Cybersecurity of Industrial Systems: Applicative Filtering and Generation of Attack Scenarios

Sécurité des systèmes industriels : filtrage applicatif et recherche de scénarios d'attaques

Maxime Puys

Ph.D Advisors: Marie-Laure Potet and Jean-Louis Roch

VERIMAG, University of Grenoble Alpes / Grenoble-INP, France

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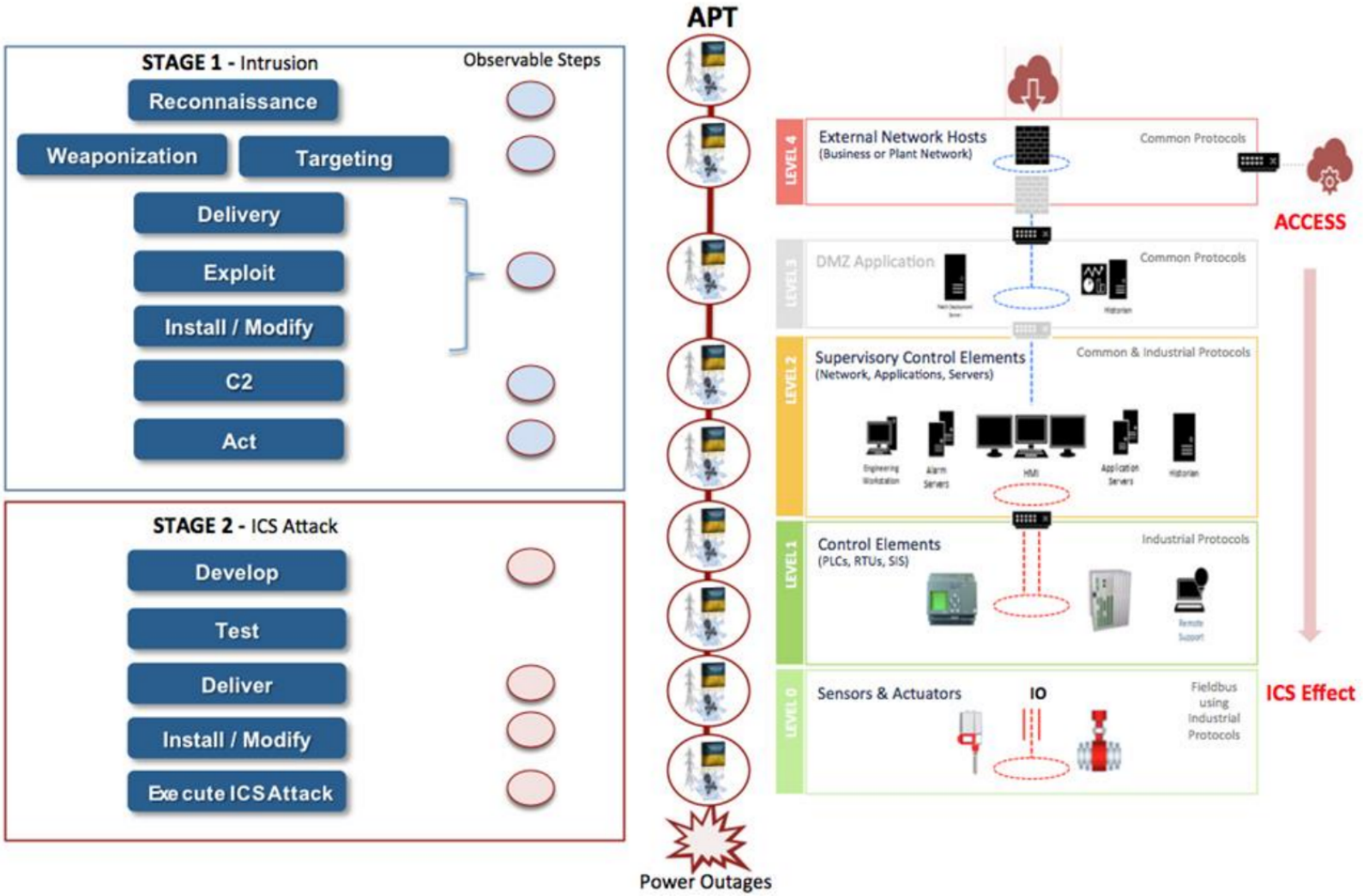
Blackout in Ukrain [LAC16]

- Occured on Dec. 23rd, 2015, lasted up to 6 hours.
- Approxilately 225,000 custommers impacted.



Advanced Persistent Threat

Definition (Wikipedia)

Set of stealthy and continuous computer hacking processes, often orchestrated by a person or persons targeting a specific entity.

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1. **Initial compromise** – Social engineering, phishing, malware.
2. **Establish Foothold** – Backdoors, tunnels (allowing stealth access).
3. **Escalate privileges** – Gain admin password, spread to LAN.
4. **Internal reconnaissance** – Collect information.
5. **Attack preparation** – Develop targeted exploit, train, rehearse.
6. **Complete mission** – Launch attack.
7. **Cover traces** – Remove logs, maintain access for further attacks.

Industrial Systems are Interesting Targets for APT

- Critical infrastructures:
  - $\Rightarrow$ Potentially important damages.
- Less aware of cybersecurity risks:
  - $\Rightarrow$ Easier initial compromission, less defenses.
- Legacy components;
- Proprietary (often customized) softwares/protocols/API:
  - $\Rightarrow$ Wider attack surface.

Protection becoming a priority for government agencies

- **Laws** to ensure security (*Opérateurs d'Importance Vitale*).
- Publications from government agencies (e.g.: ANSSI in France).

Challenges for Industrial Systems Cybersecurity

Recently Targeted by Cyberattacks

Historically **isolated** from networks:

$\Rightarrow$ Secure by design.

Properties to Ensure Differ from IT Systems

Industrial systems require mainly:

- availability, integrity, authentication, **dependability**.

$\Rightarrow$ No focus on confidentiality.

Need to Combine Safety and Security

- Safety = Protection against **identified/natural difficulties**.
- Security = Protection against **malicious adversaries**.
  - $\Rightarrow$ Often opposing to safety (e.g.: cryptography vs. real time).

Thesis Problematic

Wide cyberattack surface:

- Vectors: social engineering, **networks**, mobile devices, softwares, etc).
- In case of networks, possible targeted OSI layers: physical, ..., **security, applicative**.

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Problematic

Uncover or block applicative network attacks mainly exploiting **communication protocol weaknesses**.

$\Rightarrow$ Provide risk and vulnerability analyzes combining safety and security.

$\Rightarrow$ Provide verifications relying on formal methods.

Industrial Systems (ICS) Composition 1/2

SCADA

PLC

Process

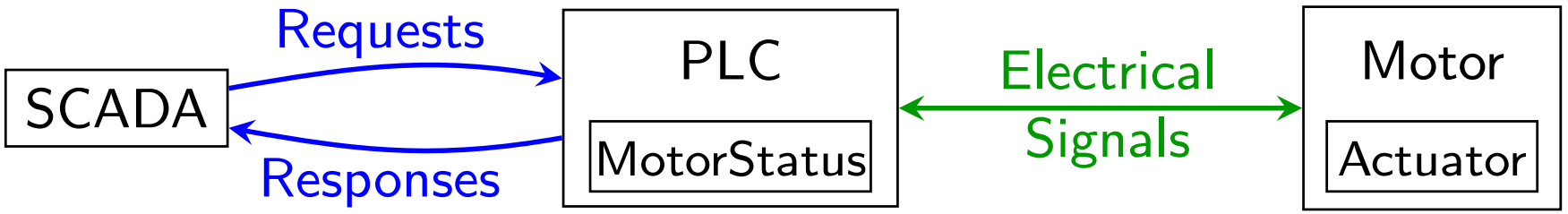
SCADA: Supervisory Control And Data Acquisition, controls and monitors the process.

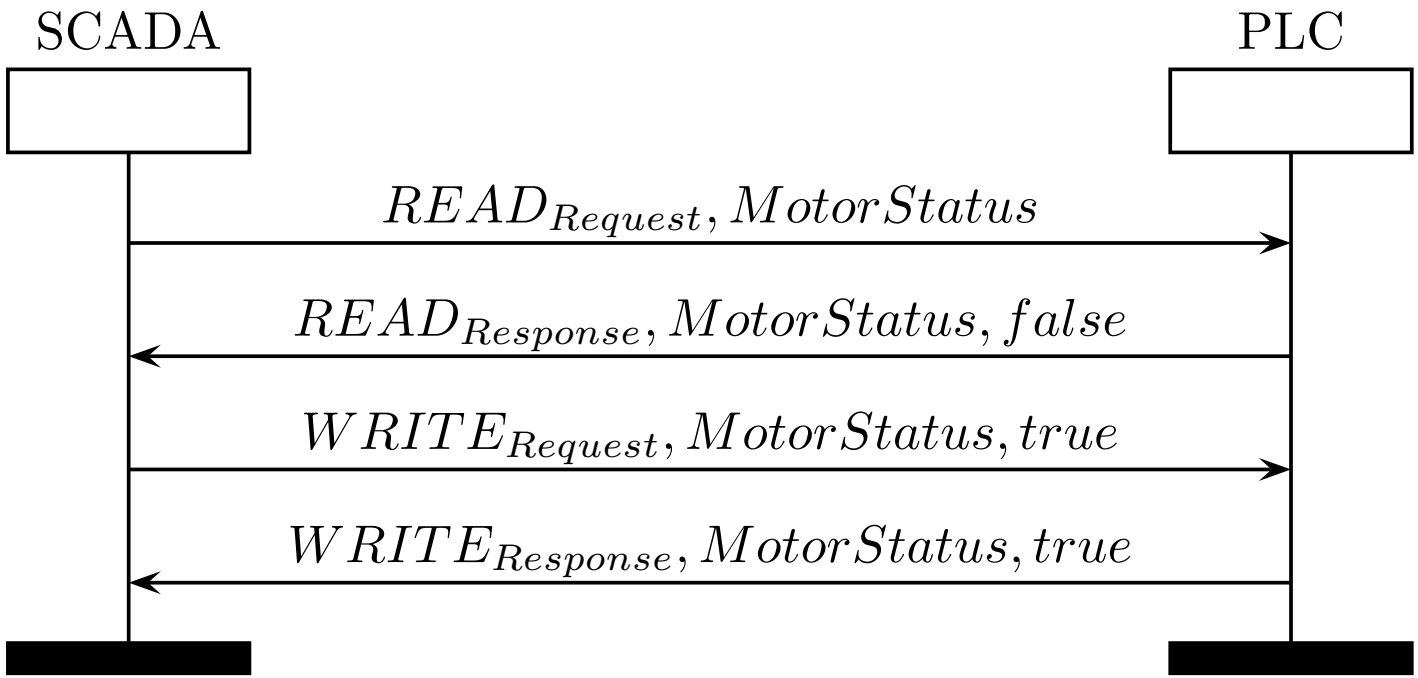
PLC: Programmable Logic Controller, interprets SCADA orders for the process.

Process: Actual industrial process managed by the system.

Industrial Systems (ICS) Composition 2/2

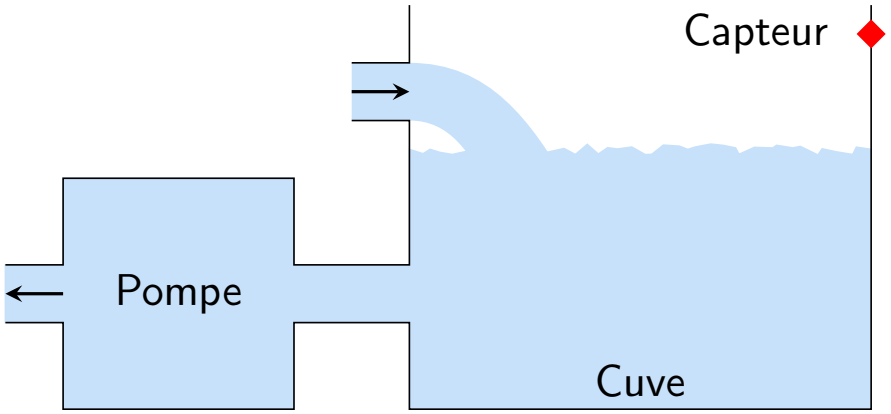
- Variables on PLC synchronized with process.
- Protocols used are specific (e.g.: MODBUS, OPC-UA).





A Common Thread: Maroochy Shire

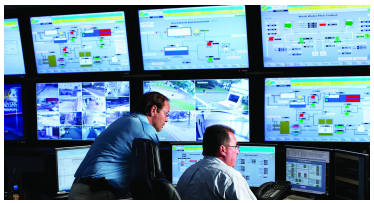
- Real attack occurring in 2000 in Australia.
- An insider spills $\sim$ 1M litters of raw sewage into nature.
- Attack over several months.



In our context, at least 3 vulnerabilities:

1. Absence of **safety mechanism** to avoid the spill.
2. Absence of **authentication mechanism** in communication protocols.
3. Absence of **prevision** of attacks.

Overview of the Thesis



Protocols

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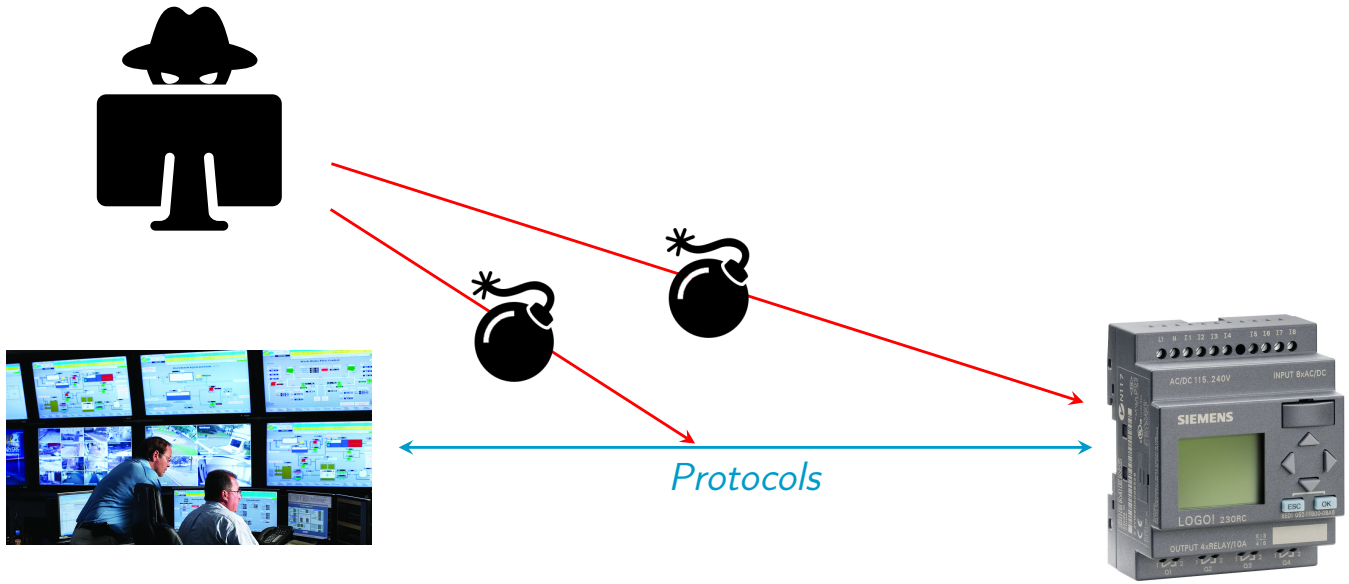
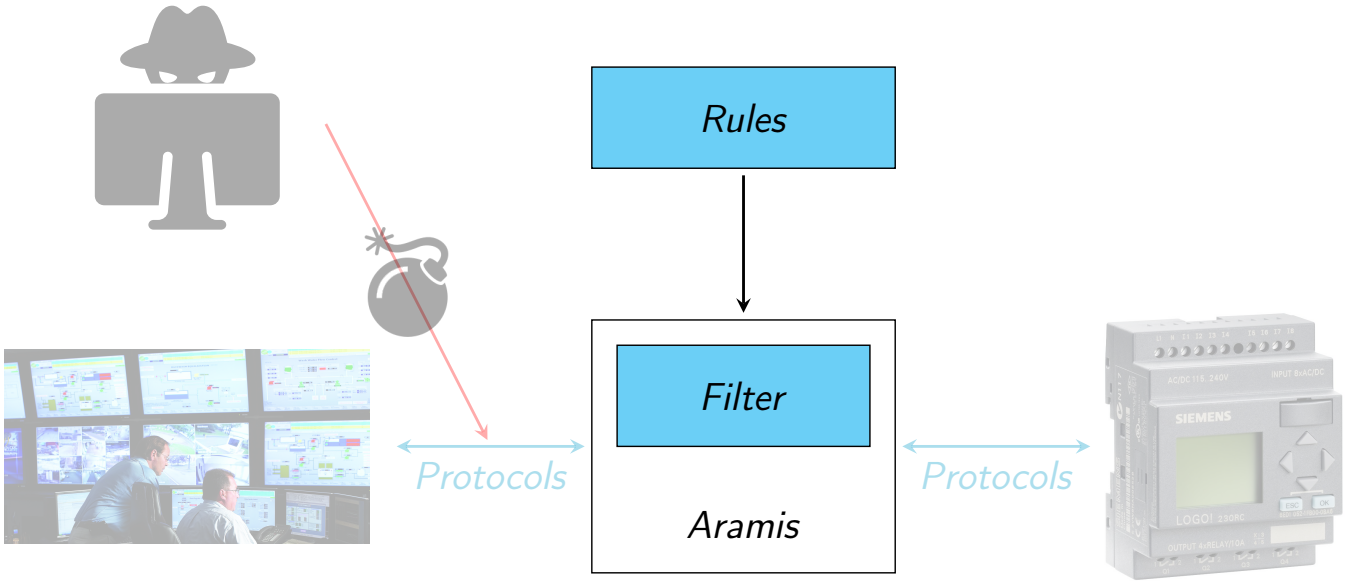
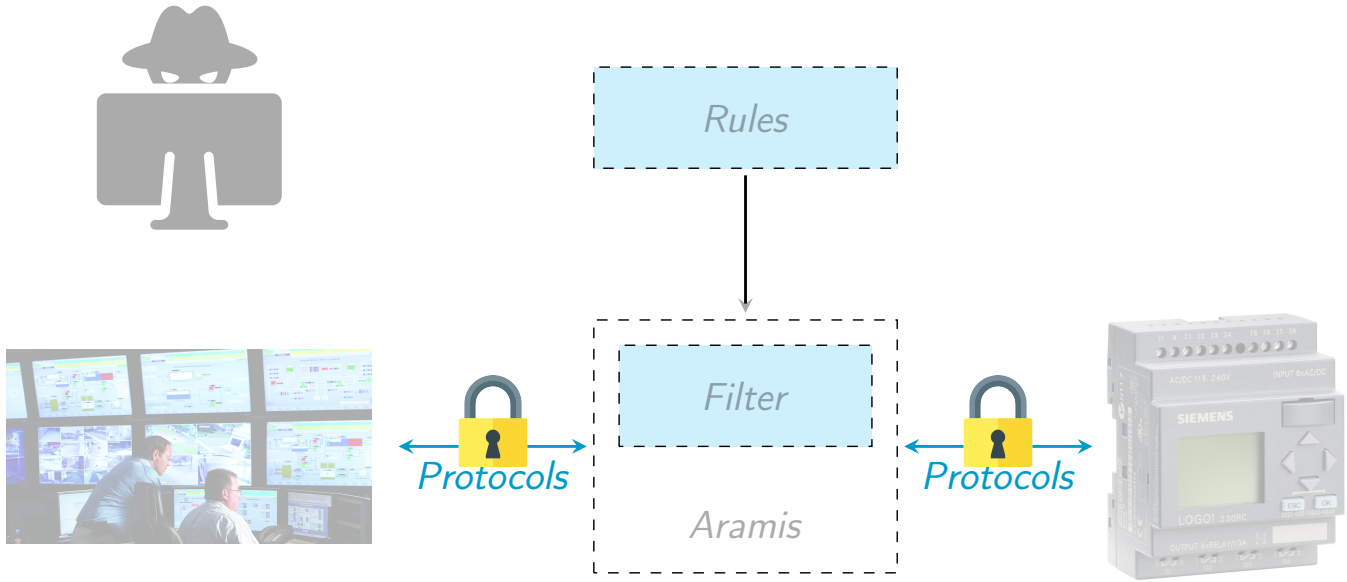


Overview of the Thesis: 1 – Applicative Filtering



Overview of the Thesis: 2 – Protocol Verification



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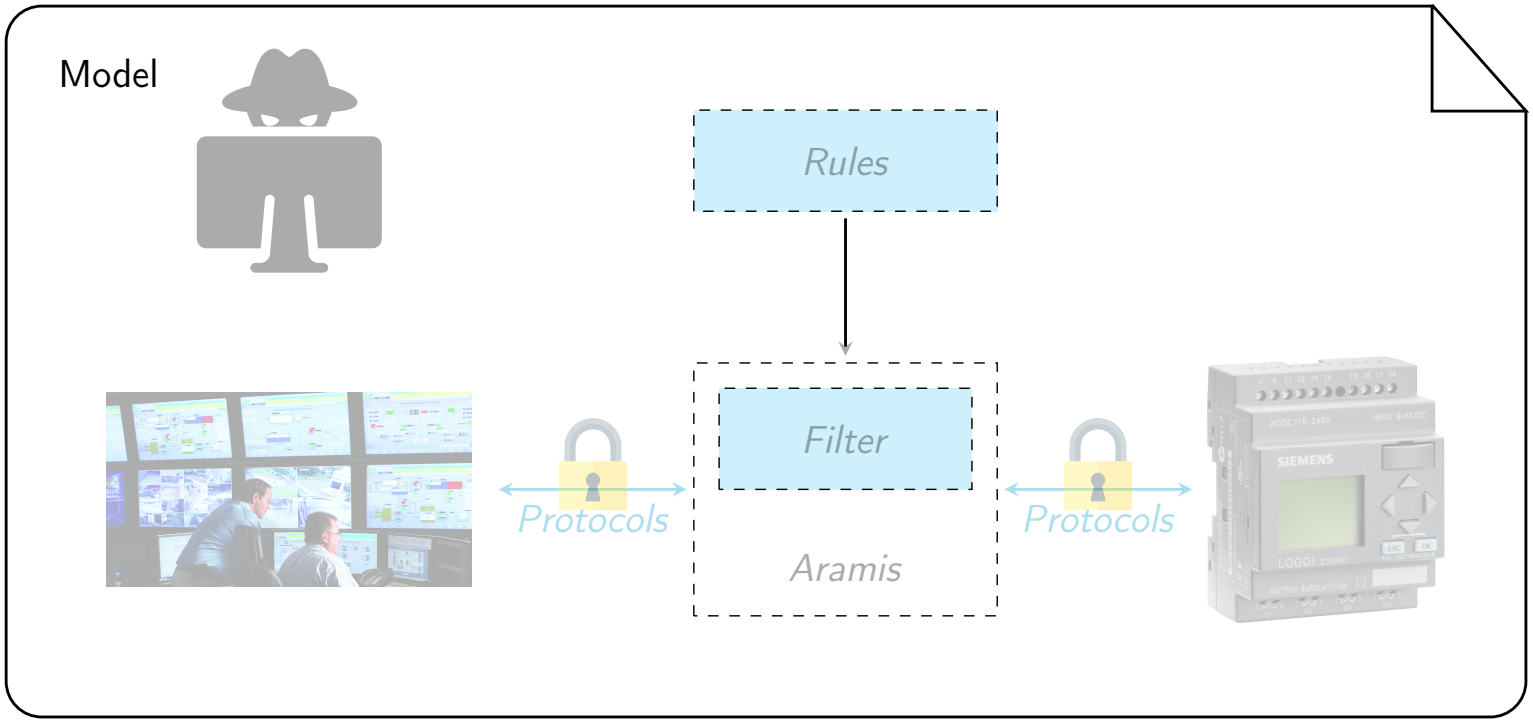

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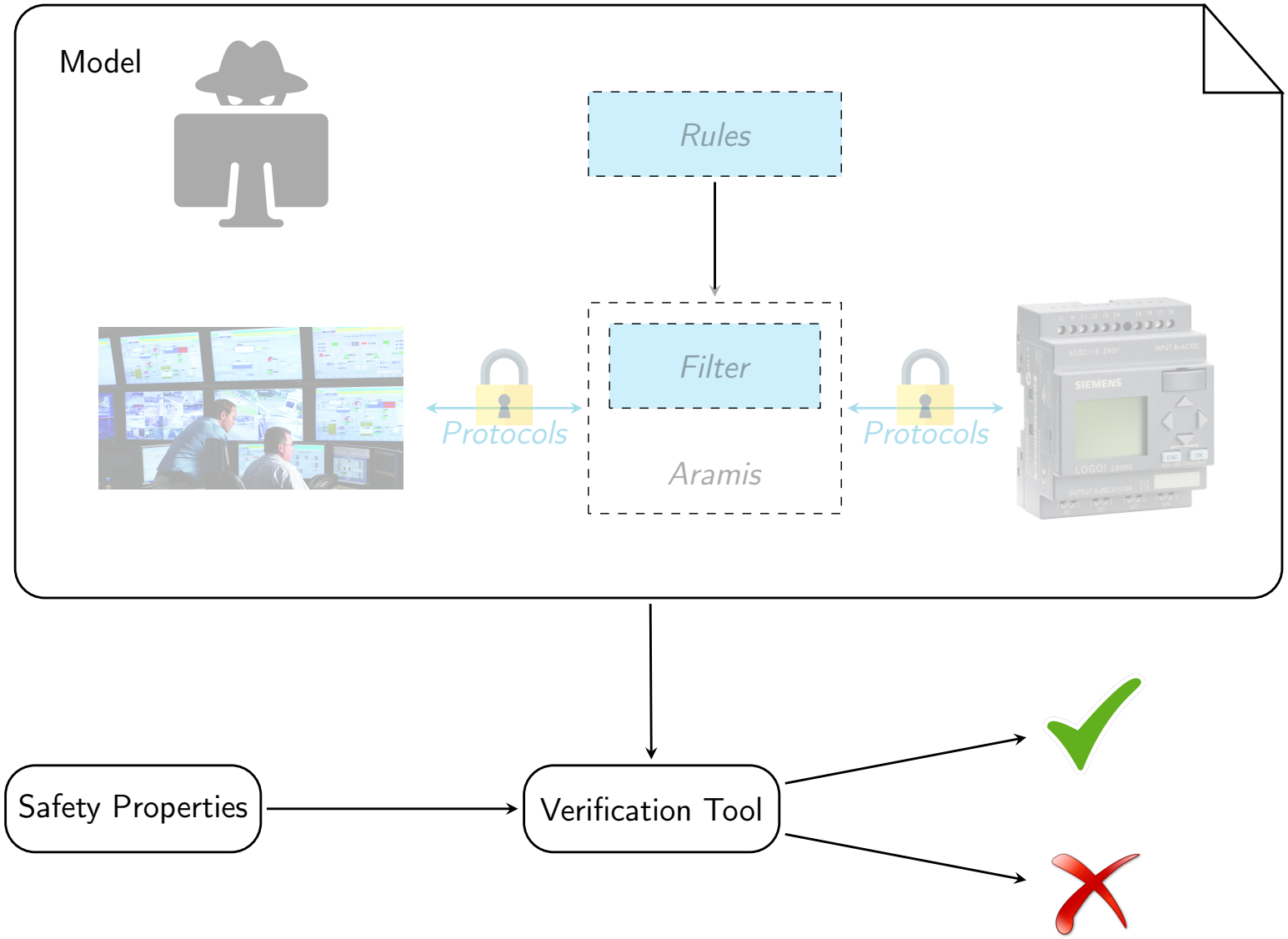

Contributions

Applicative Filtering for Industrial Systems

- Filter development, Python API for rules configuration, embedded system context.

Formal Verification of Industrial Protocols

- Formal analysis of two sub-protocols of OPC-UA.

A^{2}SPICS: Attack Scenarios Generation

- Analysis of safety properties in case of attackers.
- Experimentations with UPPAAL, ProVerif and Tamarin.

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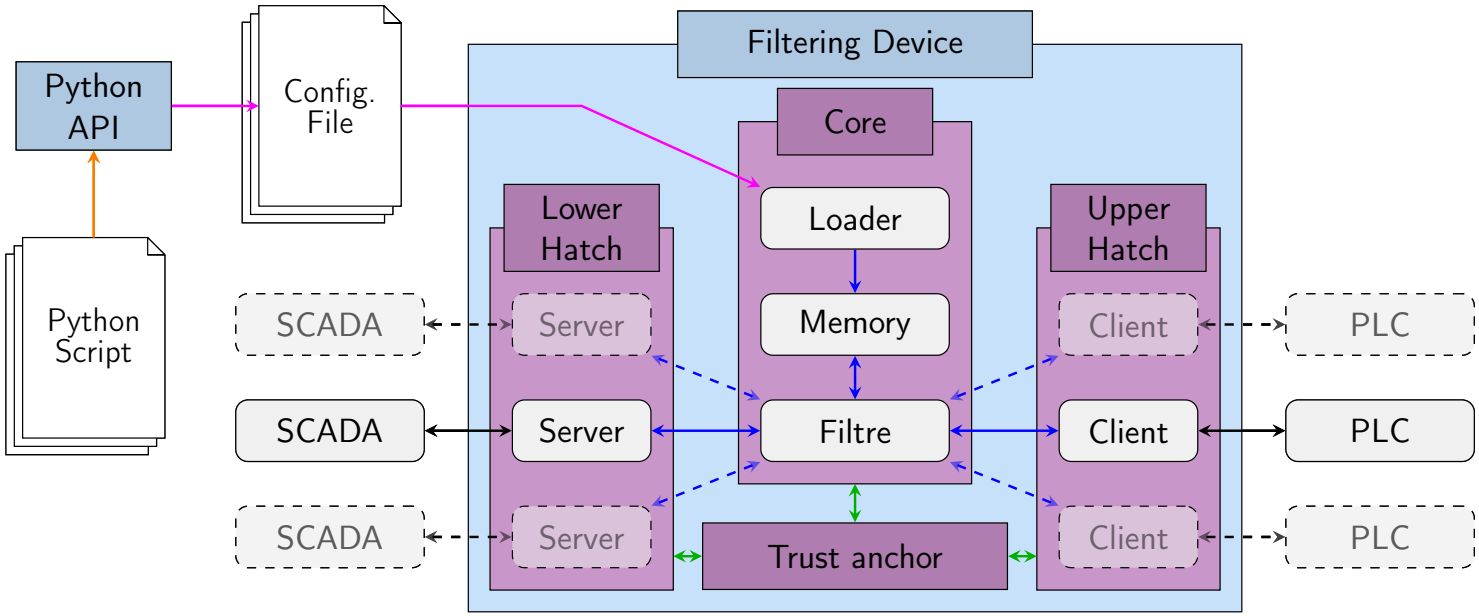
Filtering Device

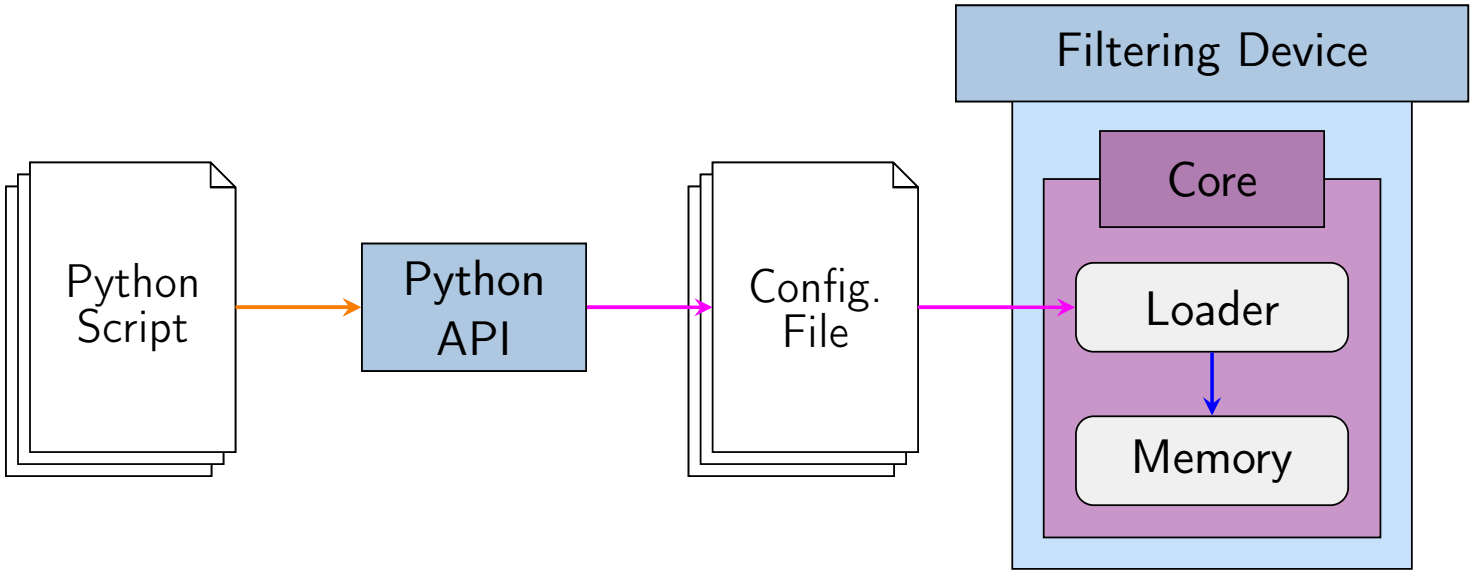
Objective: A transparent device to disrupt and **filter industrial flows**.



Filtering device's components

Filtering Device

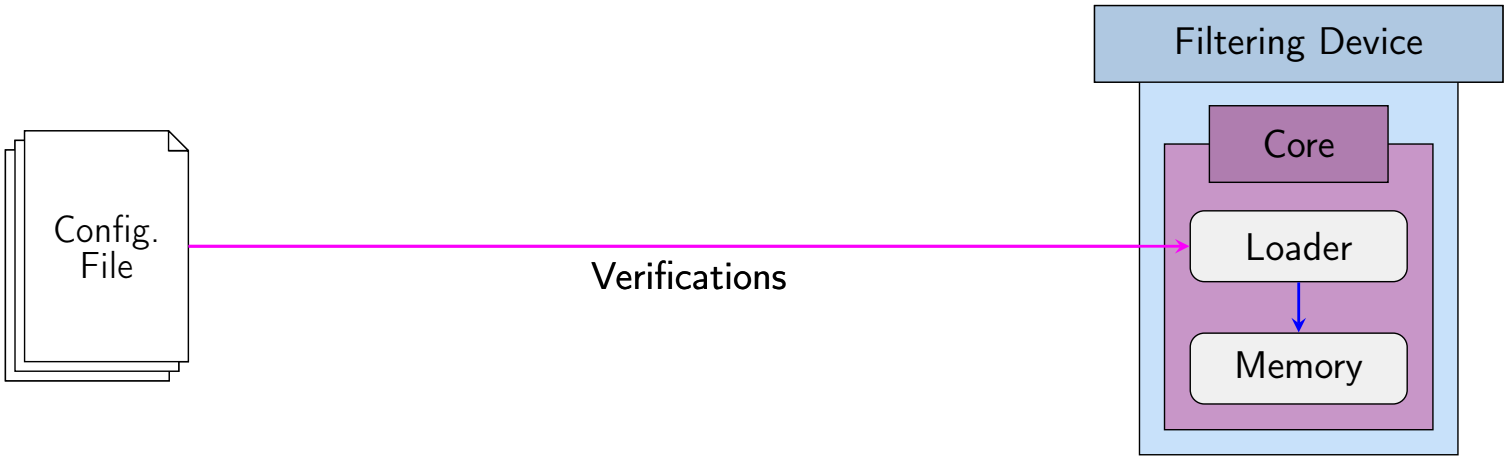
- API designed to be used by integrators (industrial constraints).



Zoom on rule writing

Filtering Device

- Verifications on configuration file by loader:
  - Rules coherence.
  - Filter storage space (rules and process state).
  - Worst-case processing time for a message.



Zoom on rule verifications

Rules Example

Stateless rules (e.g.: access control, permissions, values written).

Domain specific **stateful** rules:

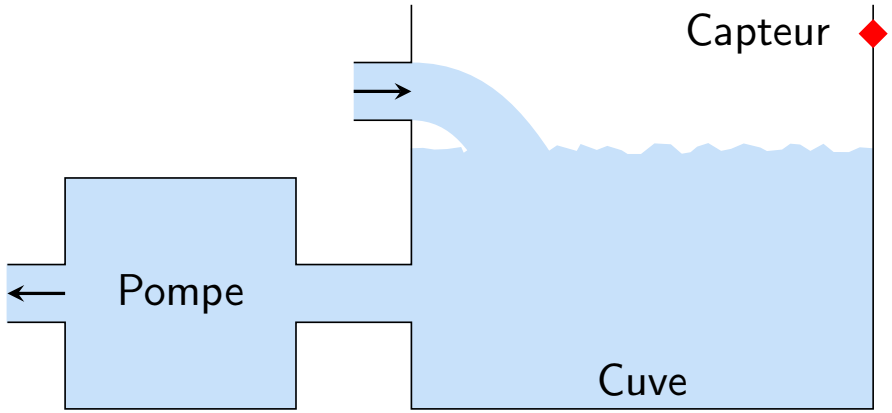
- Temporal rules (e.g.: not receive more than 1 command per minute).
- Global process state (e.g.: pump must not be stopped if tank is full).

```
rule = filter.Filter(chan, pumpState, filtre.Service.WRITE)
rule.addSubRule(
    condition=filter.And(
        filter.Equal(captor.currentValue, 1),
        filter.Equal(filter.NewValue(), 0)
    ),
    thenActions=filter.Reject("Tank full!")
)
```

Example of rule for Maroochy Shire

Back to the Common Thread: Maroochy Shire

- **Vulnerability 1:** Absence of safety mechanism to avoid the spill.

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Formal Verification of Industrial Protocols

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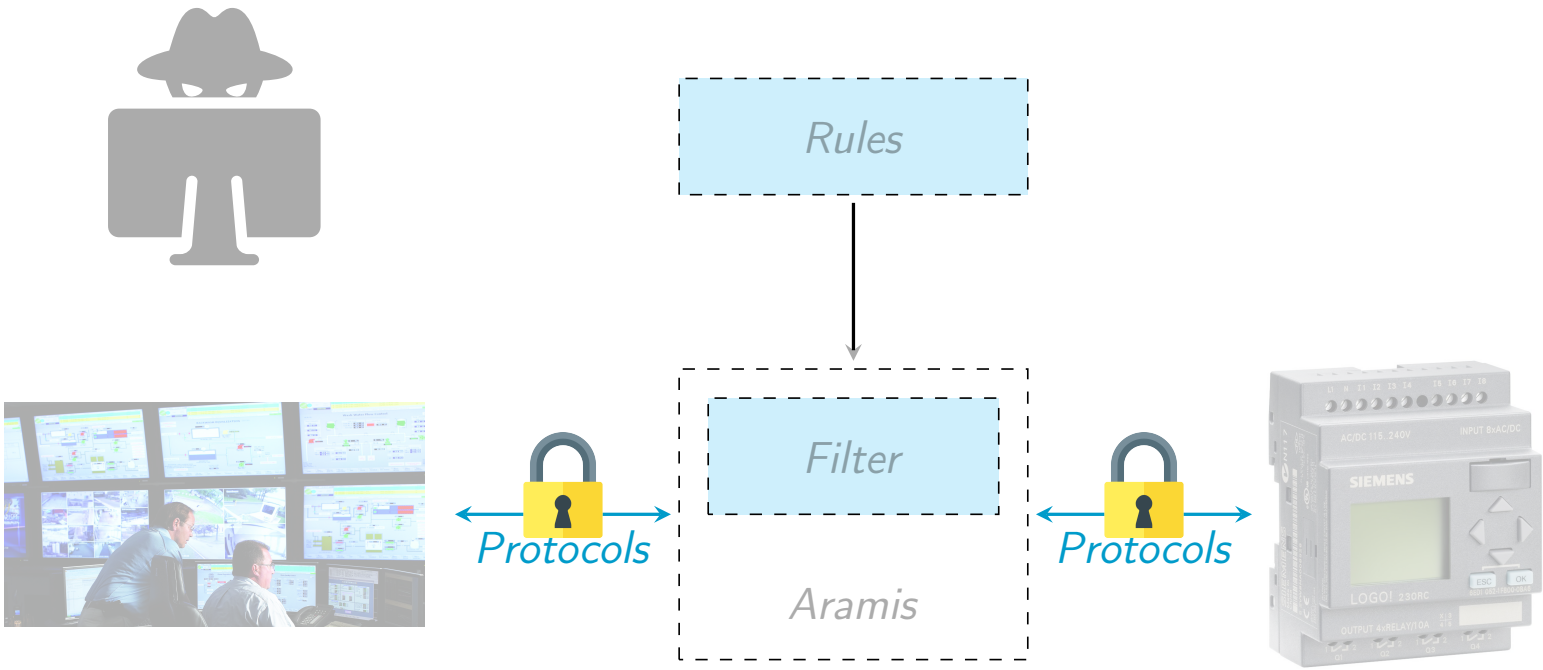

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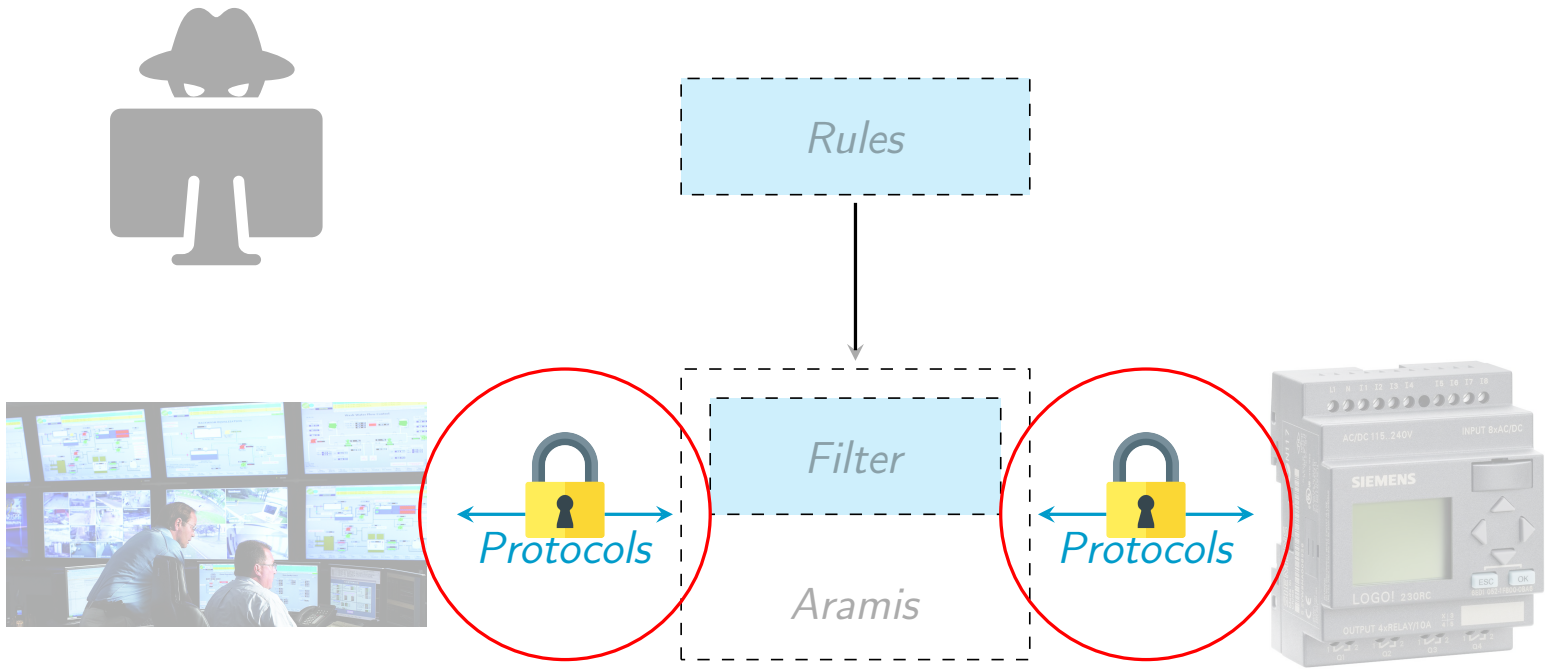


Cryptographic Protocols Verification

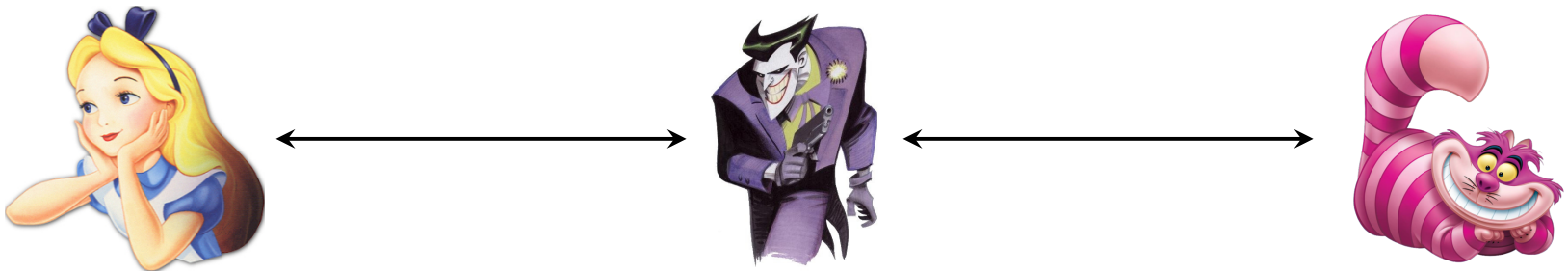
In Maroochy Shire attack, protocols provided no security against attackers:

$\Rightarrow$ Even when providing security feature, crucial to assess security.

Numerous tools exist (e.g.: Tamarin [MSCB13] or ProVerif [Bla01]):

- **Formally** verify the protocol **in presence of attacker** (Dolev-Yao).
- Check secrecy and authentication properties.

$\Rightarrow$ Not used for industrial systems.



Related Works on Verification of Industrial Protocols

Ref	Year	Studied Protocols	Analysis
[CRW04]	2004	DNP3, ICCP	Informal
[DNvHC05]	2005	OPC, MMS, IEC 61850 ICCP, EtherNet/IP	Informal
[GP05]	2005	DNP3	Formal (OFMC)
[IEC15]	2006	OPC-UA	Informal
[PY07]	2007	DNP3	Informal
[FCMT09]	2009	MODBUS	Informal
[HEK13]	2013	MODBUS	Informal
[WWSY15]	2015	MODBUS, DNP3, OPC-UA	Informal
[Amo16]	2016	DNP3	Formal (Petri nets)

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[Amo16]	2016	DNP3	Formal (Petri nets)
[PPL16]	2016	OPC-UA	Formal (ProVerif)
[DPP+17]	2017	MODBUS, OPC-UA	Formal (Tamarin)

Motivations on Studying OPC-UA Security

- Recent (2006), supposedly up to state-of-the-art.
- Probably **next standard** for industrial communications:
  - Designed by a consortium of key stakeholders.

Official specifications: 1000 pages:

- Several terms redefined afterward.
- Highly context dependent.

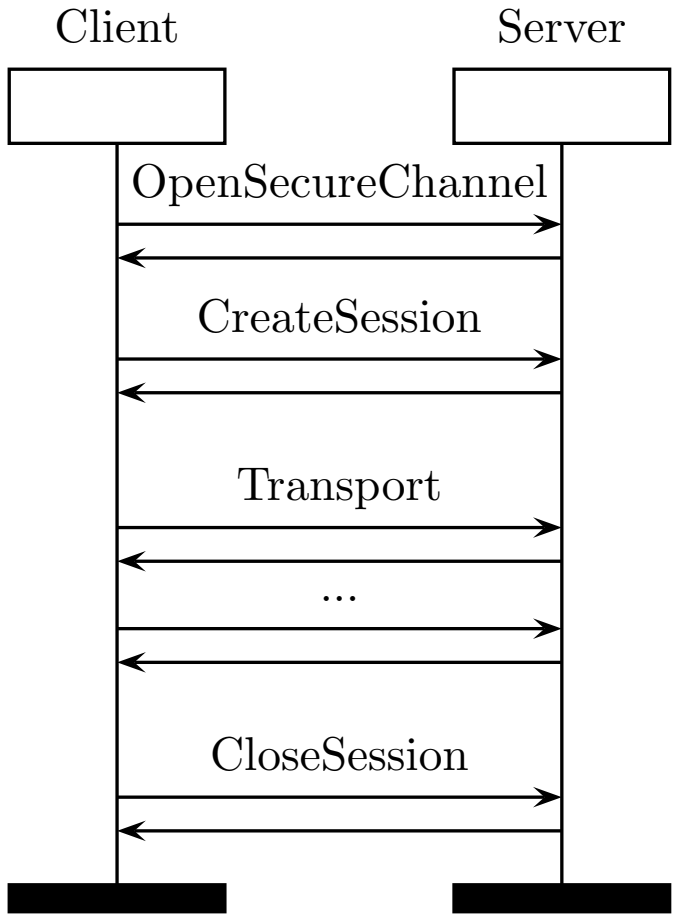
  $\Rightarrow$ Unclear on the use of some **security features**.

Idea: Models from the specifications.

Details on OPC-UA

- **Handshake** protocol followed by **transport** protocol.
- Handshake composed of two sub-protocols.

- Expected security properties different for handshake and transport.



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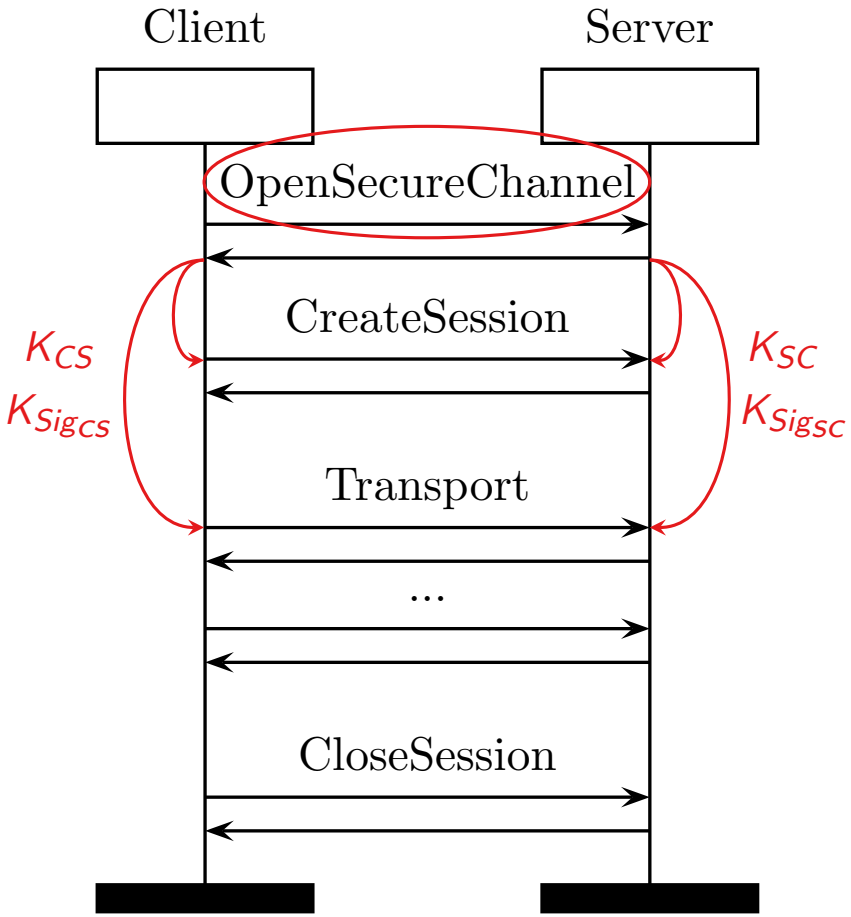

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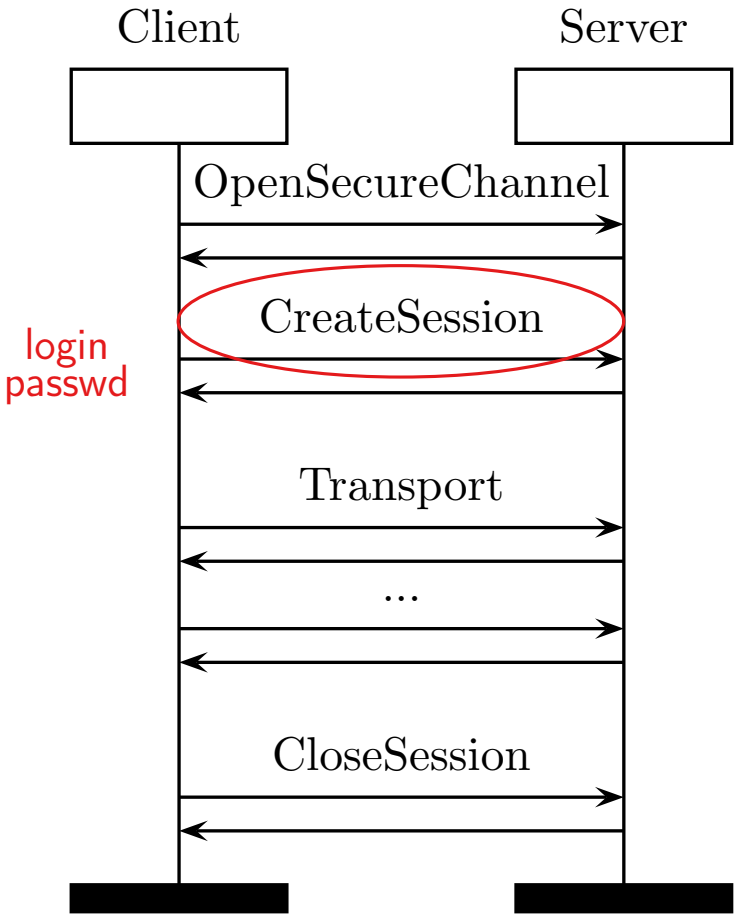

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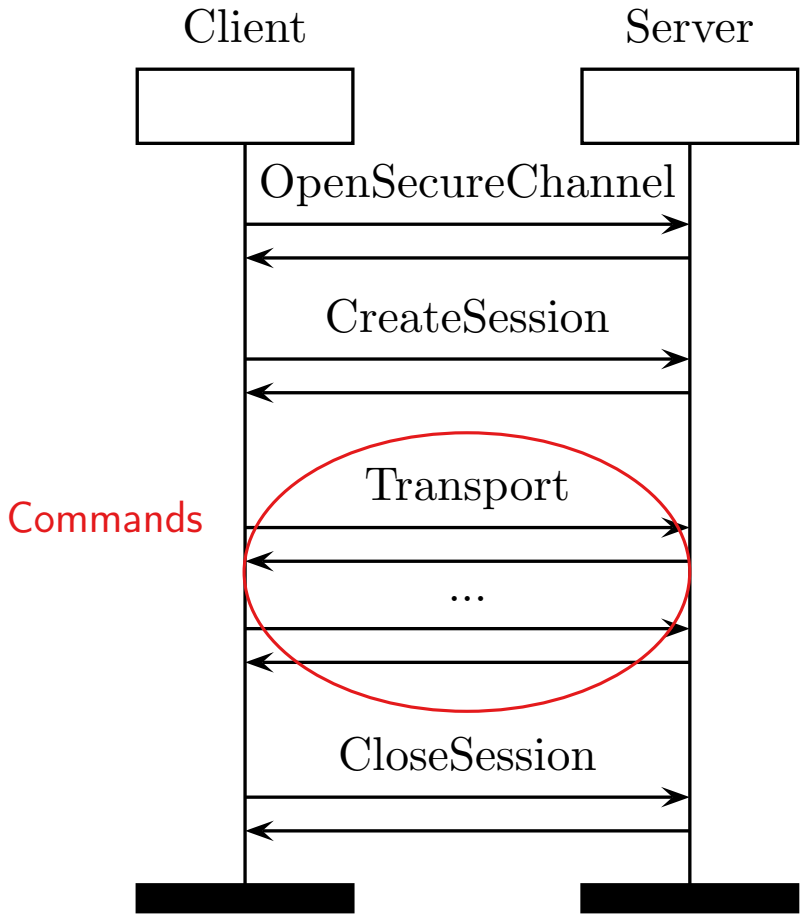


OPC-UA Handshake Analysis

Two attacks found when security features are absent

Reuse of cryptographic signatures, password leaked.
Results communicated to OPC Foundation (specifications later clarified).

Challenges

Three possibles security modes (also considered mixes during analysis).
Combination of secure protocols may not be secure.

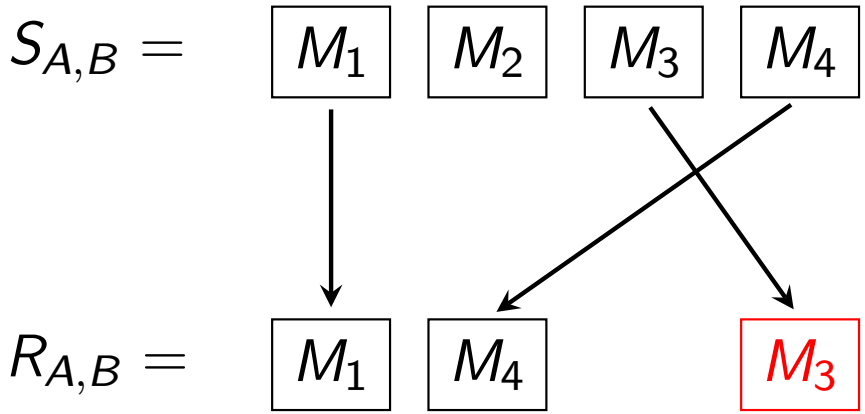
Modeling credentials with ProVerif

verifyCreds(pk(S), Login(pk(C)),Passwd(sk(C), pk(S))) = true.
User policy for password in models.

[Safecomp'16] M. Puys, M-L. Potet, and P. Lafourcade, 2016.

OPC-UA Transport Analysis

Idea: Add properties adapted to transport protocols to the tools.

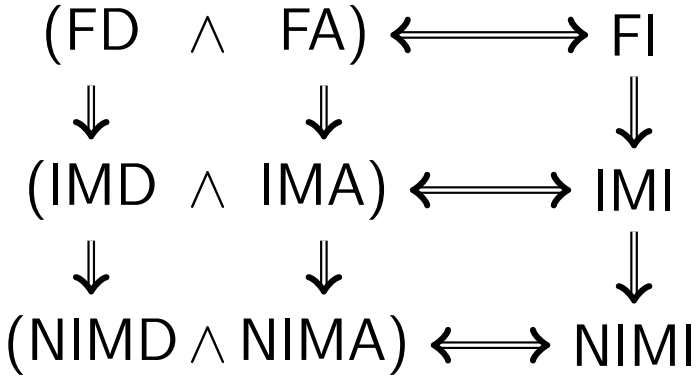


Check inclusion between $S_{A,B}$ and $R_{A,B}$:

- Classical network properties (e.g.: TCP sequence numbers)
  - $\Rightarrow$ Never implemented in protocol verification tools
- Can an intruder **tamper with these sequence numbers**?

[Secrypt'17] J. Dreier, M. Puys, M-L. Potet, P. Lafourcade, and J-L. Roch., 2017.

Flow Integrity Properties



$A \Rightarrow B$ if a protocol ensuring A also ensures B.

Implementation in collaboration with developers of Tamarin:

- Models for **sequences numbers** (i.e.: counters) and **resilient channels**.

Property FA (Flow Authenticity)

« All messages are received in the same order they have been sent. »

$$\begin{aligned}
&\forall i, j : time, A, B : agent, m, m_2 : msg.(\\
&\quad Received(A, B, m)@i \wedge Received(A, B, m_2)@j \wedge i \lessdot j \\
&) \Rightarrow (\exists k, l : time. \\
&\quad Sent(A, B, m)@k \wedge Sent(A, B, m_2)@l \wedge k \lessdot l \\
&)
\end{aligned}$$

Key Takeaways on Flow Integrity

Verification of MODBUS and OPC-UA

Protocol	MODBUS	[FCMT09]	[HEK13]	OPC-UA
Vulnerability	UNSAFE	UNSAFE	SAFE	SAFE

Challenges

In real life, machine integers are bounded and **wrap over**.
If so, all protocols are vulnerable.

$S_{A,B} =$ $\boxed{\begin{matrix} M_1 \\ \text{seq}=1 \end{matrix}}$ $\boxed{\begin{matrix} M_2 \\ \text{seq}=2 \end{matrix}}$ $\boxed{\begin{matrix} M_3 \\ \text{seq}=3 \end{matrix}}$ $\boxed{\begin{matrix} M_4 \\ \text{seq}=4 \end{matrix}}$ $\boxed{\begin{matrix} M_5 \\ \text{seq}=1 \end{matrix}}$

$R_{A,B} =$

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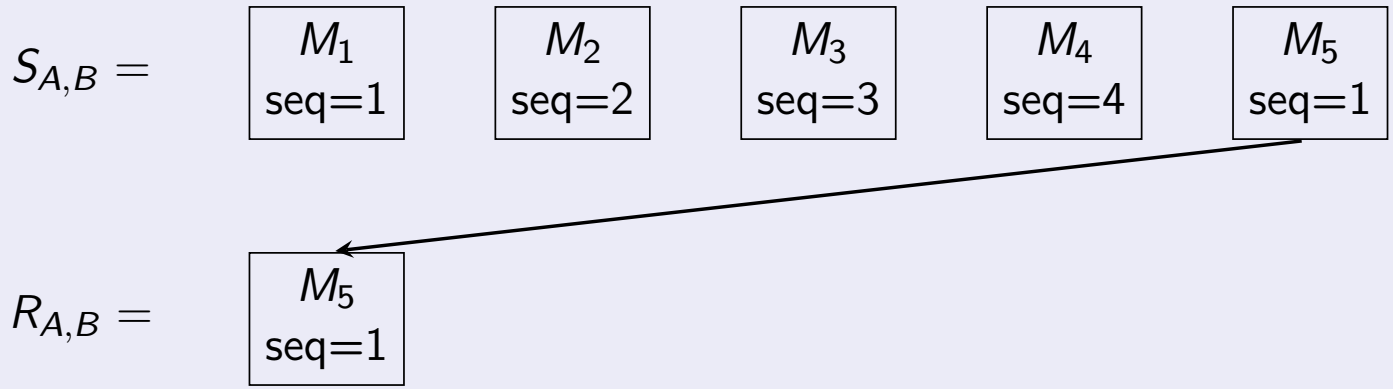

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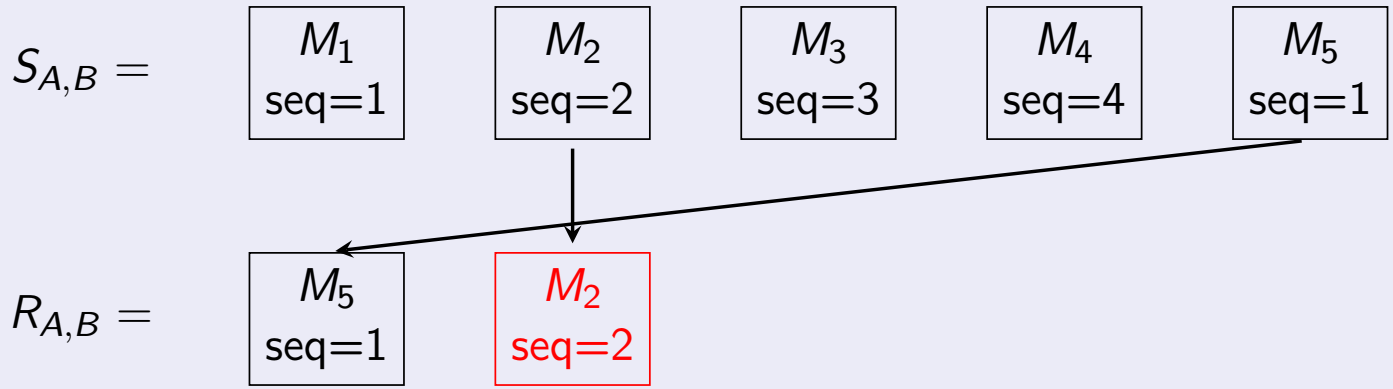
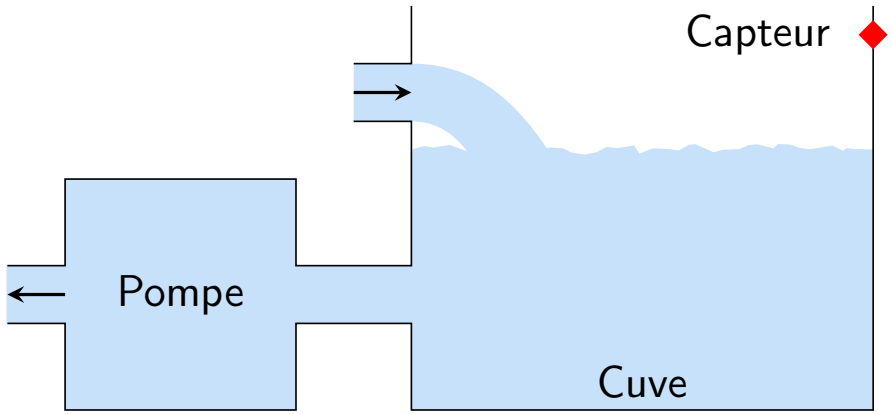


Back to the Common Thread: Maroochy Shire

- **Vulnerability 2:** Absence of authentication mechanism in communication protocols.

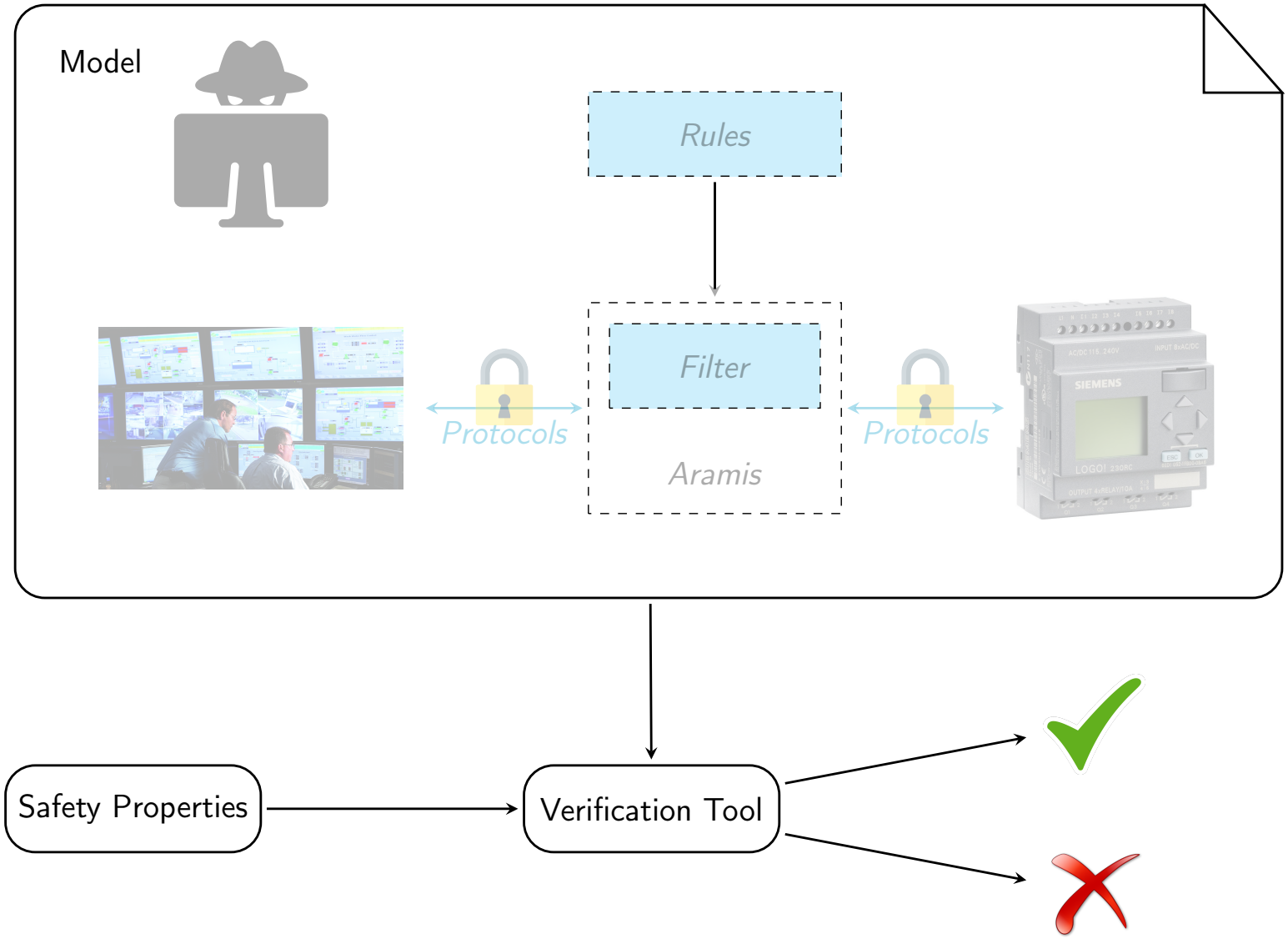


We provided proofs of security for OPC-UA:

$\Rightarrow$ Provides authentication and integrity.

A^2SPICS: Attack Scenarios Generation

Overview of the Thesis



Idea

Effects of Maroochy Shire attack lasted several months, meaning no prevision of attacks:

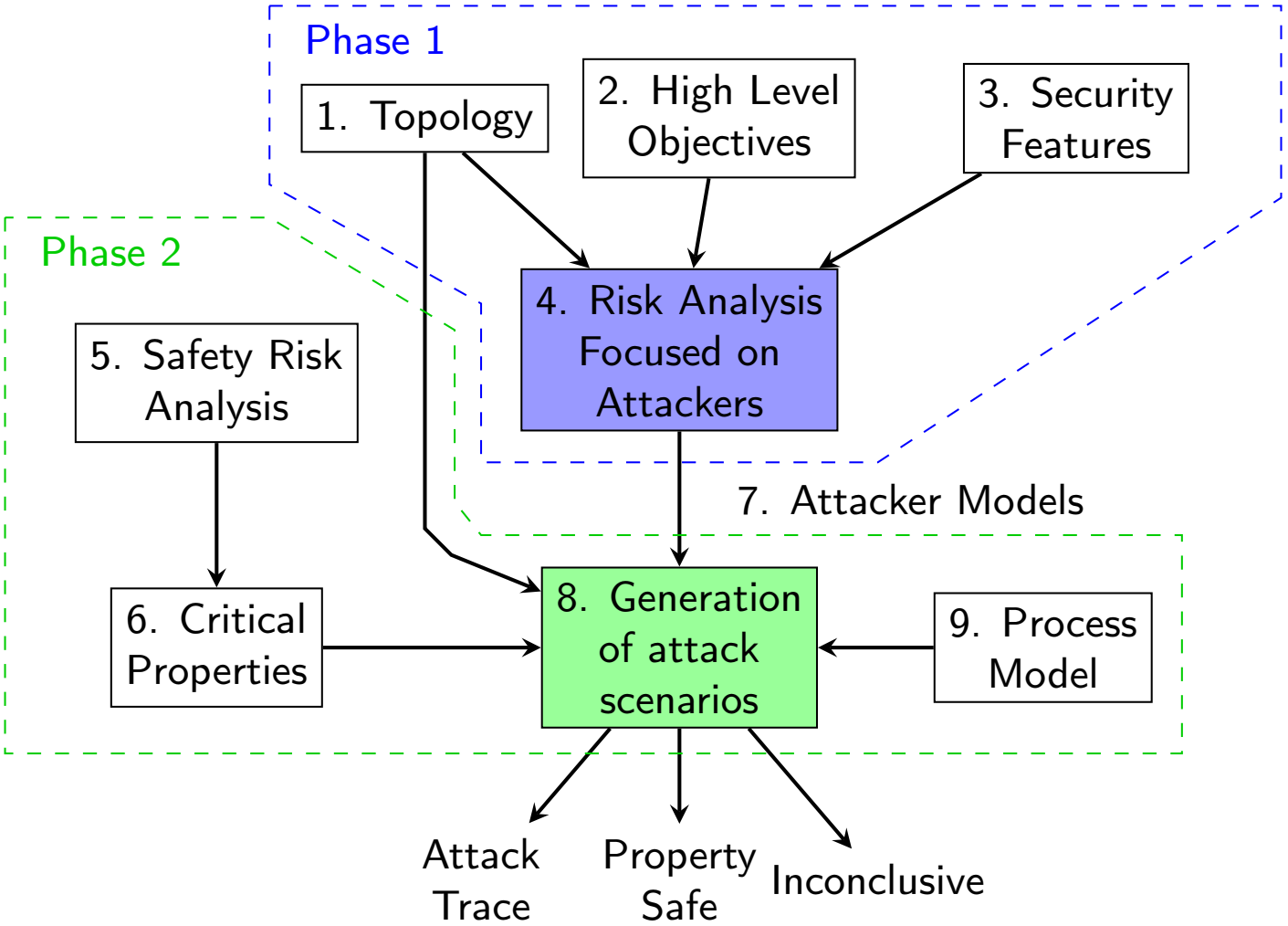
- A^{2}SPICS: Find **applicative attacks** on industrial systems:
  - Considering an attacker already in the system;
  - What possible actions on the industrial process.

Generic verification tools vs. Protocol verification tools

- Generic tools: model-checkers, smt-solvers, etc.
- Protocol verification tools: embed attacker logic.
- Trade-off: tool optimized for verification with attackers vs. states.

[FPS'17] M. Puys, M-L. Potet, and A. Khaled., 2016.

The A^{2}SPICS Approach



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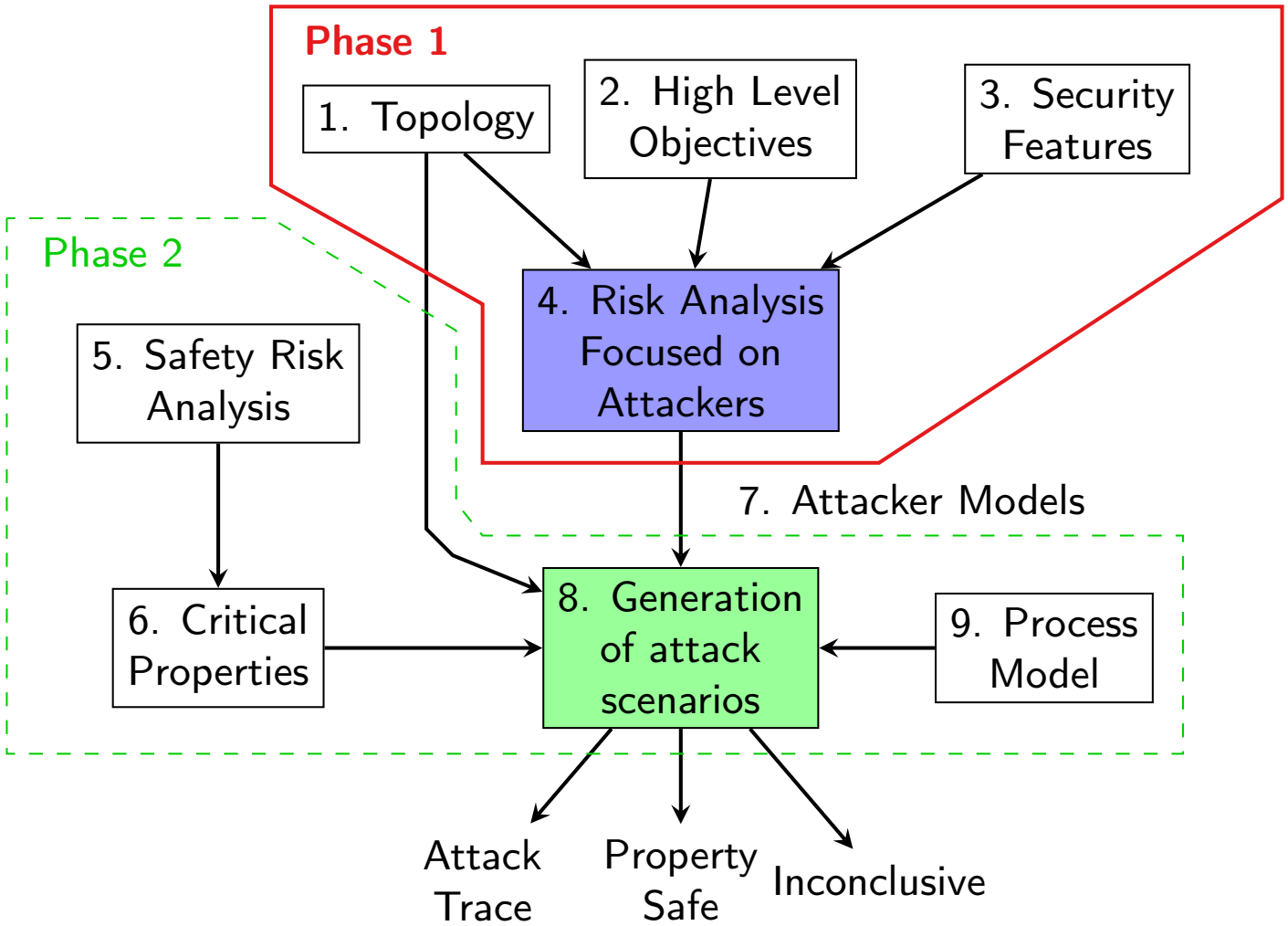
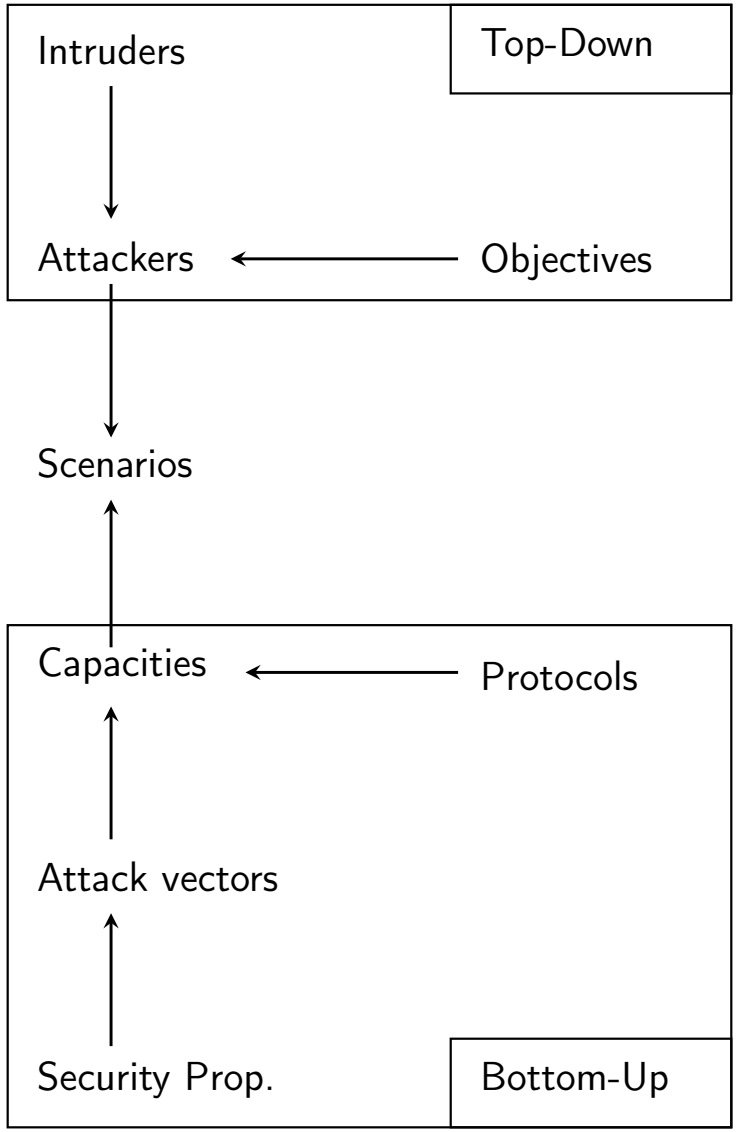


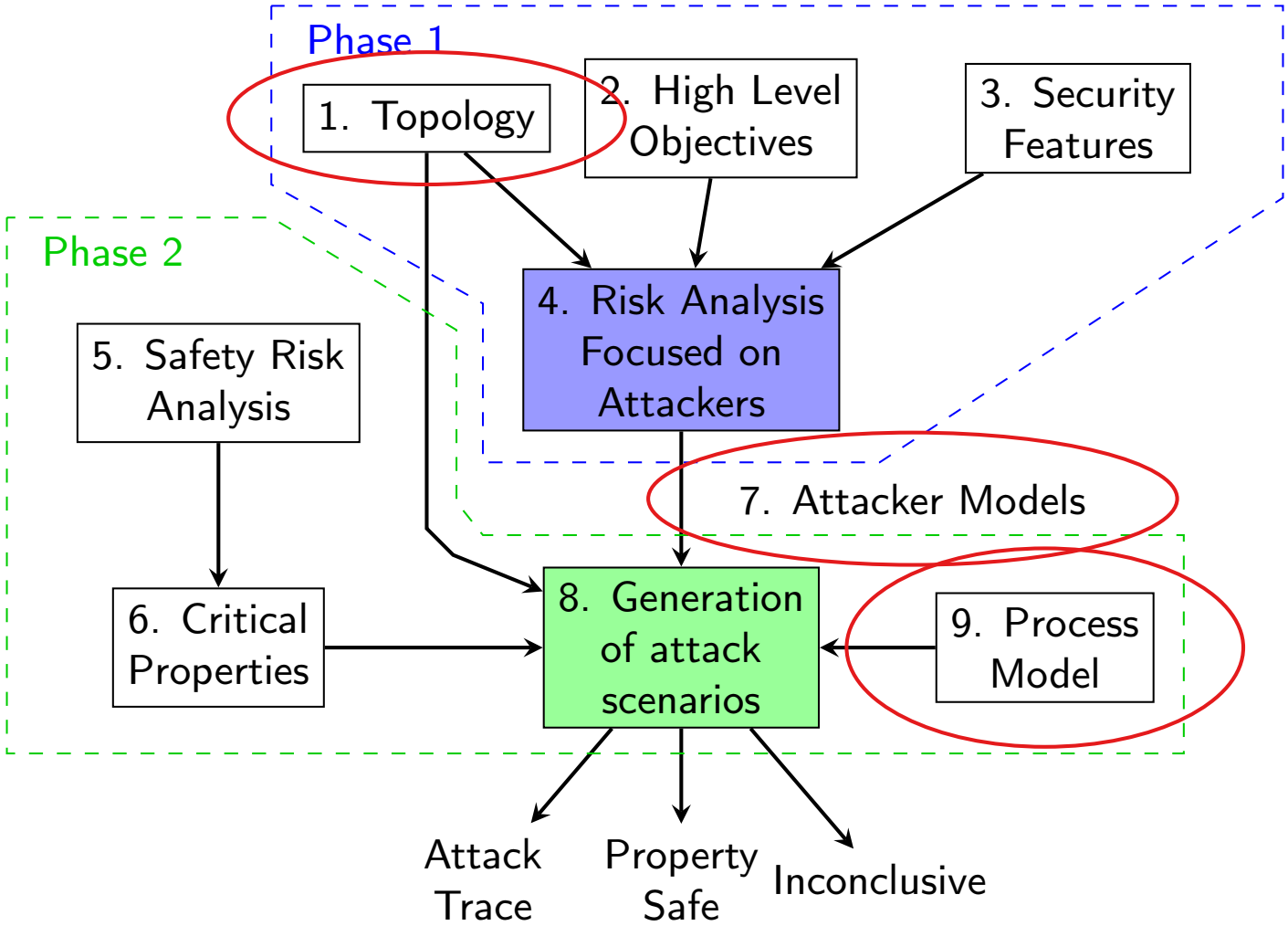
Phase 1: Attacker Models

- Risk analysis focused on attackers.
- Based on:
  - **Topology** of the system;
  - Attacker **objectives**;
  - **Security features** of protocols.
- Objectives are security vuln., e.g.:
  - Modify a message;
  - Circumvent authentication.
- Yields **attacker models** in terms of:
  - Position in the topology;
  - Capacities (actions and deduction).



[AFADL'16] M. Puys, M-L. Potet, and J-L. Roch., 2016.

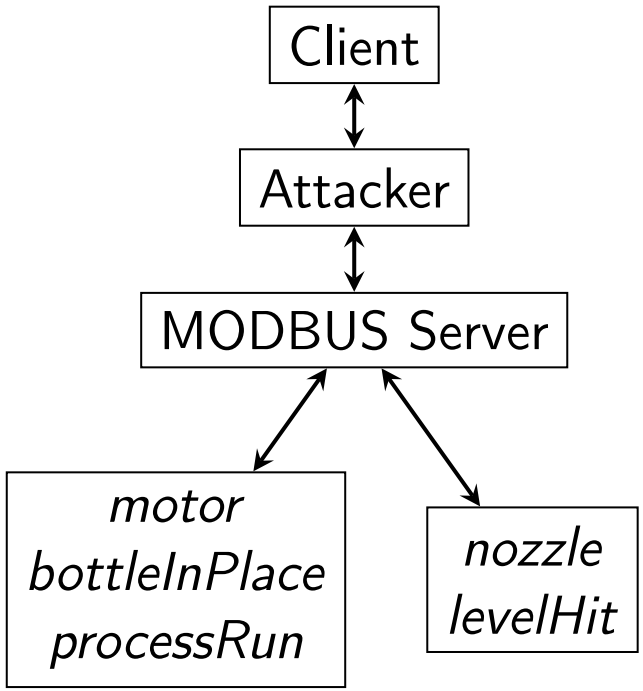
The A^{2}SPICS Approach

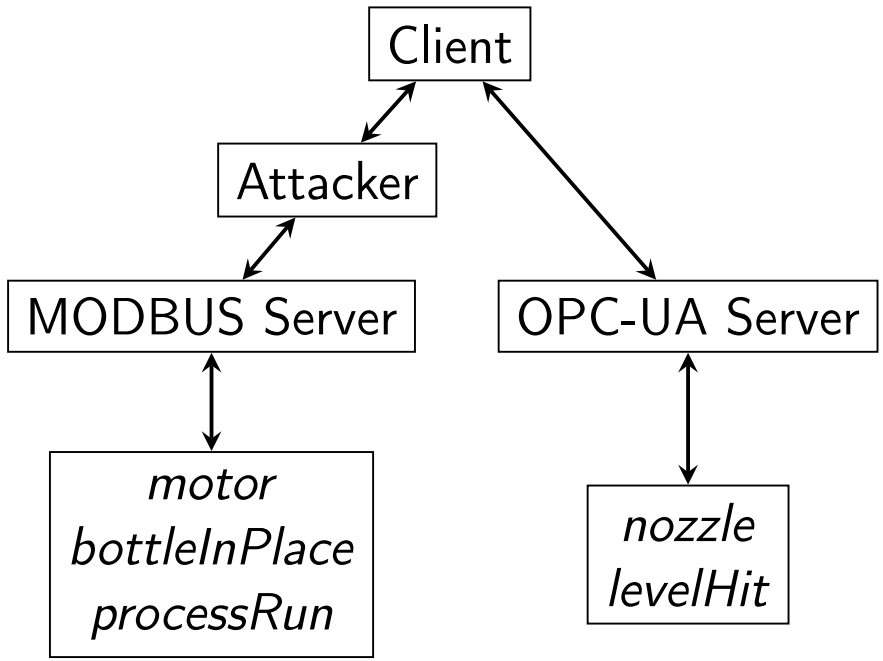


Topologies

Network topology of the system (expressed in CSP, π-calculus, etc):

- **Communication channels** between components;
- **Position** of attackers.



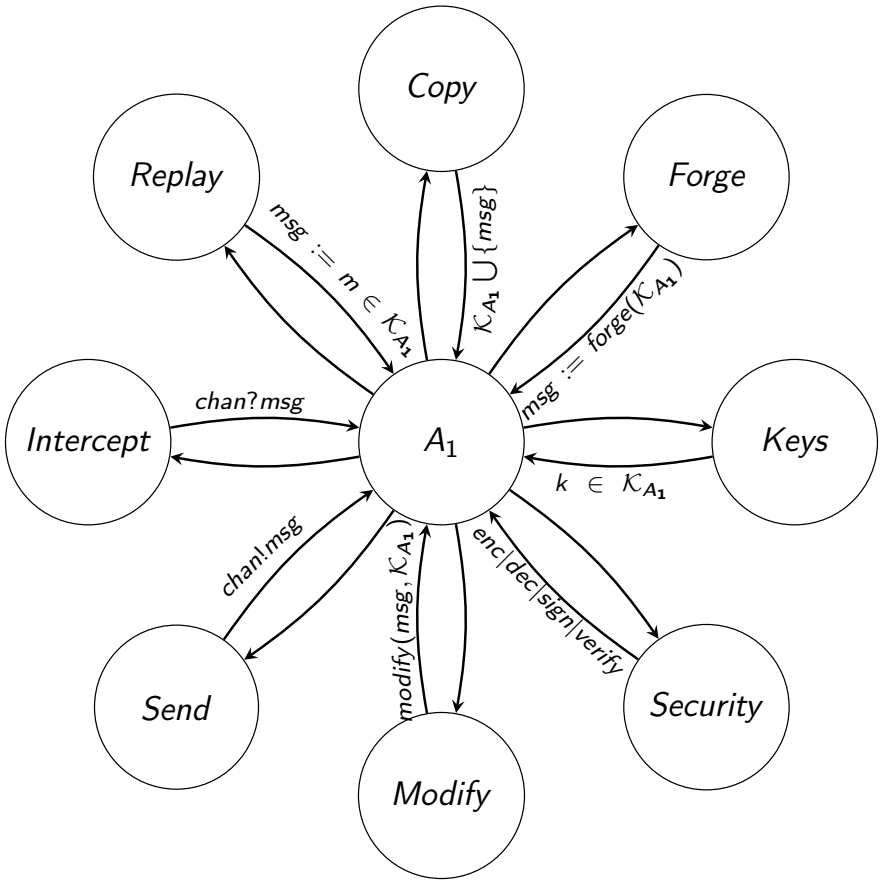


Attackers 1/2

Characterized by:

- **Position** in the topology:
  - On a channel (Man-In-The-Middle);
  - On a corrupted component (virus, malicious operator, etc).
- Capacities:
  - Possible **actions on messages** (intercept, modify, replay, etc);
  - **Deduction system** (deduce new information from knowledge, e.g.: encrypt/decrypt).
- Initial knowledge:
  - Other components;
  - Process behavior;
  - Cryptographic keys, etc.

Attackers 2/2

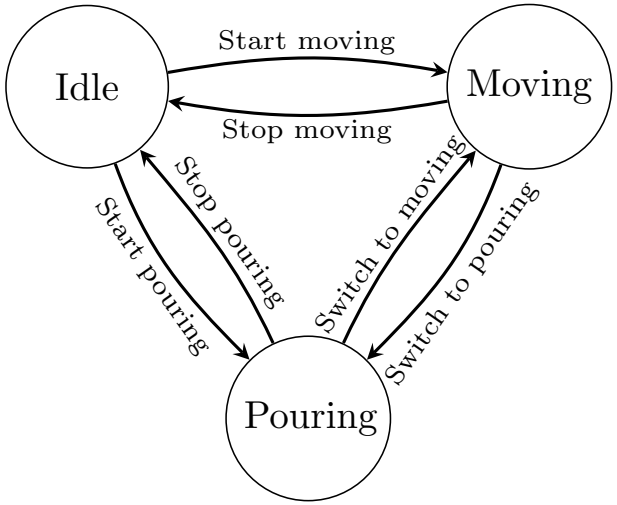


Four attackers:

- A_1 = close to Dolev-Yao;
- As instance, A_2, A_3 and A_4 are subsets of A_1.

Attacker	Modify	Forge	Replay
A_1	✓	✓	✓
A_2	✓	✗	✗
A_3	✗	✓	✗
A_4	✗	✗	✓

Behaviors and Safety Properties



Automaton of the behavior of the process

Current State	Next State	Guard	Actions
Idle	Moving	$processRun = true \wedge bottleInPlace = false$	$motor := true$
Idle	Pouring	$processRun = true \wedge bottleInPlace = true$	$nozzle := true$
Moving	Pouring	$bottleInPlace = true$	$motor := false \wedge nozzle := true$
Pouring	Moving	$levelHit = true$	$motor := true \wedge nozzle := false$
Moving	Idle	$processRun = false$	$motor := false \wedge nozzle := false$
Pouring	Idle	$processRun = false$	$motor := false \wedge nozzle := false$

Transitions Details

Properties: CTL formula:

- Φ_1: At all time and on each path, *nozzle* is never *true* if *bottleInPlace* is *false*). $A\Box \neg(nozzle = true \text{ and } bottleInPlace = false)$
- Φ_2: $A\Box \neg(motor = true \text{ and } levelHit = false)$
- Φ_3: $A\Box \neg(nozzle = true \text{ and } motor = true)$

Instrumentation using Different Tools

Implementation of A^{2}SPICS using 3 different tools:

- UPPAAL:
  - Model-checker, 1994.
  - Mainly designed for timed automata.
    $\Rightarrow$ **Safety** oriented verification tool.

- ProVerif:
  - Protocol verification tool, 2001.
    $\Rightarrow$ **Security** oriented verification tool.
  - Relying on π-calculus and Horn clauses.

- Tamarin:
  - Protocol verification tool, 2012.
    $\Rightarrow$ **Security** oriented verification tool.
  - Relying on Maude-NPA rewriting tool.

Limitations and Difficulties

For all three tools:

- Discretized time and process state (e.g.: tank either empty or full).
- Model limited to variables values.

UPPAAL: Attacker behavior is infinite

- Number of actions per attack is bounded (configurable, classical limitation of model-checking).

ProVerif: Very tedious state modeling

- Requires resilient channels, value enumeration, etc.

Tamarin: Impossible state modeling

- Backward search loops if behaviors has cycles.

Related Works

- Survey on assessment of security in industrial system ([PCB13, KPCBH15, CBB+15]).
- Comparison criteria from [KPCBH15, CBB+15]:

Ref.	Type	Focus	Process model	Probabilistic	Automated
[BFM04]	Model	A	No	No	No
[MBFB06]	Model	A	No	Yes (E)	No
[PGR08]	Model	A	No	Yes (E,H)	No
[TML10]	Model	A	No	Yes (H)	Yes
[CAL+11]	Formula	N/A	Yes	Yes (N/C)	Yes
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[RT17]	Model	A,G	Yes	No	Yes
A^{2}SPICS	Model	A,G	Yes	No	Yes

- [RT17] rely on CI-Atse (protocol verification tool):
  - Dolev-Yao intruder $\Rightarrow$ less precise control on attacker capacities.
- A^{2}SPICS aims at modeling **attackers resulting on risk analysis**.

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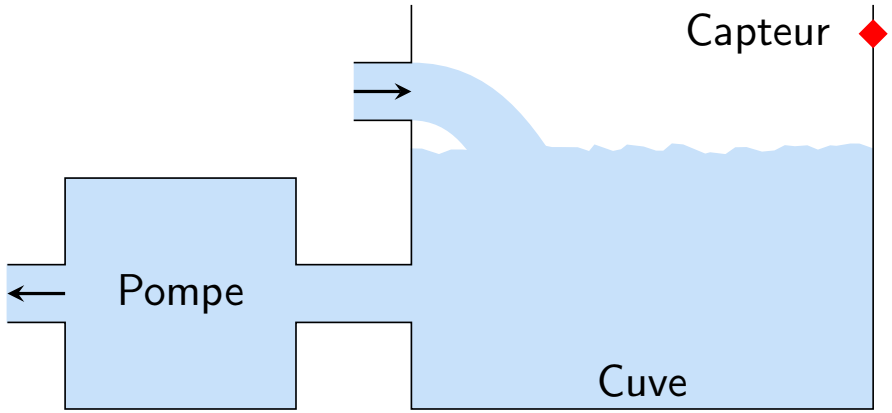
Back to the Common Thread: Maroochy Shire

- **Vulnerability 3:** Absence of prevision of attacks.

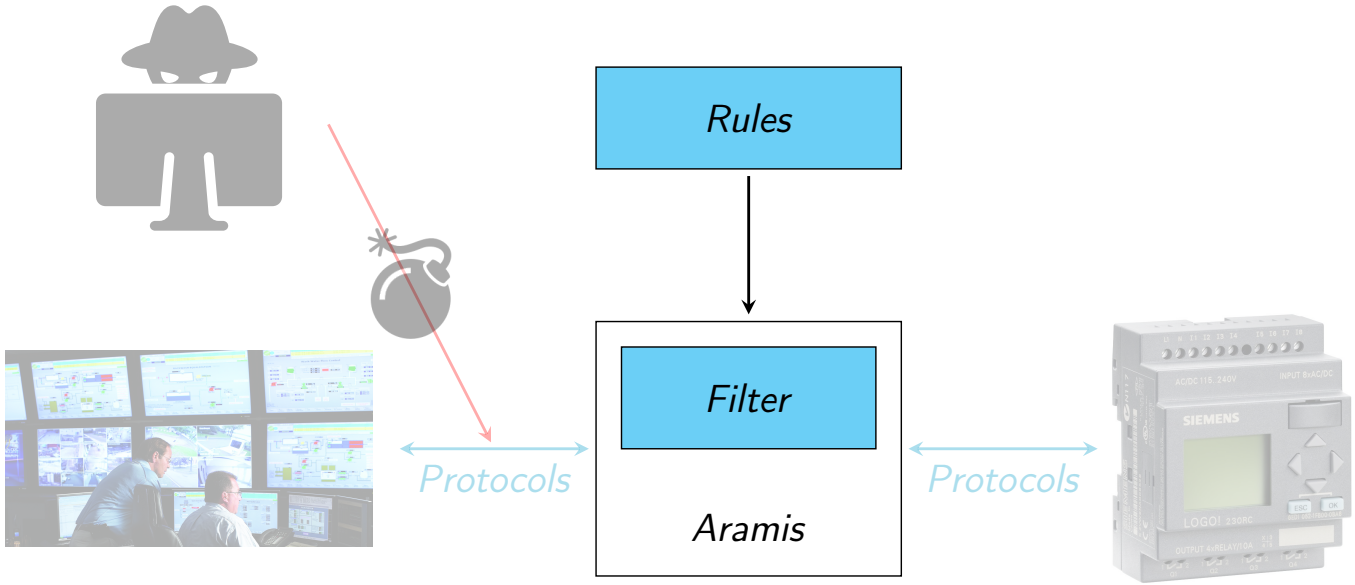


A^{2}SPICS allows to discover possible attack scenarios:

$\Rightarrow$ Counter-measures could have been installed.

Conclusion

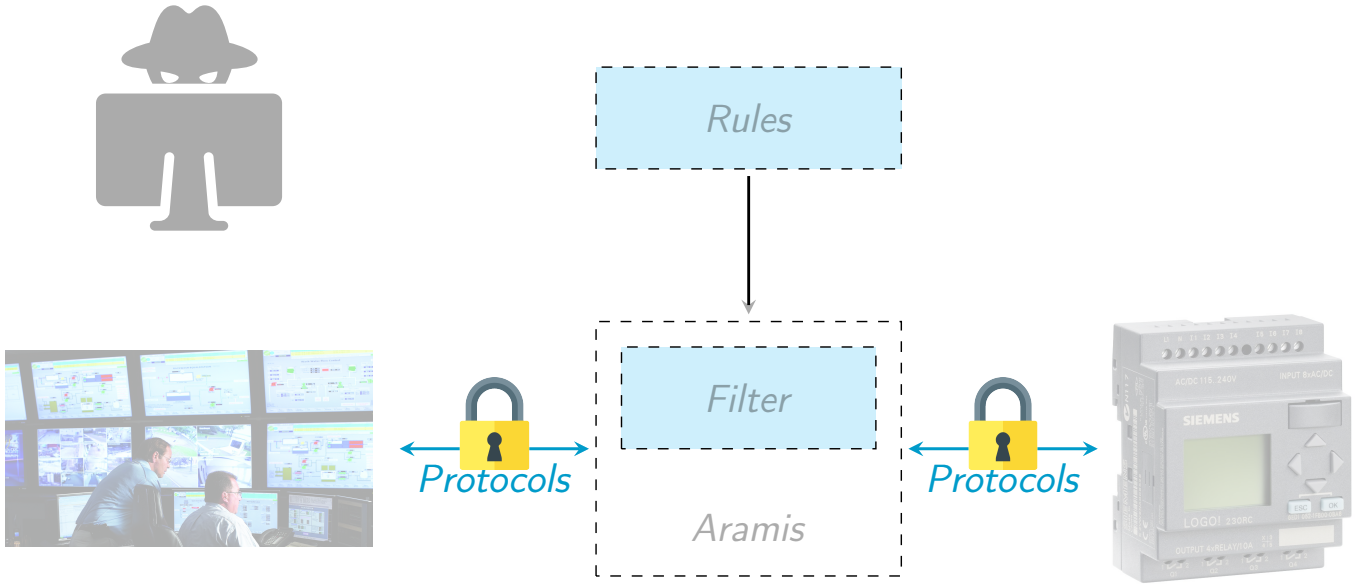
Contributions Summary



Applicative Filtering for Industrial Systems

- Filter development, Python API for rules configuration, embedded system context.

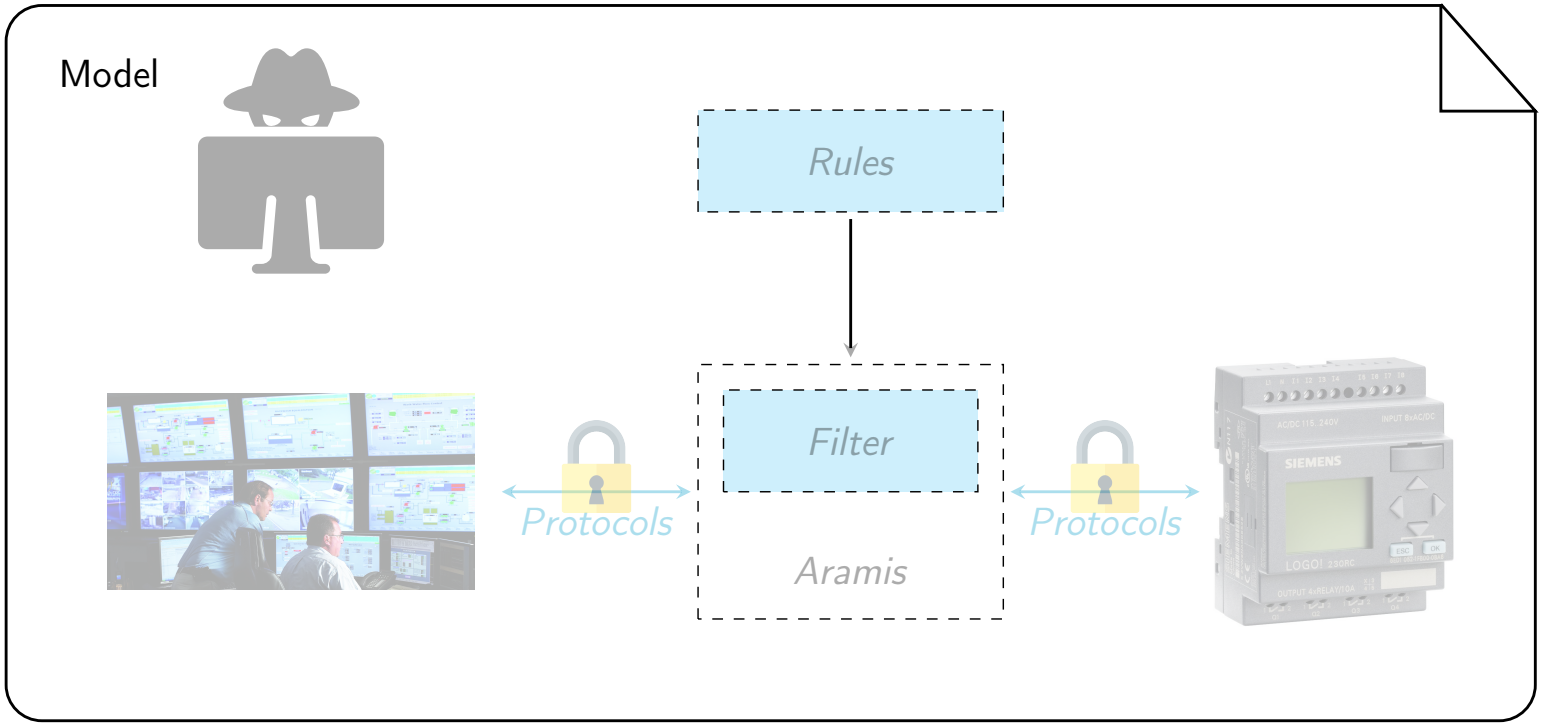
Contributions Summary



Formal Verification of Industrial Protocols

- Formal analysis of two sub-protocols of OPC-UA.

Contributions Summary



A²SPICS: Attack Scenarios Generation

- Analysis of safety properties in case of attackers.
- Experimentations with UPPAAL, ProVerif and Tamarin.

Perspectives

Applicative Filtering for Industrial Systems

- Handle method calls: simulate if method call violate rules ?

Industrial Protocol Verification

- Protocol encapsulation (e.g.: MODBUS through OPC-UA), shared keys, parts not encapsulated, etc.

A^2SPICS: Attack Scenarios Generation

- Scaling up (may require a specially crafted tool).
- Attacker collusions, resilience properties.

Links Between Contributions

Joint Use of Contributions

- Test Filtering deviceusing A^{2}SPICS method.
- Include protocol modeling in A^{2}SPICS method.

Transversal View of Cybersecurity

- Focus on multiple linked security mechanisms:
  $\Rightarrow$ Idea of defence in depth.

Open Challenges

Availability Requirement

- Rising concern with IOT (DynDNS attack, 2016).
- Also a requirement for IT systems.
- Yet among most important requirements for industrial systems.

Software Updates/Patches

- Applying patches often requires to stop/reboot system.
- How to ensure backwards compatibility.
  - Much more easier for IT systems (e.g.: virtualization).

Skill Transfert from Academia to Industry

- Strong bonds with indsutry through ARAMIS.
- Also thanks to projects PEPS CNRS ASSI and ASTRID SACADE.

Conclusion

Thanks for your attention!

Applicative Filtering for Industrial Systems:

- B. Badrignans, V. Danjean, J.-G. Dumas, P. Elbaz-Vincent, S. Machenaud, J.-B. Orfila, F. Pebay-Peyroula, F. Pebay-Peyroula, M.-L. Potet, **M. Puys**, J.-L. Richier, and J.-L. Roch. Security Architecture for Embedded Point-to-Points Splitting Protocols. WCICSS'17, 2017.
- **M. Puys**, J.-L. Roch, and M.-L. Potet. Domain specific stateful filtering with worst-case bandwidth. CRITIS'16, 2016

Industrial Protocol Verification:

- J. Dreier, **M. Puys**, M.-L. Potet, P. Lafourcade, and J.-L. Roch. Formally verifying flow integrity properties in industrial systems. SECRYPT'17, 2017. Best Student Paper Award.
- **M. Puys**, M.-L. Potet, and P. Lafourcade. Formal analysis of security properties on the OPC-UA SCADA protocol. SAFECOMP'16, 2016.

A^{2}SPICS– Attack Scenarios Generation:

- **M. Puys**, M.-L. Potet, and A. Khaled. Generation of applicative attacks scenarios against industrial systems. FPS'17, 2017.
- **M. Puys**, M.-L. Potet, and J.-L. Roch. Génération systématique de scénarios d'attaques contre des systèmes industriels. AFADL'16, 2016

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- J.-G. Dumas, P. Lafourcade, J.-B. Orfila, and **M. Puys**. Dual protocols for private multi-party matrix multiplication and trust computations. Computers & Security, 2017.
- J.-G. Dumas, P. Lafourcade, J.-B. Orfila, and **M. Puys**. Private multi-party matrix multiplication and trust computations. SECRYPT'16, 2016. Best Paper Award.
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Jannik Dreier, Maxime Puys, Marie-Laure Potet, Pascal Lafourcade, and Jean-Louis Roch, *Formally verifying flow integrity properties in industrial systems*, SECRYPT 2017 - 14th International Conference on Security and Cryptography (Madrid, Spain), July 2017, p. 12.


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- Siwar Kriaa, Ludovic Pietre-Cambacedes, Marc Bouissou, and Yoran Halgand, *A survey of approaches combining safety and security for industrial control systems*, Reliability Engineering & System Safety **139** (2015), 156–178.

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Miles A McQueen, Wayne F Boyer, Mark A Flynn, and George A Beitel, *Quantitative cyber risk reduction estimation methodology for a small scada control system*, System Sciences, 2006. HICSS'06. Proceedings of the 39th Annual Hawaii International Conference on, vol. 9, IEEE, 2006, pp. 226–226.


Simon Meier, Benedikt Schmidt, Cas Cremers, and David Basin, *The tamarin prover for the symbolic analysis of security protocols*, Computer Aided Verification (Natasha Sharygina and Helmut Veith, eds.), Lecture Notes in Computer Science, vol. 8044, Springer Berlin Heidelberg, 2013, pp. 696–701 (English).

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Maxime Puys, Marie-Laure Potet, and Pascal Lafourcade, *Formal analysis of security properties on the OPC-UA SCADA protocol*, Computer Safety, Reliability, and Security - 35th International Conference, SAFECOMP 2016, Trondheim, Norway, September 21-23, 2016, Proceedings, 2016, pp. 67–75.


Sandip C Patel and Yingbing Yu, *Analysis of SCADA security models*, International Management Review **3** (2007), no. 2, 68.

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Chee-Wooi Ten, Govindarasu Manimaran, and Chen-Ching Liu, *Cybersecurity for critical infrastructures: Attack and defense modeling*, IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans **40** (2010), no. 4, 853–865.


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Industrial Systems are Ubiquitous

Electricity

Water Treatment

Chemistry

Industrial Systems are Ubiquitous

Electricity

Water Treatment

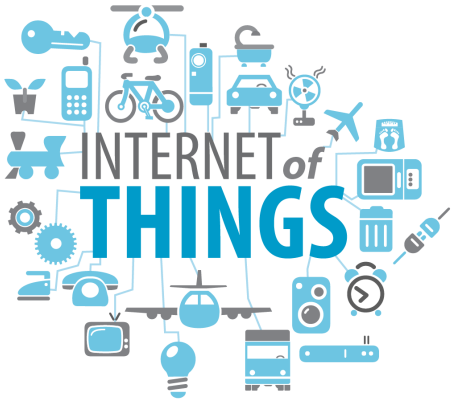
Chemistry

Food Production

Transportation

Healthcare

Industrial Internet of Things



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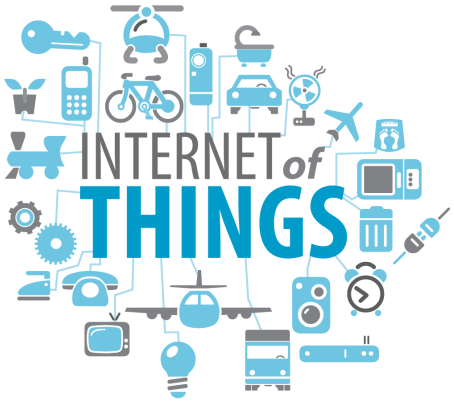


Rio Tinto Mine, Australia

Oil Platform, North Sea

« Smart » Buildings

Autonomous Industrial Systems

Purdue Model

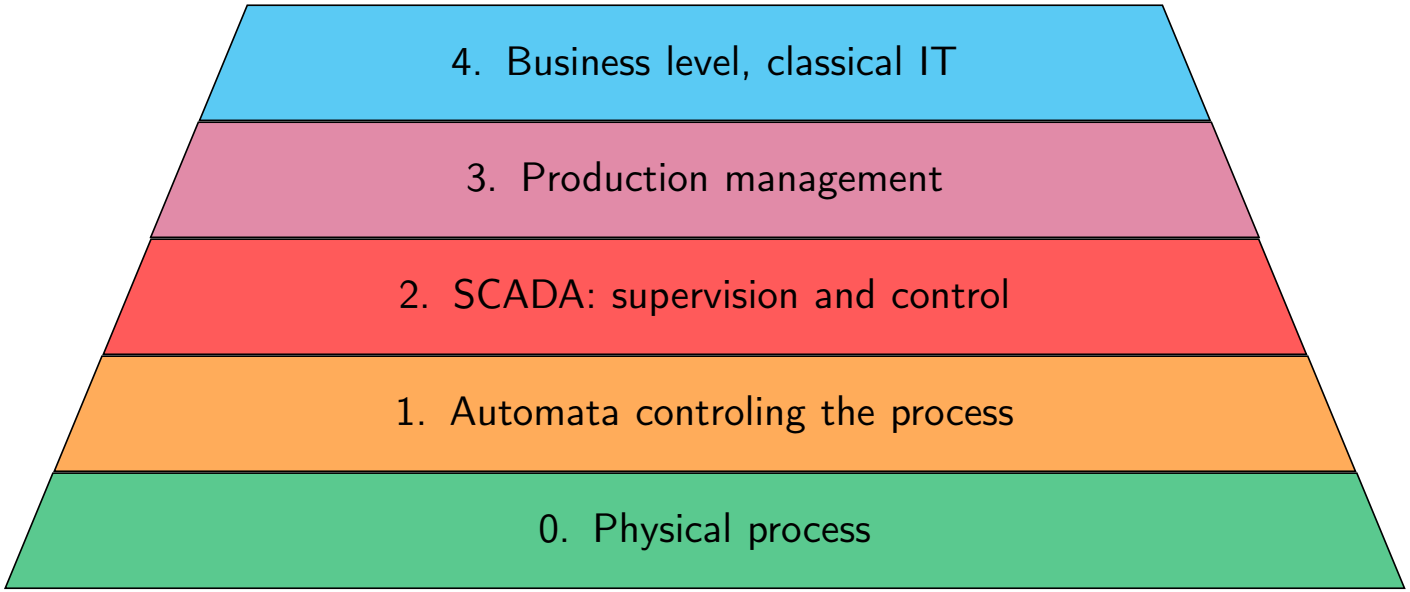


Figure : Purdue model [Wil91]

Norms and Guides on Industrial Systems Security

Generic

ISA-99/IEC-62443 (2007, 2013), ENISA (2011), ISO-27019 (2013), IEC-62541 (2015), etc.

Government Agency

CPNI (2008), BSI (2009), NIST (2011), ANSSI (2012), etc.

Domain Specific

Oil/Gaz (AGA, 2006), Electricity (IEC-62351, 2007]), Nuclear (IEC-62645, 2008), Air Traffic (CSFI, 2015), Railways (RSSB, 2016), etc.

Key Takeaways

$\Rightarrow$ Lots of documents, mainly released since 2006. Balanced partition between industry and governments, often in collaboration.

Properties to Ensure

For the process

Availability: System keeps running.

Integrity: Preservation of the coherence of a data over time.

Authenticity: An entity is who he/she pretends.

Non-repudiation: One cannot deny its actions.

Dependability: Domain specific properties.

For customer data

Confidentiality: Only authorized entities can access designated data.

Anonymity: Prevent linking a data with its owner.

Different Attackers



Different Attackers

Different Attackers

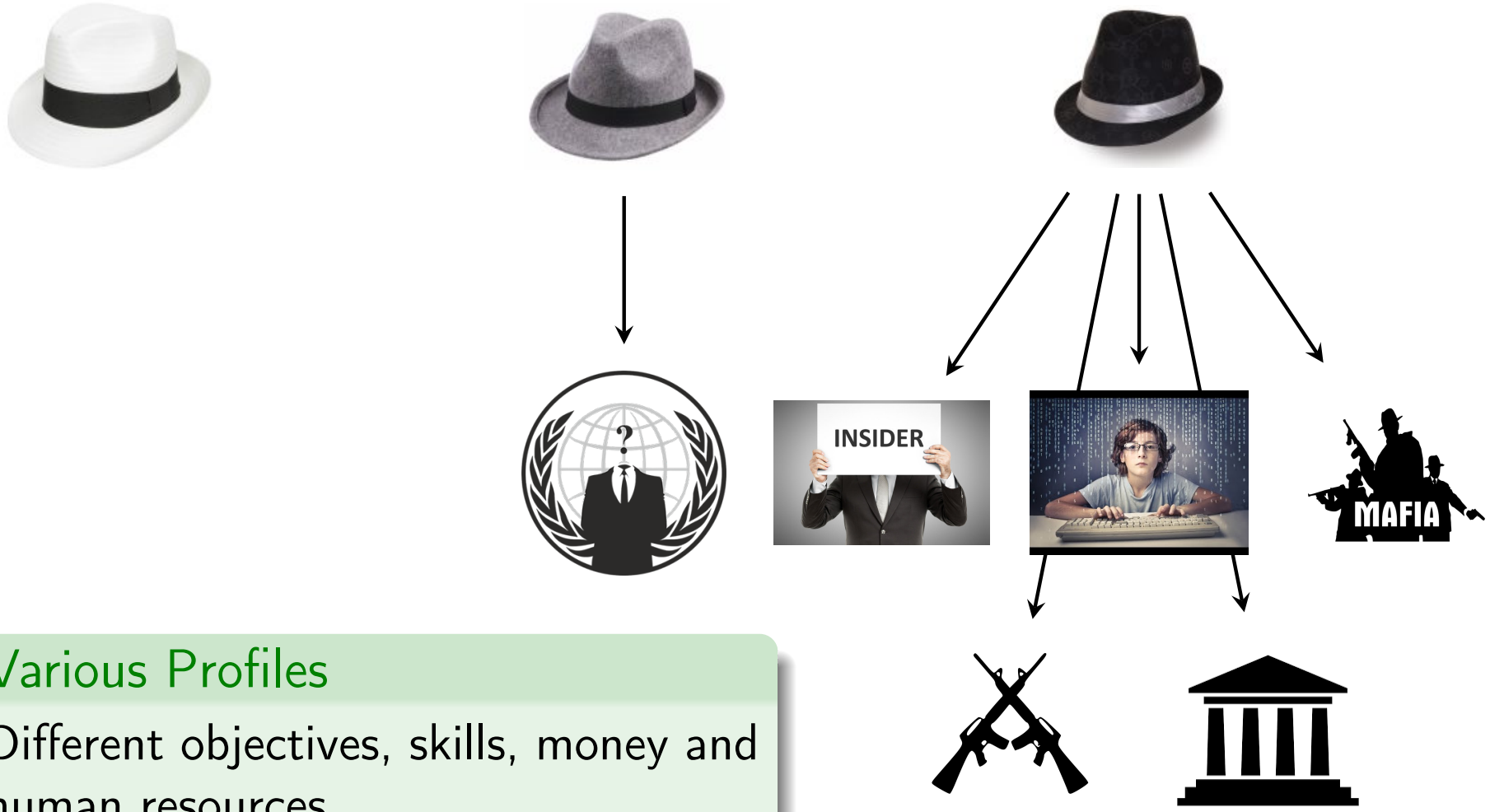
Different Attackers

Different Attackers

Different Attackers

Different Attackers

Different Attackers



Various Profiles

Different objectives, skills, money and human resources.

Worst-Case Bandwidth

Both conditions and actions have to be processed in constant time:

- Conditions are O(1) boolean predicates.
- Actions are : (i) Block or transmit the message, (ii) Log information, (iii) Update a local variable,

Thus processing one command only depends on the number of rules:

- For all predicates P, worst case processing time T of a message is $T = \sum \tau_i n_i$
- With τ_i the processing time of predicate P_i
- And n_i number of occurrences of predicate P_i

In practice, as only relevant rules are tested for a message.
Worst-case happens for an accepted message.

Open Secure Channel Sub-Protocol

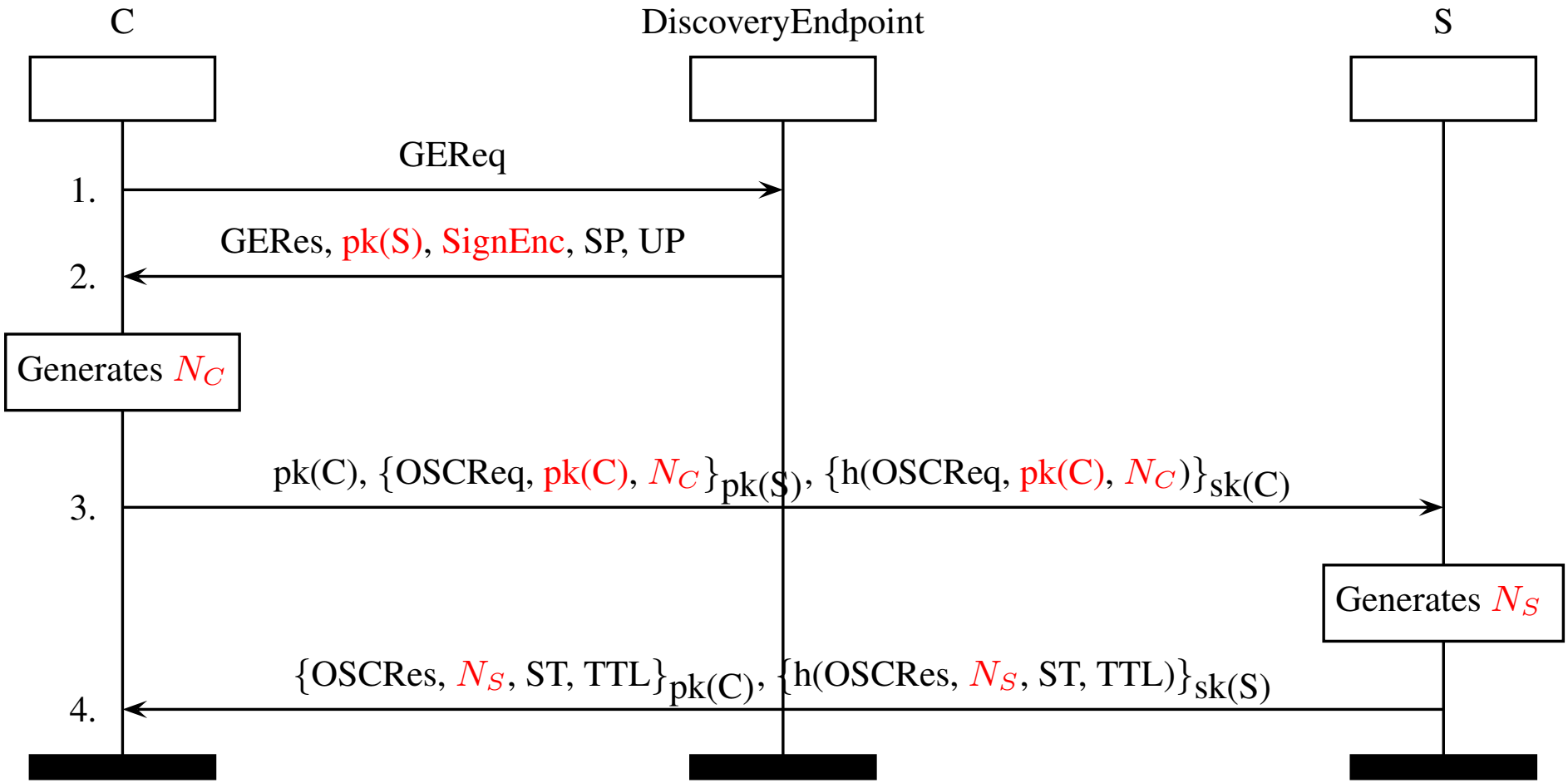


Figure : OPC-UA OpenSecureChannel

Nonce: random value for freshness or challenges/responses.

Modeling Hypotheses

- Normally, several responses to a GetEnpointRequest.
  - We suppose that the client receives and accepts a single one.
  - We tried all possible combinations.
- Client's and server's certificates are modeled by their public keys.
  - Common practice since other fields are out of the scope of tools.
- The intruder can be legitimate clients or servers (e.g.: corrupted devices, malicious operators, etc).
  - Increasing the power of the intruder.
- Objectives:
  - Secrecy of the generated keys (K_{CS}, K_{SC}) from N_C and N_S.
  - Authentication on exchanged nonces N_C and N_S.

Attack on Authentication on N_C in SignAndEncrypt

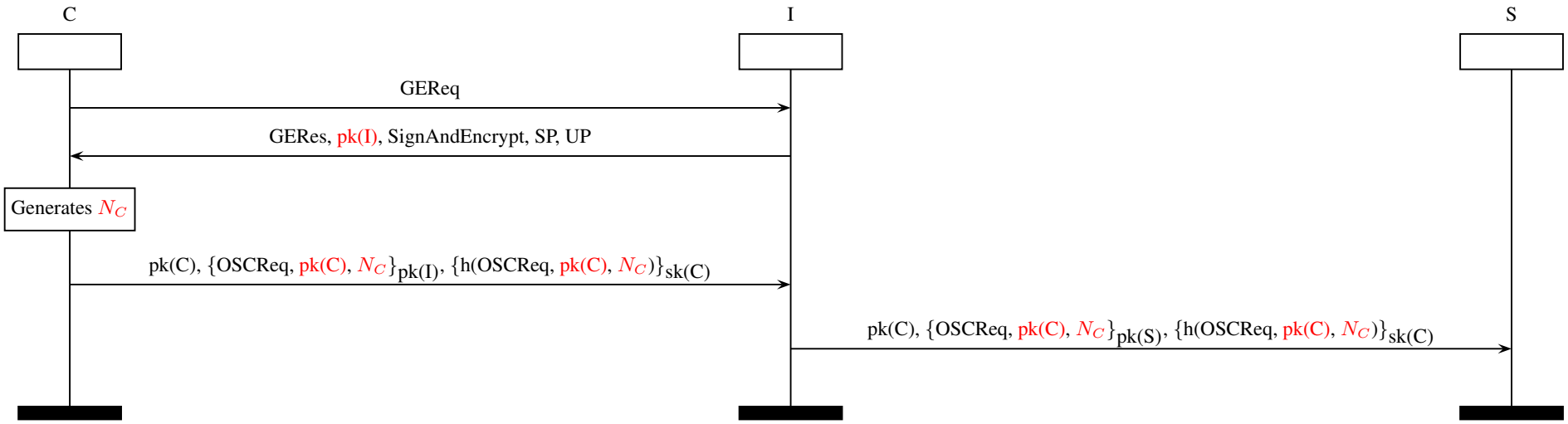


Figure : Attack on OPC-UA OpenSecureChannel

A message can be replayed because receiver is not mentioned in signature.

Create Session Sub-Protocol

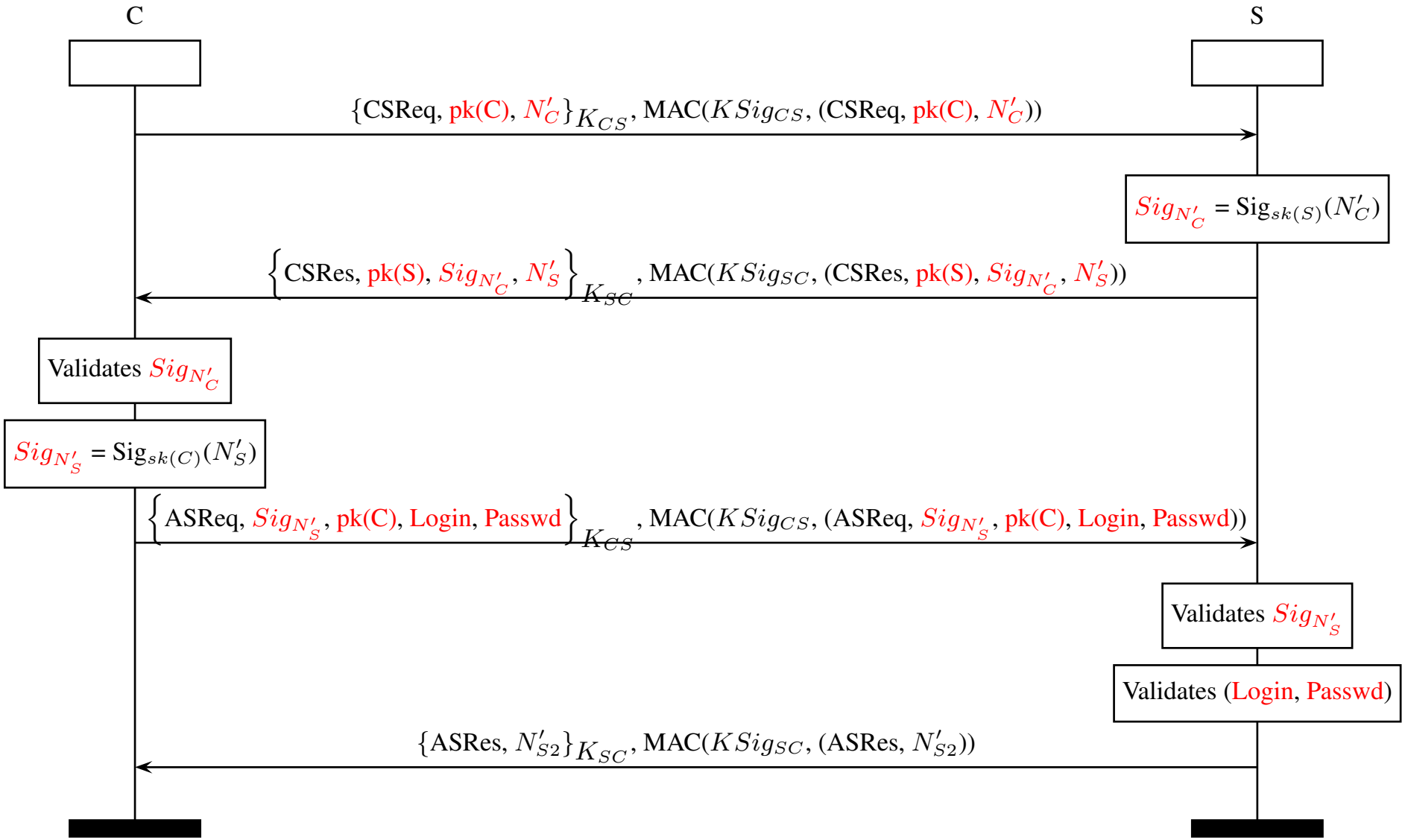


Figure : OPC-UA CreateSession

Non-Injective Message Authenticity (NIMA)

Property

« **All messages received have been sent.** »
A protocol ensures Non-Injective Message Authenticity (NIMA) between sender A and receiver B if $\textbf{\textit{set}}(R_{A,B}) \subseteq \textbf{\textit{set}}(S_{A,B})$.

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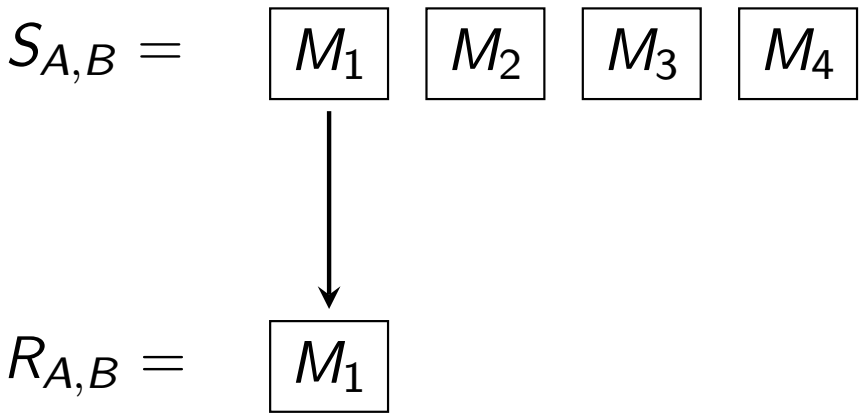

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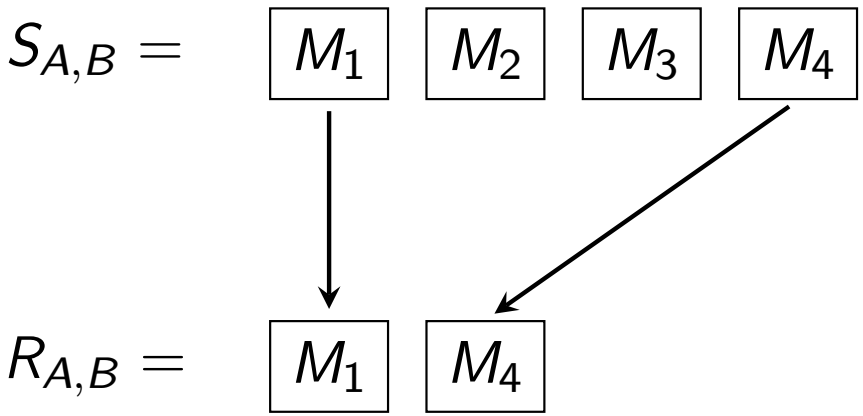

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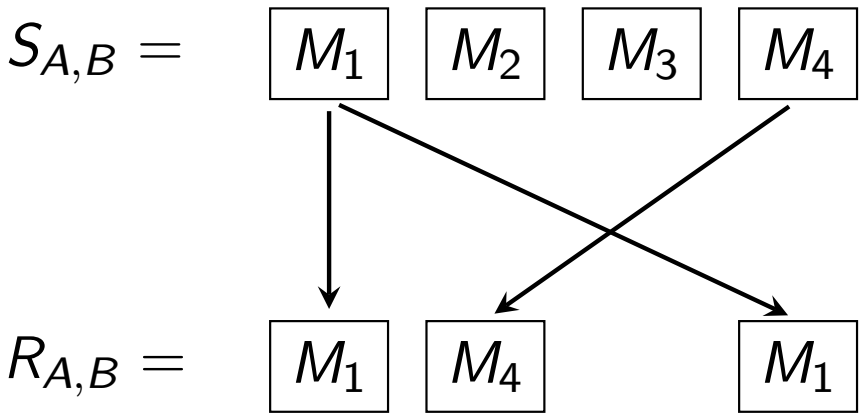

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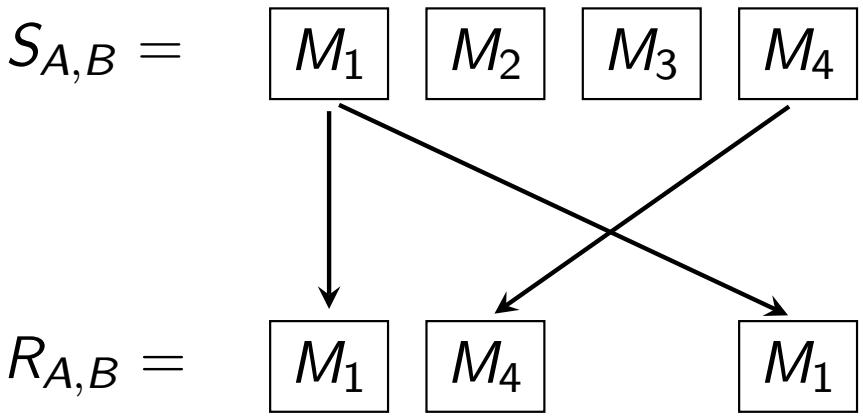

✓ NIMA verified

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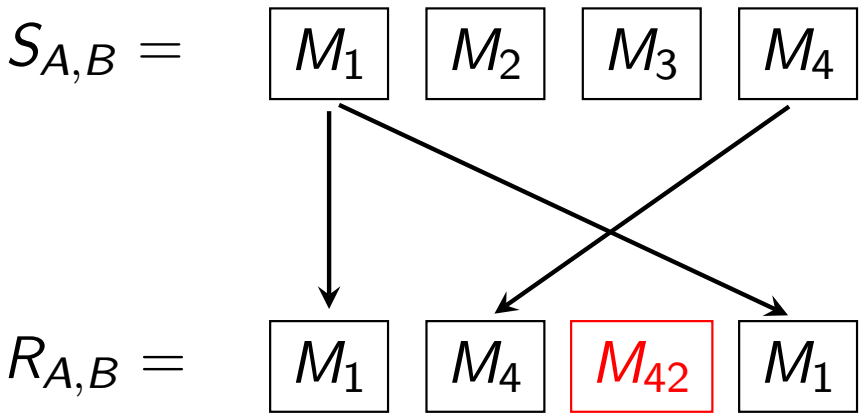

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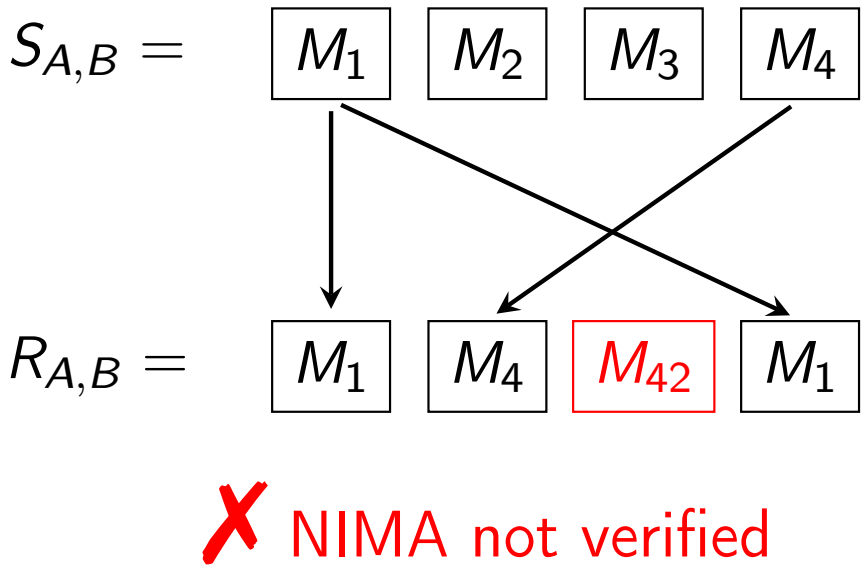

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Injective Message Authenticity (IMA)

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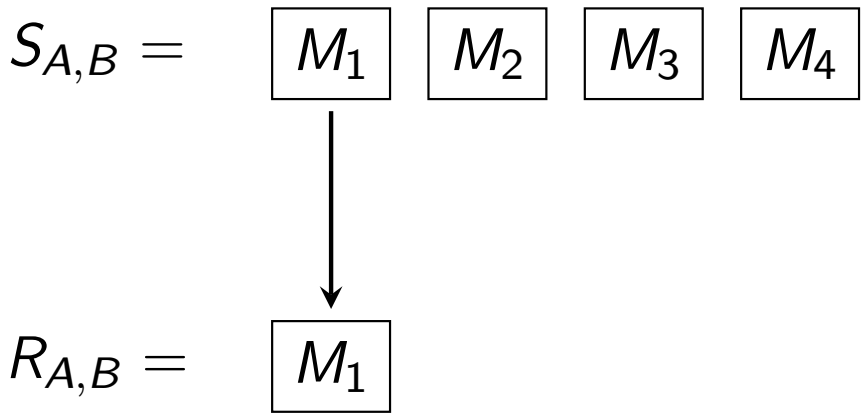

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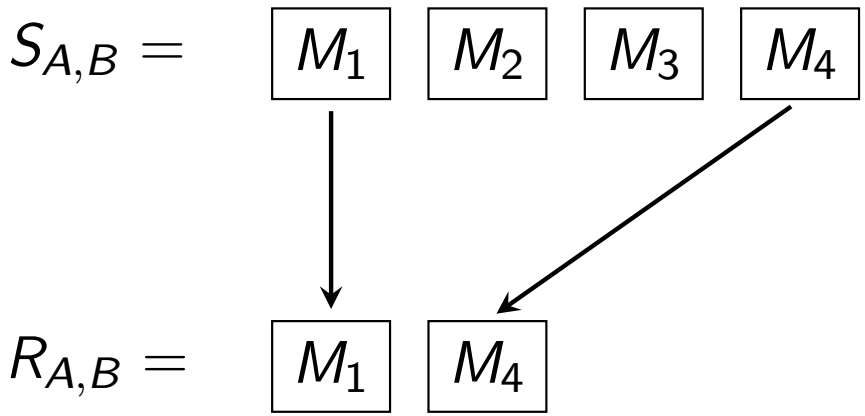

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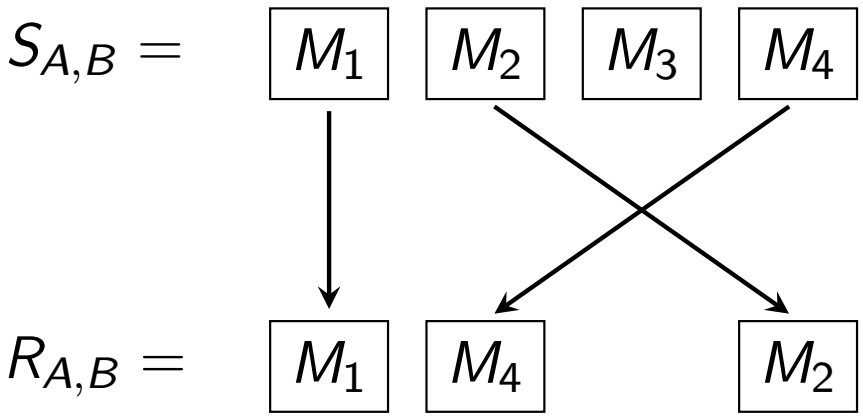

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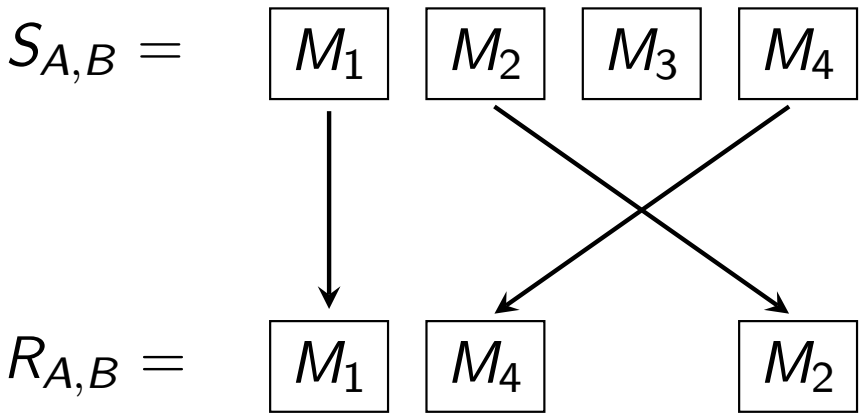

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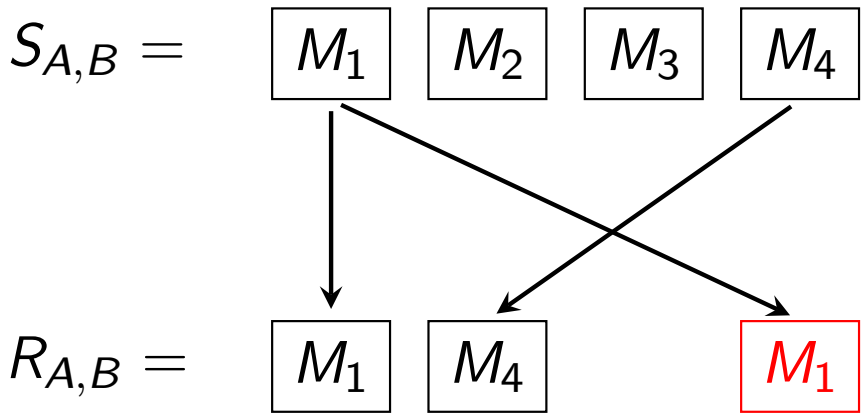

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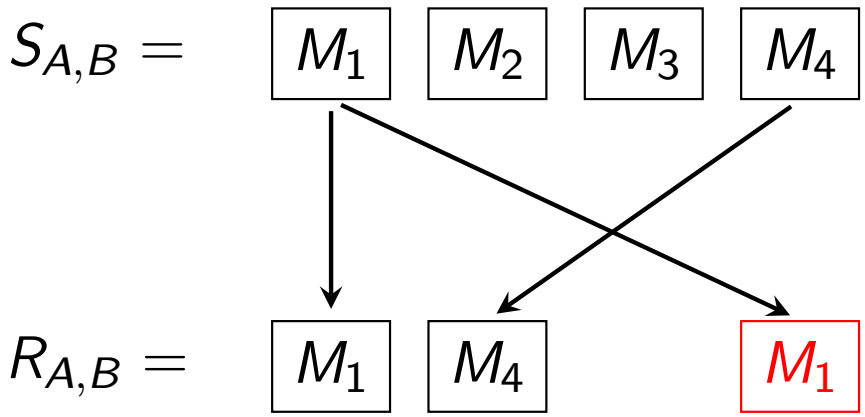

✗ IMA not verified

Flow Authenticity (FA)

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« **All messages are received in the order they have been sent.** »
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$$S_{A,B} = \boxed{M_1}\ \boxed{M_2}\ \boxed{M_3}\ \boxed{M_4}$$

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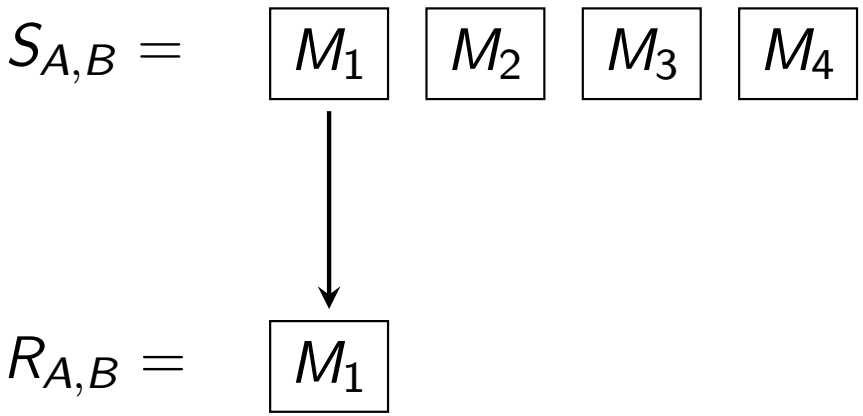

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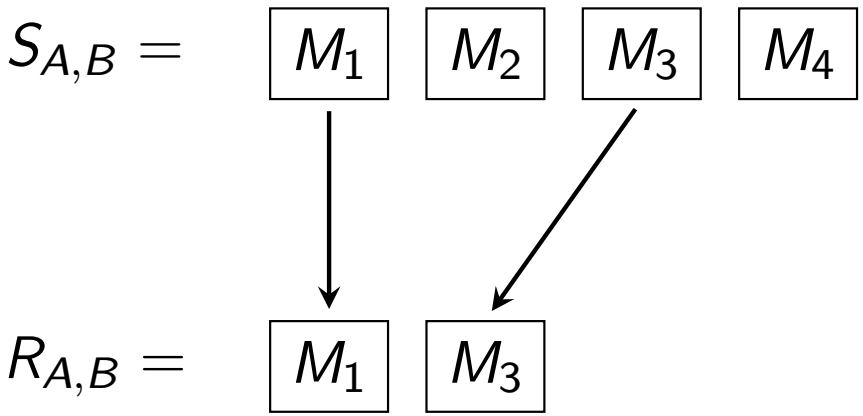

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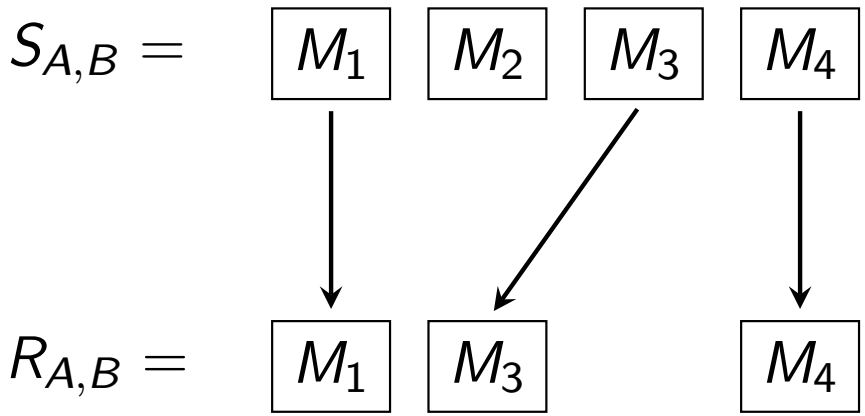

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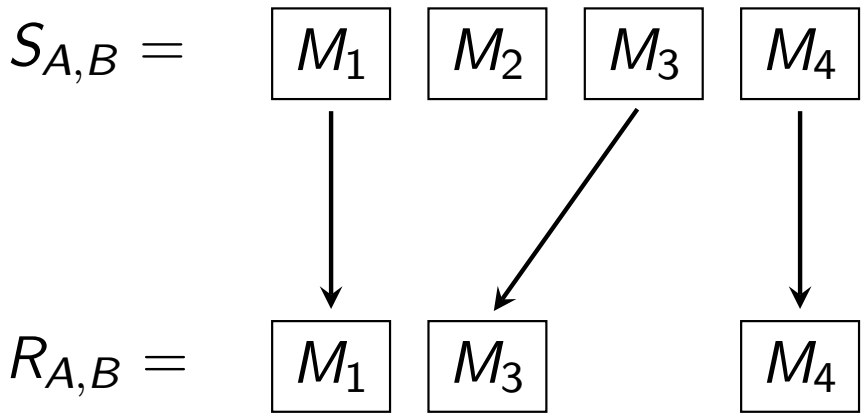

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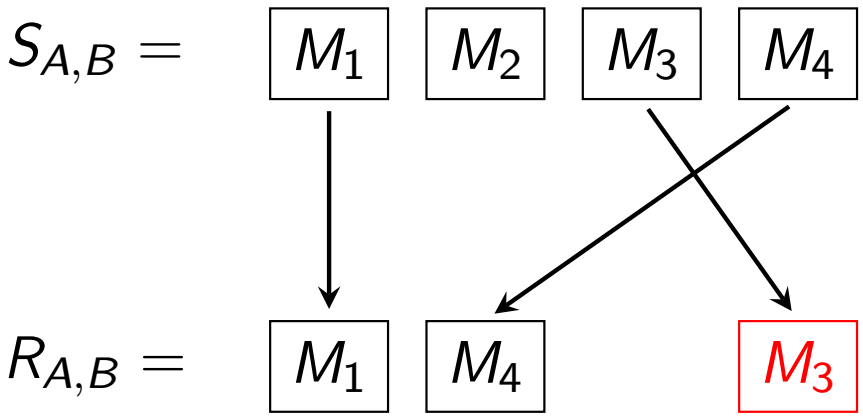

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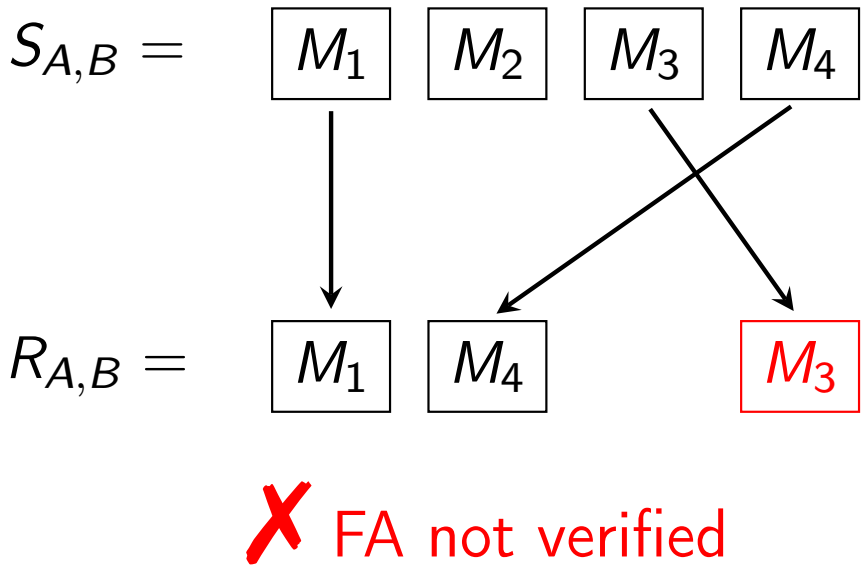

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« All messages received have been sent. »

$$\forall i : time, A, B : agent, m : msg.$$
$$Received(A, B, m)@i \Rightarrow ($$
$$\exists j : time.Sent(A, B, m)@j \wedge j \lessdot i$$
$$)$$

Injective Message Authenticity (IMA)

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« All messages received n times have been sent n times. »

$$
\begin{aligned}
&\forall i : \mathit{time}, A, B : \mathit{agent}, m : \mathit{msg}.\\
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&\qquad \exists j.\mathit{Sent}(A, B, m)@j \wedge j \lessdot i \wedge \neg(\\
&\qquad\quad \exists i2 : \mathit{time}, A2, B2 : \mathit{agent}.\\
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&\qquad)\\
&\quad)
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« All messages are received in the same order they have been sent. »

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$$\quad Received(A, B, m)@i \wedge Received(A, B, m_2)@j \wedge i \lessdot j$$
$$) \Rightarrow (\exists k, l : time.$$
$$\quad Sent(A, B, m)@k \wedge Sent(A, B, m_2)@l \wedge k \lessdot l$$
$$)$$

Resilient Channels

- Dolev-Yao intruder can block message, thus delivery is always false!
- Enforce intruder that all messages are eventually delivered.
- Security properties do not hold vacuously (still allows duplicating, reordering, delaying, forging).

$$\forall i : time, m : msg.Ch\_Sent(m)@i$$
$$\Rightarrow (\exists j.Ch\_Received(m)@j \wedge i \lessdot j)$$

Top-Down Example

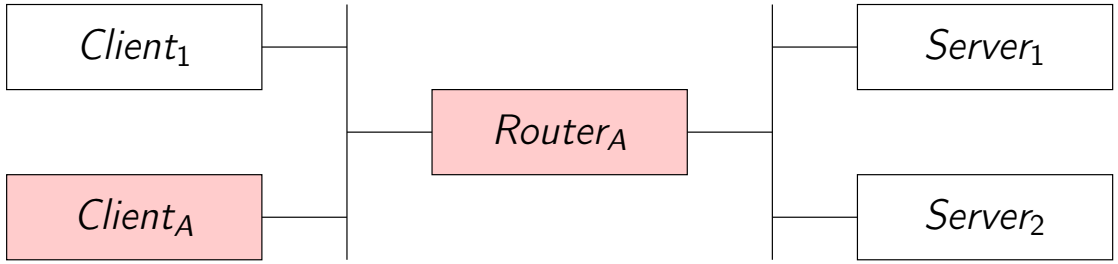

Figure : Infrastructure example

Possible security objectives:

- $IdTh$ = Identity theft,
- $AuthBP$ = Authentication by-pass,

$\mathcal{R}_{Obj}$	$IdTh$	$AuthBP$
$Client_A$	✗	✓
$Router_A$	✓	✗

Table : Objectives for each attacker

Bottom-Up Example

Possible realization of objectives:

- $Real(IdTh) = \{\{Spy\}\}$
- $Real(AuthBP) = \{\{Usurp\}, \{Replay\}\}$

$Atk.vectors$	Spy	$Usurp$	$Replay$
FTP_{Auth}	✓	✗	✓
$\text{OPC-UA}_{SignEnc}$	✗	✗	✗

Table : Atk. vectors for each protocol

Results:

- $\mathcal{S}_{Client_A,\text{FTP}_{Auth}} = \{(AuthBP, Replay)\}$
- $\mathcal{S}_{Client_A,\text{OPC-UA}_{SignEnc}} = \emptyset$
- $\mathcal{S}_{Router_A,\text{FTP}_{Auth}} = \{(IdTh, Spy)\}$
- $\mathcal{S}_{Router_A,\text{OPC-UA}_{SignEnc}} = \emptyset$

Clients and Servers

For a transport protocol:

- Encapsulate and decapsulate applicative message into packets.
- Reusable for a model to another.
- BehaviorClient generates applicative messages.
- SecurityLayer performs cryptographic operations.