Automated Testing of Crypto Software Using Differential Fuzzing

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About us

Researchers at **Kudelski Security**, based in Switzerland

Applied crypto research, source code review, consulting, etc.

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Presented at BH, Defcon, Infiltrate, Troopers, etc.

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Yolan / @anomalroil

Master's thesis about automated testing of crypto

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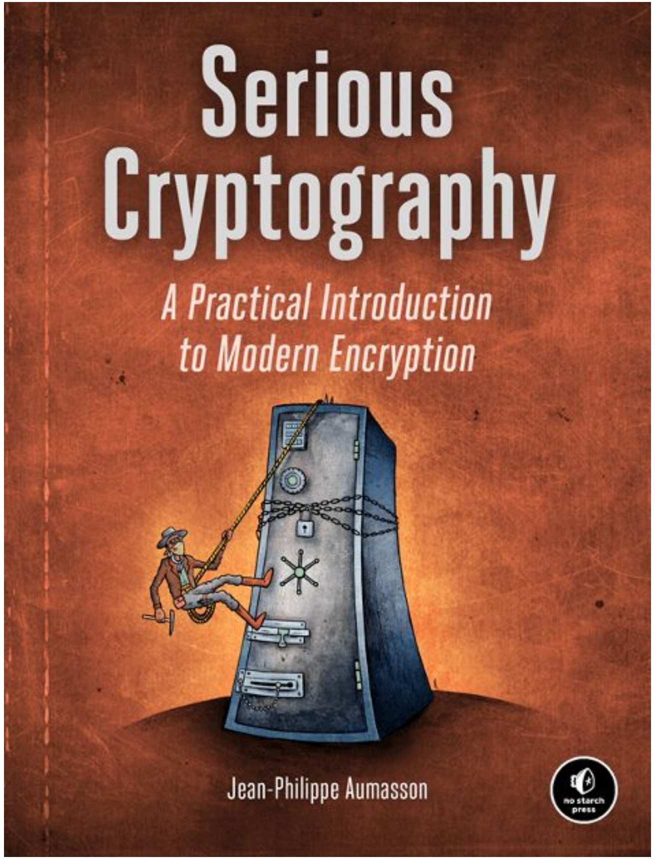


Out in **Oct. 2017**, now in early access at *http://nostarch.com*

Roadmap

1. Testing crypto
2. The approach: differential fuzzing
3. A new tool: CDF
    a. How it works
    b. Examples of tests
    c. Demo
4. Issues found
5. Conclusions

1 Testing crypto

Credit: https://unsplash.com/@sveninho

What do we want?

Testing **functionality**

- ➢ Valid inputs give correct output
- ➢ Invalid input trigger appropriate error

Testing **security**

- ➢ Program can't be abused
- ➢ Cryptographic secrets won't leak

Testing what?

Code against **code**

- When porting to a new language or platform
- Assume reference code is correct (not always true)
- As many test values as you need + internal debug values

Code against **specs**

- When implementing a standard
- Specs can be incomplete or ambiguous
- Only a handful of test values

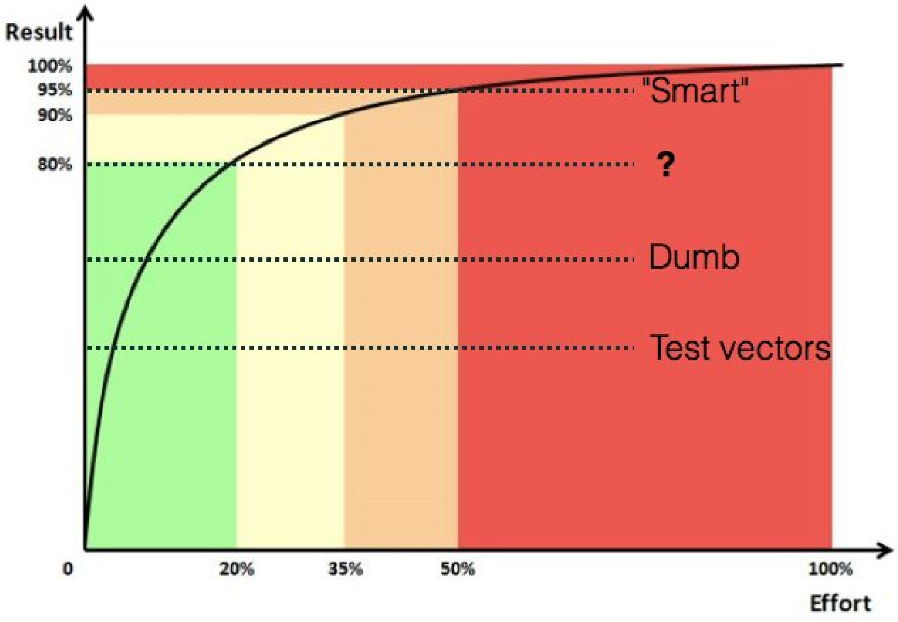
Automated testing

In order of complexity and coverage

➢ Static analyzers	About code security, not correctness
➢ Test vectors	The more values, the more coverage
➢ Dumb fuzzing	Typically looks for crashes, e.g. afl
➢ Smart fuzzing	Protocol- or state machine-specific
➢ Formal verification	Proves correctness / security properties

How to maximize the efficiency? (ease of use × coverage)

Towards cost-effective testing



Limitations of current methods

- ➢ Randomness quality
- ➢ Timing leaks
- ➢ Test vectors focus on valid inputs, not invalid ones
- ➢ Parameters space rarely covered (key sizes, etc)
- ➢ Software security $\nRightarrow$ crypto security (logic bugs)

How to better address those in a single tool?

2 Approach: differential fuzzing

Credit: https://unsplash.com/@ja5on

New tool from old ideas

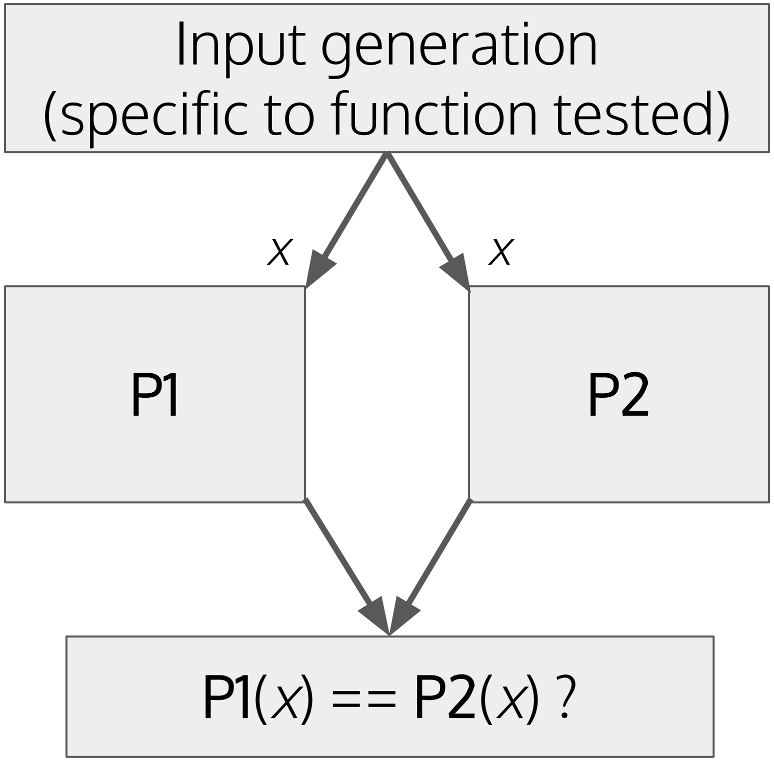
Testing crypto by comparing two implementations not new

Solar Designer @solardiz · 3 Sep 2015
Replying to @veorq
@veorq I fuzz-tested my MD4 and MD5 vs. OpenSSL's; I also retroactively fuzz-tested my crypt_blowfish vs. OpenBSD's: openwall.com/lists/announce...

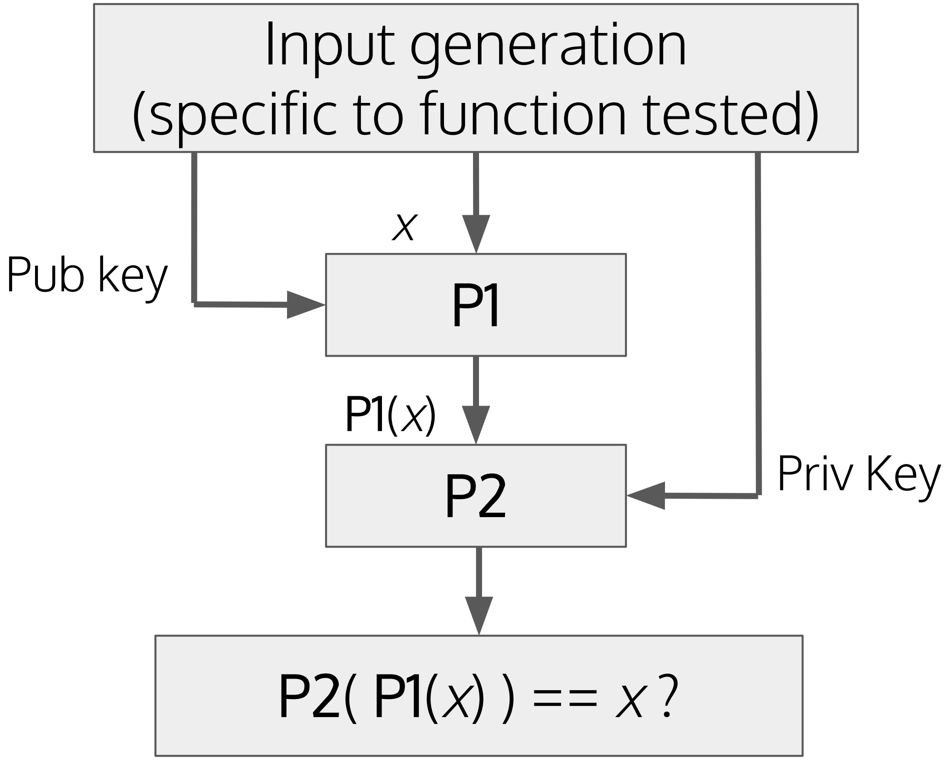
Frank Denis @jedisct1 · 3 Sep 2015
Replying to @veorq
@veorq Started this a while back to generate test vectors using different implementations, for cross impl-checking

New: tool to automate it for many different interfaces

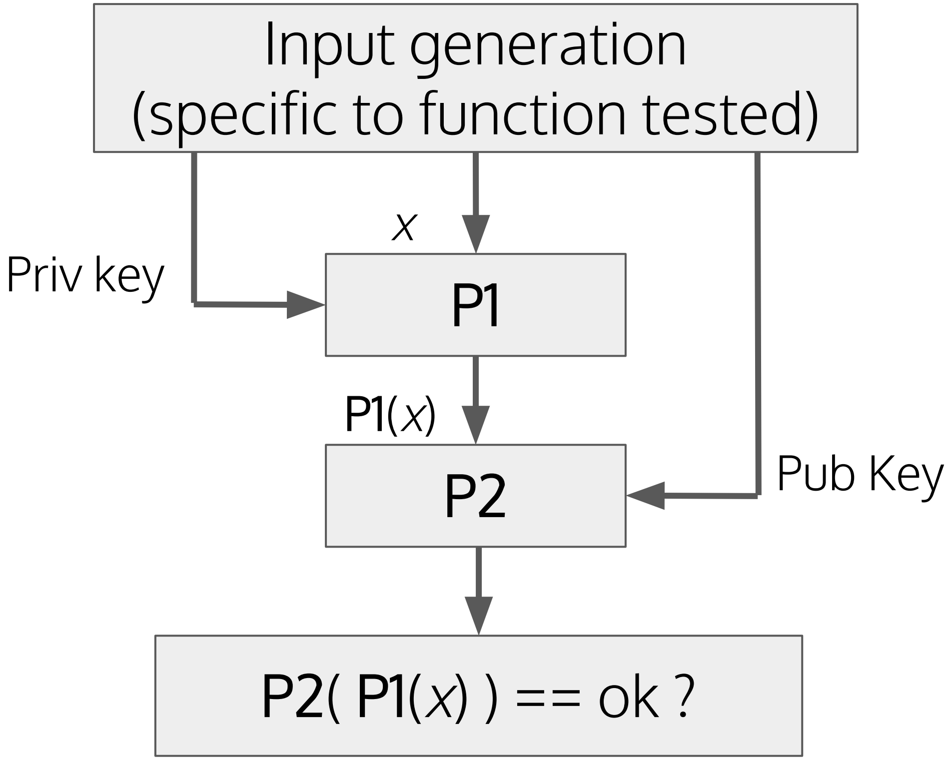
Principle for hash functions, PRNG



Principle for encryption



Principle for signatures



3 A new tool: CDF

Credit: https://unsplash.com/@timstief

CDF – Crypto Differential Fuzzing

Command-line tool in **Go**

- ➢ Native code, portable to Linux/macOS/Windows
- ➢ Concurrency support, fast enough (not speed bottleneck)

Language-agnostic

- ➢ Takes an executable file (binary or script)
- ➢ Can test crypto from any language or framework

Started in May 2016, most code written in Sept '16 - March '17

Why using CDF?

- **Correctness and security** of implementations
- **Interoperability** between implementations
- Checks include
  - **Insecure parameters** supported
  - **Non-compliance** with standards (e.g. FIPS)
  - **Edge cases** of specific algorithms (e.g. DSA)

CDF can replace test vectors, but not formal verification

Wycheproof – similar but different

From Google (Bleichenbacher, Duong, Kasper, Nguyen)

Announced in Dec. 2016, presented at RWC in Jan. 2017

- Extensive set of **unit tests**
- Specific to **Java**'s common crypto interface (so far)
- Many **bugs found** in OpenJDK, BouncyCastle, etc.
- Tests a single program, doesn't compare implementations

https://github.com/google/wycheproof

3.a How it works

Credit: https://unsplash.com/@pyeshtiaghi

So you want to test ECDSA?

Crypto++

```
void Sign(const DL_GroupParameters<T> &params, const Integer &x, const Integer &k, const Integer &e, Integer &r, Integer &s) const
{
    const Integer &q = params.GetSubgroupOrder();
    r %= q;
    Integer kInv = k.InverseMod(q);
    s = (kInv * (x*r + e)) % q;
    CRYPTOPP_ASSERT(!!r && !!s);
}
```

```
ECDSA_SIG *ECDSA_do_sign(const unsigned char *dgst, int dlen, EC_KEY *eckey)
{
    return ECDSA_do_sign_ex(dgst, dlen, NULL, NULL, eckey);
}
```

OpenSSL

```
// Sign signs a hash (which should be the result of hashing a larger message)
// using the private key, priv. If the hash is longer than the bit-length of the
// private key's curve order, the hash will be truncated to that length.  It
// returns the signature as a pair of integers. The security of the private key
// depends on the entropy of rand.
func Sign(rand io.Reader, priv *PrivateKey, hash []byte) (r, s *big.Int, err error) {
```

Go/crypto

How to deal with the different APIs?

Generic ECDSA interface in CDF

- Public key = curve point $P = (x, y)$
- Private key = number d, such that $P = dG$
- Signature = pair of numbers (r, s)

ECDSA interface in CDF for CLI input, hex-encoded:

	Input	Output
Signature	x, y, d, m	r, s
Verification	x, y, m, r, s	True / False

CDF interfaces

- ➢ General API of CDF translatable to any tested software
- ➢ Needed in order to support black-box testing

Interfaces define the inputs and expected outputs for a given crypto functionality (hashing, RSA encryption, etc.)

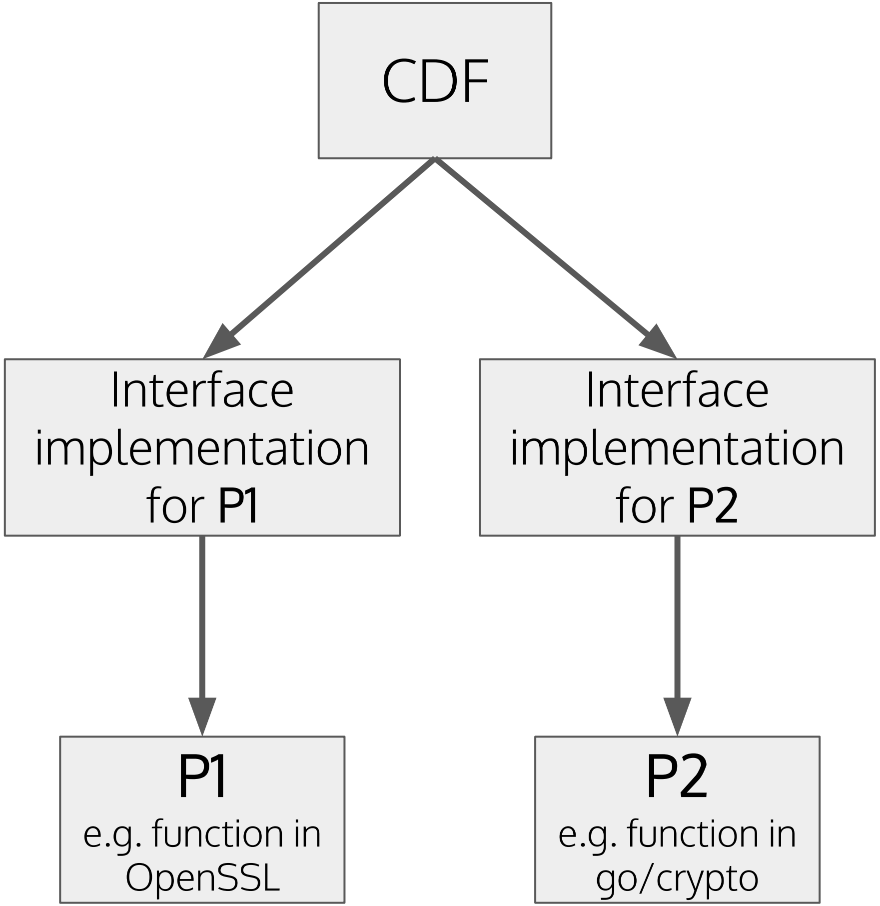
Not all inputs of an interface may be used by the tested software

How CDF works

CDF binary, compiled from Go

Executable files calling the software to be tested (e.g. libs)

Software tested, may be different libs, languages, etc.



ECDSA interface for **cryptography.io**

sign + verify, **35** sLoC (.py)

```python
from cryptography.hazmat.backends import default_backend
from cryptography.hazmat.primitives import hashes
from cryptography.hazmat.primitives.asymmetric import ec
from cryptography.hazmat.primitives.asymmetric import utils
import sys
import binascii

curve = ec.SECP256R1()
algo = ec.ECDSA(hashes.SHA256())

if len(sys.argv) == 6:
    signing = False
elif len(sys.argv) == 5:
    signing = True
else:
    print("Please provide X, Y, R, S, Msg  or X, Y, D, Msg as arguments")
    sys.exit(1)

pubnum = ec.EllipticCurvePublicNumbers(
    int(sys.argv[1], 16), int(sys.argv[2], 16), curve)

# Msg is in last args:
data = binascii.unhexlify(sys.argv.pop())
if signing:
    privateKey = ec.EllipticCurvePrivateNumbers(int(
        sys.argv[3], 16), pubnum).private_key(default_backend())
    signer = privateKey.signer(algo)
    signer.update(data)
    signature = signer.finalize()
    (r, s) = utils.decode_dss_signature(signature)
    print(format(r, 'x'))
    print(format(s, 'x'))
else:
    public_key = pubnum.public_key(default_backend())
    signature = utils.encode_dss_signature(
        int(sys.argv[3], 16), int(sys.argv[4], 16))
    verifier = public_key.verifier(signature, algo)
    verifier.update(data)
    print(verifier.verify())
```

ECDSA interface for **Go's crypto** package

sign + verify, **72** sLoC (.go)

```go
	// Key instanciation
	privatekey := new(ecdsa.PrivateKey)
	pubkey := new(ecdsa.PublicKey)

	pubkey.Curve = pubkeyCurve
	pubkey.X = fromBase16(flag.Arg(0))
	pubkey.Y = fromBase16(flag.Arg(1))

	// msg is always in latest position
	// we are decoding from hex to have truly random messages
	msg, err := hex.DecodeString(flag.Arg(len(flag.Args()) - 1))
	if err != nil {
		panic(err)
	}

	r := big.NewInt(0)
	s := big.NewInt(0)

	h.Write(msg)
	var signhash []byte
	if *custom_hash == "" { // if the flag -h is not set, its default is "" and we hash the message
		signhash = h.Sum(nil)
	} else { // even if specifying the hash is discutably useful in the non-deterministic ECDSA case
		var err error
		signhash, err = hex.DecodeString(*custom_hash)
		if err != nil {
			panic(err)
		}
	}

	if signing {
		// private key instanciation:
		privatekey.PublicKey = *pubkey
		privatekey.D = fromBase16(flag.Arg(2))

		// If signhash is longer than the bit-length of the private key's curve
		// order, signhash will be truncated to that length. It returns the
		// signature as a pair of big integers.
		r, s, serr := ecdsa.Sign(rand.Reader, privatekey, signhash)
		if serr != nil {
			log.Fatalln(serr)
		}
```

ECDSA interface for **OpenSSL**

sign + verify, **124** sLoC (.c)

```c
int ret;
ECDSA_SIG* sig;
EC_KEY* eckey;

BIGNUM* x = BN_new();
BIGNUM* y = BN_new();

BIGNUM* d = BN_new();

BN_hex2bn(&x, argv[optind]);
BN_hex2bn(&y, argv[optind + 1]);

eckey = EC_KEY_new_by_curve_name(ECPARAMS);
if (eckey == NULL) {
    printf("Failed to create new EC Key for this curve.\n");
    return -1;
}

if (!EC_KEY_set_public_key_affine_coordinates(eckey, x, y)) {
    printf("Failed to create set EC Key with the provided args.\n");
    return -1;
}

if (signing) {
    BN_hex2bn(&d, argv[optind + 2]);
    EC_KEY_set_private_key(eckey, d);

    sig = ECDSA_do_sign(hash, blen, eckey); // this return a newly initialized ECDSA_SIG
    if (sig == NULL) {
        printf("Failed to sign with those args.\n");
        return -1;
    }
    printBN(sig->r);
    printBN(sig->s);

} else {
    sig = ECDSA_SIG_new();
    BN_hex2bn(&sig->r, argv[optind + 2]);
    BN_hex2bn(&sig->s, argv[optind + 3]);
    ret = ECDSA_do_verify(hash, blen, sig, eckey);
    if (ret == -1) {
```

3.b Examples of tests

Credit: https://unsplash.com/@rubavi78

Simplest case: keyed hash (PRF, MAC)

- P1 and P2 do the same thing (hash a message using a key)
- Compare P1 and P2 behavior on different input pairs:
  - For different message lengths
  - For different key lengths
- Checks distinct outputs with 00-padded keys (HMAC …)

ECDSA

- **P1 signs, P2 verifies**, for different hash lengths
- Check support of hashes larger than group size (truncation?)
- Check degenerate cases (risks of forgery, DoS, key recovery)
  - (0, 0) public key
  - 0 private key
  - Hash = 0 and signature = (x, x)

Example of ECDSA test

```go
// testInfiniteLoop is a simple trial to verify using a wrong 00 hash and
//  using 00 as secret value that the implementation does not fall into an
//  infinite loop. Note that 00 is not amongst the range of the acceptable
//  secret values.
func testInfiniteLoop(prog string) error {
    LogInfo.Printf("testing %s against the invalid inf loop.\n", prog)
    // The point 0,0 shouldn't be accepted as a valid point, so let us try with it:
    id := "ecdsa#infloop_" + prog

    argsP := []string{"-h", "00", Config.EcdsaX, Config.EcdsaY, "00", "DEADC0DE"}
    out, err := runProg(prog, id, argsP)
    if err != nil && strings.Contains(err.Error(), "STOP") {
        LogError.Println(prog, "failed and run into an infinite loop.")
        return fmt.Errorf("%s runned into a degenerate infinite loop: %v", prog, err)
    } else if err != nil {
        LogToFile.Println("As expected,", id, "failed:", out, "\nGot error:", err)
        LogSuccess.Println(prog, "did not run into an infinite loop.")
    }
    LogToFile.Println("Unexpected,", id, "did not fail and output:", out, "\non input:", prog, argsP)
    LogWarning.Println(prog, "didn't run into an infinite loop, but did not fail when running:\n", prog,
    argsP)
    return nil
}
```

RSA encryption

- **P1** encrypts, **P2** decrypts, for different message lengths
- Checks
    - Exponents lengths supported, detecting max length
    - Support of small private exponents *d*
    - Support for messages larger than the modulus
- Detects **timing leaks**

```
// testRSAencPubMaxExponentLen will test the maximal size of the exponent
// the tested program support. Typically it would detect when a library is
// using an integer instead of a big integer to store the exponent value.
func testRSAencPubMaxExponentLen(msg string) (mainErr error) {
    TermPrepareFor(1)
    LogInfo.Println("testing max exponent lengths")
    mainErr = nil
    failed := false
```

Timing leaks detection

Based on **dudect** – *https://github.com/oreparaz/dudect*

Dude, is my code constant time?

Oscar Reparaz, Josep Balasch and Ingrid Verbauwhede
KU Leuven/COSIC and imec
Leuven, Belgium

- ➢ Searches statistical evidence of timing discrepancies between two classes of input values (e.g. valid and invalid ciphertexts)
- ➢ Leverages Welch's *t*-test
- ➢ dudect entirely rewritten in Go

3.c Demo

Credit: https://unsplash.com/@rubavi78

4 Issues found

Credit: https://unsplash.com/@toddcravens

Findings summary

Focus on widely used libraries, only tested few components

Number of issues discovered:

	go/crypto	OpenSSL	mbedTLS	PyCrypto	Crypto++
OAEP	2	0	0	0	0
ECDSA	2	2	2	n.a.	0
DSA	3	2	n.a.	3	0

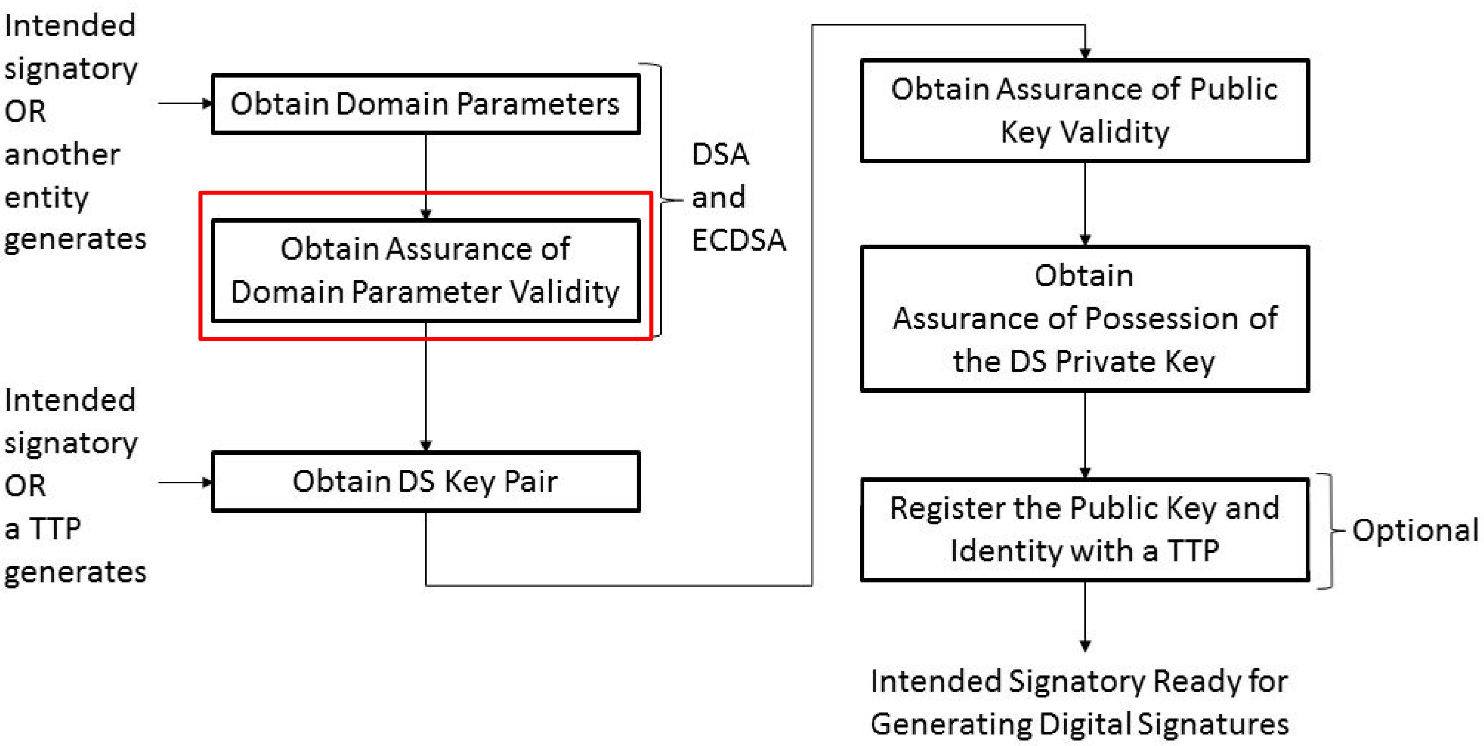
Impressive defense in depth in Crypto++...

DSA (Go, OpenSSL, PyCrypto)

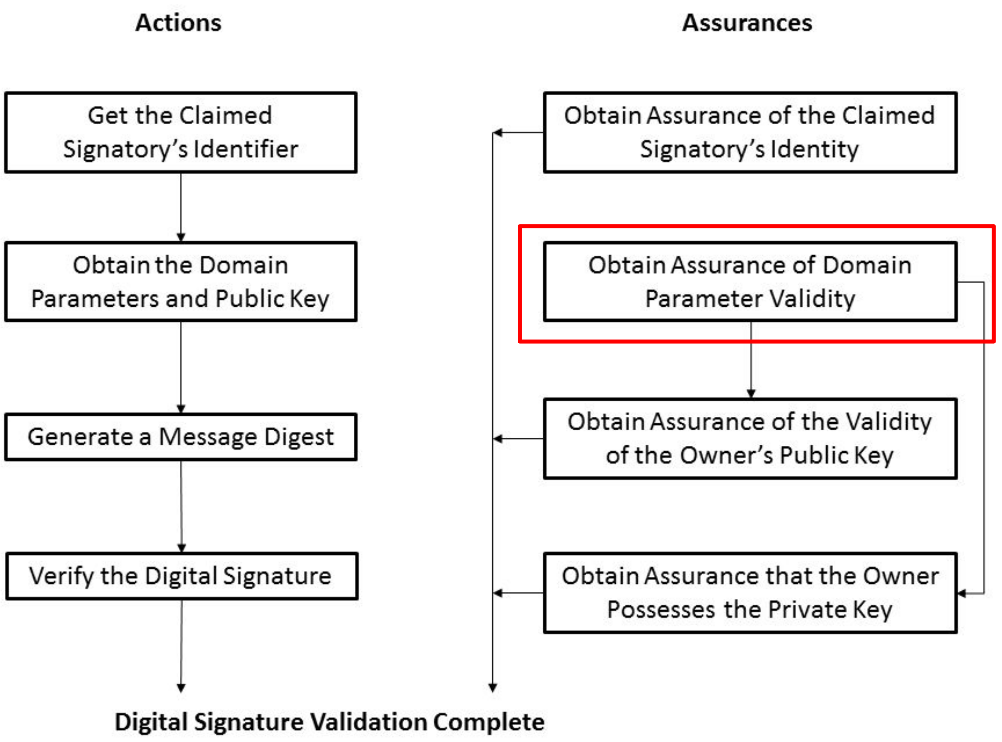
CDF detected the following:

- **DoS** on attacker-provided parameters upon verification
- **Invalid signature** issuance on invalid domain parameters
- **Always-valid** signatures issuance and verification on invalid domain parameters

(EC)DSA FIPS compliance: signature



(EC)DSA FIPS compliance: verification



Infinite loop in DSA signing (Go, OpenSSL)

Domain params (p, q, g), secret key x, pubkey $y^x \bmod p$

1. Generate a random k, $1 < k < q$
2. Calculate $r = (\, g^k \bmod p\,) \bmod q$
3. If $r = 0$, goto 1.
4. Calculate $s = k^{-1}(\,\mathrm{H}(m) + xr) \bmod q$
5. If $s = 0$, goto 1.
6. Return the signature $(\, r, s\,)$

What if $g = 0$?

Infinite loop in DSA (Go)

```
for {
    k := new(big.Int)
    buf := make([]byte, n)
    for {
        _, err = io.ReadFull(rand, buf)
        if err != nil {
            return
        }
        k.SetBytes(buf)
        if k.Sign() > 0 && k.Cmp(priv.Q) < 0 {
            break
        }
    }

    kInv := fermatInverse(k, priv.Q)

    r = new(big.Int).Exp(priv.G, k, priv.P)
    r.Mod(r, priv.Q)

    if r.Sign() == 0 {
        continue
    }
```

~~In~~finite loop in DSA (Go)

```go
	var attempts int
	for attempts = 10; attempts > 0; attempts-- {
		k := new(big.Int)
		buf := make([]byte, n)
		for {
			_, err = io.ReadFull(rand, buf)
			if err != nil {
				return
			}
			k.SetBytes(buf)
			// priv.Q must be >= 128 because the test above
			// requires it to be > 0 and that
			//    ceil(log_2(Q)) mod 8 = 0
			// Thus this loop will quickly terminate.
			if k.Sign() > 0 && k.Cmp(priv.Q) < 0 {
				break
			}
		}

		kInv := fermatInverse(k, priv.Q)

		r = new(big.Int).Exp(priv.G, k, priv.P)
		r.Mod(r, priv.Q)

		if r.Sign() == 0 {
			continue
		}
```

Fix implemented by the Go team:
Bound the number of iterations

Timing leak in RSA-OAEP (Go)

Potential timing leak in **RSA-OAEP decryption**, noted in Go's source code comments, which we experimentally confirmed

Go's OAEP *potentially* vulnerable to Manger's attack…

- Seems **unexploitable** (we measured leaks of nanoseconds..)
- Too many measurements needed to exploit it, even locally
- Timing leak ≠ timing attack

General observations

Most crypto libraries…

- ➢ Lack sanity checks and parameters validation
- ➢ Don't strictly conform to standards
- ➢ Support weak parameters

5 Conclusions

Credit: https://unsplash.com/@martinjphoto

CDF is a new tool that…

- Tests the **correctness and security** of crypto software
- Is in **Go**, portable, and supporting software any language
- Uses **differential fuzzing**, to compare different implementations of the same functionality
- Found **issues** in widely used crypto libraries

TODO: CDF needs more...

- ➢ **Interfaces**, in order to test more crypto functionalities
- ➢ **Tests**, like unit tests from Wycheproof missing in CDF
- ➢ **Applications**, to find bugs in crypto software/libs
- ➢ **Testing**, to find bugs in CDF

Thank you!

Get CDF at https://github.com/kudelskisecurity/cdf

"Besides black art, there is only automation and mechanization."

—Federico García Lorca

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