Formal Proof of a Secure OS Full Trusted Computing Base

Dominique Bolignano

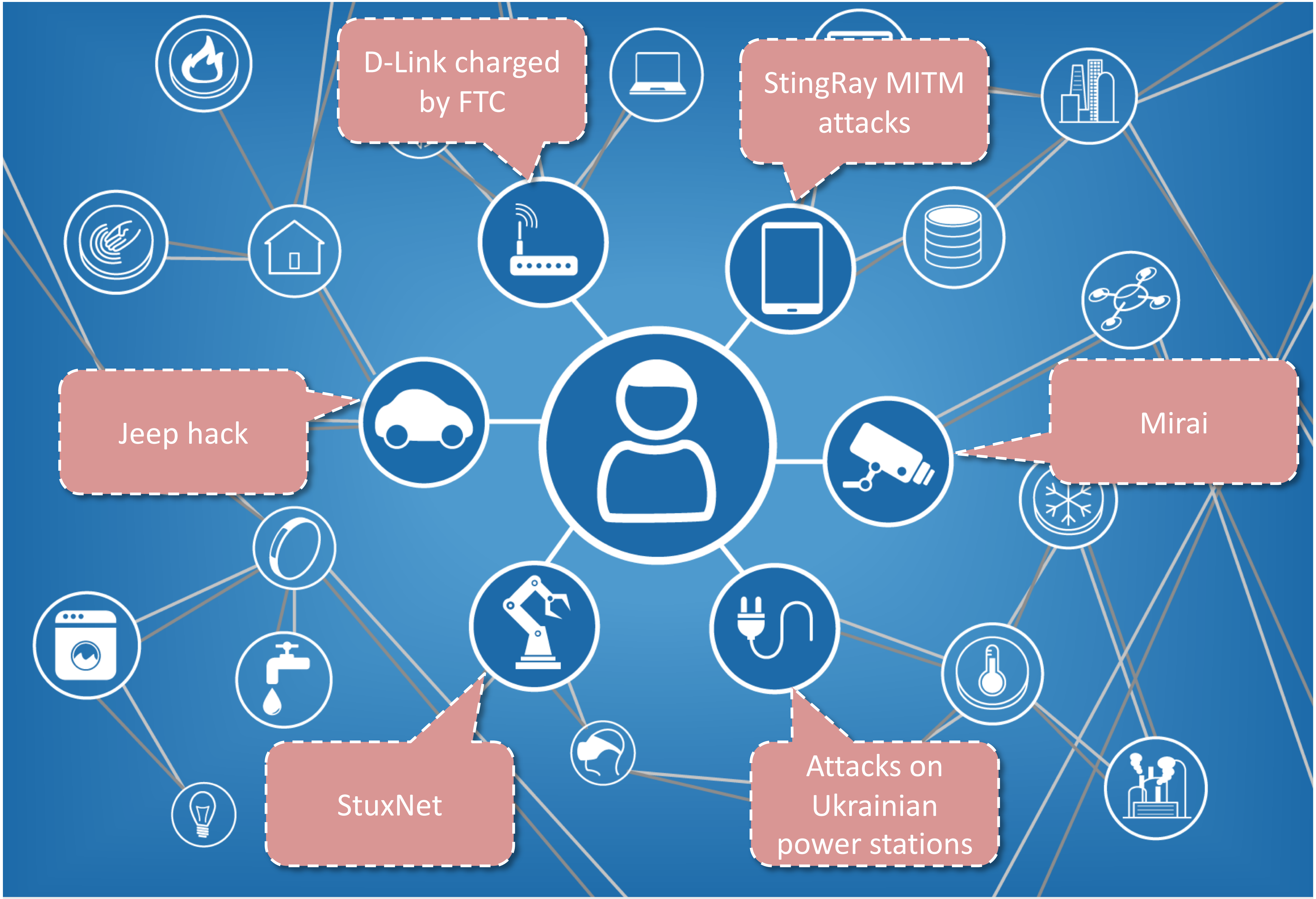
77, avenue Niel, 75017 Paris, France

contact@provenrun.com

Context and Objectives

Context

- Context :
  - Use of formal methods for security during a few decades, in particular in the context of Trusted Logic.
  - First Common Criteria EAL7 certification achieved for a smartcard OS, a Java Card environment and hardware. Formal verification of a bytecode verifier and its linking phase, etc. Deployed in billions.
  - First TEE (secure OS). Also deployed in billions.
- ProvenCore project started in 2009.
  - Development of a formally proven secure OS (proved down to the code),
  - Certifiable at the highest levels of security,


D-Link charged by FTC
StingRay MITM attacks
Jeep hack
Mirai
StuxNet
Attacks on Ukrainian power stations

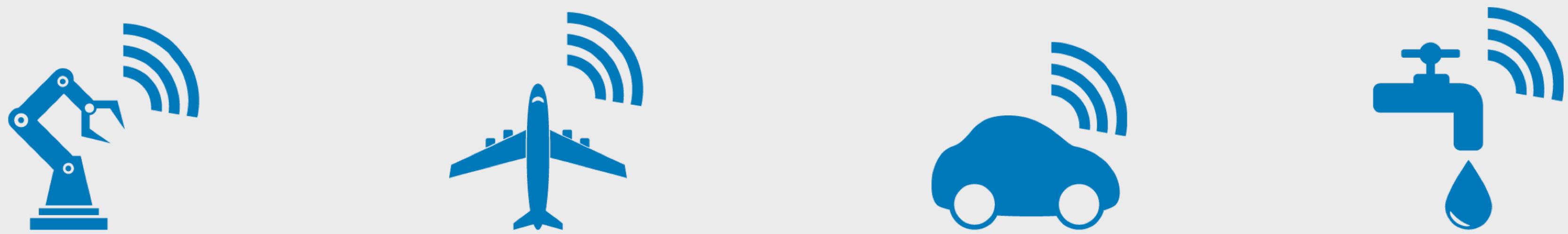
Prove & Run's answer to the challenge

- **Two critical off-the-shelf software components:**
  - ***ProvenCore*** : microkernel proven and certified for security (ARM Cortex A, Risc V, ARM Cortex M).
  - ***ProvenViso[illegible]*** [illegible]ecure hypervisor

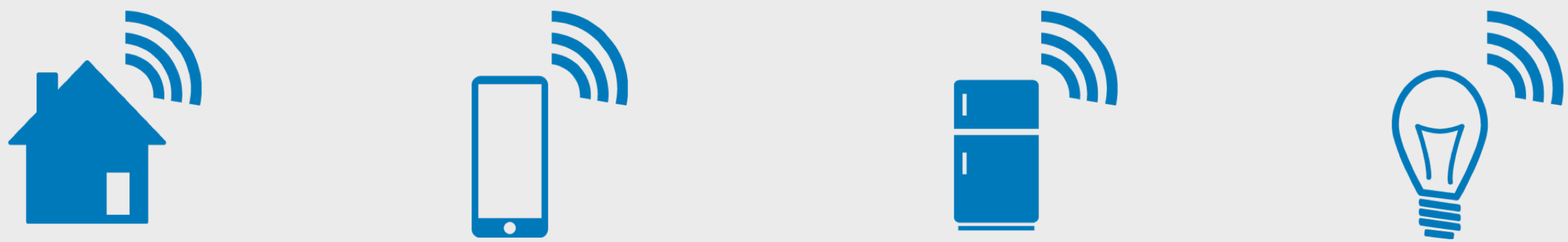
Designed to ha[illegible] TCB (Trusted Computing Base) that is <u>as close as pos[illegible]o zero-bug</u>.

Highest Level of Security ever reached
(CC EAL7 augmented) for Cortex A
World premiere

Prove & Run Value Proposition



We provide **cost effective off-the-shelf software** solutions that **dramatically improve the level of security** of your Connected Systems/Devices so as to protect them **against remote cyber-attacks**



Security certification Schemes

- Many security certification schemes exist, and many more are to come,
- The Common Criteria, which is an ISO standard is based on seven levels from EAL1 to EAL7,
- Security schemes generally have a correctness part and a robustness one.
- Correctness addresses the complete process (not only development).
- EAL7 requires in its correctness part the use formal methods down to the low level design.
- We have used formal methods down to the code.

Need for security certification

- **Exhaustive validation by trusted third party,**
  - You cannot usually check everything by yourselves,
  - You cannot take what the developer tells you for granted,
  - You need to compare the levels of security of different products,
- **Along an extensive certification scheme, i.e. The Common Criteria at its highest level :**
  - Important to not only cover the OS, but also its maintenance, its initialization, its installation, its provisionning, the associated organizational policies, etc.
  - Highest level needed because of the value at stake and the connectivity, i.e. highly profitable business models for hackers,

This is about Trust!

- **What would an organized attacker do with a given budget (automotive, avionics, ..) :**
  - **The objectives is to be able to resist to remote attacks that can be performed with a budget typically over 10 M€. (1 to 100)**
    - Identification phase of the attack
    - Exploitation phase of the attack,
- **The general architecture should be well balanced.**
- **Some of us spent most of their time, analyzing and improving security architectures in various areas (IoT, cloud, chip security architecture and firmware, etc.)**
- **ProvenCore is the main tool we used to secure such architectures.**

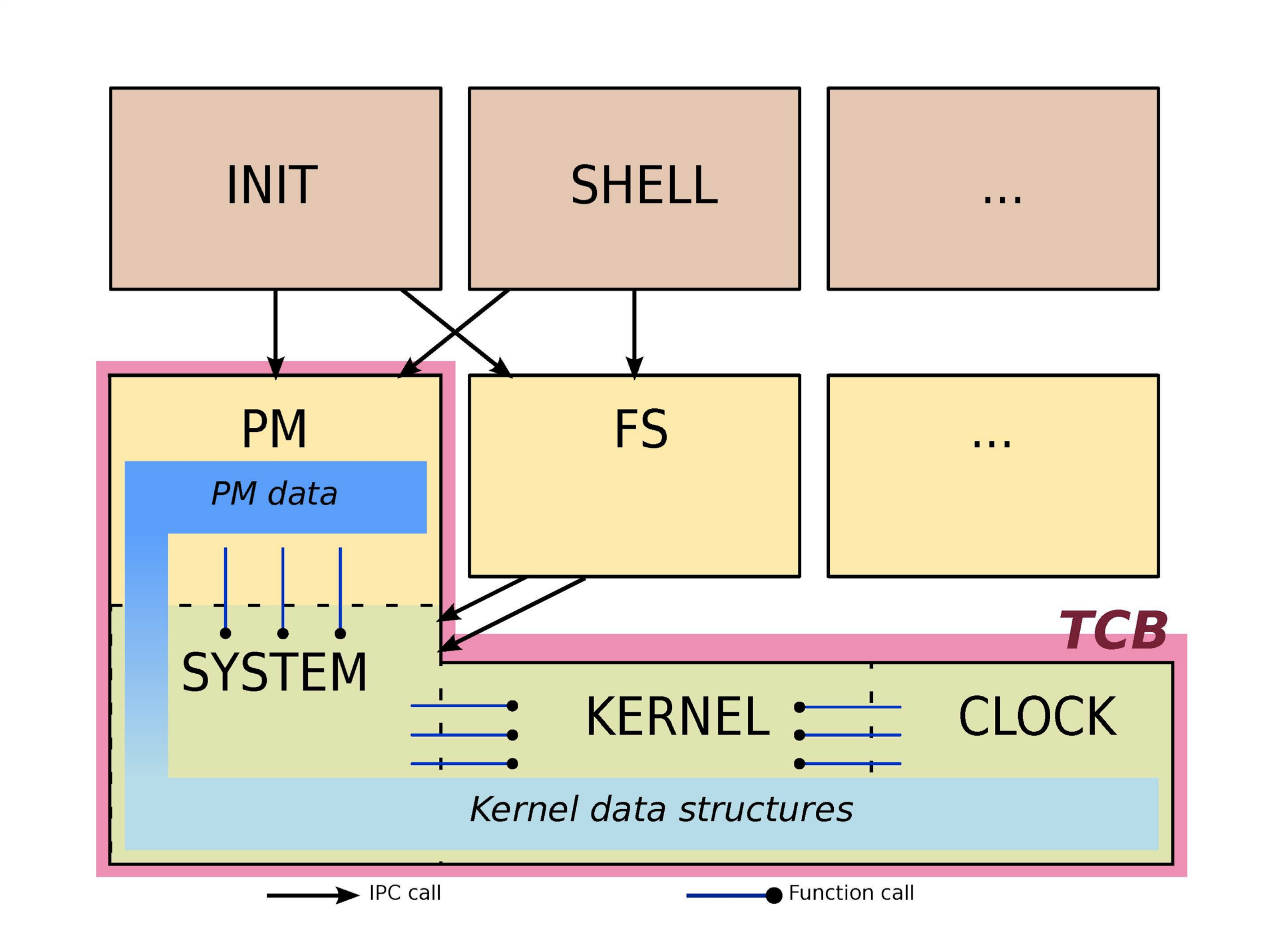
Our Strategy

- Maximize security level and more importantly the level of trust that can be achieved (for a given effort/budget),
- Use a very large base of use cases for defining functional and security requirements, and improving and assessing their adequacy.
- Stepwise approach.

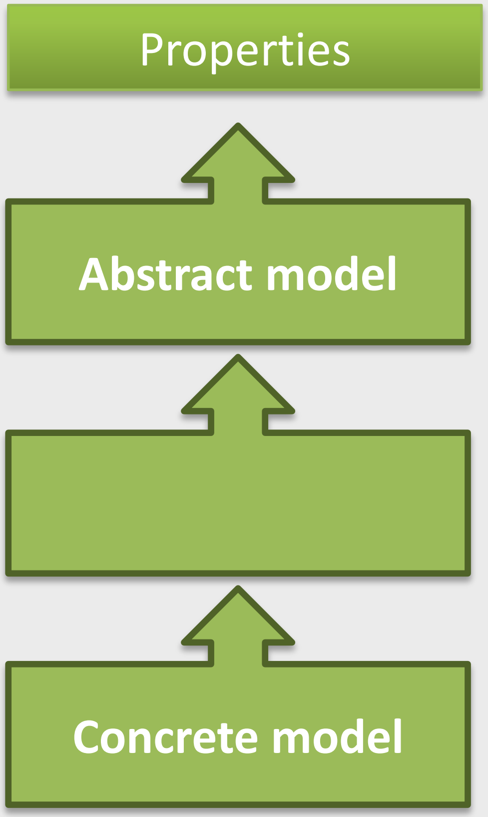
Need for specific functionalities

- **Access Control mechanisms between various applications (i.e. processes, so called Trusted Applications) themselves, between applications and peripherals,**
  - So as to enforce constraints on the flow of information to the applications themselves,
  - Static and enforced by ProvenCore based on simple access control matrix,
  - *Transferable tokens*.
- **High level APIs for applications,**
- **High level security services as applications (secure storage, cryptographic libraries, etc.).**

Trusted Computing Base

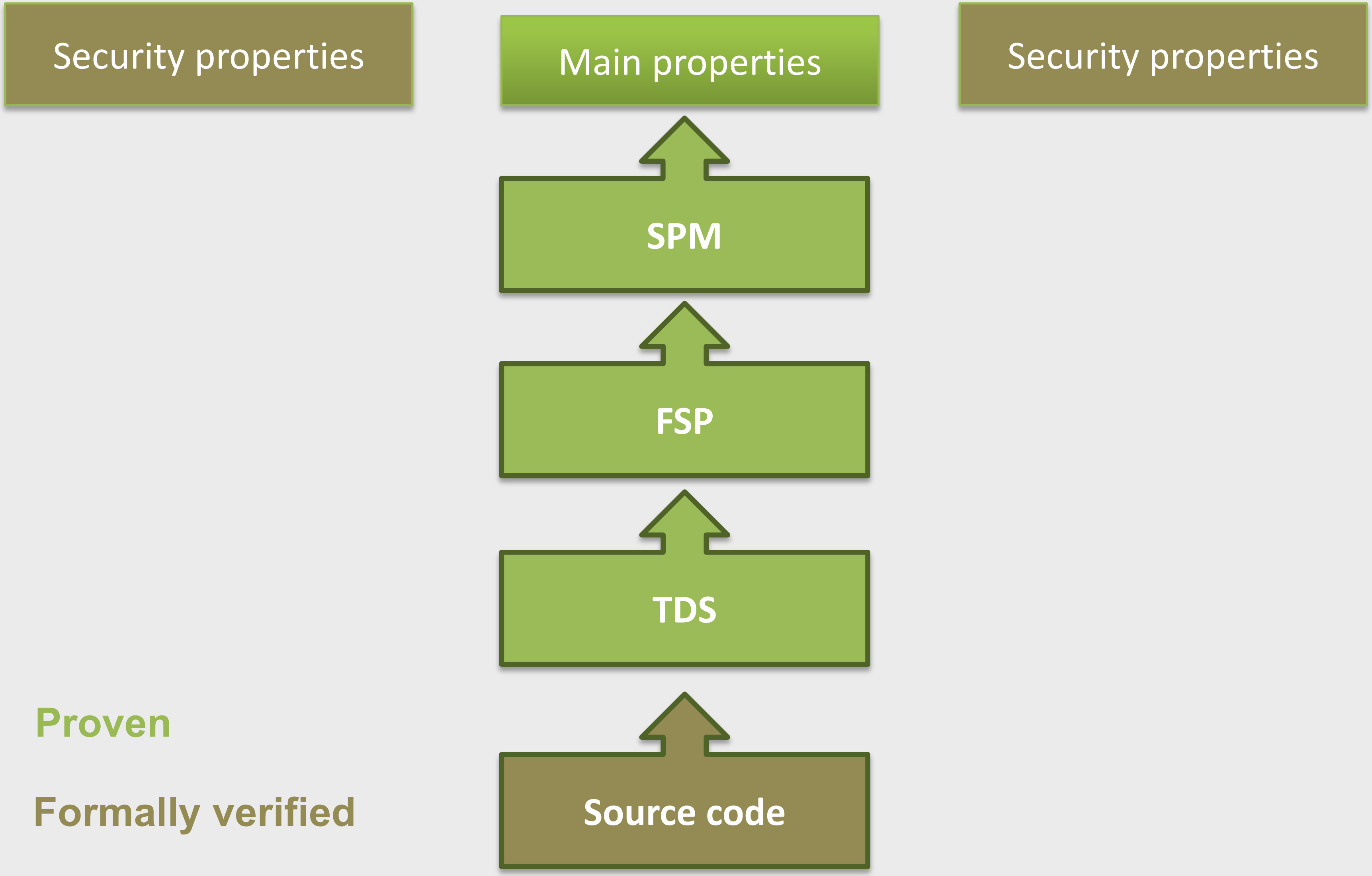


Refinement Proofs

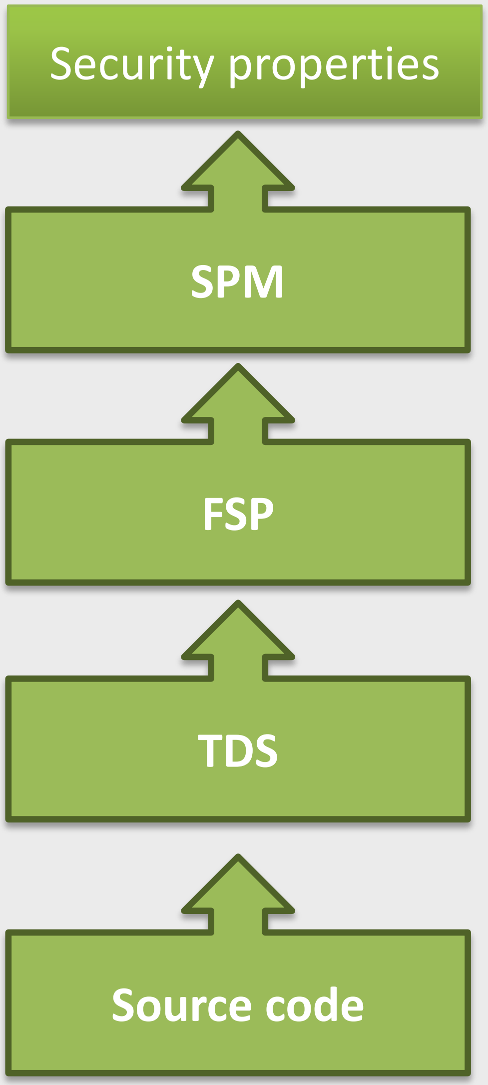


- One (or a few) abstract models
- Formal properties expressed at the highest level
- Properties should be as simple as possible to understand (see "ProvenCore: Towards a Verified Isolation Micro-Kernel", Stéphane Lescuyer, 10th HiPEAC Conference, 2015

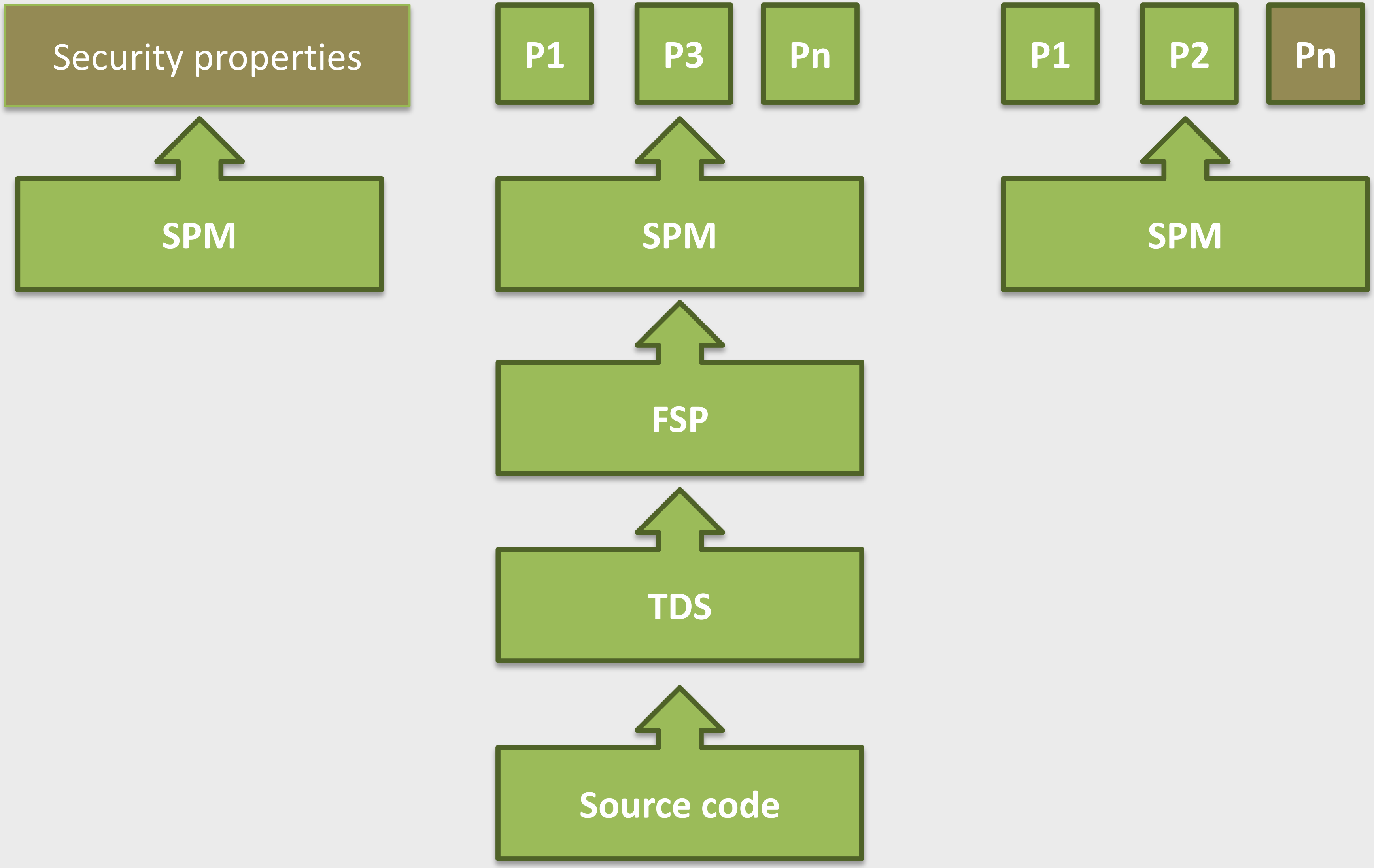
Refinement Proofs and Security Schemes



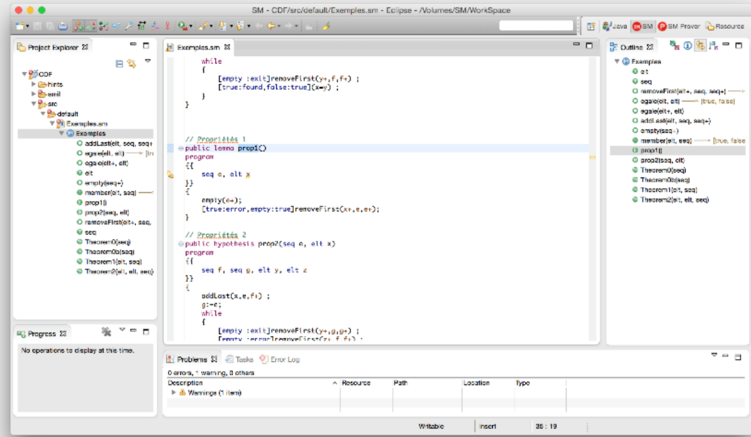
ProvenCore Case

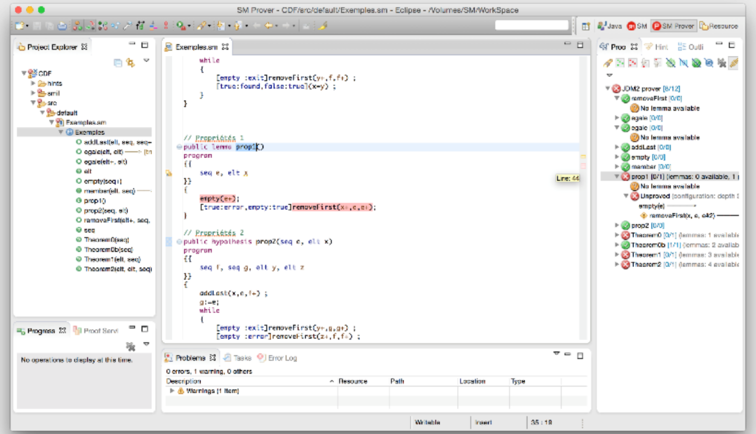


Modelling a microkernel: Properties



SMART development toolchain





Development environment

Prover: Eclipse plugin

P&R Intermediate Language: SMIL

Generator (source code and documentation): Eclipse plugin

Source Code

- Compilable
- C, Java, etc.

Certification Documentation Tests

- CC
- DO-178
- etc.

Automated

SMART language specificities

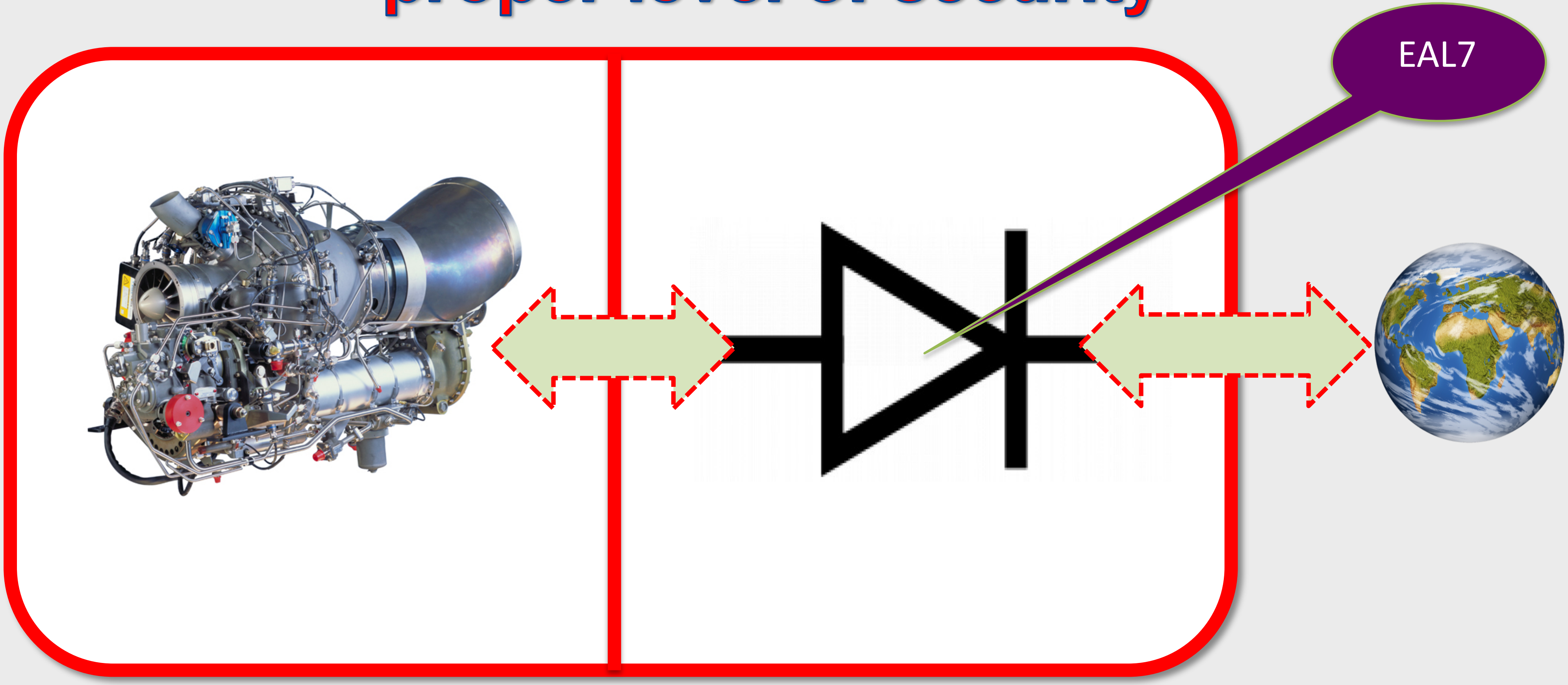
- Built to meet the identified requirements of applying formal methods at a large scale:
  - Usable by developers at high abstraction level but also and more importantly on the lowest levels
  - Allow developers to find (and rely on) paradigms that they usually use for either development, debugging or testing
  - Force developers to answer the right questions while coding and allow them to easily formalize those questions

- Language with a small and simple subset with the addition of clearly identified syntactic sugaring

Typical Use Case for ProvenCore

Filters / Applicative Firewalls

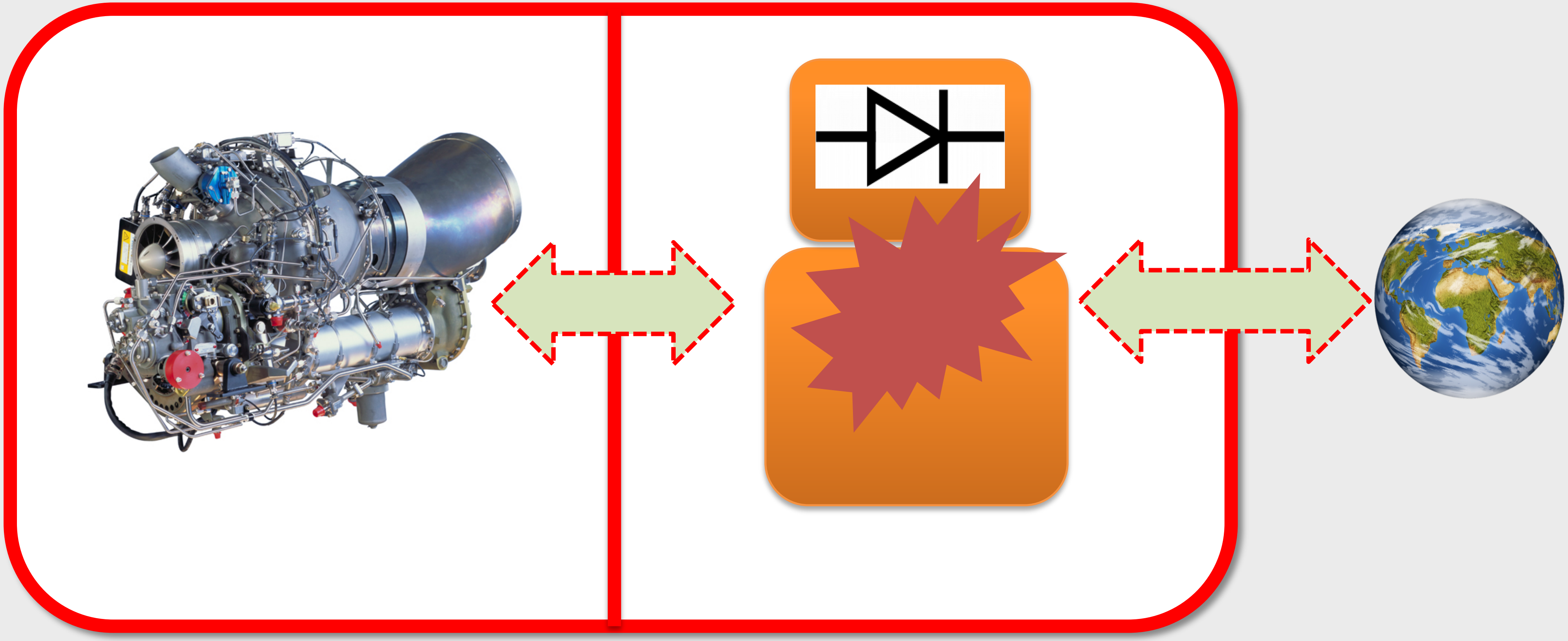
Only hardware based filter can reach proper level of security



Proven and Certified Secure Isolation

Filters / Applicative Firewalls

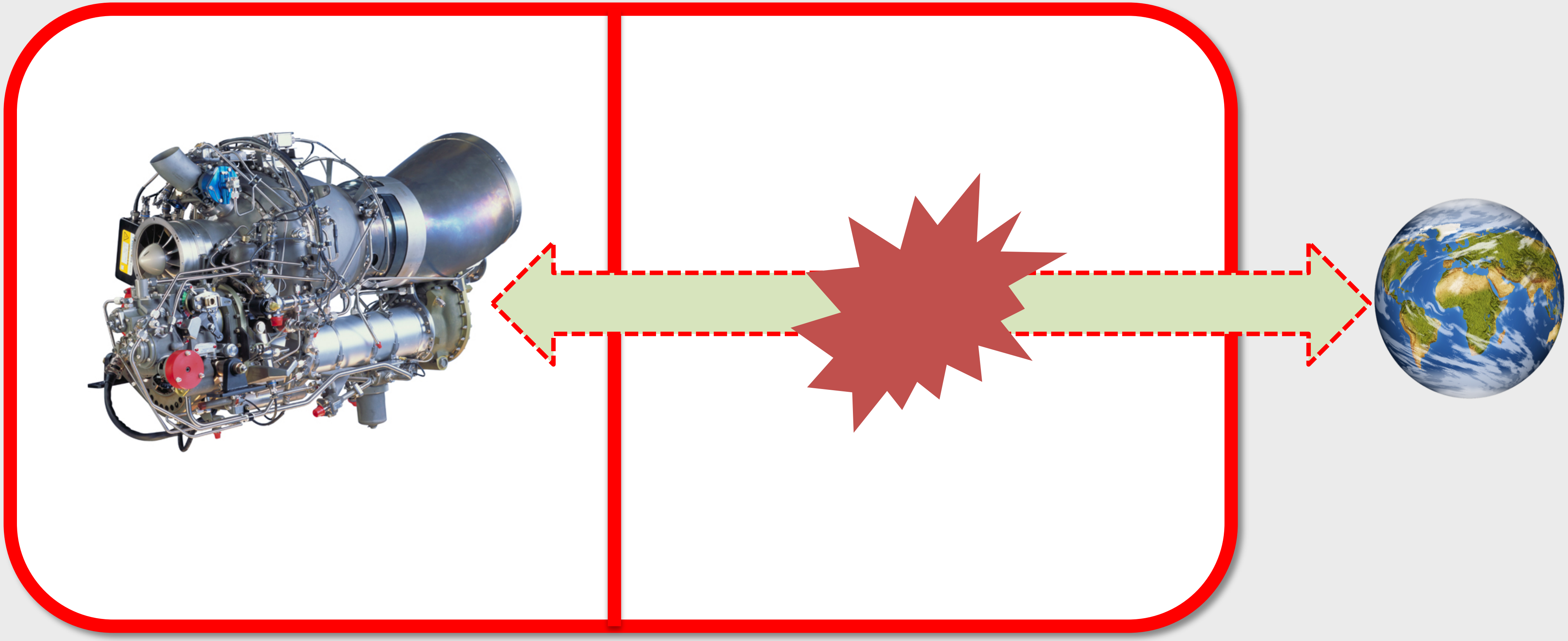
Only software can allow to achieve proper functionality …



Proven and Certified Secure Isolation

Filters / Applicative Firewalls

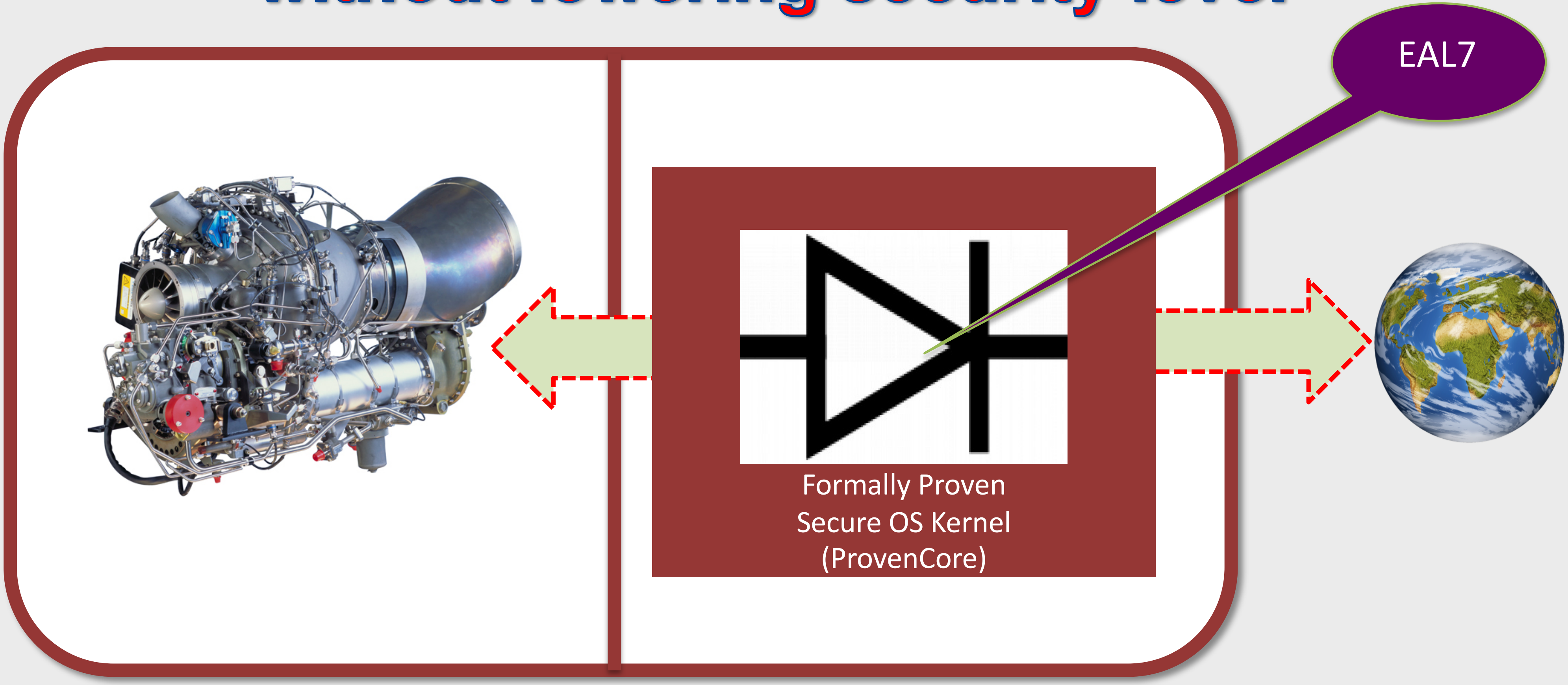
But not proper level of security



Proven and Certified Secure Isolation

Filters / Applicative Firewalls

First step : from hardware to software without lowering security level

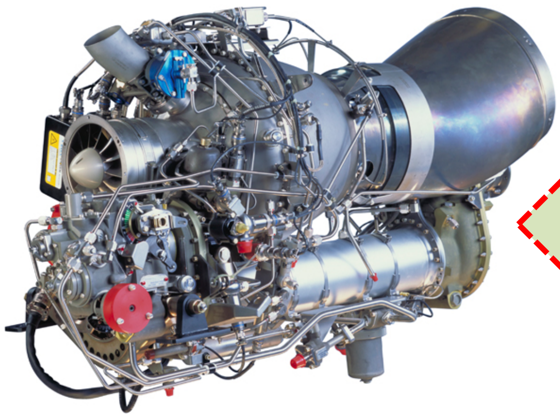


Proven and Certified Secure Isolation

Filters / Applicative Firewalls

Second step : tuning functionality without lowering security level

EAL7

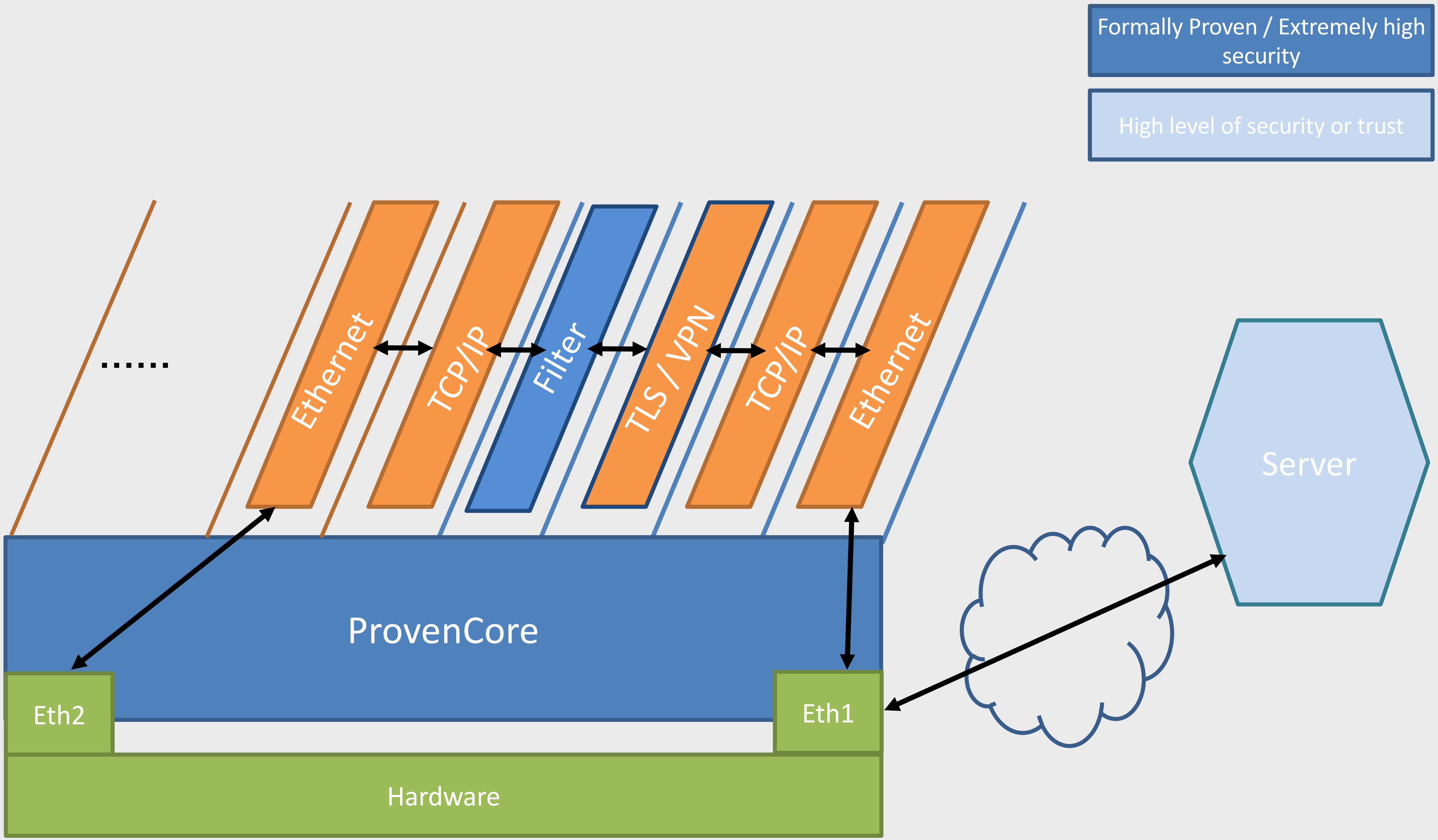


Security Policy Enforcement

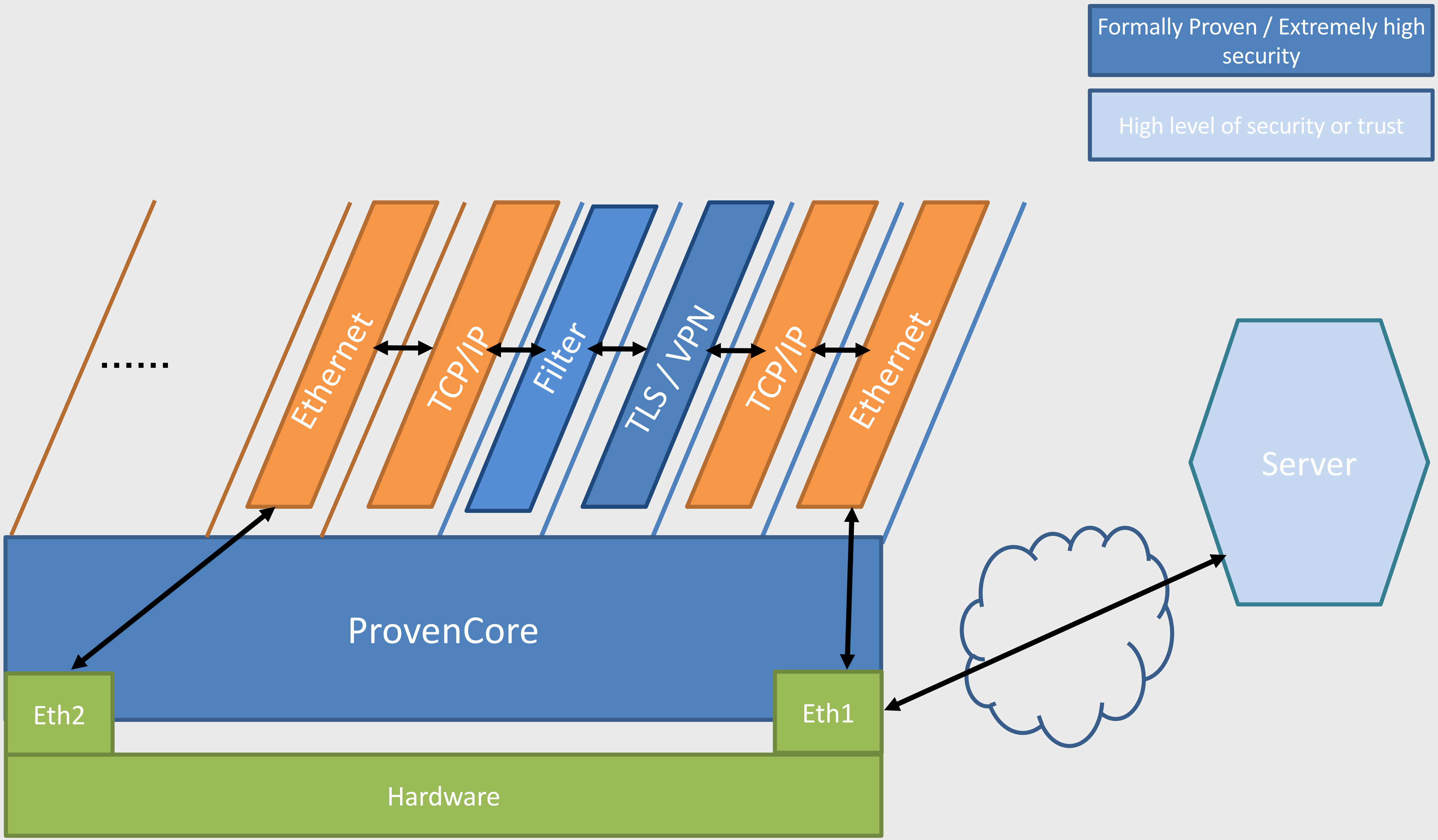
Formally Proven Secure OS Kernel (ProvenCore)

Proven and Certified Secure Isolation

Gateway with secured Filtering



Gateway with secured Filtering



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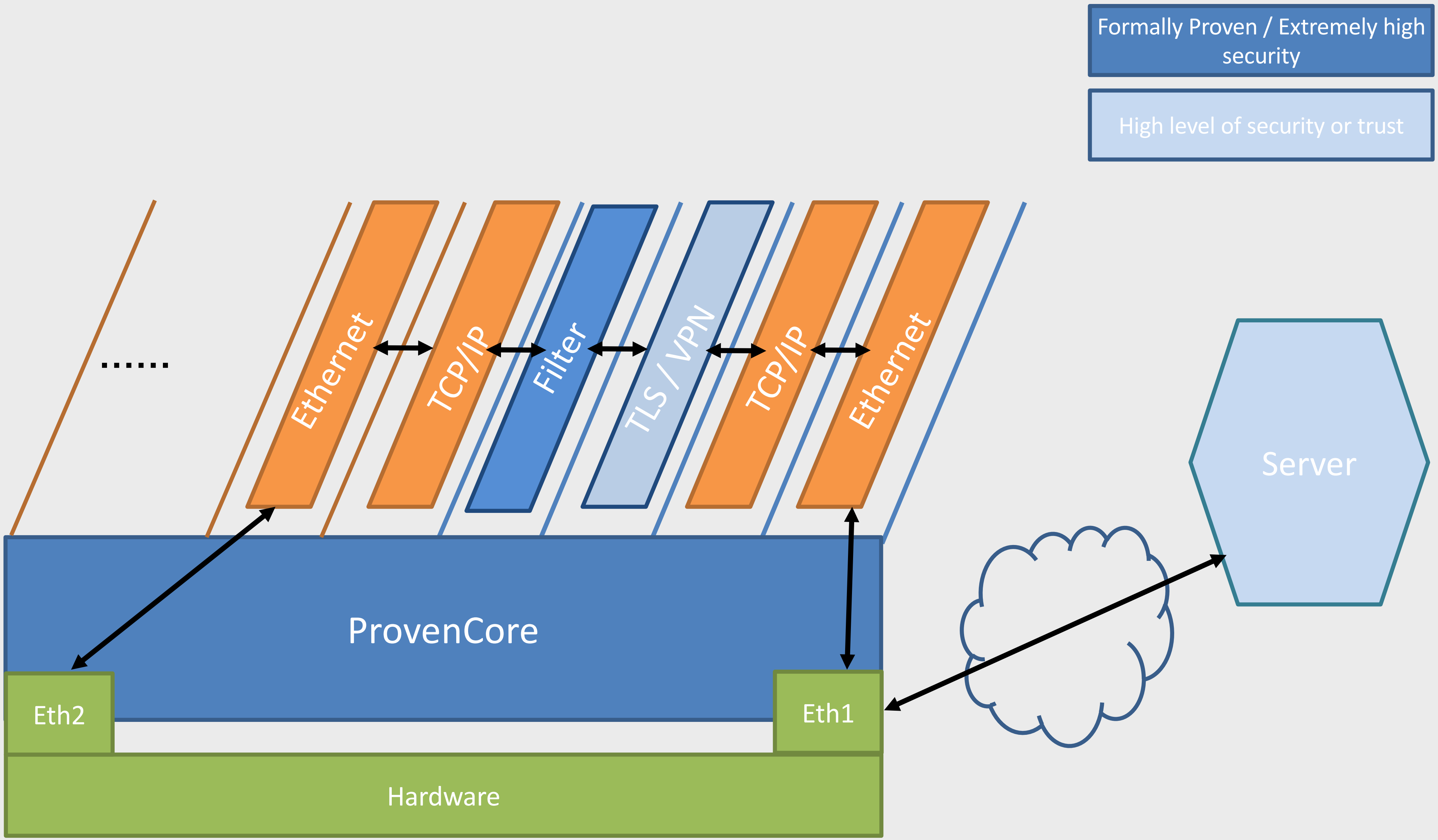
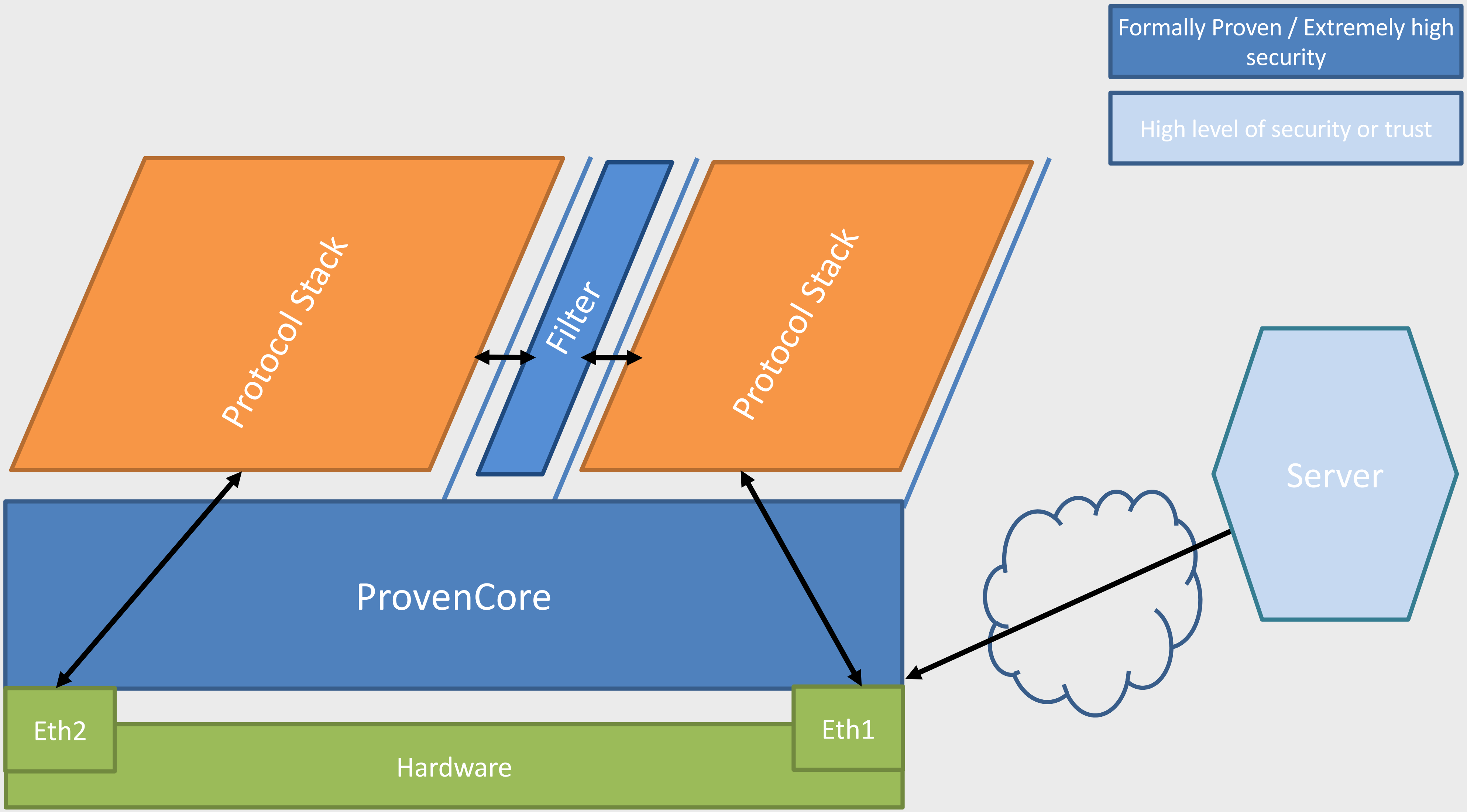


Gateway with secured Filtering



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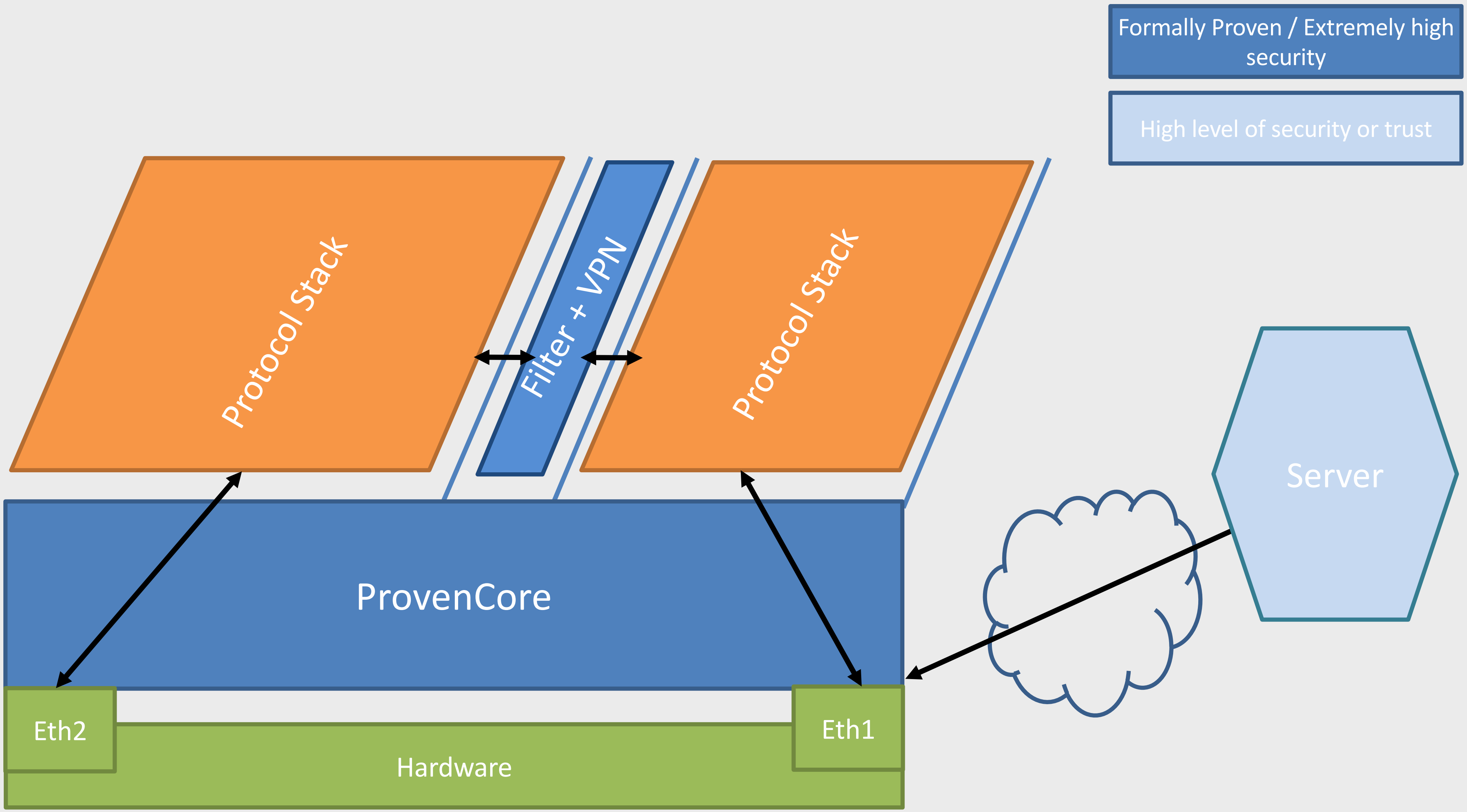

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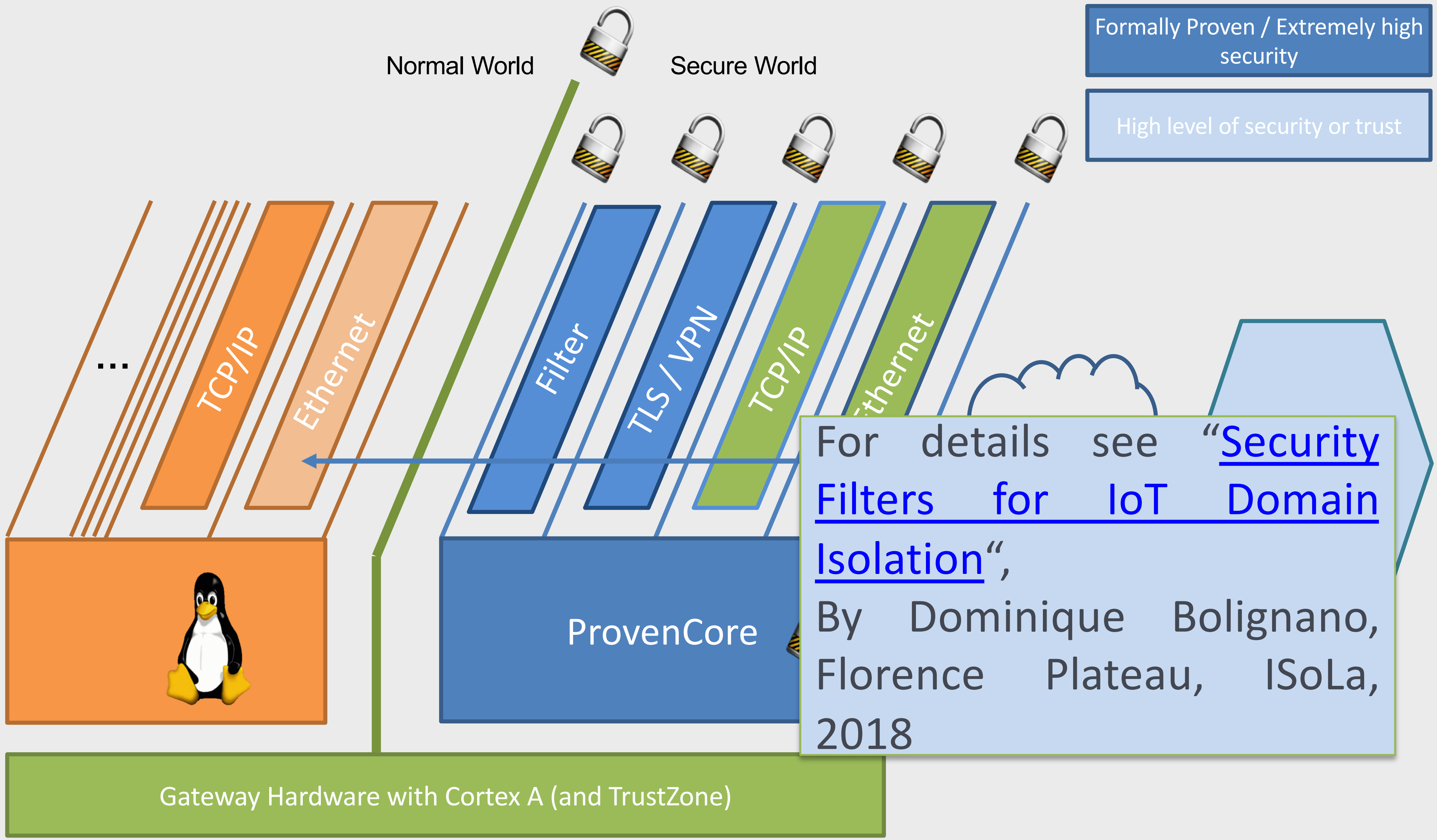

For details see "Security Filters for IoT Domain Isolation",
By Dominique Bolignano, Florence Plateau, ISoLa, 2018

Smart Language

SMART language specificities

- Functional (values manipulation) but with an imperative style
- Can be used at different abstraction levels
- Functions are partial
- Possible to associate proof obligations with logical paths in the execution graph
  - Proofs displayed as symbolic debugging
  - Makes certification easier and brings trust
- Properties can be expressed as tests
  - Invariants can also be expressed as programs or tests
- Possibility to use models/programs for proving

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Predicates

```
public member(elt x, seq e) -> [true, false]
program {{ seq f, elt y }}
{
    f := e;
    while
    {
        ?removeFirst(y+, f, f+);
        if x = y; then return true;
    }
}
```

Implicit predicates

```
public equals(elt x+, elt y)
implicit program

public removeFirst(elt x+, seq e, seq f+) -> [true, empty]
implicit program

public equals(elt x, elt y) -> [true, false]
implicit program
```

Handling by case / control structure

```
public member(elt x, seq e) -> [true, false]
program {{ seq f, elt y }}
{
    f := e;
    while
    {
        ?removeFirst(y+, f, f+);
        if x = y; then return true;
    }
}
```

Handling by case / control structure

```
public member(elt x, seq e) -> [true,false]
program {{ seq f, elt y }}
[found:true]
{
    f :=e ;
    while
    {
        [empty :false]removeFirst(y+,f,f+) ;
        [true:found,false:true](x=y) ;
    }
}
```

Handling by case / control structure

```
public member(elt x, seq e) -> [true,false]
program {{ seq f, elt y }}
[found:true]
{
    f :=e ;
    while
    {
        [empty :false]removeFirst(y+,f,f+) ;
        [true:found,false:true](x=y) ;
    }
}
```

Data / Control separation

```
public member(elt x, seq e) -> [true, false]
program {{ seq f, elt y }}
{
    f := e;
    while
    {
        ?removeFirst(y+, f, f+);
        if x = y; then return true;
    }
}
```

Impossible cases / Associated local properties

// program

```
public lemma propx(elt x,seq e)
program
{
 empty(e) => !member(x,e);
}
```

// equivalent code:

```
public lemma propxa(elt x,seq e)
program
[OK:true]
{
     [false:OK]empty(e);
     [true:error,false:true]member(x,e);
}
```

Impossible cases / Associated local properties

// code chunks

// Property (1):

```
{
 empty(e+) => !?removeFirst(_, e, _);
}
```

// equivalent code:

```
{
    empty(e+);
    [true:error,empty:true]removeFirst(_x+,e,e+);
}
```

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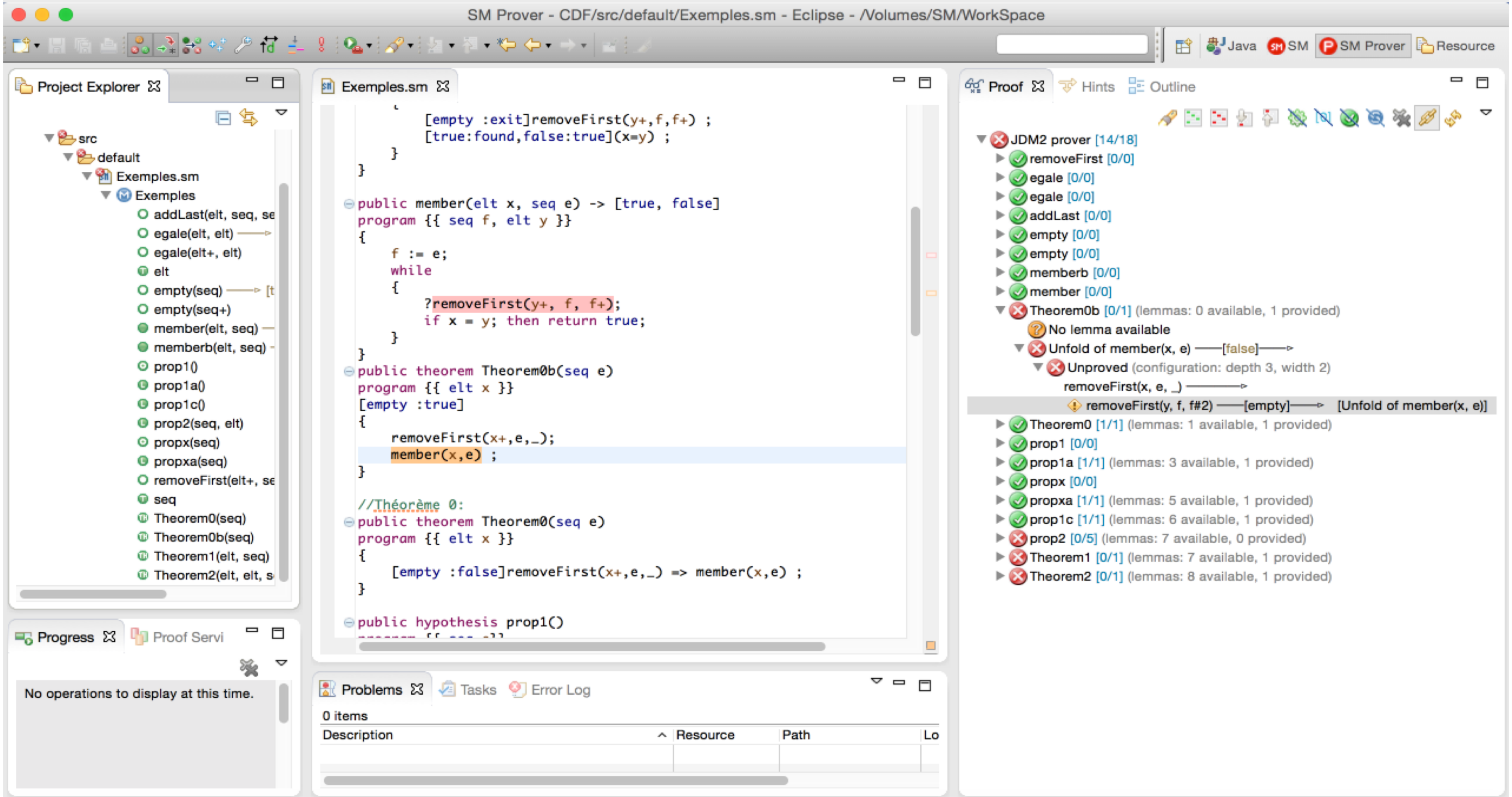
A more concrete example



A more concrete example

```
public theorem Theorem0b(seq e)
program {{ elt x }}
[empty :true]
{
    removeFirst(x+,e,_);
    member(x,e) ;
}
```

- memberb [0/0]
- Theorem0b [0/1] (lemmas: 0 available, 1 provided)
- Theorem0 [1/1] (lemmas: 1 available, 1 provided)
- prop1 [0/0]
- prop1a [1/1] (lemmas: 3 available, 1 provided)
- propx [0/0]
- propxa [1/1] (lemmas: 5 available, 1 provided)

A more concrete example

```
public theorem Theorem0b(seq e)
program {{ elt x }}
[empty :true]
{
    removeFirst(x+,e,_);
    member(x,e) ;
}
```

- memberb [0/0]
- Theorem0b [0/1] (lemmas: 0 available, 1 provided)
  - No lemma available
  - Unproved (configuration: depth 3, width 2)
    - removeFirst(x, e, _) ——▹
    - member(x, e) ——[false]——▹
- Theorem0 [1/1] (lemmas: 1 available, 1 provided)

A more concrete example

```
public member(elt x, seq e) -> [true, false]
program {{ seq f, elt y }}
{
    f := e;
    while
    {
        ?removeFirst(y+, f, f+);
        if x = y; then return true;
    }
}
public theorem Theorem0b(seq e)
program {{ elt x }}
[empty :true]
{
    removeFirst(x+,e,_);
    member(x,e) ;
}
```

```
▸ egale [0/0]
▸ addLast [0/0]
▸ empty [0/0]
▸ empty [0/0]
▸ memberb [0/0]
▸ member [0/0]
▾ Theorem0b [0/1] (lemmas: 0 available, 1 provided)
    No lemma available
  ▾ Unfold of member(x, e) ——[false]——▹
    ▾ Unproved (configuration: depth 3, width 2)
        removeFirst(x, e, _) ————▹
          removeFirst(y, f, f#2) ——[empty]——▹ [Unfold of member(x, e)]
▸ Theorem0 [1/1] (lemmas: 1 available, 1 provided)
▸ prop1 [0/0]
▸ prop1a [1/1] (lemmas: 3 available, 1 provided)
▸ propx [0/0]
```

SMART language specificities

- Functional (values manipulation) but with a imperative style
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  - Proofs pictured and guided as symbolic debugging
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A more concrete example

// code chunks // Property (2)

```
{
    addLast(x,e,f+) ;
    g:=e;
    while
    {
        [empty :exit]removeFirst(y+,g,g+) ;
        [empty :error]removeFirst(z+,f,f+) ;
        [false:error](y=z) ;
    }
    [empty :error]removeFirst(z+,f,f+) ;
    [false:error](x=z) ;
    [true:error, empty:true]removeFirst(z+,f,f+) ;
}
```

A more concrete example

```
// Propriétés 2
public lemma prop2(seq e, elt x)
program {{ seq f, seq g, elt y, elt z }}
{
    addLast(x,e,f+) ;
    g:=e;
    while
    {
        [empty :exit]removeFirst(y+,g,g+) ;
        [empty :error]removeFirst(z+,f,f+) ;
        [false:error](y=z) ;
    }
    [empty :error]removeFirst(z+,f,f+) ;
    [false:error](x=z) ;
    [true:error, empty:true]removeFirst(z+,f,f+) ;
}
```

A more concrete example

```
public hypothesis prop1()
program {{ seq e}}
{
 empty(e+) => !?removeFirst(_, e, _);
}

public hypothesis prop2(seq e, elt x)
program {{ seq f, seq g, elt y, elt z }}
{
    addLast(x,e,f+) ;
    g:=e;
    while
    {
        [empty :exit]removeFirst(y+,g,g+) ;
        [empty :error]removeFirst(z+,f,f+) ;
        [false:error](y=z) ;
    }
    [empty :error]removeFirst(z+,f,f+) ;
    [false:error](x=z) ;
    [true:error, empty:true]removeFirst(z+,f,f+) ;
}
```

Example of properties to be proven

- Theorem0: removeFirst(x+,e,f+) => member(x,e) ;
- Theorem1: addLast(x,e,f+) => member(x,f) ;
- Theorem2: member(x,e) => addLast(y,e,f+) => member(x,f) ;

```
//Théorème 0:
public theorem Theorem0(seq e)
program {{ elt x }}
{
    [empty :false]removeFirst(x+,e,_) => member(x,e) ;
}


//Théorème 1:
public theorem Theorem1(elt x,seq e)
program {{ seq f }}
{
    addLast(x,e,f+) => member(x,f) ;
}

// Théorème 2:
public theorem Theorem2(elt x, elt y, seq e)
program {{  seq f }}
{
    member(x,e) => addLast(y,e,f+) => member(x,f) ;
}
```

Intermediate language: SMIL

```
//Théorème 0:
public theorem Theorem0(seq e)
program {{ elt x }}
{
    [empty :false]removeFirst(x+,e,_) => member(x,e) ;
}

public theorem Theorem0b(seq e)
program {{ elt x }}
[empty :true]
{
    removeFirst(x+,e,_);
    member(x,e) ;
}
```

Indexed variables. Logical traces. Proof structures. Congruence

```
// Theorem0 : Unfold
[empty:true]
{
        removeFirst(x+,e,_);
        {
                f :=e ;
                while
                {
                        [empty :error]removeFirst(y+,f,f+) ;
                        [true:empty,false :true](x=y) ;
                }
        }
}
```

Indexed variables. Logical traces. Proof structures. Congruence

```
// Theorem0 : Unfold
[empty:true]
{
        removeFirst(x+,e,_);
        {
                f :=e ;
                while
                {
                        [empty :error]removeFirst(y+,f,f+) ;
                        [true:empty,false :true](x=y) ;
                }
        }
}
// b* -> [b] b*
```

Indexed variables. Logical traces. Proof structures. Congruence

```
// Theorem0 : Unfold + Unrolled
[empty:true]
{
        removeFirst(x+,e,_);
        {
                f :=e ;
                [empty:error]removeFirst(y+,f,f+) ;
                [true:empty, false:true](x=y) ;
                while
                {
                        [empty :error]removeFirst(y+,f,f+) ;
                        [true:OK, false:true](x=y) ;
                }
        }
}
```

Indexed variables. Logical traces. Proof structures. Congruence

Logical trace:

- [true]removeFirst(x1+,e1,g1+) ;
- [true]equals(f1+,e1);
- [empty:error]removeFirst(y1+,f,f+) ;

Transitive closing of congruence:

- [true]removeFirst(x1+,e1,g1+) ;
- [true]equals(e1+,e1);
- [empty:error]removeFirst(x1+,e1,g1+) ;

Indexed variables. Logical traces. Proof structures. Congruence

Logical trace:

- [true]removeFirst(x1+,e1,g1+) ;
- [true]equals(f1+,e1);
- [true]removeFirst(y1+,f,f+) ;
- [false :true](x1=y1) ;

Transitive closing of congruence:

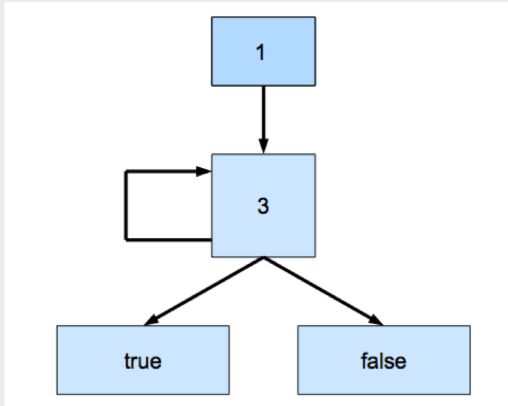
- [true]removeFirst(x1+,e1,g1+) ;
- [true]equals(e1+,e1);
- [true]removeFirst(x1+,e1,g1+) ;
- [false :error](x1=x1) ;

Indexed variables. Logical traces. Proof structures. Congruence

```
// Theorem0 : Unfold + Unrolled
[empty:true]
{
        removeFirst(x+,e,_);
        {
                f :=e ;
                [empty:error]removeFirst(y+,f,f+) ;
                [true:empty, false:error](x=y) ;
                while
                {
                        [empty :error]removeFirst(y+,f,f+) ;
                        [true:OK, false:true](x=y) ;
                }
        }
}
```

Composition with Synchronization

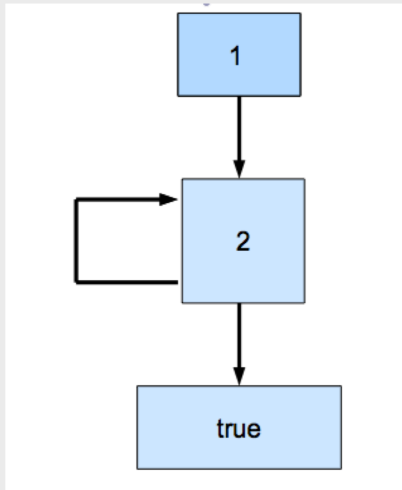
```
// Theorem1 Unfold
[OK:true]
{
1:          [empty :OK]addLast(x,e,f+);
            {
2:                    g:=f ;
                      while
                      {
3:                              [empty:false]removeFirst(y+,g,g+);
4:                              [true:OK, false:true](x=y);
            }
            }
}
```



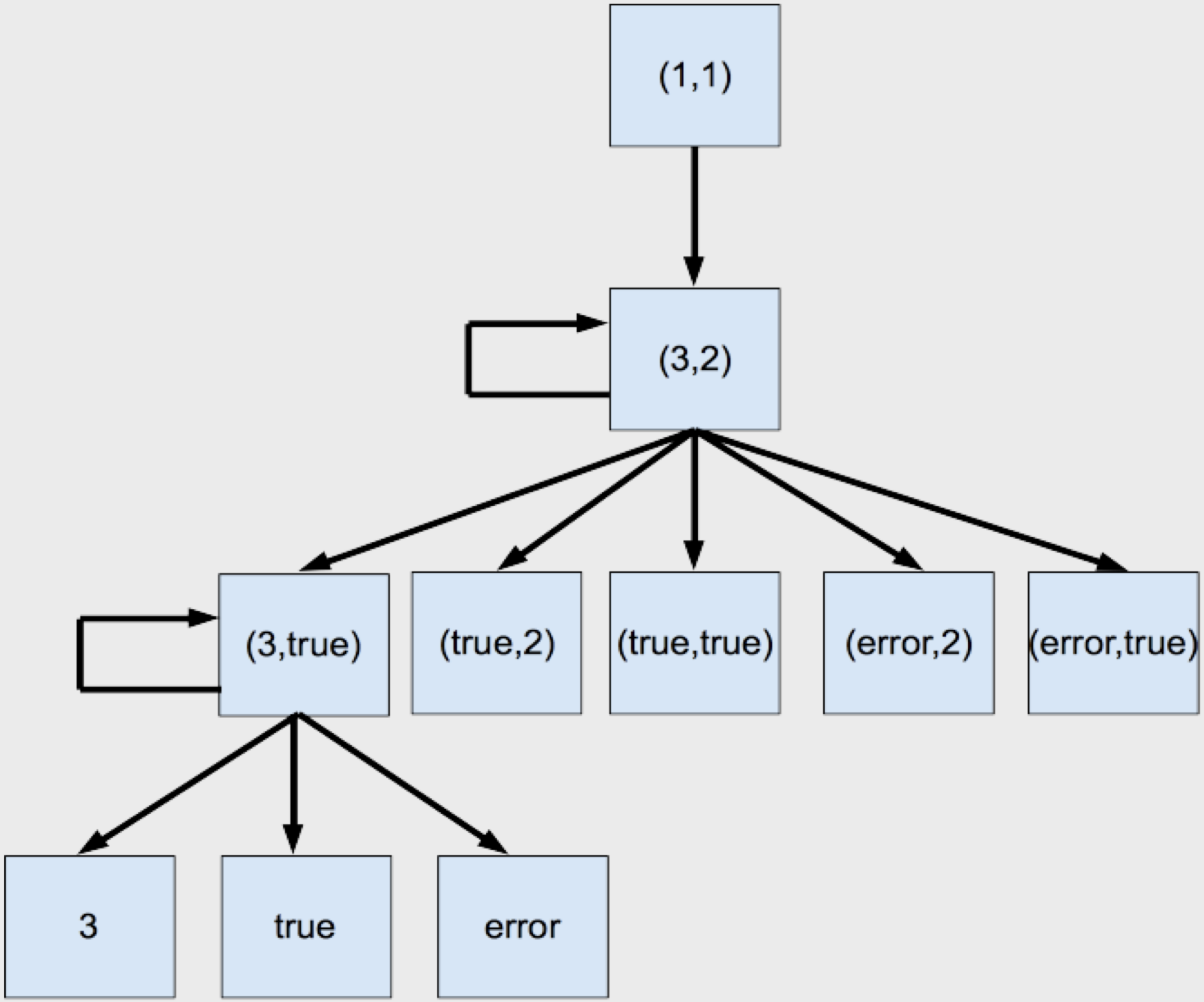
Rappel Theorem1: addLast(x,e,f+) ; => member(x,f) ;

Composition with Synchronization

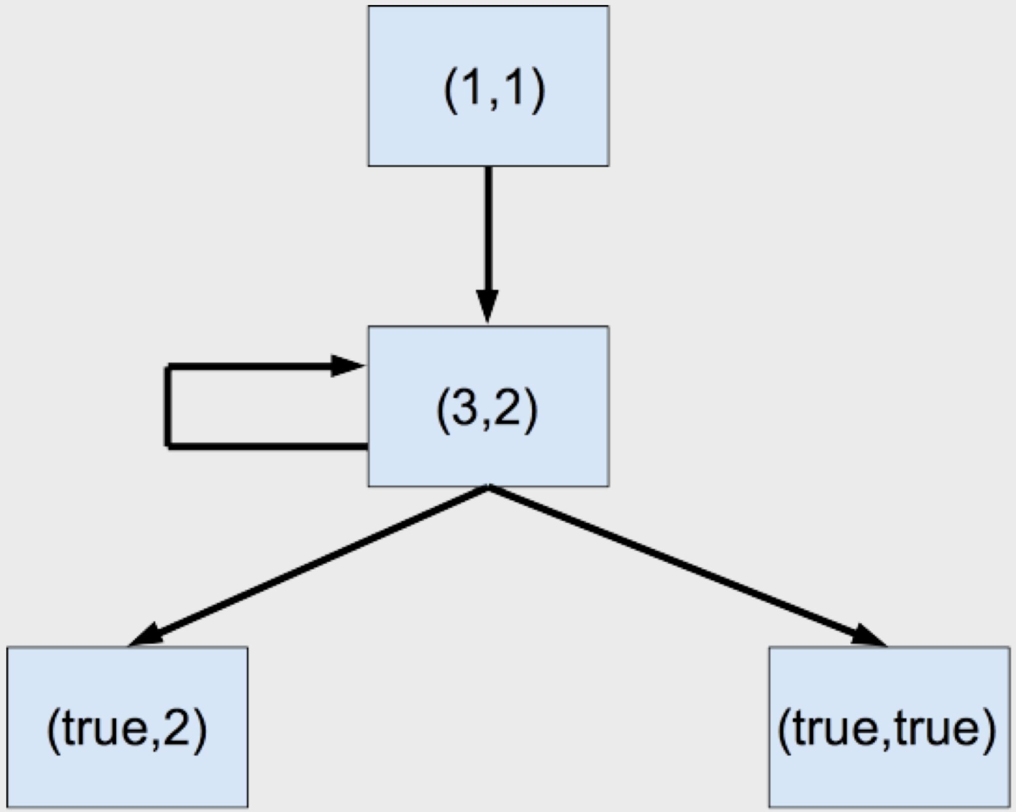
```
// code chunks  // Property (2)
{
1:      addLast(x,e,f+) ;
        while
        {
2:              [empty :exit]removeFirst(y+,e,e+) ;
3:              [empty :error]removeFirst(z+,f,f+) ;
4:              [false:error](y=z) ;
        }
5:      [empty :error]removeFirst(z+,f,f+) ;
6:      [false:error](x=z) ;
7:      [true:error,empty :true]removeFirst(z+,f,f+) ;
}
```



Composition Theorem1Unfold Axiom2

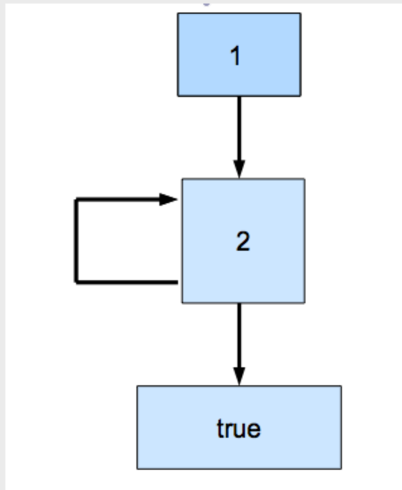


Simplification Composition Theorem1Unfold Axiom2 (propagation congruence)



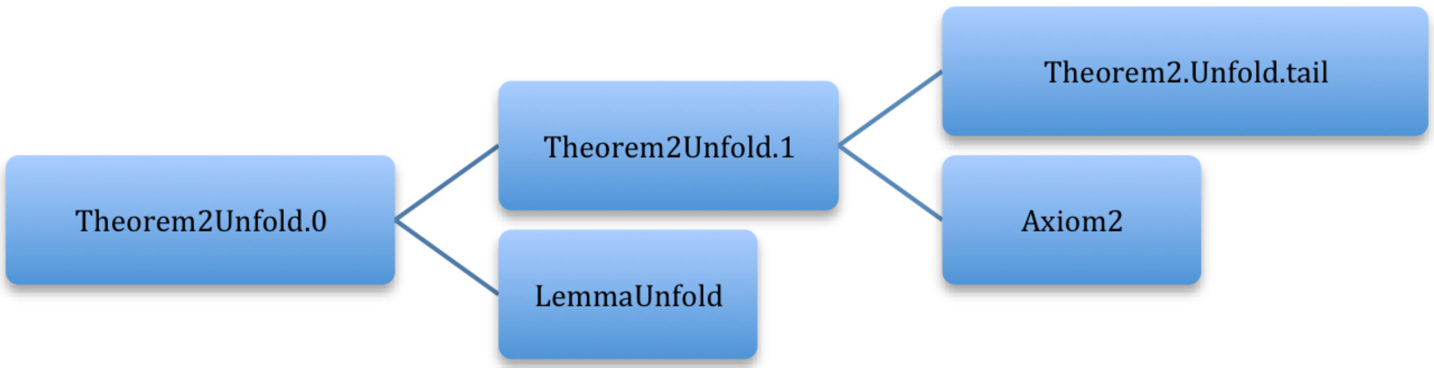
Composition with Synchronization

```
// code chunks  // Property (2)
{
1:      addLast(x,e,f+) ;
        while
        {
2:              [empty :exit]removeFirst(y+,e,e+) ;
3:              [empty :error]removeFirst(z+,f,f+) ;
                [false:error](y=z) ;
        }
4:      [empty :error]removeFirst(z+,f,f+) ;
5:      [false:error](x=z) ;
6:      [true:error,empty :true]removeFirst(z+,f,f+) ;
}
```



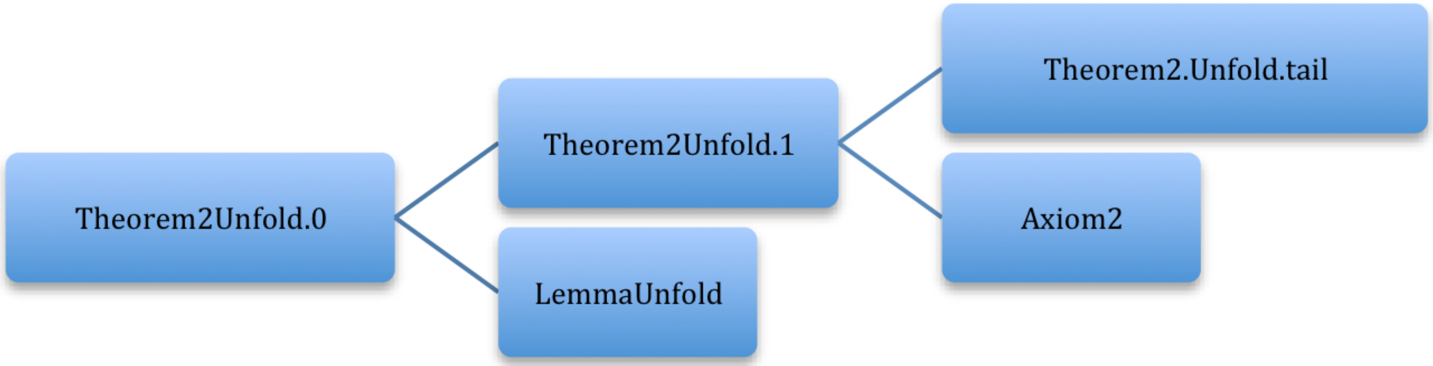
Theorem2: member(x,e); addLast(y,e,f+); => member(x,f) ;

New example of (double) composition for theorem 2 proof



LemmaUnfold : member(x,e) => member(x,e) ;

New example of (double) composition for theorem 2 proof



LemmaUnfold : [false:true]member(x,e) ;

Further Documentation

- “Inferring Frame Conditions with Static Correlation Analysis“, Oana Andreescu, Thomas Jensen, Stéphane Lescuyer, Benoît Montagu, POPL, 2019
- “Security Filters for IoT Domain Isolation“, Dominique Bolignano, Florence Plateau, ISoLa, 2018
- “Formally Proven and Certified Off-The-Shelf Software Components“, Dominique Bolignano, C&SAR, 2016
- “Proven Security for the Internet of Things“, Dominique Bolignano, Embedded Conference 2016
- “ProvenCore: Towards a Verified Isolation Micro-Kernel“, Stéphane Lescuyer, 10th HiPEAC Conference, 2015

Conclusions / Future Work

- Applicable to a very large range of market segments and situations
- Everything doesn’t need to be modelled nor proven (hypotheses, resistance to physical attacks, properties appropriateness, unsuitable architectures, human chain, etc.)
- More features to be added,
- Enlarging the scope of evaluation to hardware is planned,
- Some optimizations to be done if required,
- Other kernels to be handled,