REDOCS'24

Designing a metamorphic test program in Rust for cryptographic primitives

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“It is not a bug, just an interesting unexpected behavior”

extrapolated from Fenzi *et al.*, 2018

Outline

- Research Objectives
- Background
  - Cryptographic Primitives
  - Security Requirements
  - Testing Crypto Requirements
- RQ0. Metamorphic testing
  - Metamorphic Testing Recipe
  - Practical Example : Kyber KEM
  - Experimentation and Results
- RQ1. Experimentation Details
  - Metamorphic Tests
  - Statistical Tests
- RQ2. Writing a Rust library
  - Introduction to Rust
  - Rust Crypto
  - Our library : `metamorphic-testing-rs`
- Conclusions
  - Key Takeaways

Research Objectives

1. **RQ0.** Review of a broad set of cryptographic primitives
2. **RQ1.** Build new metamorphic testing protocols
3. **RQ2.** Test *Rust Crypto* [1] for bugs

[1] https://github.com/RustCrypto

Outline

Background

Cryptographic Primitives

Security Requirements

Testing Crypto Requirements

Cryptographic Primitives Principles

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- Hash Functions (*e.g.*, SHA-256)
- Key Exchange Mechanism (KEM) (*e.g.* Kyber)
- Symmetric Encryption (SE) (*e.g.*, AES)
- Message Authentication Codes (*e.g.*, HMAC-SHA256)

Outline

Background

Cryptographic Primitives

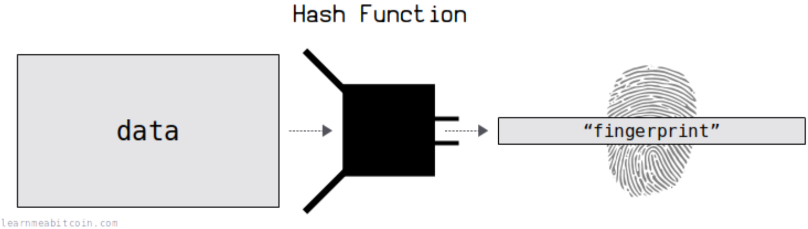
Security Requirements

Testing Crypto Requirements

What are security requirements ?

Explicit and **necessary** properties of crypto primitives

Hash Functions



Hash Function Security Reqs.

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1. First preimage resistance
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Hash Security Reqs :

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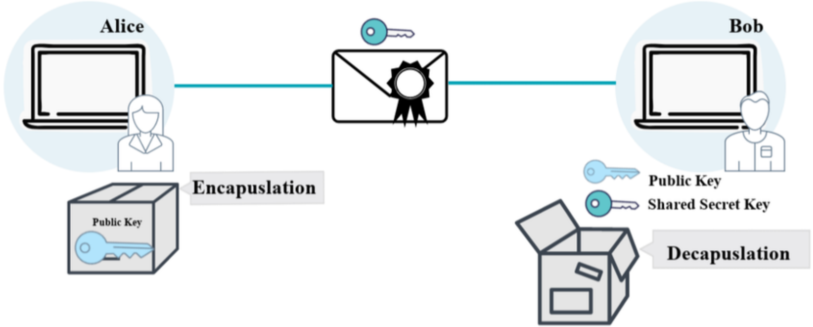
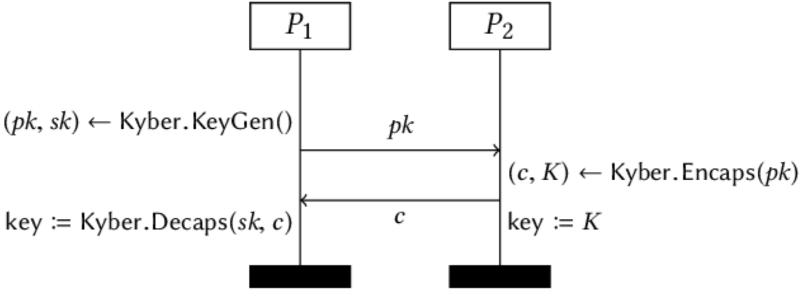
2. Second preimage resistance
   i.e. Cannot retrieve x' from $H(x)$ s.t. $H(x') = H(x)$
3. Collision resistance
   i.e. Cannot retrieve (x, y) s.t. $H(x) = H(y)$

Key Encapsulation Mechanisms (KEM)



Key Encapsulation Mechanisms (KEM) (2)



P_1

P_2

$(pk, sk) \leftarrow \text{Kyber.KeyGen}()$

pk

$(c, K) \leftarrow \text{Kyber.Encaps}(pk)$

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$\text{key} := \text{Kyber.Decaps}(sk, c)$

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KEM Security Requirements

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   i.e. Indistinguishability of secrets under Chosen Plaintext Attack

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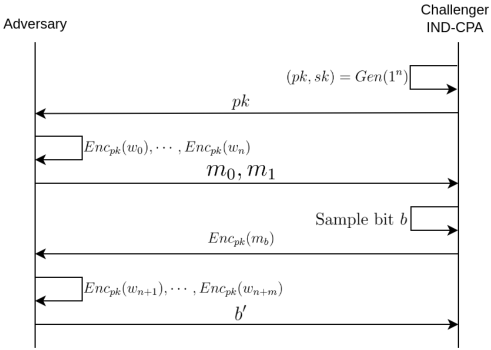

Outline

Background

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Testing security requirements (old way)

Algo. testing using tests vectors

```
**Input:** $p \leftarrow \{0,1\}^l$ // *Test vector input*
**Input:** $h_T \leftarrow SHA3_{REF}(p)$ // *Test vector ouput*
**Output:** Ok:pass

$h_t \leftarrow SHA3_{TEST}(p)$
$\texttt{assert}(h_t == h_T)$ // *Compare to Ref.*
```

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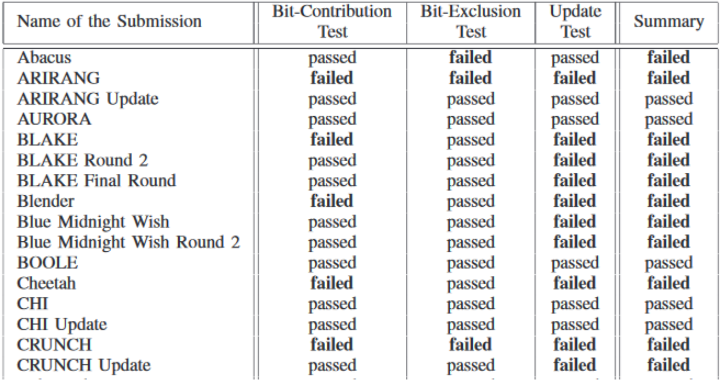
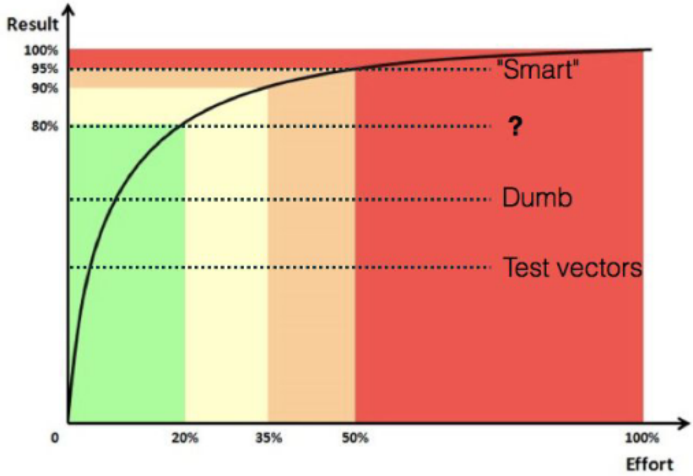
Just *trust* the reference implementation ... or don't ?



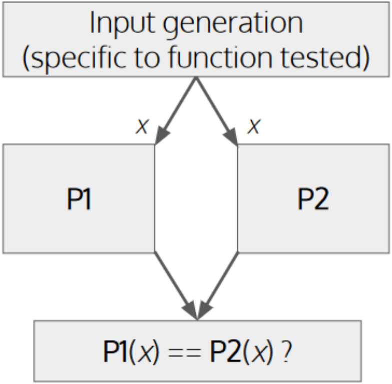
Name of the Submission	Bit-Contribution Test	Bit-Exclusion Test	Update Test	Summary
Abacus	passed	**failed**	passed	**failed**
ARIRANG	**failed**	**failed**	**failed**	**failed**
ARIRANG Update	passed	passed	passed	passed
AURORA	passed	passed	passed	passed
BLAKE	**failed**	passed	**failed**	**failed**
BLAKE Round 2	passed	passed	**failed**	**failed**
BLAKE Final Round	passed	passed	**failed**	**failed**
Blender	**failed**	passed	**failed**	**failed**
Blue Midnight Wish	passed	passed	**failed**	**failed**
Blue Midnight Wish Round 2	passed	passed	**failed**	**failed**
BOOLE	passed	passed	passed	passed
Cheetah	**failed**	passed	**failed**	**failed**
CHI	passed	passed	passed	passed
CHI Update	passed	passed	passed	passed
CRUNCH	**failed**	**failed**	**failed**	**failed**
CRUNCH Update	passed	passed	**failed**	**failed**

Figure: *Post-mortem* testing of SHA-3 NIST reference implem. [Mou+18]

Differential Fuzzing with CDF (2017) (1)



Differential Fuzzing with CDF (2017) (2)



Differential Fuzzing with CDF (2017) (3)

Problem

What if you don't have two different implementations ?

Outline

RQ0. Metamorphic testing

- Metamorphic Testing Recipe
- Practical Example : Kyber KEM
- Experimentation and Results

Metamorphic Testing Recipe

1. **Identify Metamorphic Relations (MRs)**
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3. **Maul Input**
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1. **Identify Metamorphic Relations (MRs)**
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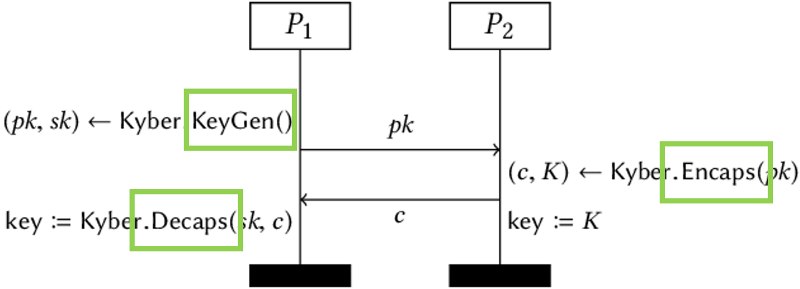
2. **Generate Initial Test Cases**
   → Run the program with initial inputs
3. **Maul Input**
   → Modify input based on MRs and generate new test cases.
4. **Verify Outputs**
   → Ensure modified inputs produce expected results from MR.

Metamorphic Test Gadgets



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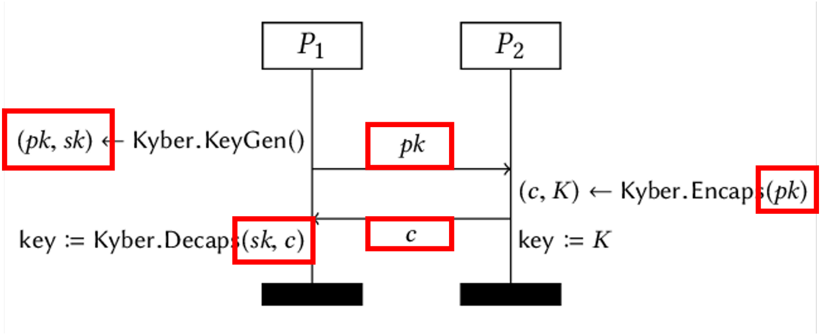
Metamorphic Test Inputs


P_1
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$(pk, sk) \leftarrow$ Kyber.KeyGen()
pk
$(c, K) \leftarrow$ Kyber.Encaps(pk)
c
key := Kyber.Decaps(sk, c)
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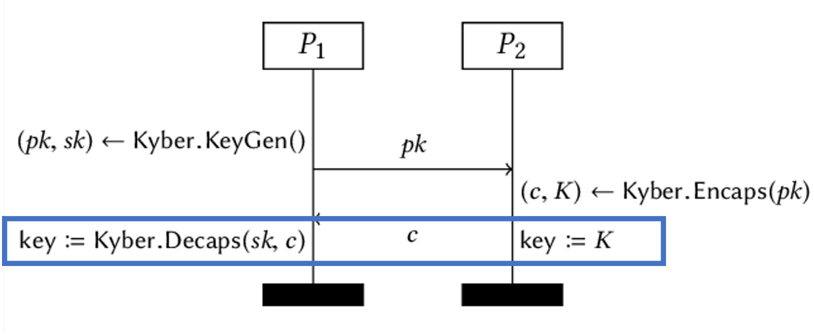
Metamorphic Test MR



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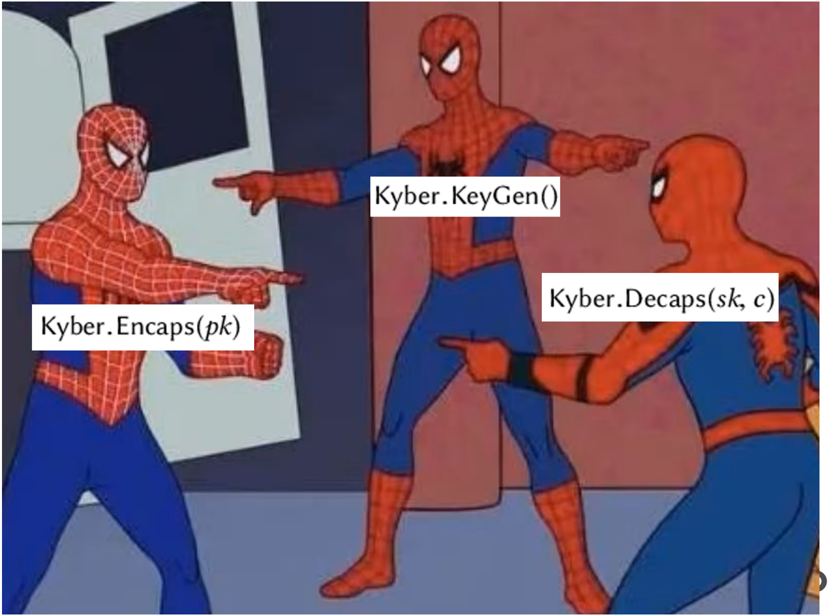
MRs in a nutshell



Metamorphic Example

Target MR :

$$\texttt{Kyber} \quad : \quad \texttt{encaps}(pk, r) = \texttt{decaps}(sk, \texttt{encaps}(pk, r))$$

Associated Test :

Input: $r \leftarrow_{\$} \{0, 1\}^l$

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```
$pk, sk \leftarrow \texttt{Gen}(r)$
$ss, c \leftarrow \texttt{Encaps}(pk)$
**for** $i \leq len(pk)$ **do**
    $pk' \leftarrow \texttt{Maul}(pk)$
    $ss', c' \leftarrow \texttt{Encaps}(pk')$
```

Metamorphic Example

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    $\texttt{assert}((ss', \_)! = (ss, \_))$
end for
```

Examples `Maul()`

- **Bit-Contribution**
  → *verify all input bits impact output*

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- **Bit-Exclusion**
  → *verify padding related functions*
- **Update**
  → *verify `SHA3`-like compress & update cycles*

Bit Contribution `Maul()`

Skeleton

```
Input: $x$
for $i \leq l = len(x)$ do
    $x' \leftarrow \{0\}^{l-i} || \{1\}^i$
    call
end for
```

Bit Contribution `Maul()`

Skeleton

```
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end for
```

Test Hash Function

```
Input: $x$
$h \leftarrow \mathtt{SHA256}(x)$
for $i \leq l = len(x)$ do
    $x' \leftarrow \{0\}^{l-i} || \{1\}^{i}$
    $h' \leftarrow \mathtt{SHA256}(x')$
    $\mathtt{assert}(h' ! = h)$
end for
```

Bit Exclusion `Maul()`

Skeleton

```
Input: $x$
$l_1 \leftarrow \text{len}(x) \mod 8$
$l_2 \leftarrow \text{len}(x)$
for $i = l_2 - 1$ to $l_1$ do
    $x' \leftarrow \{x\}^{l_2} || \{0\}^i$
    call
end for
```

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```

Test Hash Function

```
Input: $x$
$h \leftarrow \texttt{SHA256}(x)$
for $i \leq l = len(x)$ do
    $x' \leftarrow$ Maul()
    $h' \leftarrow \texttt{SHA256}(x')$
    assert$(h'! = h)$
end for
```

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    $\texttt{assert}(h'! = h)$
end for
```

Note : This is especially useful for C programs

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```

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**for** i = 0 **to** $\texttt{len}$(pk) **do**
    $pk' \leftarrow \texttt{Maul}(pk)$
    $(ss', c') \leftarrow \texttt{Encaps}(pk')$
    **assert** $(ss' \neq ss)$
**end for**
```

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Experimentation and Results

Overview of conducted tests (1)

Total : 69 test rounds, 21 primitives tested, 1 *bug* found (twice)

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Crate	MR	Maul()	API	Bugs
PQC_KYBER	$\mathtt{encaps}(pk, r) = \mathtt{decaps}(sk, \mathtt{encaps}(pk, r))$	$\mathtt{gen}(\mathtt{maul}(\mathbf{r}))$	No	0
		$\mathtt{encaps}(pk, \mathtt{maul}(r))$	Yes	0
		$\mathtt{encaps}(\mathtt{maul}(pk), r)$	Yes	0
		$\mathtt{decaps}(\mathtt{maul}(sk), r)$	Yes	1
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Total : 69 test rounds, 21 primitives tested, 1 *bug* found (twice)

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		$\texttt{decaps}(sk, \texttt{maul}(r))$	Yes	0
ML-KEM	$\texttt{encaps}(pk, r) = \texttt{decaps}(sk, \texttt{encaps}(pk, r))$	$\texttt{gen}(\texttt{maul}(\mathbf{r}))$	No	0
		$\texttt{encaps}(pk, \texttt{maul}(r)$	Yes	0
		$\texttt{encaps}(\texttt{maul}(pk), r)$	Yes	0
		$\texttt{decaps}(\texttt{maul}(sk), r)$	Yes	1
		$\texttt{decaps}(sk, \texttt{maul}(r))$	Yes	0

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Crate	MR	`Maul()`	API	Bugs
`SHA2`	$\mathtt{H}(x) \sim U(0, 2^{\mathbf{256}})$	$\mathtt{H}(\mathtt{maul}(x))$	No	0
	$\mathtt{H}(x) \sim U(0, 2^{\mathbf{512}})$	$\mathtt{H}(\mathtt{maul}(x))$	No	0
	$\mathtt{H}(x) \neq \mathtt{H}(x')$	$\mathtt{H}(x) = \mathtt{update}(\mathtt{H}(x_{\mathbf{1}}), \mathtt{H}(x_{\mathbf{2}}), \ldots)$	No	0

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`SHA3`	$\mathtt{H}(x) \sim U(0, 2^{256})$	$\mathtt{H}(\mathtt{maul}(x))$	No	0
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PBKDF2	$\mathtt{PBKDF2}(x) \sim U(0, 2^{160})$	$\mathtt{pbkdf2}(\mathtt{SHA2}(\mathtt{maul}(x)))$	No	0
		$\mathtt{pbkdf2}(\mathtt{SHA2}(\mathtt{maul}(x)))$	No	0
		$\mathtt{pbkdf2}(\mathtt{SHA3}(\mathtt{maul}(x)))$	No	0
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		$\mathtt{pbkdf2}(\mathtt{SHA3}(\mathtt{maul}(x)))$	No	0
		$\mathtt{pbkdf2}(\mathtt{SHA3}(\mathtt{maul}(x)))$	No	0
SHA2 Compression	$\mathtt{H}(x) \sim U(0, 2^{256})$	$\mathtt{H}(\mathtt{maul}(x))$	No	0
	$\mathtt{H}(x) \sim U(0, 2^{512})$	$\mathtt{H}(\mathtt{maul}(x))$	No	0
SHA3 Compression	$\mathtt{H}(x) \sim U(0, 2^{256})$	$\mathtt{H}(\mathtt{maul}(x))$	No	0
	$\mathtt{H}(x) \sim U(0, 2^{512})$	$\mathtt{H}(\mathtt{maul}(x))$	No	0

Overview of conducted tests (1)

Crate	MR	Maul()	API	Bugs
SHA2	$\mathtt{H}(x) \sim U(0, 2^{256})$	$\mathtt{H}(\mathtt{maul}(x))$	No	0
	$\mathtt{H}(x) \sim U(0, 2^{512})$	$\mathtt{H}(\mathtt{maul}(x))$	No	0
	$\mathtt{H}(x) \neq \mathtt{H}(x')$	$\mathtt{H}(x) = \mathtt{update}(\mathtt{H}(x_1), \mathtt{H}(x_2), \ldots)$	No	0
SHA3	$\mathtt{H}(x) \sim U(0, 2^{256})$	$\mathtt{H}(\mathtt{maul}(x))$	No	0
	$\mathtt{H}(x) \sim U(0, 2^{512})$	$\mathtt{H}(\mathtt{maul}(x))$	No	0
	$\mathtt{H}(x) \neq \mathtt{H}(x')$	$\mathtt{H}(x) = \mathtt{update}(\mathtt{H}(x_1), \mathtt{H}(x_2), \ldots)$	No	0
PBKDF2	$\mathtt{PBKDF2}(x) \sim U(0, 2^{160})$	$\mathtt{pbkdf2}(\mathtt{SHA2}(\mathtt{maul}(x)))$	No	0
		$\mathtt{pbkdf2}(\mathtt{SHA2}(\mathtt{maul}(x)))$	No	0
		$\mathtt{pbkdf2}(\mathtt{SHA3}(\mathtt{maul}(x)))$	No	0
		$\mathtt{pbkdf2}(\mathtt{SHA3}(\mathtt{maul}(x)))$	No	0
SHA2 Compression	$\mathtt{H}(x) \sim U(0, 2^{256})$	$\mathtt{H}(\mathtt{maul}(x))$	No	0
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BLAKE2	$\mathtt{H}(x) \sim U(0, 2^{k})$	$\mathtt{H}(\mathtt{maul}(x))$	Yes	0
BLAKE3	$\mathtt{H}(x) \sim U(0, 2^{k})$	$\mathtt{H}(\mathtt{maul}(x))$	Yes	0

Outline

RQ1. Experimentation Details

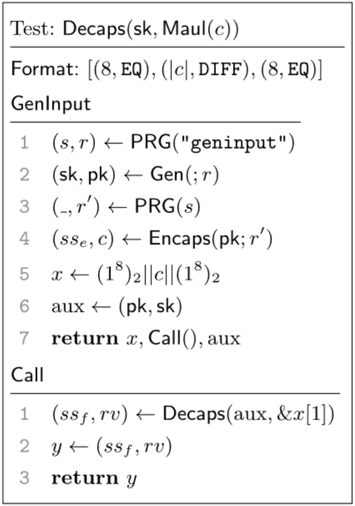
- Metamorphic Tests
- Statistical Tests

Kyber KEM - Test 2

```
Test: $\mathsf{Encaps}(\mathsf{Maul}(\mathsf{pk}); r)$
Format: $[(8, \texttt{EQ}), (|\mathsf{pk}|, \texttt{DIFF}), (8, \texttt{EQ})]$
GenInput
    $(\_, r) \leftarrow \mathsf{PRG}(\texttt{"geninput"})$
    $(\mathsf{pk}, \mathsf{sk}, rv) \leftarrow \mathsf{Gen}(; r)$
    $x \leftarrow (1^8)_2 || \mathsf{pk} || (1^8)_2$
    $\mathrm{aux} \leftarrow \mathsf{sk}$
    return $x, \mathsf{Call}(), \mathrm{aux}$
Call
    $(\_, r) \leftarrow \mathsf{PRG}(\texttt{"call"})$
    $(ss, c, rv) \leftarrow \mathsf{Encaps}(\&x[1]; r)$
    $y \leftarrow (ss || c, rv)$
    return $y$
```

```
Test: $\mathsf{Decaps}(\mathsf{sk}, \mathsf{Encaps}(\mathsf{Maul}(\mathsf{pk}); r))$
Format: $[(8, \texttt{EQ}), (|\mathsf{pk}|, \texttt{DIFF}), (8, \texttt{EQ})]$
GenInput
    $(\_, r) \leftarrow \mathsf{PRG}(\texttt{"geninput"})$
    $(\mathsf{pk}, \mathsf{sk}, rv) \leftarrow \mathsf{Gen}(; r)$
    $x \leftarrow (1^8)_2 || \mathsf{pk} || (1^8)_2$
    $\mathrm{aux} \leftarrow \mathsf{sk}$
    return $x, \mathsf{Call}(), \mathrm{aux}$
Call
    $(\_, r) \leftarrow \mathsf{PRG}(\texttt{"call"})$
    $(ss_e, c) \leftarrow \mathsf{Encaps}(\&x[1]; r)$
    $(ss_f, rv) \leftarrow \mathsf{Decaps}(c, \mathrm{aux})$
    $eq \leftarrow [\![ss_e = ss_f]\!]$
    $y \leftarrow (eq, rv)$
    return $y$
```

Kyber KEM - Test 3



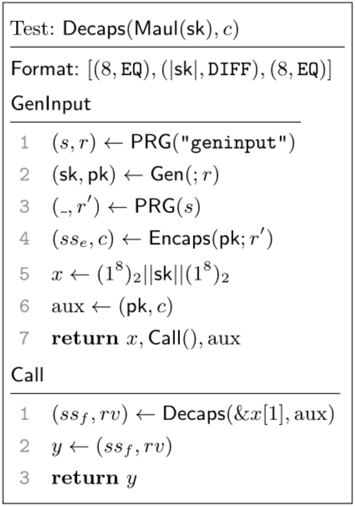
```
Test: Decaps(sk, Maul($c$))

Format: $[(8, \texttt{EQ}), (|c|, \texttt{DIFF}), (8, \texttt{EQ})]$

GenInput
    $(s, r) \leftarrow \mathsf{PRG}(\texttt{"geninput"})$
    $(\mathsf{sk}, \mathsf{pk}) \leftarrow \mathsf{Gen}(; r)$
    $(\_, r') \leftarrow \mathsf{PRG}(s)$
    $(ss_e, c) \leftarrow \mathsf{Encaps}(\mathsf{pk}; r')$
    $x \leftarrow (1^8)_2||c||(1^8)_2$
    $\mathrm{aux} \leftarrow (\mathsf{pk}, \mathsf{sk})$
    return $x$, Call(), aux

Call
    $(ss_f, rv) \leftarrow \mathsf{Decaps}(\mathrm{aux}, \&x[1])$
    $y \leftarrow (ss_f, rv)$
    return $y$
```

Kyber KEM - Test 4 (1)



Test: Decaps(Maul(sk), c)

Format: $[(8, \texttt{EQ}), (|\mathsf{sk}|, \texttt{DIFF}), (8, \texttt{EQ})]$

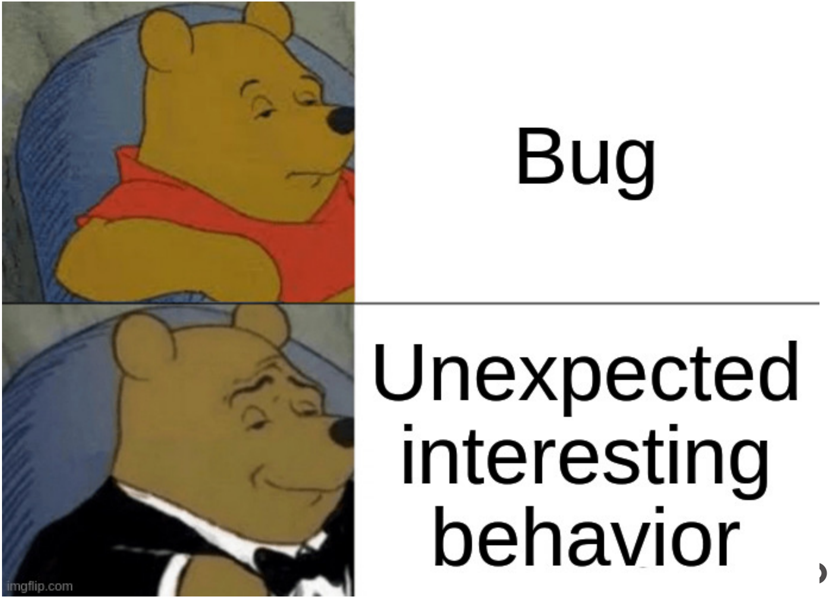
GenInput

```
$(s, r) \leftarrow$ PRG("geninput")
$(\mathsf{sk}, \mathsf{pk}) \leftarrow$ Gen$(; r)$
$(\_, r') \leftarrow$ PRG$(s)$
$(ss_e, c) \leftarrow$ Encaps$(\mathsf{pk}; r')$
$x \leftarrow (1^8)_2 || \mathsf{sk} || (1^8)_2$
$\mathrm{aux} \leftarrow (\mathsf{pk}, c)$
return $x$, Call(), $\mathrm{aux}$
```

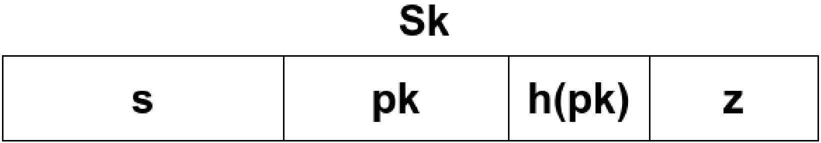
Call

```
$(ss_f, rv) \leftarrow$ Decaps$(\&x[1], \mathrm{aux})$
$y \leftarrow (ss_f, rv)$
return $y$
```

2 interpretations ...



Kyber KEM - Test 4 (2)



Sk

s	pk	h(pk)	z

Figure: Kyber KEM secret key layout

Testing SHA-1,2,3

```
Test: $\mathsf{Hash}(\mathsf{Maul}(x))$

Format: $[(8, \texttt{EQ}), (\ell, \texttt{DIFF}), (8, \texttt{EQ})]$

GenInput
    $x \leftarrow (1^8)_2||(0^\ell)_2||(1^8)_2$
    $\mathrm{aux} \leftarrow \perp$
    $\textbf{return } x, \mathsf{Call}(), \mathrm{aux}$

Call
    $y \leftarrow \mathsf{Hash}(\&x[1])$
    $\textbf{return } y$
```

Outline

RQ1. Experimentation Details

- Metamorphic Tests
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statistical tests

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- They ensure bit distribution “looks like random"
- It’s like ensuring that a dice isn’t loaded by throwing it multiple times
- We used TestU01 test suite on outputs from different HMAC and hash compression algorithms

Outline

RQ2. Writing a Rust library

- Introduction to Rust
- Rust Crypto
- Our library : `metamorphic-testing-rs`

Rust

What is Rust ?

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What is Rust ?

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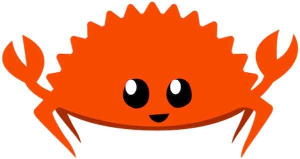
- Emphasis on memory safety
- Try to avoid runtime errors
- Many critical use-cases (Network stack, Kernel, . . .)
- Best programming language



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Biggest cryptographic library but others do exist (Ring...)

How to test crypto function with Rust ?

```
use sha3::{Digest, Sha3_256};

let mut hasher = Sha3_256::new();
hasher.update(b"abc");
let hash = hasher.finalize();
```

Figure: Rust code to use SHA3 256

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A metamorphic test is a set of five functions : `GenInput`, `GenState`, `Call`, `Maul`, `Check`

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```
$\sigma \leftarrow \texttt{GenState}()$
$x \leftarrow \texttt{GenInput}(n)$
$y \leftarrow \texttt{Call}(\sigma, x)$
for $i$ in $1, \ldots,$ runs do
    $\sigma', x' \leftarrow \texttt{Maul}(\sigma, x, i)$
    $y' \leftarrow \texttt{Call}(\sigma', x')$
    $\texttt{Check}(y, y')$
end for
```

Figure: Fenzi inspired test framework

Applying our framework to SHA in Rust

How to apply our Bit Inclusion test to SHA3 256 ?

Applying our framework to SHA in Rust

How to apply our Bit Inclusion test to SHA3 256 ?

```
fn gen_state() -> Sha3_256 {
    return Sha3_256::new();
}

fn gen_input(n: usize) -> Vec<u8> {
    return Rand::randbytes(n).to_vec();
}

fn call(state: Sha3_256, input: Vec<u8>) -> Hash{
    state.update(input);
    return state.finalize();
}

fn maul(state: Sha3_256, input: Vec<u8>, i: usize) -> (Sha3_256, Vec<u8>) {
    let output = input;
    flip_bit_at_index(&mut output, i);
    return (state, output);
}

fn check(ref_output: Vec<u8>, output: Vec<u8>) -> bool {
    return ref_output != output;
}
```

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Rust library[2] allowing to create and run metamorphic tests

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- Only two lines of code to add a new hash implementation from Rust Crypto
- Run tests in parallel to improve speed
- Free and open source

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Outline

Conclusions

Key Takeaways

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1. Metamorphic testing is useful when no oracle is available
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5. Future works : test more primitives (NTLM ;))

Thank you !