Formal Security Assessment of Modbus Protocol

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Introduction

Critical Infrastructures

- **Large, complex heterogeneous systems**
  - Example: water treatment, power distribution, or logistics
- Our day-to-day basis depends on
- Disruptions of services may provoke issues, from economical to personal damages
  - Different origins: from man made to unexpected acts of nature
  - **Intended and unintended**

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Introduction

- **Automated and distributed control systems rapidly adopt information and communication technology solutions**
  - Support operation and monitoring of industrial and critical processes

Problem: legacy devices running routable protocols

- Isolated components at the beginning: not any more
- New attack surface: communication protocol

Fact: attacks to critical infrastructures are increasing

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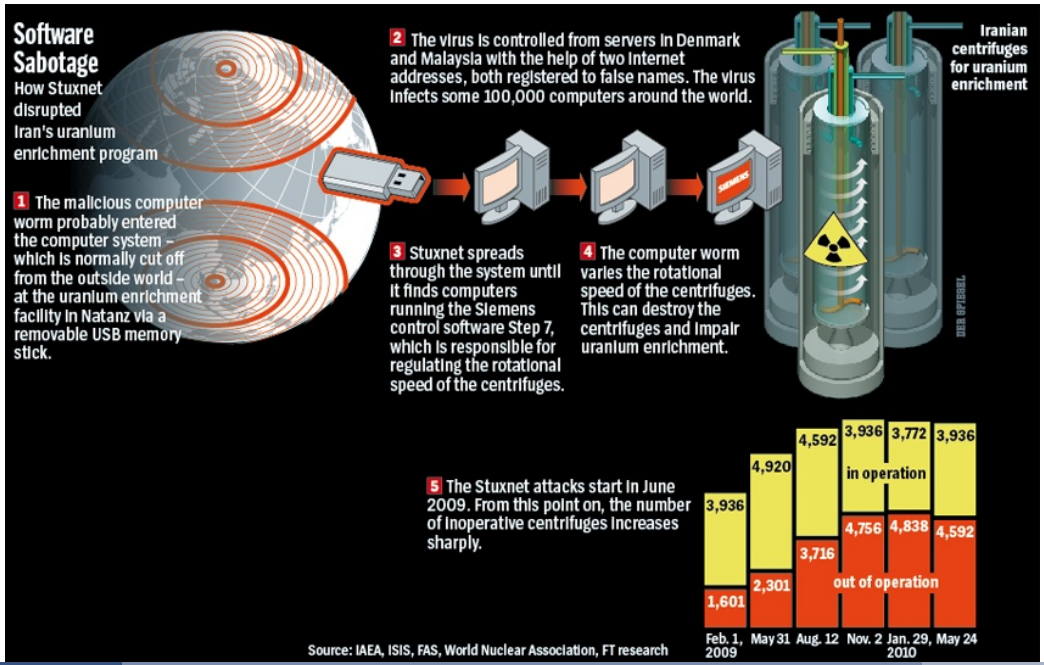
Introduction

Advanced Persistent Threats examples

- `Operation Aurora`: attributed to China, in 2010 a lot of companies from different domains (such as Google, Yahoo, Morgan Stanley, or Dow Chemicals) were attacked
- `Stuxnet`: attributed to US-Israel and discovered in 2010, affected to Siemens PLCs of SCADA networks in Iran nuclear facilities
- Others: `GhostNet`, `Duqu`, `Flame`, `...`



Introduction

Modbus protocol: main characteristics

Characteristics

- Top layer of OSI model
- Designed by Modicon in 1979 to operate using a RS232 port
  - Widely deployed and adopted as *de facto* standard
  - Now, it operates over different links (serial buses, routable networks over TCP/IP, or intercommunicated buses
    - Each device has a unique identifier
- **Request/response (master/slave) protocol**

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Modbus protocol: communication issues and security

- Type of commands:
  - Read/write commands
  - Device identification
  - Diagnostic
- Command format:
  - Destination, code function, and sub-code function (may be none)
- **Communication flow**:
  - Master device initiates a command query containing destination device
  - Destination device performs the function requested by the master, and replies

What about security?

- **No authentication**
- **No encryption at any form**
- **No integrity**

Introduction

Contribution

- **Security analysis assessment of the Modbus protocol using formal models**
  - From a high-level formalism based on hierarchical state machines, we derive a Promela model to apply model checking
- **Formal verification of the weaknesses of Modbus protocol** (in particular, to man-in-the-middle attacks)
- A **formal framework to evaluate solutions against security concerns** is provided

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Related work

Security of Modbus protocol

- **Classification of attacks** (Huitsing et al., 2008)
  - Modbus protocol specification, vendor implementations, control system assets
  - 60 attack identified, including spoofing, replay, and flooding attacks
- **Impact of malicious traffic injection** (Kobayashi et al., 2009)
- **Vulnerable to spoofing** confirmed by Bathia et al., 2014
  - Two detection algorithms proposed: anomaly and signature
- **Intrusion detection in network layer** (Goldenberg and Wool, 2013)

Defenses proposed

- **Modbus protocol enhancement** (Fovino et al., 2009)
  - Accounts for **authentication, non-repudiation, and replay protection**
  - **Overhead in performance and packet size**

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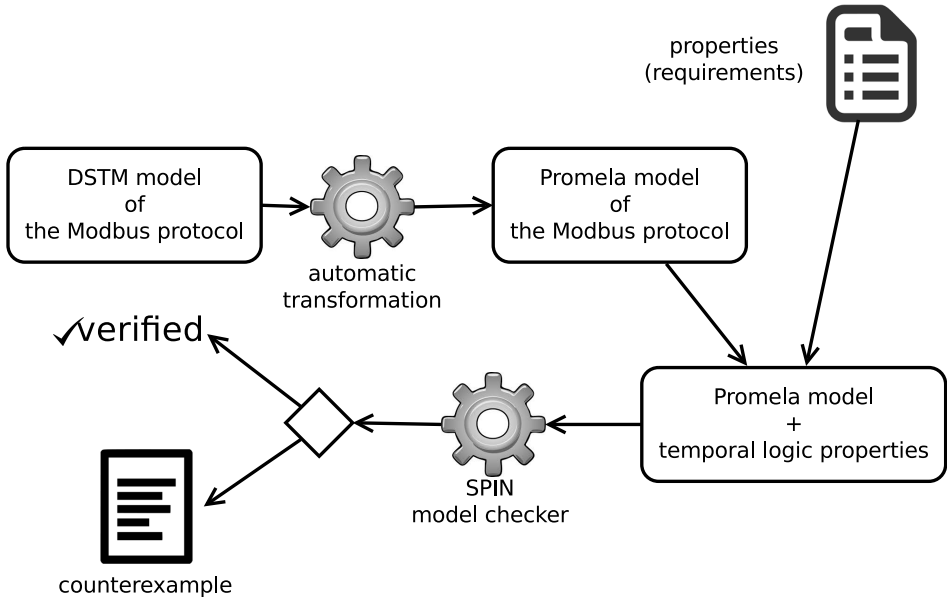
General Approach

From high-level syntax to low-level syntax



Model transformation

- **Dynamic StaTe Machine** (DSTM): extension of hierarchical state machines
- **Promela notation analyzable by SPIN**
  - Promela model **enriched with temporal logic formulas derived from the set of requirements to assess**
  - **Automatic counterexample generation** when properties are violated

General Approach

Dynamic StaTe Machine formalism (1)

Reasons

- Formal (textual and graphical) syntax semantics of both structural elements and annotations over transition (i.e., triggers, conditions, and actions)
- External messages are non-deterministically generated
- Automatic transformation from DSTM to Promela exists

- **Extension of hierarchical state machines**: novel semantics for fork and join
  - Removes the constraint of branches of a control flow exiting a fork must always be merged by a join element
- **Dynamic and recursive instantiation of machines**
- **Preemptive termination**
- **Passing parameters (to the machine) at instantiation time**

General Approach

Dynamic StaTe Machine formalism (2)

Description

- **Collection of parametric machines, channels (internal and external), and variables**
- **Definition of own datatypes allowed**
- **Datatypes**: basic, compound (records), multi-types (collection)
- **Channels**
  - *Internal*: entirely managed by the specified state machines; buffered with predefined length. Messages are consumed when reading
  - *External*: unbuffered. Message is valid during a single step and can be only read without removal

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General Approach

Dynamic StaTe Machine formalism (3)

Workflow execution

- At starting of each step, a new message is present over external channels
  - **Generated in the previous step**
  - (or) **Randomly generated over possibilities given by the datatype**

- **Machine components**: vertices (nodes) and transitions
  - Initial, entering, and exiting nodes
- **Boxes represent single or multiple machine instantiation**
  - Needs machine parameters

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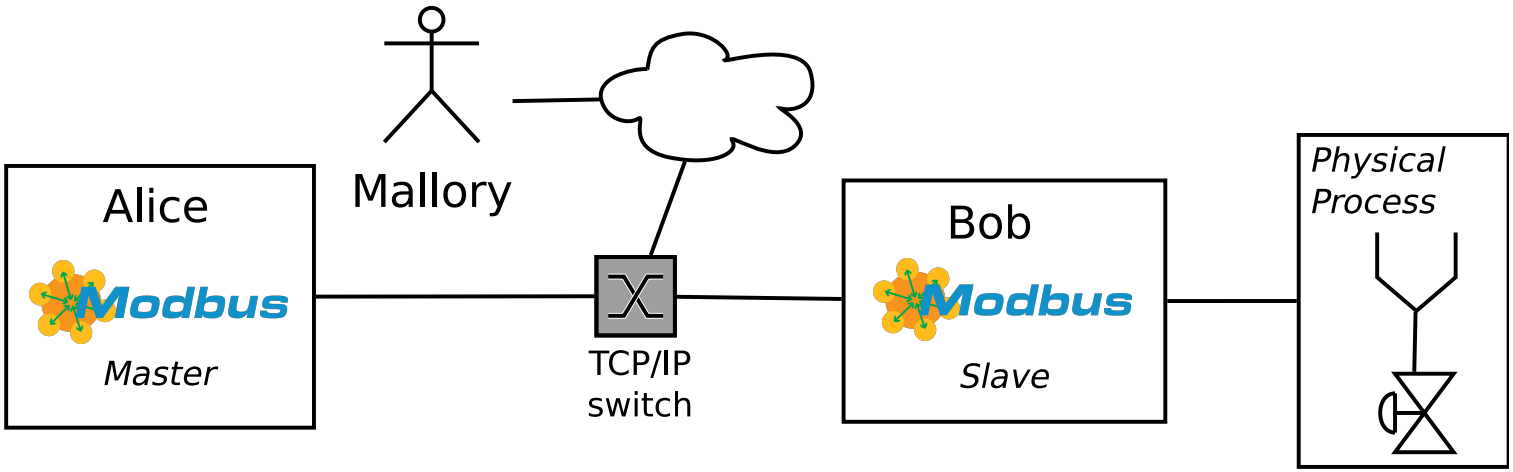
Security Analysis of Modbus Protocol

Reference scenario



Question here:

Can Alice receive messages that indicate a value of the physical process equal to one while the process is indeed stuck at zero?

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Security Analysis of Modbus Protocol

Datatypes and variables

```
//enumerations
Enum address {slaveA, masterA};
Enum fcode {RIR, DIA};
Enum subcode {NONE, RCM, FLOM};
Enum answer {EXCEPTION, SAMPLE};
//structures
Struct toMasterMsg {address, answer, Int};
Struct toSlaveMsg {address, fcode, subcode};
//channels
Chn external toMaster of toMasterMsg;
Chn external toSlave of toSlaveMsg;
//master's variables
Int sampleToMaster;
//slave's variables
address vaddress;
fcode vfcode;
subcode vsubcode;
Bool listenOnlyMode;
Int phenSample;
```

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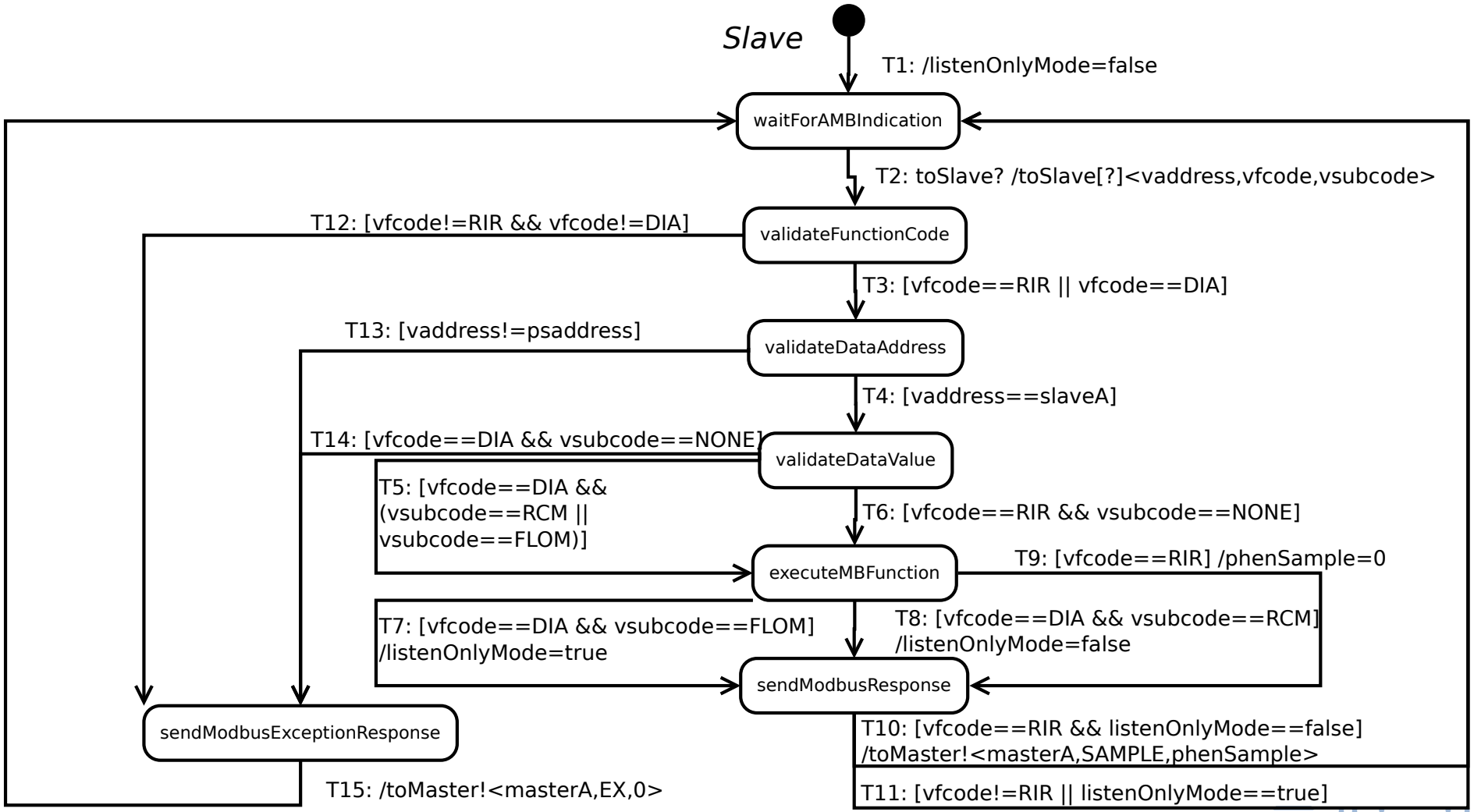
DSTM models of Modbus slave



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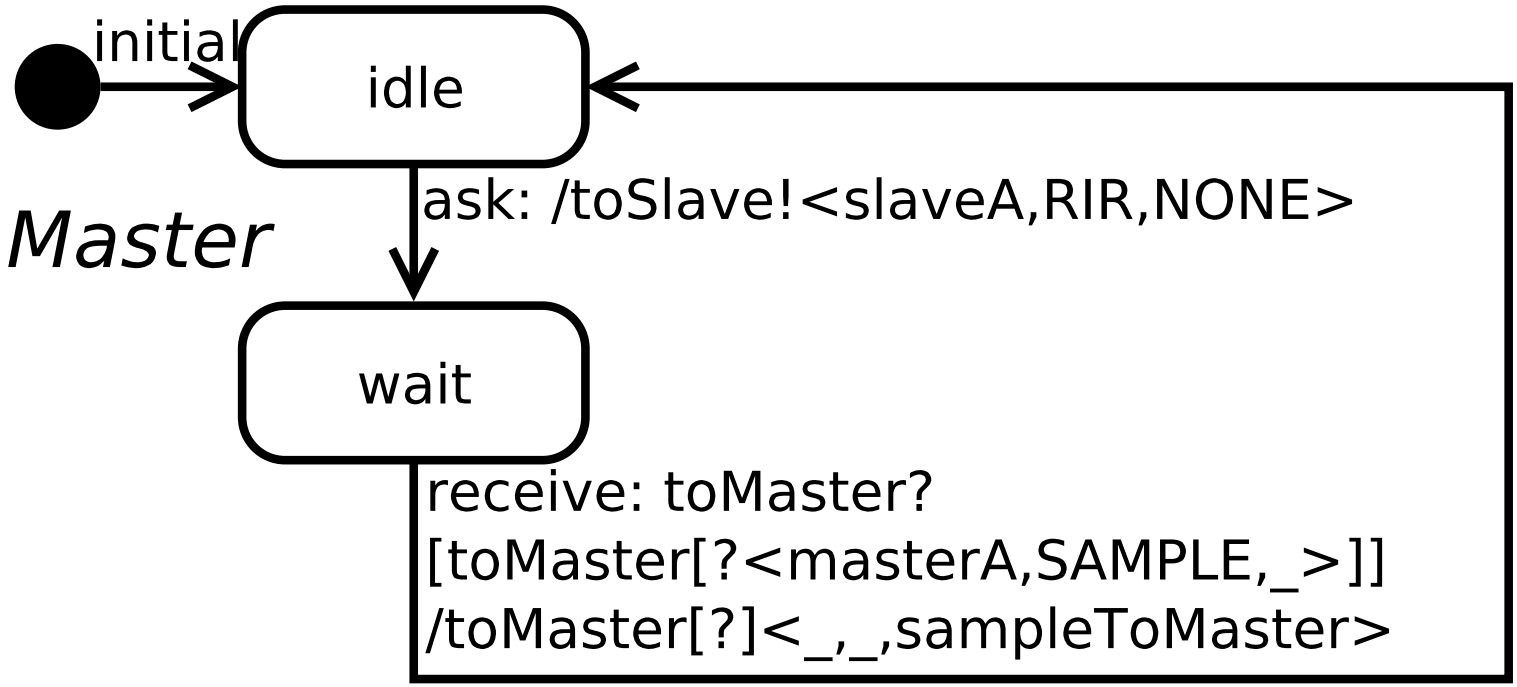
DSTM models of Modbus master



Property definition and evaluation

"it is always true that, once `SM` is equal to 1, it still remains equals to 1"

$$AG((SM == 1) \Longrightarrow AG(SM == 1))$$

Security Analysis of Modbus Protocol

Counterexample generated by SPIN

```
M->A: <masterA,SAMPLE,0>
M->B: <slaveA,RIR,NONE>
M->A: <masterA,SAMPLE,0>
...
M->B: <slaveA,RIR,NONE>
M->A: <masterA,SAMPLE,0>
A->B
B->A
M->B: <slaveA,DIA,FLOM>
M->A: <masterA,SAMPLE,0>
A->B
M->A: <masterA,SAMPLE,0>
M->B: <slaveA,RIR,NONE>
M->A: <masterA,SAMPLE,0>
```

```
A->B
M->A: <masterA,SAMPLE,0>
M->B: <slaveA,RIR,NONE>
M->A: <masterA,SAMPLE,0>
A->B
M->A: <masterA,SAMPLE,0>
M->B: <slaveA,DIA,FLOM>
M->A: <masterA,SAMPLE,1>
A->B
M->A: <masterA,SAMPLE,0>
M->B: <slaveA,RIR,NONE>
M->A: <masterA,SAMPLE,1>
A->B
M->A: <masterA,SAMPLE,0>
M->B: <slaveA,RIR,NONE>
M->A: <masterA,SAMPLE,1>
...
```

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Security Analysis of Modbus Protocol

Discussion

- **Plausibility of this scenario**: Modbus specification addresses diagnostic functions only in serial line and ModbusPlus communication
  - Exist solutions extending these functionalities also in scenarios which exploit the tunneling of serial communication over TCP/IP and TCP/IP Modbus gateways
- **Performance**: negligible time to generate counterexample
  - Only a subset of functionalities are modeled
  - Optimizing strategies are necessary: SPIN does not generate the shortest possible counterexample

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Conclusions

- Automated and distributed control systems built using legacy devices and running legacy protocols
- Rapidly evolving to routable networks, increasing attack surface
- Modbus is widely adopted in industrial control systems
  - **Not designed to operate in a hostile environment**

Contribution

- **Analyzed Modbus with formal models**
  - From a high-level formalism based on hierarchical state-machines to a model suitable for model-checking
  - **We proved the existence of man-in-the-middle attacks**

Future work

- **Complete the modeling of Modbus protocol**
- **Formally prove other attacks**

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