Problems and pitfalls in the implementation of cryptographic systems

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Agenda

- Introduction to cryptography engineering
- Implementation errors and secure software
- Keeping secrets
- Implementation issues: randomness, seed, user’s password, storing password
- Side-channel attack, Timing attack
- Crypto libraries: NaCl, libsodium
- Examples: use libsodium in PHP

Cryptography engineering

- *“Cryptographic engineering is the name we have coined to refer to the theory and practice of engineering of cryptographic systems”*
  Çetin Kaya Koç in Cryptographic Engineering
- A **cryptographic engineer** designs, implements, tests, and validates cryptographic systems
- She is also interested in **breaking** them for the purpose of checking their robustness and also building countermeasures to prevent or mitigate future attacks

Weakest link property

A security system is only as strong as its weakest link

Adversarial setting

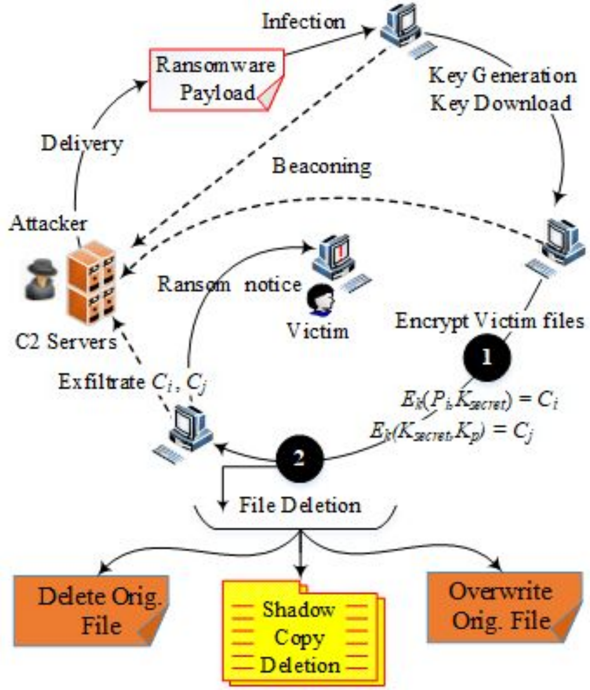
- One of the biggest differences between security systems and almost any other type of engineering is the **adversarial setting**
- Most engineers have to contend with problems like heat, cold, humidity, pressure, etc.
- All these factors affect designs, but their effect is **fairly predictable**
- In security an opponent is intelligent, clever, malicious
- They don’t play by the rules, and they are **completely unpredictable**

Cryptographers are professional paranoids

Source: John Klossner technology cartoons

Threat model

- **Every system can be attacked**
- The whole point of a security system is to provide access to some people and not to others
- In the end, you will always have to trust some people in some way, and these people in turn can attack your system
- **What are you trying to protect against?**



Cryptography is not the solution

- **Cryptography is not the solution to your security problems**
- It might be part of the solution, or it might be part of the problem
- In many situations, cryptography starts out by making the problem worse, and it isn't at all clear that using cryptography is an improvement
- **Cryptography has many uses**
- It is a crucial part of many good security system
- It can also make systems weaker when used in inappropriate ways
- It's very dangerous, it can provide a **feeling of security** but not actual security

Cryptography is very difficult

- **Cryptography is fiendishly difficult**
- Even seasoned experts design systems that are broken a few years later
- This is common enough that we are not surprised when it happens
- The weakest-link property and the adversarial setting conspire to make life for a cryptographer very hard
- Another significant problem is the **lack of testing**
- There is no known way of testing whether a system is secure
- A bad cryptography looks just like good cryptography, until it is seriously attacked

Cryptography is the easy part

- Even though cryptography itself is difficult, it is still one of the easy parts of a security system
- A cryptographic component has fairly well defined boundaries and requirements
- An entire security system is much more difficult to clearly define, since it involves many more aspects
- Another huge problem is the software quality, security cannot be effective if a software contains thousands of bug that lead to security holes

Implementation errors

- **Implementation errors are by far the biggest security problem in real-world systems**
- One major part is, as always, the operating system (OS)
- But none of the operating system in widespread use is designed with security as a primary goal
- The logical conclusion is that **is impossible to implement a security system**
- When we design a cryptographic system, we do our best to make sure that at least our part is secure

Secure software

- **We can write correct software**
- This is **not good enough for a security system**
- Correct software has a specified functionality, eg. if you click a button A then B will happen
- Secure software has an additional requirement: **a lack of functionality**; eg. no matter what an attacker does, she cannot do X
- This is very different, you can test for functionality, but not for lack of functionality
- **We actually don’t know how to create secure code**!

Keeping secrets

Keeping secrets

- **Anytime you work with cryptography, you are dealing with secrets**
- For the secure channel we have two type of secrets:
    - **keys**;
    - **data**;
- Both of these are transient secrets, we don't have to store them for a long time
- The data is only stored while we process each message
- The key are only stored for the duration of the secure channel
- **Transient secrets are keep in memory**

Wiping state

- A basic rule of writing security software is to wipe any information as soon as you no longer need it
- The longer you keep it, the higher the chance that someone will be able to access it
- Free a variable (deallocates the memory) is not enough, you need to override the old data
- This is related to the programming language used
  - in C using memset();
  - in C++ using destructor;
  - more difficult in Java because the heap is garbage-collected

Wiping state in Java

- One solution to mitigate the heap state is to run a program with **try-finally** statement
- At least we can ensure that the finalization routines are run at program exit
- The finally block contains some code to force a garbage collect, using **System.gc()** and **System.runFinalization()**

Swap file

- Most operating systems use a virtual memory system to increase the number of programs that can be run in parallel
- While a program is running, not all of its data is kept in memory; some is stored in a **swap file**:
  - when the program tries to access data that is not in memory, the program is interrupted;
  - the virtual memory system reads the required data from the swap file into a piece of memory;
  - the program is allowed to continue;
  - when the virtual memory system requires more free memory, it will take an arbitrary piece of memory and write it to the swap file

Swap file (2)

- In some operating systems there are system calls that you can use to inform the virtual memory system that specific parts of the memory are not to be swapped out:
  - in Windows, we can use the **VirtualLock()** API;
  - in Unix systems, the **mlock()** system call is often implemented in such a way that locked memory is never swapped to disk

Cache

- Modern computers have hierarchy of memories
- The cache keeps a copy of the most recently used data from the main memory
- This is a smaller but faster memory
- It is not a great danger from a security perspective since only the OS can access the cache memory
- We need to trust the OS, there is very little we can do about this

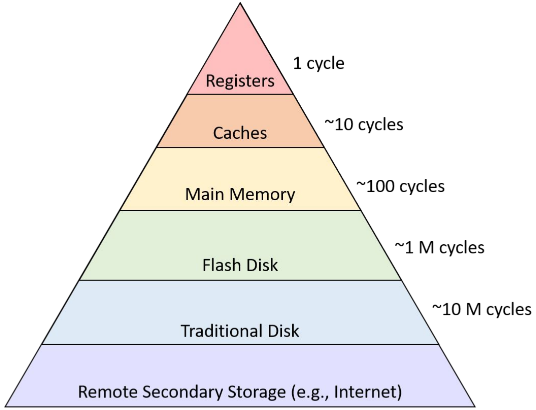


Image source: Dive Into Systems

Data retention by memory

- Simply overwriting data in memory does not delete the data
- This effect depends on the type of memory involved, basically when if you store data in a memory location, the location slowly starts to “learn” the data
- If you switch off the computer, the old data cannot be completely lost
- It is arguable whether this is a significant threat
- Workaround: instead of storing $\boldsymbol{m}$, we generate a random string $\boldsymbol{R}$ and we store $\boldsymbol{R}$ and $\boldsymbol{R} \oplus \boldsymbol{m}$, see [15] and [16] in references
- Preventing data retention: Eraser (Windows), shred (Linux)

Data integrity

- In addition to keeping secrets, we should protect the integrity of the data we are storing
- We use MAC to protect the integrity during the transit but if the data can be modified in memory we still have problems

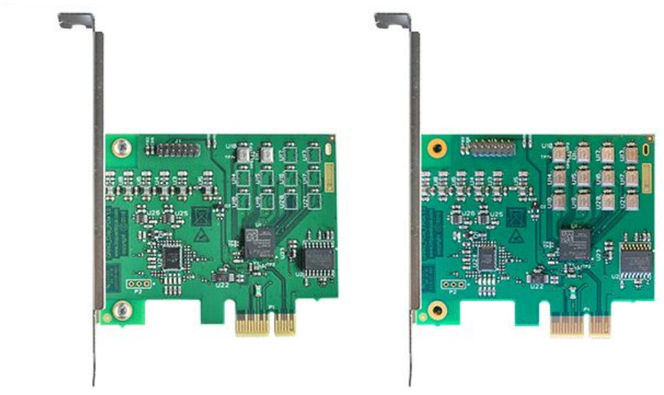
Implementation issues

Randomness

- Generating good randomness is a vital part of many cryptographic operations and it is one of the most difficult ones
- In computer languages we use **pseudorandom data** (not really random)
- It is generated from a **seed** by a **deterministic algorithm**
- If you know the seed you can predict the pseudorandom data
- In cryptography we use pseudorandom number generator (**PRNG**) that are **considered strong**: even if an attacker sees a lot of the random data generated by PRNG, she should not be able to predict anything about the rest of the output

Seed

- The seed is a crucial part of a PRNG
- How can we choose a random seed?
  - Windows: Cryptography API, Next Generation
  - Linux: getrandom()
  - Linux: /dev/urandom
  - Quantum Random Number Generation



Source image: Quantis QRNG PCIe New Generation

User’s password

- **Not random**
- Predictable (most of the time)
- Only a subset of ASCII codes (typically 68 vs 256)
- **Never use it as encryption/authentication key!**
- Use Key Derivation Function (KDF) to generate a key from a user’s password
- Eg. PBKDF2, Argon2i, Lyra2, Catena, yescrypt, Makwa, Balloon hashing

How to store user’s password

- Hashing is the best approach to store a user’s password (eg. in a file or a database)
- Which hash algorithm to use?
- **MD5** and **SHA** family hash are not good, they are vulnerable to brute force attack using GPU (few seconds in some cases)
- Good hash algorithms are the following adaptive functions:
  - **bcrypt** (CPU intensive)
  - **scrypt** (CPU and memory intensive)
  - **Argon2** (CPU, memory and degree of parallelism intensive)

Bruteforce attack

- A graphics processing unit (**GPU**) is a specialized CPU used in video games to execute multiple operation in parallel
- It can be used to run hash algorithms in parallel to perform a brute force attack
- A GPU has **thousands of core** (eg. 4000), a CPU just multiple (eg. 16)
- Using hashcat software and GPUs you can crack a 8 characters password in seconds!

Source image: 25-GPU cluster

Side-channel attacks

Side-channel attack

- Attack based on **information gained from the implementation** of a computer system, rather than weaknesses in the implemented algorithm itself

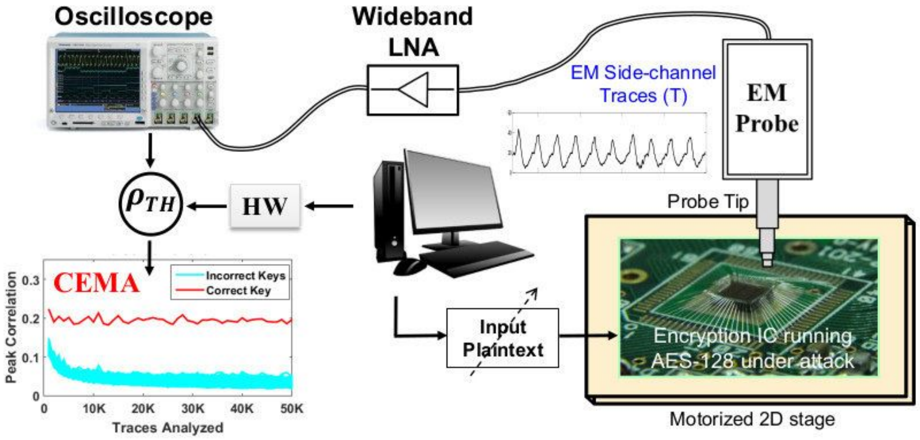
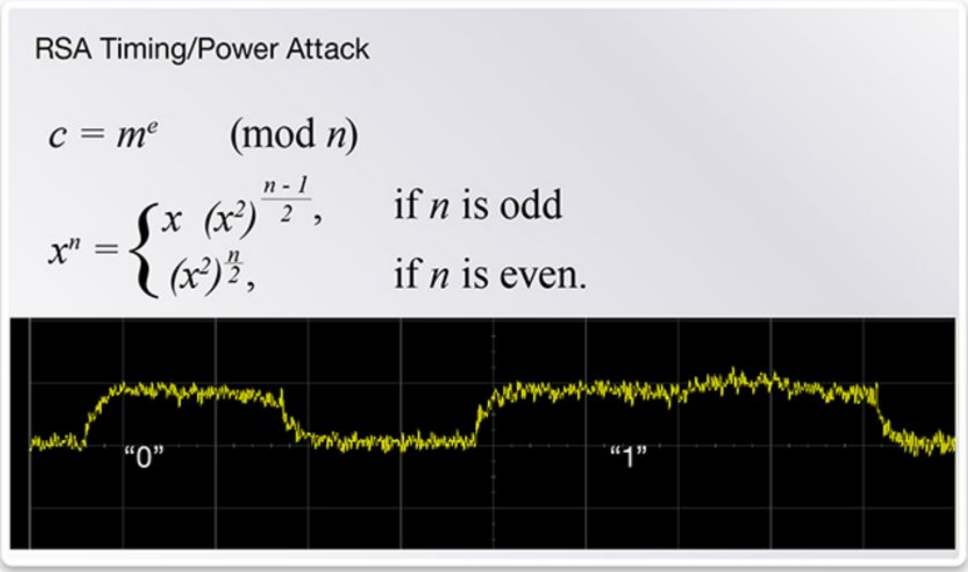


Image source: STELLAR, a Generic EM Side-Channel Attack Protection through Ground-Up Root-cause Analysis

Decode RSA key using power analysis



Source: [Protecting Against Side-Channel Attacks with an Ultra-Low Power Processor]

Timing attack

- An attacker **measures the CPU time** to perform some procedures involving a secret (e.g. encryption key). If this time depends on the secret, the attacker may be able to deduce information about the secret
- In 2006 *A. Shamir, E.Tromer and D.A. Osvik* used a timing attack to extract the full encryption key in **65 ms** using a Linux dm-crypt device with 128-bit AES in ECB mode (see [18] in references)

Prevent timing attack

- We need to reduce the information that an attacker can retrieve measuring the execution time
- For instance:
  - implement algorithm with constant execution time, eg. not related to the size of the key
  - avoid the usage of lookup tables in encryption algorithms to prevent cache timing effects

Example: compare strings

- What information an attacker can deduce from the following code?

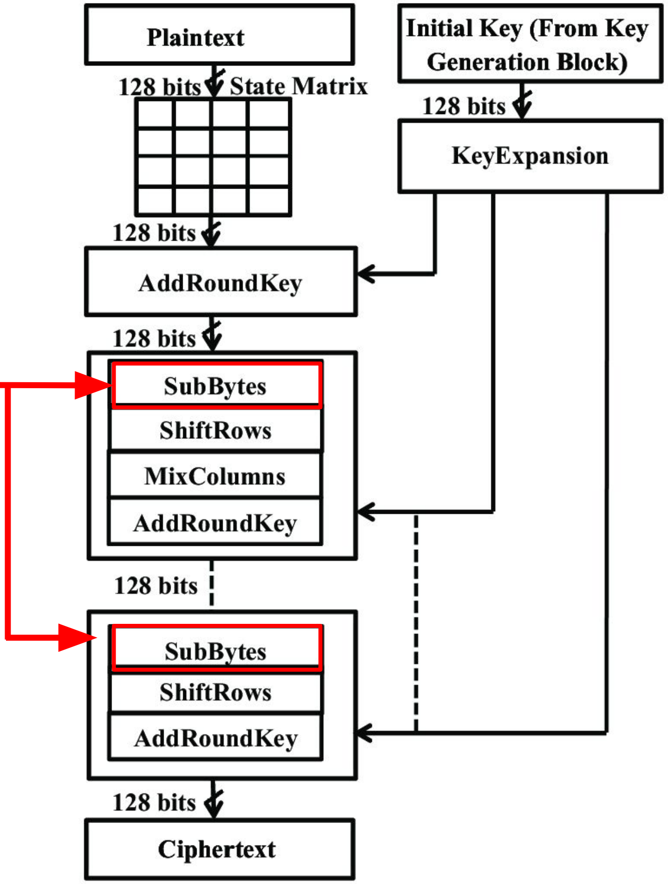
```
function compare(string $expected, string $actual): bool
{
    $lenExpected = strlen($expected);
    $lenActual   = strlen($actual);
    if ($lenExpected !== $lenActual) {
        return false;
    }
    for($i=0; $i < $lenActual; $i++) {
        if ($expected[$i] !== $actual[$i]) {
            return false;
        }
    }
    return true;
}
```

Cache-timing attacks

- **Cache-timing attacks** are software side-channel attacks exploiting the timing variability of data loads from memory
- This variability is due to the fact that all modern microprocessors use a hierarchy of caches to reduce load latency
- If a load operation can retrieve data from one of the caches (**cache hit**), the load takes less time than if the data has to be retrieved from RAM (**cache miss**)

S-box in AES

- The S-box maps an 8-bit input, c, to an 8-bit output
- The S-box is used in **SubBytes** function
- C. Ashokkumar et. al. showed that **“S-Box” Implementation of AES is NOT side channel resistant**, using a lookup table (see [21] in references)



S-box in C

https://github.com/kokke/tiny-AES-c/blob/master/aes.c#L76-L96

```
// The lookup-tables are marked const so they can be placed in read-only storage instead of RAM
// The numbers below can be computed dynamically trading ROM for RAM -
// This can be useful in (embedded) bootloader applications, where ROM is often limited.
static const uint8_t sbox[256] = {
  //0     1    2      3     4    5     6     7      8    9     A      B    C     D     E     F
  0x63, 0x7c, 0x77, 0x7b, 0xf2, 0x6b, 0x6f, 0xc5, 0x30, 0x01, 0x67, 0x2b, 0xfe, 0xd7, 0xab, 0x76,
  0xca, 0x82, 0xc9, 0x7d, 0xfa, 0x59, 0x47, 0xf0, 0xad, 0xd4, 0xa2, 0xaf, 0x9c, 0xa4, 0x72, 0xc0,
  0xb7, 0xfd, 0x93, 0x26, 0x36, 0x3f, 0xf7, 0xcc, 0x34, 0xa5, 0xe5, 0xf1, 0x71, 0xd8, 0x31, 0x15,
  0x04, 0xc7, 0x23, 0xc3, 0x18, 0x96, 0x05, 0x9a, 0x07, 0x12, 0x80, 0xe2, 0xeb, 0x27, 0xb2, 0x75,
  0x09, 0x83, 0x2c, 0x1a, 0x1b, 0x6e, 0x5a, 0xa0, 0x52, 0x3b, 0xd6, 0xb3, 0x29, 0xe3, 0x2f, 0x84,
  0x53, 0xd1, 0x00, 0xed, 0x20, 0xfc, 0xb1, 0x5b, 0x6a, 0xcb, 0xbe, 0x39, 0x4a, 0x4c, 0x58, 0xcf,
  0xd0, 0xef, 0xaa, 0xfb, 0x43, 0x4d, 0x33, 0x85, 0x45, 0xf9, 0x02, 0x7f, 0x50, 0x3c, 0x9f, 0xa8,
  0x51, 0xa3, 0x40, 0x8f, 0x92, 0x9d, 0x38, 0xf5, 0xbc, 0xb6, 0xda, 0x21, 0x10, 0xff, 0xf3, 0xd2,
  0xcd, 0x0c, 0x13, 0xec, 0x5f, 0x97, 0x44, 0x17, 0xc4, 0xa7, 0x7e, 0x3d, 0x64, 0x5d, 0x19, 0x73,
  0x60, 0x81, 0x4f, 0xdc, 0x22, 0x2a, 0x90, 0x88, 0x46, 0xee, 0xb8, 0x14, 0xde, 0x5e, 0x0b, 0xdb,
  0xe0, 0x32, 0x3a, 0x0a, 0x49, 0x06, 0x24, 0x5c, 0xc2, 0xd3, 0xac, 0x62, 0x91, 0x95, 0xe4, 0x79,
  0xe7, 0xc8, 0x37, 0x6d, 0x8d, 0xd5, 0x4e, 0xa9, 0x6c, 0x56, 0xf4, 0xea, 0x65, 0x7a, 0xae, 0x08,
  0xba, 0x78, 0x25, 0x2e, 0x1c, 0xa6, 0xb4, 0xc6, 0xe8, 0xdd, 0x74, 0x1f, 0x4b, 0xbd, 0x8b, 0x8a,
  0x70, 0x3e, 0xb5, 0x66, 0x48, 0x03, 0xf6, 0x0e, 0x61, 0x35, 0x57, 0xb9, 0x86, 0xc1, 0x1d, 0x9e,
  0xe1, 0xf8, 0x98, 0x11, 0x69, 0xd9, 0x8e, 0x94, 0x9b, 0x1e, 0x87, 0xe9, 0xce, 0x55, 0x28, 0xdf,
  0x8c, 0xa1, 0x89, 0x0d, 0xbf, 0xe6, 0x42, 0x68, 0x41, 0x99, 0x2d, 0x0f, 0xb0, 0x54, 0xbb, 0x16
};
```

Bitslicing

- The **bitslicing** technique has been introduced by Eli Biham in 1997 (see [20] in references)
- Essentially, bitslicing simulates a hardware implementation in software: the entire algorithm is represented as a sequence of atomic Boolean operations
- **This sequence is executed in constant time**
- We can use it to implement S-box in AES (see [19] in references)

Bitslicing in AES

tiny-AES-c, implementation

```
static void SubBytes(state_t* state)
{
 uint8_t i, j;
 for (i = 0; i < 4; ++i)
 {
   for (j = 0; j < 4; ++j)
   {
     (*state)[j][i] =
getSBoxValue((*state)[j][i]);
   }
 }
}
```

https://github.com/kokke/tiny-AES-c/blob/master/aes.c#L251-L261

AES bitslicing

```
static void SubBytes(state_t* state)
{
 AES_state s = {{0}};
 LoadBytes(&s, state);
 SBoxBS(&s);
 SaveBytes(state, &s);
}
```

```
static void SBoxBS(AES_state *s) {
   uint16_t U0 = s->slice[7], U1 = s->slice[6], U2 = s->slice[5], U3 = s->slice[4];
   uint16_t U4 = s->slice[3], U5 = s->slice[2], U6 = s->slice[1], U7 = s->slice[0];

   uint16_t T1, T2, T3, T4, T5, T6, T7, T8, T9, T10, T11, T12, T13, T14, T15, T16;
   uint16_t T17, T18, T19, T20, T21, T22, T23, T24, T25, T26, T27, D;
   uint16_t M1, M6, M11, M13, M15, M20, M21, M22, M23, M25, M37, M38, M39, M40;
   uint16_t M41, M42, M43, M44, M45, M46, M47, M48, M49, M50, M51, M52, M53, M54;
   uint16_t M55, M56, M57, M58, M59, M60, M61, M62, M63;

   T1 = U0 ^ U3;
   T2 = U0 ^ U5;
   T3 = U0 ^ U6;
   ...
}
```

Crypto library: NaCl

NaCl

- NaCl: Networking and Cryptography library
- High-speed software library for network communication, encryption, decryption, signatures, etc
- Developed by Prof. Daniel J. Bernstein, and others
- Highly-secure primitives and constructions, implemented with extreme care to avoid **side-channel attacks**

Sodium

- **Sodium** (libsodium) is a fork of NaCl
- A portable, cross-compilable, installable, packageable, API-compatible version of NaCl
- Same implementations of crypto primitives as NaCl
- Shared library and a standard set of headers (portable implementation)
- Official web site: libsodium.org

Sodium: features

- Authenticated public-key and authenticated shared-key encryption
- Public-key and shared-key signatures
- Hashing
- Keyed hashes for short messages
- Secure pseudo-random numbers generation
- Zeroing memory

Sodium: algorithms

- **Curve25519**, Diffie–Hellman key-exchange function
- **Salsa20**, ChaCha20 stream ciphers
- **Poly1305**, message-authentication code
- **Ed25519,** public-key signature system
- **Argon2** and **Scrypt,** password hashing
- **AES-GCM**, authenticated encryption algorithm

Examples: use libsodium in PHP

Sodium in PHP

- Available (as standard library) from **PHP 7.2**
- 85 functions with prefix **sodium_**
- e.g. sodium_crypto_box_keypair()

Symmetric encryption

```php
// code1.php at https://github.com/ezimuel/sodium-php-talk
$msg = 'This is a super secret message!';
// Generating an encryption key and a nonce
$key   = random_bytes(SODIUM_CRYPTO_SECRETBOX_KEYBYTES);  // 256 bit
$nonce = random_bytes(SODIUM_CRYPTO_SECRETBOX_NONCEBYTES);  // 24 bytes
// Encrypt
$ciphertext = sodium_crypto_secretbox($msg, $nonce, $key);
// Decrypt
$plaintext = sodium_crypto_secretbox_open($ciphertext, $nonce, $key);

echo $plaintext === $msg ? 'Success' : 'Error';
```

Algorithms: **XSalsa20** for encrypt and **Poly1305** for MAC

Symmetric authentication

```php
// code2.php at https://github.com/ezimuel/sodium-php-talk
$msg = 'This is the message to authenticate!' ;
$key = random_bytes(SODIUM_CRYPTO_SECRETBOX_KEYBYTES);  // 256 bit

// Generate the Message Authentication Code
$mac = sodium_crypto_auth($msg, $key);

// Altering $mac or $msg, verification will fail
echo sodium_crypto_auth_verify($mac, $msg, $key) ? 'Success' : 'Error';
```

Algorithm: **HMAC-SHA512**

Public key encryption

```php
// code3.php at https://github.com/ezimuel/sodium-php-talk
$aliceKeypair = sodium_crypto_box_keypair();
$alicePublicKey = sodium_crypto_box_publickey($aliceKeypair);
$aliceSecretKey = sodium_crypto_box_secretkey($aliceKeypair);

$bobKeypair = sodium_crypto_box_keypair();
$bobPublicKey = sodium_crypto_box_publickey($bobKeypair); // 32 bytes
$bobSecretKey = sodium_crypto_box_secretkey($bobKeypair); // 32 bytes

$msg = 'Hi Bob, this is Alice!';
$nonce = random_bytes(SODIUM_CRYPTO_BOX_NONCEBYTES); // 24 bytes
$keyEncrypt = $aliceSecretKey . $bobPublicKey;
$ciphertext = sodium_crypto_box($msg, $nonce, $keyEncrypt);
$keyDecrypt = $bobSecretKey . $alicePublicKey;
$plaintext = sodium_crypto_box_open($ciphertext, $nonce, $keyDecrypt);
echo $plaintext === $msg ? 'Success' : 'Error';
```

Algorithms:
XSalsa20 for encrypt,
Poly1305 for MAC, and
XS25519 for key exchange

Digital signature

```php
// code4.php at https://github.com/ezimuel/sodium-php-talk
$keypair = sodium_crypto_sign_keypair();
$publicKey = sodium_crypto_sign_publickey($keypair); // 32 bytes
$secretKey = sodium_crypto_sign_secretkey($keypair); // 64 bytes

$msg = 'This message is from Alice';
// Sign a message
$signedMsg = sodium_crypto_sign($msg, $secretKey);
// Or generate only the signature (detached mode)
$signature = sodium_crypto_sign_detached($msg, $secretKey); // 64 bytes
// Verify the signed message
$original = sodium_crypto_sign_open($signedMsg, $publicKey);
echo $original === $msg ? 'Signed msg ok' : 'Error signed msg';
// Verify the signature
echo sodium_crypto_sign_verify_detached($signature, $msg, $publicKey) ?
    'Signature ok' : 'Error signature';
```

Algorithm: **Ed25519**

AEAD AES-256-GCM

```php
// code5.php at https://github.com/ezimuel/sodium-php-talk
$msg = 'Super secret message!';
$key = random_bytes(SODIUM_CRYPTO_AEAD_AES256GCM_KEYBYTES);
$nonce = random_bytes(SODIUM_CRYPTO_AEAD_AES256GCM_NPUBBYTES);
// AEAD encryption
$ad = 'Additional public data';
$ciphertext = sodium_crypto_aead_aes256gcm_encrypt($msg, $ad, $nonce, $key);
// AEAD decryption
$decrypted = sodium_crypto_aead_aes256gcm_decrypt($ciphertext, $ad, $nonce, $key);
if ($decrypted === false) {
   throw new \Exception("Decryption failed");
}
echo $decrypted === $msg ? 'OK' : 'Error';
```

ARGON2i

```
// code6.php at https://github.com/ezimuel/sodium-php-talk
$password = 'password';
$hash = sodium_crypto_pwhash_str (
   $password,
   SODIUM_CRYPTO_PWHASH_OPSLIMIT_INTERACTIVE,
   SODIUM_CRYPTO_PWHASH_MEMLIMIT_INTERACTIVE
); // 97 bytes
echo sodium_crypto_pwhash_str_verify ($hash, $password) ?
    'OK' : 'Error';
```

An example of output:

```
$argon2id$v=19$m=65536,t=2,p=1$EF1BpShRmCYHN7ryxlhtBg$zLZO4IWjx3E...
```

KDF using ARGON2i

```
// code8.php at https://github.com/ezimuel/sodium-php-talk
$password = 'password';
$salt = random_bytes(SODIUM_CRYPTO_PWHASH_SALTBYTES);

$key = sodium_crypto_pwhash(
   32,
   $password,
   $salt,
   SODIUM_CRYPTO_PWHASH_OPSLIMIT_INTERACTIVE,
   SODIUM_CRYPTO_PWHASH_MEMLIMIT_INTERACTIVE
);
```

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Thanks!

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