PV204 Security technologies

Trusted element, side channels attacks

Łukasz Chmielewski *chmiel@fi.muni.cz*
Centre for Research on Cryptography and Security, Masaryk University

CRoCS
Centre for Research on Cryptography and Security

The masterplan for this lab

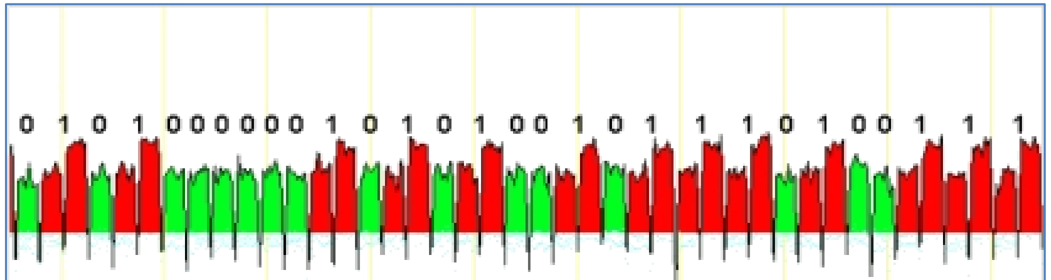
1. Project, teams
2. Implementation of modular exponentiation (RSA)
3. Understand naïve and square&multiply algorithm
   - Toy example with integers (32 bits)
4. Understand how to measure operation (clock())
   - Pre-prepared functions – console or file output
   - Visualization of multiple measurements (R, http://plot.ly, matplotlib...)
     - Online:
       - http://www.shodor.org/interactivate/activities/Histogram/
       - https://www.aatbio.com/tools/online-histogram-maker
   - What can be inferred from measurements
5. Use large datatype MPI instead of `int` (> 10^2 bits)
6. Understand blinding as a protection technique
7. Assignment

Faster modexp: Square and multiply algorithm

Executed always

Executed only when d_j == 1

```
// M = C^d mod N
// Square and multiply algorithm
x = C                          // start with ciphertext
for j = 1 to n {               // process all bits of private exponent
    x = x*x mod N              // shift to next bit by x * x (always)
    if (d_j == 1) {            // j-th bit of private exponent d
      x = x*C mod N            // if 1 then multiple by Ciphertext
    }
}
return x        // plaintext M
```



Gilbert Goodwill, http://www.embedded.com/print/4408435

- How to measure?
  - Exact detection from simple power trace
  - Extraction from overall time of multiple measurements

Naïve vs. square and multiply algorithm

- **`SideChannelExercise.zip`** source code from IS
- Inspect naïve and square&multiply algorithm
  - Limited to integers (unsigned long) for simplicity
- Measure timings
  - Pre-prepared measurement functions
    - measureExponentiation()
      - clock() used for measurement (usually 1ms granularity)
    - measureExponentiationRepeat()
      - Make defined number of repeats and stores results into file
- Identify dependency of algorithm on secret value

Setup

- Create new Visual Studio 2015 Project (or newer)
  - File->New->Project->VisualC++->Win32 Console app
  - Turn off ‘Precompiled header’ and ‘SDL checks’
- Paste SideChannelExercise.cpp from IS instead of project’s main file
- Copy all remaining files into the directory where stdafx.cpp is
- Add bignum.c into compilation
  - Solution->Source files->Add->Existing item
- Try to compile
- Insert breakpoint (begin of main()) – F9
- Run program in debug mode – F5
- Execute the next step of the program – F10

Naïve modular exponentiation algorithm

```
typedef unsigned long ULONG;
const int ULONG_LENGTH = sizeof(ULONG);

ULONG naiveExponentiation(ULONG message, ULONG exponent, ULONG modulus) {
	ULONG result = message;
	for (int i = 1; i < exponent; i++) {
		result *= message;
		result %= modulus;
	}

	return result;
}
```

- What is disadvantage of this algorithm?
- Is algorithm vulnerable to timing side-channel?
- Is algorithm vulnerable to another side-channel?

```
typedef unsigned long ULONG;
const int ULONG_LENGTH = sizeof(ULONG);

ULONG squareAndMultiply(ULONG message, ULONG exponent, ULONG modulus) {
	// Obtain effective length of exponent in bits
	int sizeExponent = ULONG_LENGTH;
	ULONG mask = 1;
	ULONG bit = 0;
	for (int i = 0; i < ULONG_LENGTH * 8; i++) {
		bit = exponent & mask;
		if (bit != 0) { sizeExponent = i + 1; }
		mask <<= 1;
	}
	// Compute square and multiply algorithm
	ULONG result = 1;
	for (int i = sizeExponent - 1; i >= 0; i--) {
		result *= result;
		result %= modulus;
		if ((exponent & (1 << i)) != 0) { // given bit is not 0
			result *= message;
			result %= modulus;
		}
	}
	return result;
}
```

Pair activity: Analysis of square&multiply algorithm

- Form pairs (e.g., with your neighbour) [approximately 21 minutes]
- Look and code together (before ready to answer the question)
- Two roles:
  - Educator – explains the answer to the given question to his/her pair
  - Sceptic – tries to find any flaw or weak point in Educator's reasoning
- Educator keep explaining until Sceptic can't find any flaw
  - not more than 3 mins per question
  - Sceptic notes down interesting issues raised
- Switch roles after every question (from next slide)

Pair activity: Analysis of square&multiply algorithm

Pre-prepared function **`squareAndMultiply()`**

1. What is the advantage of this algorithm with respect to naïve algorithm?
2. Is int (ULONG) enough for cryptographic security?
3. Is the algorithm vulnerable to timing side-channel?
4. Which part of the code is dependent on secret value?

Pre-prepared function **`measureExponentiation(65535, 65535, 1000003L, SQUAREANDMULTIPLY);`**

1. How is measured time depending on a secret value?
2. Is this algorithm easier or harder for attackers to mount timing attack wrt naïve exp?
3. How to mask dependency on secret exponent?

Big integers (MPI from mbedTLS library)

- 32 bits are not enough, 4096 is recommended (RSA)
  - No native type in C/C++, use mbedTLS's MPI

```
void squareAndMultiplyMPI(const mpi* message, const mpi* exponent, const mpi* modulus,
                          mpi* result) {
    // Obtain length of exponent in bits
    int sizeExponent = 0;
    int maxBitLength = mpi_size(exponent) * 8;
    for (int i = 0; i < maxBitLength; i++) {
        if (mpi_get_bit(exponent, i) != 0) { sizeExponent = i + 1; }
    }
    // Compute square and multiply algorithm
    mpi_lset(result, 1);
    for (int i = sizeExponent - 1; i >= 0; i--) {
        mpi_mul_mpi(result, result, result); // result *= result;
        mpi_mod_mpi(result, result, modulus); // result %= modulus;
        if (mpi_get_bit(exponent, i) != 0) { // given bit is not 0
            mpi_mul_mpi(result, result, message);
            mpi_mod_mpi(result, result, modulus);
        }
    }}
```

Create large (pseudo-)random MPI

- generateRNG() is function callback to fill single int

```
mpi message; mpi_init(&message);
mpi exponent; mpi_init(&exponent);
mpi modulus; mpi_init(&modulus);

// Cryptographically large number (2048b)
const int NUMBER_SIZE = 256;
// Init with pseudorandom values (prng will always start with same value)
mpi_fill_random(&message, NUMBER_SIZE, generateRNG, NULL);
mpi_fill_random(&exponent, NUMBER_SIZE, generateRNG, NULL);
mpi_fill_random(&modulus, NUMBER_SIZE, generateRNG, NULL);
// Fix MSb and LSb of modulus to 1
modulus.p[0] |= 1; mpi_set_bit(&modulus, 1, 1);

measureExponentiationMPI(&message, &exponent, &modulus, SQUAREANDMULTIPLY);
```

Measure times with MPI

- Operation with large MPI can be measured
  - 100-1000 cycles (up to 1 sec)
- Visualize histogram of multiple measurements
  - Pre-prepared measurements functions with file output
    - measureExponentiationRepeat()
  - https://plot.ly (Histogram, Traces→Range/bins 1)
  - pyplot, R…
- Try repeated measurement with the same data
- Try repeated measurement with the different data
- Are measured times constant? Why?

Fix: Blinding

- Create squareAndMultiplyBlindedMPI() as improved version of squareAndMultiplyMPI()
  1. Generate random value *r* and compute r^e mod N
  2. Compute blinded ciphertext $b = c * r^e \mod N$
  3. Decrypt *b* and then divide result by *r*

$$(r^e \cdot c)^d \cdot r^{-1} \mod n = r^{ed} \cdot r^{-1} \cdot c^d \mod n = r \cdot r^{-1} \cdot c^d \mod n = m.$$

- (r is random number, but invertible mod N)

Defense introduced by OpenSSL

- RSA blinding: RSA_blinding_on()
  - https://www.openssl.org/news/secadv_20030317.txt
- Decryption without protection: M = c^d mod N
- Blinding of ciphertext *c* before decryption
  1. Generate random value *r* and compute r^e mod N
  2. Compute blinded ciphertext *b* = *c* * r^e *mod N*
  3. Decrypt *b* and then divide result by *r*
     - *r* is removed and only decrypted plaintext remains

$$(r^e \cdot c)^d \cdot r^{-1} \mod n = r^{ed} \cdot r^{-1} \cdot c^d \mod n = r \cdot r^{-1} \cdot c^d \mod n = m.$$

Assignment 5: Protection via bogus branch

- Modify squareAndMultiplyMPI() code (use version without blinding)
  - When exponent's bit is not 1, add "bogus" branch as a protection against leakage

```
if (mpi_get_bit(exponent, i) != 0) { ...// given bit is not 0)
```

  - Remember to have multiplications in both branches.
  - Test correctness and submit the code with the report.
- Perform analysis on the original and protected version
  - Timing measurements for 1000 measurements, visualize as histograms
  - Scenario 1: Same data, same exponent; Scenario 2: Same exponent, low hamming weight of data;
  - Scenario 3: Same exponent, the high hamming weight of data; Scenario 4: Low/high hw exponent and random data.
- Compile and evaluate in Debug and Release profiles
  - Can you observe any difference? Why? What are security implications?
- IMPORTANT: Think! Some scenarios make sense. Some not.
  - Make an explicit claim in the discussion of every scenario if it makes sense from a security point of view
- Final 10% (1 point): eliminate `if` statements by using memory accesses instead.
  - Test correctness and submit the code with the report.
  - Compare timing of that solution to the first implementation in the assignment. How does it compare?
- Reminder: 5 points for this exercise

Assignment 5: Protection via bogus branch

```
x0=x; x1=x^2
for j=k-2 to 0 {
  if dj=0
    x1=x0*x1; x0=x0^2
  else
    x0=x0*x1; x1=x1^2
  x1=x1 mod N
  x0=x0 mod N
}
return x1
```

```
x0=x; x1=x^2
for j=k-2 to 0 {
  b=dj
  x(1-b)=x0*x1; xb=xb^2
  x1=x1 mod N
  x0=x0 mod N
}
return x1
```

Assignment 5 – what to submit

- Source code of your protected operation
- 2 pages of text and figures
  - Describe how bogus branch is removing the dependency of execution time on the secret exponent
  - Description of setup (methodology, sw, hw)
  - Visualized measurements (histograms, 4 scenarios)
  - Discussion of difference observed
  - Discussion of attack feasibility against original/protected implementation
- Max 1 page for final 10%: free format
- Submit **before 13.4. 23:59am** into IS HW vault
  - Soft deadline: -1.5 points for every started 24 hours

Assignment – some hints

- Don't forget to precisely specify your configuration (platform, compiler, options used). Is someone to replicate your experiment with the information you provided?
- It does make only little sense to compare the protected and unprotected version of code for a specific type of data (e.g., only for low-hamming weight exponents). The protected version runs slower, but that is not an interesting observation. What is interesting observation is if you can distinguish (for a particular implementation) between exponents with low and high hamming weights respectively. If yes, then a leak is present.

- No assignment next week!

- Consultation will be on Wednesday morning:
  - 9.30-11.00 in person in A406 or
  - We make an appointment by email

Example vizualization (credits: J. Masarik)