SCADA systems security: verifying integrity properties

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Cybersecurity Institute
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Industrial Systems

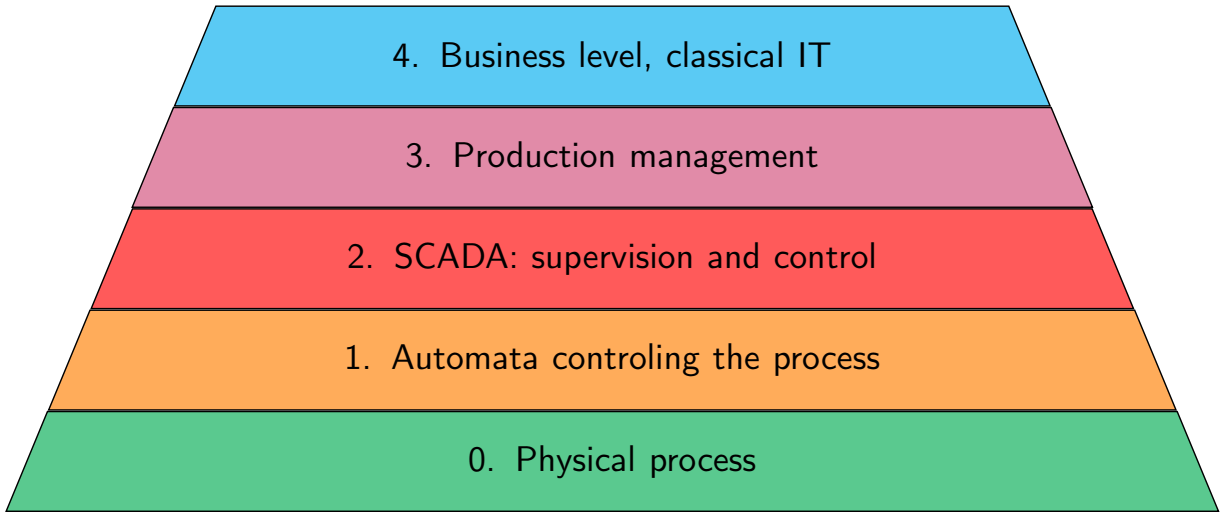
- SCADA : Supervisory Control and Data Acquisition
- Critical industrial infrastructures: energy, water, oil, gas

Hot topic : cybersecurity

- Since Stuxnet (2009):
  - Complex attack ending up in increasing speed of Iranian centrifuges to damage them.
  - Also attacked the process monitoring to trick operators.
- Protection becoming a priority for government agencies.

Industrial Protocols

- Allow industrial devices to communicate.
- Must guarantee security properties such as:
  - Authentication
  - Integrity
  - (Secrecy when dealing with customer data).
  - (Non-repudiation)



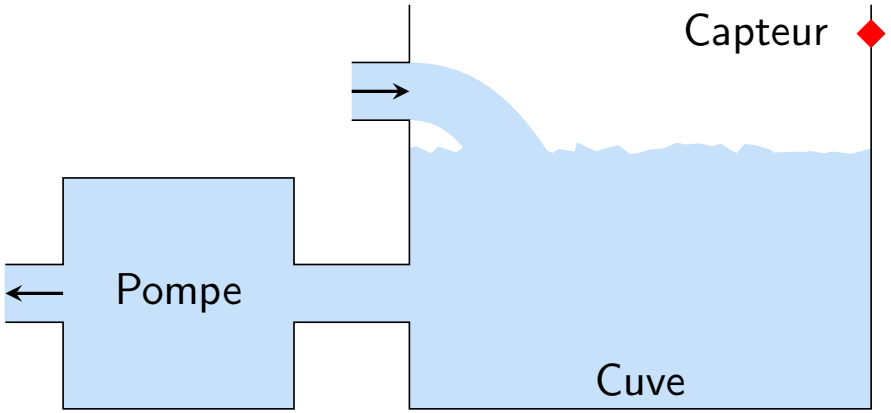
[Wil91] Theodore J Williams. *A reference model for computer integrated manufacturing (cim): A description from the viewpoint of industrial automation: Prepared by cim reference model committee international purdue workshop on industrial computer systems*, Instrument Society of America, 1991.

Differences between Industrial and Business IT

- Really long-term installations, hard to patch, lot of legacy hosts.
- Security objectives are different from traditional systems:
  - Availability, integrity, authentication and non-repudiation.
- Messages are READ/WRITE commands to PLCs.
  - Sometimes SUBSCRIPTIONS, RPCs or grouped commands.
  - Industrial protocols: MODBUS, OPC-UA.
- Attack examples:
  - change the value of a WRITE request to change a temperature,
  - change a READ response to mislead operators.

A Common Thread: Maroochy Shire

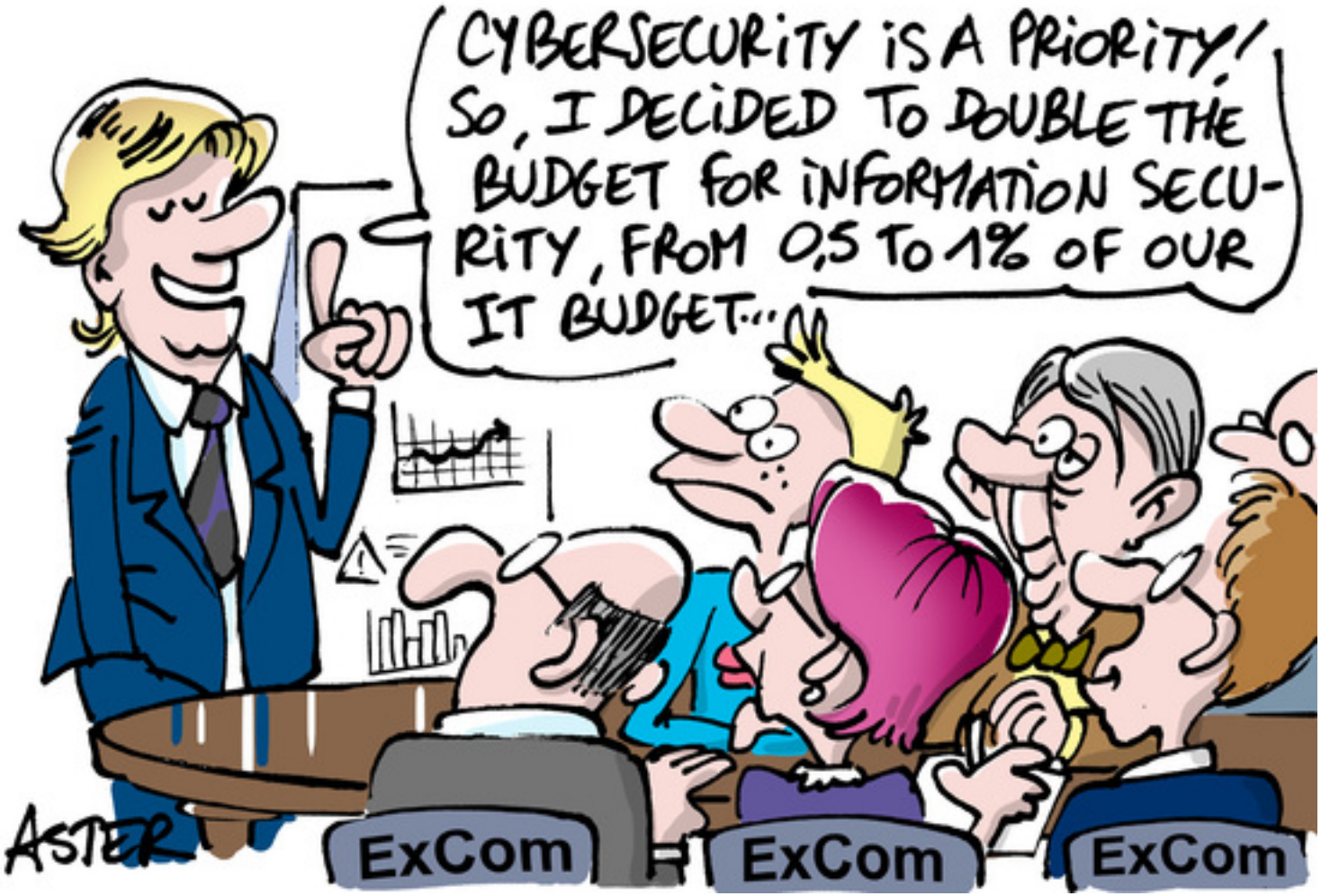
- Real attack occurring in 2000 in Australia.
- An insider spills $\sim$ 1M litters of raw sewage into nature.
- Attack over several months.



In our context, at least 3 vulnerabilities:

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

How to asset industrial system integrity?



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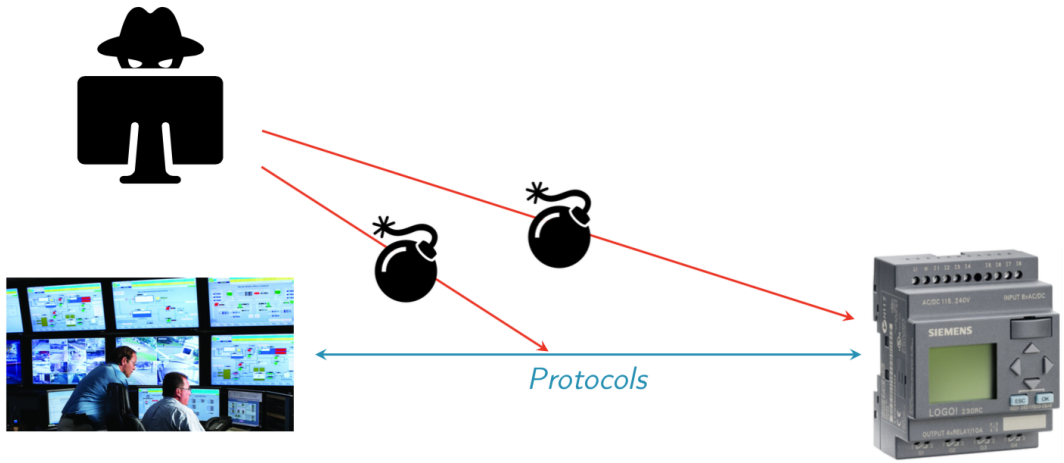

- On line : eg firewall, stateful monitoring and filtering.
- Off line : formal verification.

Formal Verification

- Crucial for industrial systems due to:
  1. Their interactions with physical world.
  2. Their really long lifetime and difficulty to patch.

$\Rightarrow$ Better check the protocol beforehand to save time and money.

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Cryptographic Protocols Verification 1/2

Mutual Authentication Protocol: Needham-Schroeder

1. $A \rightarrow B : \{A, N_A\}_{KB}$
2. $A \leftarrow B : \{N_A, N_B\}_{KA}$
3. $A \rightarrow B : \{N_B\}_{KB}$

Designed and **proved** in 1978.
Broken in 1995 (17 years after) **with an automated tool**.

Cryptographic Protocols Verification 1/2

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Designed and **proved** in 1978.
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Man-In-The-Middle attack

1. $A \rightarrow I : \{A, N_A\}_{KI}$
2. $A \leftarrow I : \{N_A, N_B\}_{KA}$
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1. $I \rightarrow B : \{A, N_A\}_{KB}$
2. $I \leftarrow B : \{N_A, N_B\}_{KA}$
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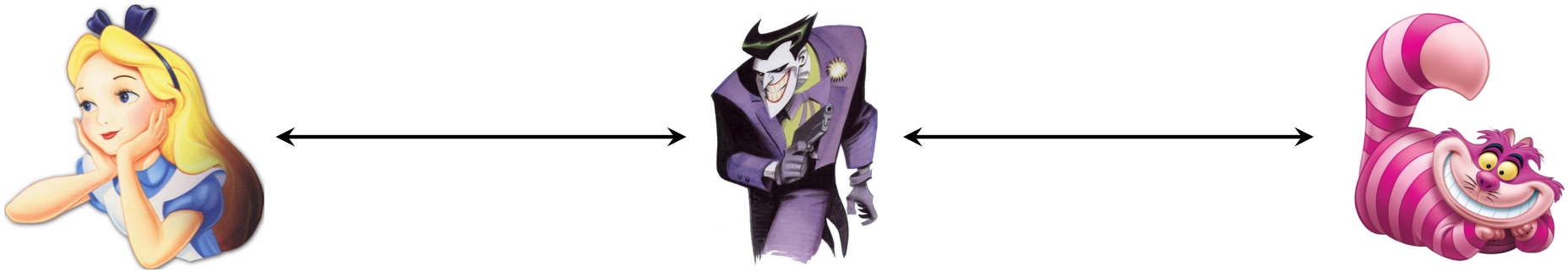
Cryptographic Protocols Verification 2/2

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

- They automatically verify the protocol in presence of an intruder.
- Used to prove IT protocols (TLS, SSH).
- Verified properties: secret, authentication, observational equivalence



Dolev-Yao Intruder [DY81]

Controls the network.
Cryptography is supposed perfect.
Intruder is able to deduce possible messages from his knowledge:

- E.g.: If he has a ciphertext and the key, he can deduce the plaintext.

Related Works on industrial protocol

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
[PPL16]	2016	OPC-UA	Formal (ProVerif)
[DPPLR17]	2017	MODBUS, OPC-UA	Formal(Tamarin)

J. Dreier, M. Puys, M.-L. Potet, P. Lafourcade, and J.-L. Roch. *Formally verifying flow integrity properties in industrial systems*. SECRYPT'17, 2017.

- Formalized properties for industrial systems
- Implemented them in the Tamarin prover
- Tested on 2 real industrial protocols and academic works

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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 $\textbf{\textit{set}}(R_{A,B}) \subseteq \textbf{\textit{set}}(S_{A,B})$.

$$S_{A,B} = \boxed{M_1}\ \boxed{M_2}\ \boxed{M_3}\ \boxed{M_4}$$

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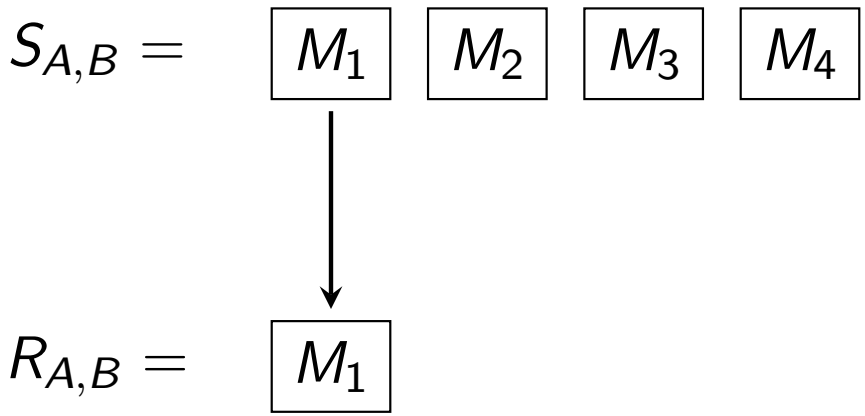

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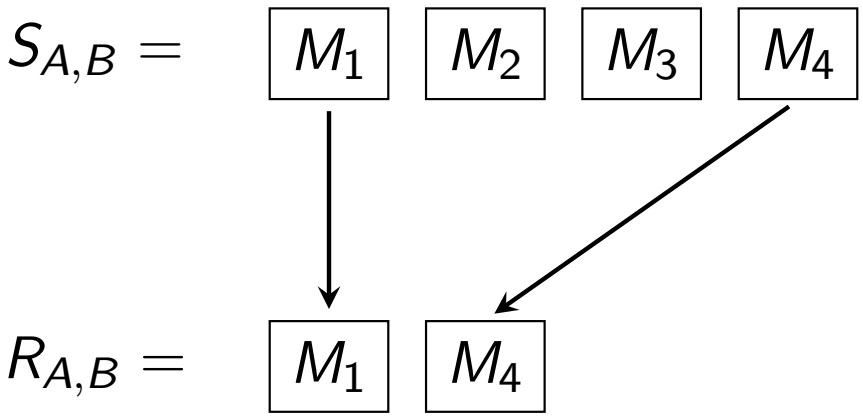

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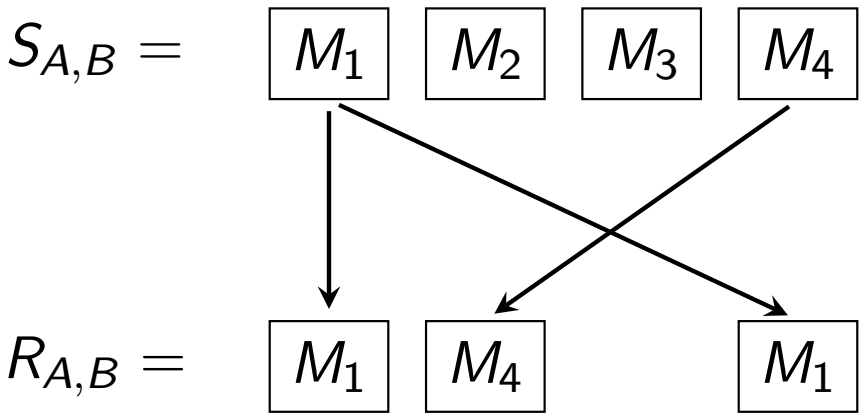

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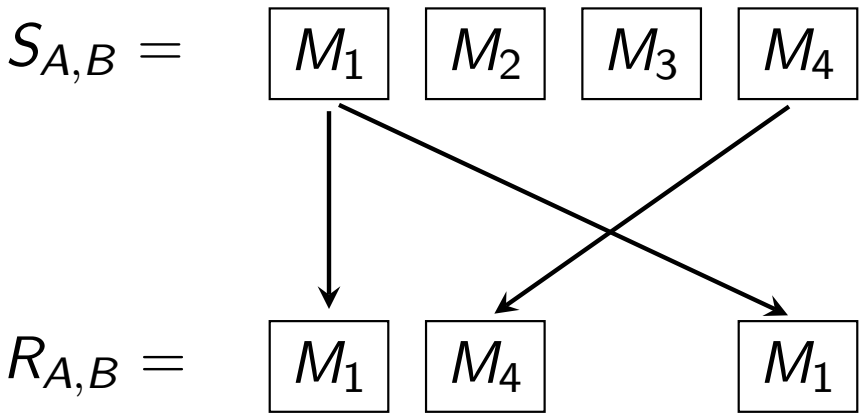

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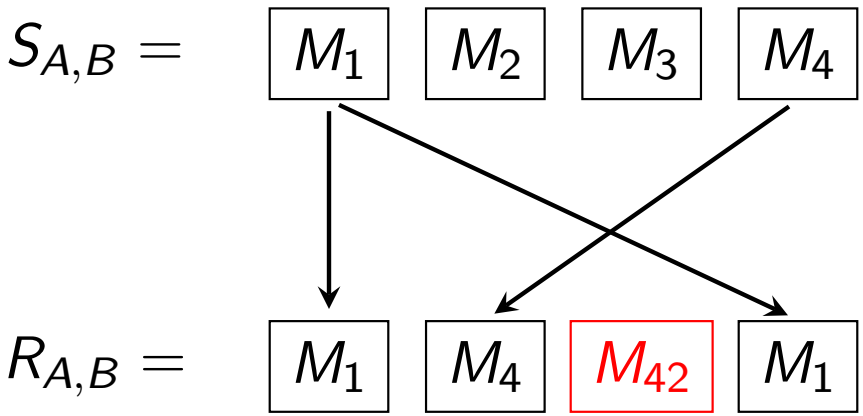

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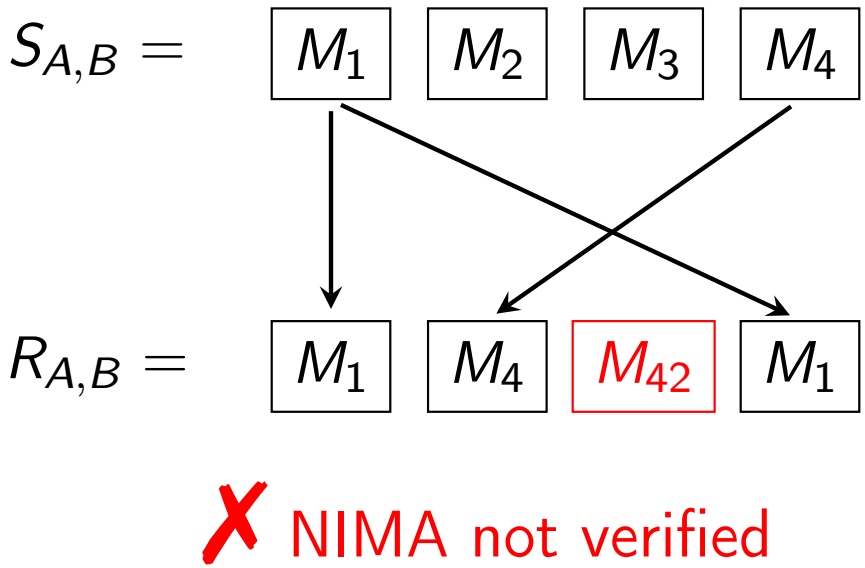

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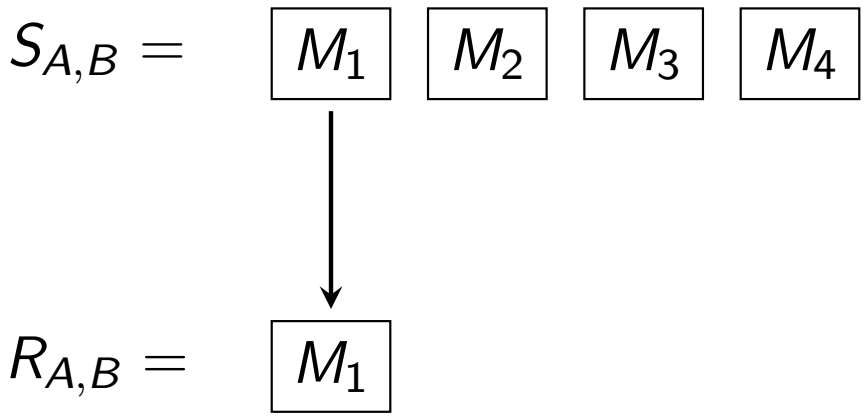

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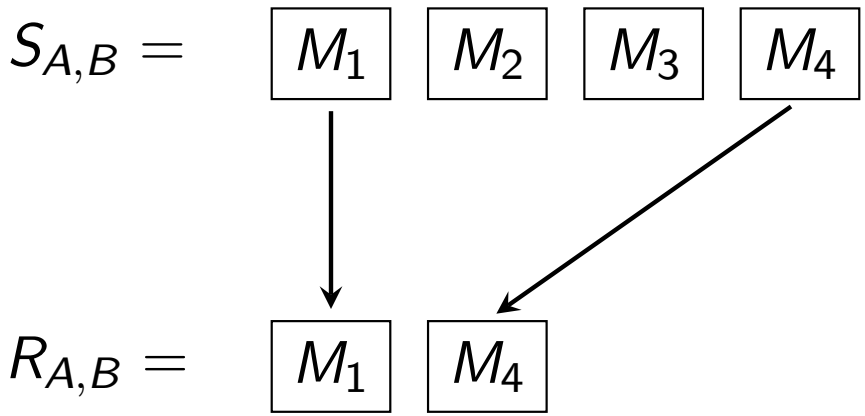

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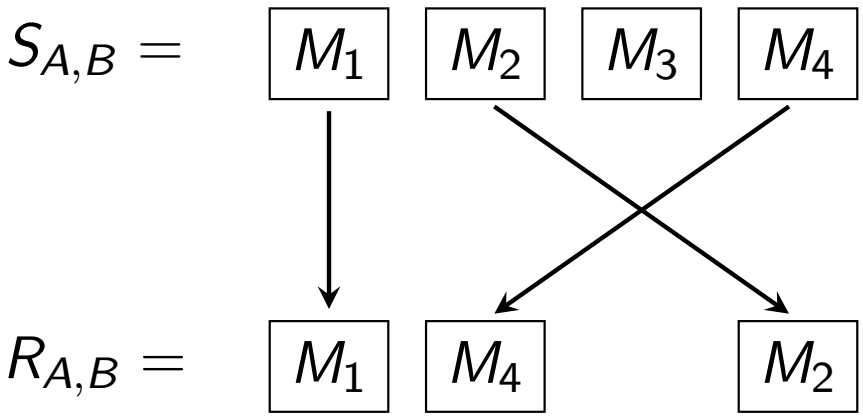

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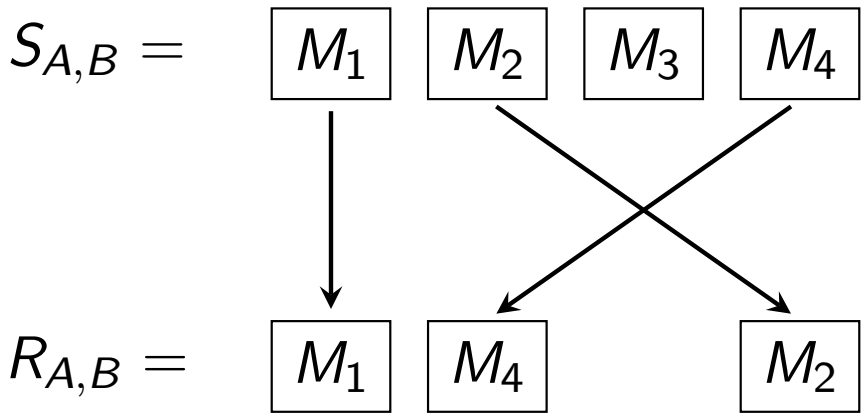

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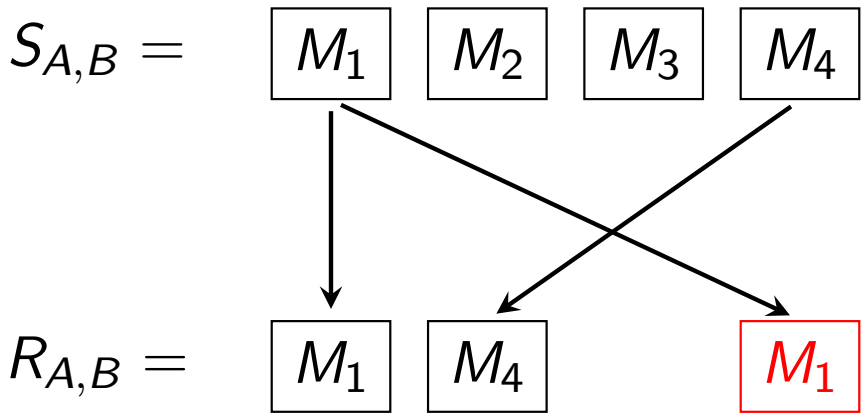

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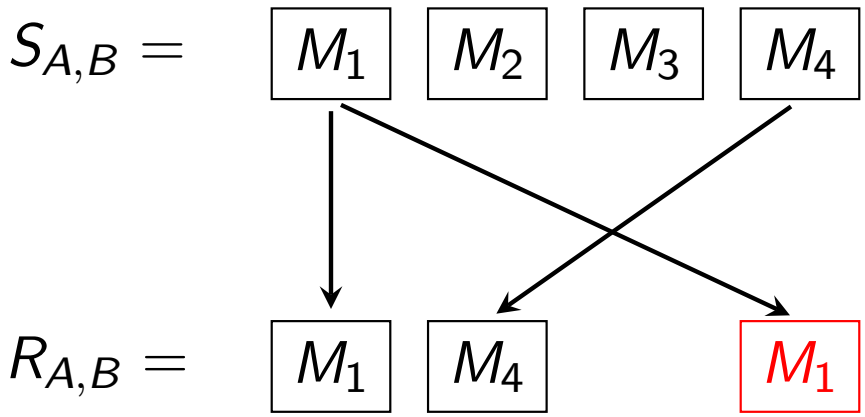

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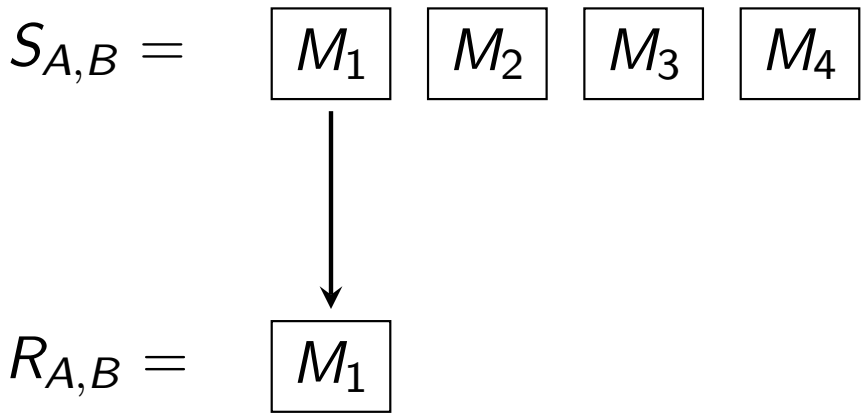

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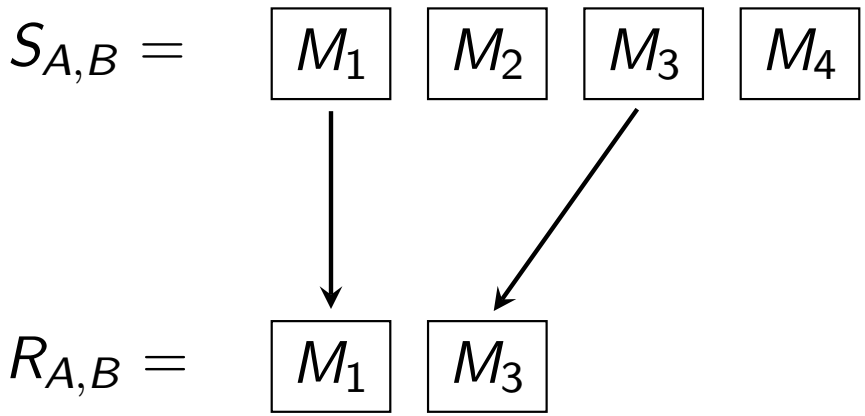

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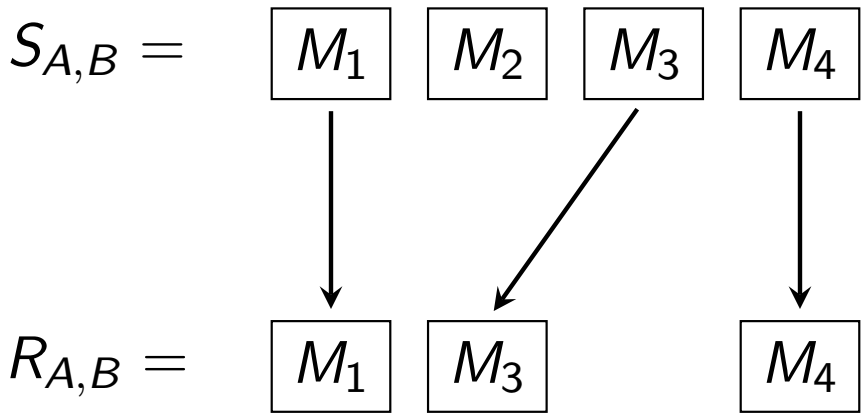

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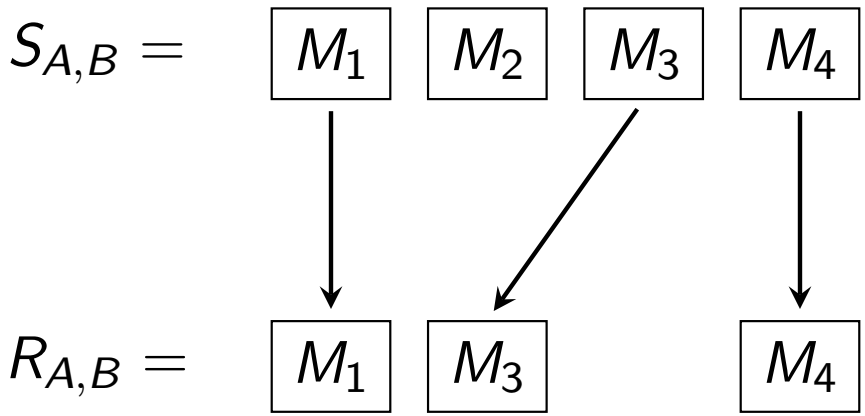

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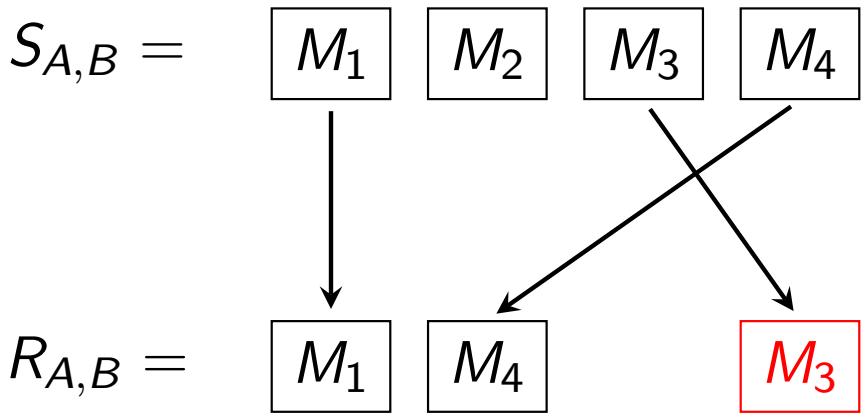

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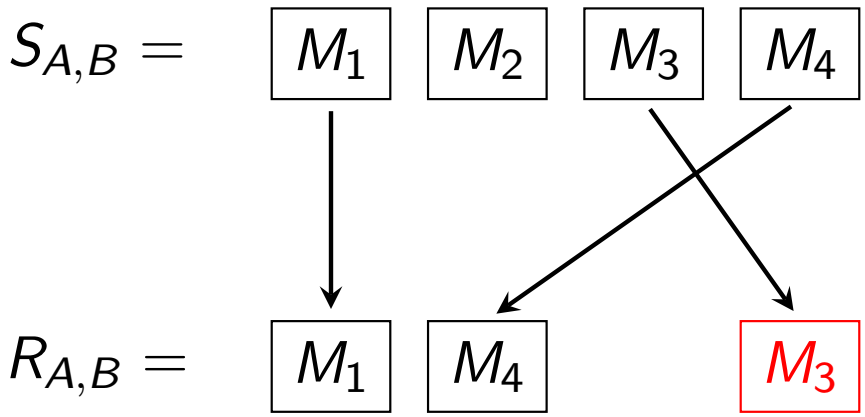
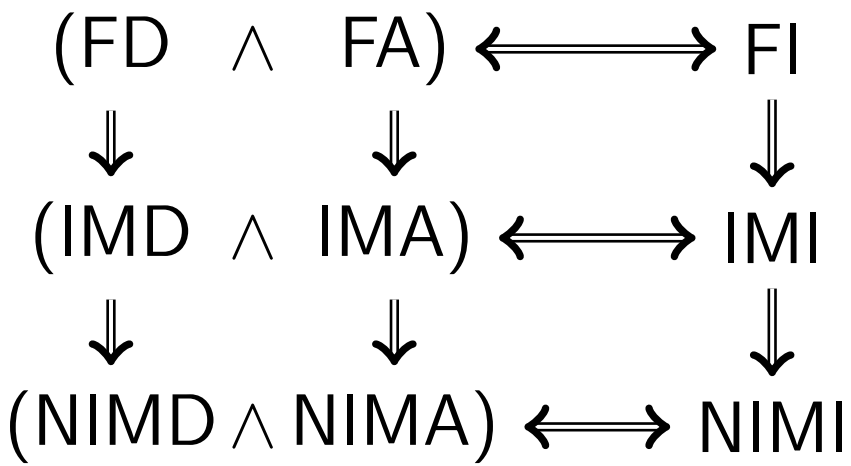


✗ FA not verified

Flow integrity properties and relations

Suffix: **A**=Authenticity ; **D**=Delivery ; **I** = Integrity.



[DPPLR17] Relationships: $A \Rightarrow B$ if a protocol ensuring A also ensures B.

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

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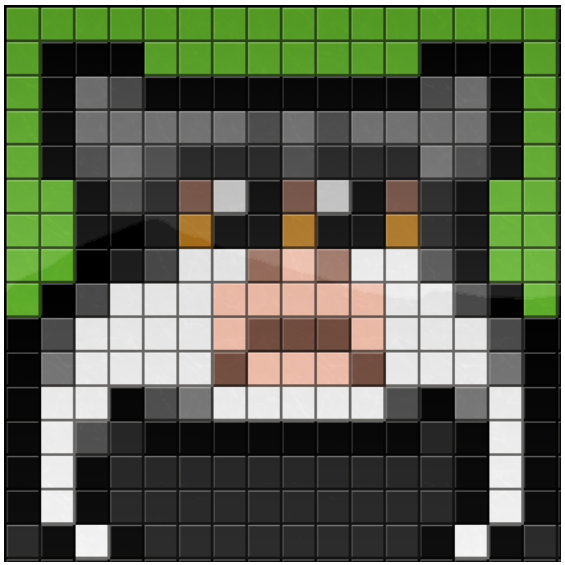
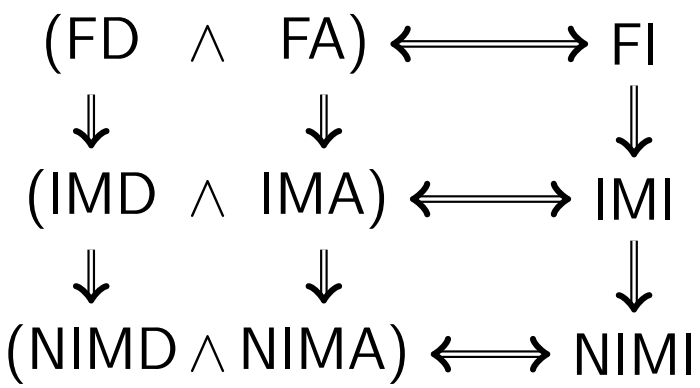
Tamarin Prover



- Automated cryptographic verification tool
- Developed since 2012 at ETH Zurich, Univ. of Oxford and Loria Nancy
- Protocols modeled using multiset rewritting rules
- Verified properties:
  - Trace properties: First order logical with time points
  - Observational equivalence

`https://github.com/tamarin-prover/tamarin-prover`

Flow Integrity Properties in Tamarin



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. »

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

Application to Industrial Protocols

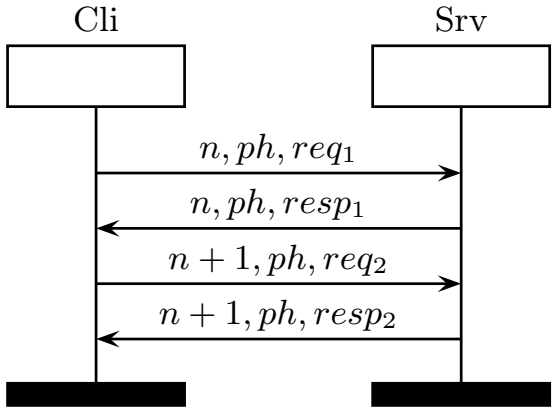
MODBUS (1979)

- No security at all.
- Some academic works to secure it:
  - Cryptographic asymmetric signatures [FCMT09]
  - Message Authentication Codes [HEK13]

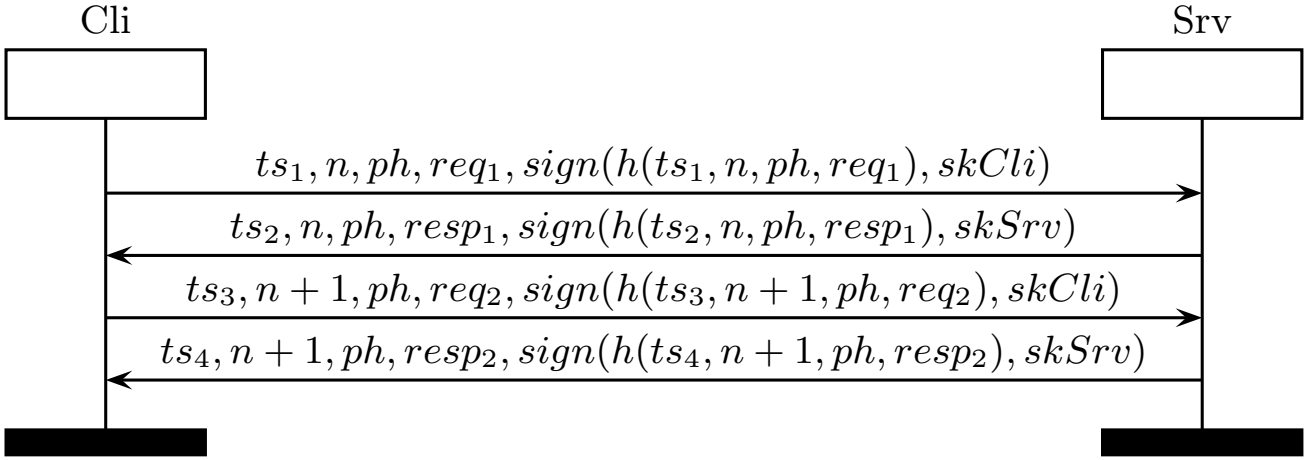
OPC-UA (2006)

- Security layer: OPC-UA SecureConversation (similar to TLS).
- Next standard for industry (consortium of key stakeholders)
- Currently developed and maintained (1000 pages of specification)
- Three security modes:
  - None, Sign, SignAndEncrypt.

MODBUS

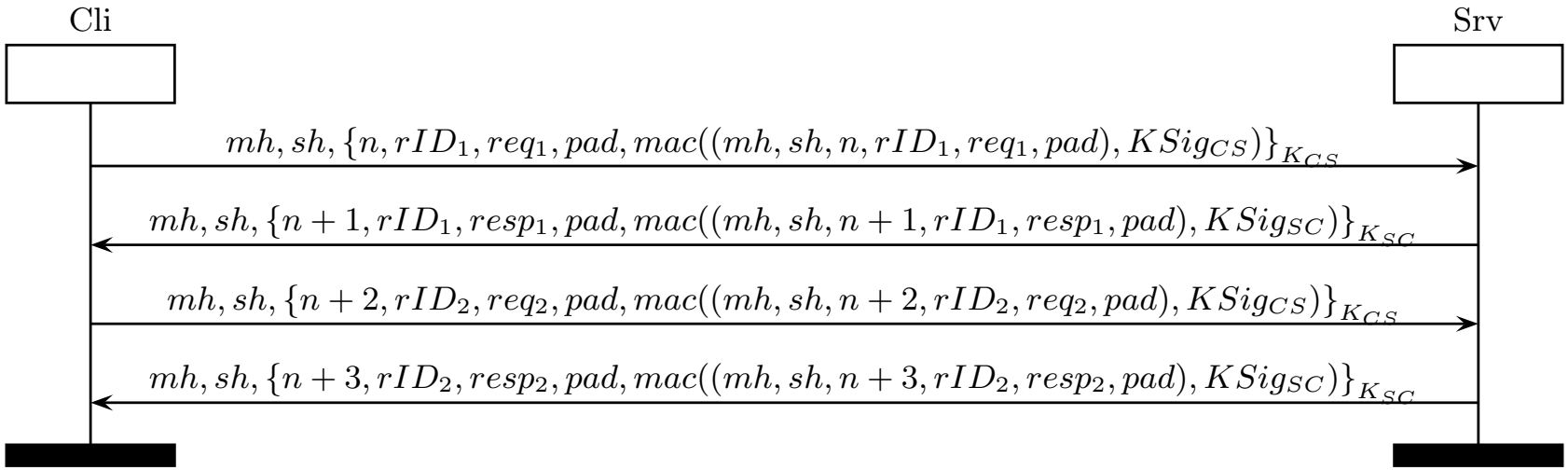


Textbook MODBUS [MOD04]



Secure MODBUS from [FCMT09]

OPC-UA



OPC-UA [IEC15]

Results on MODBUS and OPC-UA

Protocol	NIMI	IMI	FI
Textbook MODBUS [MOD04]	UNSAFE	UNSAFE	UNSAFE
MODBUS Sign [FCMT09]	UNSAFE	UNSAFE	UNSAFE
MODBUS MAC [HEK13]	SAFE	SAFE	SAFE

Results for MODBUS assuming an resilient channel.

Protocol	NIMI	IMI	FI
OPC-UA None	UNSAFE	UNSAFE	UNSAFE
OPC-UA Sign	SAFE	SAFE	SAFE
OPC-UA SignAndEncrypt	SAFE	SAFE	SAFE

Results for OPC-UA [IEC15], assuming a resilient channel.

Results on OPC-UA with bounded counters

- In real life, machine integers are bounded and wrap over.

Protocol	NIMA	IMA	FA	NIMD	IMD	FD
OPC-UA SignAndEncrypt with bounded numbers Insecure Channel	SAFE	SAFE	UNSAFE	UNSAFE	UNSAFE	UNSAFE

Results on OPC-UA with bounded counters

- In real life, machine integers are bounded and wrap over.

Protocol	NIMA	IMA	FA	NIMD	IMD	FD
OPC-UA SignAndEncrypt with bounded numbers Insecure Channel	SAFE	SAFE	UNSAFE	UNSAFE	UNSAFE	UNSAFE

Attack on FA with bounded counters (modulo 4)

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

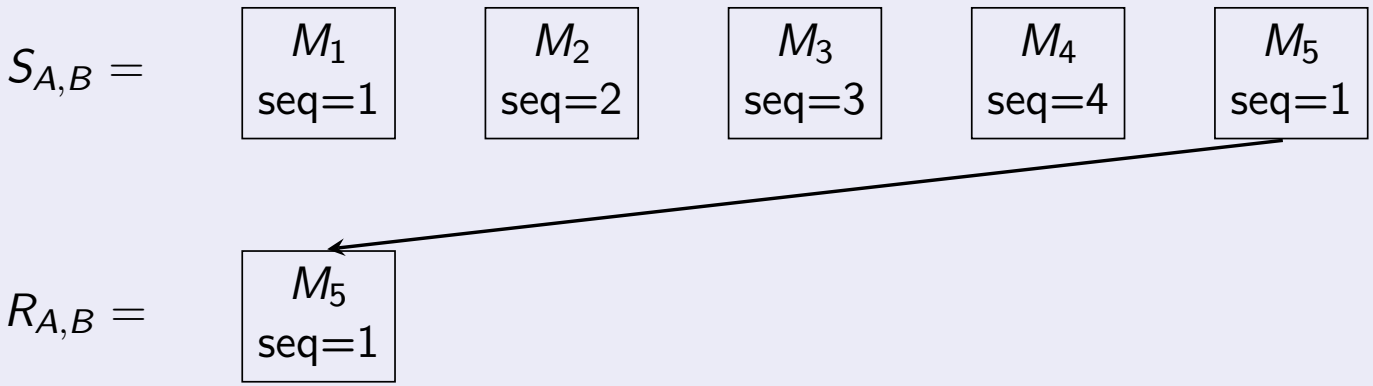
$R_{A,B} =$

Results on OPC-UA with bounded counters

- In real life, machine integers are bounded and wrap over.

Protocol	NIMA	IMA	FA	NIMD	IMD	FD
OPC-UA SignAndEncrypt with bounded numbers Insecure Channel	SAFE	SAFE	UNSAFE	UNSAFE	UNSAFE	UNSAFE

Attack on FA with bounded counters (modulo 4)



Results on OPC-UA with bounded counters

- In real life, machine integers are bounded and wrap over.

Protocol	NIMA	IMA	FA	NIMD	IMD	FD
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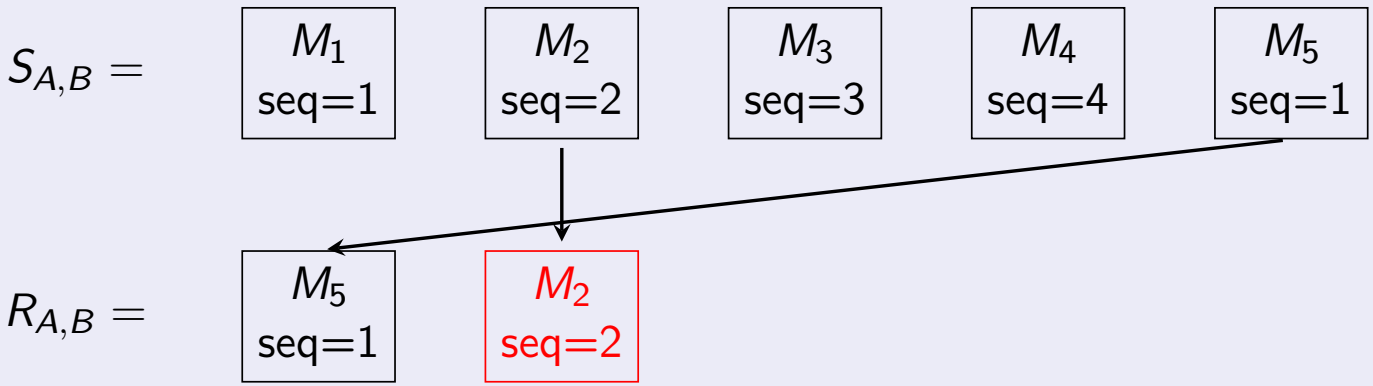

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Protocol	NIMA	IMA	FA	NIMD	IMD	FD
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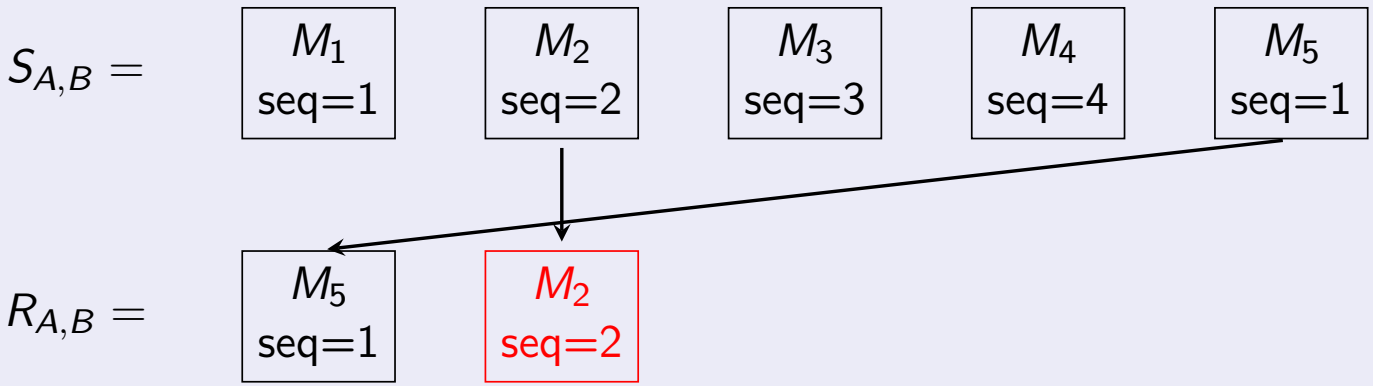
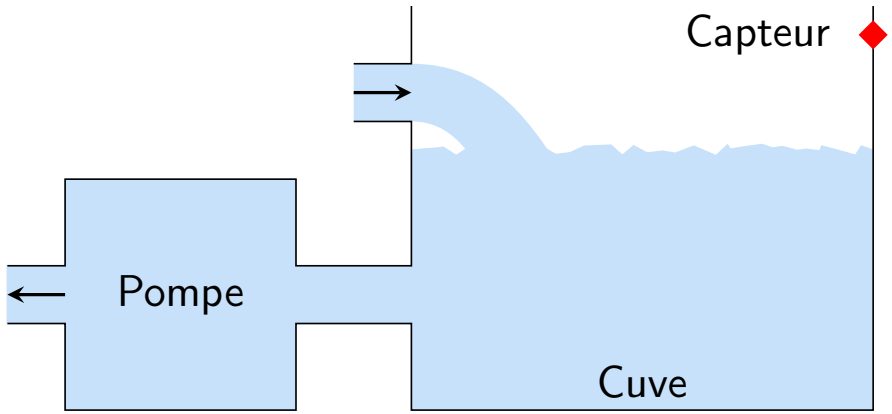


- Paper [DPPLR17] coined by OPC Fundation (that develops OPCUA):
  - interactions to understand attacks;
  - exchanges on the evaluation of CVSS score
- to appear: erratum on standard clarifying recommandation.
  - In practice, OPC-UA renegociates keys when sequence numbers wrap.

Back to the Common Thread: Maroochy Shire

- **Vulnerability 1:** Absence of authentication mechanism in communication protocols.

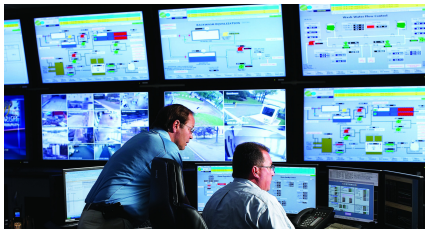


Methodology to catch properties required by industrial protocols.
Proofs of security for OPC-UA:

$\Rightarrow$ Provides authentication and integrity.

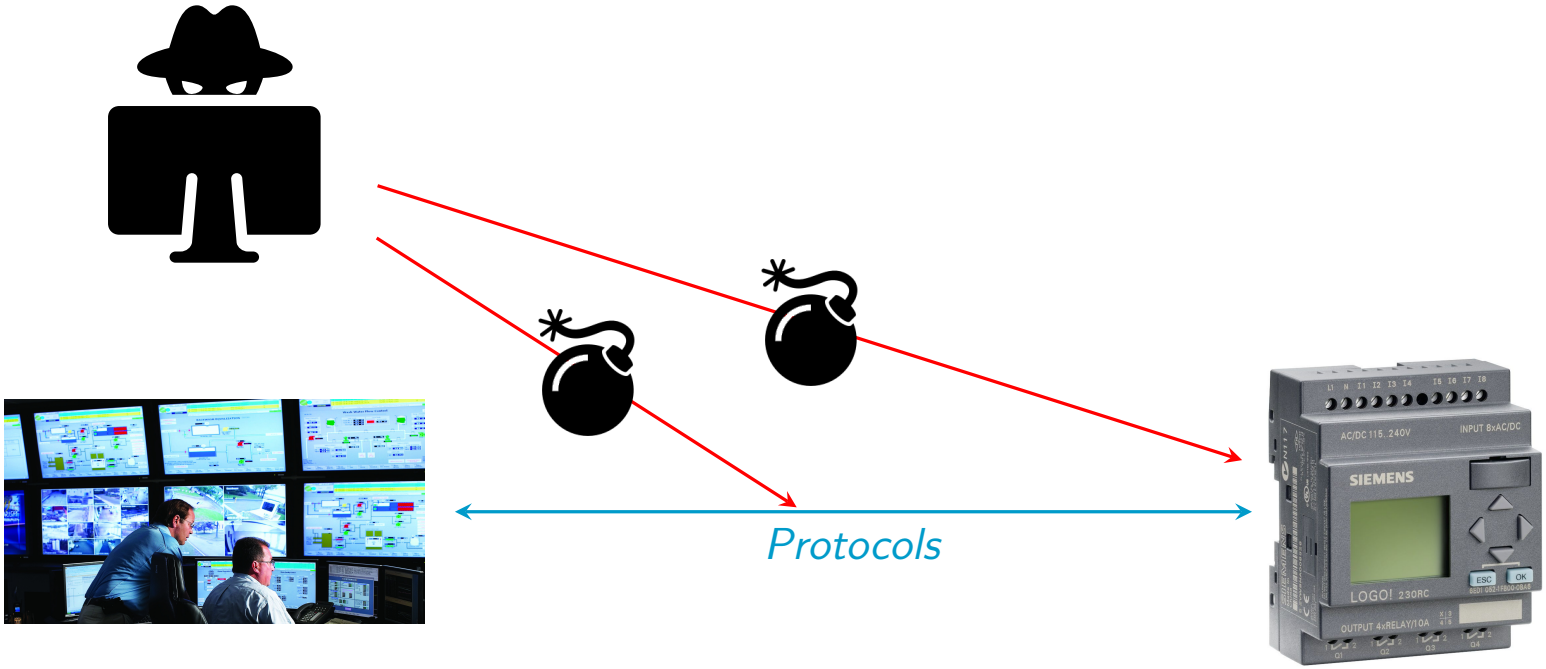
Table of Contents

Content Integrity by Applicative Filtering

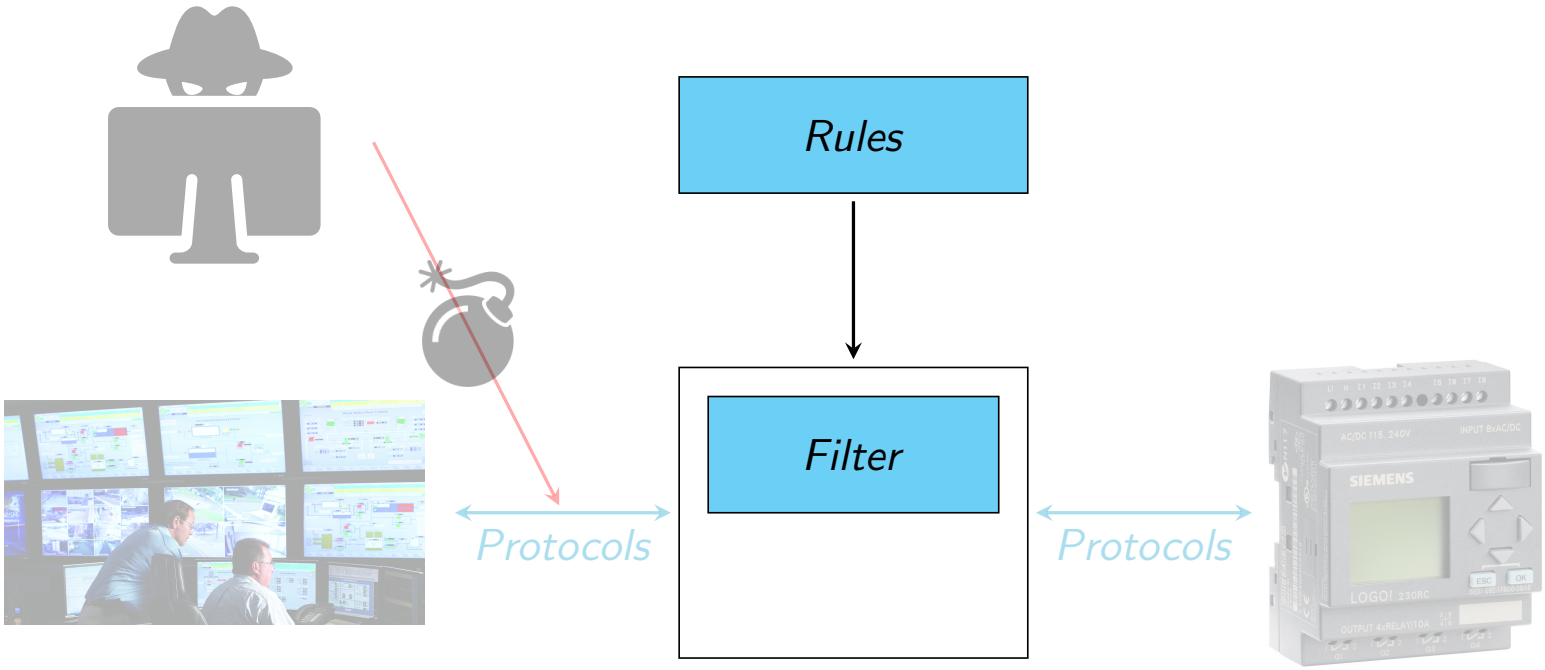


Protocols

Content Integrity by Applicative Filtering



Content Integrity by Applicative Filtering



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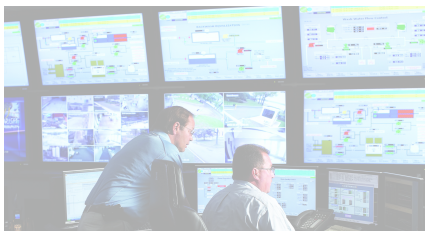
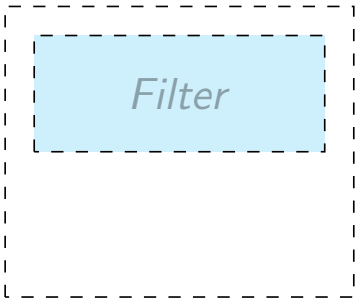
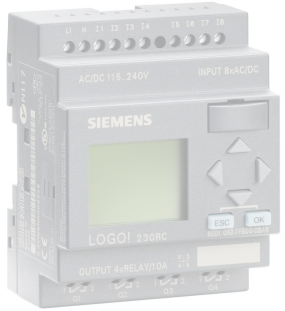




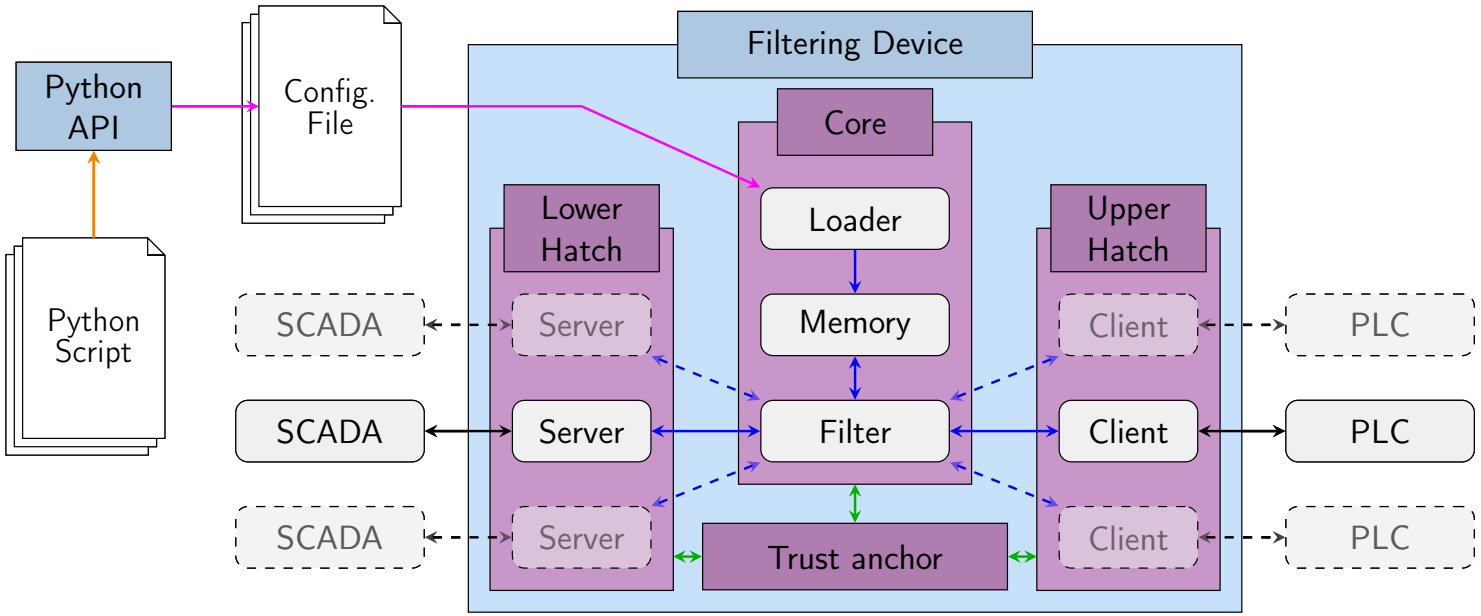


ARAMIS : Applicative Filtering Device

France PIA project lead by Atos Worldgrid, supervised by ANSSI.

Partners: Atos, CEA, Seclab, University Grenoble Alpes

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



[WCICSS'17] B. Badrignans *et al.* Security Architecture for Embedded Point-to-Points Splitting Protocols, 2017.

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).

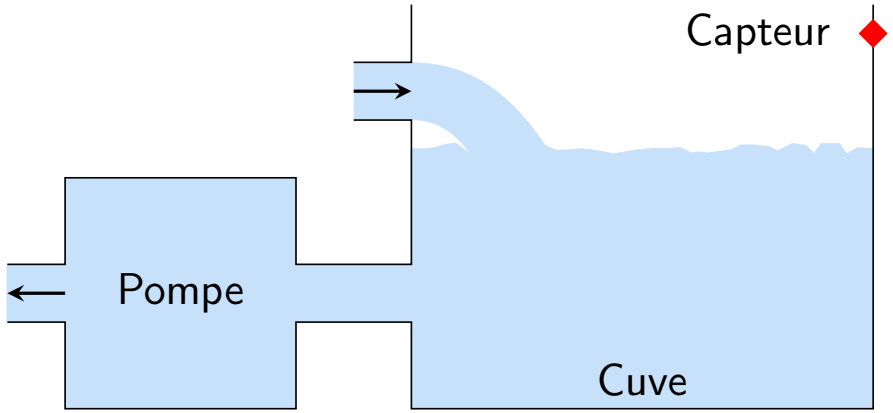
Case studies on real life examples:

- Demonstration of a prototype showed to ANSSI.

[CRITIS'16] M. Puys, J.-L. Roch, and M.-L. Potet. Domain specific stateful filtering with worst-case bandwidth, 2016.

Back to the Common Thread: Maroochy Shire

- **Vulnerability 2:** Absence of safety mechanism to avoid the spill.




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

Conclusion and Perspectives

- Industrial protocols need security proofs
  - Integrity is critical
- Flow integrity : formal verificaton
  - OPCUA protocol with Tamarin
- Content integrity : on-line verification
  - Both stateless and stateful verifications
- Perspective: Process integrity
  ↪verification that commands have been performed
  - Secure by Design (isolated system)
  - Secure by Proof of Results (eg interactive proof)
  - Secure by Proof of Consensus (eg blockchain)

Conclusion and Perspectives

Thanks for your attention!

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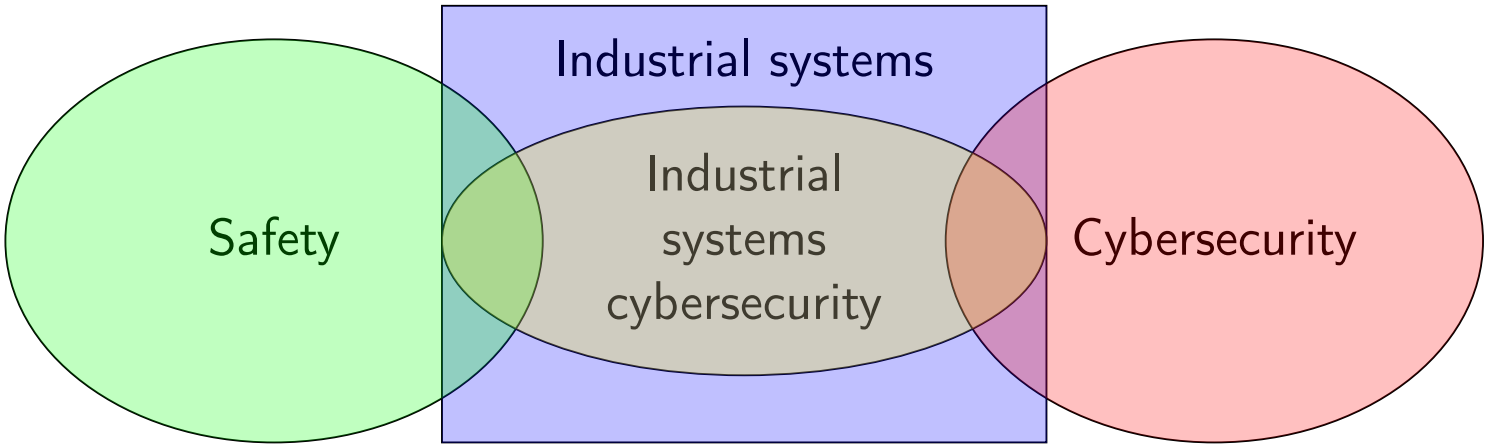
Jean-Louis.Roch@grenoble-inp.fr

Disambiguation

Security concepts

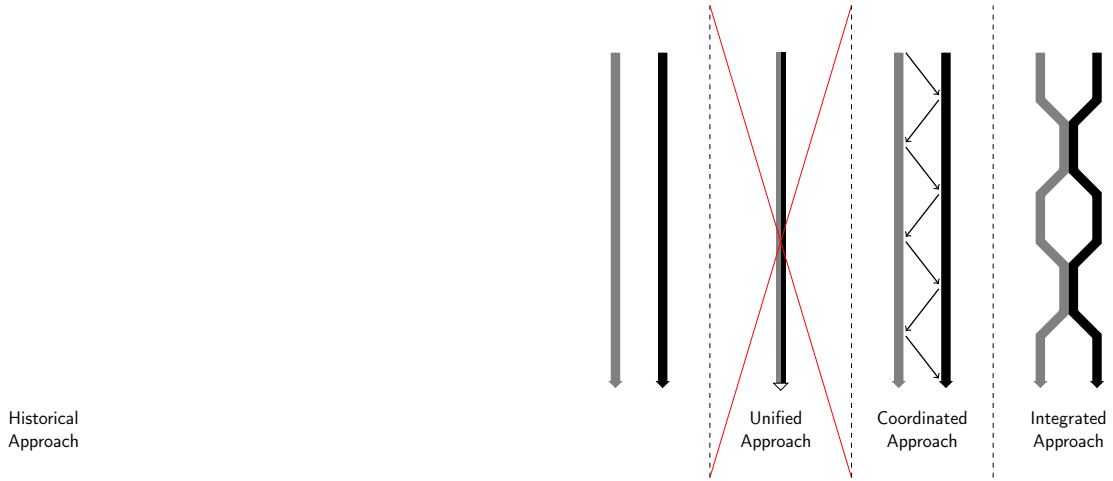
- Safety = Protection against identified/natural difficulties.
  - Historic industrial concern.
- Cybersecurity = Protection against malicious adversaries.
  - Often called Security.



Relations among security concepts

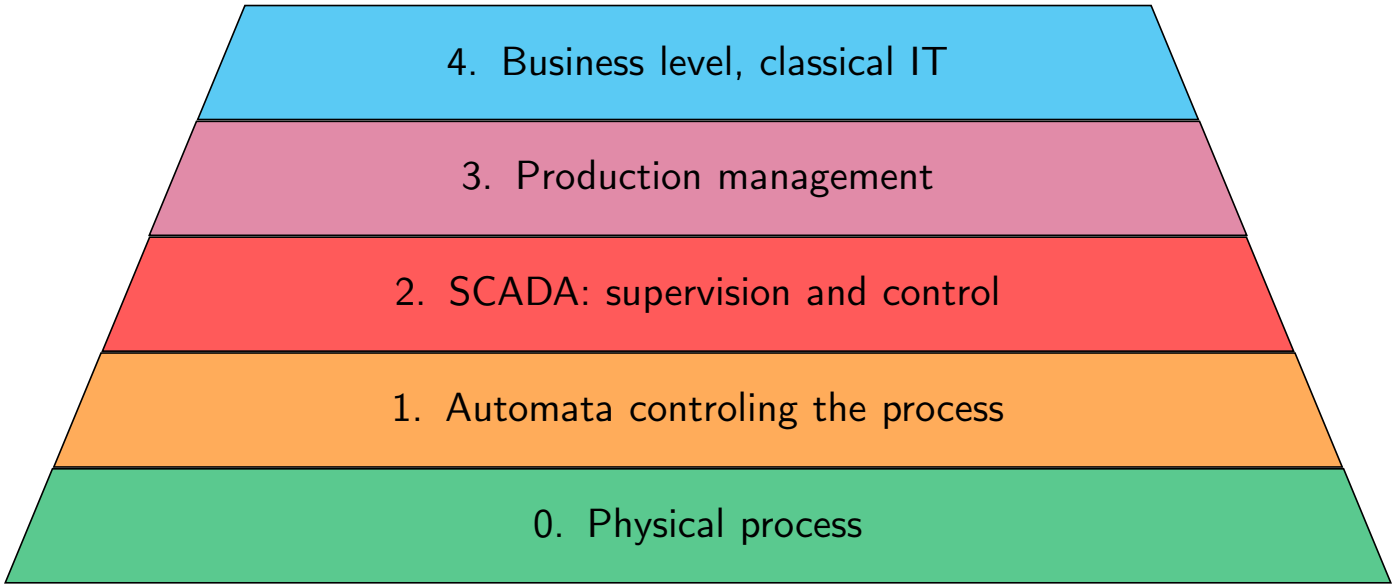
- Ludovic Pietre-Cambacedes' thesis: On the relationships between safety and security, Telecom ParisTech and EDF, 2010.

Safety and Security



How to link safety and security [PC10]

Purdue Model



Purdue model [Wil91]

Motivations on Studying OPC-UA Security

Official specifications: 978 pages.

Several terms redefined afterward:

For this reason, the OpenSecureChannel Service **is not the same as the one specified in the Part 4.** – Part 6, Release 1.02, Page 41.

Highly context dependent:

Some SecurityProtocols do not encrypt the entire Message with an asymmetric key. **Instead, they use the AsymmetricKeyWrapAlgorithm to encrypt a symmetric key** [...]. – Part 6, Release 1.02, Page 27.

The AsymmetricKeyWrapAlgorithm element of the SecurityPolicy structure defined in Table 22 **is not used by UASC implementations.** – Part 6, Release 1.02, Page 37.

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- D. Dzung, M. Naedele, T.P. von Hoff, and M. Crevatin, *Security for industrial communication systems*, Proceedings of the IEEE **93** (2005), no. 6, 1152–1177.
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JH Graham and SC Patel, *Correctness proofs for SCADA communication protocols*, Proceedings of the Ninth World Multi-Conference on Systemics, Cybernetics and Informatics, 2005, pp. 392–397.

G. Hayes and K. El-Khatib, *Securing MODBUS transactions using hash-based message authentication codes and stream transmission control protocol*, Communications and Information Technology (ICCIT), 2013 Third International Conference on, June 2013, pp. 179–184.

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- Ludovic Piètre-Cambacédès, *The relationships between safety and security*, Theses, Télécom ParisTech, November 2010.

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


Theodore J Williams, *A reference model for computer integrated manufacturing (cim): A description from the viewpoint of industrial automation: Prepared by cim reference model committee international purdue workshop on industrial computer systems*, Instrument Society of America, 1991.

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