS attacks

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RBF Mechanism – Specification

- Rule: **sequence of actions** conditioned by **if-then-else** statements

```
if(<CONDITION>) ACTION1
else ACTION2
```

- Conditions: *comparison operations* on packet header & router state (attributes)

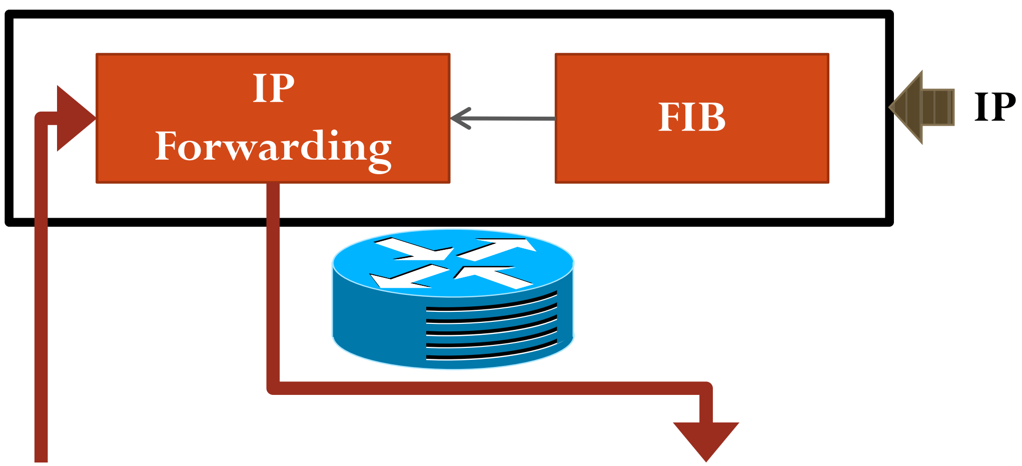
RBF Mechanism – Actions

Rule ***actions*** are:

1. **Modify packet header (attributes)**
2. **Drop packet**
3. **Forward packet (destination / next waypoint)**
4. **Invoke upper layer functionality (if available)**

Rule Forwarding Mechanism

Current IP routers



Rule Forwarding Mechanism

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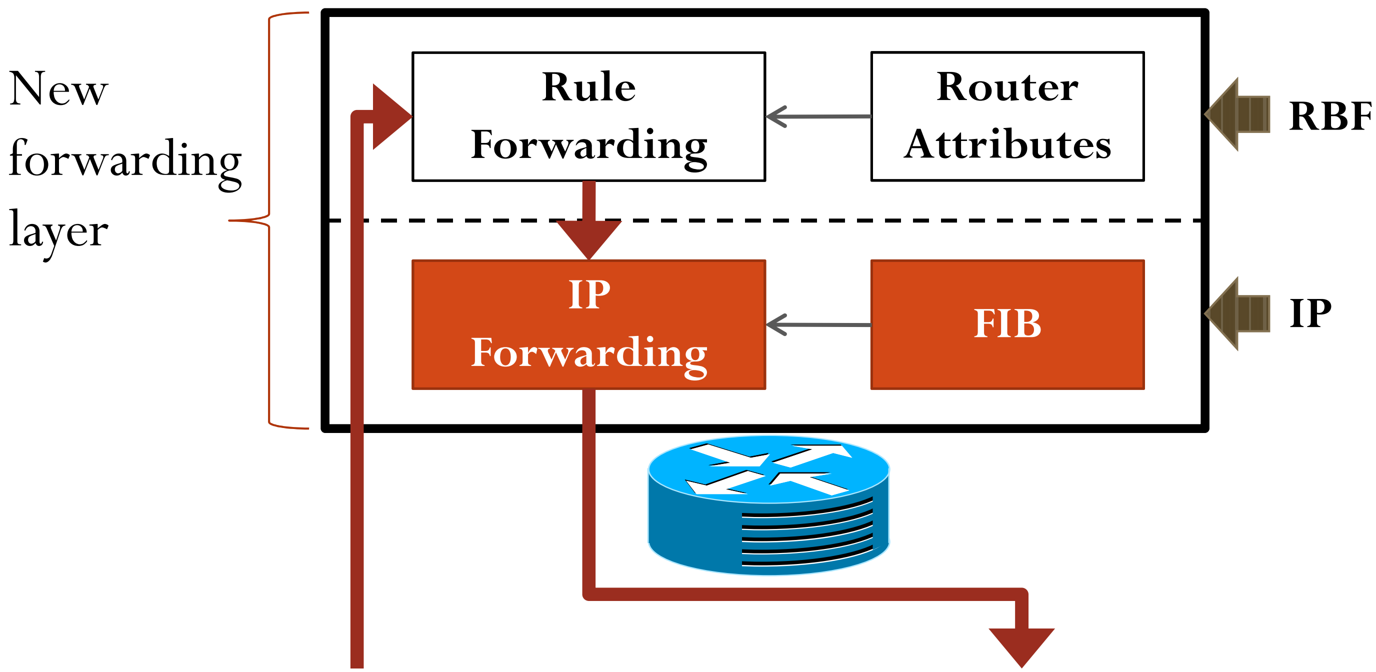

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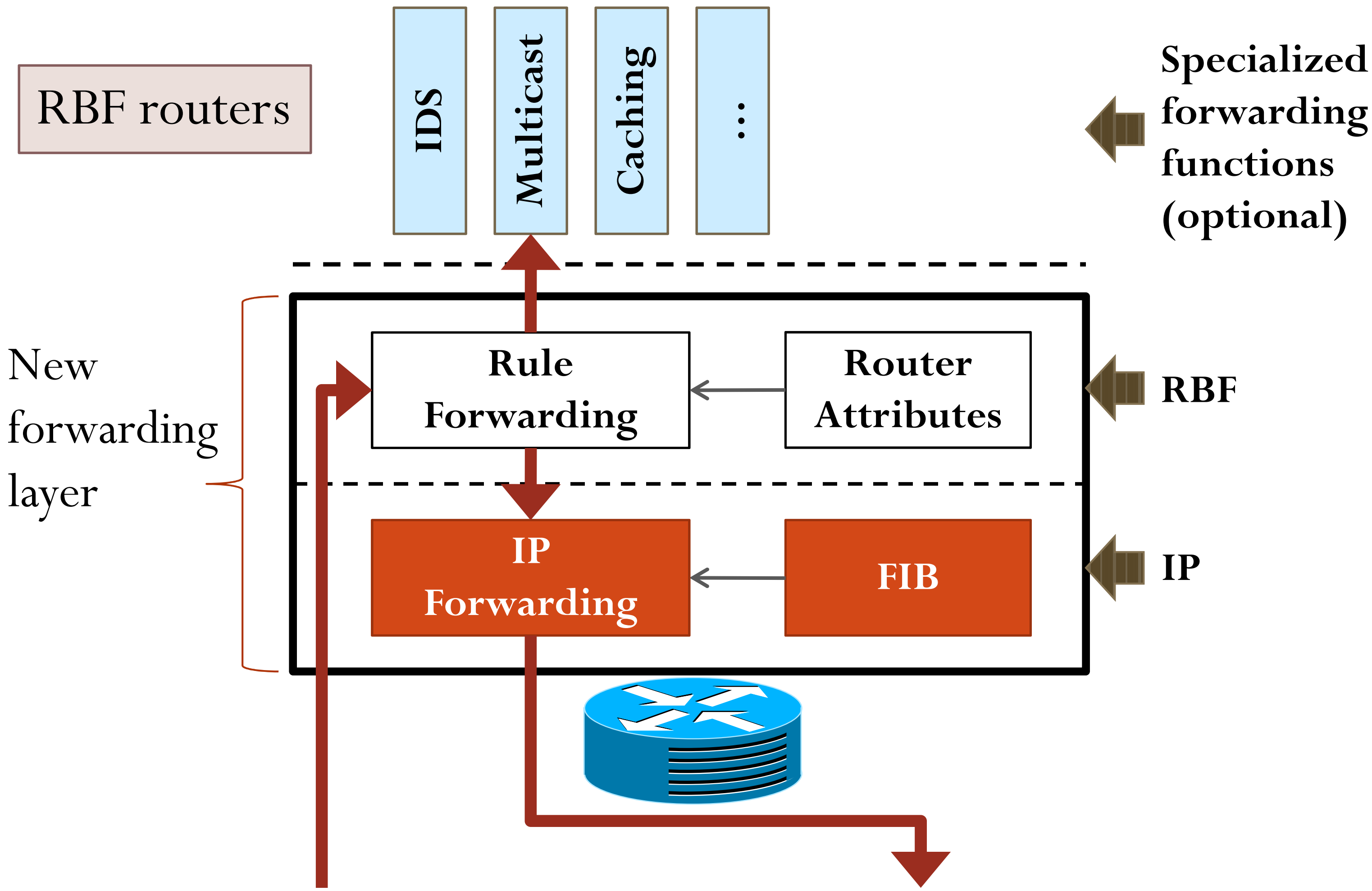

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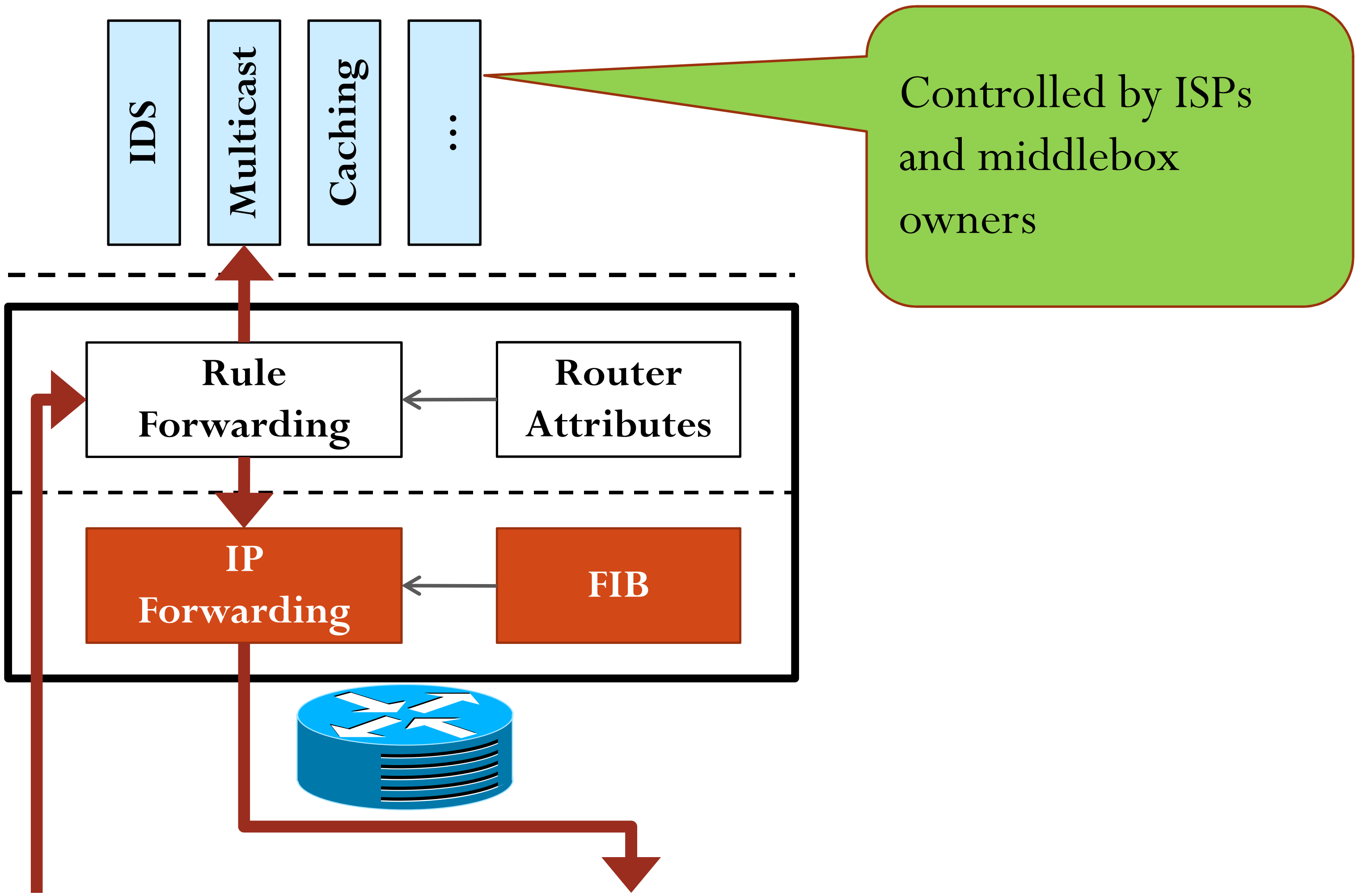

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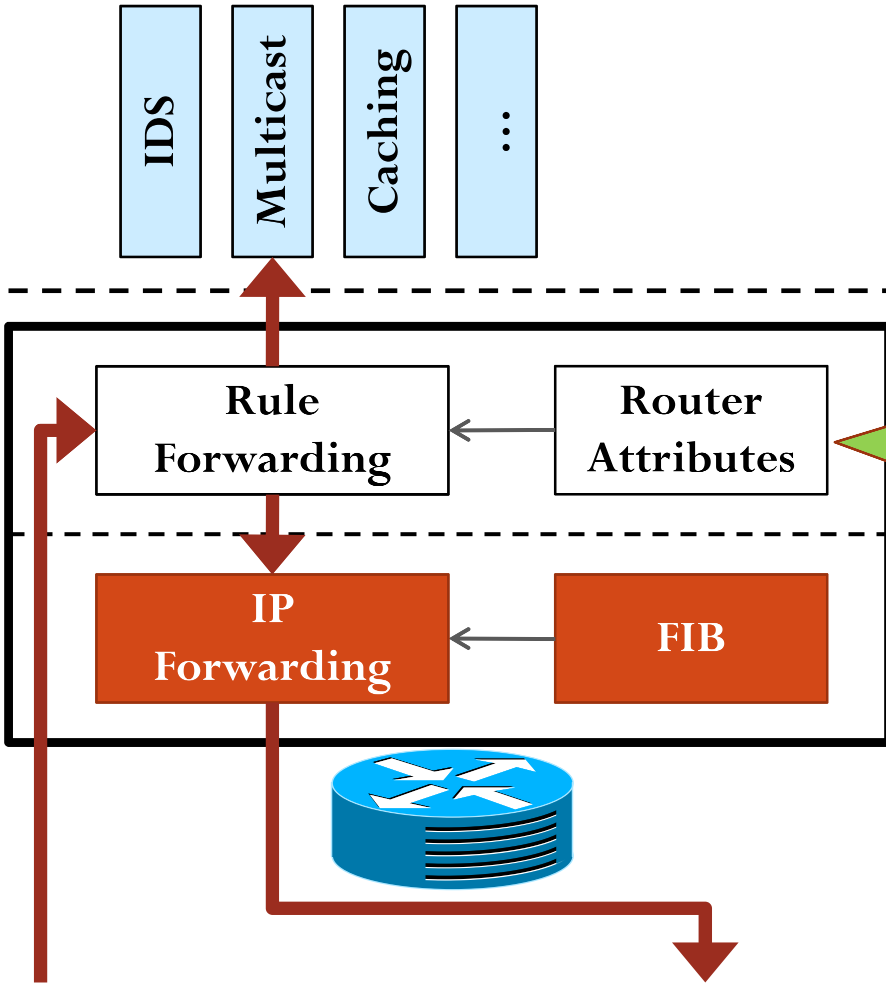

Examples:

- router's address
- queue size
- availability of specialized function

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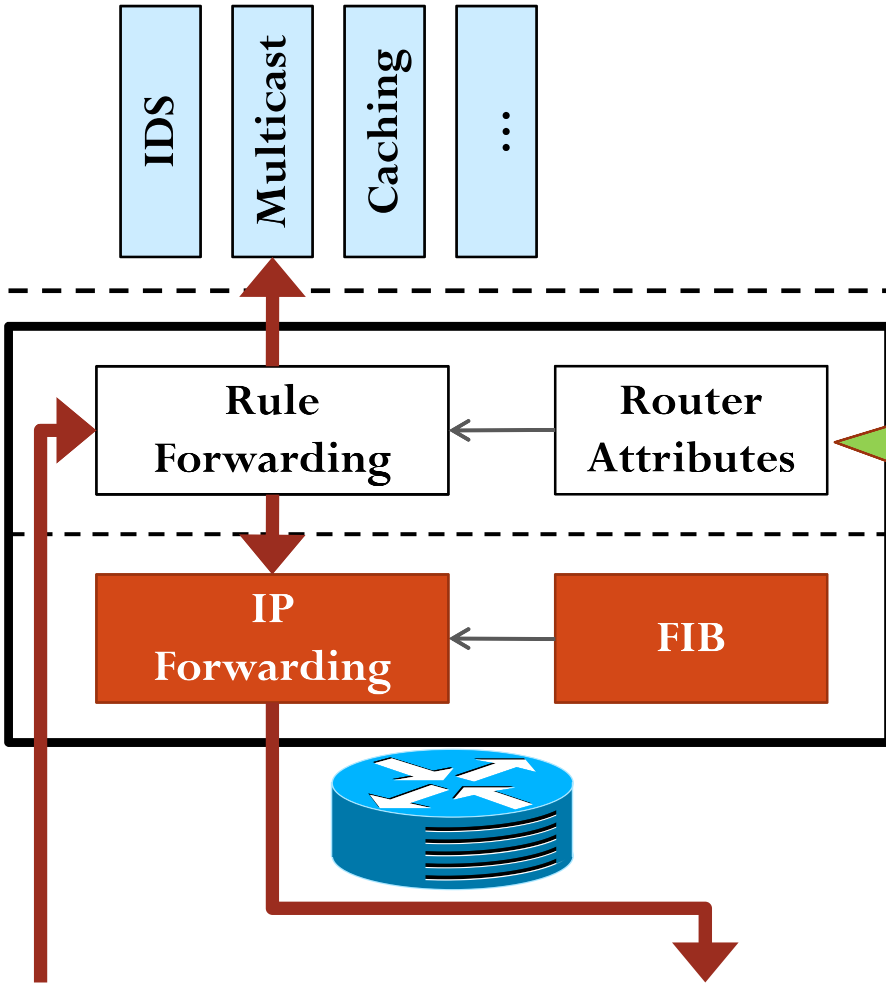

Rules cannot modify router attributes

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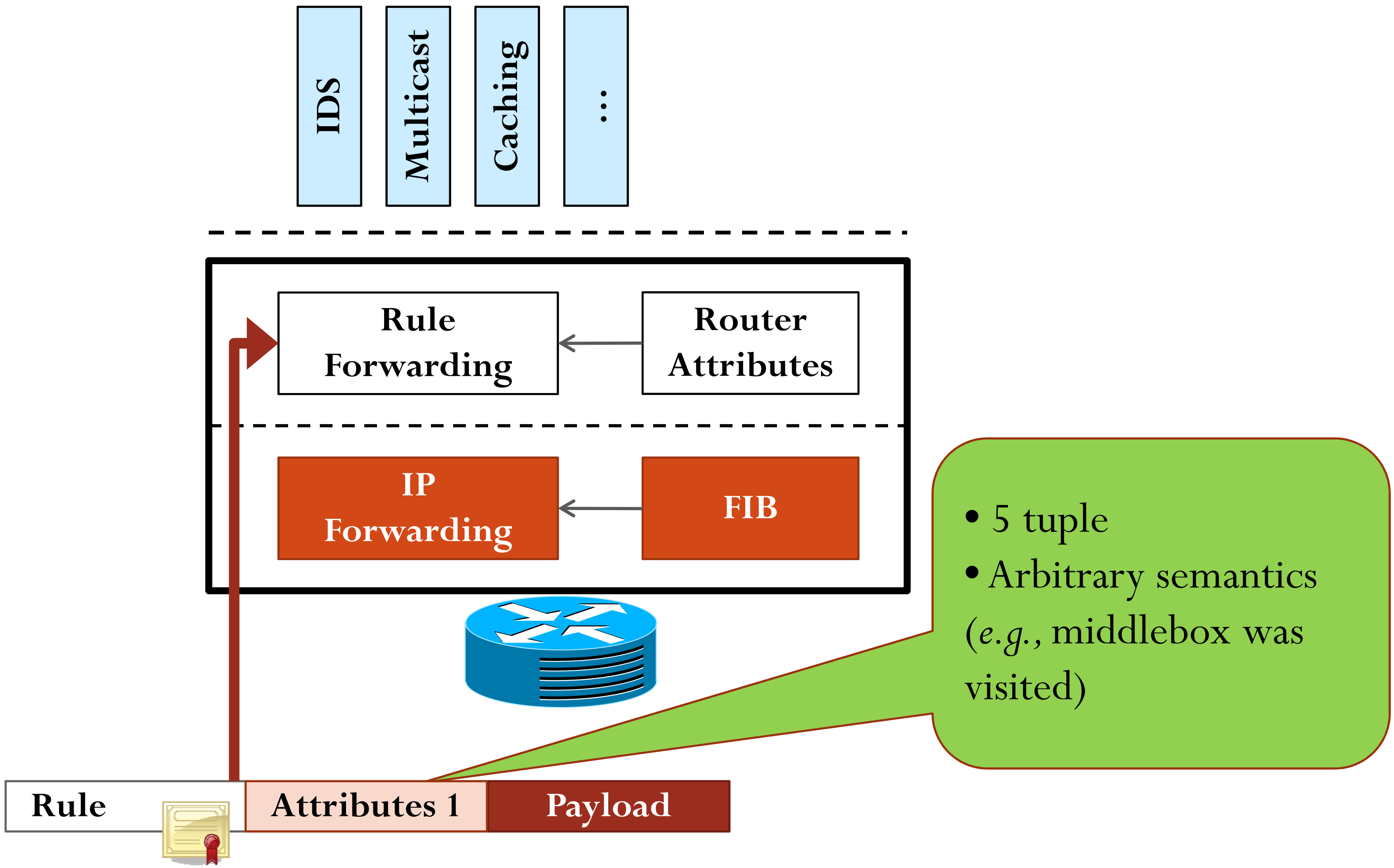

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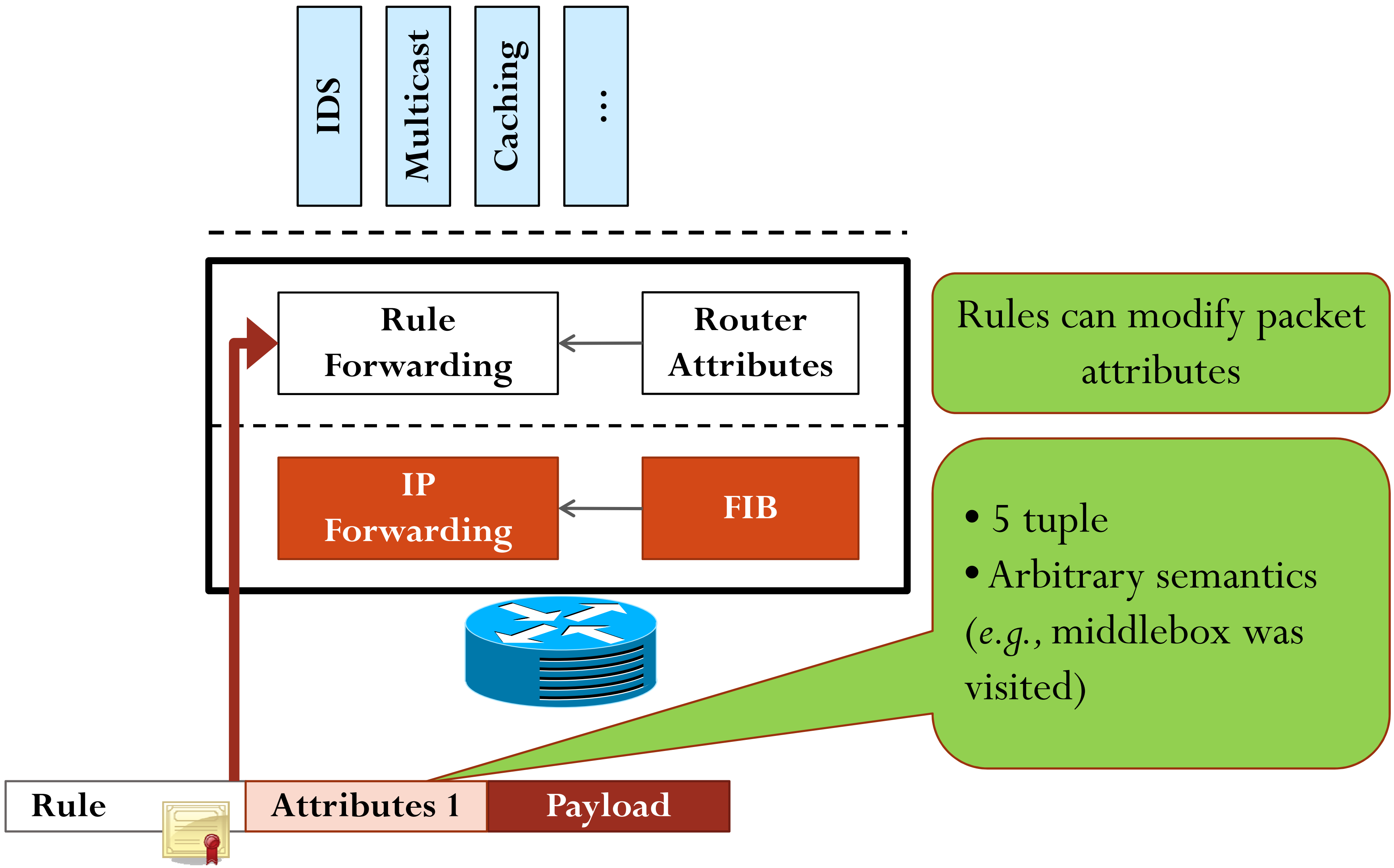

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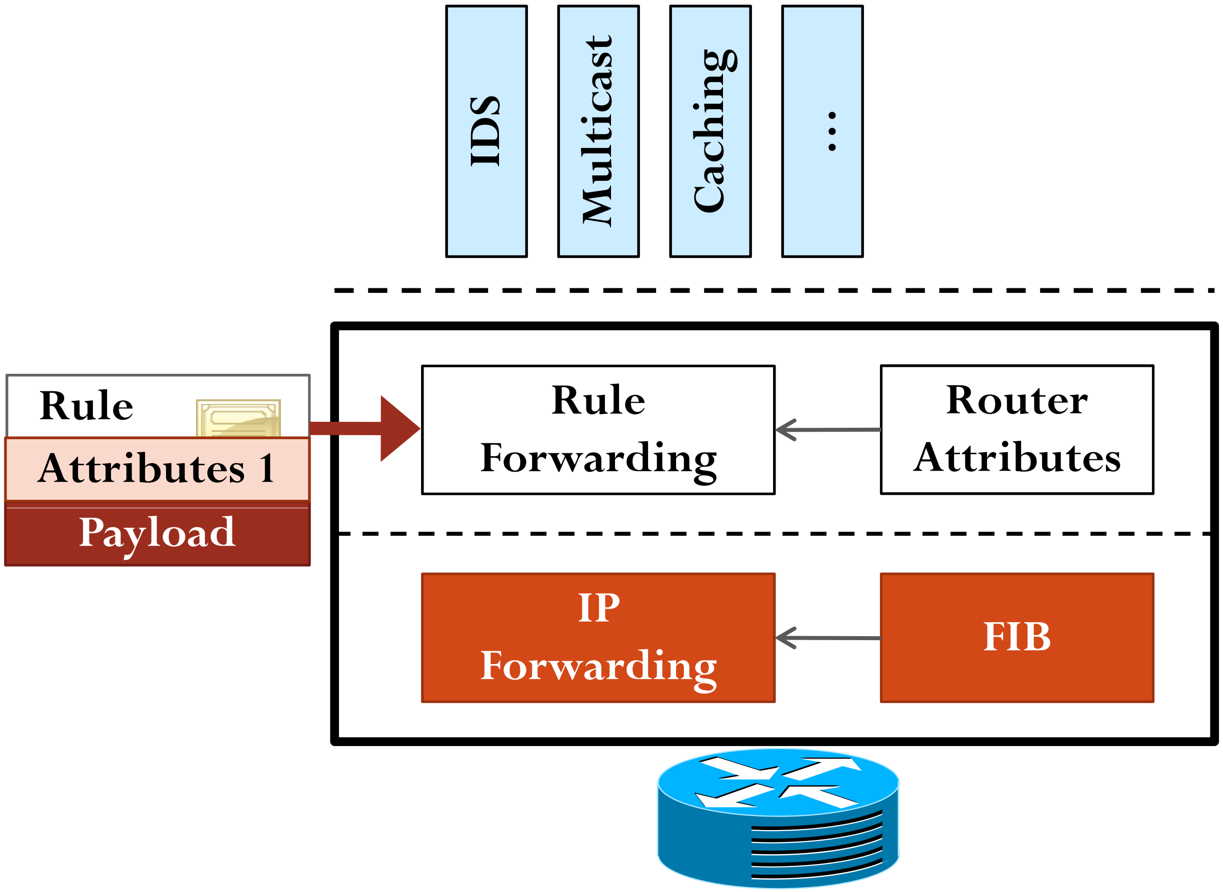

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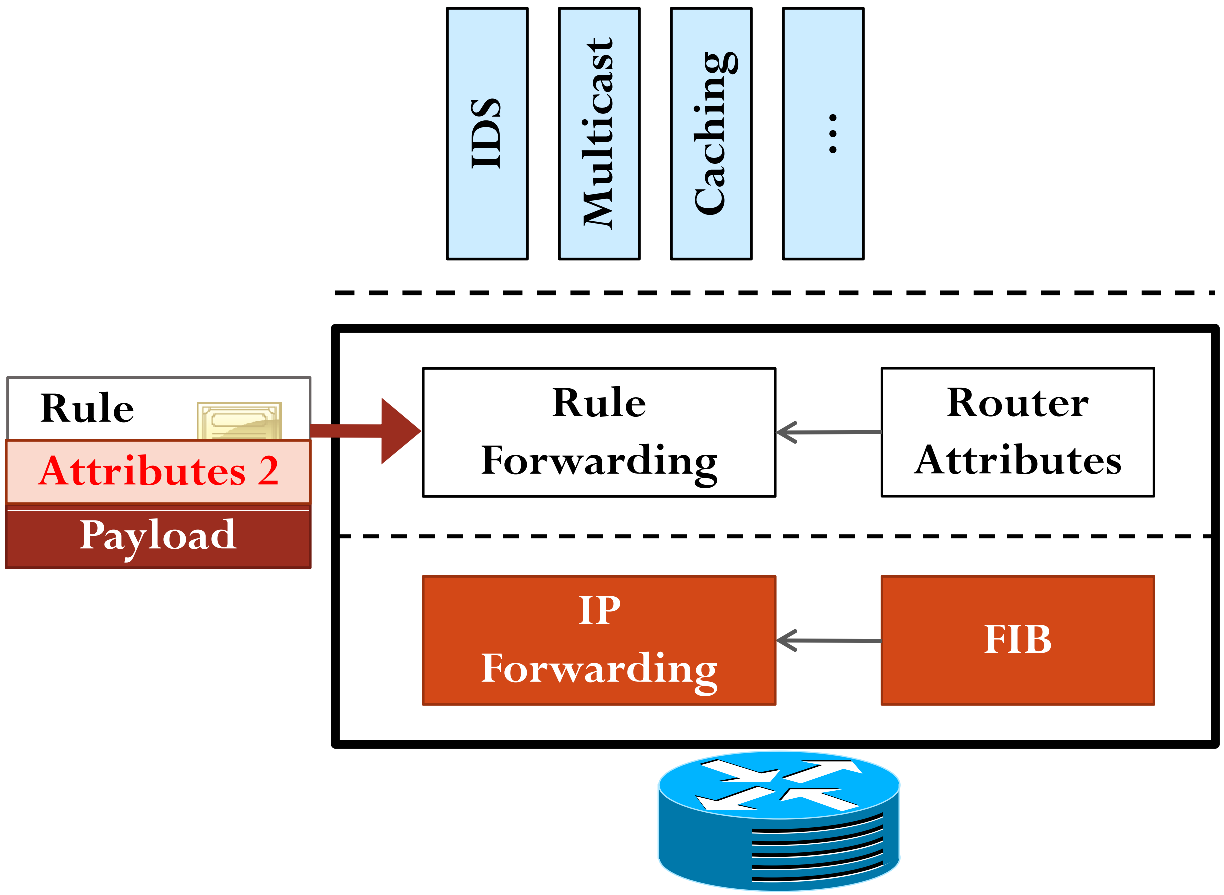
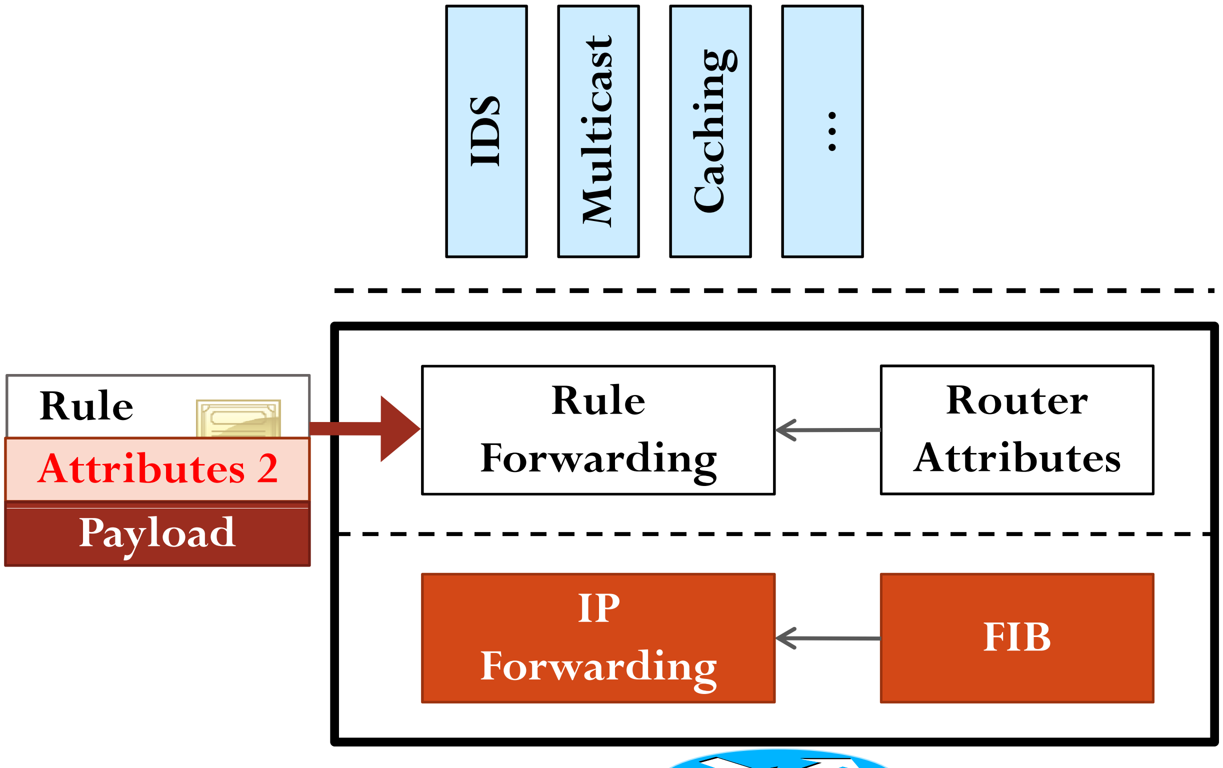


Rule can:

1. Modify packet attributes

Rule Forwarding Mechanism



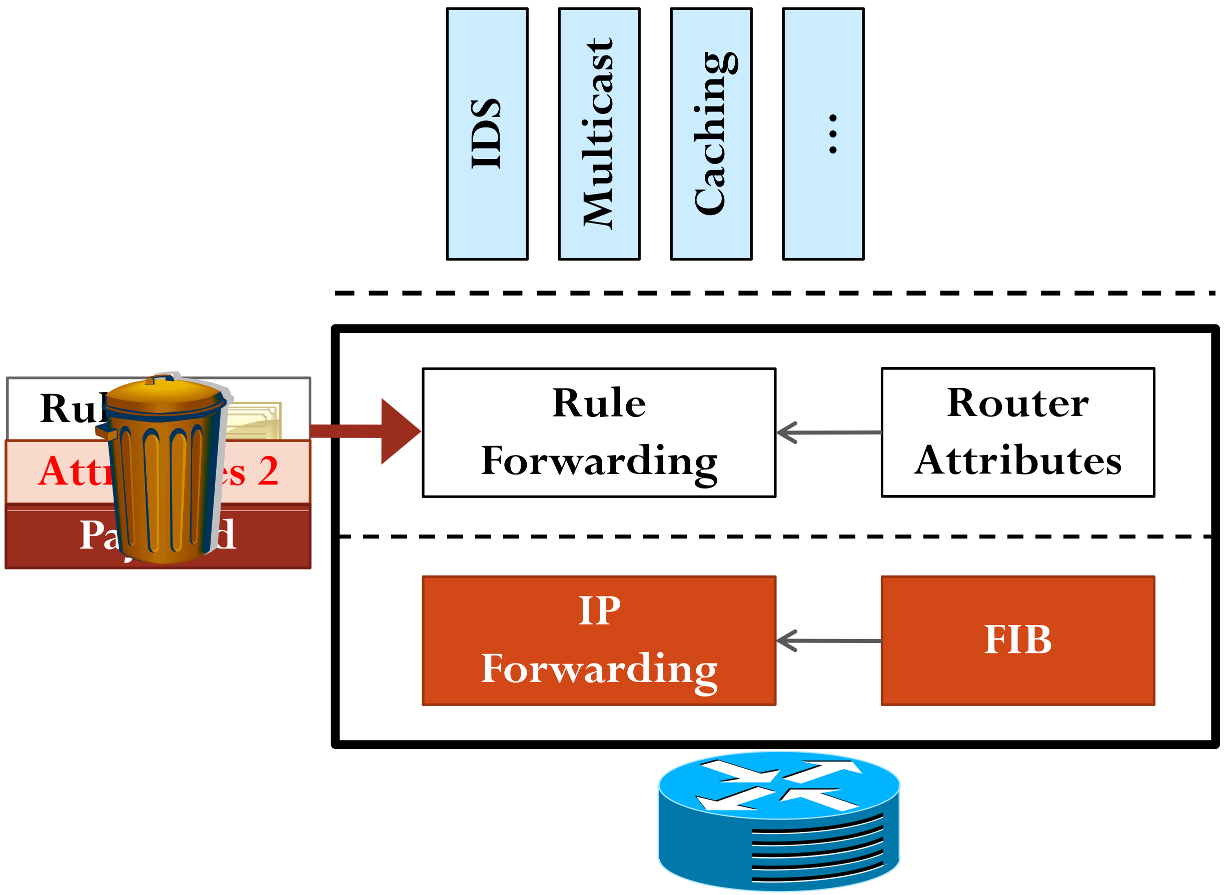
Rule can:

1. Modify packet attributes

Example:

```
if(router.congestion > pkt.max_congestion)
    pkt.max_congestion = router.congestion
sendto D
```

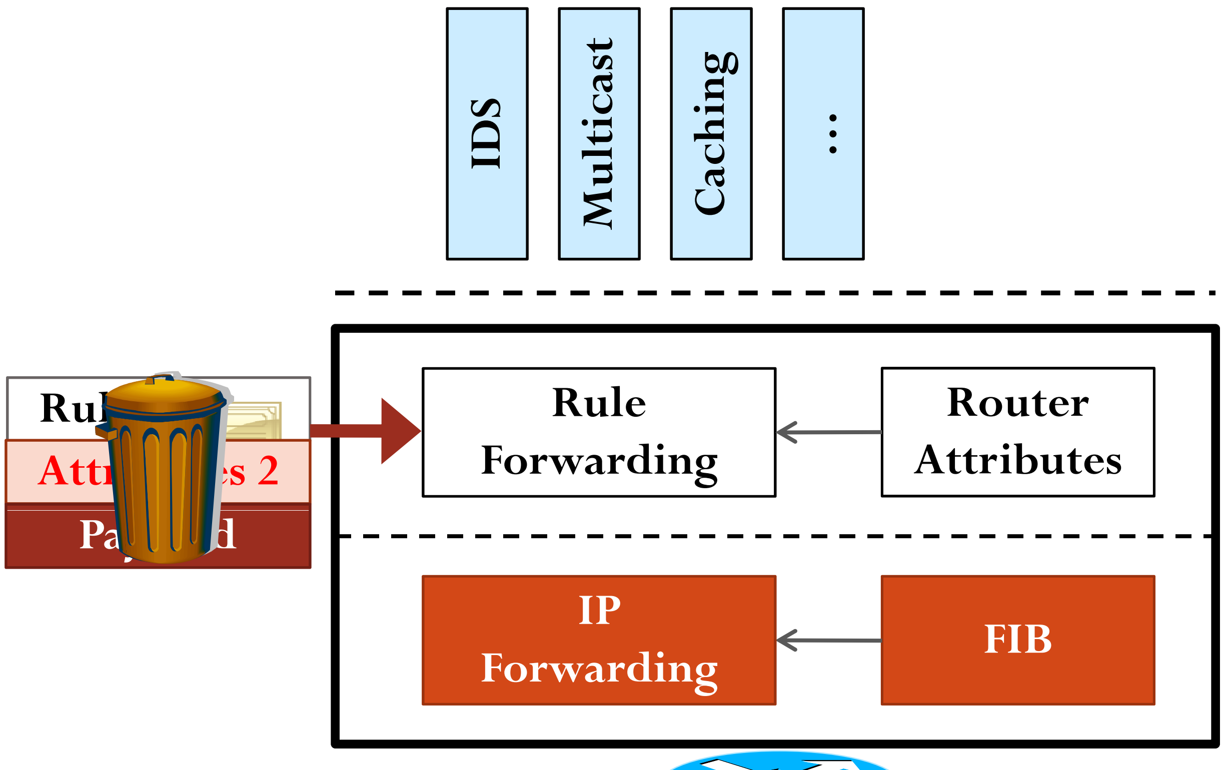
Rule Forwarding Mechanism



Rule can:

1. Modify packet attributes
2. Drop packet

Rule Forwarding Mechanism



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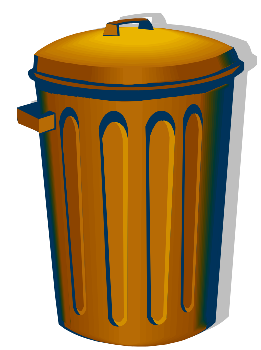
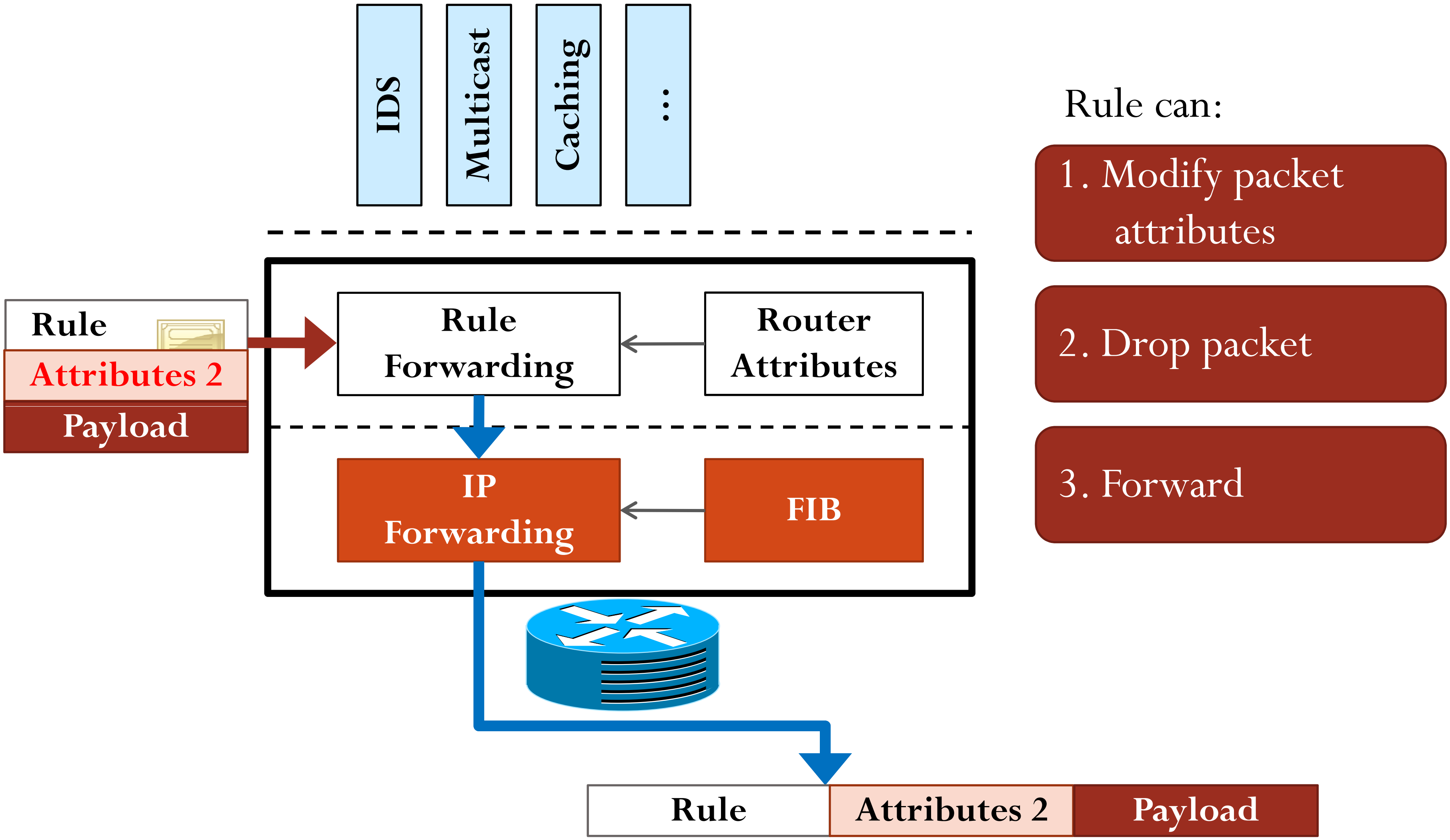


Example:

```
if(pkt.source != S)
    drop
sendto D
```

Rule Forwarding Mechanism



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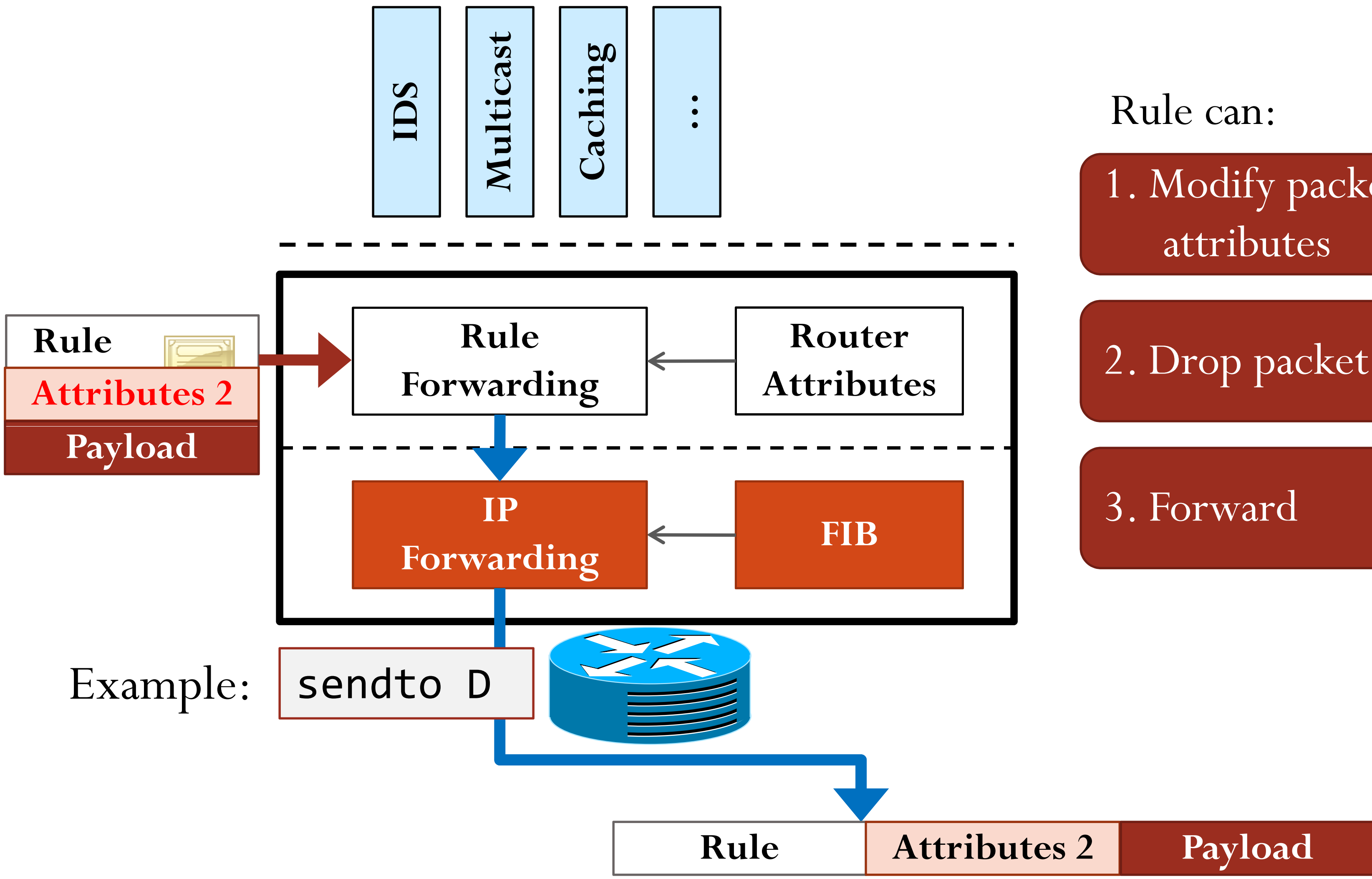
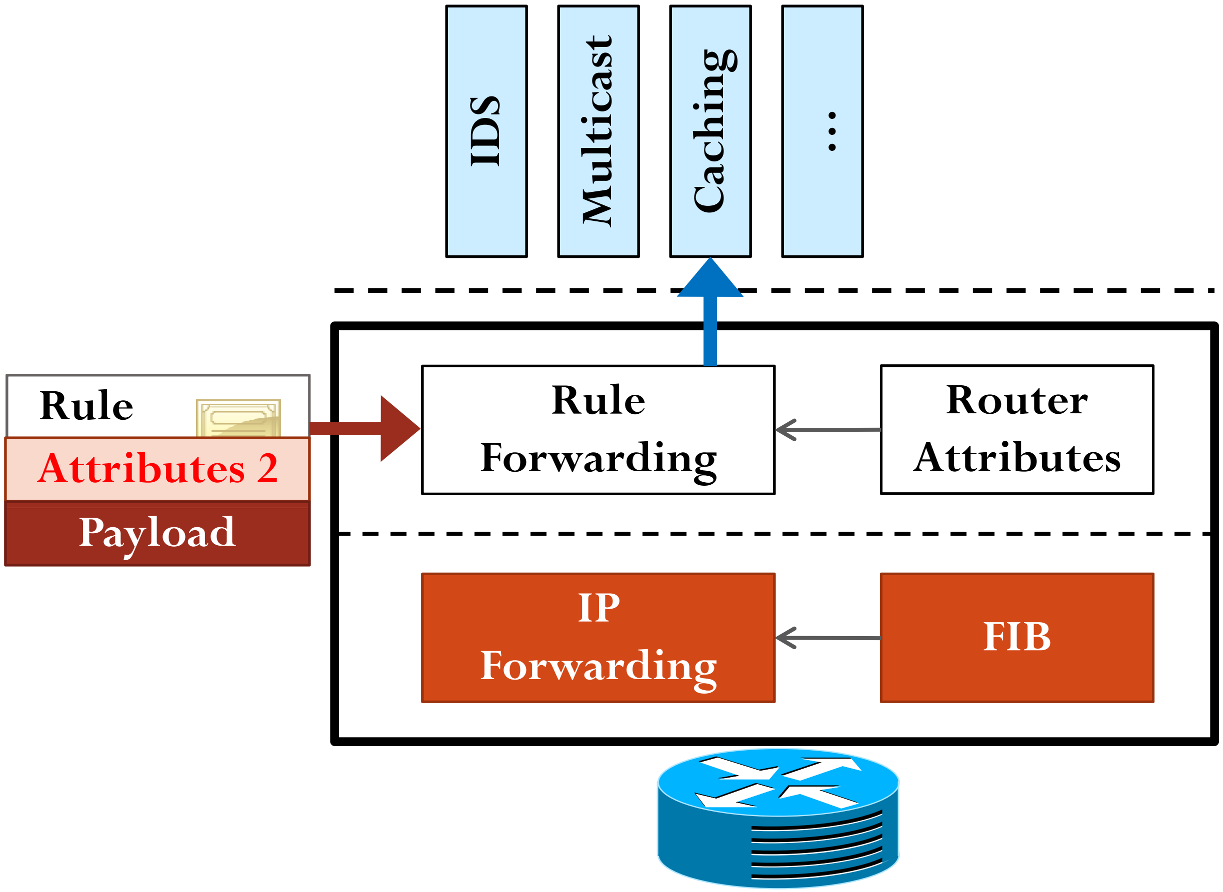


Rule can:

1. Modify packet attributes
2. Drop packet
3. Forward

Rule Forwarding Mechanism



Rule can:

1. Modify packet attributes
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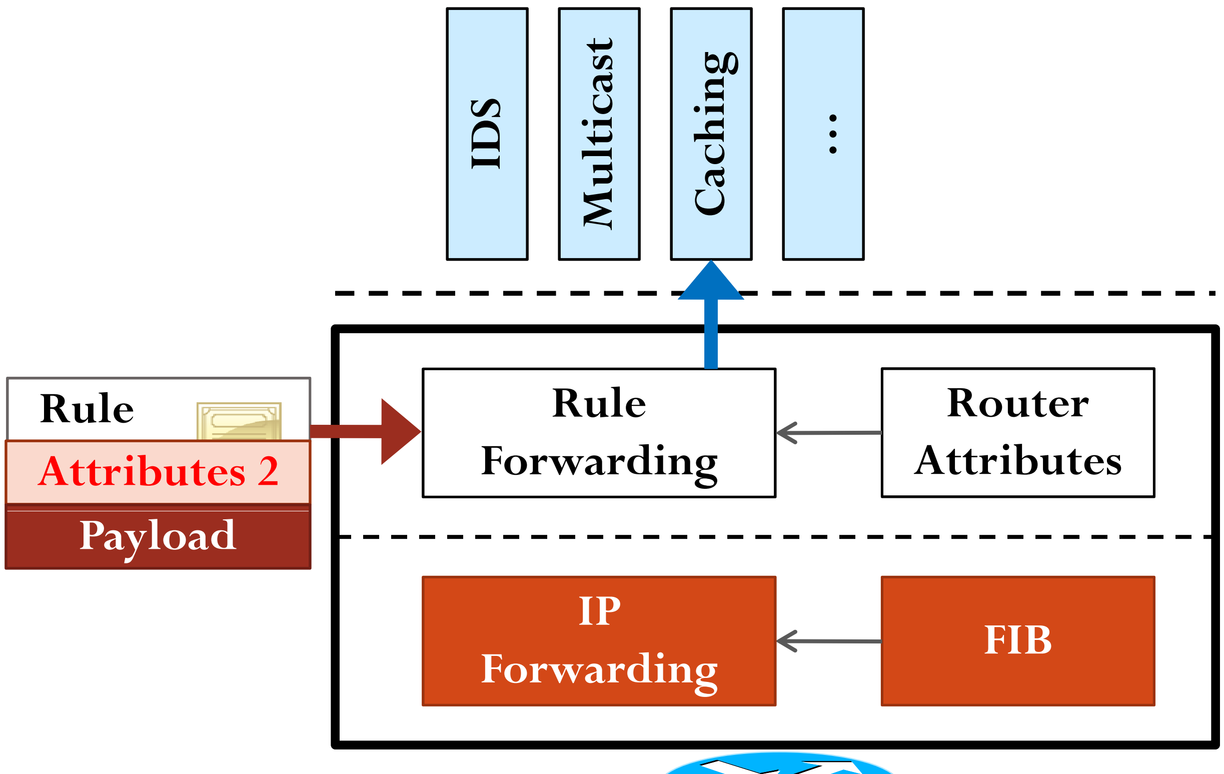
Rule Forwarding Mechanism



Rule can:

1. Modify packet attributes
2. Drop packet
3. Forward
4. Invoke

Example:

```
if(router.has_caching == TRUE)
    invoke CachingFunc
sendto D
```

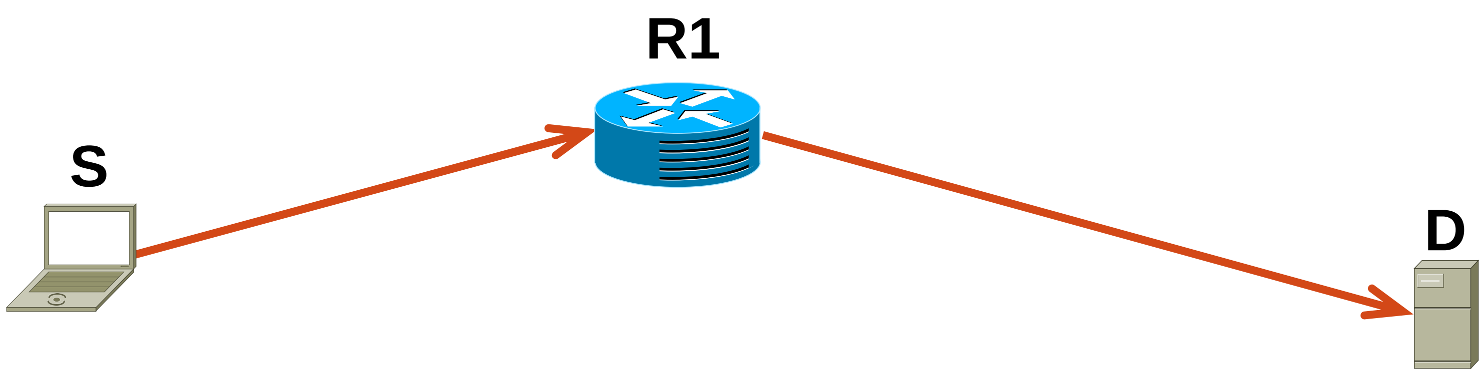
RBF Mechanism – Rule Lease

- Each rule has an associated **lease** period

- Routers drop expired rules

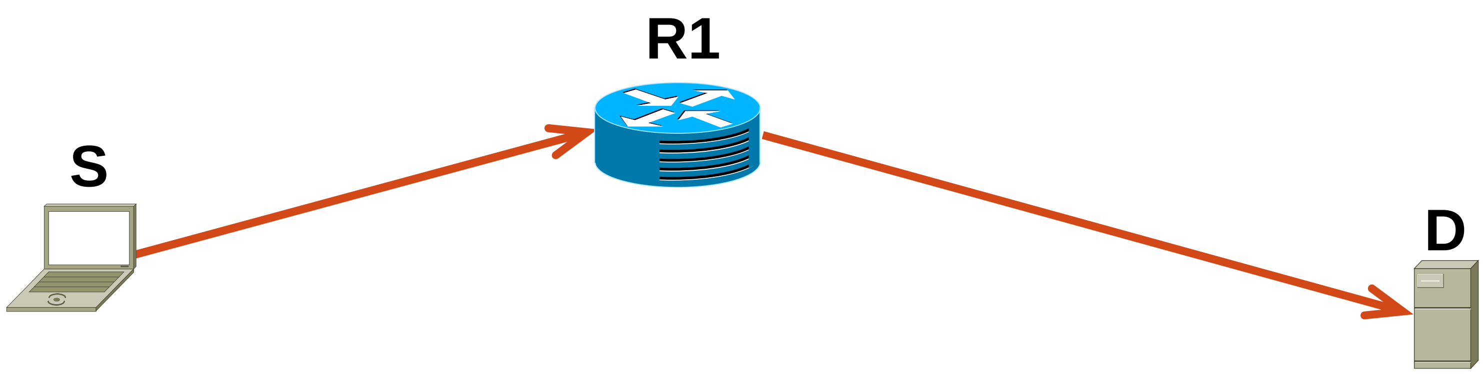
Examples – Waypoint

```
R_D:
  “Go to R1 before reaching D”
```



Examples – Waypoint

```
R_D:
  if(packet.been_to_R1 == 0)
    if(router.address != R1)
      sendto R1
    else packet.been_to_R1 = 1
  if(packet.been_to_R1 == 1)
    sendto D
```



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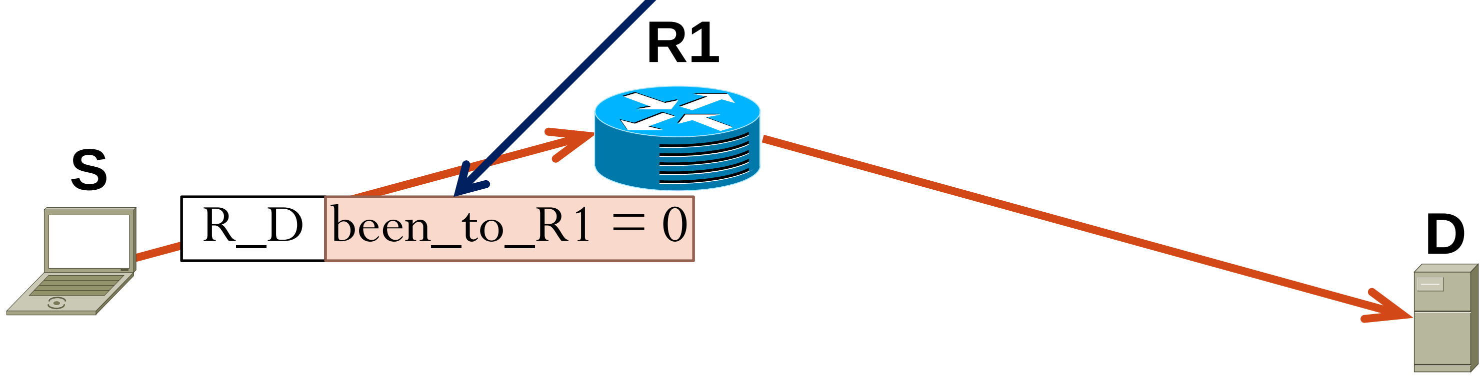
Packet attribute indicating whether packet has visited R1



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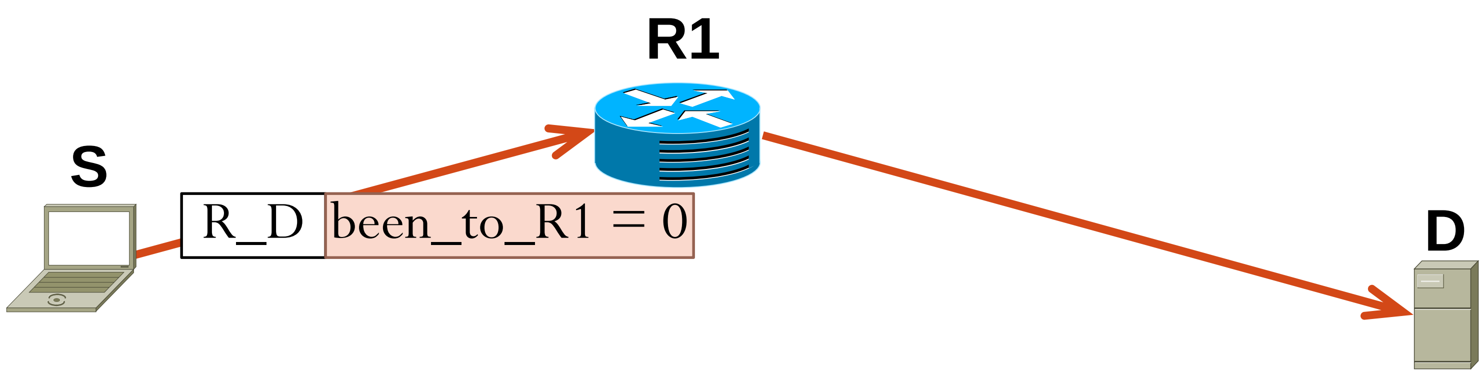
Before waypoint R1



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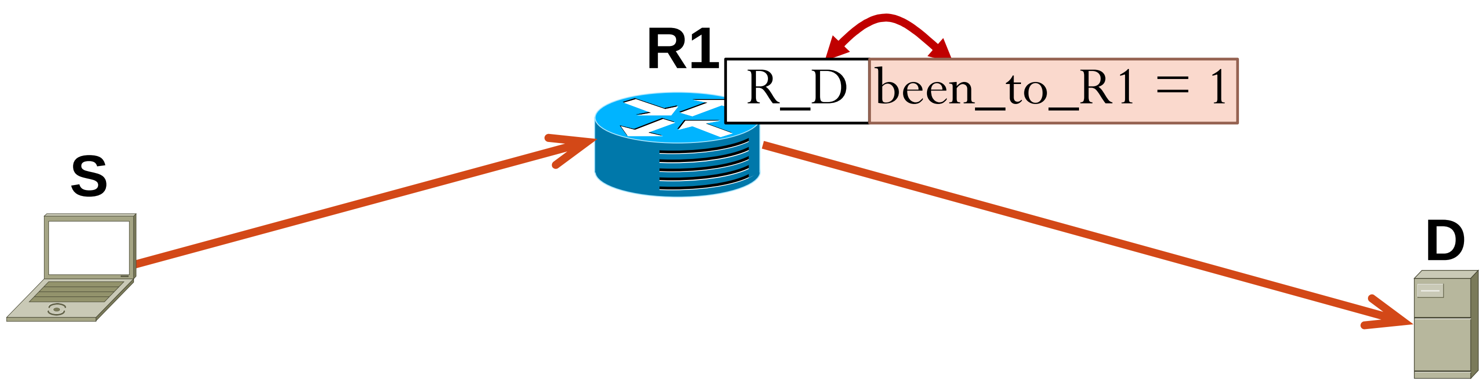
```

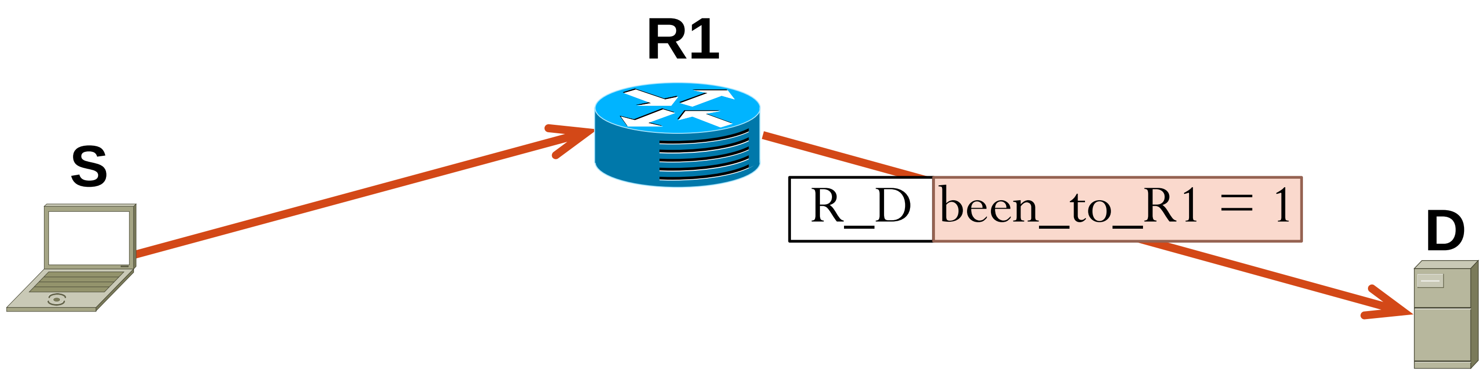
At the waypoint



Examples – Waypoint

```
R_D:
  if(packet.been_to_R1 == 0)
    if(router.address != R1)
      sendto R1
    else packet.been_to_R1 = 1
  if(packet.been_to_R1 == 1)
    sendto D
```

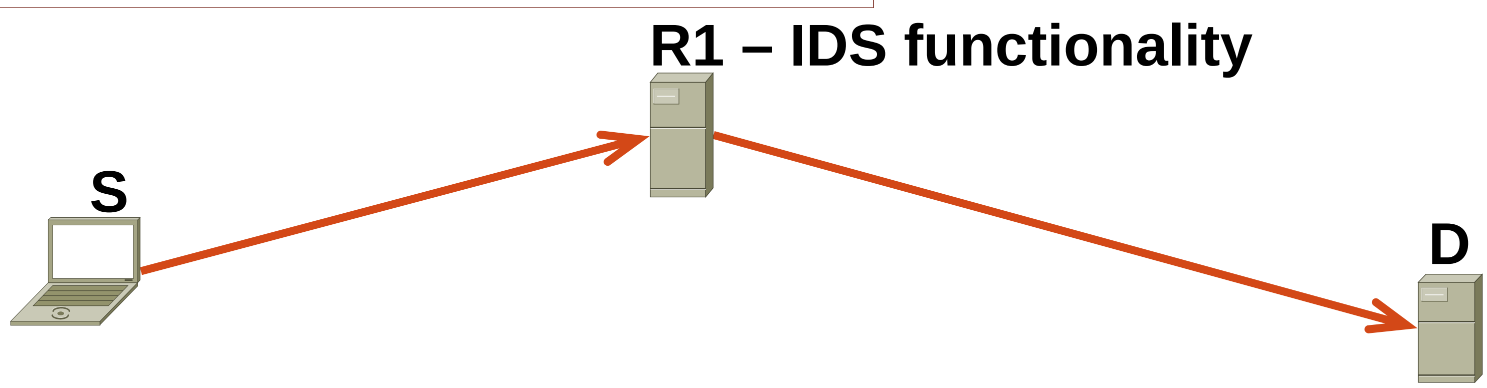
After the waypoint



Examples – Middlebox

```
R_D:
  if(packet.been_to_R1 == 0)
    if(router.address != R1)
      sendto R1
    else
      packet.been_to_R1 = 1
      invoke IDS_func
  if(packet.been_to_R1 == 1)
    sendto D
```

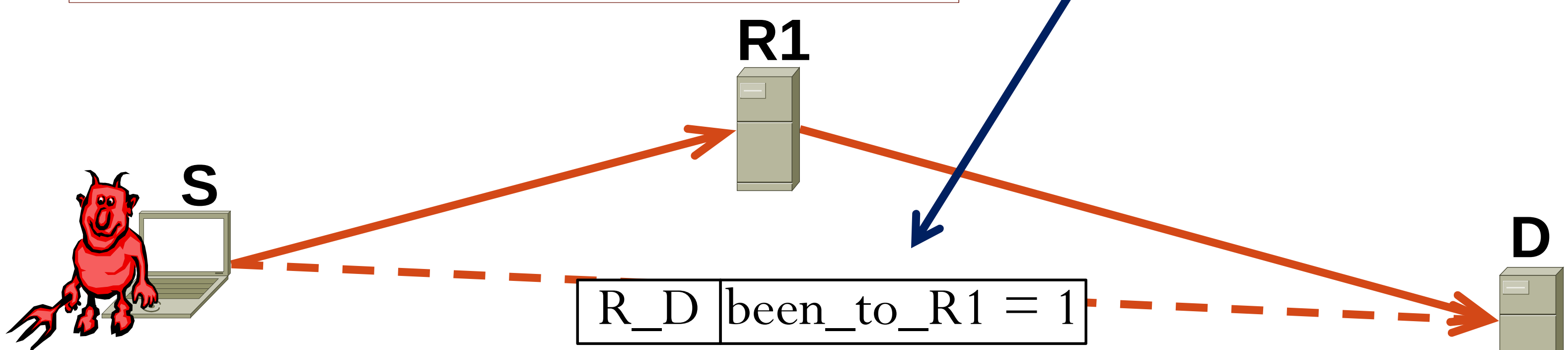
Addition to the waypoint rule



Examples – Secure Middlebox

```
R_D:
  if(packet.been_to_R1 == 0)
    if(router.address != R1)
      sendto R1
    else
      packet.been_to_R1 = 1
      invoke IDS_func
  if(packet.been_to_R1 == 1)
    sendto D
```

Malicious user could set the packet attributes so that packet appears to have visited the middlebox



Examples – Secure Middlebox (1)

```
R_D:
  if(packet.been_to_R1 == 0)
    if(router.address != R1)
      sendto R1
    else
      packet.been_to_R1 = 1
      packet.source = R1
      invoke IDS_func
  if(packet.been_to_R1 == 1)
    if(packet.source == R1)
      sendto D
```

Allow only packets from R1 when state equals 1

Anti-spoofing does not allow spoofing the source attribute

Examples – Secure Middlebox (2)

```
R_D:
  if(packet.been_to_R1 == 0)
    if(router.address != R1)
      sendto R1
    else
      packet.been_to_R1 = 1
      invoke Crypto_proof
  if(packet.been_to_R1 == 1)
    packet. been_to_R1 = 2
    invoke IDS_func
  if(packet.been_to_R1 == 2)
    if(router.address != D)
      sendto D
    else
      invoke Verify_and_Deliver
```

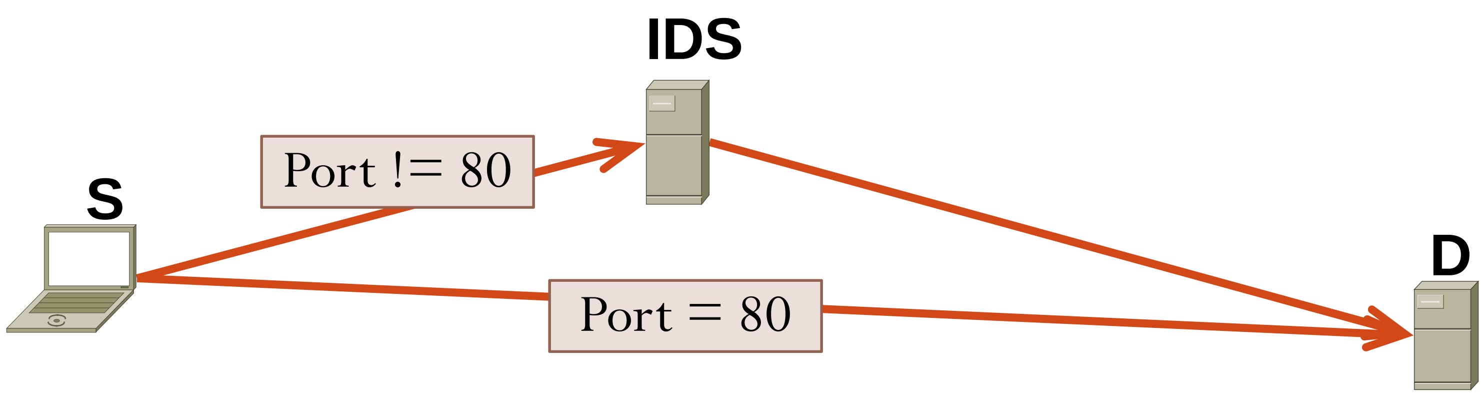
Invoke functionality to (cryptographically) prove packet visited middlebox

Invoke functionality to verify the middlebox proofs at D

Examples – Conditioned Middlebox

```
R_D:
  if(packet.dest_port == 80)
    sendto D
  else
    //Middlebox rule
    ...
```

Use the Middlebox only for packets not destined to port 80



Examples – DoS protection

- Create "capability-like rules", *e.g.*, for a client with address S

```
R_S_D:
  if(packet.source != S)
    drop
  sendto D
```

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- D can control number of simultaneous clients by controlling number of authorized rules (a rule for each client)

Examples – DoS protection

- Create "capability-like rules", *e.g.*, for a client with address S

```
R_S_D:
  if(packet.source != S)
    drop
  sendto D
```

- D can control number of simultaneous clients by controlling number of authorized rules (a rule for each client)
- Need to grant rules on demand
  - Dynamic (vs. static DNS)
  - Provision this service against DDoS (denial of rule)
  - DNS redirects to third parties providing this service

RBF Examples

- Filter ports/prefixes – only receive specific traffic
- Protect against DoS attacks
- Mobility
- Middleboxes
- Secure loose path forwarding – select provider, reliability
- Multiple paths
- Anycast
- Record path state – network probing, ECN, path identifier
- On-path redirection – Delay Tolerant Networks
- Use on-path router functions deployed by ISPs – Multicast, caching, WAN optimizers, content-routing, energy efficiency
- …

Rule Properties

1. Flexible

Rule Properties

1. Flexible

- Rules enable endpoints to:
  a) Block unwanted packets in the network
  b) Control path selection using waypoints
  c) Use router state in forwarding decisions and record this state
  d) Use specialized functions at middleboxes and routers, if available

Rule Properties

1. Flexible
2. Policy Compliant

Rule Properties

1. Flexible
2. Policy Compliant
    - Rules are certified by trusted entities – Rule Certifying Entities (RCEs)
    - Rules are above routing-controlled layer – IP
        - Route discovery and computation fully controlled by ISPs

Rule Properties

1. Flexible
2. Policy Compliant
3. Safe

Rule Properties

1. Flexible
2. Policy Compliant
3. Safe
    - Bounded forwarding time
        - No loops, only comparison operations, cannot modify payload
    - Cannot modify router state
    - Cannot amplify traffic
        - No network loops (static analysis), cannot replicate packets
    - Invoked functions are fully controlled by ISPs/Mbox owners
        - Resource isolation and access control to prevent attacks
        - Rules merely offer a (policy compliant) mechanism to use them

Related Work

1. Flexibility
2. Policy-Compliance
3. Some of each

Related Work

1. Flexibility
    - Active Networks, ESP, Overlays (*e.g.*, i3, DOA), Loose path forwarding, DTN, Mobility (*e.g.*, Mobile IP, HIP), Multiple paths (*e.g.*, MIRO), *etc.*
    - Rules vs. Active Networks:
        - Forwarding directives vs. programs
        - Safe and statically analyzable
        - Policy-compliance for multiple-parties
        - Allow invoking ISP deployed functions for processing

Related Work

1. Flexibility
2. Policy-Compliance

- In-network filters (PushBack, AITF, StopIt, PredicateRouting, Off-by-default), Network Capabilities (TVA, SIFF)
- RBF:
  - Adds flexibility
  - Adds multi-party policy compliance

Related Work

1. Flexibility
2. Policy-Compliance
3. Some of each

- *E.g.* Platypus, NUTSS, ICING enable policy-compliant source routing
- RBF:
  - Generalizes flexibility
  - Enables richer policies based on *entire* forwarding behavior

Outline

- Motivation & Solution Overview
- Rule-Based Forwarding Architecture – Overview
- Rule Forwarding Mechanism & Examples
- Evaluation

Evaluation – Questions

- Size overhead of rules
- Forwarding overhead
  - Fast path (no rule verification)
  - Slow path (involves rule verification)
- Performance isolation between invoked functions and forwarding
- Load on RCEs
- Security analysis

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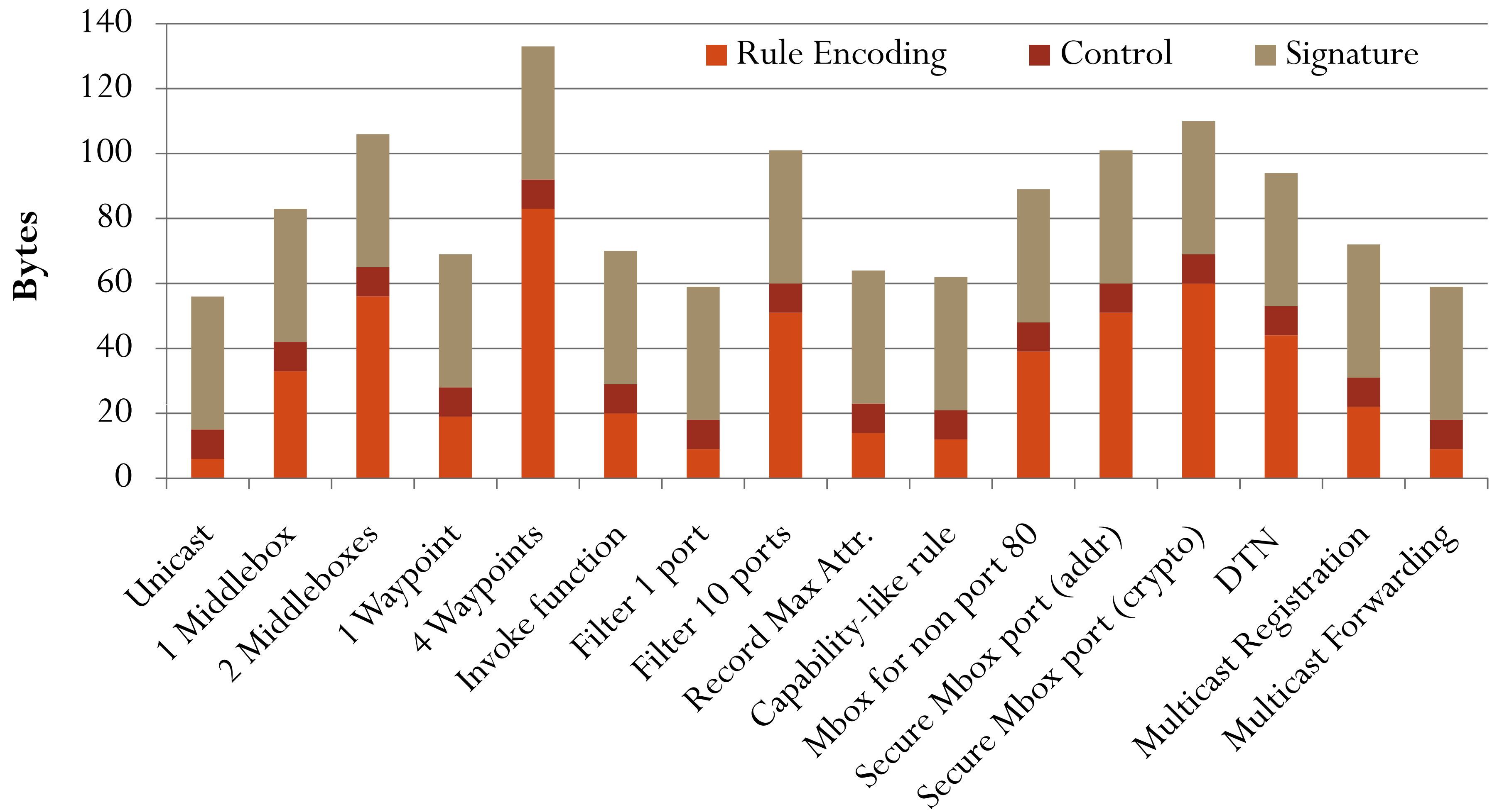
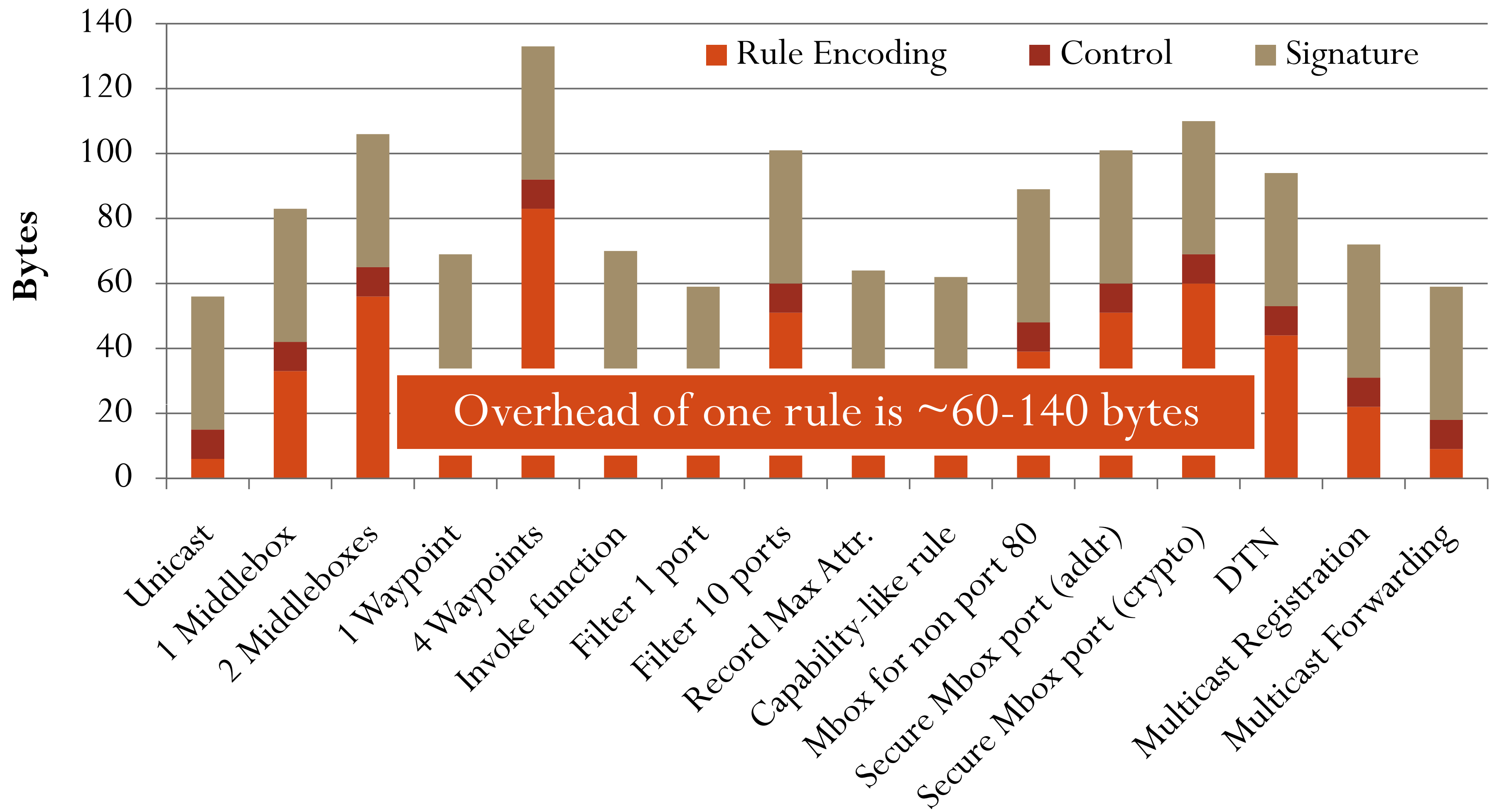
Evaluation – Rule Sizes



Evaluation – Rule Sizes



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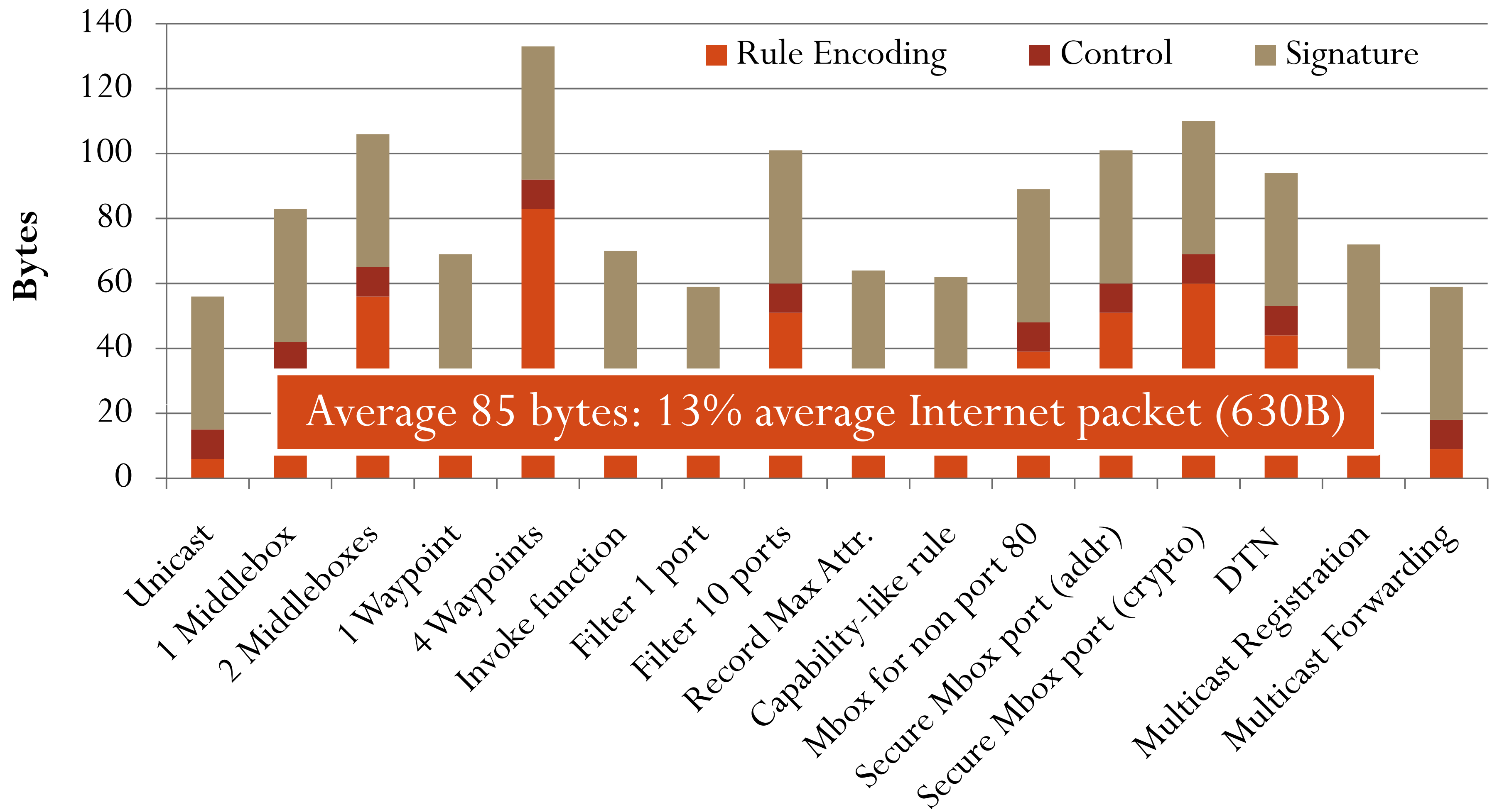

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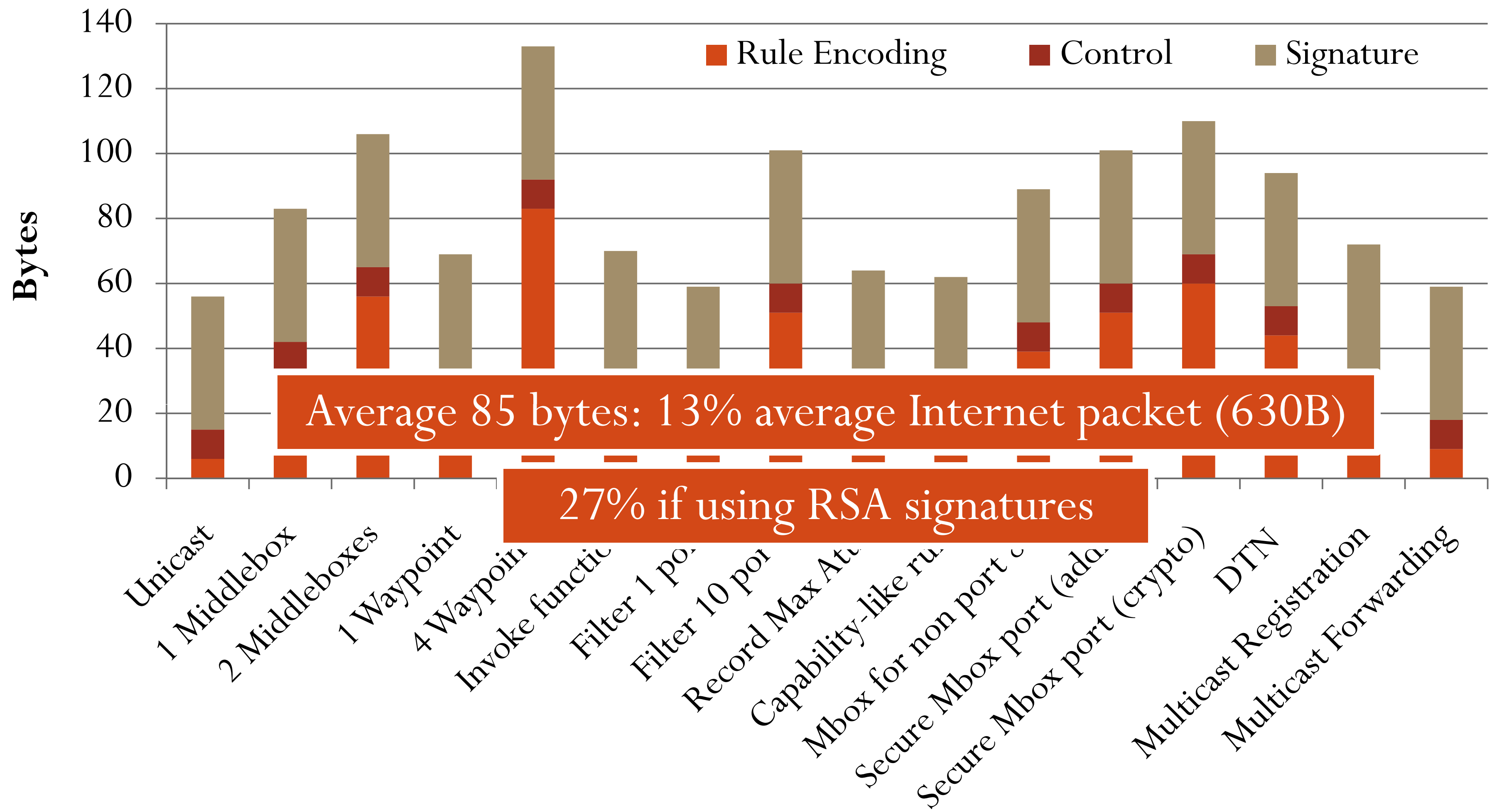
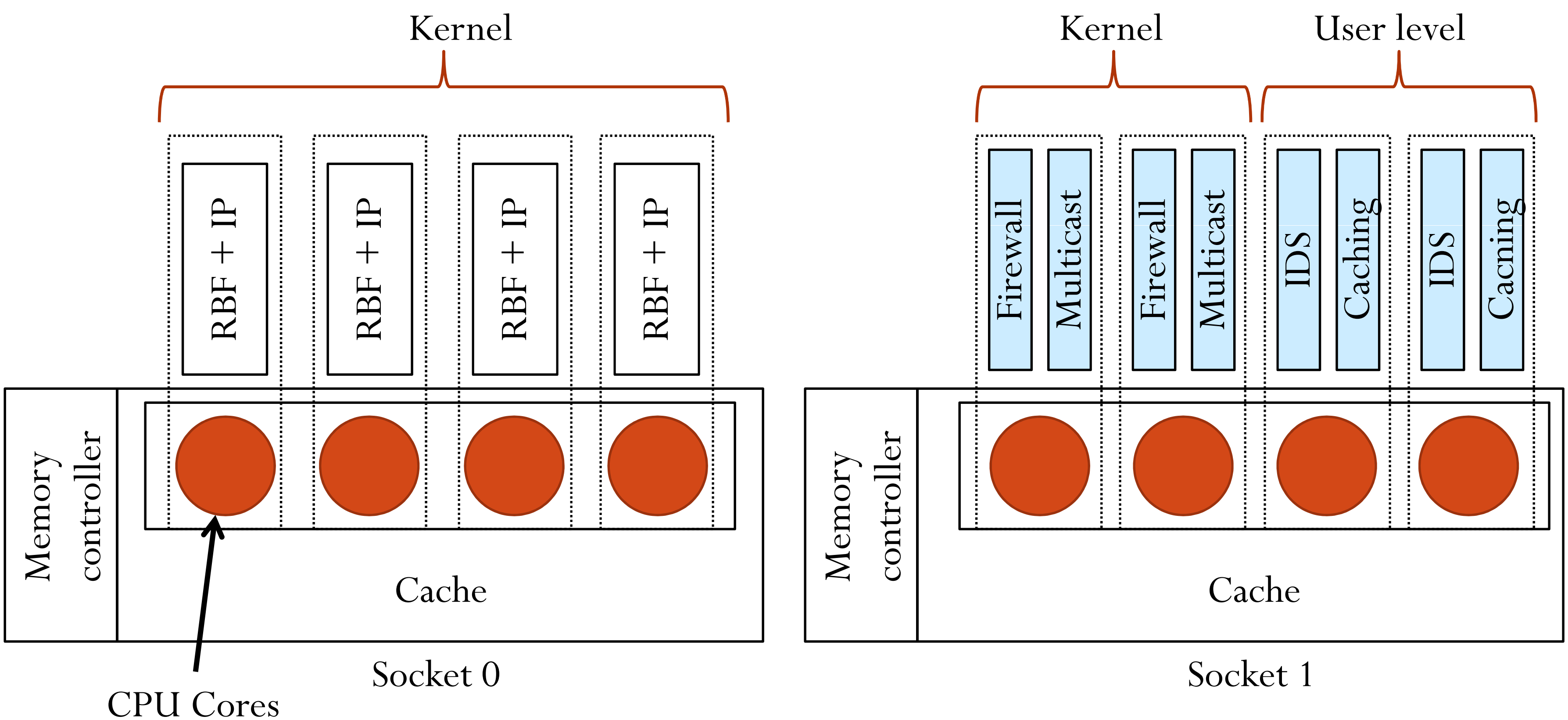


Average 85 bytes: 13% average Internet packet (630B)

27% if using RSA signatures

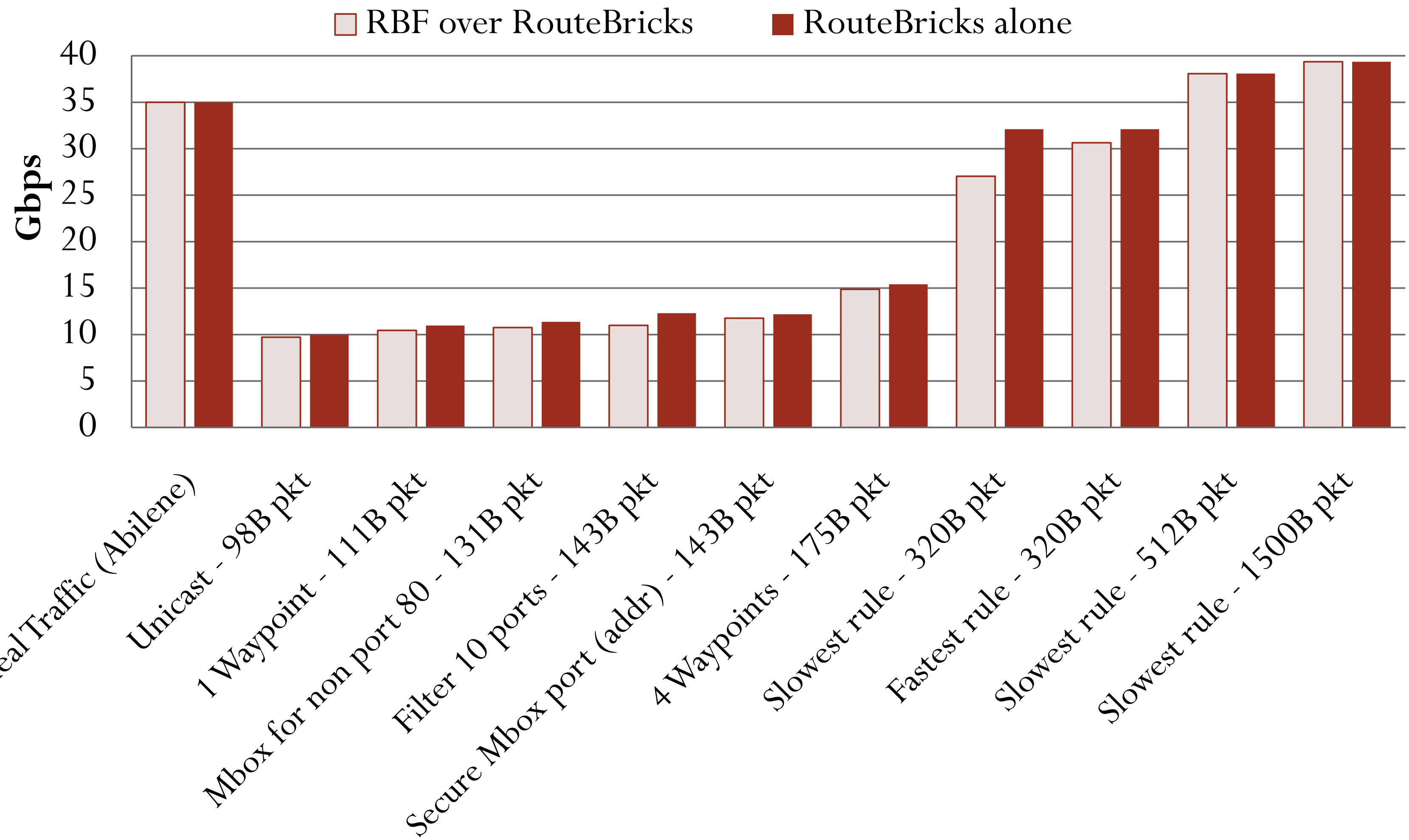
Evaluation – Prototype RBF Router

- Software router on top of RouteBricks [SOSP 2009]
- 8 core Nehalem server, 2 dual-port NICs
- Example router setup:

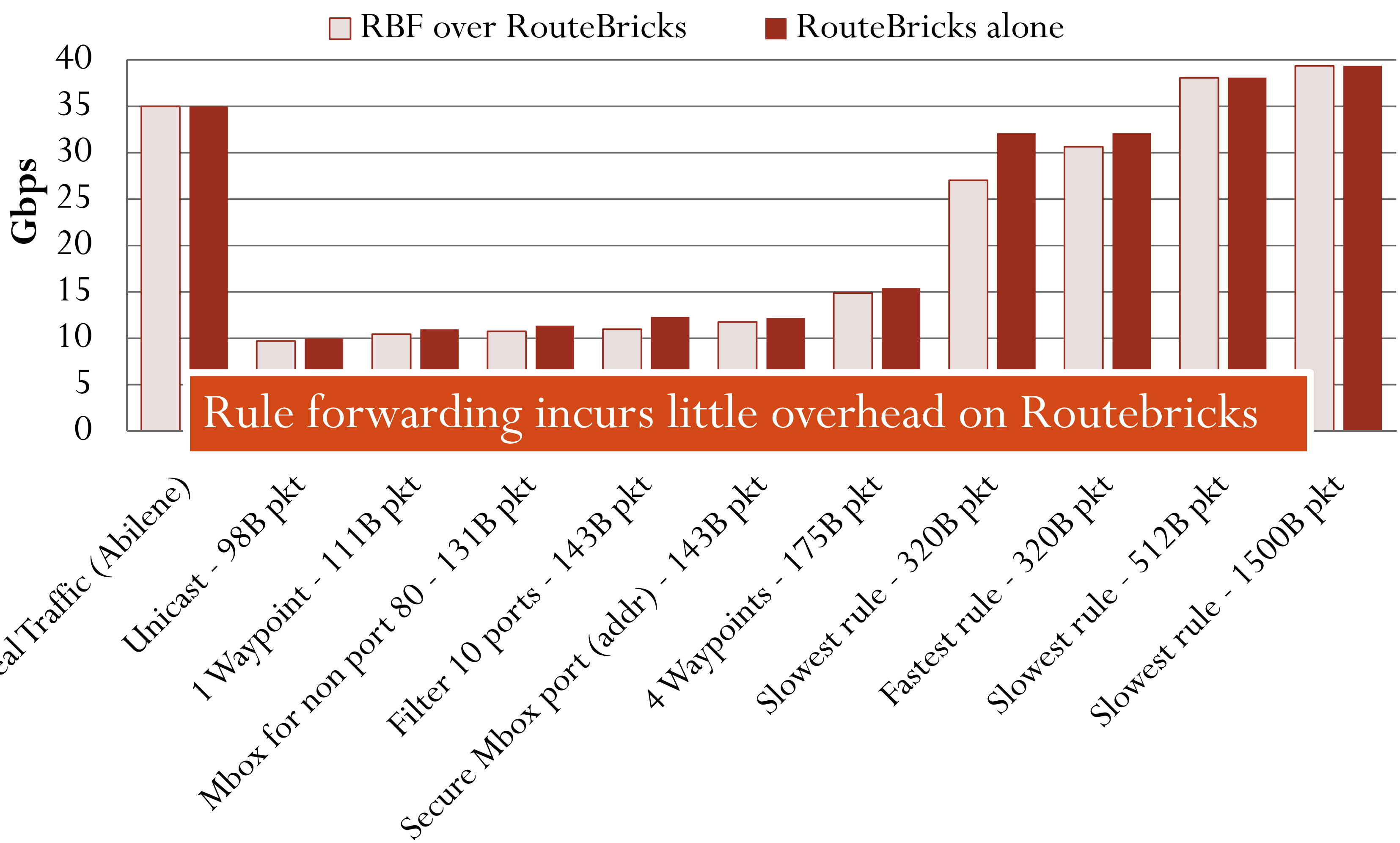


Evaluation – Forwarding Using Rules

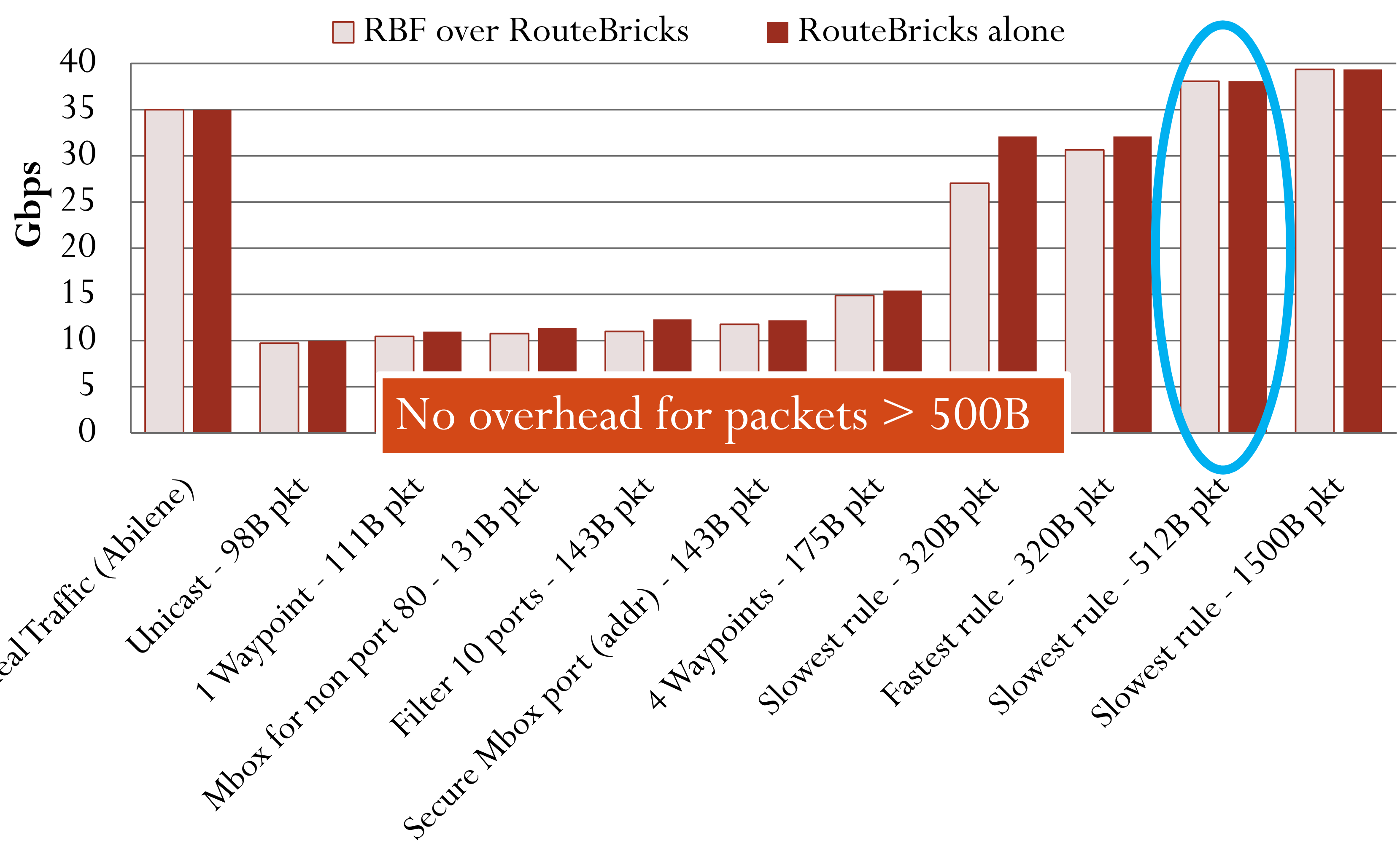
- No signature verification, using all 8 cores



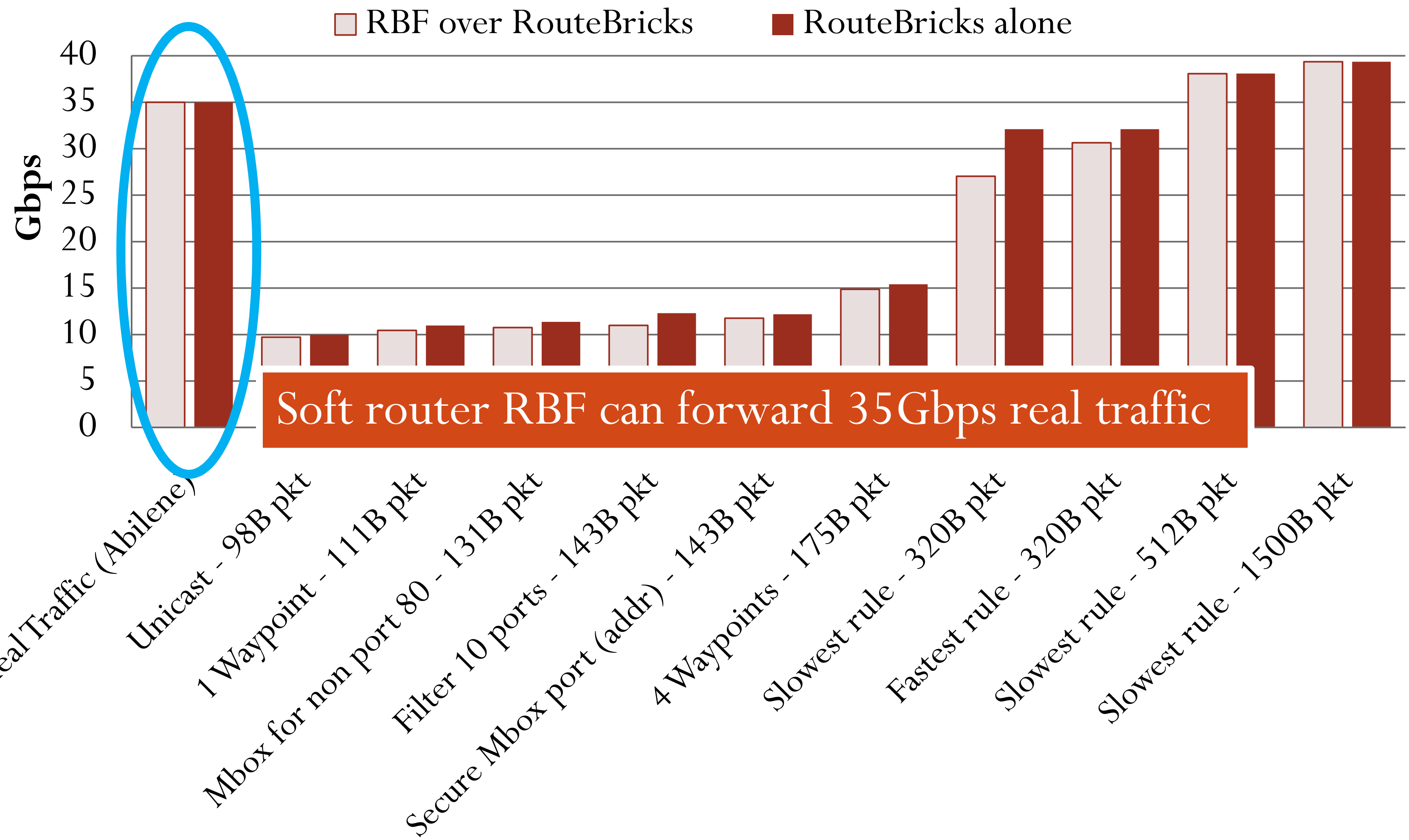
Evaluation – Forwarding Using Rules



Evaluation – Forwarding Using Rules



Evaluation – Forwarding Using Rules



Evaluation – Signature Verification

- Only at *trust boundary routers* (lower traffic than core)

- Result can be *cached*
  - Cache is small (*e.g.*, 19 bytes/rule) and exact match lookup
  - Packets from new flows represent 1% of backbone link capacity on average, worst case 5% of packets
    - Doable with existing hardware (crypto processors, ASICs)
    - 10% slow down on prototype router with RSA signatures & real traffic

- Can be parallelized!

Summary

- ***RBF – flexible and policy compliant*** architecture
  - Packets carry rules

- ***Rule – contains forwarding directives***
  - *Flexible*: if-then-else conditions on packet & router attributes, modify packet header and use in-network functions
  - *Policy-compliant*: signed by third parties – RCEs
  - *Safe*: cannot corrupt routers or amplify traffic