Verified Secure Routing

verifiedSCION

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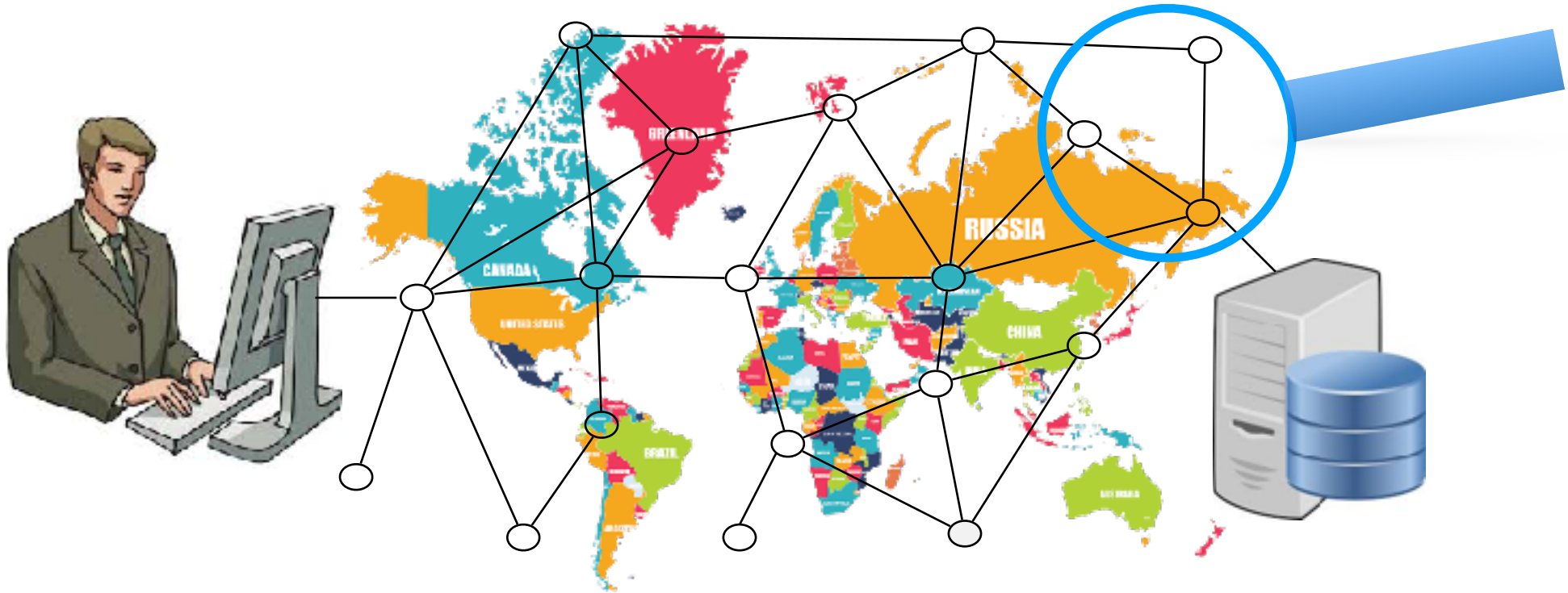
Scion Design & Development Team

Motivation and Context

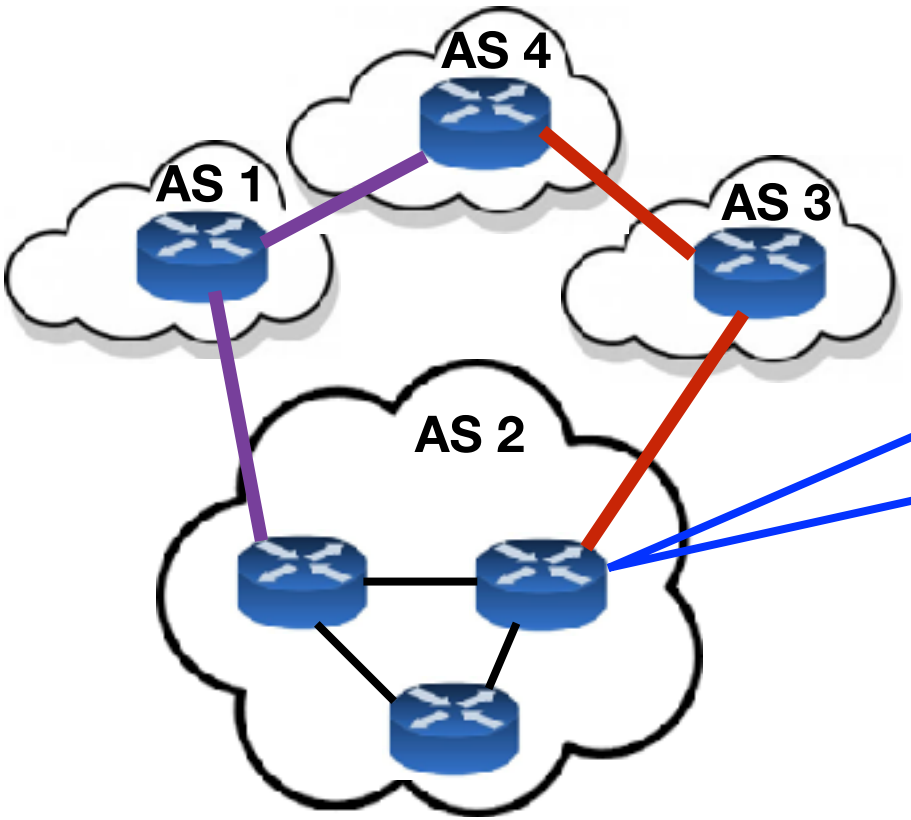
Routing problems with the status quo (inter-AS routing)

Routing between autonomous systems



- **Network of networks run by different institutions**
- **Nodes correspond to Autonomous Systems (ASes)**
  - Set of **routers** run by common institution (Telcos, ISPs, companies)
  - 50,000+ ASes, e.g., your typical university or large corporation.

Autonomous systems and routers

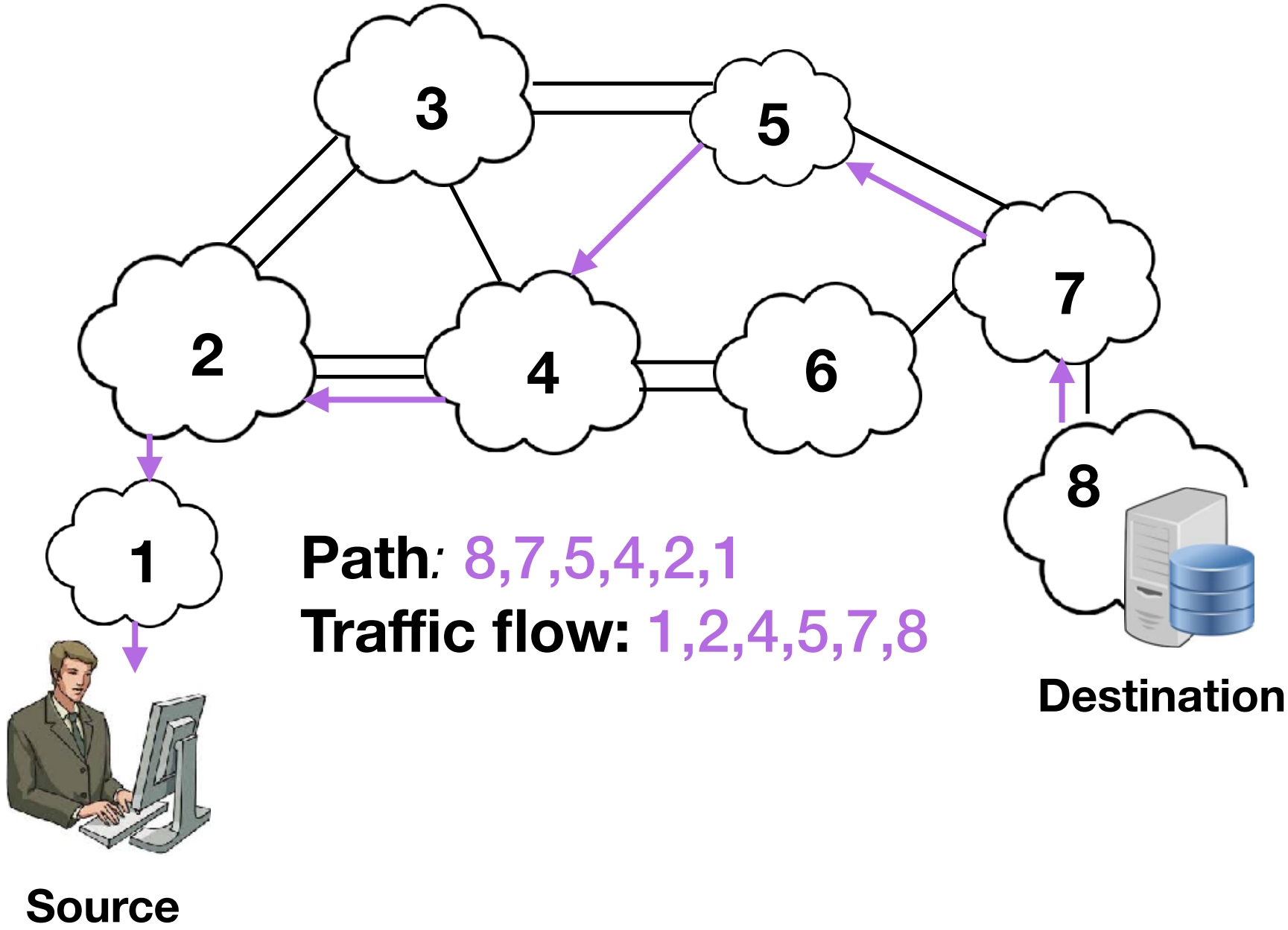


1. finds paths **between ASes** (and within ASes)
2. forwards data along paths

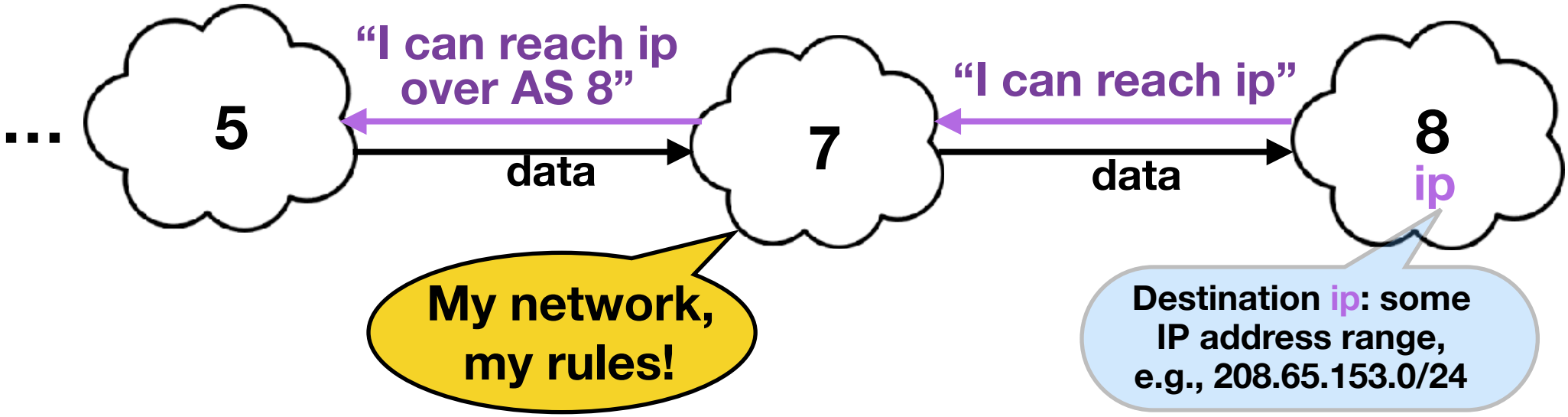
- **Multiple paths between ASes: 2,1,4 and 2,3,4**
- **Computed in background by *Border Gateway Protocol* (BGP) and just one will be selected and used to configure routers**

Path between two ASes

computed using Border Gateway Protocol (BGP)

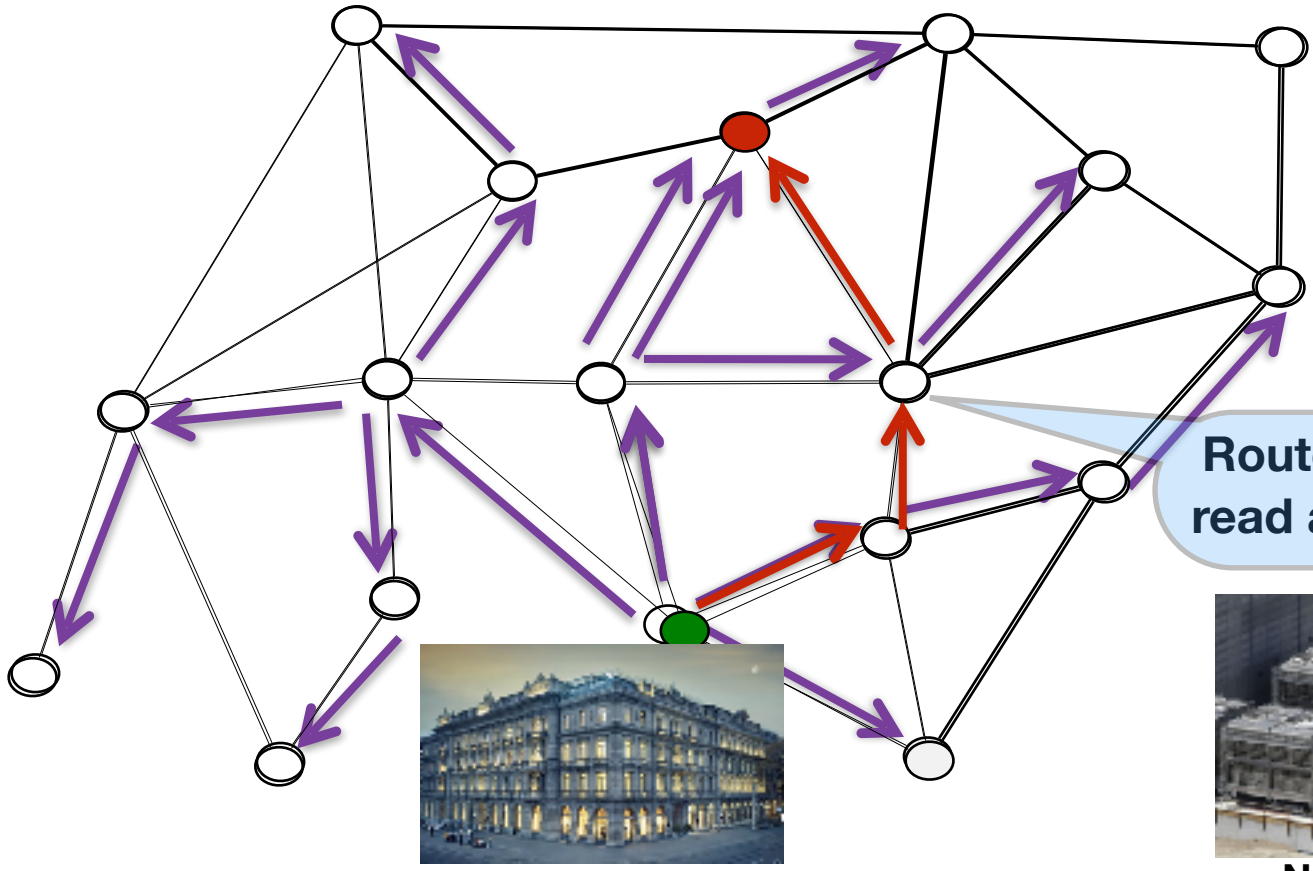


Boarder Gateway Protocol



- **ASes exchange reachability information** (*paths*)
- **Policies programmed by network operators**
  - Decisions on what is accepted, rejected, or propagated
  - Any AS can announce any address range it wants
- **It is all based on trust! Motivations may vary!**

Who controls the Internet?



Routers on path can read and modify data

NSA data storage center Utah

- **Control over paths is completely distributed**
  - Border Gateway Protocol (BGP): all nodes flood path announcements
- **No inbound traffic control**

Who controls Internet paths?

Three concrete examples

208.65.153.0/22

YouTube

208.65.153.0/24

PTA

Pakistan Telecommunication Authority

Pakistan DoS against Youtube (2 hours, 2008)

Strange snafu hijacks UK nuke maker's traffic, routes it through Ukraine

Lockheed, banks, and helicopter designer also affected by border gateway mishap.

by Dan Goodin - Mar 13, 2015 5:13pm CET

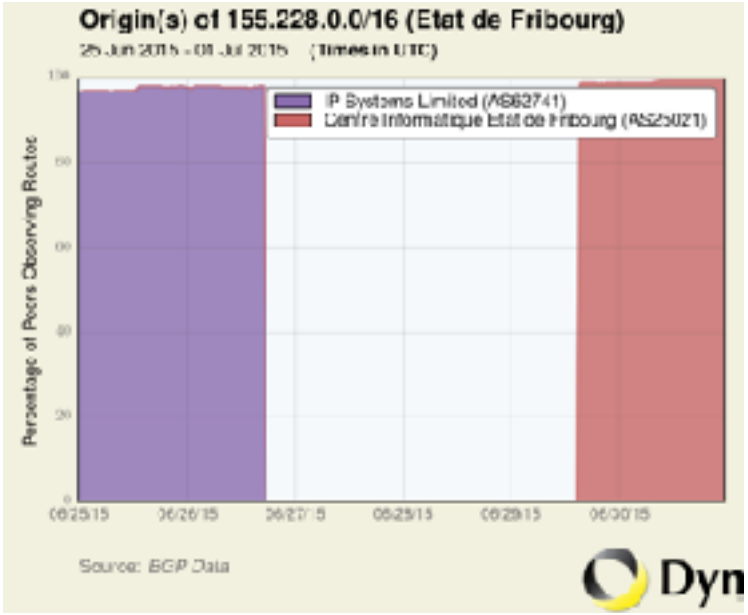
Share Tweet Email

Redirected traffic to UK Atomic Weapons Establishment

Internet traffic for 167 important British Telecom customers—including a UK defense contractor that helps deliver the country's nuclear warhead program—were mysteriously diverted to servers in Ukraine before being passed along to their final destination.

The snafu may have allowed adversaries to eavesdrop on or tamper with communications sent and received by the UK's Atomic Weapons Establishment, one of the effected British Telecom customers. Other organizations with hijacked traffic include defense contractor Lockheed Martin, Toronto Dominion Bank, Anglo-Italian helicopter company AgustaWestland, and the UK

Ukraine ISP hijacks UK routes including UK Atomic Weapons



Fribourg's government address space stolen for 3 days by SPAMers

Scion

Routing as it should be

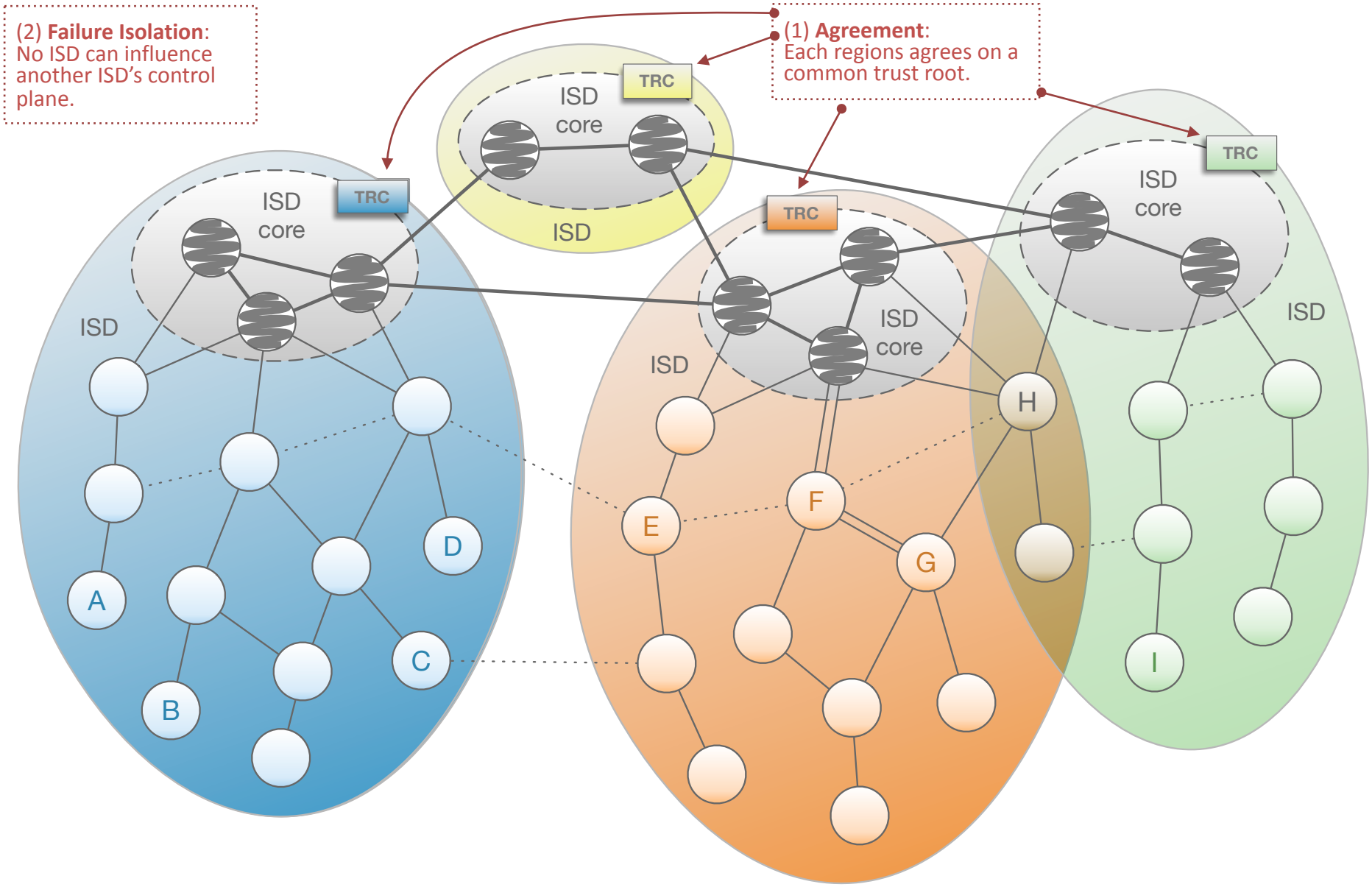
Scion Project
Secure Future Internet Architecture

- Design & Implementation, 75+ man years
- Design of routing / forwarding protocols, support ecosystem, and numerous extensions
- Clean slate, yet compatible with existing Internet
- Not just a research prototype:
  Growing deployment on 5 continents, 4 ISDs, 26 ASes
- See **www.scion-architecture.net** and related publications
  CACM 2017, IEEE S&P 2011, CCS 2015, NDSS 2016, S&P 2016

SCION Overview

- **Isolation Domains** (ISD)
- **Control Plane**: routing
  - Path exploration
  - Path registration
  - Path resolution
- **Data Plane**: packet forwarding

SCION Isolation Domain (ISD)



SCION Routing (Control Plane)

Routing Phases:

(1) Path Exploration

(2) Path Registration

(3) Path Resolution

Beaconing

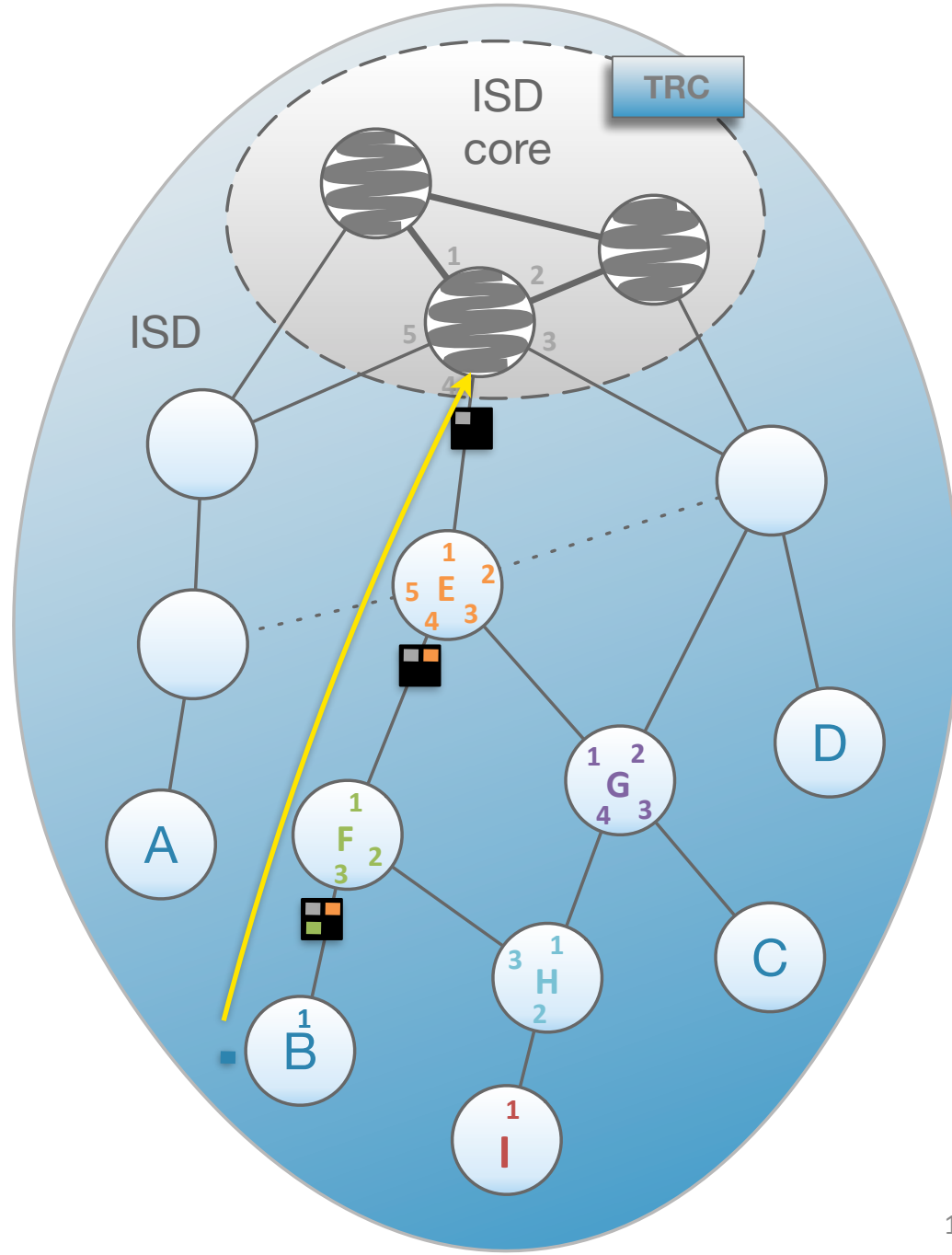
PCB

Core: Out: 4

AS E:
In: 1, Out: 4

AS F:
In: 1, Out: 3

AS B: In: 1



- Path Construction Beacons (PCB) are Sequence of signed Hop Fields
- Hop Fields (HF) carry the routing information for one AS

AS X:
In: y, Out: z

SCION Routing (Control Plane)

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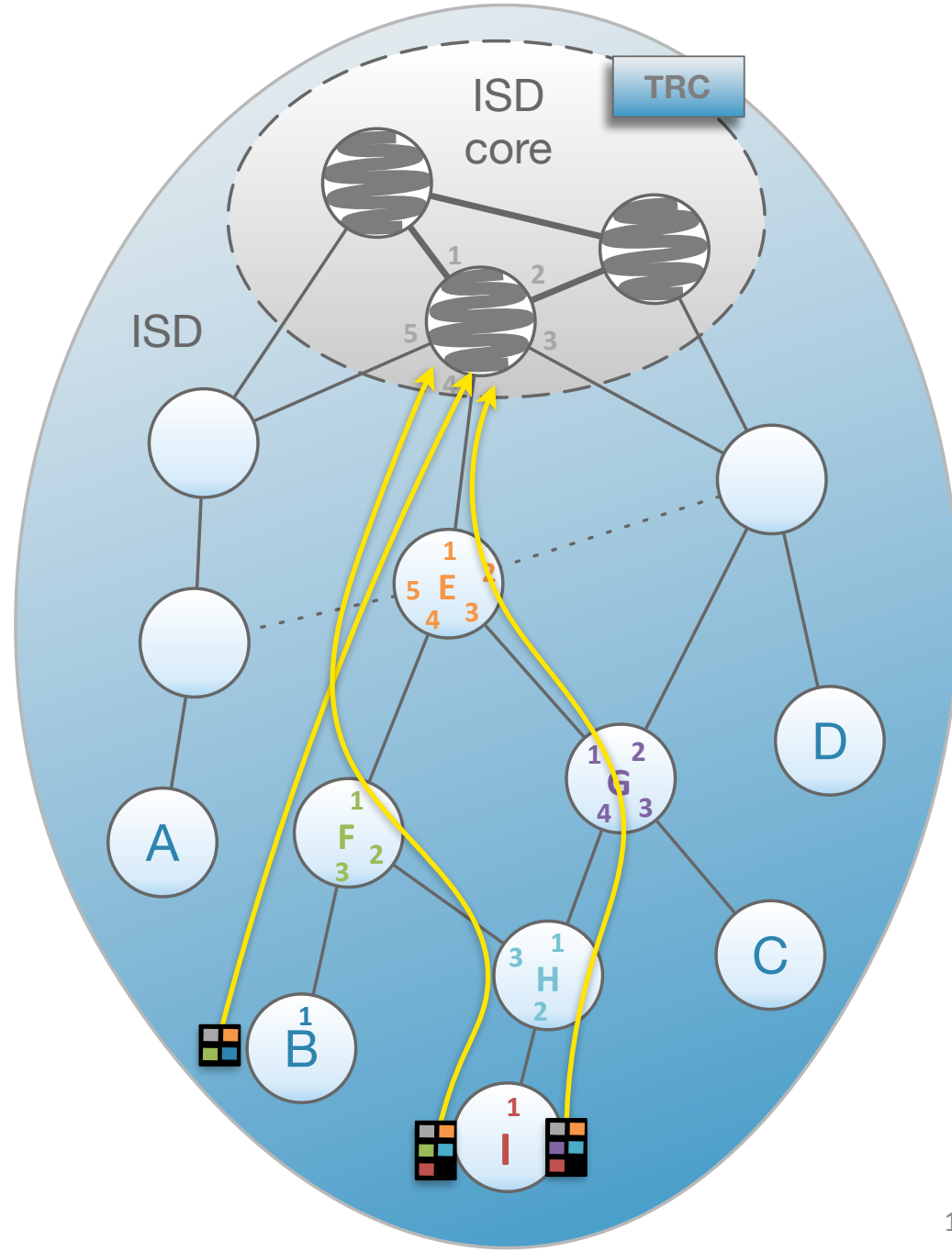

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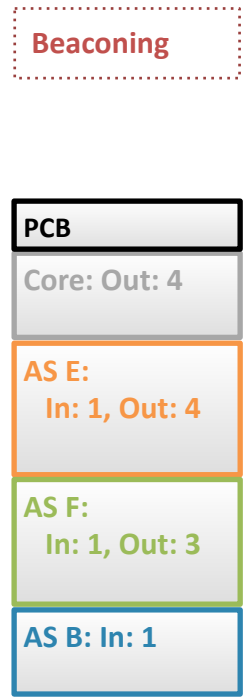

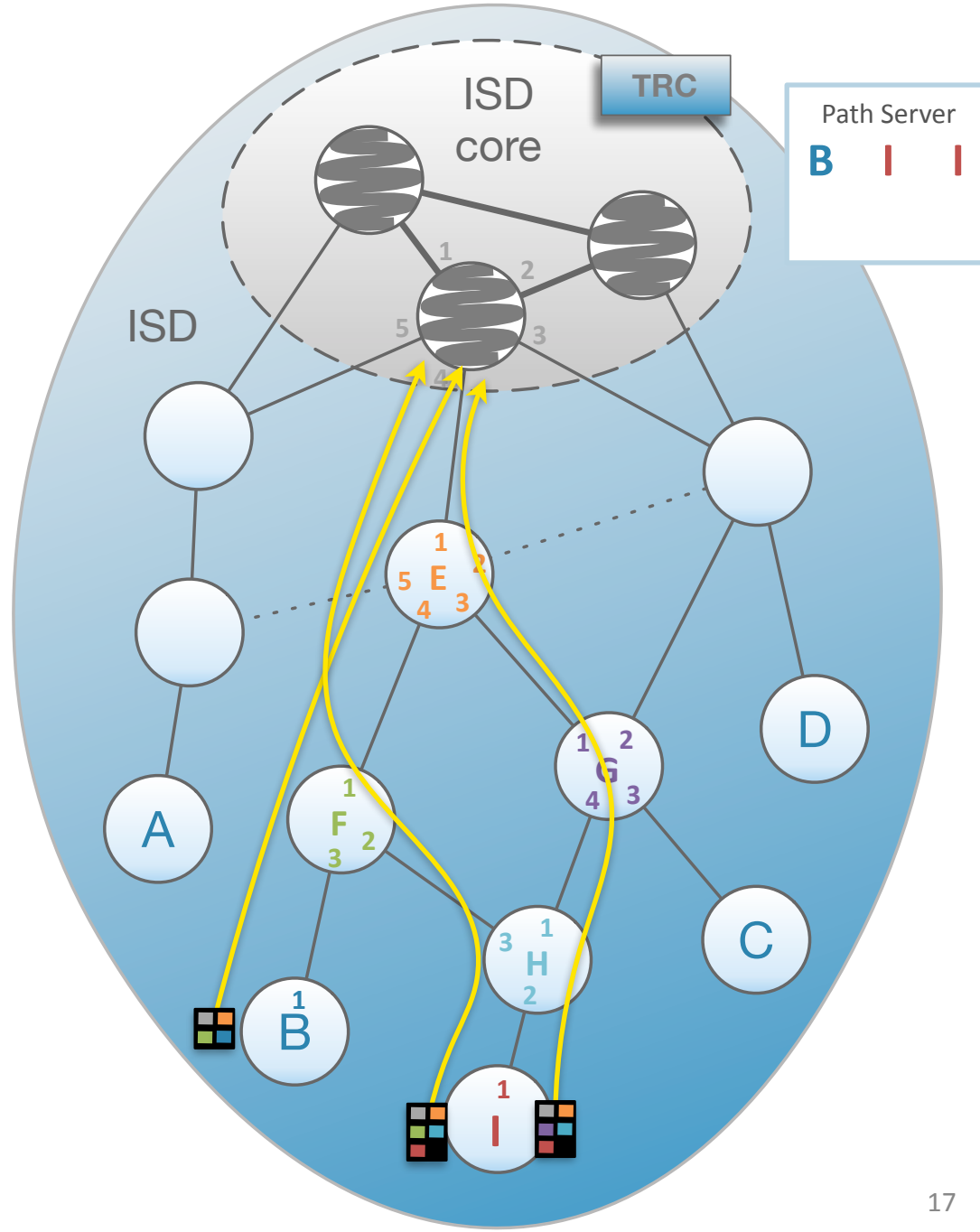

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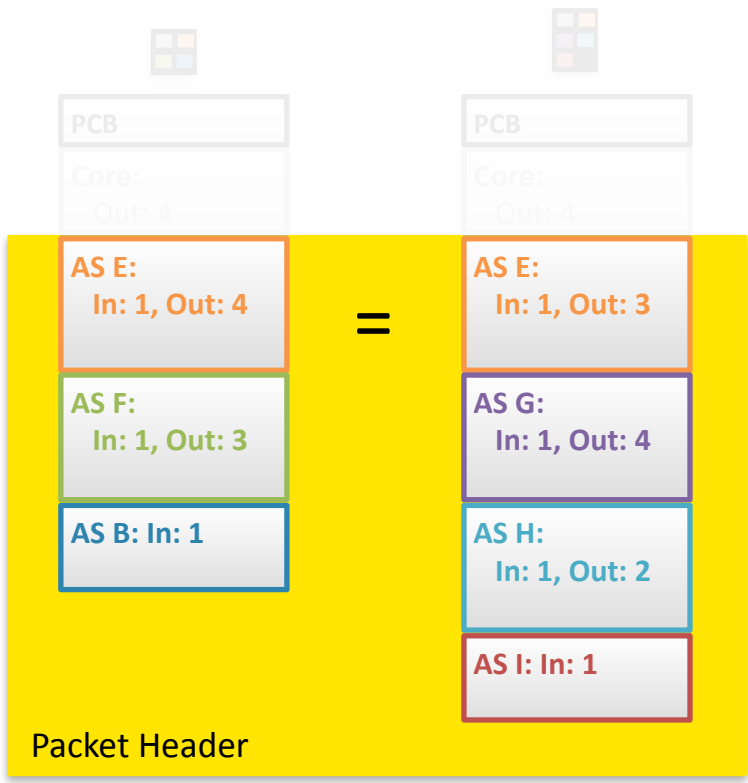
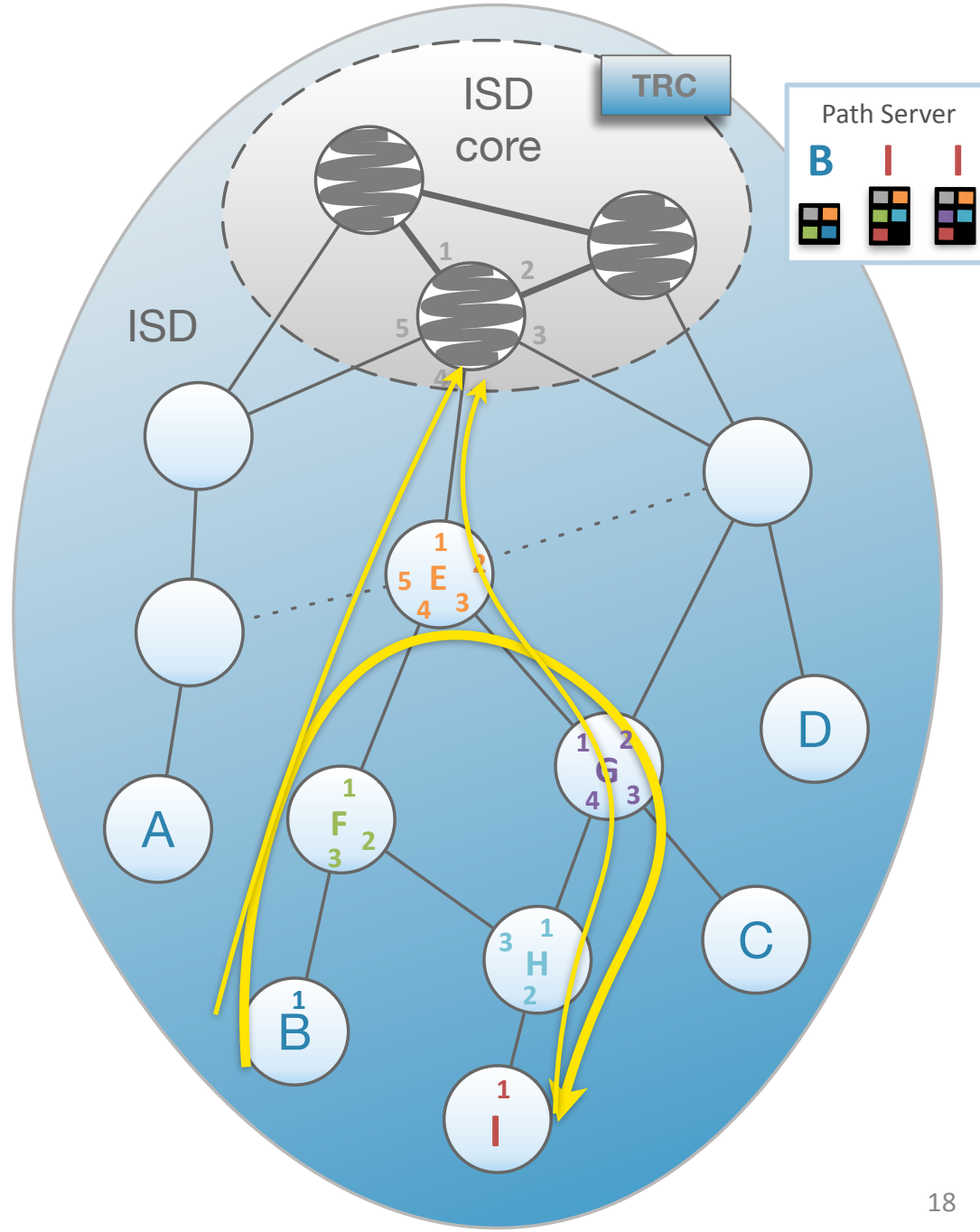




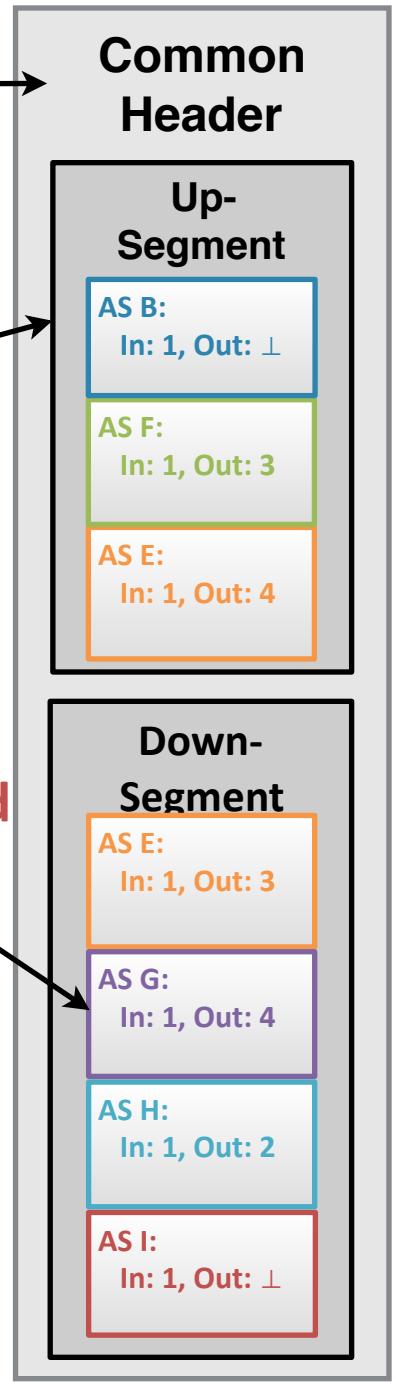
SCION Forwarding (Data Plane)

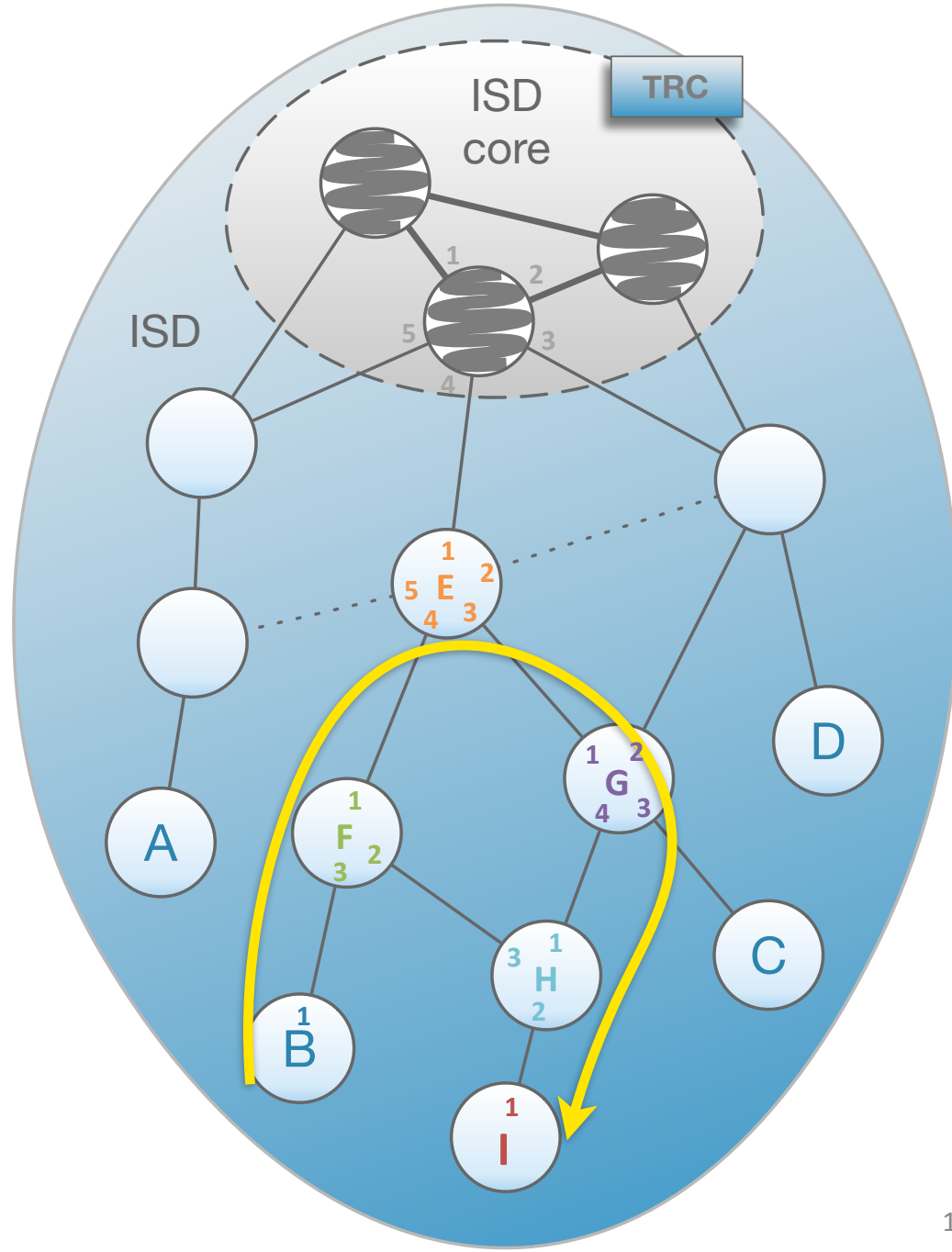
Packet header

Forwarding along:
- Up-Segment
- Core-Segment
- Down-Segment

Segments are sequences of Hop Field (HFs).

Hop Field contain routing information of one AS.





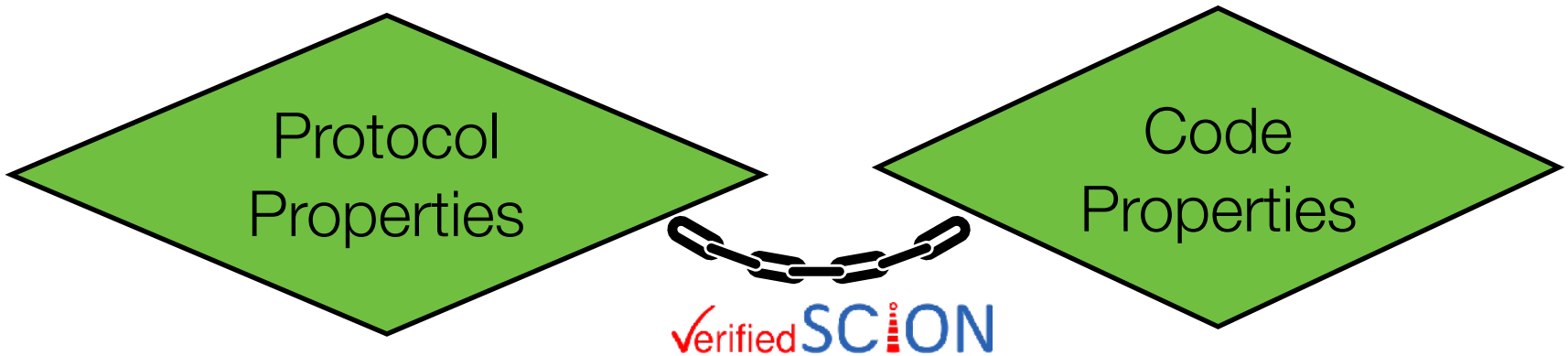
Verification

High-level, omitting formal details

Can We Verify Scion?

- Control and data plane guarantees
- Functional correctness of actual code
  - Suitable for high-assurance business cases
  - Ensures that routers are backdoor-free
- **Scion routers are simple and stateless**
  - This is the key to their (feasible) verification
  - Not possible for current Internet with highly complex routers and giant code bases of millions of lines

Correctness and Security
SCION approach



Verification of the **protocol** at the **network level**

- **Abstract models** of network & network-wide properties
- **Protocol verification guarantees** that security properties hold in an adversarial environment, **assuming** that each SCION component **behaves as specified**

Verification of the **components** at the **code level**

- **Code-level guarantees** (e.g., secure information flow)
- **Guarantees** that each SCION component **behaves as specified**

Data Plane ← **Initial focus** → **Router code**

Network-Level Verification: Approach

- **Formal specification** of network and network-wide properties
  - Description of network topology, beaconing and path construction, …
  - Network adversary (on and off-path)
  - Network-wide security properties

- **Formal verification**: refinement used to go from high-level models to precise assumptions on the individual components needed to ensure security properties.
  - Correctness by construction: **stepwise refinement** between (transition) systems
  - Proofs: forward simulation and invariant preservation
  - Invariants preserved under refinement

- **Tool support**: verification using Isabelle/HOL system with ETH Zurich developed theory extensions.

Scion Properties

On both control and data planes

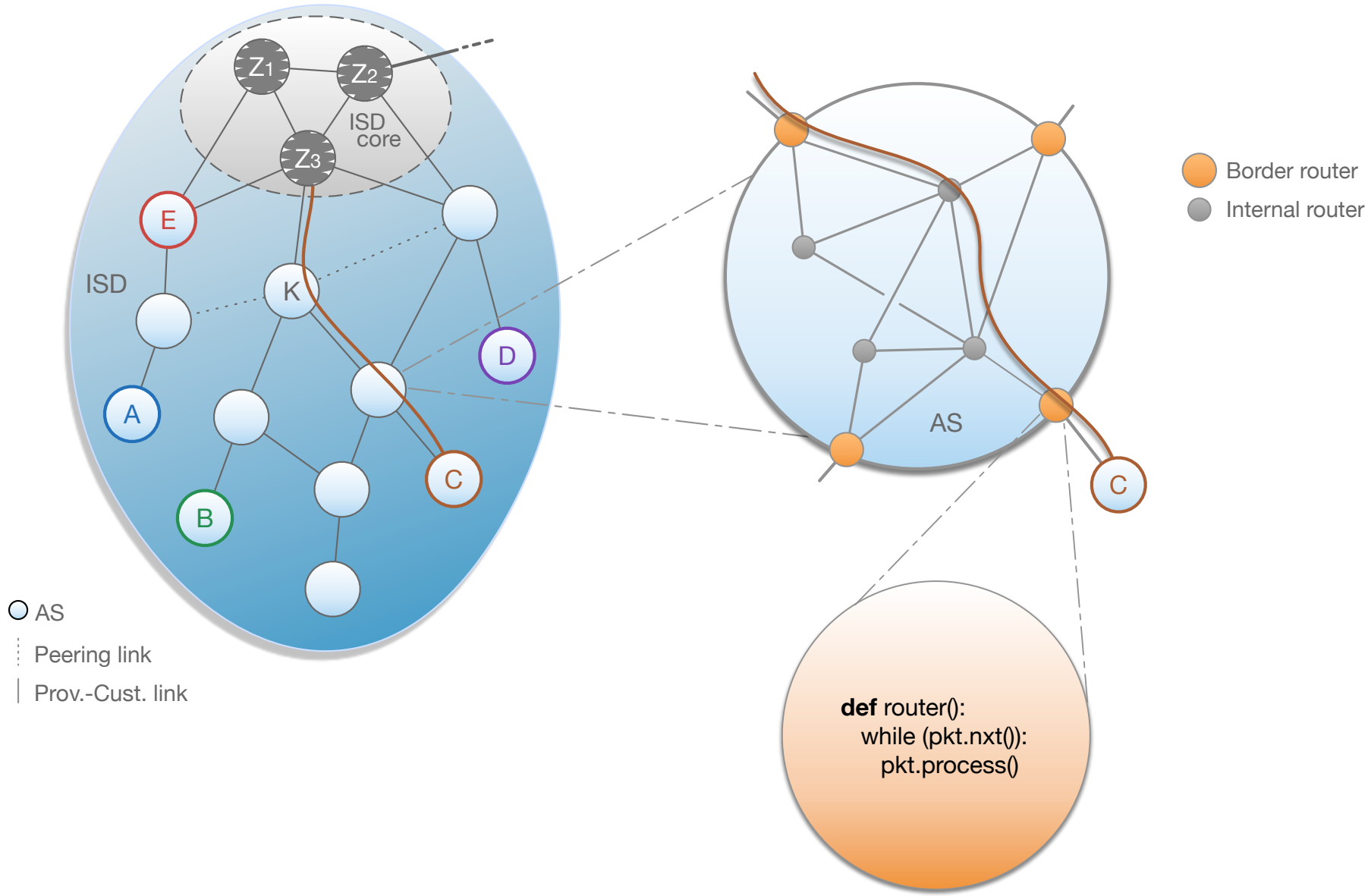
Control planes properties: address **beacons' authenticity**

- Security critical, but not in focus of this talk

Data plane properties: address how **routers forward messages**

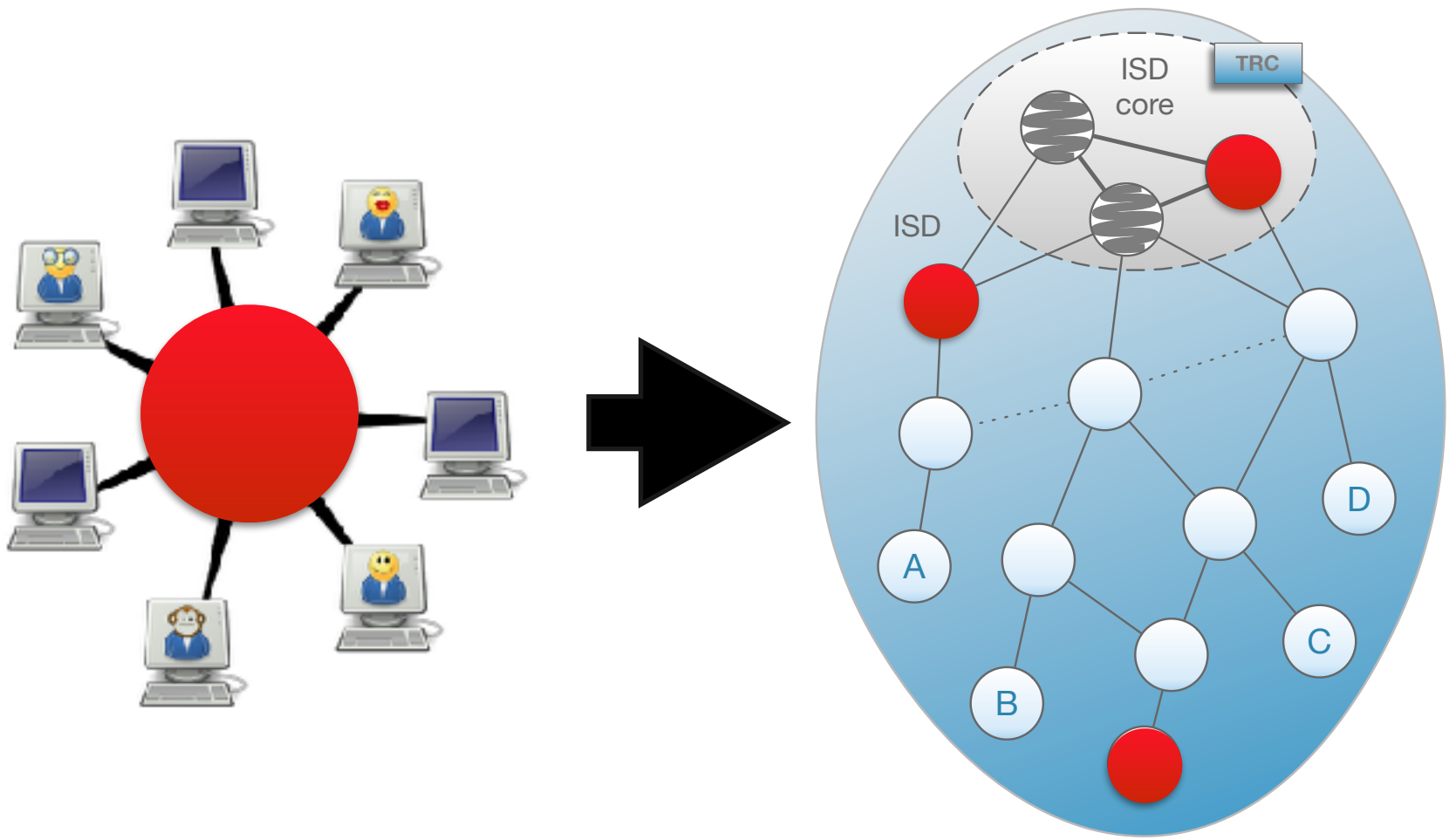
- **Path Authorization:** Packets traverse the network only along previously authorized paths.
- **Weak Detectability:** An active attacker cannot hide his presence on the path.

SCION Border Routers



Concrete Attacker Model

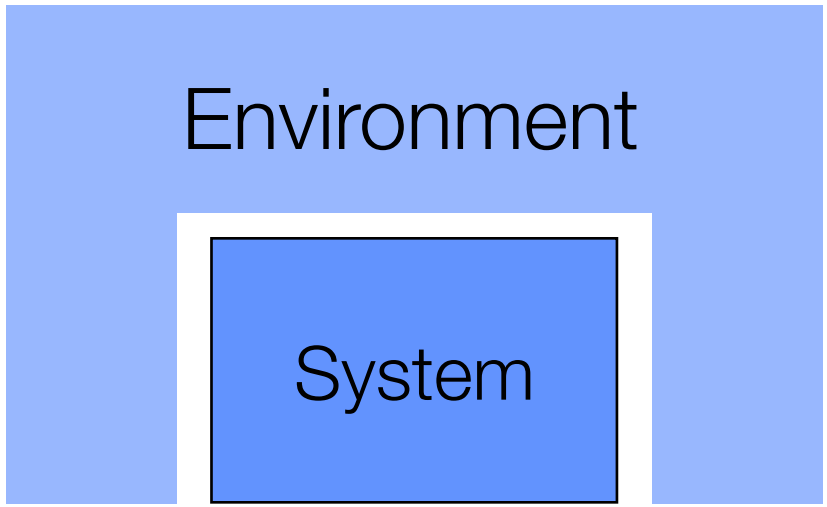
We use a localized, colluding Dolev-Yao attacker model



Attacker controls the entire network

Attacker controls entire ASes

System & Environment



Attacker

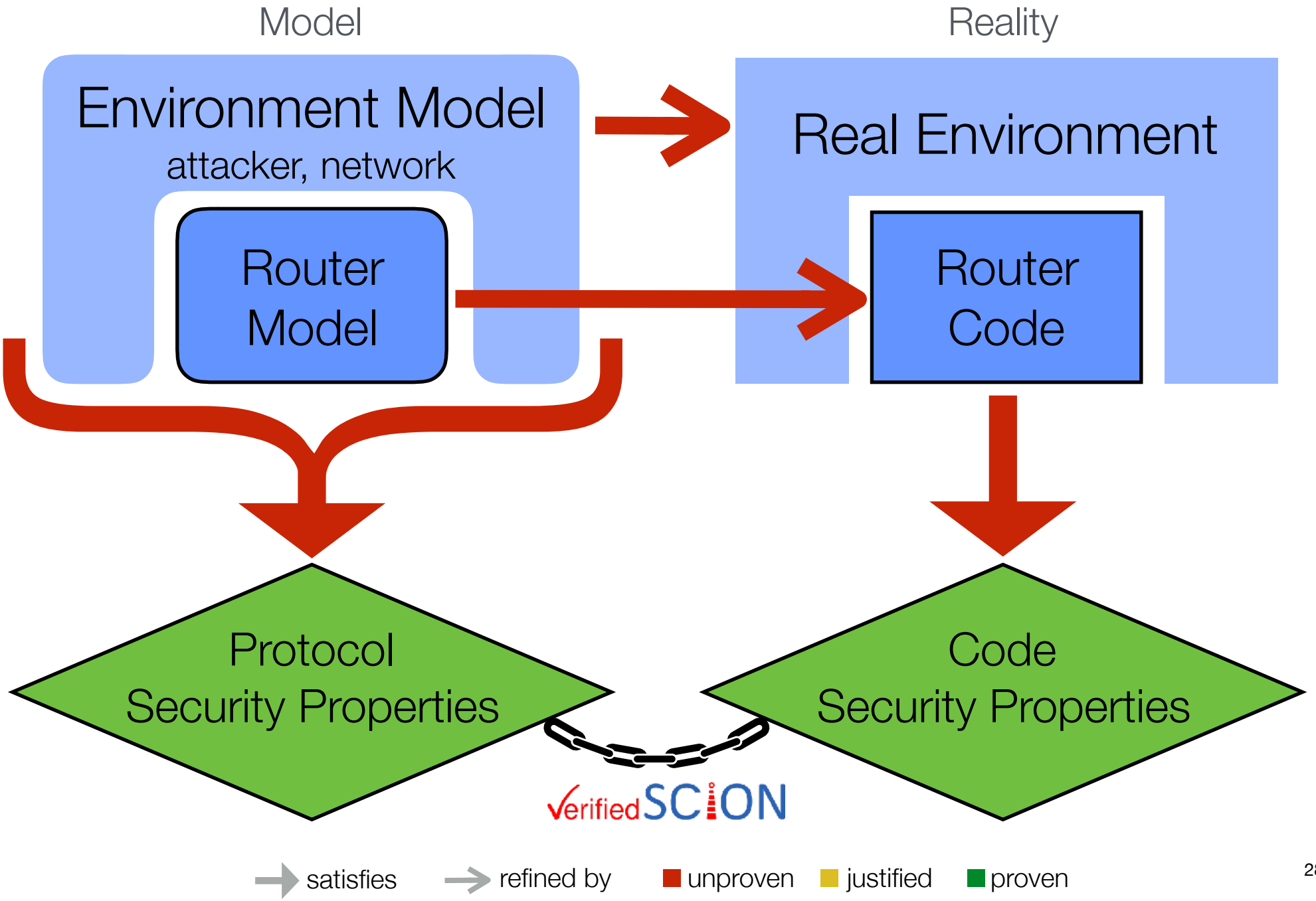
Network

End hosts

OS & Libraries

Border Router

SCION Router Verification Overview



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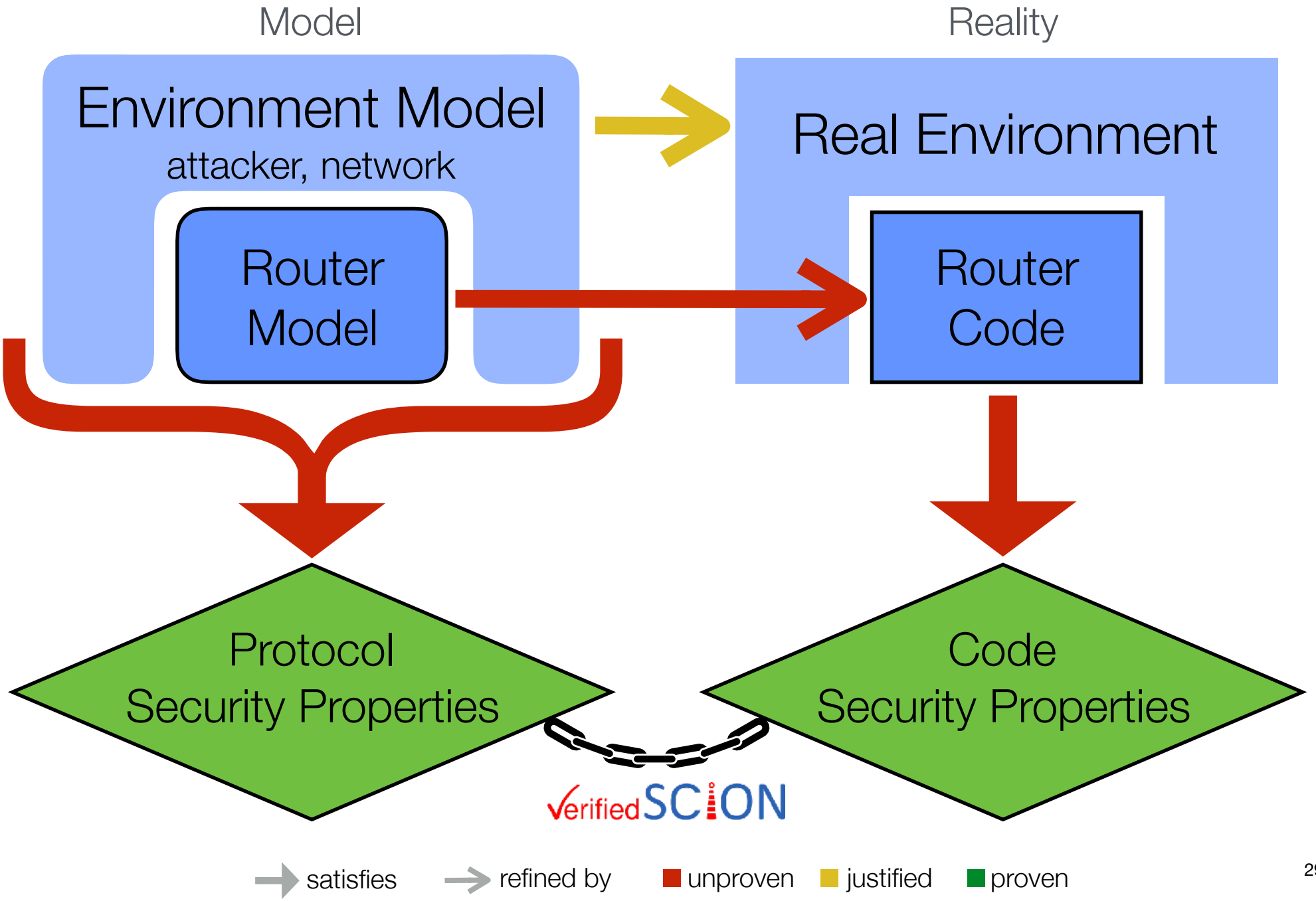
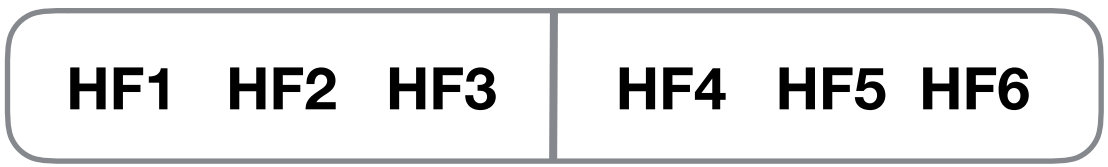


Abstract Packet Format

The Path is the Packet

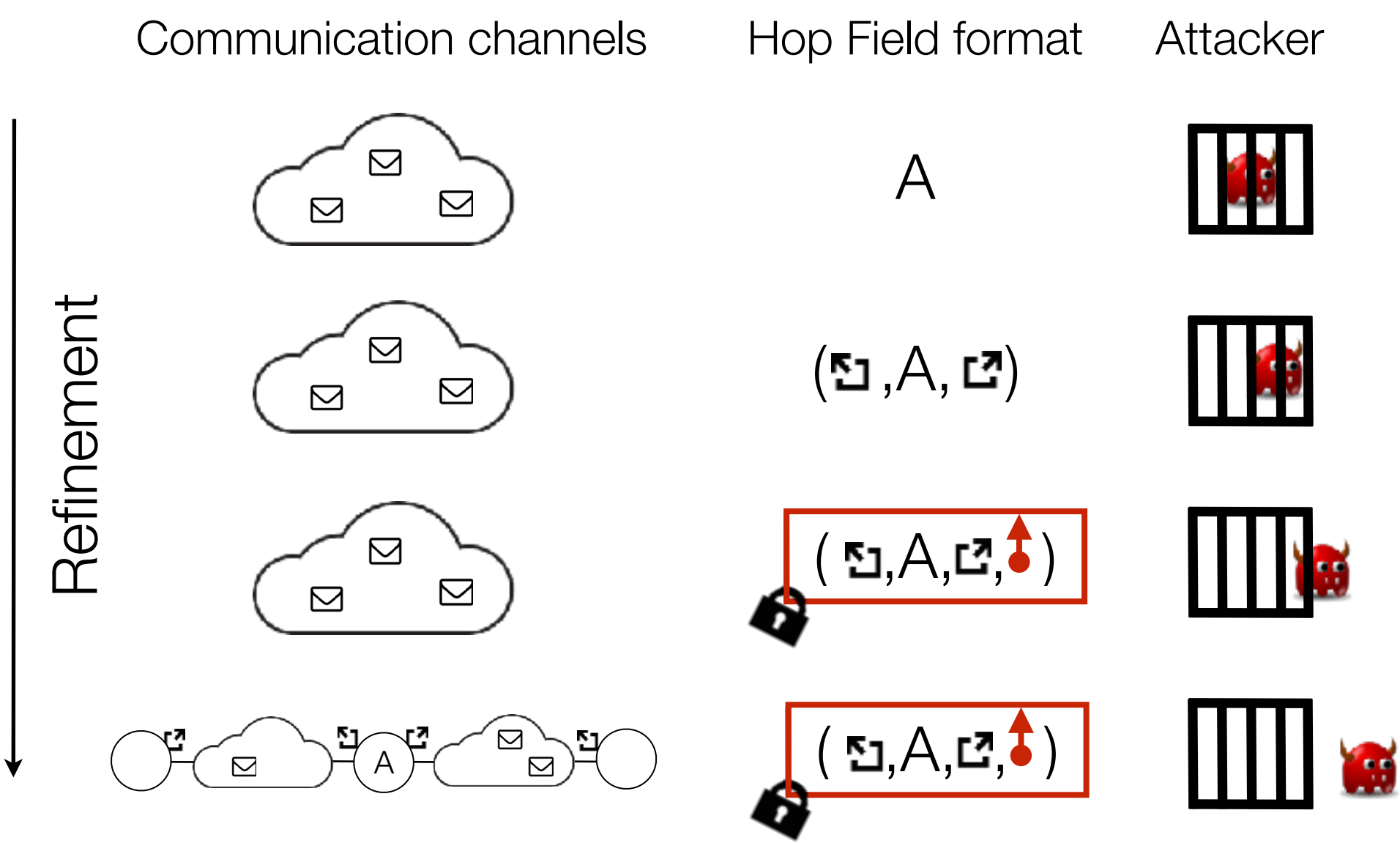
The Path (consisting of Past and Future)
contains **Hop Fields (HF)**

Example:



A Hop Field contains routing information of one AS

Refinement Overview



Idea: strengthen attacker while increasing protection of paths.

: Message set : Neighbor ASes : MAC : Fields protected by MAC

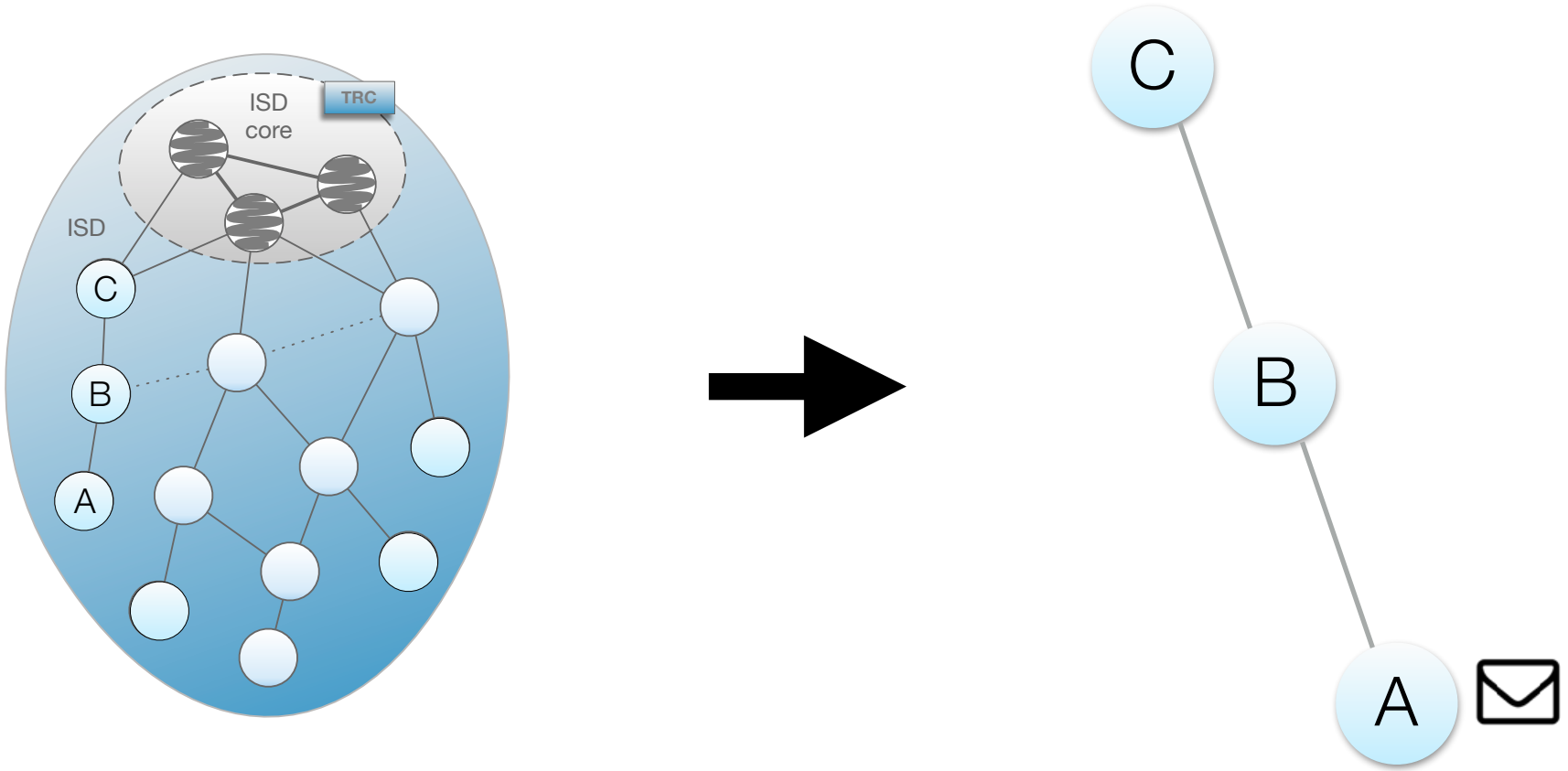
Simplified Scenario (Initially)

Packet traversal along a single up-segment

- A set of authorized-paths from path server is given as parameter
- Path is an up-segment. Simplify setting for now:
  - Ignore for now core- and down-segments
  - No peering or core links
  - No inter-domain communication (single ISD)
  - No changes in link status (up/down)

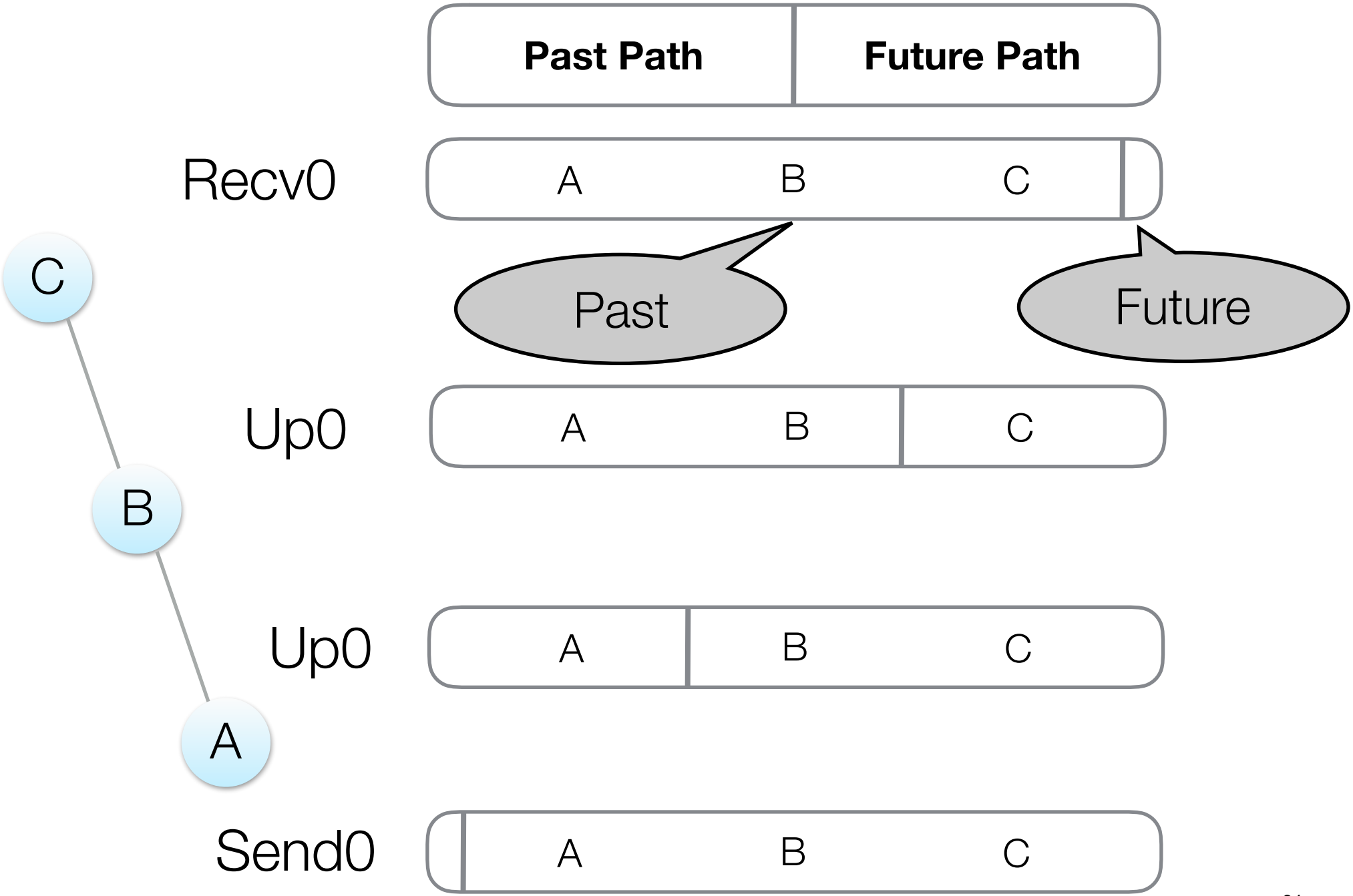
Verification is still challenging enough!

Simplified Scenario



Data Plane Model 0

Example of one Packet along a simple Path



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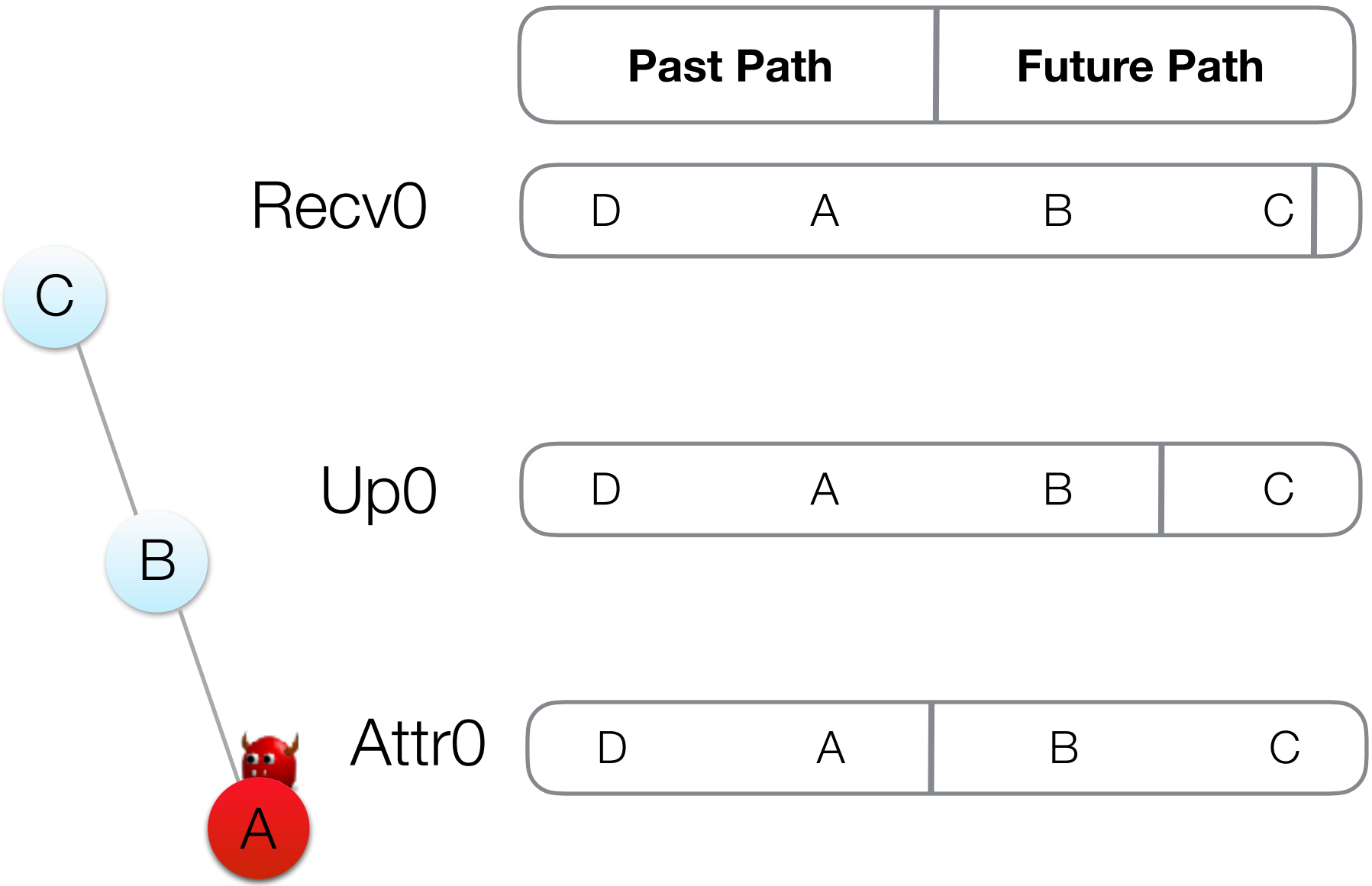
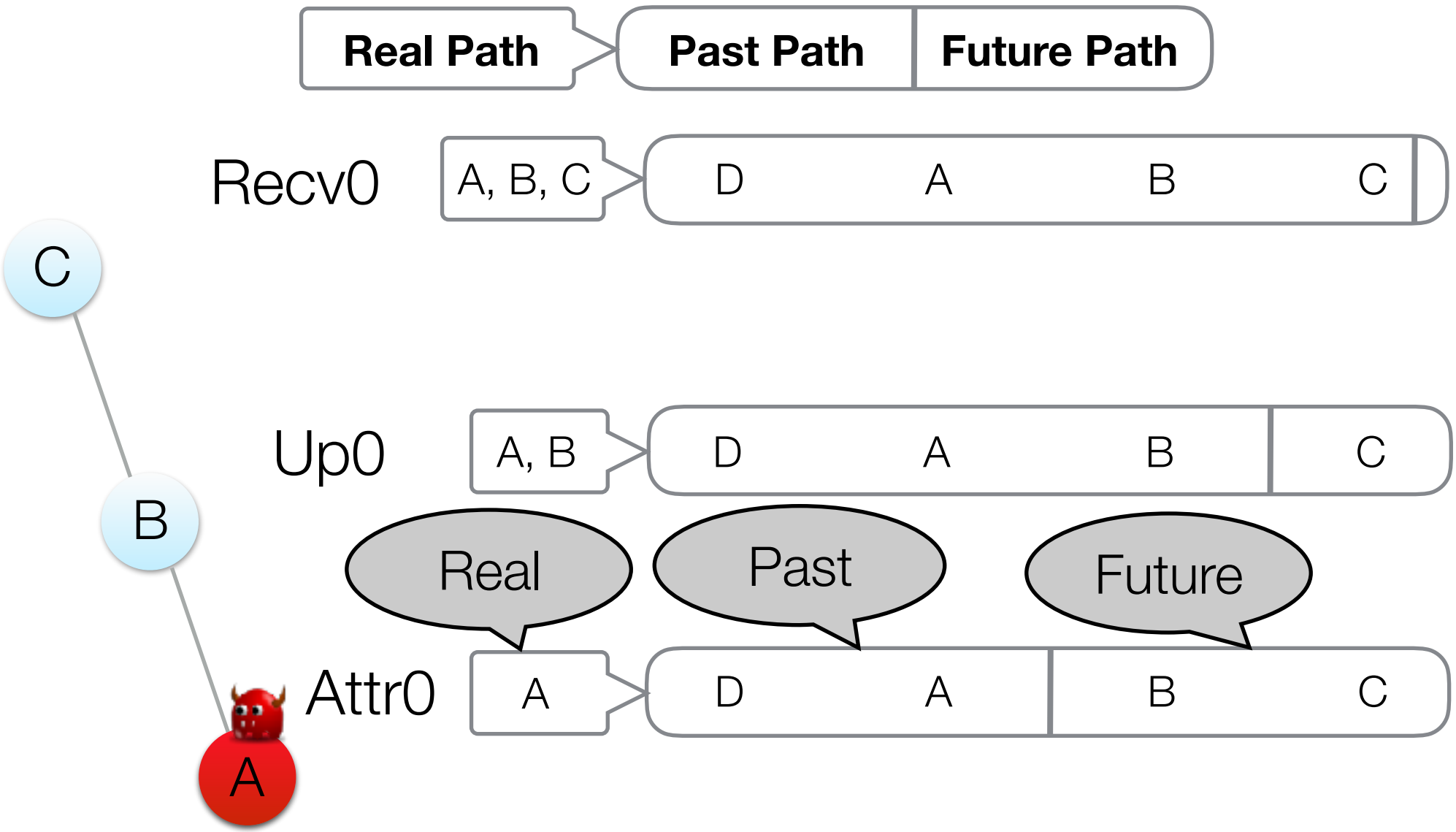


Problem: Past Path is unreliable

Real Path

- Add a new component to the message: the real path
  - records the actually traversed path so far
- Not part of the system, no correspondence in implementation
  - used for property specification only
  - Corresponds to a “history variable”

Data Plane Model 0



Formalized Properties of Model 0

Interface with control plane: We assume a set authorized-paths that contains the paths determined by the control plane.

- **Path Authorization** Packets traverse the network only along previously authorized paths.

- **Weak Detectability** An attacker cannot hide his presence on the path. This follows from property: the real path is a suffix of the past path.

Data Plane Model 1

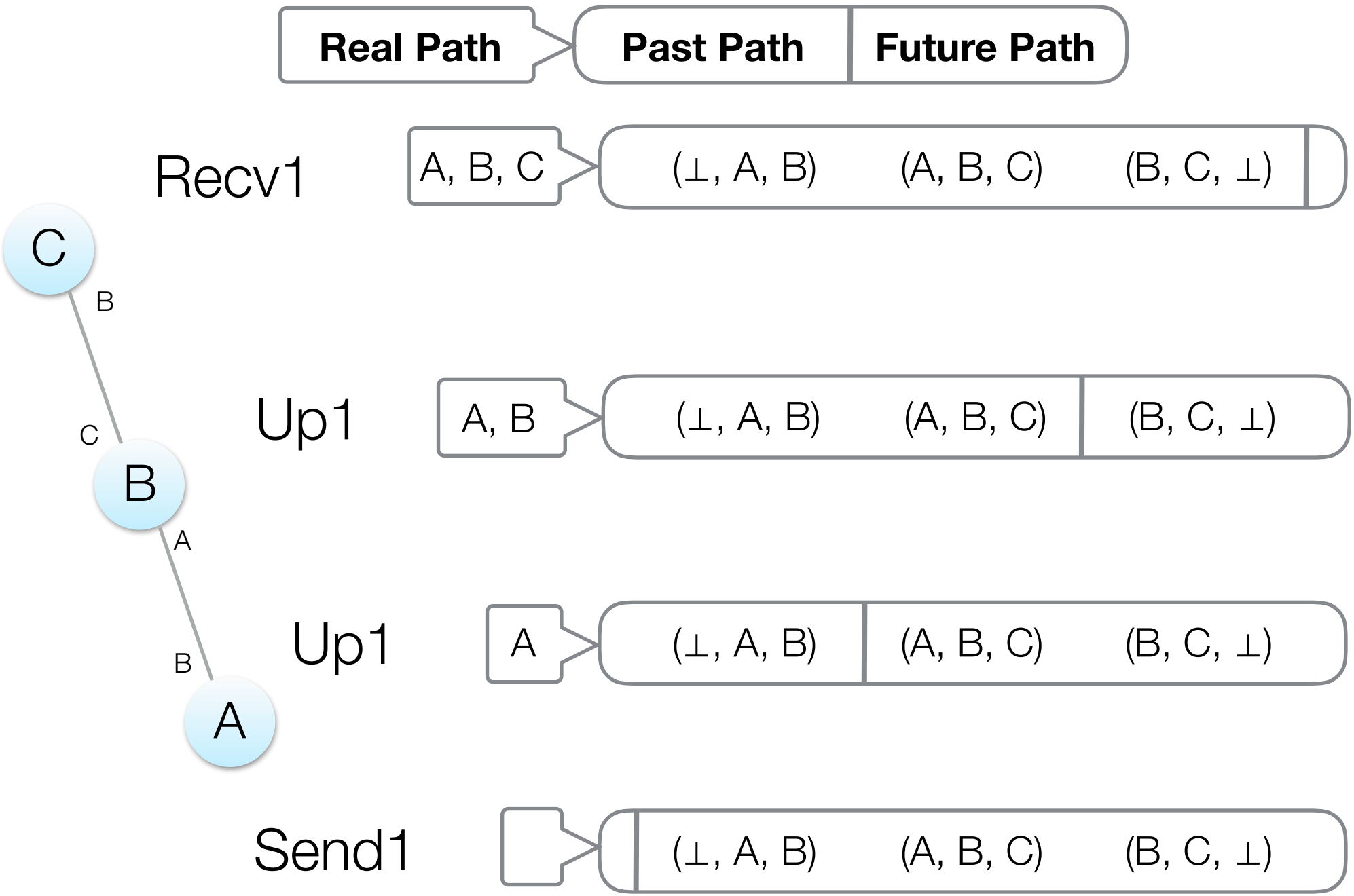
Hop Field format is refined:

Model 0 → Model 1

A → (↖ ,A, ↗)

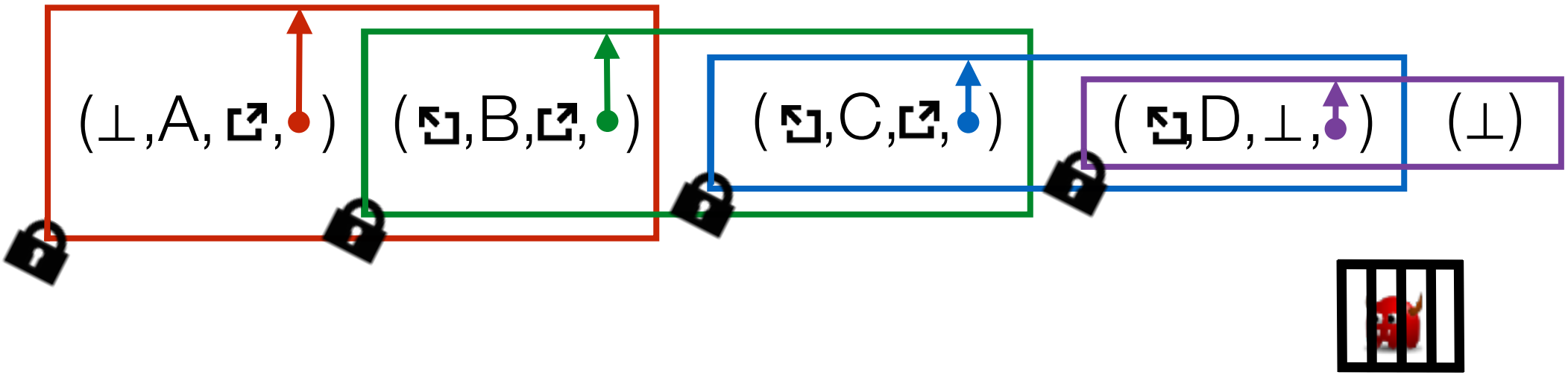
Added: references to previous and next AS

Data Plane Model 1



Data Plane Model 2: "Chaining" of MACs

Hop Field format is further refined by adding a MAC

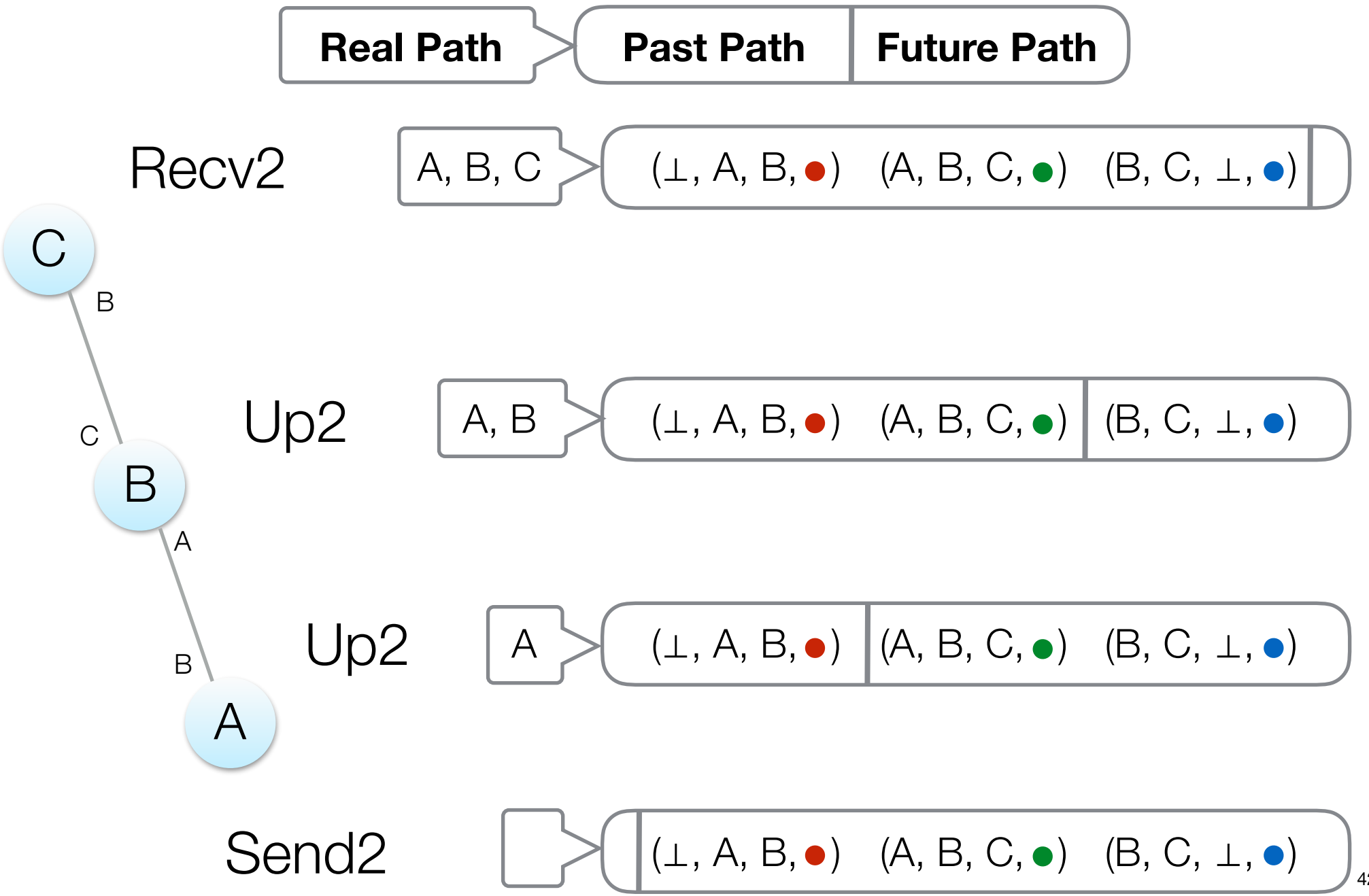


- MAC at *A* is produced with a *key(A)* known only to *A*
- MAC includes data and MAC of subsequent Hop Field (needed for verification)

Simplified representation:

(↖, A,↗,●) (↖, B,↗,●) (↖, C,↗,●) (↖, D,↗,●)

Data Plane Model 2

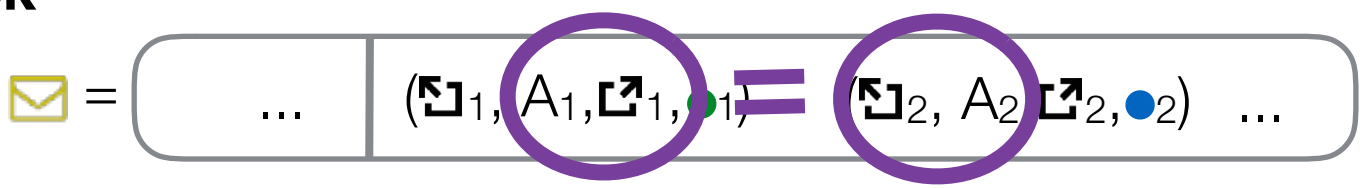


Up-Event in Model 2

Guard

In select in 

Check



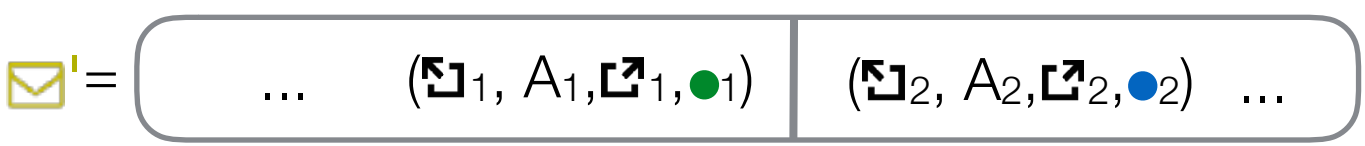
$\wedge$ $\bullet_1$= valid MAC using *key*(A_1)

$\wedge$ $\bullet_2$= valid MAC using *key*(A_2)

$\wedge$ $\nearrow_1 = A_2 \wedge \nwarrow_2 = A_1$

Action

Out put ✉' in  where



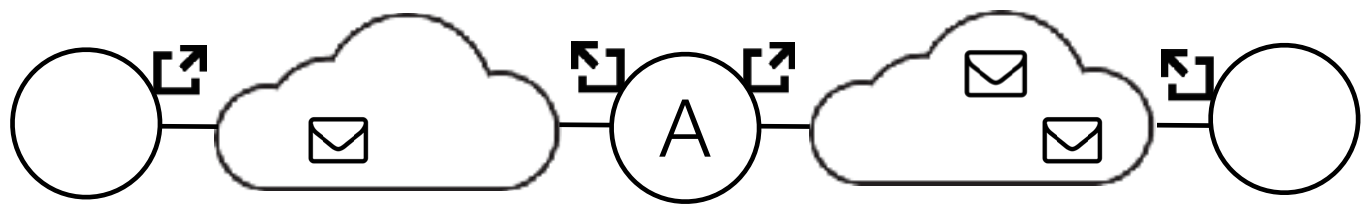
Refining Model 2

Model 2

Global Message Set

Refinement

Model 3

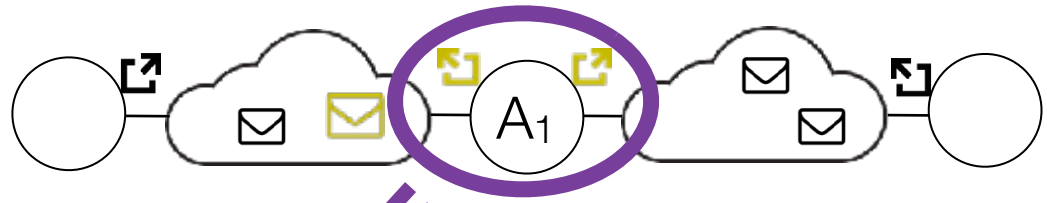


Inter-AS Message Sets

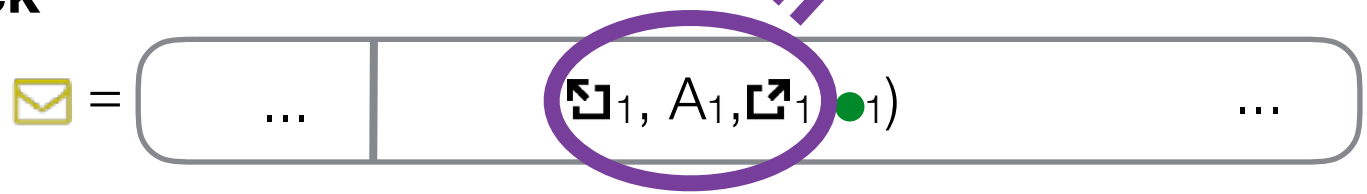
Up-Event in Model 3

Guard

In select from



Check



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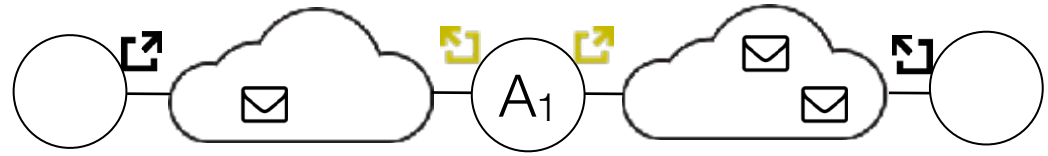
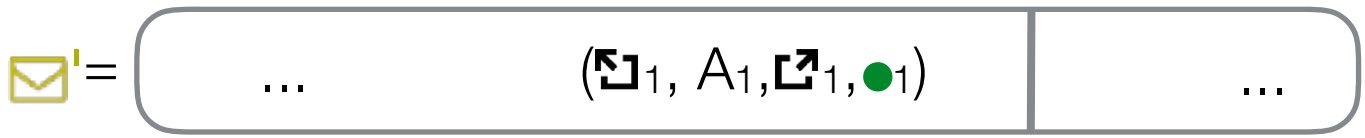
$\wedge$ $_1$ = $\wedge$ $_1$ =

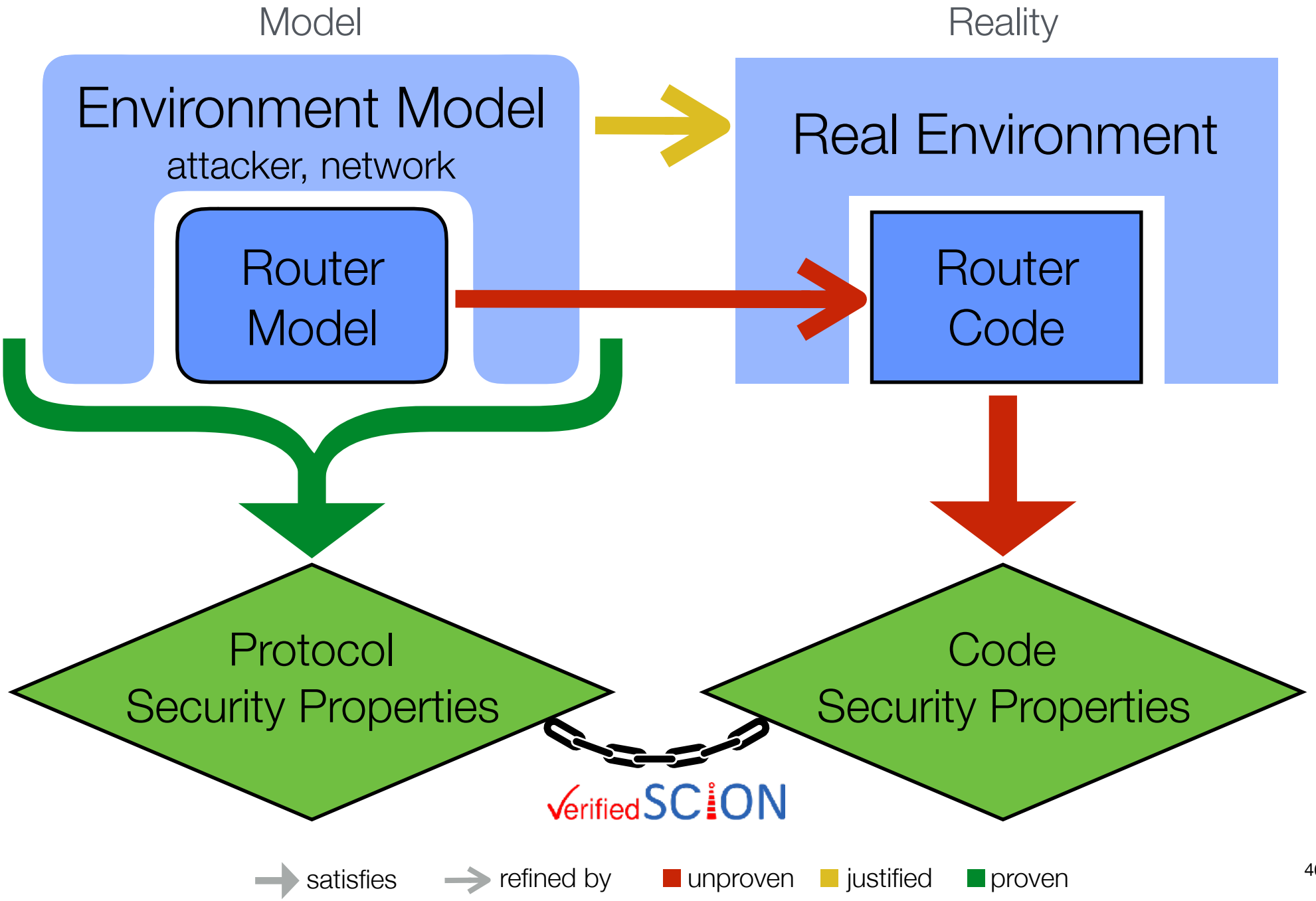
Action

Out put ' in

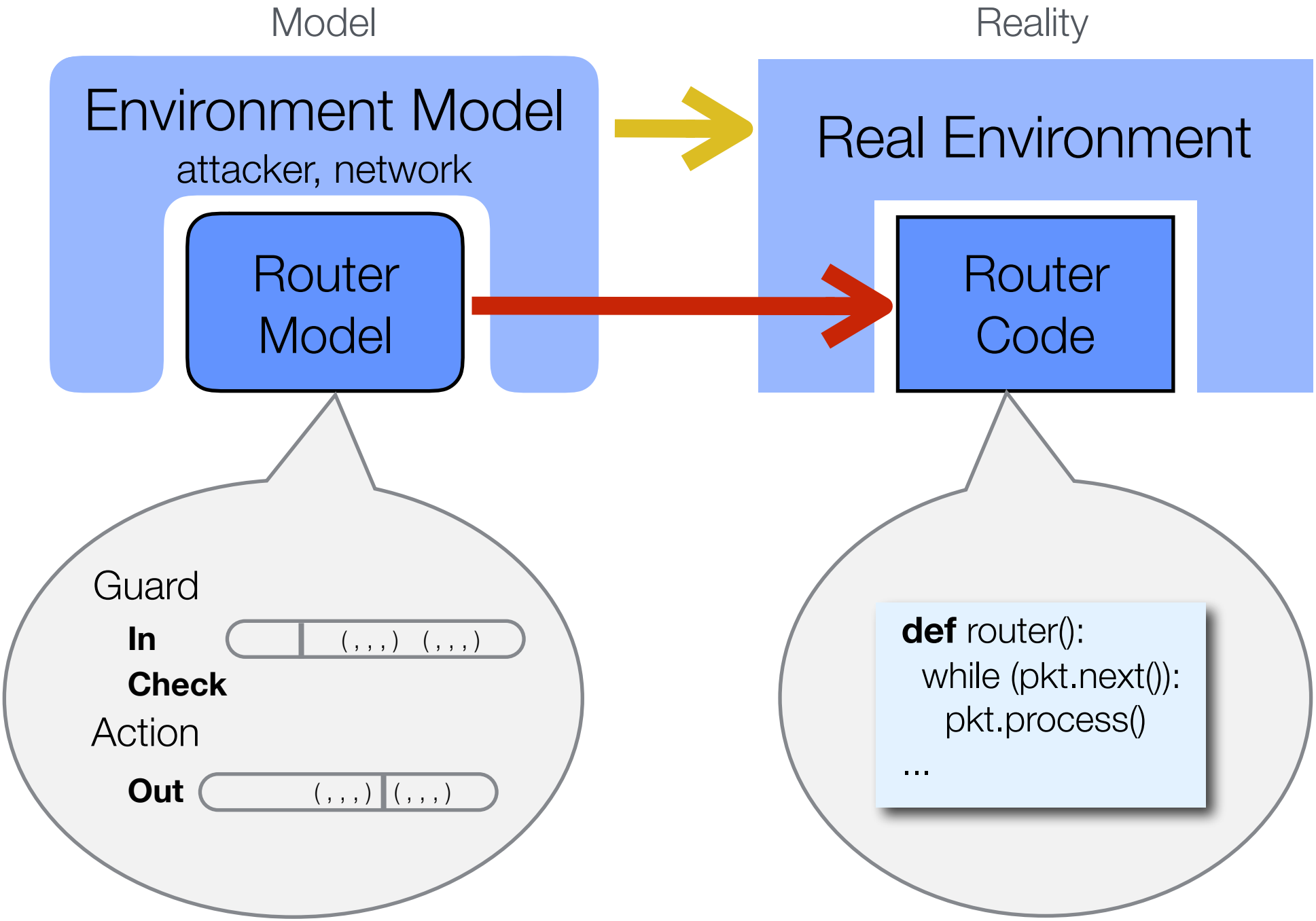




SCION Router Verification Overview

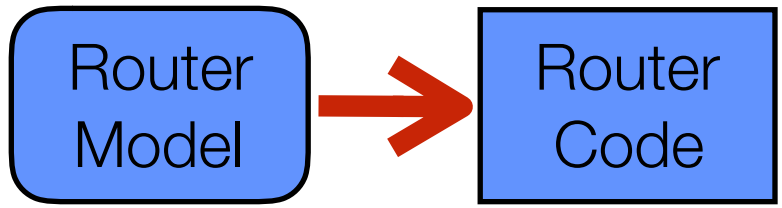


Router Model vs. Code

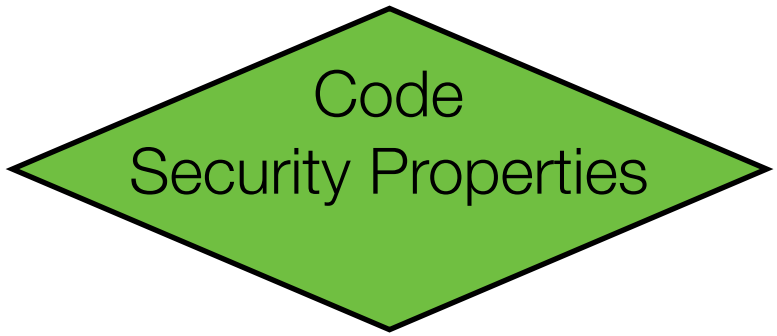


Code-Level Verification

- Main goal: prove **functional correctness**.
  - Code refines the protocol.

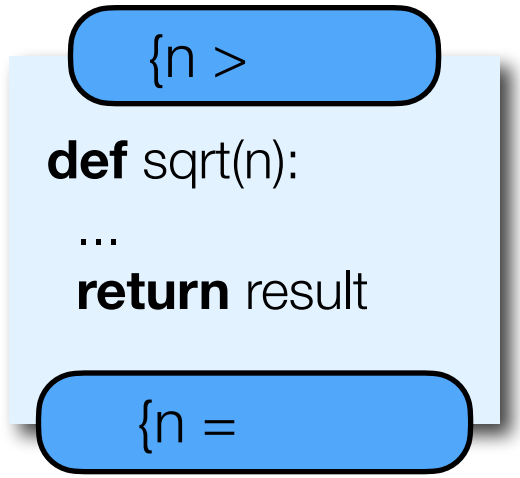


- Other desirable properties **only on code level**:
  - **Safety**: Code does not raise runtime exceptions or have data races.
  - **Secure information flow**: Code does not leak any information about crypto keys.
  - **Liveness and deadlock freedom**



- Focus on the SCION code base.
  - Used libraries are given specifications, **assumed** to be correct.
  - Runtime, OS, ..., are **assumed** to be correct.

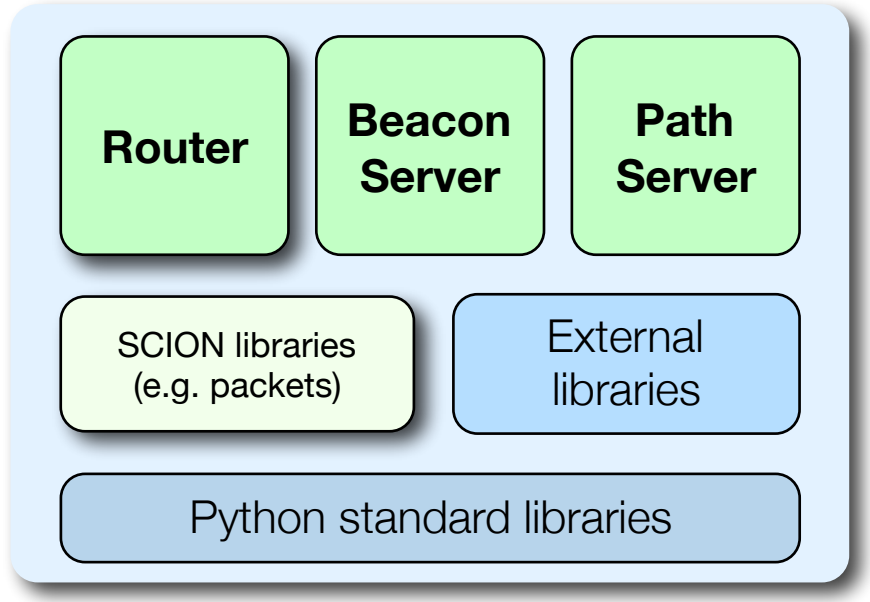
Program Verification

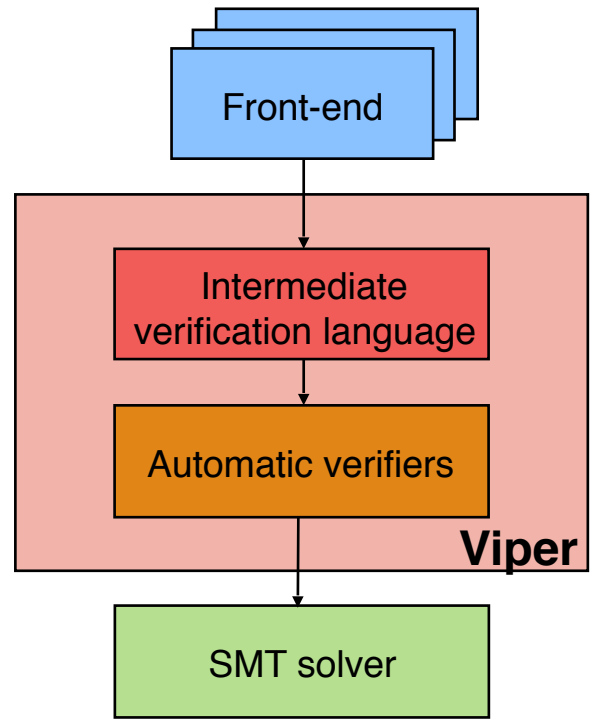


- Formal **specification** for each method
  - Pre- and postcondition, loop invariants
- Formal **proof** that implementation satisfies specification.
  - Assuming **precondition** holds at the beginning, prove that **postcondition** holds after return (partial correctness).
  - For all possible inputs, schedules, callers, ...
  - Additional proof obligations for special properties, like progress

Code-based Verification

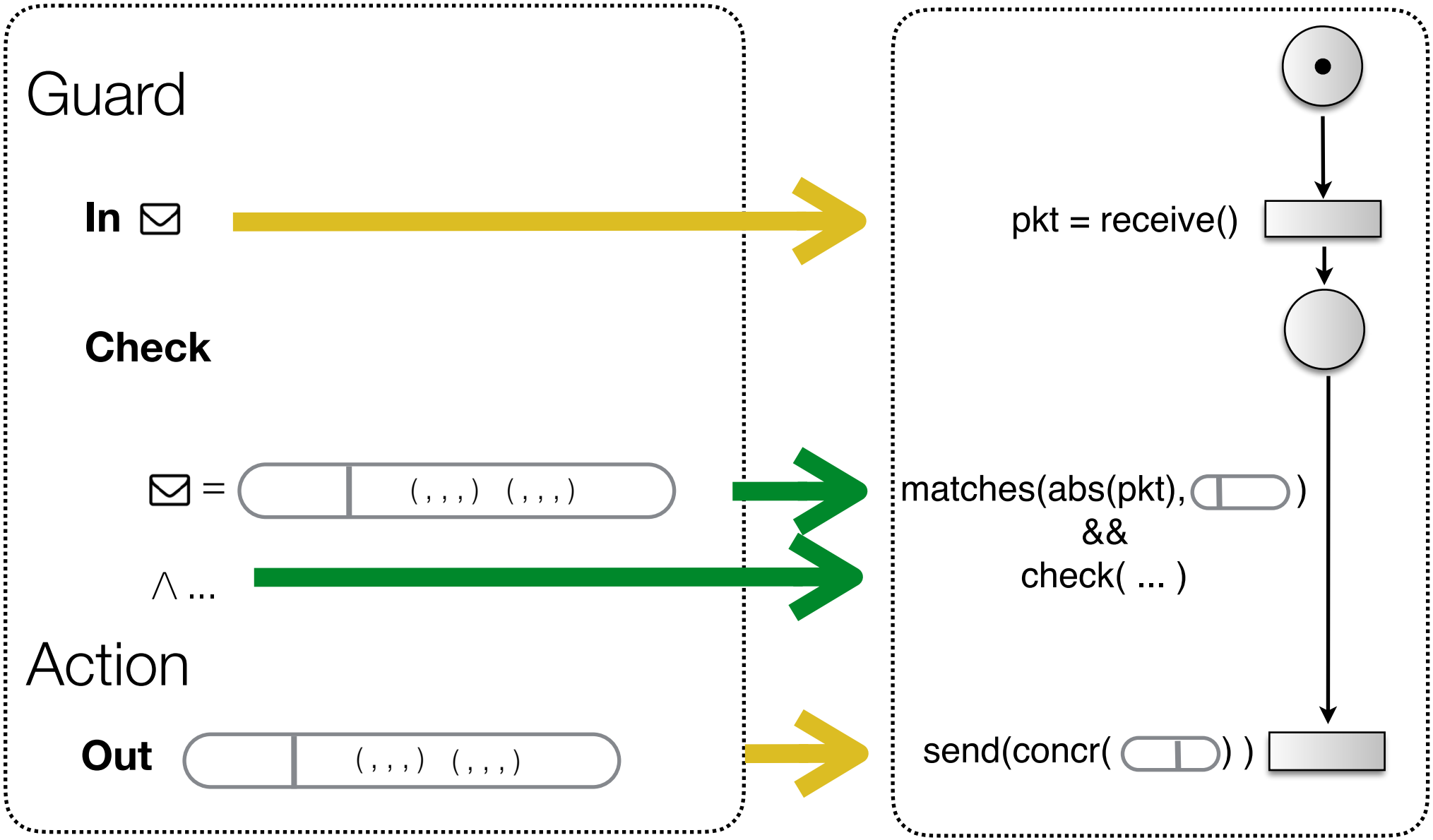
- Scion in Python 3
  - ~11k LOC
- Substantial subset of Python
  - Most standard OOP features
  - e.g. inheritance, exceptions, concurrency
- Focus on router first
- Use Viper Toolchain with Python front end





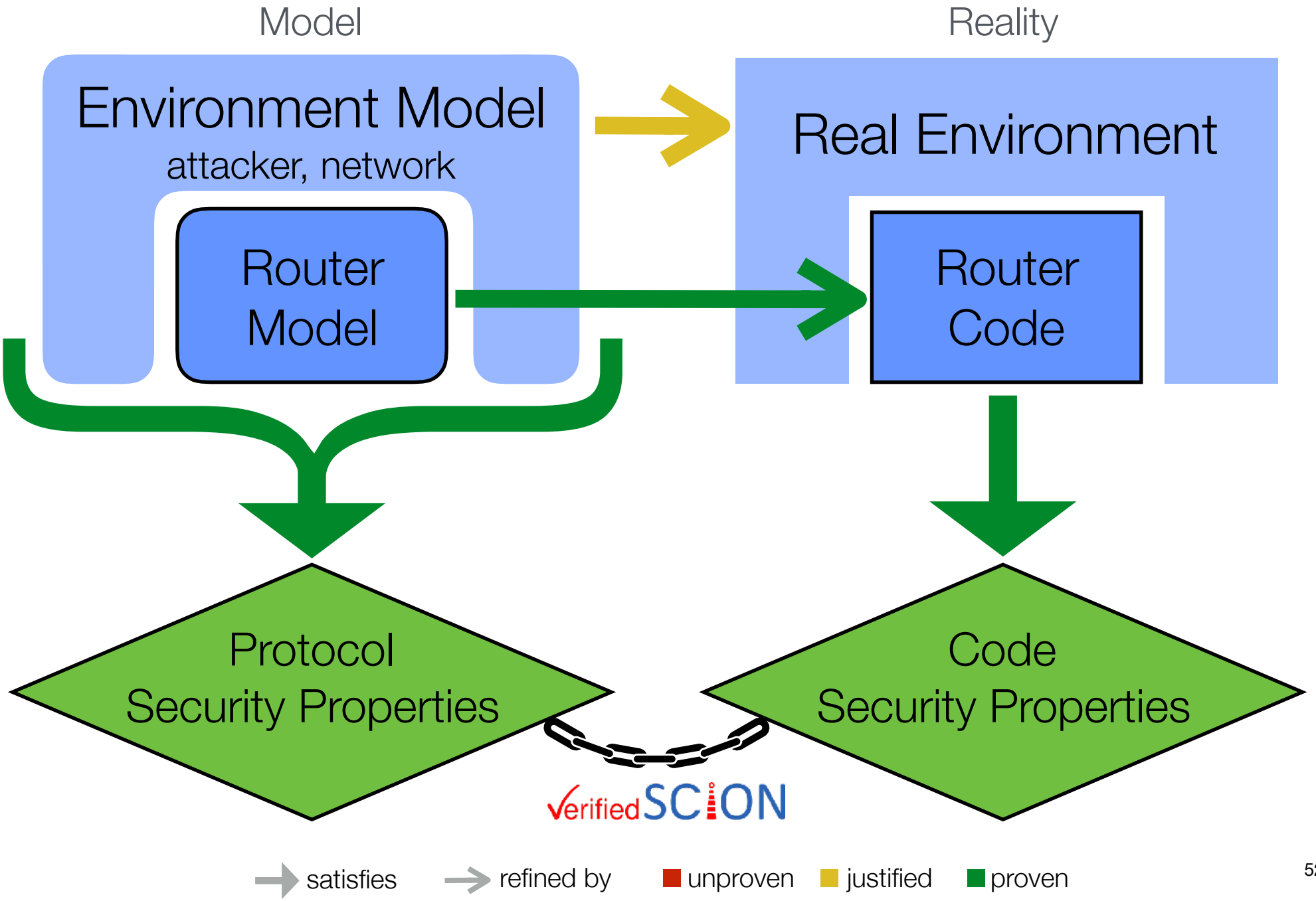
Linking it all up via Input-Output Specifications

(Code can be viewed as a transition system)



Based on: Pennickx, Jacobs, Piessens, "Sound, modular and compositional verification of the input/output behavior of programs", ESOP 2015.

SCION Router Verification Overview



Status

- Code verification tools built and prototyped
- First three levels of refinement completed
  - Improved understanding of protocols and properties
  - Uncovered numerous bugs and omissions
    - Revealed during modeling & formalization
    - Verified against implementation
- Next step: formally connect the two parts

Conclusions

- Internet, as designed, is insecure
- Scion architecture offers much stronger guarantees
- These can be put on a formal footing via

  refinement + code-level verification

- **Long term objective**: guaranteed back-door-free routers, made in Switzerland

Want to be a Scion AS?