Lecture 3
Programming with OpenSSL

ENGG5105/CSCI5470 Computer and Network Security

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Patrick P. C. Lee

Review

- Cryptographic primitives:
  - Symmetric key cryptography
    - AES
  - Hash function
    - MD5, SHA-1
  - Public key cryptography
    - RSA: for encryption
    - Diffie Hellman: for key exchange
  - Digital signature
    - DSA (based on public key crypto)
  - Certificates
    - X.509v3 (based on public key crypto)

SSL and OpenSSL

- SSL is the security protocol behind secure HTTP (HTTPS). It can secure any protocol that works over TCP
  - Will cover the theoretical details in “Web Security” module
- OpenSSL is a full-featured implementation of SSL, including TLS (transport layer security)

Overview of OpenSSL

- **OpenSSL** is an open-source implementation of cryptographic functions. It includes executable commands with cryptographic functions, and a library of APIs with which programmers can use to develop cryptographic applications.
- Its design follows the object-oriented principle. Each cryptographic algorithm is built upon a **context**, an object that holds the necessary parameters.

Installation of OpenSSL

- How to install:
  - Get the latest stable source from http://www.openssl.org, and run (as root):

```
# ./config
# make
# make test
# make install
```

  - Or simply:

```
apt-get install openssl libssl-dev
```

- How to compile (as normal users):

```
% gcc -Wall test_openssl.c -o test_openssl -lcrypto
```

BIGNUM – Arbitrary Precision Math

- Public key cryptography handles very large integers. Standard C data types are not enough
- **BIGNUM** package has virtually no limits on upper bounds of numbers
- Header file: #include <openssl/bn.h>
- Reference:
  - http://www.openssl.org/docs/crypto/bn.html

Initializing & Destroying BIGNUMs

- A BIGNUM is an object (or context) that contains dynamically allocated memory

```
BIGNUM static_bn, *dynamic_bn;

/* initialize a static BIGNUM */
BN_init(&static_bn);

/* allocate a dynamic BIGNUM */
dynamic_bn = BN_new();

/* free the BIGNUMs */
BN_free(dynamic_bn);
BN_free(&static_bn);
```

Copying BIGNUMs

- Deep copy is required when you copy a BIGNUM object

```
BIGNUM a, b, *c;

/* wrong way */
a = b;
*c = b;

/* right away */
BN_copy(&a, &b);   /* copies b to a */
c = BN_dup(&b);    /* creates c and initialize it to same value as b */
```

BIGNUM to Binary

- Sometimes you need to convert a BIGNUM into binary representation for:
  - Store it in a file
  - Send it via a socket connection
- Similarly, we can convert a BIGNUM into a decimal or hexadecimal representation

BIGNUM to Binary

- How to convert?

```
BIGNUM* num;

/* converting from BIGNUM to binary */
len = BN_num_bytes(num)
buf = (unsigned char*)calloc(len, sizeof(unsigned char));
len = BN_bn2bin(num, buf);

/* converting from binary to BIGNUM */
BN_bin2bn(buf, len, num);
num = BN_bin2bn(buf, len, NULL);
```

BIGNUM to Binary

- Pitfall – if you don't pay attention to the actual length of the binary string.
- Suppose I work on 1024-bit RSA

```
const int RSA_SIZE = 128;   /* in bytes */
BIGNUM* num;

/* .. set num to 3 as public key */

/* converting from BIGNUM to binary */
buf = (unsigned char*)calloc(RSA_SIZE, sizeof(unsigned char));
BN_bn2bin(num, buf);

/* converting from binary to BIGNUM (use 128 bytes directly) */
BN_bin2bn(buf, RSA_SIZE, num);
num = BN_bin2bn(buf, RSA_SIZE, NULL);

/* WRONG RESULT: num <> 3 */
```

BIGNUM to Binary

- The binary representation of BIGNUM is in **big-endian format**.
  - i.e., most significant byte is in lowest address
- After BN_bn2bin(),

Address	0	1	2	…	127
	3	0	0		0

- After BN_bin2bn(), num = $3 * 2^{127 * 8}$

BIGNUM to Binary

- You can store the actual length separately. Or, to save the overhead of storing the length, move the significant string to the right

```
const int RSA_SIZE = 128;
BIGNUM* num;

/* .. set num to 3 as public key */

/* converting from BIGNUM to binary */
buf = (unsigned char*)calloc(RSA_SIZE, sizeof(unsigned char));
BN_bn2bin(num, buf + RSA_SIZE - BN_num_bytes(num));
```

Math Operations of BIGNUM

- Many operations are included in BIGNUM package, including modular arithmetic.
- Example: BN_mod_exp()

```
BIGNUM *r, *g, *x, *p;
BN_CTX* ctx = BN_CTX_new();   /* store temporary results */

/* .. call BN_new() on r, g, x, p */

/* r = g^x mod p */
BN_mod_exp(r, g, x, p, ctx);

/* when done, free r, g, x, p, and ctx */
```

- BN_CTX stores temporary values of operations so as to improve the performance.

Generating Prime BIGNUM

- BN_generate_prime() generates pseudorandom prime numbers
- Instead of factoring, check if a number is prime after a number of primality tests
  - The generation is quite efficient

```
BIGNUM* prime = BN_generate_prime(NULL, bits, safe, NULL, NULL,
                                  callback, NULL);
```

- Safe primes – p is prime and (p-1)/2 is also prime.

Symmetric Key Crypto in OpenSSL

- We choose AES with CBC
- We need to pad the last block if the plaintext length is not a multiple of block size (i.e., 128 bits / 16 bytes)
  - In general, you can add a few more junk blocks to decouple the plaintext length and ciphertext length, with a tradeoff of longer ciphertext

AES with CBC in OpenSSL

- Find the actual length of the encrypted message. Make it a multiple of 128 bits

```
#include <openssl/aes.h>
...
unsigned int message_len = strlen((char*)input_string) + 1; // including'\0'
unsigned encrypt_len = (message_len % AES_BLOCK_SIZE == 0) ?
     message_len : (message_len / AES_BLOCK_SIZE + 1) * AES_BLOCK_SIZE;
```

- Define the key (assuming 128 bits)

```
unsigned char key[16];
AES_KEY aes;
int ret = AES_set_encrypt_key(key, 128, &aes);  // ret < 0 → error
```

- Define the IV:

```
unsigned char iv[AES_BLOCK_SIZE];
memset(iv, 0, AES_BLOCK_SIZE);
```

AES with CBC in OpenSSL

- Encrypt the plaintext (note that **`iv`** will be updated)

```
AES_cbc_encrypt(input_string, encrypt_string, encrypt_len, &aes, iv,
          AES_ENCRYPT);
```

- Decrypt the ciphertext. The decryption side must synchronize on the **`iv`** and **`key`**.
  - **`iv`** can be sent in plain, but **`key`** must be sent securely

```
AES_set_decrypt_key(key, 128, &aes);
memset(iv, 0, AES_BLOCK_SIZE);
...
AES_cbc_encrypt(encrypt_string, decrypt_string, encrypt_len, &aes, iv,
       AES_DECRYPT);
```

Public Key Crypto in OpenSSL

- Focus on:
  - RSA for public key encryption
  - Diffie-Hellman for key management
  - DSA for digital signatures
- Public key crypto operates on BIGNUMs

```
typedef struct {
   BIGNUM *n; // public modulus
   BIGNUM *e; // public exponent
   BIGNUM *d; // private exponent
   BIGNUM *p; // secret prime factor
   BIGNUM *q; // secret prime factor
   // …
} RSA;
```

RSA in OpenSSL

- Bob first generates the RSA keys, e.g., 1024 bits and exponent 3.

```
#include <openssl/rsa.h>
RSA* rsa = RSA_generate_key(1024, 3, NULL, NULL);
```

- Bob passes public keys to Alice

```
#include <openssl/bn.h>
unsigned char* n_b = (unsigned char*)calloc(RSA_size(rsa), sizeof(unsigned char));
unsigned char* e_b = (unsigned char*)calloc(RSA_size(rsa), sizeof(unsigned char));
int n_size = BN_bn2bin(rsa->n, n_b);
int b_size = BN_bn2bin(rsa->e, e_b);
```

- Alice constructs the RSA context from public params

```
RSA* encrypt_rsa = RSA_new();
encrypt_rsa->n = BN_bin2bn(n_b, n_size, NULL);
encrypt_rsa->e = BN_bin2bn(e_b, b_size, NULL);
```

RSA in OpenSSL

- Alice can now encrypt data.

```
unsigned char* encrypt_string = (unsigned char*) calloc(RSA_size(encrypt_rsa),
    sizeof(unsigned char));
int encrypt_size = RSA_public_encrypt(strlen((char*)input_string),
    input_string, encrypt_string, encrypt_rsa, RSA_PKCS1_OAEP_PADDING);
```

- RSA_PKCS1_OAEP_PADDING is recommended. The size of the input message block must be smaller than RSA(size) - 41.
- Bob can then decrypt

```
unsigned char* decrypt_string = (unsigned char*)calloc(RSA_size(rsa),
    sizeof(unsigned char));
int decrypt_size = RSA_private_decrypt(encrypt_size, encrypt_string,
    decrypt_string, rsa, RSA_PKCS1_OAEP_PADDING);
```

RSA in OpenSSL

- Padding encodes packets before encryption
- Padding schemes in RSA
  - RSA_PKCS1_PADDING:
    - plaintext length smaller than RSA_size(rsa) – 11
  - RSA_PKCS1_OAEP_PADDING:
    - plaintext length smaller than RSA_size(rsa) – 41
  - RSA_SSLV23_PADDING:
    - rarely used
  - RSA_NO_PADDING:
    - Assumes the caller performs padding. Plaintext length must equal to RSA_size(rsa), not recommended.

RSA in OpenSSL

- Instead of generating parameters in a program, you can do it in command line and save parameters into a PEM file for permanent use
  - PEM file is a base64-encoded file format that represents keys in a file
  - E.g., generate 1024-bit parameters

```
% openssl genrsa -out rsa1024.pem 1024
```

- The private key contains public key info as well.
- In program, call PEM_read_RSAPrivateKey()

```
RSA* rsa = PEM_read_RSAPrivateKey(fp, NULL, NULL, NULL));
```

Diffie-Hellman in OpenSSL

- Header file: #include <openssl/dh.h>
- A DH struct:

```
typedef struct {
   BIGNUM *p;        // prime number
   BIGNUM *g;        // generator
   BIGNUM *pub_key;  // public key
   BIGNUM *priv_key; // private key
} DH;
```

Diffie-Hellman in OpenSSL

- Generate DH parameters in command line (e.g., prime p and generator g)

```
% openssl dhparam -out dh1024.pem 1024
```

- Read parameters from the file

```
#include <openssl/dh.h>
#include <openssl/pem.h>

FILE* fp = fopen(“dh1024.pem”, “r”);
DH* dh1 = PEM_read_DHparams(fp, NULL, NULL, NULL);
```

Diffie-Hellman in OpenSSL

- No keys are in the file. You need to generate keys separately

```
DH_generate_key(dh1);
```

- Compute the secret key, assuming public key was sent over network and reconstructed into BIGNUM object

```
unsigned char* key1 = (unsigned char*)calloc(DH_size(dh1),
      sizeof(unsigned char));
unsigned char* key2 = (unsigned char*)calloc(DH_size(dh2),
      sizeof(unsigned char));
DH_compute_key(key1, dh2_pub_key, dh1);
DH_compute_key(key2, dh1_pub_key, dh2);
```

DSA in OpenSSL

- Sender generates DSA parameters (e.g., 1024 bits)

```
#include <openssl/dsa.h>
…
DSA* dsa = DSA_generate_parameters(1024, NULL, 0, NULL,
      NULL, NULL);
```

- And generate the keys

```
DSA_generate_key(dsa);
```

DSA in OpenSSL

- To sign a message:

```
unsigned char* sign_string = (unsigned char*)calloc(DSA_size(dsa),
      sizeof(unsigned char));
int ret = DSA_sign(0, input_string, strlen((char*)input_string),
      sign_string, &sig_len, dsa);
```

- To verify a message

```
int is_valid = DSA_verify(0, input_string,
       strlen((char*)input_string), sign_string, sig_len, dsa);
```

  - is_valid = 1 means verified, 0 or -1 mean wrong signature

Hash Functions in OpenSSL

- Based on three functions:
  - *Init(): initialize the hash structure
  - *Update(): keep adding messages to be hashed (can be called multiple times)
  - *Final(): compute the hash value
- Example: md5

```
#include <openssl/md5.h>

MD5_CTX hash_ctx;
MD5_Init(&hash_ctx);    // initialize

char input_string[100];
strcpy(input_string, "abcdedfg");
MD5_Update(&hash_ctx, input_string, strlen(input_string)); // update

unsigned char hash_ret[16];
MD5_Final(hash_ret, &hash_ctx);   // compute the hash vlaue
```

Certificates in OpenSSL

- Goal: verify a signature using a public key certificate issued by a certificate authority
- Main idea: generate certificates in command line, and call the certs from programs through APIs

Certificates in OpenSSL

- Step 1: we need a CA. First, create a self-signed certificate

```
% openssl genrsa -aes128 -out cakey.pem 1024
% openssl req -x509 -newkey rsa:1024 -out cacert.pem -outform PEM -days 365 \
     -key cakey.pem
```

  - Let's use "5470" as the passphrase.
  - Specify a one-year expiration period using "-days"
  - The Certificate is encoded in PEM format. You can see the content with the command:

```
% openssl x509 -in cacert.pem -text -noout
```

  - Default configuration is used for certificate generation. Can provide our own configuration.
  - Two files created:
    - cakey.pem – private key of CA
    - cacert.pem – certificate of CA

Certificates in OpenSSL

- Step 2: When a user wants to apply for a certificate, the CA will generate a new public/private key pair and the corresponding certificate request.

```
% openssl genrsa -aes128 -out key.pem 1024
% openssl req -new -key key.pem -keyform PEM -out req.pem \
  -outform PEM
```

The above command will encrypt the private key file (key.pem) with a passphrase when the certificate is issued. It will prompt for a passphrase.

Let’s use “5470” for the passphrase.

Certificates in OpenSSL

- Step 3: The CA will then generate a certificate based on the request.

```
% openssl ca -in req.pem -out cert.pem -config ca.conf
```

See ca.conf for the format. Note that before calling the command, we must have prepared two files: index.txt (which could be empty) and serial (which stores a number, e.g., 01). The private key file (key.pem) and the certificate (cert.pem) will be given to the user.

Certificates in OpenSSL

- How to verify if the certificate is correctly created?

```
% openssl verify –CAfile cacert.pem cert.pem
```

How should I sign/verify?

- People who sign:
  - Use the private key to sign
  - Issue the public key certificate
- People who verify:
  - Use the public key in the certificate to verify
- Here, we demonstrate the use of **EVP** API:
  - EVP API provides a common interface to every cipher OpenSSL exports
  - When you change to a new cipher algorithm, you only register the new algorithm during initialization

Signing with Private Key in OpenSSL

- Step 1: load the private key file.
  Since the file is encrypted, we need to specify which encryption algorithm is used. To save troubles, we just call OpenSSL add all algorithms() to include all possible cipher and digest algorithms.

```
#include <openssl/evp.h>
#include <openssl/pem.h>
...
OpenSSL_add_all_algorithms();
...
// load the private key
FILE* fp = fopen("key.pem", "r")) == NULL);
EVP_PKEY* priv_key = PEM_read_PrivateKey(fp, NULL, NULL, (char*)"5470");
fclose(fp);
if (priv_key == NULL) {
   fprintf(stderr, "cannot read private key.\n");
   exit(-1);
}
```

Signing with Private Key in OpenSSL

- Step 2: sign the message digest
  You don’t need to sign the whole message.
  Just sign the (shorter) message digest.

```
int sig_len = 128; // 1024-bit key
unsigned char sign_string[128];
EVP_MD_CTX evp_md_ctx;

EVP_SignInit(&evp_md_ctx, EVP_sha1());
EVP_SignUpdate(&evp_md_ctx, input_string, strlen((char*)input_string));
if (EVP_SignFinal(&evp_md_ctx, sign_string, &sig_len, priv_key) == 0) {
   fprintf(stderr, "Unable to sign.\n");
   exit(-1);
}
```

Verifying with Cert in OpenSSL

- Step 1: Before we can verify a message, we need to first obtain the certificate of the signer. The certificate also contains the public key.

```
X509* cert;
EVP_PKEY* pub_key;

FILE* fp = fopen("cert.pem", "r"));
if ((cert = PEM_read_X509(fp, NULL, NULL, NULL)) == NULL) {
   fprintf(stderr, "cannot read cert file\n");
   exit(-1);
}
fclose(fp);
if ((pub_key = X509_get_pubkey(cert)) == NULL) {
   fprintf(stderr, "cannot read x509's public key\n");
   exit(-1);
}
```

Verifying with Cert in OpenSSL

- Step 2: verify the message digest

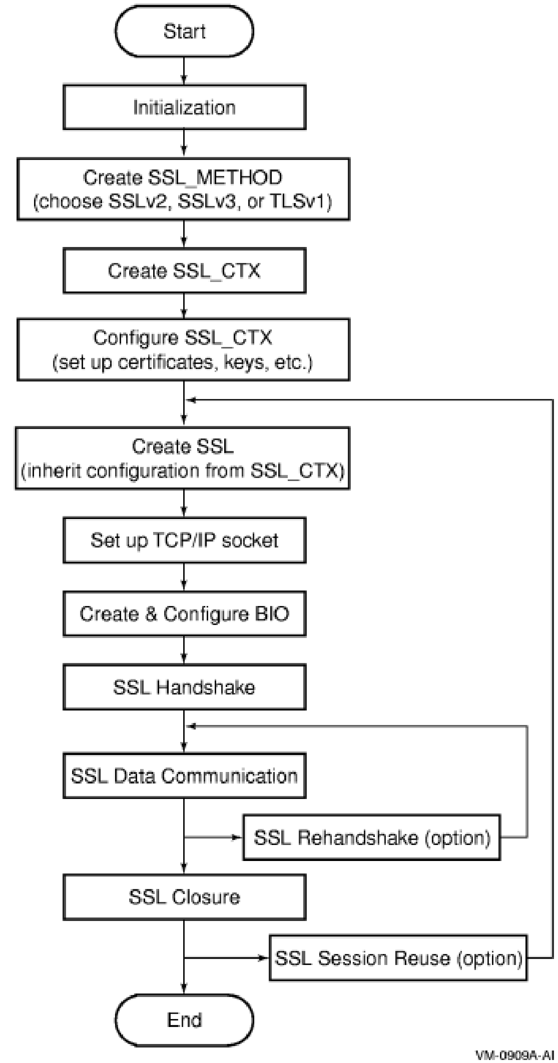
```
EVP_VerifyInit(&evp_md_ctx, EVP_sha1());
EVP_VerifyUpdate(&evp_md_ctx, input_string, strlen((char*)input_string));
if (EVP_VerifyFinal(&evp_md_ctx, sign_string, sig_len, pub_key)) {
   printf("Verified\n");
} else {
   printf("Wrong\n");
}
```

SSL/TLS Programming

- Our goal is to enhance socket programming with Secure Sockets Layer (SSL) and Transport Layer Security (TLS)
- We only provide templates here, with many subtlties ignored.

SSL/TLS Programming

- Flow of SSL programming
  - Can be viewed as extensions of socket programming



Steps of SSL/TLS Programming

- Step 1: Initialize the SSL library to register all cipher and hash algorithms
- Step 2: Create the SSL context structure
  - e.g., specify the SSL versions
- Step 3: Set up certificates and keys
  - SSL server
    - server’s own certificate (mandatory)
    - CA certificate (optional)
  - SSL client
    - CA’s certificate (mandatory) for verifying server’s cert
    - client’s own certificate (optional)

Steps of SSL/TLS Programming

- Step 4: Set up certificate verification
  - can specify the chain length (verify_depth)
  - Client can set SSL_VERIFY_PEER to verify server's certificate is indeed issued by CA's cert
- Step 5: Create SSL structure and TCP/IP sockets, and bind them together

Steps of SSL/TLS Programming

- Step 6: SSL handshake
  - invoked when client calls SSL_connect()
  - if certificate verification is specified before, the actual verification will be carried out in this phase
- Step 7: Transmit SSL data
- Step 8: Shutdown SSL structure
- **See source code**

Summary on OpenSSL

- Low-level design: BIGNUM
  - Use BIGNUM to build your own cryptographic primitive
- Mid-level design: Cryptographic primitives
  - Use different combinations of cryptographic primitives to design a cryptosystem
- High-level design: SSL programming
  - Follow the SSL implementation