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Security Goals for an Accordion Mode: Release of Unverified Plaintext and Multi-user security

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Our approach summarised

"Secure by design" philosophy
- Security should not depend on end-users being experts in cryptography
- High threat use cases require long-term security

Prioritise confidence over efficiency
- Robustness over performance
- Simplicity of security analysis

Formalising Two Security Goals

Release of Unverified Plaintext (RUP)

- Motivation
- A real-world RUP vulnerability
- Subtleties in security definitions
- NIST’s encode-then-encipher proposal achieves strong RUP security

Security Calculations

- Real-world advantage bounds must be usable in practice
- What parameters we can control
- Designing bounds to be instantiated

Application to MRAE

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Release of Unverified Plaintext (RUP)

Release of Unverified Plaintext

RUP happens when failed decryption attempts are not fully discarded

Examples:
- Buffers containing putative plaintext not cleared
- Authentication checks omitted
- Compiler reorders authentication check with follow-on processing
- Implementation returns error codes/does padding checks
- Can lead to practical attacks, eg Efail [10]

Effect:
- Decryptor leaks the putative plaintext despite failure of verification
- Decryptor processes the putative plaintext despite failure of verification

Possible risks:
- Adversary learns secret information from this leak
- Adversarial control of putative plaintext influences actions of the decryptor

We view robustness against RUP as essential

RUP security games

Typical setup: give distinguisher access to third “decrypt leakage” oracle
In ideal case, $Leak$ is simulated by $\mathcal{S}$
In real case, $Leak$ chosen to model likely mis-implementation of decryption

$$vs?$$

$$Enc, Dec, Leak \qquad \qquad \$, \perp, \mathcal{S}$$

Defining $Leak$ can be complicated:

- Is “likely mis-implementation” well defined?
- Should we also allow for leakage of any variable-length buffer, as well as putative plaintext?

RUP security games – Further issues

$vs?$

$Enc, Dec, Leak$ $\quad$ $\$, \perp, \mathcal{S}$

Defining $\mathcal{S}$ is nuanced:

- Security notions PA1 [1], AE-RUP [6] allow $\mathcal{S}$ to use the transcript of queries to Enc
  - Too weak: implies leakage can contain information about plaintexts
  - E.g. GCM is PA1 secure, but would not block Efail

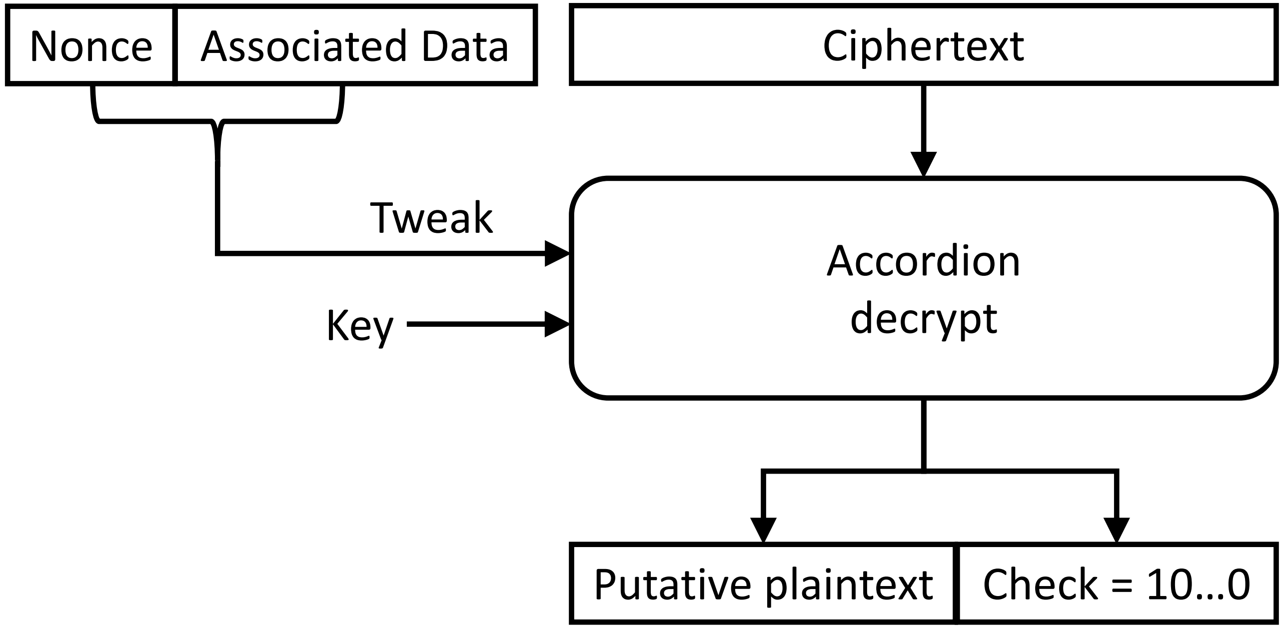
- Security notion SAE [3] is stronger - $\mathcal{S}$ may not view past transcript
  - Implies leakage cannot contain information about plaintexts
  - Still too weak: attacker can still exert control over leakage
  - E.g. an implementation that forwards the ciphertext on decryption failure is SAE secure, but undesirable

- On fresh inputs, $\mathcal{S}$ should output independent uniform random data
  - The proposal RUPAE [2] achieves this
  - We see strong RUP security - in this sense - as essential

RUP from Encode-then-Encipher

At birthday security levels, strong RUP security automatically follows from the proposed encode-then-encipher technique [7]

NCSC would like to see strong RUP security added as a design goal for the proposed accordion mode for AEAD



- Here the Accordion is a tweakable VIL-SPRP, so adversaries have no capability to learn from, or control, outputs to this function or its inverse

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Security Calculations

Security Bounds

A simple birthday advantage bound from a security proof might look like:

$$c\sigma^2/2^n$$

However, we deploy systems with many independent users, and wish to model adversaries attacking them all at once

Making a block cipher assumption, applying a standard hybrid argument for multi-user security (with per-user query restrictions), and requiring a security margin yields:

$$\mu c\sigma^2/2^n + \mu t/2^k \leq \varepsilon$$

Note that unlike some texts (e.g. [4]), we model each user as maintaining an independent query limit

Var.	Meaning
c	Small constant in proof
σ	Adversary query complexity budget
n	Block cipher block size
μ	Number of users (keys)
t	Adversary work budget
k	Block cipher key size
ε	Security margin

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Security budgets can be exceeded in large deployments

Taking the $\mu t/2^k$ term as negligible and rearranging gives:

$$\mu\sigma^2/\epsilon \leq 2^n$$

An example large deployment:

- $\mu \approx 2^{20}$ independent keys (users)
- each processing $\sigma \approx 2^{50}$ data
- for AES block size $n = 128$
- With proof constant $c \approx 16$
- Choice of confidence $\varepsilon \approx 10^{-9}$ as in NIST [8]

The inequality does not hold for large deployments

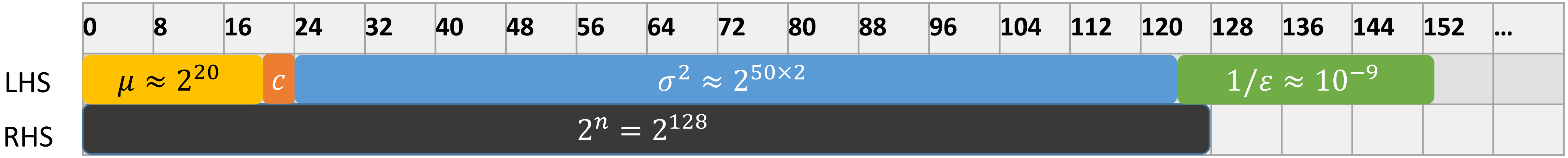

Figure: "Security budget", illustrates log-contribution of each term in the inequality

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Visualisations for different types of bound

Design	Visualization of inequality	Comments
Birthday bound with AES	μ, c, $\sigma^2 \approx 2^{50\times2}$, $1/\varepsilon$ $2^n = 2^{128}$	Not provably secure
Birthday bound with AES, restrictive per-user query limit	μ, c, $\sigma^2 \approx 2^{37\times2}$, $1/\varepsilon$ $2^n = 2^{128}$	Provably secure, but increasingly impractical to deploy
Beyond-birthday $\sigma^3/2^{2n}$ with AES	μ, c, $\sigma^3 \approx 2^{50\times3}$, $1/\varepsilon$ $2^{2n} = 2^{2\times128}$ …	Can be deployed now with AES as drop-in GCM replacement
Birthday mode, wider primitive $\sigma^2/2^N$, $N \gg 128$	μ, c, $\sigma^2 \approx 2^{50\times2}$, $1/\varepsilon$ *Larger Security budget* …	Desirable longer-term option

What variables can we control?

$$\mu\sigma^2/2^n + \mu t/2^k \leq \epsilon$$

Reconsider what terms make up this bound:

A more fine-grained bound can be helpful when instantiating, because we have more or less control over different variables

- Some we can easily enforce bounds
- Some we can estimate weak bounds from modelling
- Some are very hard to estimate

- Some common examples:

Var	Purpose	Restrictions
$\boldsymbol{\sigma_e}$	Total encrypted blocks per key	Each user can track and restrict independently
$\boldsymbol{\Sigma_e}$	Total encrypted blocks, all keys	Can’t enforce restriction without system-wide coordination
$\boldsymbol{\sigma_d}$	Total decrypted blocks per key	Can’t enforce a tight decryption limit (would enable DDOS attacks) can sometimes deduce soft limit from device bandwidth
$\boldsymbol{\mu}$	number of users/keys	Cannot enforce restriction without system-wide coordination Easier to estimate when keys are rotated on fixed schedule
$\boldsymbol{\epsilon}$	Security margin	Codifies user risk tolerance

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Visualisations of choices of variables (not to scale)

Design	Visualization of inequality	Comments
Generic Birthday bound	μ · c · σ · σ · $1/\varepsilon$ $2^n = 2^{128}$	For comparison, a σ^2 bound as before.
Representative of a tighter birthday bound	μ · c · q_e · $q_e + q_d \approx q_d$ · $1/\varepsilon$ $2^n = 2^{128}$	Even just splitting out q_e, q_d gets us closer to our goal
GCM Reconsidered [9, Thm 2]	μ · c · $q_e + q_d \approx q_d$ · $\sigma + q_e \approx \sigma$ · $1/\varepsilon$ $2^n = 2^{128}$	$\approx 64(q_e + q_d)(\sigma + q_e)/2^n$
VIGORNIAN first term [5, Thm 32]	μ · c · $q_e + 2q_d \approx 2q_d$ · $q_e + 2q_d \approx 2q_d$ · $q_e + 2q_d \approx 2q_d$ · $1/\varepsilon$ $2^{2n} = 2^{2\times128}$ …	$\approx 2^{10}\,\mu(q_e + 2q_d)^3/2^{2n}$

Interactions between MRAE and other security goals

Nonce repeats in decrypt queries

- Note that it is not feasible to prevent these
- In the event of RUP, security is bounded by the MRAE security level, even in a nonce-respecting mode

Limitation of MRAE security:

- Standard security analysis for an AEAD mode assesses against a TPRF
- By contrast, best attainable security while remaining decryptable is a TPRI [e.g. 7]
    - Tweakable Pseudo-Random Injection: distinct inputs on the same tweak give distinct outputs
- Security separation of TPRI and TPRF is birthday in the length of the output
    - distinction arises in the event of nonce repeats
- AEAD cannot generically attain TPRF security better than birthday in short message lengths

Should we adopt alternative idealisation of PRI?

- Potentially beyond-birthday secure even when misused
- Non-standard security notion likely not well understood by protocol designers, leading to fragility

Summary

Release of Unverified Plaintext (RUP)

- We hold “Secure by design” philosophy – security should not depend on end-users being experts in cryptography
- Subtleties in security definitions – we prefer a strong definition
- NIST’s encode-then-encipher proposal achieves this strong notion of RUP security
- We would like to see this added as a requirement

Security Calculations

- Real-world advantage bounds must be usable in practice
- Bounds should be constructed from parameters we can control

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