verifiedSCION: Verified Secure Routing

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Joint work with

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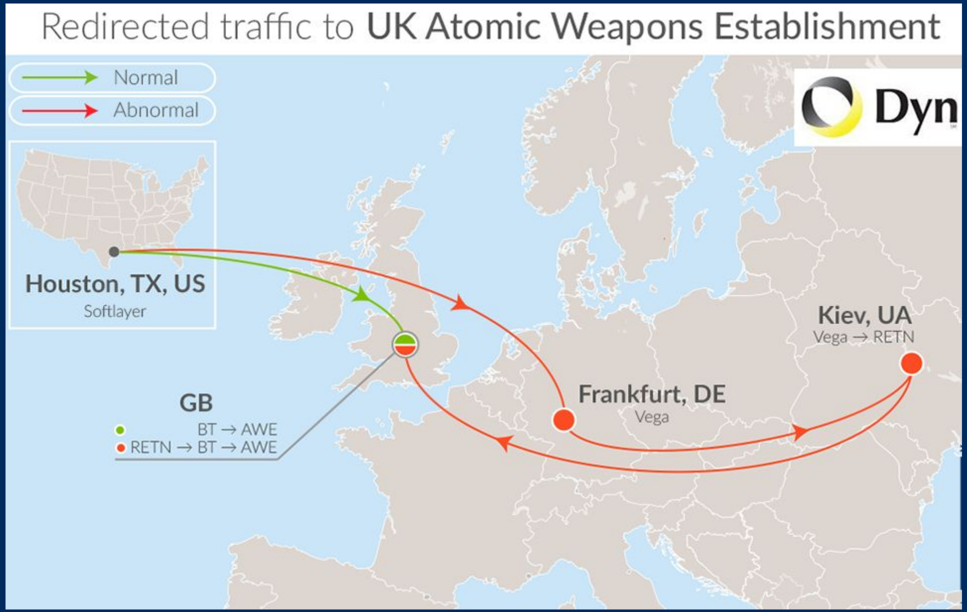
ETH zürich

- Internet is a network of Autonomous Systems (AS)
- Each AS is a network of routers run by an institution
- Routes between AS are discovered using Border Gateway Protocol (BGP)
- Based on trust, for instance, any AS can announce any IP address range

- There are numerous ways to attack Internet routing



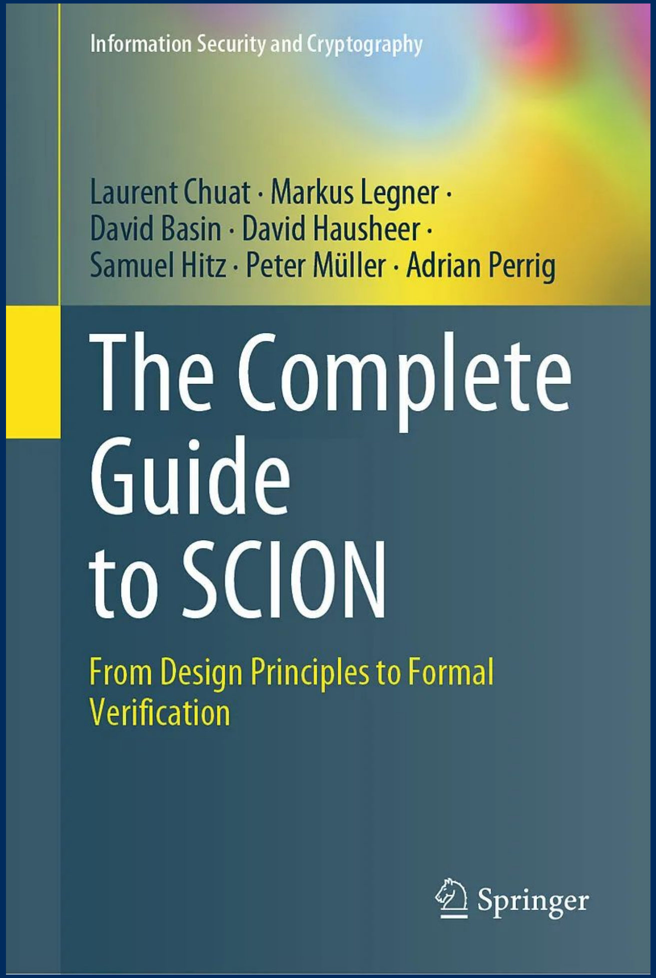
- In 2013, Ukrainian ISP announced route prefixes to British Telecom AS
- Traffic of some UK customers was redirected to Ukraine, including UK's Atomic Weapons Establishment

- Senders have no control over the taken routes
- Routers on path can read and modify data

Scion Internet Architecture

- Scion is a new architecture for inter-domain routing
    - Path control, e.g., geofencing
    - Multipath communication
    - DDoS protection

- Research and commercial deployments

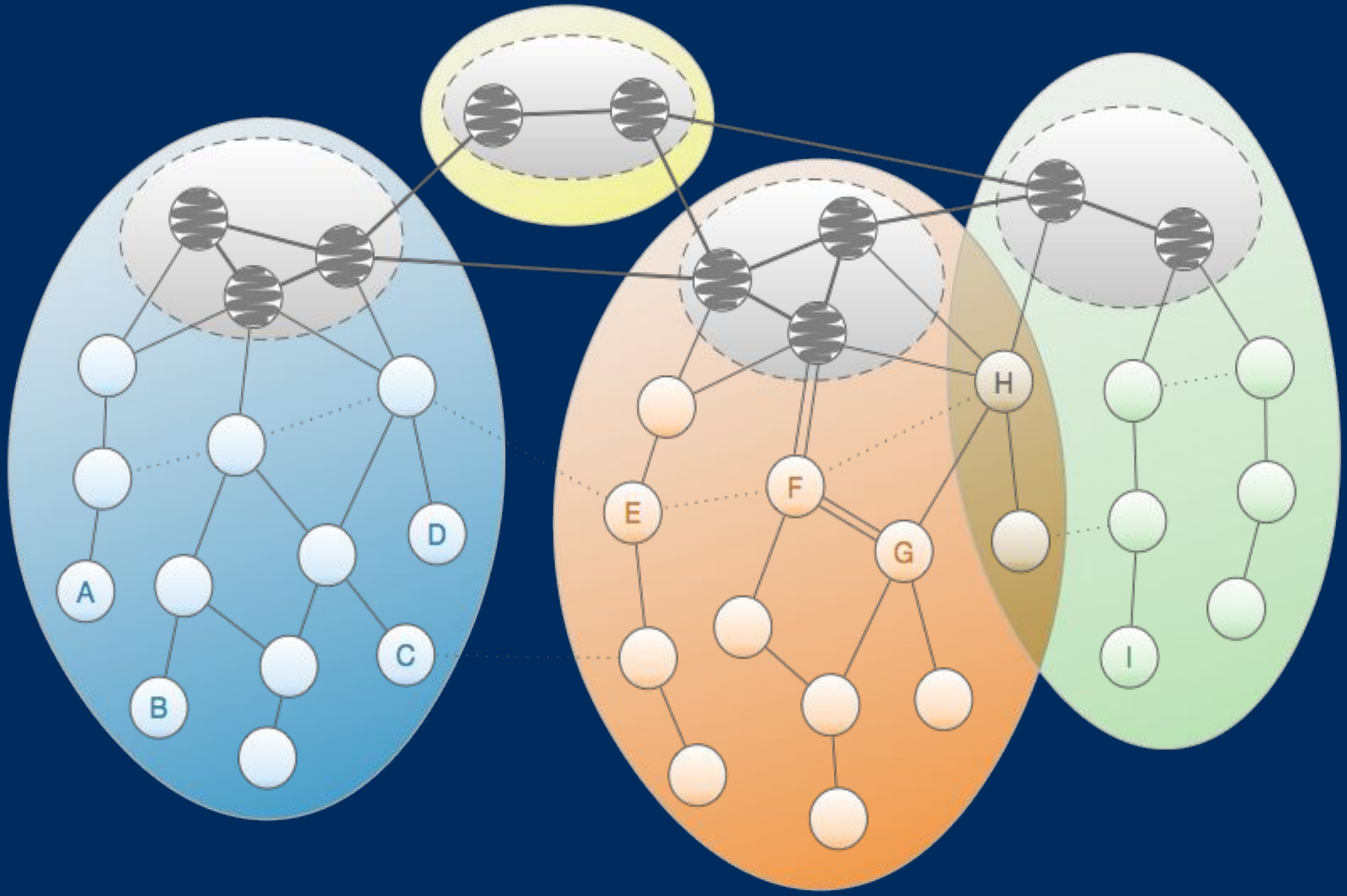


VerifiedSCION

Formal end-to-end verification of security and correctness

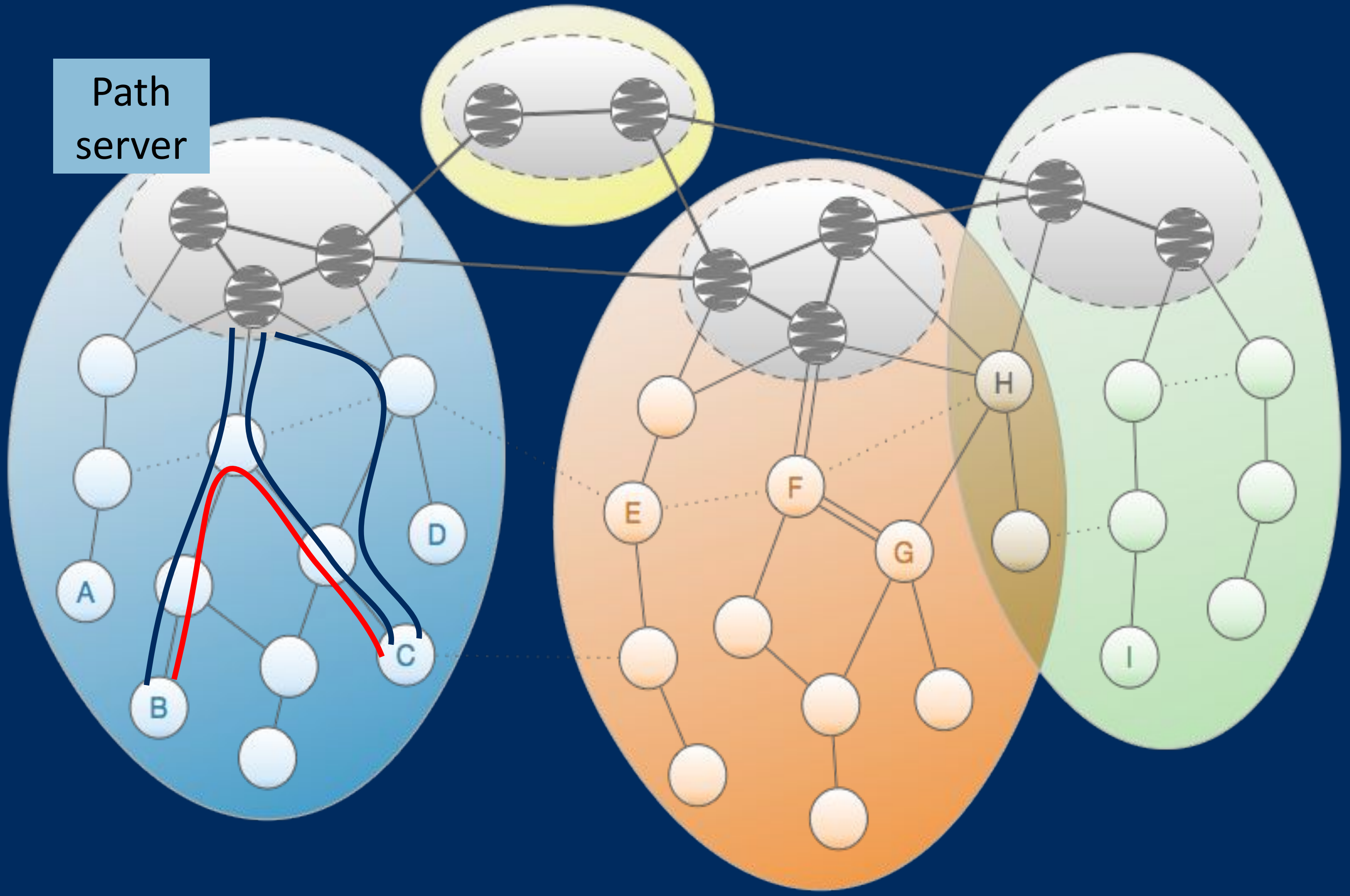
Isolation Domains

ASes are organized into isolation domains with independent control planes and root of trust



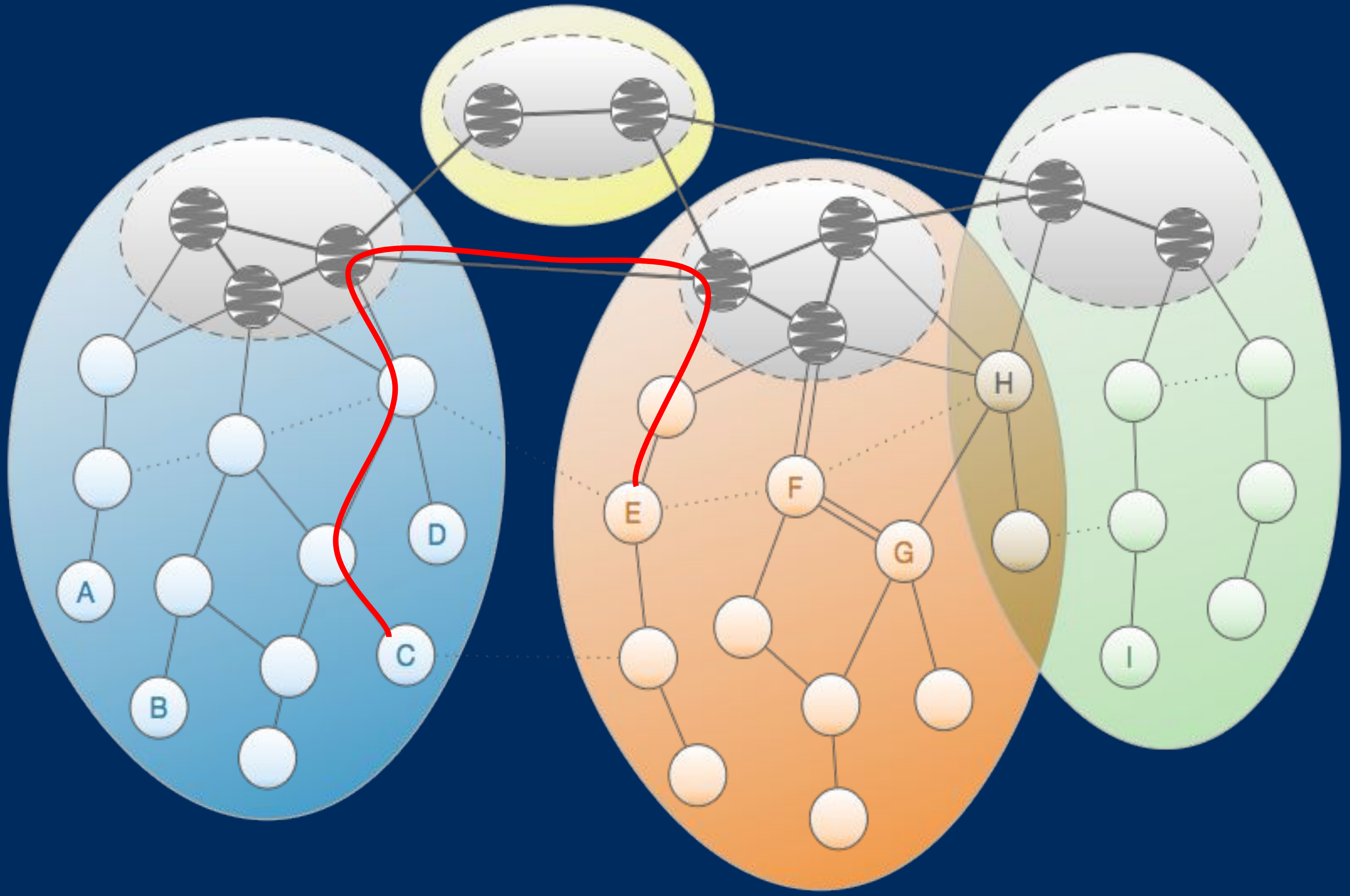
Scion Routing

- Path exploration
  - Paths are sequences of signed hop fields
  - Each hop field carries routing information for one AS (input and output ports)
- Path registration with path server
- Path selection
  - Path is stored in packet header



Scion Forwarding

- Path is stored in packet header
- Consisting of up segment, core segment, and down segment



Security and Correctness

- Protocol-level properties

  Path validity: Constructed paths are valid and reflect the routing decisions by on-path ASes.

  Path authorization: Packets travel only along previously authorized paths

  Detectability: An active attacker cannot hide their presence on the path

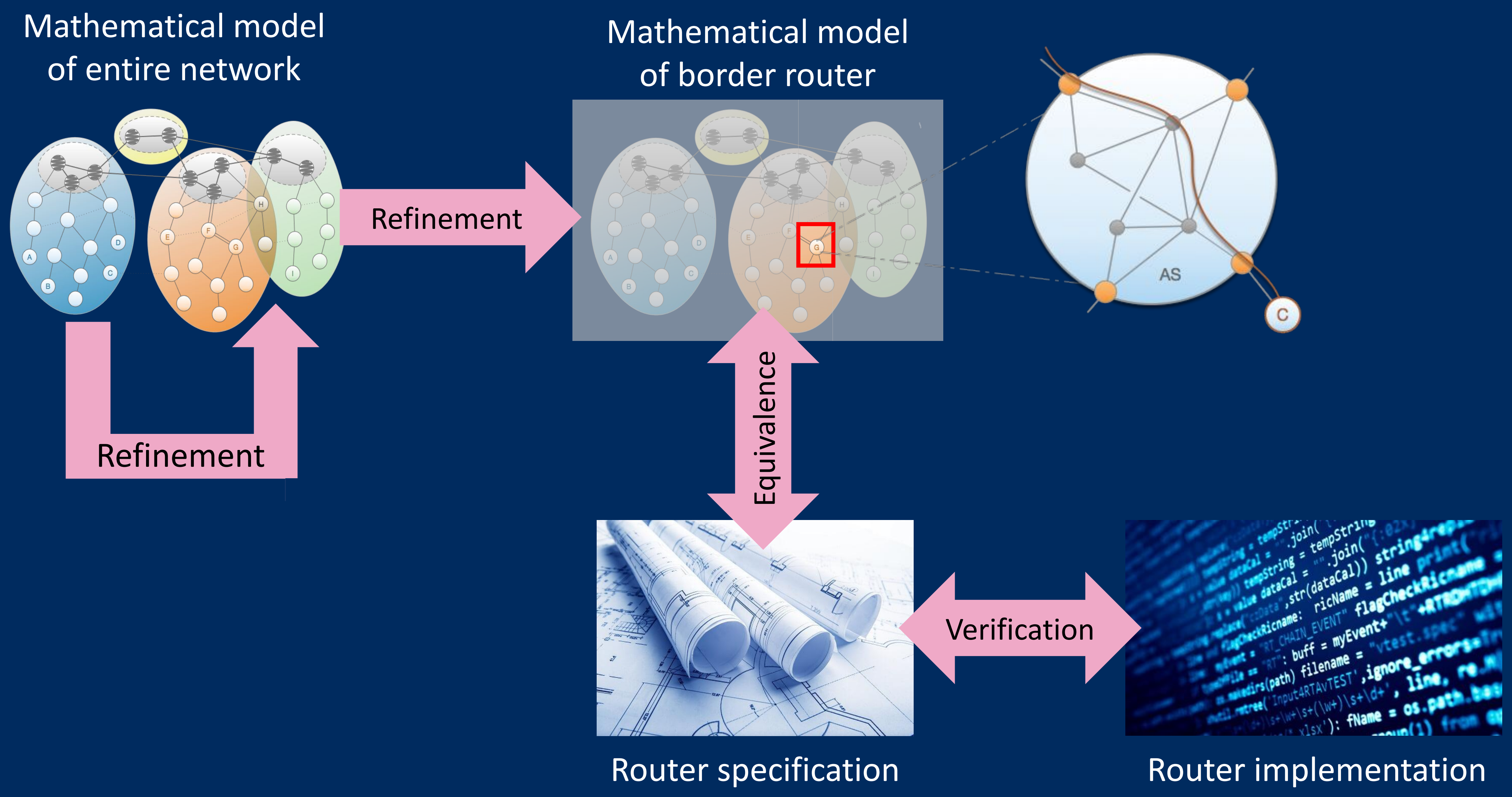
- Code-level properties

  Safety: No run-time errors

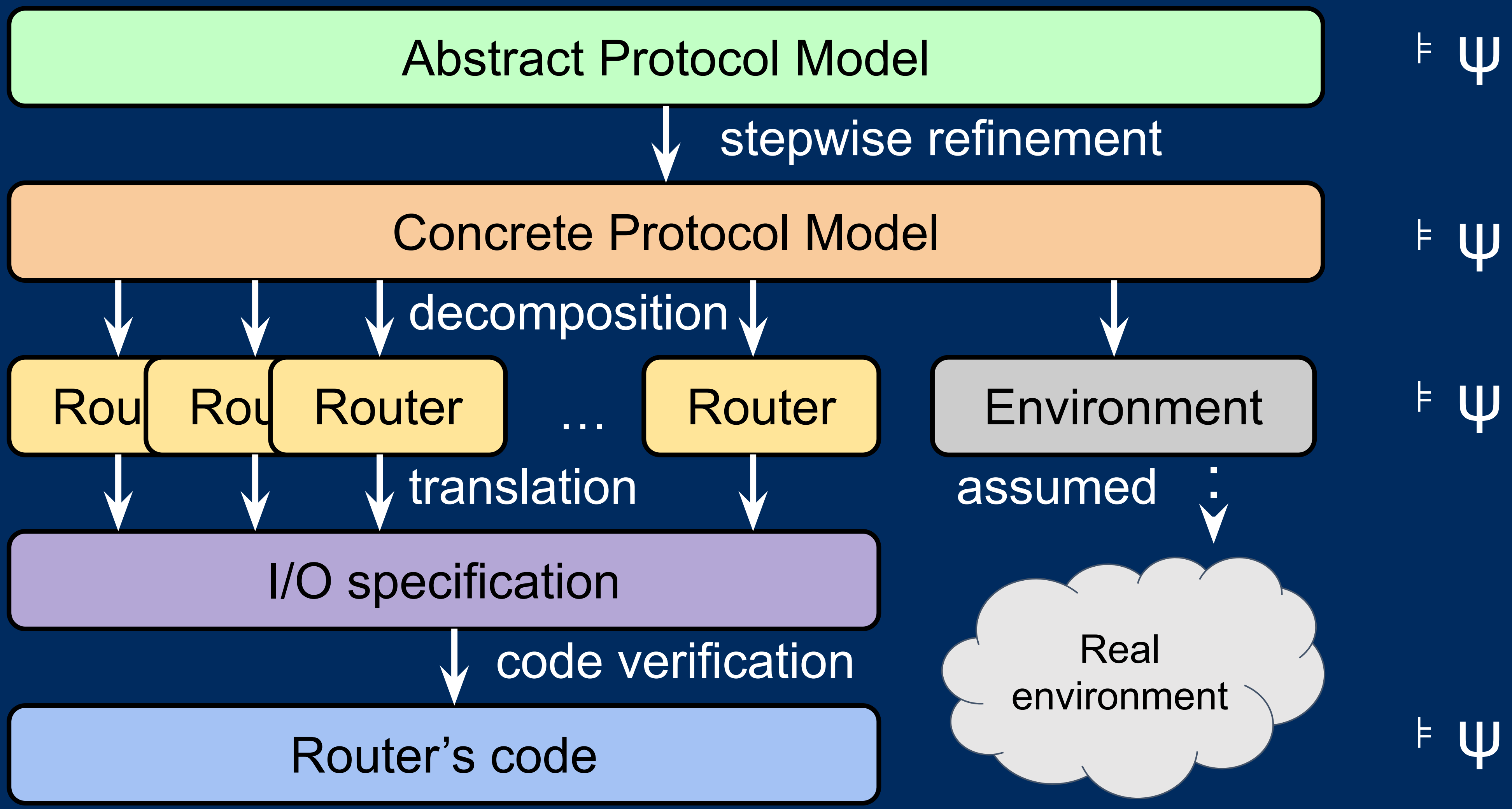
  Correctness: Routers and servers implement protocol correctly

  Progress: Required I/O happens eventually

  Secure information flow: Code does not leak information about crypto keys


Mathematical model of entire network
Refinement
Refinement
Mathematical model of border router
AS
C
Equivalence
Verification
Router specification
Router implementation

Igloo Framework (OOPSLA 20)



Protocol Models

- Formalize the design model as transition system

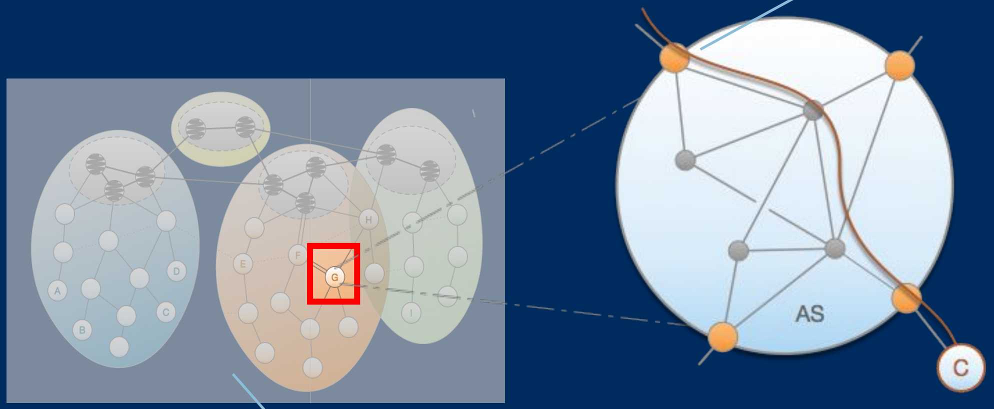
```
var in: Multiset<Msg>
var out: Multiset<Msg>

initially
  in = { }
  out = { }

event process(M, M')
  guard  M ∈ in ∧ valid(M) ∧
       reply(M, M')
  action
    in := in \ { M }
    out := out ∪ {M'}
```

- Model describes

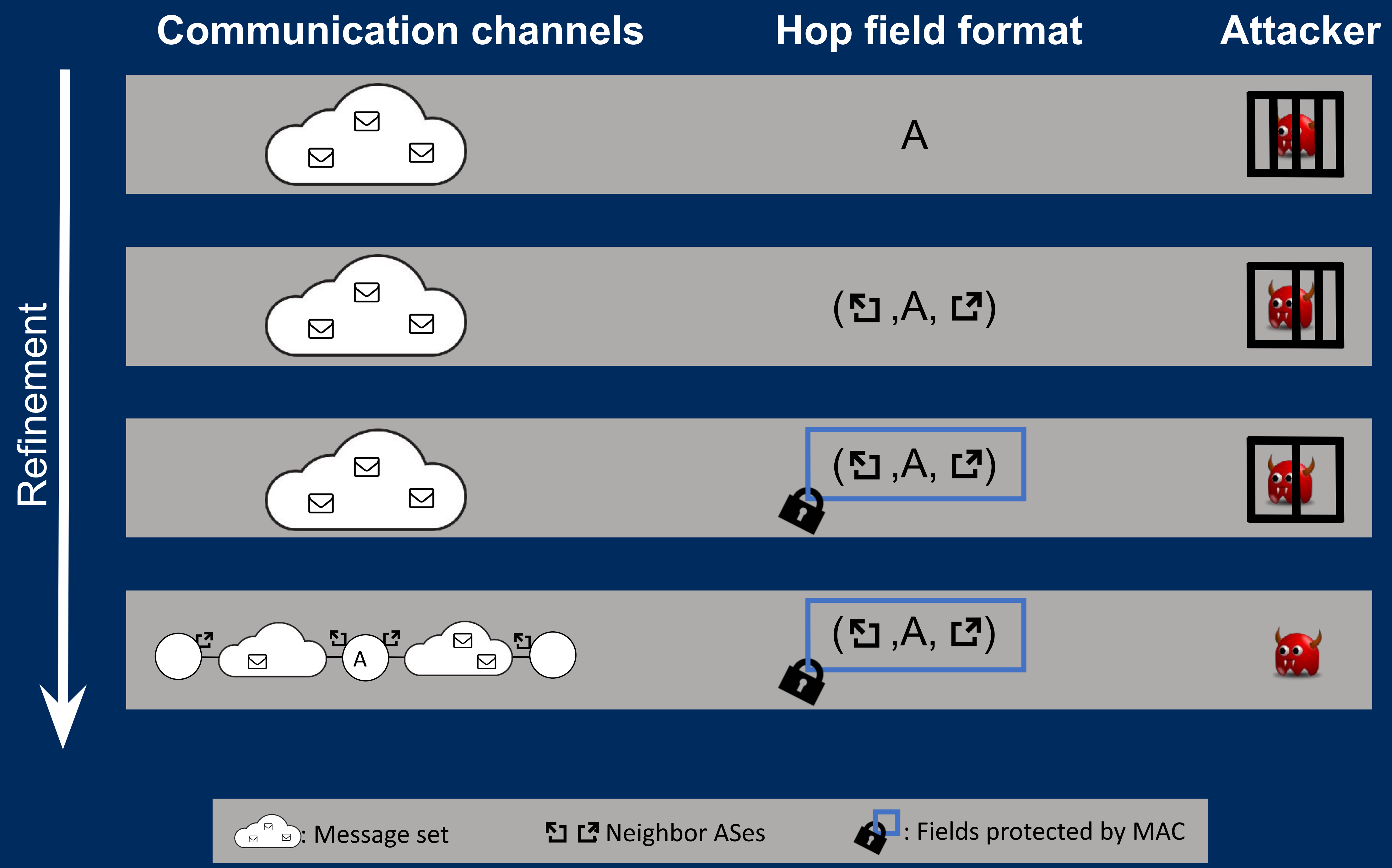
System:
Border router



Environment:
Network
End hosts
Attacker

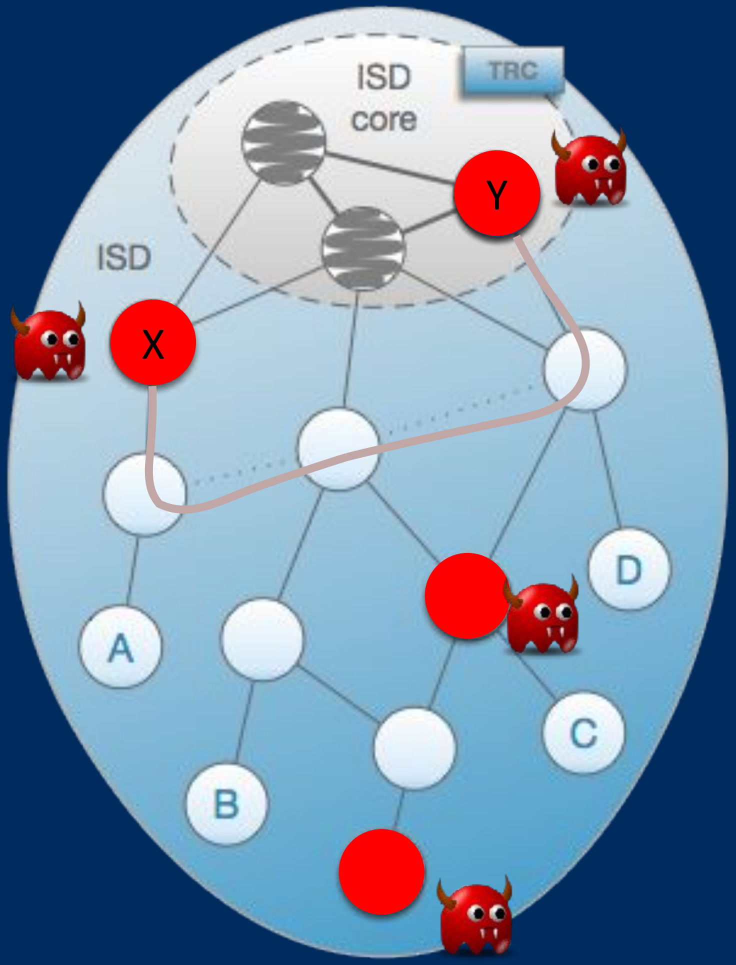
Stepwise Refinement

- Protocol models are developed by stepwise refinement
- Prove properties of most abstract model
- Each refinement
  - Incorporates additional system requirements or environment assumptions
  - Preserves properties of more-abstract system
  - Is tool-checked in Isabelle
- Strategy: strengthen attacker while increasing protection of paths


Communication channels
Hop field format
Attacker
Refinement
A
(⮤ ,A, ⮥)
(⮤ ,A, ⮥)
(⮤ ,A, ⮥)
A
: Message set
Neighbor ASes
: Fields protected by MAC

Attacker Model

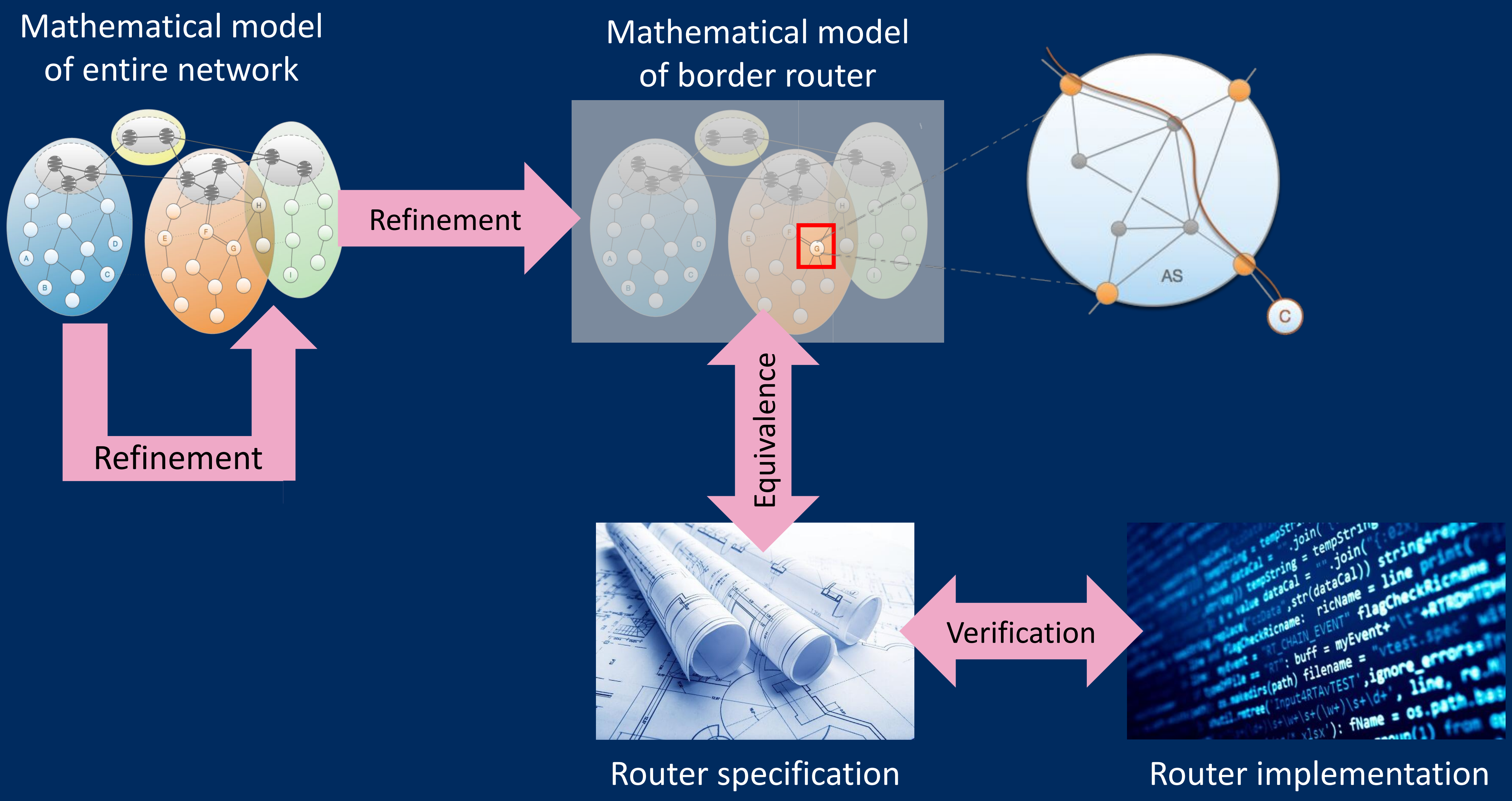
- Localized, colluding Dolev-Yao attacker model
- Attacker:
  - Actively controls some ASes
  - Can observe, block, and inject messages
  - Can eavesdrop globally
- Cryptography is assumed to be perfect



Results of Protocol Verification

- A formal model of the network components and their environment
- Model serves as formal specification for the implementation
- Proofs of the desired properties under the assumption that each component satisfies its specification
- 16,100 lines (models and proofs)

- Improved understanding of protocols and properties
- Revealed design flaws that enabled five different security attacks
- Issues were found during modeling and formalization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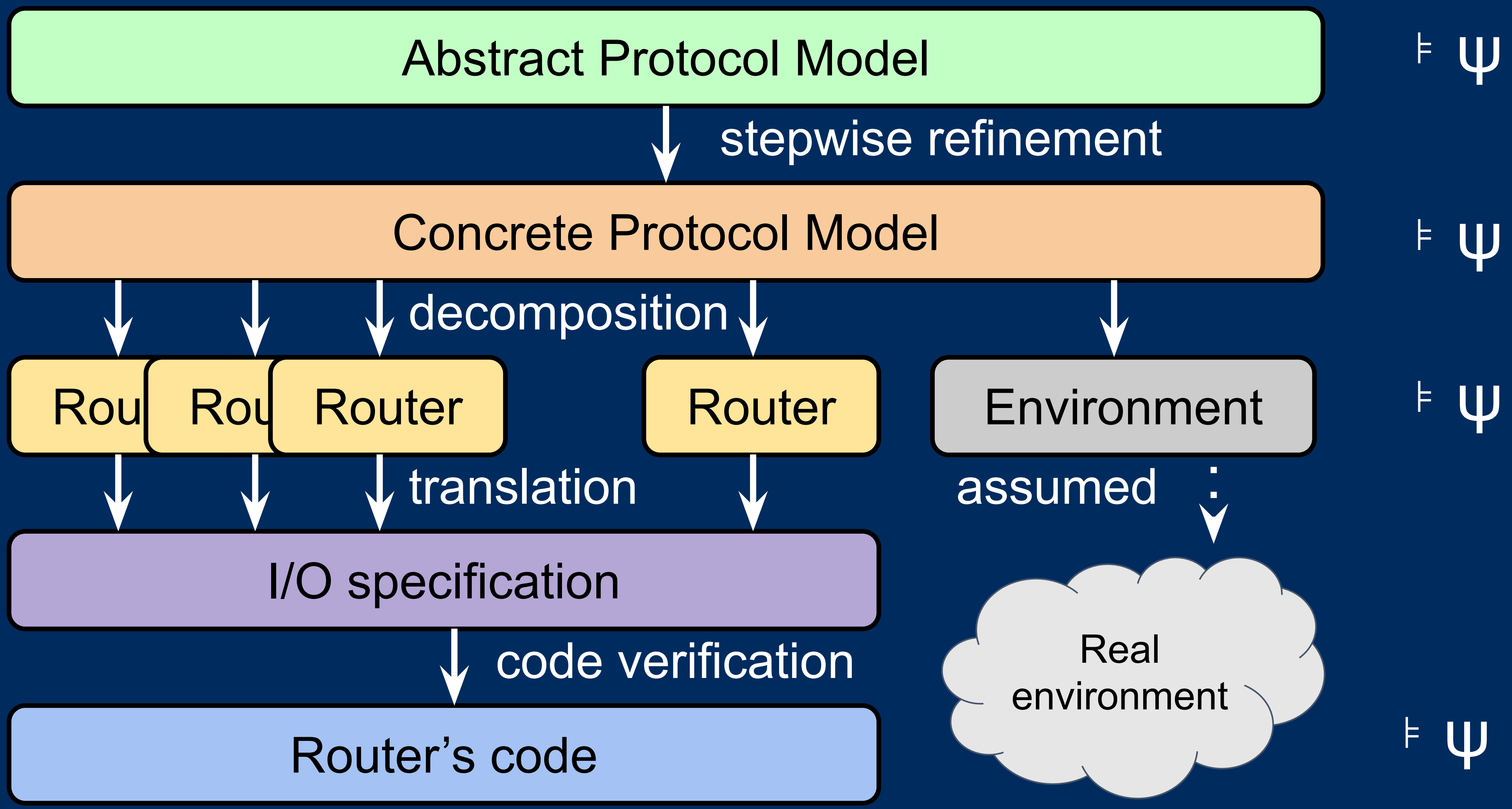
Igloo Framework (OOPSLA 20)



Decomposition

- Last refinement step must include explicit I/O events
  - components and environment interact *only* via I/O events
  - I/O event represents atomic I/O operation in implementation

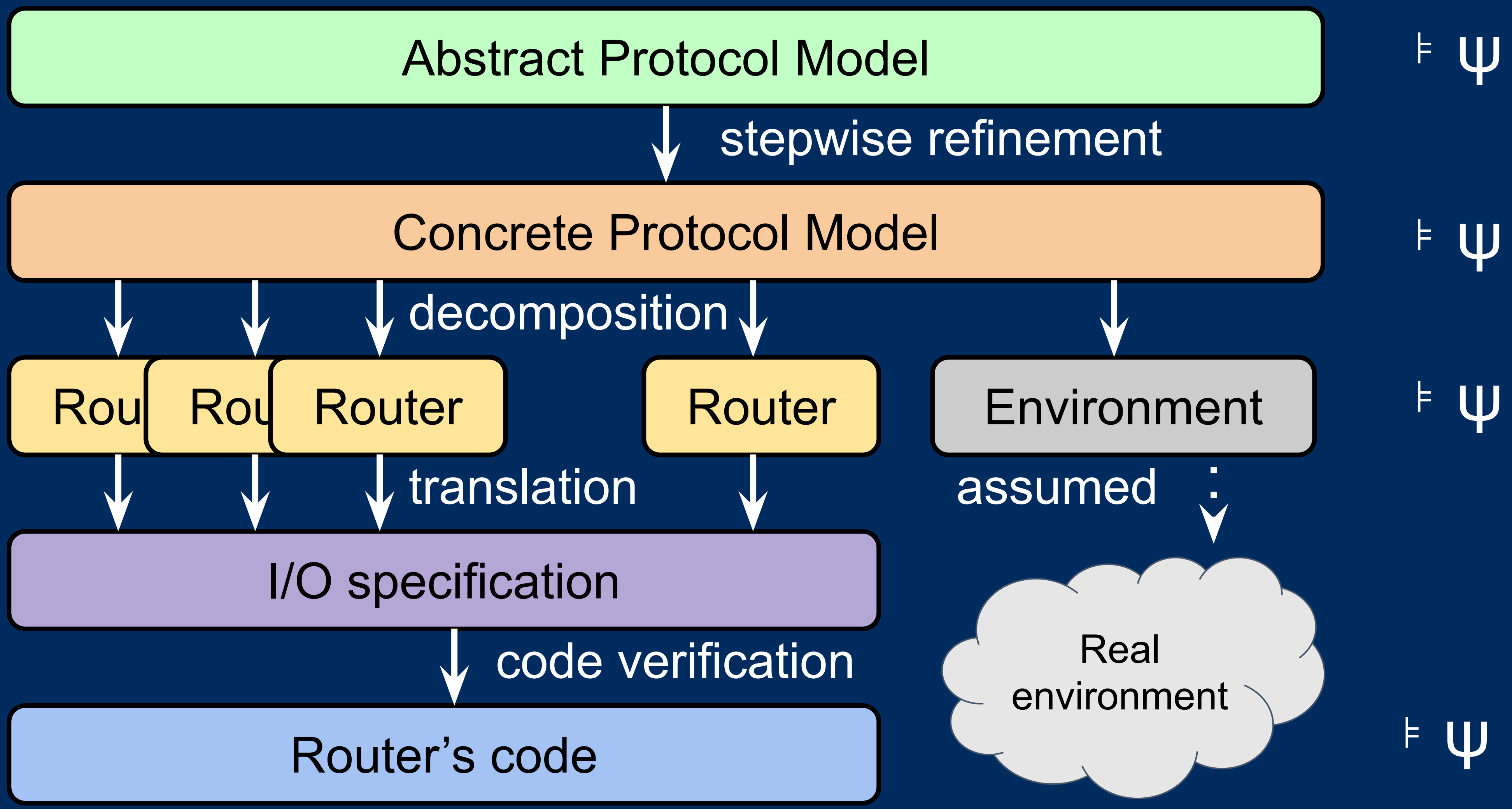
```
var in: Multiset<Msg>
var out: Multiset<Msg>

event process(M, M’)
  guard  M ∈ in ∧
      valid(M) ∧
       reply(M, M’)
  action
   in := in \ { M }
   out := out ∪ {M’}
```

Refinement

```
…
var i_buf : Multiset<Msg>
var o_buf : Multiset<Msg>

event receive(M)
  guard  M ∈ in
  action
   in := in \ { M }
   i_buf := i_buf ∪ {M}
```

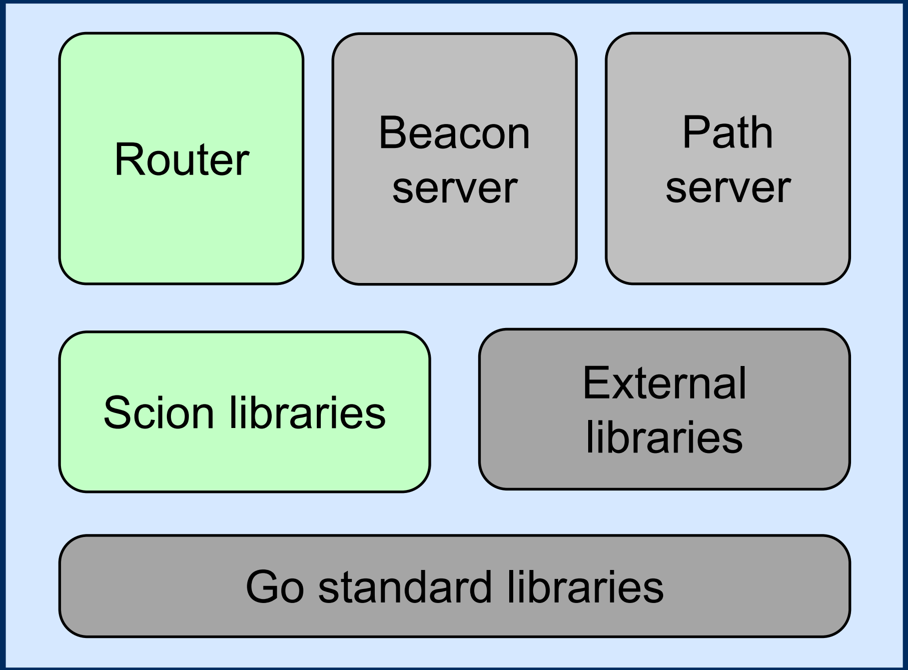
```
event process(M, M’)
  guard  M ∈ i_buf ∧
      valid(M) ∧
       reply(M, M’)
  action
   i_buf := i_buf \ { M }
   o_buf := o_buf ∪ {M’}

event send(M, Addr)
  …
```

Igloo Framework (OOPSLA 20)



Scion Implementation

- Open-source implementation
  - 35kloc of Go (Router: 4.7kloc)
  - Uses concurrency, async, globals
- Verify safety, functional correctness, progress, secure information flow
- Assume correctness of external libraries, Go compiler, OS, hardware



Gobra: Verification for Go (CAV 21)

```
func indexOf(l [ ]int, i, val int) (res int)
  requires 0 <= i && i < len(l)
  requires forall j int :: i <= j && j < len(l) ==> acc(&l[ j ])

  decreases len(l) - i

  ensures forall j int :: i <= j && j < len(l) ==> acc(&l[ j ])
  ensures res != -1 ==> i <= res && res < len(l) &&
    (forall j int :: i <= j && j < res ==> l[ j ] != val) && l[ res ] == val
{
  if l[ i ] == val             { return i }
  else if i >= len(l) - 1      { return -1 }
  else                         { return indexOf(l, i+1, val) }
}
```

- No run-time errors
- No data races
- Functional properties
- Termination
- I/O behavior
- Secure information flow

Gobra Toolchain

GO

```
func main(a [ ]int) int {
    var b int = a[3]
    …
}
```

Error: Slice access a[3] might be out of bounds

gobra

Program translation

Error translation

VIPER

```
method main(a: Ref)
        returns (res: Int)
  requires slice(a) ...
{
  var b: Int
  b := lookup(a, 3)
  …
}
```

Error: Insufficient permission to access loc(a, 3).val

Z3

✔

Separation Logic

- Associate each heap location with a permission
- Permissions are held by method executions
- Access to a memory location requires permission

```
func indexOf(l [ ]int, i, val int) (res int)
  requires forall j int :: i <= j && j < len(l) ==> acc(&l[ j ])
```

- Permissions can be transferred, but not duplicated or forged
- Guarantees memory safety, data race freedom, enables local reasoning

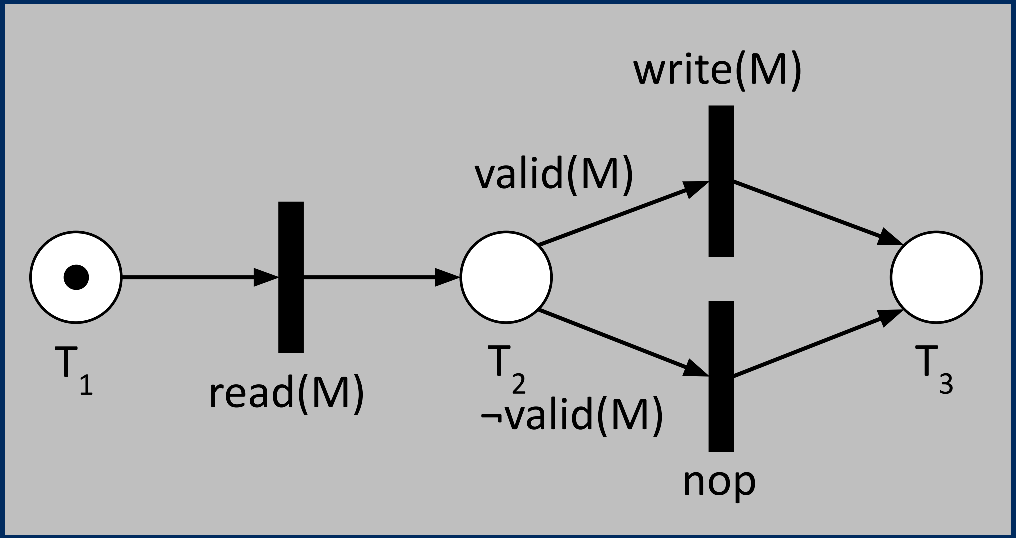
I/O Permissions

- Permissions can be used to reason about resources
- Here: permission to perform an I/O operation

```
func write(value string)
  requires writeIO(value)
```

I/O Behavior as Petri Nets

- Adaptation of work by Penninckx et al., ESOP 15
- Petri nets specify permitted I/O behavior
  - Traces of basic I/O operations
  - Sequences, parallelism, non-determinism
- Petri nets are encoded as (recursive) predicates



predicate router(T_1) {
  $\forall M\ \exists T_2, T_3 \cdot$
    readIO(T_1,M,T_2) *
    (valid(M) ⇒ writeIO(T_2,M,T_3)) *
    (¬ valid(M) ⇒ nop(T_2,T_3)) *
    router(T_3)
}

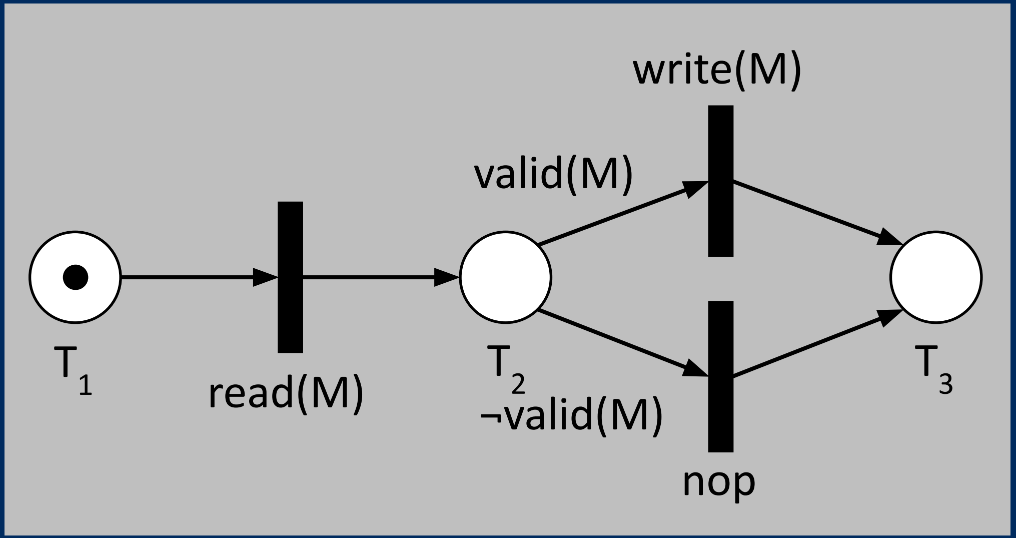
Specification of I/O Behavior

- Basic I/O operations
  - Require I/O permission
  - Require token in appropriate place
  - Advance token

```
func write(value string)
  requires token(T) * writeIO(T, value, T')
  ensures token(T')
```

- Method precondition characterizes permitted I/O behavior

```
func main()
  requires token(T) * router(T)
```




```
predicate router(T₁) {
  ∀M ∃T₂, T₃ ·
    readIO(T₁,M,T₂) *
    (valid(M) ⇒ writeIO(T₂,M,T₃)) *
    (¬ valid(M) ⇒ nop(T₂,T₃)) *
    router(T₃)
}
```

From Model to I/O Specification

- Refine component model to have an event for each basic I/O operation

I/O event write(val)

func write(value **string**)

- Encode entire event system as recursive predicate

event drop(M)
guard ¬valid(M)
action
  buf := buf \ { M }

predicate system(T_1, state) {
  (∀args · guard(args, state) ⇒
      ∃T_2 · opIO(T_1,args,T_2) * system(T_2, state')) *
  …

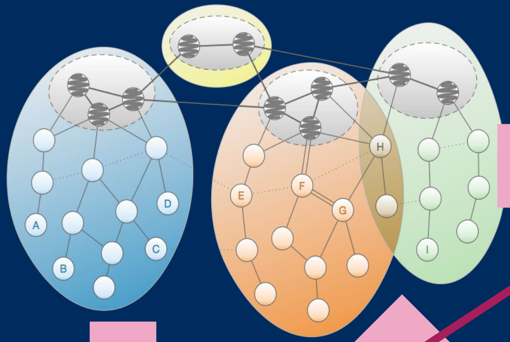
predicate router(T_1, buf) {
  (∀M · ¬valid(M) ⇒ router(T_1, buf \ { M })) *
  …

Status of Code Verification

- Completed verification of SCION router (4,700 LoC)
    - Memory safety
    - Functional correctness
    - I/O behavior
    - Termination
- 13,400 lines of annotations (2.8 LoS per LoC)
- Required only three code changes

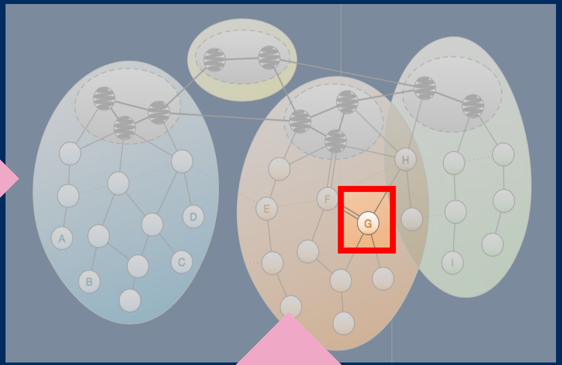
- Identified 13 confirmed issues related to memory safety, functional correctness, and I/O behavior
(plus 2 performance issues)
- Despite extensive code reviews, testing, and fuzzing

Mathematical model of entire network



Refinement

Mathematical model of border router

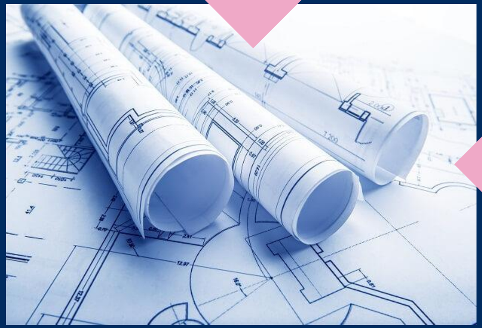


Equivalence

- Developed by stepwise refinement
- Verified in Isabelle

- Properties encoded in permission logic
- Verified in Gobra/Viper

- Transition system encoded as I/O specification
- Verified in Isabelle



Router specification

Verification

Router implementation