Analysing the Impact of the Subtle Differences between AEADs on Protocol Security




Cas Cremers* **Alexander Dax*** Charlie Jacomme‡ Mang Zhao*

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‡ *INRIA Paris*

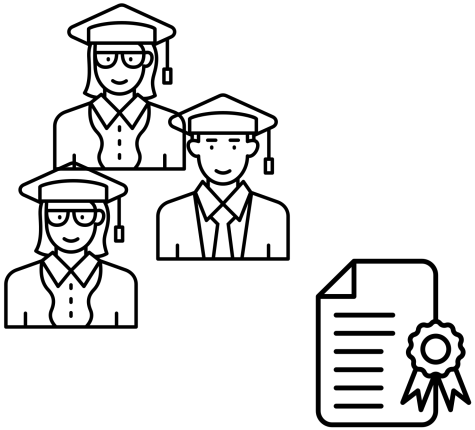
Setting: Protocol Analysis

Major Goal

Proving protocols secure

Discovering Attacks on Protocols

Classic Approach



Manual cryptographic proofs

Our Research Area

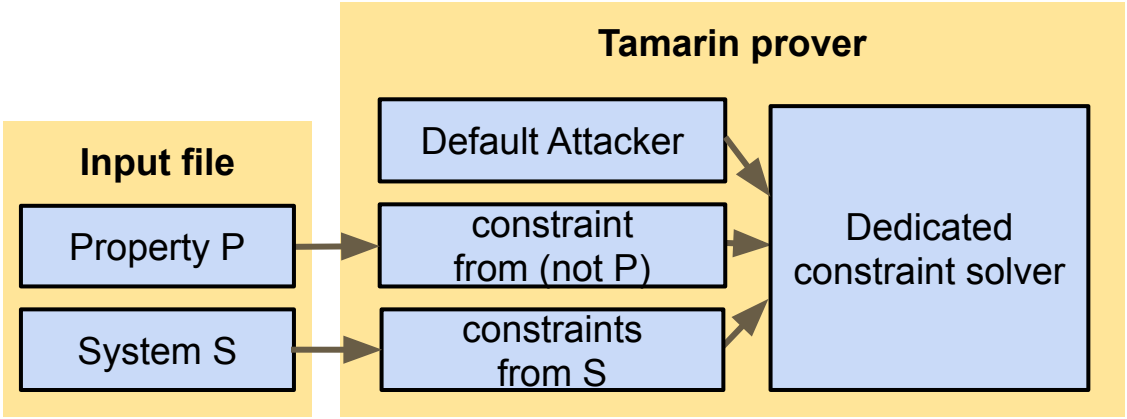
Automated Analysis

- Started in the 90s
- Big technical progress in recent years
- Used for large scale protocol analysis, e.g., TLS1.3, WPA2, EMV, LAKE.

We use the Tamarin Prover!

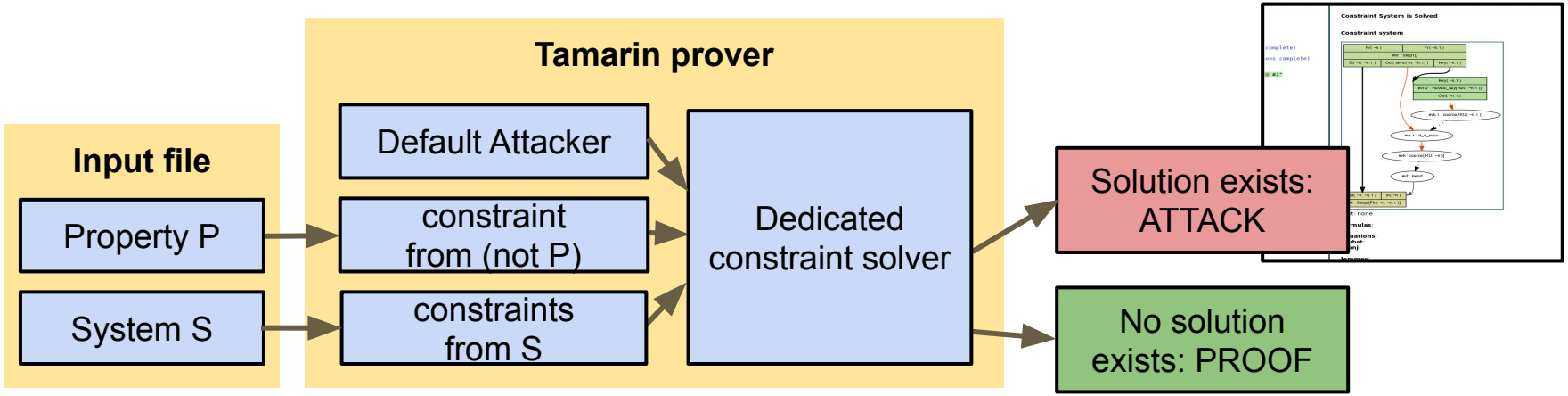
The Tamarin Prover

The Tamarin Prover



The Tamarin Prover

CISPA HELMHOLTZ CENTER FOR INFORMATION SECURITY



The Tamarin Prover

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Input file

Property P

System S

Tamarin prover

Default Attacker

constraint from (not P)

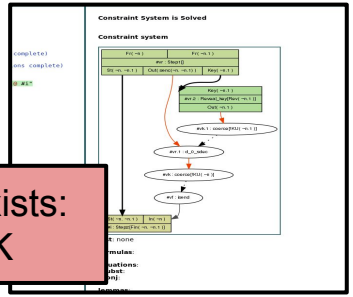
constraints from S

Dedicated constraint solver

Solution exists: ATTACK

No solution exists: PROOF

Run out of time or memory



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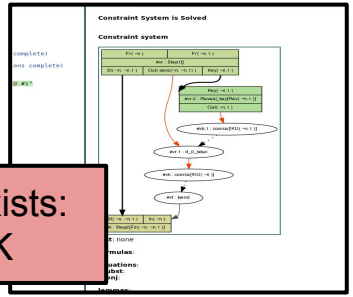
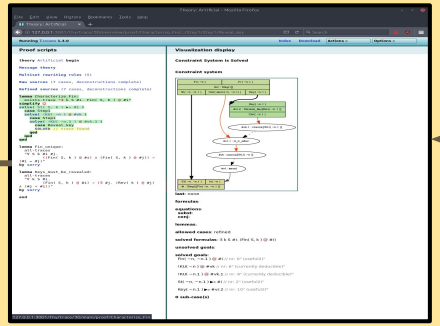
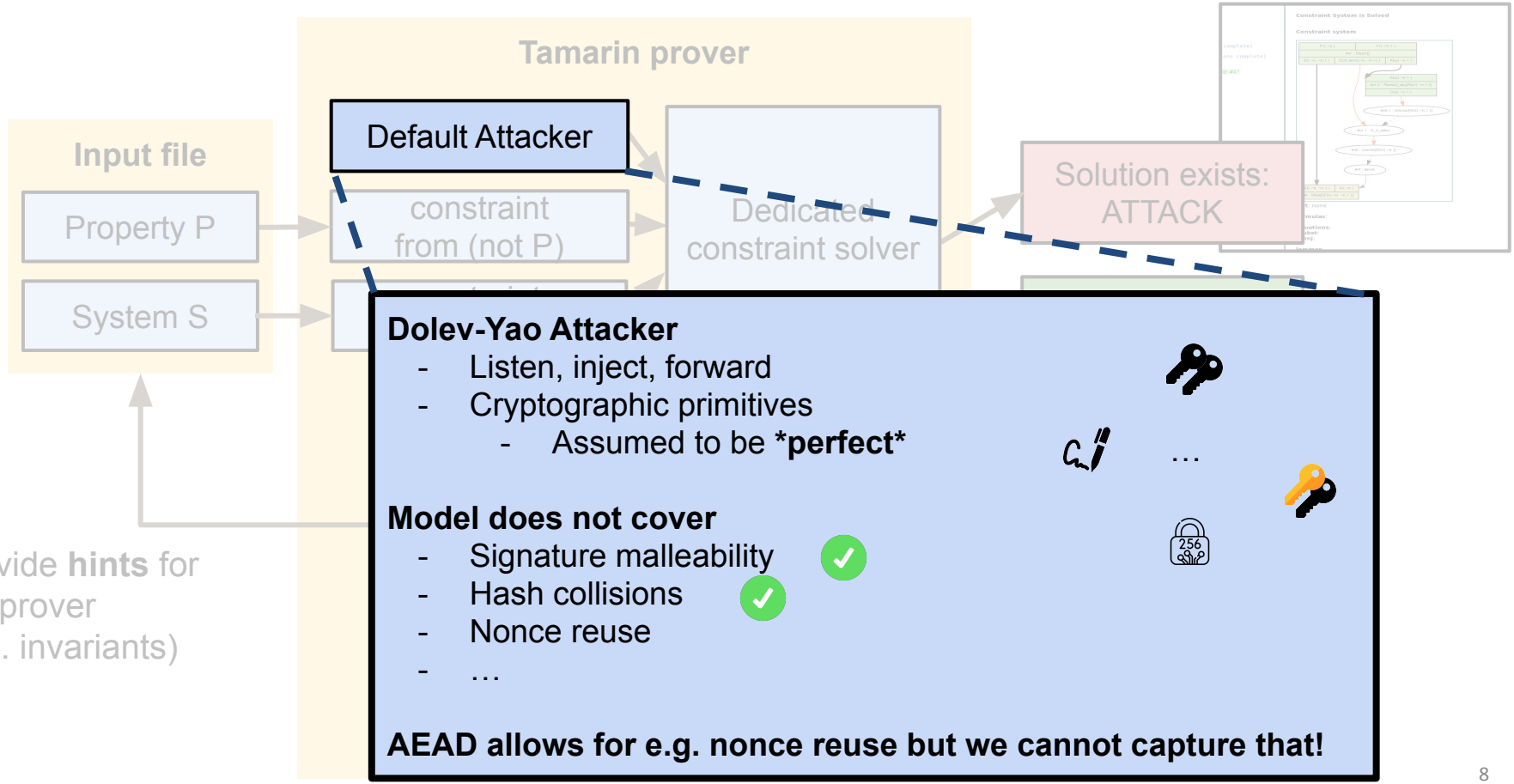




Interactive mode
(Inspect or guide partial proof)

Provide **hints** for the prover (e.g. invariants)

Authenticated Encryption with Associated Data



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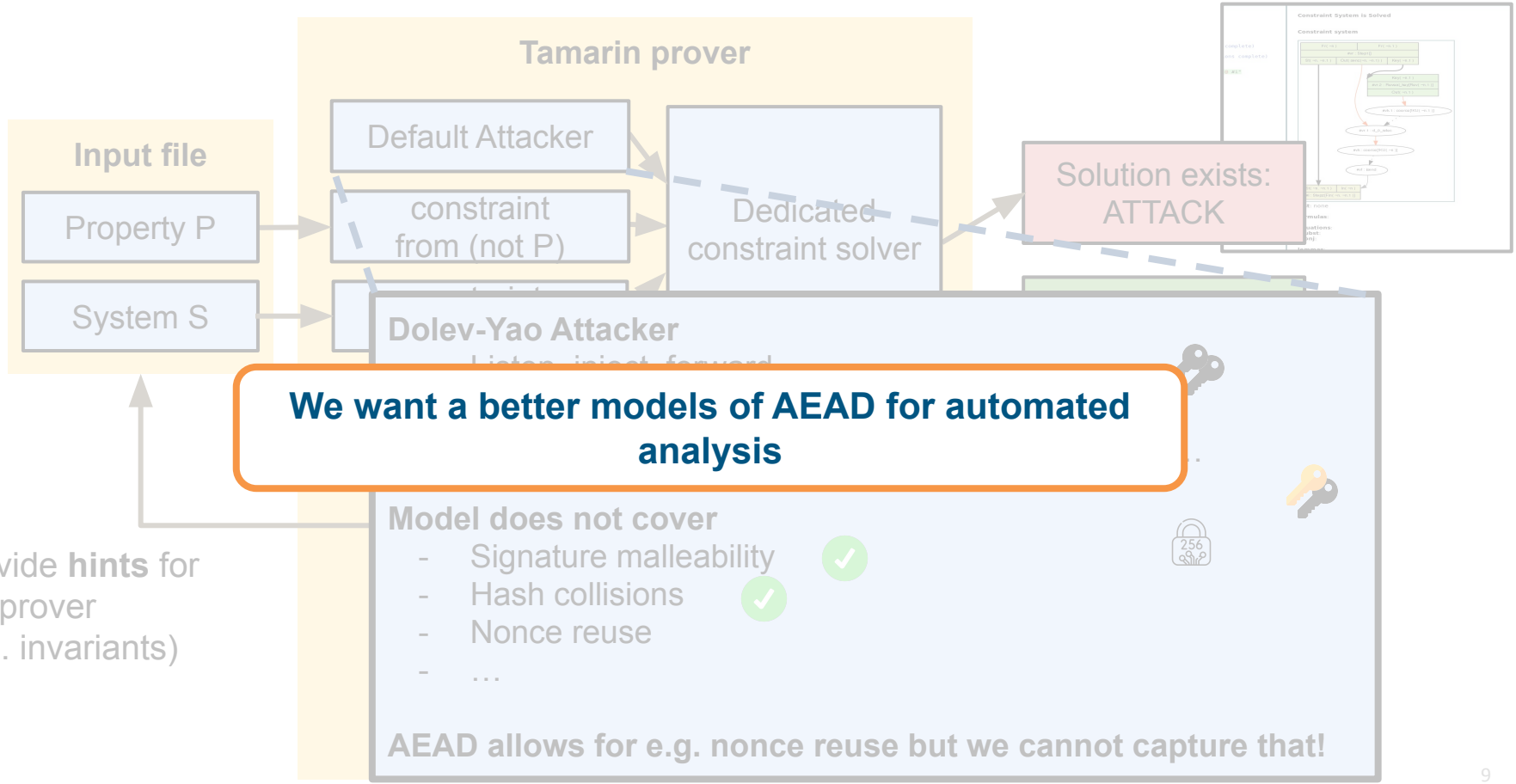
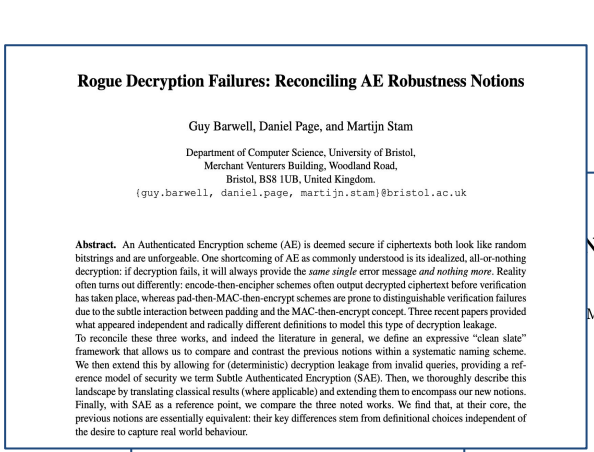


AEAD is complex!


Rogue Decryption Failures: Reconciling AE Robustness Notions

Guy Barwell, Daniel Page, and Martijn Stam

Department of Computer Science, University of Bristol,
Merchant Venturers Building, Woodland Road,
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{guy.barwell, daniel.page, martijn.stam}@bristol.ac.uk

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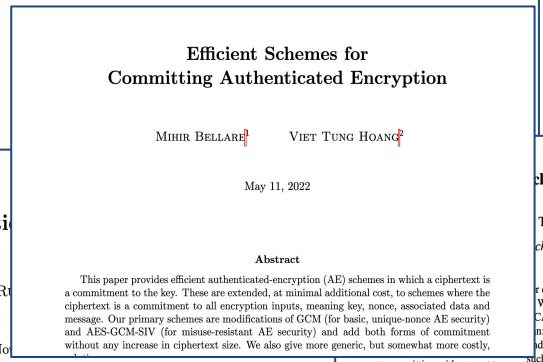
To reconcile these three works, and indeed the literature in general, we define an expressive "clean slate" framework that allows us to compare and contrast the previous notions within a systematic naming scheme. We then extend this by allowing for (deterministic) decryption leakage from invalid queries, providing a reference model of security we term Subtle Authenticated Encryption (SAE). Then, we thoroughly describe this landscape by translating classical results (where applicable) and extending them to encompass our new notions. Finally, with SAE as a reference point, we compare the three noted works. We find that, at their core, the previous notions are essentially equivalent: their key differences stem from definitional choices independent of the desire to capture real world behaviour.


John Chan and Phillip Rogaway

Keywords: anonymous encryption · authenticated encryption · nonces · privacy · provable security · symmetric encryption

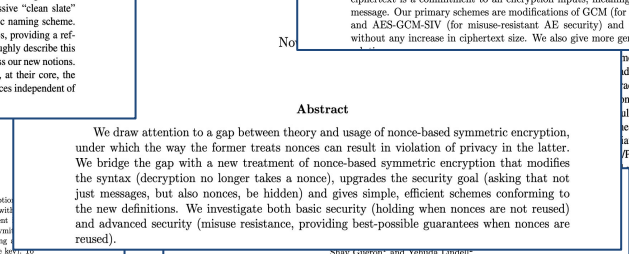

Efficient Schemes for
Committing Authenticated Encryption

Mihir Bellare[1] Viet Tung Hoang[2]

May 11, 2022

Abstract

This paper provides efficient authenticated-encryption (AE) schemes in which a ciphertext is a commitment to the key. These are extended, at minimal additional cost, to schemes where the ciphertext is a commitment to all encryption inputs, meaning key, nonce, associated data and message. Our primary schemes are modifications of GCM (for basic, unique-nonce AE security) and AES-GCM-SIV (for misuse-resistant AE security) and add both forms of commitment without any increase in ciphertext size. We also give more generic, but somewhat more costly,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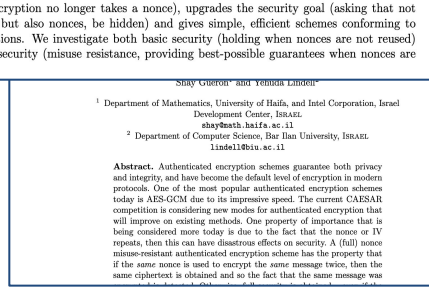
Shay Gueron[1] and Yehuda Lindell[2]

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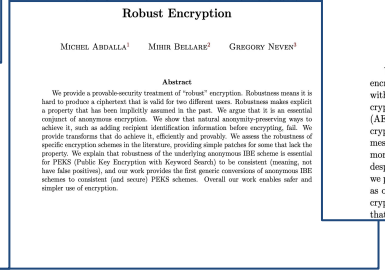
Robust Encryption

Michel Abdalla[1] Mihir Bellare[2] Gregory Neven[3]

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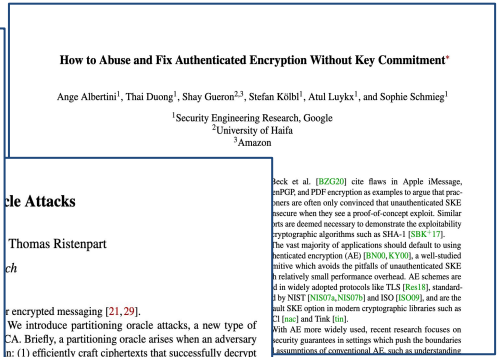
How to Abuse and Fix Authenticated Encryption Without Key Commitment*

Ange Albertini[1], Thai Duong[1], Shay Gueron[2,3], Stefan Kölbl[1], Atul Luykx[1], and Sophie Schmieg[1]

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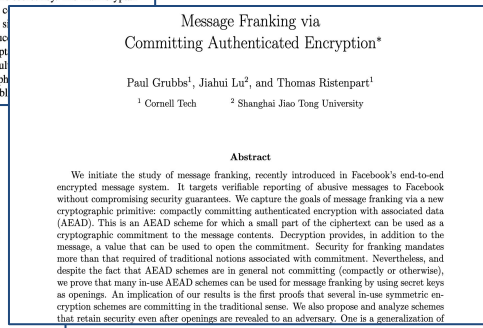
Message Franking via
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Paul Grubbs[1], Jiahui Lu[2], and Thomas Ristenpart[1]

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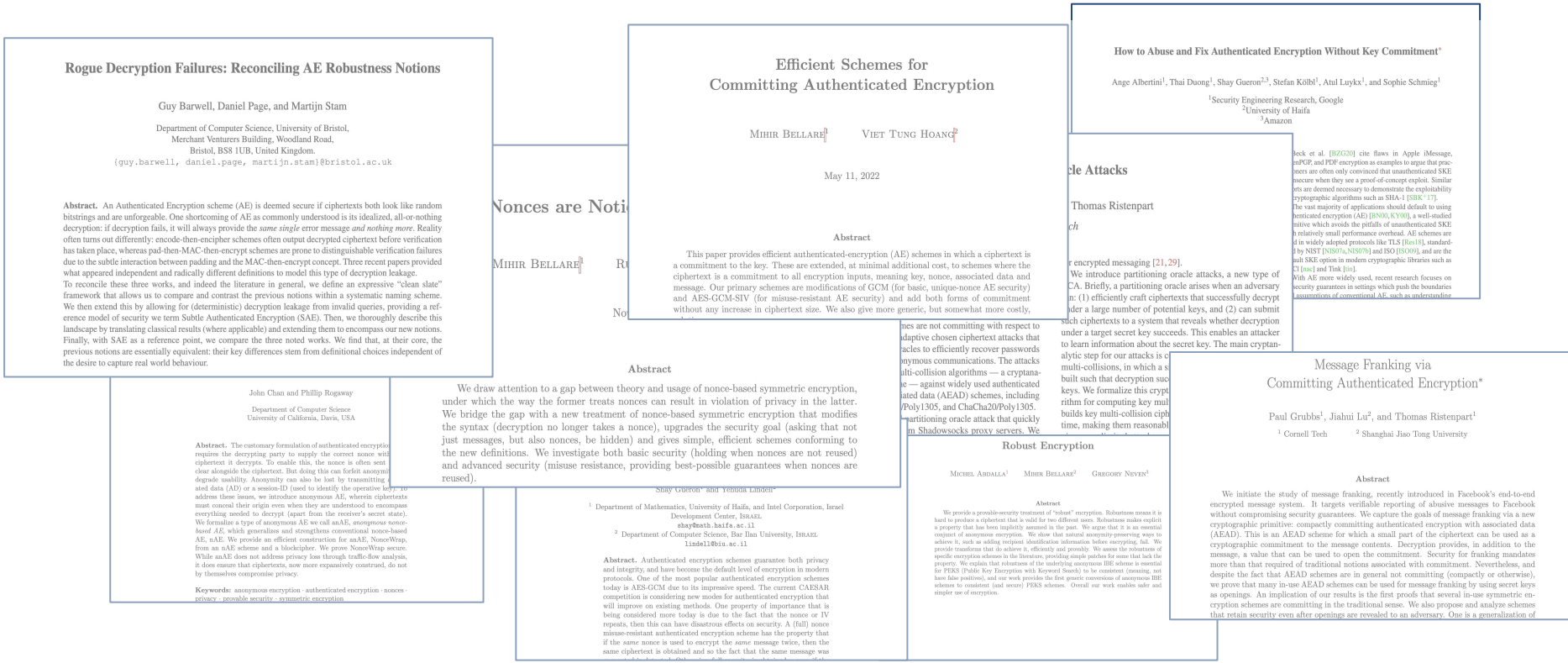
Only Academic Definitions!

Many competing definitions as we speak!

AEAD is complex!



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Nonces are Noti

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cle Attacks

Thomas Ristenpart

ch

g encrypted messaging [21, 29].
We introduce partitioning oracle attacks, a new type of
CA. Briefly, a partitioning oracle arises when an adversary
n: (1) efficiently craft ciphertexts that successfully decrypt
nder a large number of potential keys, and (2) can submit
uch ciphertexts to a system that reveals whether decryption
under a target secret key succeeds. This enables an attacker
to learn information about the secret key. The main cryptan-
alytic step for our attacks is c
multi-collisions, in which a s
built such that decryption suc
keys. We formalize this crypt
rithm for computing key mul
builds key multi-collision ciph
time, making them reasonabl
m Shadowsocks proxy servers. We

Beck et al. [BZG20] cite flaws in Apple iMessage,
enPGP, and PDF encryption as examples to argue that prac-
tioners are often only convinced that unauthenticated SKE
secure when they see a proof-of-concept exploit. Similar
rts are deemed necessary to demonstrate the exploitability
ryptographic algorithms such as SHA-1 [SBK+17].
The vast majority of applications should default to using
henticated encryption (AE) [BN00, KY00], a well-studied
mitive which avoids the pitfalls of unauthenticated SKE
h relatively small performance overhead. AE schemes are
d in widely adopted protocols like TLS [Res18], standard-
d by NIST [NIS07a, NIS07b] and ISO [ISO09], and are the
ault SKE option in modern cryptographic libraries such as
CI [Inac] and Tink [tin].
With AE more widely used, recent research focuses on
security guarantees in settings which push the boundaries
assumptions of conventional AE, such as understanding

John Chan and Phillip Rogaway

Department of Computer Science
University of California, Davis, USA

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requires the decrypting party to supply the correct nonce wit
ciphertext it decrypts. To enable this, the nonce is often sent
clear alongside the ciphertext. But doing this can forfeit anonymi
degrade usability. Anonymity can also be lost by transmitting
ated data (AD) or a session-ID (used to identify the operative key). To
address these issues, we introduce anonymous AE, wherein ciphertexts
must conceal their origin even when they are understood to encompass
everything needed to decrypt (apart from the receiver's secret state).
We formalize a type of anonymous AE we call anAE, *anonymous nonce-based AE*, which generalizes and strengthens conventional nonce-based AE, nAE. We provide an efficient construction for anAE, NonceWrap, from an nAE scheme and a blockcipher. We prove NonceWrap secure. While anAE does not address privacy loss through traffic-flow analysis, it does ensure that ciphertexts, now more expansively construed, do not by themselves compromise privacy.

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Many ways to misuse and misunderstand AEADs

Our Approach

1. We collected
   - definitions of AEAD constructions and properties
   - known AEAD attacks on the protocol level
2. We highlighted the relations of properties and proving the missing ones
3. We classified of the known attack vectors

What should we model?

4. We developed of multiple (symbolic) models to address the attack vector classes

Model it

5. We conducted case studies to show usefulness and feasibility of the new models
   - All case studies were analyzed completely automatic under all models

Test the model

AEAD Security in practice

We identify three big theoretical classes, that also allow to capture most practical attacks:

- Integrity & Privacy
- Collision Resistance
- Nonce Reuse Resistance

Concrete AEAD	Integrity and Privacy	Full Collision Resistance	Nonce Misuse Resistance
XSalsa20-Poly1305	●	✗	✗ Xor of plaintexts
AES-GCM	✓	✗	✗ Forgeability + xor of plaintexts
ChaCha20-Poly1305	✓	✗	✗ Xor of plaintexts
OCB3	✓	✗	✗ Forgeability + equality of blocks
EtM (unrelated keys)	✓	✗	✗ Encryption dependent
AES-CCM	✓	●	✗ Xor of plaintexts
AES-EAX	✓	●	✗ Xor of plaintexts
EtM (related keys)	✓	✓	✗ Encryption dependent
CAU-C4	✓	✓	✗ Forgeability + Xor of plaintexts
AES-GCM-SIV	✓	✗	✓
CAU-SIV-C4	✓	✓	✓

✓ : proven in the cited work(s). ● : we conjecture that this holds, but do not know of a proof.
✗ : does not hold, with reference or explanation of counterexample.

Our theoretical models of AEAD weaknesses

Weaknesses in the main classes:

- Integrity & Privacy weakness
- Collisions
- Nonce Reuse

For completion

Additional AEAD misuses:

- Decryption Misuse
- Tag Misuse
- Commit

Each weakness (class)

- has potentially multiple variants
- is modelled as an attacker capability
- can be combined in arbitrary fashion with the other classes

Case Study Methodology: Two Approaches

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Targeted Approach:

Check the protocol in the closest scenario from the real world

Preemptive Approach:

Check the protocol in all possible AEAD threat models

Case Study Methodology: Two Approaches

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Targeted Approach:

Check the protocol in the closest scenario from the real world, by extracting the info from the real world (in)-security of the concrete AEAD scheme used (see table)

Suitable for protocol analysis if:

- the concrete AEAD construction is known

Results:

- Is there currently an attack on the protocol?

Concrete AEAD	Integrity and Privacy	Full Collision Resistance	Nonce Misuse Resistance
XSalsa20-Poly1305	•	✗	✗ Xor of plaintexts
AES-GCM	✓	✗	✗ Forgeability + xor of plaintexts
ChaCha20-Poly1305	✓	✗	✗ Xor of plaintexts
OCB3	✓	✗	✗ Forgeability + equality of blocks
EtM (unrelated keys)	✓	✗	✗ Encryption dependent
AES-CCM	✓	•	✗ Xor of plaintexts
AES-EAX	✓	•	✗ Xor of plaintexts
EtM (related keys)	✓	✓	✗ Encryption dependent
CAU-C4	✓	✓	✗ Forgeability + Xor of plaintexts
AES-GCM-SIV	✓	✗	✓
CAU-SIV-C4	✓	✓	✓

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Case Study Methodology: Two Approaches

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AEAD_Wrapper(Model):

Run all combinations automatically and report the results

Preemptive Approach:

Check the protocol in all possible AEADs threat models

Suitable for protocol analysis if:

- one wants to find the requirements of the AEAD for a given protocol

Results:

- Minimal threat models that lead to potential attack
- Strongest threat models under which the protocol remains secure

Case Studies: Targeted Approach

Protocol	YubiHSM	SFrame	FB Message Franking
Attacked property	Key Secrecy	Authentication	Reporting
AEAD instance	AES-CCM	AES-GCM, EtM CTR	AES-GCM
Attack Model	Nonce Misuse	Tag	Collision
Time	2s	<1s	1s

Case Studies: Preemptive Approach

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Content agreement: Do all people within a group see the same set of messages?

Protocol	GPG SED	GPG SEIPDv2	Saltpack	Web Push API	WhatsApp	Scuttlebutt
Property	Content Agreement	Content Agreement	Content Agreement	Server Accountability	Content Agreement	Content Agreement
AEAD instance	PGP-CFB	AES-OCB	XSalsa20-Poly1305	AES-GCM	EtM CBC	XSalsa20-Poly1305
Assigned Class	Collision	Collision	Collision	Collision	Collision	Collision
Status	Yes, but deprecated	Infeasible	Infeasible	Reported	Reported	Reported

The full automated Tamarin analysis took less than 2 hours!

Take-Away and Summary

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Formal Methods are useful in Protocol Design and Analysis!

New Insight when using Authenticated Encryption within Protocols:

- New relations between AEAD properties
- Classification of Protocol vulnerabilities caused by AE
  - May be useful for *draft-irtf-cfrg-aead-properties*

https://tamarin-prover.github.io/

(First!) Automated analysis of protocols that rely on AEADs

- Useful during protocol design
- Automatic detection of vulnerabilities/unwanted behavior caused by AEAD
- Extendable!

Alexander Dax: alexander.dax@cispa.de

Artifact: https://github.com/AutomatedAnalysisOf/AEADProtocols

Paper: https://www.usenix.org/conference/usenixsecurity23/presentation/cremers-protocols

Usenix 2023 Distinguished Paper Award!

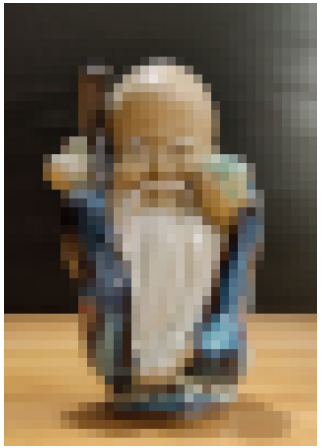
Formal security protocol analysis

Since early 1990's: **two main approaches**:

Reality

Computational

Prove probability of attack is negligible
Detailed models of encryption / signature



Symbolic

Focus on logical parts of the protocol design
Treat encryption / signature as black box

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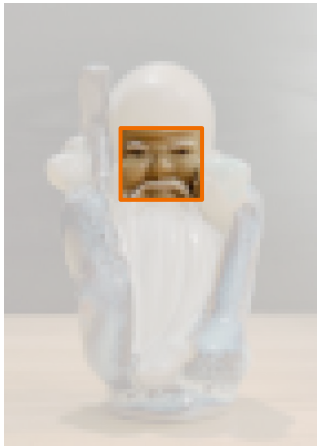

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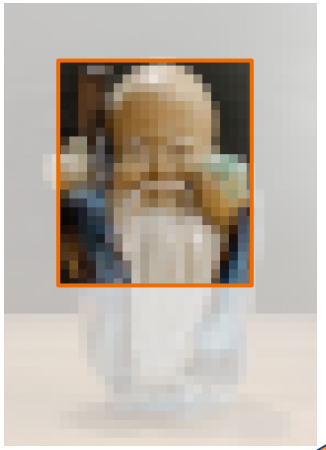

Symbolic

Focus on logical parts of the protocol design
Treat encryption / signature as black box

Our AEAD analysis using the Tamarin prover

Classify AEAD notions and attacks

Gather relations between the existing AEAD notions and properties …

…and prove the missing ones

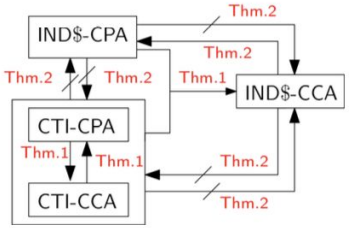

Figure 3: The relation between integrity and privacy for AEAD.

We identify three big theoretical classes, that also allow to capture most practical attacks:

- Integrity & Privacy
- Collision Resistance
- Nonce Reuse