High-level Cryptographic Abstractions

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Abstract

The interfaces exposed by commonly used cryptographic libraries are clumsy, complicated, and assume an understanding of cryptographic algorithms. This paper proposes high-level abstractions consisting of simple cryptographic primitives and declarative configuration. These abstractions can be implemented on top of any cryptographic library in any language. We have implemented these abstractions in Python, and used them to write a variety of well-known security protocols, including Signal, Kerberos, and TLS.

We show that programs using our abstractions are much smaller and easier to write than using low-level libraries, and are safe against the vast majority of cryptographic misuse reported in the literature. Size of security protocol implementations are reduced by about a third on average when written with our abstractions. We also show that our implementation incurs a small overhead, less than 5 microseconds for shared key operations and less than 341 microseconds (< 1%) for public key operations.

1 Introduction

Existing cryptographic libraries are difficult to use. They require expertise that most developers lack, and place tedious burdens on experienced developers. The danger posed by this difficulty increases due to the proliferation of distributed computing, which requires that more developers make more extensive use of cryptographic libraries. The difficulty of using these libraries is not new [13, 71], but the extent of the problem grows as computers become more deeply embedded in our everyday lives. Mobile computing and the Internet of Things (IoT) especially encourage the storage and transmission of sensitive data. Consumers will expect such data to be properly secured, requiring that developers make greater use of cryptographic libraries.

A symptom that reveals the underlying problem with existing cryptographic libraries is the issue of cryptographic misuse, improper use of cryptographic APIs leading to violations of security requirements [42, pp. 73]. A string of papers, beginning in 2012, have documented widespread cryptographic misuse in mobile applications [17, 31, 42, 43, 50, 51, 56, 75]. These works define specific types of cryptographic misuse and build tools to detect them.

For example, Egele et al. [42] found that 88% of the 11,748 Android apps analyzed by their tool, CryptoLint, contained at least one cryptographic misuse. A similar study by Ma et al. [56] found that 99% of the 8,640 Android apps they analyzed contained at least one cryptographic misuse. However, detecting misuse is not sufficient to prevent all misuse.

This paper proposes SecAlgo, high-level abstractions for cryptographic operations, in order to alleviate the difficulty of using cryptographic libraries to write secure programs. SecAlgo reduces programmer effort,
| Misuse type | Description | Number of apps with this misuse type |
|-------------|-------------|-------------------------------------|
| M1K         | Insufficient key size | CryptoLint [42] CMA [75] CNKX [31] CDRep [56] |
| M2K         | Constant or hardcoded keys | 3644 0 4 882 |
| M1S         | Encryption in ECB mode | 7656 7 16 887 |
| M2S         | Encryption with predictable IV | 1932 8 2 979 |
| M3S         | Encryption with obsolete algorithm | - 8 16 - |
| M1A         | RSA encryption without OAEP | - 3 2 - |
| M1H         | Hashing with obsolete algorithm | - 38 16 5582 |
| Total apps  | Total number of apps analyzed | 11748 45 49 8640 |

Table 1: Misuse type and number of apps containing that type, plus total number of apps studied, in [42], [75], [31], and [56]. Listed are misuse types prevented by SecAlgo; three other types studied [31, 42, 56] (a constant salt for password-based encryption (PBE), < 1000 iterations for PBE, and improper seeding for Java SecureRandom objects), not prevented by SecAlgo, are not listed. '-' means that the study did not report about instances of the corresponding misuse type.

increases clarity of secure programs, and prevents many significant types of cryptographic misuse. SecAlgo can be implemented on top of any cryptographic library in any language. We have implemented SecAlgo in Python, and used it to write a variety of well-known security protocols, including Signal, Kerberos, and TLS.

We first describe the need for high-level cryptographic abstractions in Section 2. High-level abstractions for cryptographic operations are defined in Section 3 and their implementation is described in Section 4. Section 5 illustrates the use of SecAlgo for implementing security protocols. Section 6 presents experimental results. Section 7 discusses related work and concludes.

2 Need for high-level cryptographic abstractions

There are two reasons to believe that we need better abstractions for cryptographic operations: (1) APIs for existing cryptographic libraries make it too difficult to properly use cryptographic primitives and (2) educating developers is not a sufficient solution to the problem.

Difficulty of proper use.
The low-level APIs provided by cryptographic libraries require many decisions, including ones that must be coordinated, sometimes repeatedly, in order to correctly use cryptographic primitives. Making these decisions demands significant expertise and tedious manual effort. Even experienced programmers are likely to make mistakes. Such mistakes will compromise the security objective the programmer tries to achieve through use of the cryptographic primitives.

This difficulty of proper use is the source of cryptographic misuse. The study results listed in Table 1 indicate that misuse occurs in mobile applications at a concerning rate. This widespread cryptographic misuse is the best evidence for the difficulty of using cryptographic libraries with low-level APIs.

Educating developers is not a sufficient solution.
Proper use of cryptographic APIs requires considerable security expertise. Given this, it is tempting to believe that we can address the difficulty of using these APIs by providing clear, thorough documentation
and high-quality examples of proper use.

We should, of course, strive to provide such documentation, but it will not suffice as a solution. The real issue is the sheer number of low-level decisions that must be made when using low-level APIs. Even experienced users struggle to avoid mistakes when confronted with this complexity.

We need a solution that directly addresses this complexity by protecting both experts and non-experts from mistakes caused by carelessness, neglect, limited time and attention, exhaustion, and other conditions that afflict humans confronted with unnecessary complexity.

Solution through abstraction.

Given that cryptographic libraries are overly difficult to use and that this difficulty cannot be overcome just through better education and training, it is necessary to create new abstractions for cryptographic operations. These abstractions can offer the cryptographic operations needed to provide security guarantees for secure applications. At the same time these abstractions can hide the complexity that causes cryptographic misuse.

3 High-level cryptographic abstractions

The abstractions in SecAlgo are of two kinds: (1) high-level cryptographic operations to provide confidentiality, integrity, and authenticity, and (2) declarative configurations. We describe language constructs for the first kind along with their essential arguments; additional arguments can be specified either as optional arguments or using configuration. Properly chosen configuration values—as determined by the current best practices in security—are used by default.

SecAlgo abstractions aim to serve both experts and non-experts. Experts can use optional arguments and configuration to call and compose a wide range of cryptographic operations. Non-experts can rely on the default arguments and configurations to use safe cryptographic operations.

Abstractions for cryptographic operations.

SecAlgo has five basic cryptographic operations for writing security protocols and secure applications: key generation, encryption, decryption, signing, and verification. SecAlgo provides an abstraction for each basic operation. We use a generic syntax in this section; each operation can be implemented in any programming language as a single API function.

SecAlgo creates this set of abstractions because they greatly simplify the implementation of security protocols and applications—they include the configuration of multiple types of interrelated arguments among a set of choices for each argument, and the state configured at key generation is maintained through subsequent, continued uses of the other four operations. This contrasts with operations such as computing a hash or generating a random value, that return only a simple value to be used subsequently.

Key generation is of the following form, where type $t$ is the name of a particular cryptographic algorithm, such as AES or RSA, or a generic shared or public.

\[
\text{keygen type } t
\]

It generates and returns a key or pair of keys suitable for the cryptographic algorithm corresponding to type $t$.

- If $t$ is the name of a specific shared-key (also called symmetric-key) algorithm, such as AES, or is the generic shared, then keygen returns a single value, a shared key. This value will be labeled with the
name of the algorithm given as \( t \). If the generic shared type is used, then the key is labeled with the name of the configured shared-key algorithm.

- If \( t \) is the name of a specific public-key (also called asymmetric-key) algorithm, such as RSA, or is the generic public, then \texttt{keygen} returns a pair of values, a private key and a public key. Each key is labeled with the name of the algorithm for which it is generated. The two components of the pair can be retrieved by using a simultaneous assignment (in languages that support such assignments, such as Python) or by using two retrieval operations.

The size of the key can be specified as an optional argument to \texttt{keygen}, in an additional clause \texttt{size \( s \)} or otherwise declared as part of the configuration; if the size is left unspecified the default is used. If \( t \) names a block cipher, such as AES, then a mode of operation \([39]\)—an algorithm for repeatedly applying the block cipher to encrypt an arbitrary size plaintext, such as Cipher Block Chaining (CBC)—must also be specified. Like key size, the mode of operation can be specified as an optional argument in an additional clause \texttt{mode \( m \)} or declared as a part of the configuration. If left unspecified, the default mode of operation is used.

**Encryption and decryption** provide confidentiality, also known as secrecy, and are of the forms below.

\[
\begin{align*}
&\text{encrypt text } \texttt{txt} \text{ key } \texttt{k} \\
&\text{decrypt text } \texttt{txt} \text{ key } \texttt{k}
\end{align*}
\]

Function \texttt{encrypt} encrypts text \( \texttt{txt} \) with key \( \texttt{k} \) and returns the resulting encrypted text. Function \texttt{decrypt} decrypts text \( \texttt{txt} \) with key \( \texttt{k} \) and returns the resulting decrypted text. They call the appropriate low-level library functions as determined by the key type, size, and mode.

**Signing and verification** provide authentication, integrity, and non-repudiation, and are of the forms below.

\[
\begin{align*}
&\text{sign text } \texttt{txt} \text{ key } \texttt{k} \\
&\text{verify text } \texttt{txt} \text{ sig } \texttt{s} \text{ key } \texttt{k}
\end{align*}
\]

Function \texttt{sign} signs text \( \texttt{txt} \) with key \( \texttt{k} \) and returns the signature. Function \texttt{verify} verifies signature \( \texttt{s} \) against text \( \texttt{txt} \) with key \( \texttt{k} \) and returns a boolean value, true if verification succeeds and false otherwise. \texttt{sign} and \texttt{verify} call the appropriate low-level library functions as determined by the key type and size.

**Declarative configuration.**

Configuration declaratively specifies values of parameters for cryptographic operations, and is of the form below, where configuration item \texttt{item} is assigned the value \texttt{value}.

\[
\text{configure \ item} = \texttt{value}
\]

Table\([2]\) lists supported configuration items, their allowed values, and default values.

Declarative configuration allows security experts to exert control over the operation of high-level cryptographic abstractions in a clear and simple way. Proper default configuration values—ones that capture the best practices as determined by security experts—are defined. This relieves developers of the burden of making choices about security algorithms, key sizes, modes etc. for which they lack the relevant expertise or which are unnecessarily tedious to decide and code at a low level.

Configurations can be declared to apply globally, for particular sets of processes or communication channels, for particular scopes such as the method-scope, or specified as optional arguments to individual operations. Configurations declared for an enclosed scope override those declared for an enclosing scope.
Table 2: Configuration items, allowed values, and the default value. * for key size indicates that allowed values depend on the algorithm and backend library selected. ** for key size indicates the default value that follows the NIST advice [64].

| Item                      | Allowed values                  | Default value   | References                      |
|---------------------------|---------------------------------|-----------------|---------------------------------|
| key_type_shared           | AES, Blowfish, 3DES, Salsa20, Chacha20 | AES             | AES [9], Blowfish [73], 3DES [65], Salsa20 [21], Chacha20 [20] |
| key_type_public           | RSA, DSA, ECDSA                 | RSA             | RSA [59], DSA, ECDSA [62]       |
| key_size_shared           | positive integer*               | 256**           |                                 |
| key_size_public           | positive integer*               | 2048**          |                                 |
| block_cipher_mode         | CBC, CTR, CFB, EAX, GCM, CCM, SIV, OCB | CBC             | CBC, CTR, CFB [39], EAX [18], GCM [41], CCM [40], SIV [45], OCB [48] |
| signing_hash              | SHA224, SHA256, SHA384, SHA512 | SHA256          |                                 |
| backend_library           | PyCrypto, PyNaCl, PyCryptodome, cryptography.io | PyCrypto       | PyCrypto [52], PyNaCl [5], PyCryptodome [72], cryptography.io [1] |

4 Implementation

We have developed a prototype implementation of SecAlgo as a Python module—a library of Python functions, one for each of the five basic operations described in the previous section.

SecAlgo is implemented on top of PyCrypto [52] for shared-key encryption using block ciphers (AES and Triple DES) in classical modes (CBC, CTR, CFB), message authentication code creation (HMAC), public key encryption (RSA), and public key digital signing (RSA, DSA).

In addition, SecAlgo utilizes PyNaCl [5], PyCryptodome [72], and cryptography.io [1] for authenticated encryption modes for block ciphers (CCM [40], EAX [18], GCM [41], SIV [45], OCB [48]), safe stream ciphers (Salsa20 [21], Chacha20 [20]), key derivation functions (HKDF [47]), elliptic curve digital signing [22], and elliptic curve Diffie-Hellman shared secret computation [19].

Some of these features (authenticated encryption modes, stream ciphers, elliptic curve digital signing) fall under our five abstractions. For the other operations, SecAlgo provides a high-level wrapper API around a fixed library implementation with a fixed set of parameters—choice of library implementation or configuration is currently not provided for these operations.

Key generation.

Implementation of keygen uses functions in the low-level cryptographic libraries based on the type, size, and mode of operation specified.

To use only safe algorithms and implementations, SecAlgo checks all arguments of keygen against whitelists for approved combinations of algorithm types, key sizes, modes of operation, and hash functions. If the check fails, then keygen terminates and reports an error.

SecAlgo also makes sure that all key material—the bytes that form the shared secret for symmetric keys, or the modulus and exponents that form the public and private keys for RSA—is generated through calls to cryptographically strong pseudo-random number generators, which are usually provided by low-level cryptographic libraries and operating systems.
SecAlgo stores key material in a structure that also contains labels for algorithm type, key size, block cipher mode of operation, public vs. private key (if the type is a public key cipher) and the name of the hash function used by MAC and digital signing algorithms. The implementation uses Python’s `dict` to hold the key material and labels.

**Encrypt, decrypt, sign, and verify.**

For encryption, decryption, signing, and verification, SecAlgo manages low-level details so that they remain hidden.

First, SecAlgo verifies that the input data is in a proper representation for submission to the cryptographic functions of the low-level cryptographic library. This includes making sure the input data is of the correct type and, if required by the encryption algorithm and mode of operation, of the proper size.

For example, PyCrypto requires that plaintexts are bytes-like objects [52] (a bytes-like object is one that supports the Buffer Protocol, such as `bytes`, `bytearray`, or `memoryview`). If the input data is not of a compatible type and cannot be safely converted to the required type, then an error is signaled to the user.

Additionally, shared-key block algorithms have a block size—a fixed number of bytes to which the algorithm can be applied. Some modes of operation (such as CBC) require that every block of plaintext input must be of the block size. When using these modes for messages whose length is not divisible by the block size, SecAlgo automatically pads the data using a method that is safe for the encryption algorithm. For example, when using a block cipher in CBC mode, SecAlgo applies the PKCS7 [46] padding algorithm, which appends $N$ bytes of value $N$ to pad the plaintext to a multiple of the block size, where:

$$N = \text{block size} - (\text{plaintext length} \mod \text{block size})$$

Any padding is stripped from the decrypted data before it is returned.

Also, SecAlgo generates and handles any auxiliary values used by the selected algorithm or mode of operation: initialization vectors, counters, and nonces. For example, Counter (CTR) mode encryption uses a counter, which can be any function that produces a sequence of block-size bytes values guaranteed not to repeat for a large number of iterations. SecAlgo follows a standard method [39] to generate the initial counter value by using a random value for the top-half of the counter and setting the bottom-half to 0. The random top-half value of the counter is prepended to the ciphertext.

Finally, for public key encryption, SecAlgo uses a straightforward hybrid encryption [32] scheme to encrypt arbitrary amounts of plaintext data. A single call to a public key encryption method can only encrypt a number of bytes that is less than the public key size. SecAlgo first checks the size of the plaintext to determine whether it can be encrypted directly using the public key algorithm, given the key size. If not, SecAlgo generates a 256-bit shared key and encrypts the data using AES in CBC mode. The new shared key is then encrypted with the public key algorithm. The public–key–encrypted AES key is prepended to the AES–in–CBC–mode–encrypted data, and this concatenation is returned.

5 Application: Implementing security protocols

To demonstrate the use of SecAlgo, we have implemented a collection of well-known security protocols. Our goal is to write clear, high-level implementations of classical security protocols, such as Needham-Schroeder and others in the SPORE repository [6], as well as significant parts of more substantial protocols: TLS version 1.2 [38] (for which we have implemented the Handshake Protocol, Change Cipher Spec Protocol, and the Record Protocol), Kerberos version 5 [68] (for which we have implemented the basic handshake),
1. \( A \rightarrow AS : A, B \)
2. \( AS \rightarrow A : CA, CB \)
3. \( A \rightarrow B : CA, CB, \{\{CK, T\}\}_S_A \) \( P_B \)

Where:
- \( A \) and \( B \) are users, and \( AS \) is a centralized key distribution facility called an Authentication Server.
- \( T \) is a timestamp
- \( P_X \) and \( S_X \) denote user \( X \)'s public key and secret (signature) key respectively
- \( CA = \{A, P_A, T\}_S_A \) and \( CB = \{B, P_B, T\}_S_A \)
- The key \( CK \) is then used for encrypting messages transmitted between \( A \) and \( B \).

1. \( A \rightarrow B : \{\{CK\}\}_S_A \) \( P_B \)
2. \( B \rightarrow A : \{msg\}_CK \)

Figure 1: Top: Denning-Sacco public key distribution protocol [36, p. 535]. Bottom: Simplified Denning-Sacco key distribution protocol [27].

and the Signal protocol [3, 60] (including its components the Double Ratchet protocol [76] and the Extended Triple Diffie-Hellman (X3DH) protocol [61]).

Table 3 lists 10 of the protocols we implemented plus a simplified version of one of them, Denning-Sacco key distribution protocol, to be used as a precise example.

We implemented these protocols using SecAlgo plus the DistAlgo language [53,55]. DistAlgo is an extension of Python, so DistAlgo programs can easily use SecAlgo. DistAlgo provides high-level abstractions for creating distributed processes, functions for passing messages, and synchronization. The combination of SecAlgo with DistAlgo enables us to write clear, high-level implementations of security protocols.

The top part of Figure 1 shows the Denning-Sacco key distribution protocol [36] (a variation on the Needham-Schroeder public key authentication protocol [66]). There are three parties, an initiator (A), a responder (B), and a trusted authentication server (AS). The goal is to securely establish a new shared key (CK) known only to A and B. A acquires certificates containing its own public key (CA) and B’s public key (CB). These certificates are passed by A to B in message 3. With the keys contained in these certificates, A and B use public key cryptography to protect the confidentiality and integrity of the new shared key, and to authenticate each other.

A simplified version of the Denning-Sacco protocol [27] is shown in the bottom part of Figure 1. It assumes that A and B both already possess the other’s public key. As a result, A does not need to get certificates containing those public keys from AS, which eliminates AS and the first two messages. The simplified protocol also does away with the timestamp (T) associated with the new shared key.
from sealgo import *

class RoleA (process):  # type A process
def setup(skA, B, pkB):  # take in params
    pass

def run():
    k = keygen('shared')  # new shared key
    send((1, encrypt((k, sign(k, skA)), pkB)), to= B)
    await (some(received((2, enc_m), from_= _B)))
    m = decrypt(enc_m, k)
    output('Decrypted secret:', m)

class RoleB (process):  # type B process
def setup(skB, pkA):  # take in params
    self.m = 'secret'  # set secret msg

def run():
    await(False)

def receive(msg=(1, enc_k), from_= A):
    k, sig = decrypt(enc_k, skB)
    if verify(k, sig, pkA):
        send((2, encrypt(m, k)), to= A)

def main():
    skA,pkA = keygen('public')  # prv,pub key of A
    skB,pkB = keygen('public')  # prv,pub key of B
    B = new(RoleB, (skB, pkA))  # create B
    A = new(RoleA, (skA,B,pkB))  # create A
    start(B)
    start(A)

Figure 2: Simplified Denning-Sacco key distribution protocol.

Figure 2 shows the simplified Denning-Sacco protocol in SecAlgo plus DistAlgo. On line 9 message 1 of the simplified protocol is sent, and on lines 21-23 that message is received, the encrypted shared key and signature are decrypted, and then the signature on the shared key is verified. Lines 10-11 and 24 illustrate the use of the new shared key to transmit encrypted messages readable only by A and B. A message (m) is encrypted and sent on line 24, received on line 10, and decrypted on line 11.

Each role in a protocol can be defined as a distinct process class. By extending process, a process in DistAlgo can send messages (lines 9 and 24), handle received messages (line 21), and await for synchronization conditions to become true (line 10).

This example illustrates several important features of SecAlgo:

1. Functions encrypt and decrypt can transparently provide both shared-key and public-key cryptographic operations as determined by the key type (shared-key on lines 11 and 24; public-key on lines 9 and 22).

2. Functions, encrypt, decrypt, sign, and verify, compose smoothly at a high level needing no extra effort (see lines 9 and 22-23).
3. The developer is relieved of any extra tasks associated with using cryptographic operations. There is no need to generate an IV or a counter, or to pad plaintexts, for those algorithms that require it. All those tasks are managed in the background.

This last point demonstrates how SecAlgo simplifies decision-making about cryptographic operations. Even for the simplified Denning-Sacco protocol:

- The protocol contains three calls to \texttt{keygen}, two calls each to \texttt{encrypt} and \texttt{decrypt}, and one call each to \texttt{sign} and \texttt{verify}.
- Those three calls to \texttt{keygen} contain between 9 and 18 decisions regarding operation, algorithm, key size, mode of operation, padding, decisions with 66 possible outcomes.

These decision points are all occasions for a programmer, even an experienced one, to make mistakes. SecAlgo defaults ensure that all those decisions are made safely.

6 Experiments and Results

We show that SecAlgo allows secure programs to be written much more easily than using lower-level libraries and incurs a minimum overhead. We also show that SecAlgo prevents all types of cryptographic misuse listed in Table 1.

We compare measurements of programs that directly use SecAlgo with those that use the following lower-level libraries upon which SecAlgo is built:

- PyCrypto: The most widely-used general-purpose cryptography library for Python [10, Table 1].
- cryptography.io: The second-most widely-used general purpose cryptography library for Python [10, Table 1].
- PyCryptodome: A fork of PyCrypto extended to include newer cryptographic operations; still not in wide use [10, Table 1].
- PyNaCl: The best available Python interface for Curve 25519 elliptic curve cryptography [10].

The last three libraries provide additional operations not available in PyCrypto.

6.1 Code size and programming effort

SecAlgo has been used to implement over 20 security protocols, including those listed in Table 3. We compare implementations in SecAlgo with alternative implementations that use the lower-level cryptographic libraries PyCrypto, cryptography.io, PyCryptodome, and PyNaCl directly, and with abstract specifications written for protocol verification tools. We also compare with implementations in Java, C#, and Python for NS-SK, the corrected Needham–Schroeder shared key protocol.

Table 4 gives the LOC (number of lines of code without comments) for the protocols listed in Table 3. We use LOC as an indirect measure of programming effort and program clarity. This is common practice in programming language literature.
| Protocol | Description |
|----------|-------------|
| NS-SK    | Corrected Needham-Schroeder protocol for key distribution by key server via shared key encryption [66] |
| NS-PK    | Corrected Needham-Schroeder protocol for mutual authentication via public key encryption [66, 67] |
| DS       | Denning-Sacco protocol for key distribution by key server and mutual authentication via public key encryption [36] |
| DS Simp  | Simplified Denning-Sacco protocol for key distribution and mutual authentication via public key encryption [27] |
| DHKE-1   | Diffie-Hellman key exchange protocol with mutual authentication via public key signatures [74] |
| SDH      | Signed Diffie-Hellman key exchange protocol [30] |
| X3DH     | Extended Triple Diffie-Hellman key exchange with mutual authentication via elliptic curve public key signatures [61] |
| DR       | Double Ratchet (aka Axolotl) encrypted message exchange protocol via shared key authenticated encryption [76] |
| Signal   | Signal: A ratcheting forward secrecy protocol for synchronous and asynchronous messaging environments [3, 60] |
| KRB-5    | Kerberos, version 5, protocol for key distribution by key server and mutual authentication via shared key encryption [68] |
| TLS-1.2  | Transport Layer Security (Handshake), version 1.2, for key exchange and mutual authentication via public key encryption [38] |

Table 3: Well-known security protocols.

| Protocols | SecAlgo+DistAlgo | PyCrypto+DistAlgo | Scyther | AVISPA | ProVerif | Tamarin | CryptoVerif |
|-----------|------------------|-------------------|---------|--------|----------|---------|-------------|
| NS-PK     | 47               | 96                | 36      | 55     | 107      | 109     | 116         |
| NS-SK     | 46               | 68                | 41      |        | 82       | 94      |             |
| DS        | 50               | 102               |         | 96     |          |         |             |
| DS Simp   | 26               | 69                |         |        |          |         |             |
| DHKE-1    | 63               | 113               | 41      |        |          |         |             |
| SDH       | 39               | 73                | 35      | 41     | 48       | 89      |             |
| X3DH      | 140              | 151               |         |        |          |         |             |
| DR        | 182              | 199               |         |        |          |         |             |
| Signal    | 321              | 349               |         |        |          |         |             |
| KRB-5     | 171              | 213               | 94      | 137    |          |         |             |
| TLS       | (v. 1.2) 430     | (v. 1.2) 478      | (v. 1.0) 53 | (v. 1.0) 107 | (v. 1.3) 397 | (v. 1.0) 128 |

Table 4: LOC of protocol implementations (executable on distributed machines) in SecAlgo+DistAlgo and PyCrypto+DistAlgo, and of abstract specifications in other languages and tools. Our implementations of X3DH, DR, and Signal include 58 lines of Python code taken directly from the specification [76]. Empty entry means we did not find a corresponding specification.

**Ease of programming using SecAlgo.**

The simplified function calls, automated generation of auxiliary values, declarative configuration, and carefully selected default options in the implementation of SecAlgo result in a reduction of the number of lines required to invoke cryptographic operations, and a simplification of those lines, when compared to other libraries.
For example, to encrypt a string using AES in CBC mode with a 32 byte key using PyCrypto, one must do the following:

```python
k = Random.new().read(32)
iv = Random.new().read(AES.blocksize)
cipher = AES.new(k, AES.MODE_CBC, iv)
ct = iv + cipher.encrypt(pad(pickle.dumps(pt)))
```

We can perform the same operation in SecAlgo as follows, where `key` is optional as in Python:

```python
k = keygen('shared')
ct = encrypt(pt, key = k)
```

We see a similar reduction in the number and complexity of lines of code for the other cryptographic operations supported by SecAlgo. In addition, we can alter the algorithm, keysize, and mode by declaring a new configuration, without having to alter either the call to `keygen` or the call to `encrypt`.

Our experience is that writing protocols using SecAlgo plus DistAlgo is much easier than using other languages and libraries. For simpler protocols like the first 6 in Table 3, we were able to implement them in SecAlgo plus DistAlgo, with LOC shown in column 2 of Table 4 by simply following their protocol narrations.

Seven relatively simple protocols, not listed in Table 3, were written by undergraduates and high-school students who, despite having had no or little familiarity with Python and being entirely new to SecAlgo and cryptography (as well as to DistAlgo and distributed programming), were able to complete the implementation in a couple of weeks with minimal assistance.

For X3DH, DR, and Signal protocols, we were able to easily use the core protocol specification from [76], which uses pseudocode that is simply Python code. We then added implementations of the lower-level cryptographic functions, which they call “external functions”, using other libraries for elliptic curve cryptography (Curve 25519 for both signing and Diffie-Hellman) and key derivation (HKDF).

**Comparison with using PyCrypto.**

We also implemented the protocols in Table 3 using PyCrypto (and PyNaCl for X3DH, DR, and Signal) plus DistAlgo. Column 3 of Table 4 shows the LOC of these implementations. Executing these programs produces the same calls to the underlying cryptography libraries as those in column 2.

Table 5 lists the number of calls to SecAlgo functions that appear in each protocol implementation. Each SecAlgo function call uses 1 or more fewer lines of code compared with using PyCrypto and other lower-level libraries. As a result, protocol implementations written using SecAlgo are shorter and simpler than those written using PyCrypto and other lower-level libraries.

The average percentage difference in LOC across all implementations written using SecAlgo (shown in column 2 of Table 4) compared to those written using low-level libraries (shown in column 3 of Table 4) is 31%, that is, using SecAlgo reduces LOC of protocol implementations by almost a third on average.

**Comparison with abstract protocol specifications.**

Columns 4 to 8 of Table 4 show LOC of abstract specifications for the protocols in Table 3 in the best security protocol specification languages (for all we could find), as written by experts in these languages. These specifications are not executable, and are used as input to specialized verifiers of the respective languages. Our executable SecAlgo programs are actually similar in size to the most abstract of these specifications, as evidenced by the similar LOC. The SecAlgo plus DistAlgo implementations of all but the last 2 protocols have smaller LOC than all of the abstract specifications except for those in Scyther (SPDL [35]).
| Protocol | keygen | encrypt | decrypt | sign | verify | Total |
|----------|--------|---------|---------|------|--------|-------|
| NS-SK    | 3      | 5       | 5       | 0    | 0      | 13    |
| NS-PK    | 3      | 3       | 3       | 2    | 2      | 13    |
| DS       | 4      | 1       | 1       | 3    | 5      | 14    |
| DS Simp  | 3      | 2       | 2       | 1    | 1      | 9     |
| DHKE-1   | 7      | 0       | 0       | 4    | 4      | 15    |
| SDH      | 5      | 0       | 0       | 2    | 2      | 9     |
| X3DH     | 18     | 1       | 1       | 2    | 2      | 24    |
| DR       | 11     | 1       | 1       | 3    | 1      | 17    |
| Signal   | 29     | 2       | 2       | 5    | 3      | 41    |
| KRB-5    | 6      | 6       | 6       | 6    | 6      | 30    |
| TLS-1.2  | 14     | 3       | 3       | 4    | 3      | 27    |

Table 5: Number of calls to SecAlgo functions in each protocol implementation.

| Language | Crypto library       | NS-SK |
|----------|----------------------|-------|
| C#       | .NET Cryptography [7] | 364   |
| Java     | JCA [70]             | 351   |
| Python   | PyCrypto [52]        | 217   |
| Python   | SecAlgo              | 170   |
| DistAlgo | PyCrypto [52]        | 68    |
| DistAlgo | SecAlgo              | 46    |

Table 6: LOC of NS-SK implementations using different languages and libraries.

For the last 2 protocols, TLS and Kerberos, the most significant cause of the larger LOC of the SecAlgo plus DistAlgo implementation is functionalities omitted from the abstract specifications. For example, the abstract specifications of TLS include only the TLS Handshake protocol, whereas the SecAlgo plus DistAlgo implementation also includes the TLS Record protocol and the TLS ChangeCipherSpec protocol. For Kerberos, none of the abstract specifications construct tickets with actual timestamps, or use those timestamps to validate tickets, whereas the SecAlgo plus DistAlgo implementation does both.

Comparison with using other programming languages for NS-SK.

Table compares implementations of NS-SK in C#, Java, PyCrypto plus Python, SecAlgo plus Python, PyCrypto plus DistAlgo and SecAlgo plus DistAlgo. The implementations use different libraries for distributed programming and cryptographic operations. These implementations were developed by ourselves or with our supervision, and they represent our best effort, so far, to use each language in the best way. For LOC comparison, we formatted the programs according to the suggested style of each language.

The C# and Java programs required much more effort than the Python programs, which required much more effort than the DistAlgo programs. This is also evident in the LOC comparison. Our experience writing these implementations confirmed that using high-level cryptographic and communication abstractions significantly help reduce program size and programming effort and increase program clarity.
| Crypto operation | Configuration       | PyCrypto | SecAlgo | Increase | % Increase |
|------------------|---------------------|----------|---------|----------|------------|
| keygen           | AES, 256, CBC, PKCS7| 47.36    | 49.55   | 2.19     | 4.62       |
| encrypt          | AES, 256, CBC, PKCS7| 65.93    | 70.43   | 4.50     | 6.83       |
| decrypt          | AES, 256, CBC, PKCS7| 14.46    | 16.71   | 2.25     | 15.56      |
| sign             | HMAC, 256, SHA512   | 16.9     | 18.65   | 1.75     | 10.36      |
| verify           | HMAC, 256, SHA512   | 17.26    | 18.84   | 1.58     | 9.15       |
| keygen           | RSA, 2048           | 124,526.75 | 124,867.29 | 340.54 | 0.27 |
| encrypt          | RSA, 2048, OAEP     | 1,322.00 | 1,322.42 | 0.42    | 0.03       |
| decrypt          | RSA, 2048, OAEP     | 3100.17  | 3106.41 | 6.24    | 0.20       |
| sign             | RSA, 2048, PKCS1    | 2995.29  | 3008.31 | 13.02   | 0.43       |
| verify           | RSA, 2048, PKCS1    | 698.92   | 705.21  | 6.29    | 0.90       |

Table 7: Cryptographic operations and configurations used, CPU times (in microseconds) when using PyCrypto and using SecAlgo, and time increase (in microseconds) and percentage increase from PyCrypto time to SecAlgo time.

### 6.2 Running times and overhead

We discuss three running time experiments measuring (1) the time taken by SecAlgo functions compared with using the underlying lower-level cryptographic library directly, (2) the time of cryptographic operations vs. message passing in protocols, and (3) the time of NS-SK implementations using SecAlgo vs. using PyCrypto on top of DistAlgo and Python, vs. implementations in Java and C#.

All reported running times are CPU times measured on an Intel Core i5-5250U processor of 2.70GHZ with 16GB of DDR3L memory, running Ubuntu 17.10, DistAlgo 1.0.12, and Python 3.6.3. PyCrypto 2.6, PyCryptodome 3.5.1, cryptography.io 2.2.2, and PyNaCl 1.2.1 are used for cryptographic operations. For all experiments the Python garbage collector was disabled. For each measurement, protocols and cryptographic operations are run in a loop for at least one second and the CPU time is averaged over the number of iterations in order to get an accurate estimate of the CPU time for a single execution of that protocol or operation. Each of those measurements is repeated at least 50 times, and the average is taken.

#### Overhead of SecAlgo abstractions.

We fix a configuration—an algorithm, a key size, a mode of operation, and a padding—and measure the running time of each SecAlgo primitive. We measure the same operation written using PyCrypto directly. The measurement for using PyCrypto directly also includes the time needed to encode input to cryptographic functions as byte strings and the reverse for output from the cryptographic functions. This is done because it is required by the low-level libraries. We use the pickle library for Python for encoding and decoding.

Table 7 shows that SecAlgo primitives impose small overhead for all cryptographic primitives compared with using PyCrypto. The overhead is ≤ 4.5 microseconds for all shared key primitives, The overhead is ≤ 13.02 microseconds for all public key primitives except for 340.54 microseconds for keygen, but all are < 1%.

Public keys used by SecAlgo are 8 times as large as those used for shared key cryptography (2048-bit vs. 256-bit). This means that public key primitives may have more varied increases in running times due to memory effect, as observed. At the same time, because public key primitives are much more expensive, the percentage increases may be much smaller, again as observed.
Table 8: Number of calls to different cryptographic functions (in the order of expensive ones first), CPU times (in milliseconds) of protocol run and library calls, difference between the two times, and number of messages passed. An empty entry denotes 0.

* for TLS1.2 indicates that the number of messages can differ when different branching conditions hold; our experiments used the condition for which 9 messages are passed.

Running time of cryptographic operations in total protocol time.

To understand the running times of cryptographic operations among total protocol time, we measure these times for each protocol in Table 3 and we show the contributing factors by counting the number of calls to different cryptographic functions and the number of messages passed.

For protocol time, we measure the time used by each role excluding process setup time, and sum over all roles. For the time of all cryptographic operations, which we call library time, we measure the time of each SecAlgo function call and sum over all calls. We collect the counts of calls and messages for the measured execution of each protocol.

Table 8 shows the results, grouped by the kinds of cryptographic functions called and sorted by decreasing library time in each group. Cryptographic functions are listed in the order of expensive ones first: modular exponentiation (pow) for Diffie-Hellman, RSA functions, elliptic curve (EC) functions, and shared key functions (SK); among RSA functions, keygen, decrypt and sign that use private keys, and encrypt and verify that use public keys; among EC functions, keygen and the rest.

For library time, we see that it is almost fully determined by the counts of calls to more expensive functions, with two exceptions: (1) SDH and DHKE-1 both have the same numbers of expensive calls, especially power function pow to compute Diffie-Hellman shared secrets, but the larger time for SDH is because it uses values that are 3 times as large; (2) Signal uses EC, but it has many more calls to EC keygen and thus a slightly larger library time than DS Simp and TLS 1.2 that use RSA but have few calls of non-keygen functions. In fact, with the exception of Signal, the library time is sorted completely in decreasing order.

Protocol time is also mostly in decreasing order, but with three exceptions: TLS 1.2, Signal, and NS-SK. This is because protocol time is also affected by the number of messages passed during the protocol run. In fact, the three exceptions are from protocols that have the most messages.

We consider the difference between protocol and library times. We see that for each group, a larger time
difference corresponds to a larger number of messages, with one exception: SDH and DHKE-1 both have 3 messages, but the larger difference for DHKE-1 is due to additional local, non-cryptographic computations in DHKE-1 but not in SDH.

Comparison with using Python and PyCrypto on NK-SK.

Figure 3 shows the running times of NS-SK written using SecAlgo and PyCrypto on top of DistAlgo and Python, for all 4 combinations, measured by repeating NS-SK on increasing numbers of runs.

All 4 implementations show a linear increase in running time as the number of runs increases. The difference between using SecAlgo and using PyCrypto, on top of DistAlgo or on top of Python, is small: at most 2.4 seconds and between -2% and 16%. The difference can sometimes be negative because of the small overhead of SecAlgo and the usual variation in running times of multi-process protocols even when averaged over 50 runs.

Using DistAlgo is about 5 times as slow as Python, but that is expected and is the subject of DistAlgo compilation and optimizations studied separately [54].

The main result is that whether using DistAlgo or Python, using SecAlgo is at most a small increase over using PyCrypto directly, while being safe and much simpler to use.

We also measured the running times of NS-SK in C# and Java. The C# program is about twice as fast as the PyCrypto+Python implementation, while the Java program is about twice as slow as the PyCrypto+Python implementation. Both are faster than the SecAlgo+DistAlgo implementation. We did not study them further partly due to the much more complex and unattractive code compared to DistAlgo and Python, but also because the performance of cryptographic libraries in Python is becoming more competitive by library code being in C.

6.3 Misuse prevention

Table 9 summarizes how SecAlgo prevents all of the misuse types listed in Table 1. This is described in more detail below.
| Misuse type | Prevention |
|-------------|------------|
| M1K         | excluded from whitelist of approved key sizes, safe defaults |
| M2K         | keygen generates random key at runtime |
| M1S         | excluded from whitelist of approved block modes of operation |
| M2S         | encrypt generates random IV when needed |
| M3S         | excluded from whitelists of approved encryption algorithms |
| M1A         | encrypt uses OAEP padding for RSA encryption, no alternative |
| M1H         | excluded from whitelist of approved hashing algorithms |

Table 9: Summary of the way in which each misuse type is prevented by SecAlgo.

- **M1K: Insufficient key size.** This issue is handled by the `keygen` abstraction. The default key sizes for all algorithms are safe as they guarantee at least 112 bits of security, which NIST has determined as the minimum security strength allowable until 2030 [64]. A key size given explicitly at a call to `keygen` is checked against a whitelist for the algorithm and if the key size is found to be insufficient, SecAlgo throws an exception.

- **M2K: Hard-coded keys.** Hard-coded keys are unsafe because they can be extracted by binary disassembly. SecAlgo inhibits the use of hard-coded keys through `keygen`. The programmer only needs to pass in a type, or a type and size, and a safe key is generated.

- **M1S: Encryption in ECB mode.** Creation of a key for ECB mode is prevented during `keygen` because ECB is not included in the the whitelist of allowed block cipher modes in SecAlgo. The whitelist is checked again when the key is used preventing the use of keys whose tags have been manually altered in an attempt to encrypt with ECB mode. Any attempt to use unsafe block modes like ECB, detected by checking the whitelist of approved modes will be reported as an error at runtime.

- **M2S: Encryption with predictable IV.** The default behaviour of `encrypt` generates IVs automatically, thus preventing predictable IVs. SecAlgo uses a cryptographically strong random number generator to generate the random data block to use as the IV as directed by NIST SP 800-38A [39].

- **M3S: Encryption with obsolete algorithm.** As for M1S, this misuse is prevented by having a whitelist of safe algorithms. Obsolete algorithms like DES, ARC2 and ARC4 stream ciphers are not allowed by SecAlgo abstractions `keygen`, `encrypt`, and `decrypt`. Any attempt to use an obsolete algorithm will be reported as an error at runtime.

- **M1A: RSA encryption without OAEP.** Optimal Asymmetric Encryption Padding (OAEP) is the default padding scheme used with RSA by SecAlgo. SecAlgo does not offer any alternative to OAEP and thereby ensures safety.

- **M1H: Hashing with obsolete algorithm.** Unsafe hashing algorithms like MD2, MD4, MD5 and SHA-1, are not in the whitelist of allowed hashing algorithms in SecAlgo. Any attempt to use an obsolete algorithm will be reported as an error at runtime, as for M1S.
7 Related work and conclusion

There have been many efforts at building better cryptographic libraries providing simpler interfaces. These include the NaCl library [23, 24] for C and C++; libsodium [44], a portable version of NaCl with a slightly improved interface; the cryptography.io library [1] for Python; the Charm library [11, 12] for Python; the Keyczar library [2, 37] for C++, Java, and Python; and the Tink library [8] for C++, Java, Go, and Objective-C.

These libraries simplify use of cryptographic operations in ways similar to SecAlgo. Simplifying techniques to reduce the number of decisions for users include: (1) requiring fewer inputs from the user, (2) handling tedious, routine tasks automatically behind the scenes, (3) supporting better default configurations, and (4) removing unsafe algorithms and implementations.

However, these libraries fall short when compared with SecAlgo. Charm provides simplified use for only a single operation—shared key authenticated encryption. cryptography.io provides simplified use of only shared key authenticated encryption and X.509 certificate handling. Keyczar and Tink provide only shared key authenticated encryption, hybrid encryption, digital signing, and message authentication code creation. NaCl and libsodium provide a much more complete set of cryptographic operations, but provide little to no configurability but only one algorithm for most cryptographic operations.

Acar et al. [10] study the usability of five Python cryptographic libraries: PyCrypto [52], M2Crypto [4], Keyczar [2, 37], cryptography.io [1], and PyNACL [5] (a Python binding of NACL). They found that clear documentation and concrete code examples were the most significant factors determining whether subjects produced solutions that work. Furthermore, they found that code written with simplified APIs were much more likely to be secure, while code written with low-level libraries were more likely to contain mistakes that compromised their security. SecAlgo provides higher-level, simpler APIs than these previous libraries.

Egele et al. [42, p. 81] study cryptographic misuse and propose mitigation strategies: (1) introduction of better default configurations in cryptographic libraries and (2) provision of better, more complete documentation of cryptographic libraries. SecAlgo realizes the first by default configurations that implement best security practice and allows the second to be made much simpler and easier to use.

FixDroid [69] is an IDE plug-in for the Android SDK that identifies cryptographic mistakes in source code, as it is written, and provides suggested corrections. CogniCrypt [49] automatically generates Java code for a collection of common cryptographic tasks (e.g., encrypting data with a password, storing passwords, secure communication, etc.) and performs static analysis to verify that generated code is properly integrated into the user’s application. CDRep [56] acts directly on Android binaries by using static analysis to detect cryptographic mistakes and then generates and applies patches to correct them. Use of SecAlgo allows many tasks of such tools to be greatly simplified or completely eliminated.

Security protocol specification languages are for abstract formulation and verification of security protocols. Scyther [33, 34], AVISPA [14, 16], ProVerif [25, 28], and CryptoVerif [26, 29] are process or role oriented similar to SecAlgo plus DistAlgo. Tamarin [57, 58] models the state of the protocol as a multi-set of facts and models protocol actions as rewrite rules operating on these facts. SecAlgo plus DistAlgo programs are simpler than even abstract specifications written in most of these formal specification languages. Unlike these formal specification languages, SecAlgo is for building actual implementations of security protocols as well as full-fledged secure applications.

In conclusion, SecAlgo provides simpler and more powerful high-level abstractions for cryptographic operations and allows security protocols and applications to be written more easily and clearly. Future work includes possible further optimization of the implementation to minimize performance overhead, extension of abstraction and implementation framework to support more combinations of best cryptographic functions.
from different libraries, and translation into languages of protocol verification tools such as ProVerif and Scyther for formal verification.

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