Improving the Security of Quantum Platforms using Combinatorial Methods

Workshop on Secure Protocol Implementations in the Quantum Era

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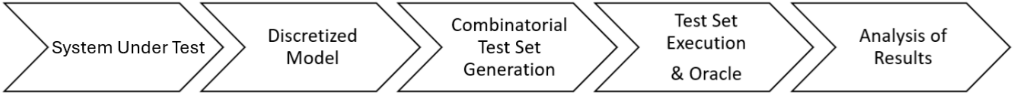
Outline of the Talk

Introduction to CT

Combinatorial Testing (CT)

- Application of combinatorial methods to (software) testing problems
- *System under Test* modelled in terms of finitely many parameters taking finitely many values
- Test set generation based on combinatorial coverage criteria
- CT has been successfully applied to
  - Software configuration testing;
  - Software input data testing;
  - Hardware testing;
  - ML/AI testing;
  - Security testing.



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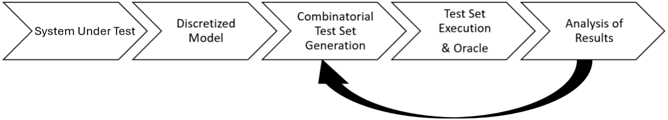
  - ML/AI testing;
  - Security testing.
  - Test-cycle iterations / Combinatorial fault localization



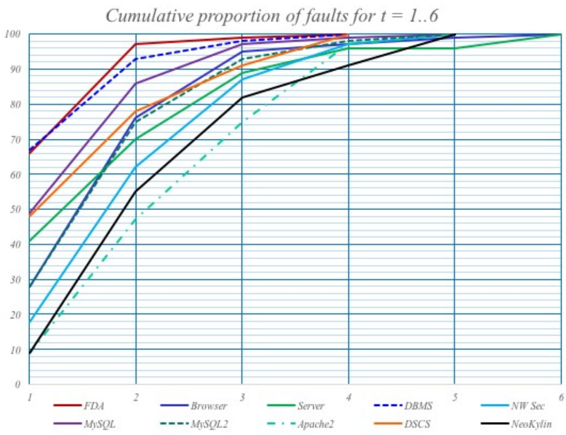


Figure: Visualization graph of results of NIST fault studies (NIST).

Implications for software testing

Observation from the NIST fault study:

- Most failures are induced by single factor faults;
- With progressively fewer failures induced by interactions between two or more factors.

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- Most failures are induced by single factor faults;
- With progressively fewer failures induced by interactions between two or more factors.

$\Longrightarrow$ Tests that cover all such few variable-interactions can be very effective!

Covering Arrays (structures in Discrete Mathematics)

Guaranteed diversity in terms of tuples

Definition

Let $t, k, v \in \mathbb{N} \wedge t \leq k$.
A covering array (CA) for the configuration $C = (t, k, v)$ is defined as

- an $N \times k$ array over a finite alphabet A of cardinality v,
- such that in any $N \times t$ subarray all possible t-tuples arising from this alphabet A appear at least once as rows in the selected subarray.

Denoted as $CA(N; t, k, v)$.

Covering Array Example

From combinatorial designs to sofware artifacts

- t-way test sets (i.e., combinatorial) derived from covering arrays
- every row is a test case; appropriate translation of values, below: 0 $\rightarrow$ False, 1 $\rightarrow$ True

0	0	0	0	0	0	0	0	0	0
0	0	1	1	1	1	1	1	1	1
0	1	0	1	0	1	0	1	0	1
0	1	1	0	1	0	1	0	1	0
1	0	0	1	1	0	0	1	0	1
1	0	1	0	0	1	1	0	1	0
1	1	0	0	1	1	0	0	1	0
1	1	1	1	0	0	1	1	0	1
0	0	0	0	1	1	1	0	0	1
0	0	1	1	0	0	0	1	1	0
1	1	0	0	0	0	1	1	1	1
1	1	1	1	1	1	0	0	0	0
0	0	0	1	0	0	1	0	1	1
0	0	1	0	1	1	0	1	0	0
1	1	1	1	0	0	0	0	1	1
1	1	0	0	1	1	1	1	0	0
1	1	0	1	0	0	1	1	0	0
1	1	1	0	1	1	0	0	0	1

Figure: Binary strength three covering array with three highlighted 3-way column selections $(\{1,2,3\},\{4,5,7\},\{8,9,10\})$.

Definition

Let S be a nonempty set with $|S| = s \in \mathbb{N}^\times$ and $N, t \in \mathbb{N}^\times$ with $0 < t \leq s$.
Then, a sequence covering array $SCA(N, S, t)$ (*SCA*) of strength t is

- an $N \times s$ matrix,
- with entries from a finite set S,
- such that every t-way permutation of symbols from S occurs in at least one row (not necessarily adjacent), and
- each row is a permutation of the s symbols.

Sequence Covering Array Example

From combinatorial designs to sofware artifacts

- Sequence test sets derived from sequence covering arrays
- every row is a test case; appropriate translation of values, for example: 1 → "Mouse left-click on button", 2 → "Switch of window-focus"

Test	Sequences					
1	1	2	3	4	5	6
2	6	5	4	3	2	1
3	4	5	6	1	2	3
4	3	2	1	6	5	4
5	2	6	1	4	3	5
6	5	3	4	1	6	2
7	1	5	6	3	2	4
8	4	2	3	6	5	1
9	3	5	1	4	2	6
10	6	2	4	1	5	3

Figure: Sequence covering array for 6 symbols of strength three with 10 rows.

Combinatorial Design structures

Properties and observations

- Combinatorial design structures arise in discrete mathematics; exhibit many connections to coding- and graph theory
- Actual design construction is an empirically observed hard combinatorial optimization problem
- Different methods proposed for their construction, including (meta-) heuristics, combinatorial- and exact algorithms
- Designs with coverage properties are often significantly smaller than corresponding "full space":
  - CA(**18**;3,10,2) vs $2^{10} = 1024$, reduction of $\approx 98.24\%$
  - SCA(**6**,$\{1, 2, 3, 4, 5, 6\}$,3) vs $6! = 720$, reduction of $\approx 98.6\%$

References on CT

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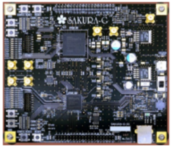
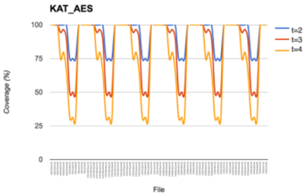
CST for TLS

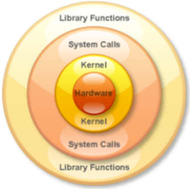
Large scale automated software testing for security

- Complex web applications
- Linux kernels
- Protocol testing & crypto alg. validation
- Hardware Trojan horse (HTH) detection

Combinatorial methods can make **software security testing** much more **efficient** and effective than conventional approaches

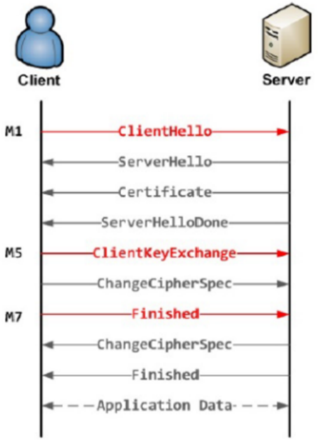






Combinatorial methods for TLS testing

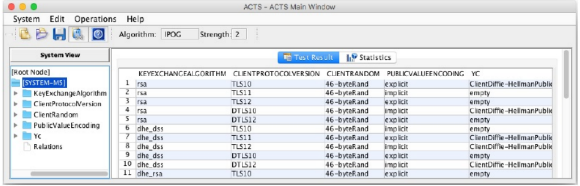
- **Input Test Space for CT:** Employ Input Parameter Modelling (IPM)
- **TLS Specification:** Select parameters and possible values for M1, M5 and M7
- Three different models are constructed which give rise to three distinctive test sets according to standard



Input models for TLS messages

M5:

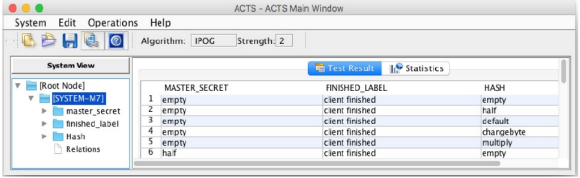
```
KeyExchangeAlgorithm : rsa,
dhe_dss, dhe_rsa, dh_dss,
dh_rsa, dh_anon
ClientProtocolVersion :
TLS10, TLS11, TLS12, DTLS10,
DTLS12
ClientRandom : 46-byteRand
PublicValueEncoding :
implicit, explicit
Yc : empty, ClientDiffie -
HellmanPublicValue
```



	KEYEXCHANGEALGORITHM	CLIENTPROTOCOLVERSION	CLIENTRANDOM	PUBLICVALUEENCODING	YC
1	rsa	TLS10	46-byteRand	explicit	ClientDiffie-HellmanPublic
2	rsa	TLS11	46-byteRand	implicit	empty
3	rsa	TLS12	46-byteRand	explicit	empty
4	rsa	DTLS10	46-byteRand	implicit	ClientDiffie-HellmanPublic
5	rsa	DTLS12	46-byteRand	explicit	empty
6	dhe_dss	TLS10	46-byteRand	implicit	empty
7	dhe_dss	TLS11	46-byteRand	explicit	ClientDiffie-HellmanPublic
8	dhe_dss	TLS12	46-byteRand	implicit	ClientDiffie-HellmanPublic
9	dhe_dss	DTLS10	46-byteRand	explicit	empty
10	dhe_dss	DTLS12	46-byteRand	implicit	ClientDiffie-HellmanPublic
11	dhe_rsa	TLS10	46-byteRand	explicit	empty

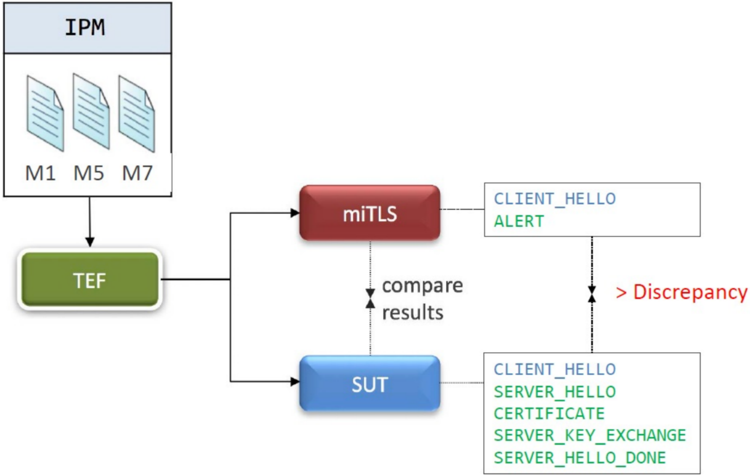
M7:

```
master_secret : empty, half,
default, changebyte, multiply
finished_label : client
finished
Hash : empty, half, default,
changebyte, multiply
```



	MASTER_SECRET	FINISHED_LABEL	HASH
1	empty	client finished	empty
2	empty	client finished	half
3	empty	client finished	default
4	empty	client finished	changebyte
5	empty	client finished	multiply
6	half	client finished	empty

Test execution framework for TLS testing



- Previous TLS versions
  - SSLv{2,3.0} (v3.0 RFC 6101, deprecated by RFC 7568)
  - TLS 1.0 (RFC 2246, deprecated by RFC 8996)
  - TLS 1.1 (RFC 4346, deprecated by RFC 8996)
  - TLS 1.2 (RFC 5246)
- TLS 1.3 (most recent)
  - RFC 8446, August 2018
  - 48.09% supported of Alexa1M (Dec 31, 2020)
  - Improved handshake
  - Stricter ciphers
- Many TLS security issues in the past:
  - Protocol issues (including POODLE, DROWN)
  - Implementation issues (including RACOON, HeartBleed)
  - Policy-related issues
- NO PQC-aspects officially in TLS available yet!

Transitioning to PQC-TLS

New situation after NIST standardization rounds completed

- NIST standardization process "completed" (as of June 24, 2025):
  - FIPS 203: Module-Lattice-Based Key-Encapsulation Mechanism Standard;
  - FIPS 204: Module-Lattice-Based Digital Signature Standard;
  - FIPS 205: Stateless Hash-Based Digital Signature Standard;
  - NIST IR 8545: HQC (Hamming Quasi-Cyclic, selected for standardization)
- Native PQC-TLS
  - Use only (NIST-standardized) PQC-schemes directly in handshake
- Parallel classic-PQC TLS (towards PQC-transition)
  - More choices for selective use in parallel
- Hybrid classic-PQC TLS (towards PQC-transition)
  - Combine classic and PQC-schemes in order to take advantage of both
- Common implementation efforts for PQC-primitives
  - Open Quantum Safe (OQS) project (among others)
- Recommendations for cipher suites (including Suite B, CNSA 1.0/2.0)

References on CST for TLS testing

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CT for X.509 certificates

Structure Modelling of X.509 for CT

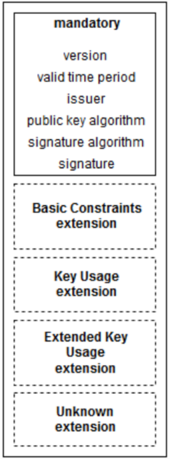

Figure: Blocks in an X.509 certificate.

```
Version(5)::= -1 | 0 | 1 | 2 | 3
Validity_Time(4)::= expired | not_yet_valid |
    start_future_end_past | valid
Issuer(3)::= Chain | Self | Unrelated
Key_Type(2)::= RSA | DSA
Signature_Type(3)::= Chain | Self | Unrelated
Signature_Algorithm(3)::= MD5 | SHA1 | SHA256
Ext_Basic_Constraints_enabled(2)::= 0 | 1
Ext_Basic_Constraints_critical(3)::= 0 | 1 |
    not_active
Ext_Basic_Constraints_CA(3)::= 0 | 1 |
    not_active
Ext_Basic_Constraints_pathlen(4)::= -1 | 0 | 1
     | not_active
Ext_Keyusage_enabled(2)::= 0 | 1
Ext_Keyusage_critical(3)::= 0 | 1 | not_active
Ext_Extended_Keyusage_enabled(2)::= 0 | 1
Ext_Extended_Keyusage_critical(3)::= 0 | 1 |
    not_active
Ext_unknown_enabled(2)::= 0 | 1
Ext_unknown_critical(3)::= 0 | 1 | not_active
```

Figure: IPM for X.509 certificate for CT.

Certificate generation with CT

Guaranteed combinatorial coverage of the input space

- Combinatorial sampling strategies:
  - *Intra-block*
  - *Inter-block*
  - *flat*

Mandatory Block				Basic Constraint Extension Block			
version	hash	key	signature	active	critical	is_authority	pathlen
0	md5	dsa	self	true	false	false	1
0	sha1	rsa	unrelated	false	dummy	dummy	dummy
0	sha256	dsa	parent	true	true	true	0
1	md5	rsa	unrelated	true	true	false	0
1	sha1	rsa	parent	true	false	true	1
1	sha256	dsa	self	false	dummy	dummy	dummy
2	md5	rsa	parent	false	dummy	dummy	dummy
2	sha1	dsa	self	true	true	true	0
2	sha256	rsa	unrelated	true	false	false	1
1	md5	dsa	unrelated	true	false	true	0
2	sha1	dsa	parent	true	true	false	1
0	sha256	rsa	self	false	dummy	dummy	dummy

Figure: Pairwise (i.e., 2-way) abstract test set for simplified certificate model.

t	Intra	Inter	Flat
2	20	28	26
3	73	107	126
4	210	372	536
5	551	1,110	1,965
6	1,020	2,709	6,598
7	1,020	4,904	20,487

Figure: Strength vs generated number of certificates.

Test execution results and comparison

Error	BouncyCastle	wolfSSL	GnuTLS	NSS	OpenJDK	OpenSSL	mbed
untrusted	✓	✓	✓	✓	✓	✓	✓
expired or not yet valid	✓	✓	✓	✓	✓	✓	✓
parse-error	✓	✓	✓	✓	✓	✗	✓
crash	✗	✓	✗	✗	✗	✗	✗
use of insecure algorithm	✗	✗	✓	✓	✗	✗	✓
invalid signature	✗	✓	✓	✓	✗	✗	✗
unknown critical extension	✗	✗	✗	✓	✗	✓	✗
extension in non-v3 cert	✗	✗	✗	✗	✓	✗	✗
use of weak key	✗	✗	✗	✗	✗	✗	✓
name constraint violation	✗	✗	✗	✓	✗	✗	✗
key usage not allowed	✗	✗	✗	✓	✗	✗	✗

Figure: Observed returned error tuples.

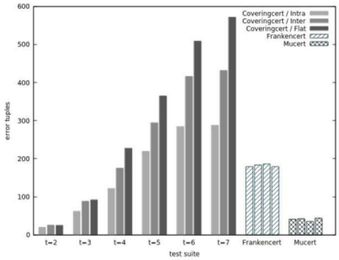

Figure: Number of different error tuples per test set.

Quo Vadis, X.509?

Status & Current and future challenges for X.509

- Widely used standard for PKC-based authentication (including RFC 5280)
- Currently standandized for classic cryptographic schemes only
  - 'draft-ietf-tls-hybrid-design-13', most recent update June 17, 2025: Hybrid key exchange in TLS 1.3
  - 'draft-ounsworth-pq-composite-sigs-13', most recent update March 4, 2024: Composite ML-DSA for use in Internet PKI
- Proposed transition approaches:
  - PQC-native
  - Classic/PQC-combined via extensions in certificates
  - Hybrid (i.e., composite algorithms) between classic and pqc
  - Classic and PQC independently in parallel deployed
- Certificate (chain) validation: Under which conditions will a presented certificate (chain) by accepted?
  - Root certificate
  - (Zero or more) Intermediate certificate(s)
  - Leaf certificate
- Transition-plath for certificate authorities:
  - Root certificates in Mozilla Root Store expire up to year 2046
  - New root certificates according to which (hybrid?) PQC-scheme?
  - How to distribute new root certificates in parallel to software (hardware?) support?

References on CT for X.509 certificate testing

SPIQE 2025

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Introduction to CT

CST for TLS

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Conclusion & Future Work

- K. Kleine and D. E. Simos, "Coveringcerts: Combinatorial Methods for X.509 Certificate Testing," 2017 IEEE International Conference on Software Testing, Verification and Validation (ICST), Tokyo, Japan, 2017, pp. 69-79, doi: 10.1109/ICST.2017.14.

Conclusion & Future Work

More (Testing) Challenges for PQC ahead!

- Transition has to start as soon as possible ("SNDL: store-now, decrypt later" attack)
- Hybrid classic-pqc schemes starting to be used in industry
  - META internally with implementation Fizz: Hybridization of Kyber with X25519
- Hybrid schemes evaluation for official FIPS-compliance?
- 75 billion IoT devices in use by 2025 (NCCOE/NIST)
  1. Already use lightweight cryptographic schemes
  2. Upgrade software/hardware to support PQC-TLS?
  3. Upgrade software/hardware to support PQC-X.509?
- How to test compatibility & security of more of billions of devices?
  - Native/hybrid approaches?
  - How to distribute "PQC-root certificates" in parallel with classic ones?
- How to react when flaw is discovered in one of the 4 (5?) PQC-schemes standardized by NIST?
  - In the context of native/hybrid PQC-TLS?
  - In the context of native/hybrid PQC-X.509?
- Impact of EO (June 6, 2025): "SUSTAINING SELECT EFFORTS TO STRENGTHEN THE NATION'S CYBERSECURITY AND AMENDING EXECUTIVE ORDER 13694 AND EXECUTIVE ORDER 14144"

Conclusion & Future Work

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- Testing systems using PQC is critical!
- Combinatorial methods provide the means to obtain:
  - Guarantees of structural coverage of the input space;
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Future Work

- Explore (some) of the C(S)T-ideas presented!

Thank you very much for your attention!

Questions?

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