



Constant-Time Big Numbers (for Go)

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Contents

1	Introduction	3
2	Background	3
2.1	Big Numbers in Cryptography	3
2.1.1	Big Numbers in <code>go/crypto</code>	4
2.2	Timing Attacks	4
2.2.1	Actual Attacks	4
2.2.2	Our Threat-Model	4
2.3	Vulnerabilities in <code>big.Int</code>	4
2.3.1	Padding and Truncation	4
2.3.2	Leaky Algorithms	4
2.3.3	Mitigations	4
3	Implementation	4
3.1	Strategies for numbers in Cryptography	4
3.2	The <code>safenum</code> library	4
3.2.1	Handling Size	4
3.3	Some Basic Techniques	4
3.4	Some Algorithm Choices	5
4	Results	5
4.1	Comparison with <code>big.Int</code>	5
4.2	Comparison with <code>go/crypto</code>	5
5	Further Work	5
5.1	Upstreaming to <code>go/crypto</code>	5
6	Conclusion	5
	Acknowledgements	5

1 Introduction

With the Internet cemented as a principal keystone in communication, and ever increasing activity taking place digitally, the importance of secure communication and Cryptography has never been greater. Thankfully, after 50 years of Public Key Cryptography [3], we have good theoretical systems to provide these guarantees.

Most of these systems rely on modular arithmetic with large numbers, such as RSA or Elliptic Curve Cryptography [7, 6]. Working with such numbers is not natively supported by hardware, requiring a "Big Number" software library to provide this functionality.

Unfortunately, even though Public Key Cryptosystems have been heavily scrutinized *in theory*, in practice many vulnerabilities arise in software implementations of these systems.

One particularly pernicious class of vulnerability are **timing attacks** [4], where an implementation leaks information about secret values through its execution time or cache usage, among many side-channels.

Libraries for Big Numbers that are not designed with Cryptography in mind are pervasively vulnerable to this class of attack.

In particular, Go [1] provides a general purpose Big Number type, `big.Int`, which suffers from these vulnerabilities, as we detail later in this report. Unfortunately, this library gets used for Cryptography [2], including inside of Go's own standard library, in `go/crypto`.

We've addressed this issue by creating a library [5] designed to work with Big Numbers in the context of Public Key Cryptography. Our library provides the necessary operations for implementing these systems, all while avoiding the leakage of secret information. To demonstrate its utility, we've modified Go's `go/crypto` package, replacing the use of `big.Int` in the DSA and RSA systems.

2 Background

In this section, we explain how Big Numbers are used in Public Key Cryptography, what timing attacks are, and how they affect our threat model, as well as what kind of side-channels are present in Go's `big.Int` type.

2.1 Big Numbers in Cryptography

As mentioned previously, most Public Key Cryptosystems rely on modular arithmetic.

In RSA [7], for example, a public key (e, N) consists of modulus $N \in \mathbb{N}$, usually 2048 bits long, and an exponent taken modulo $\varphi(N)$. To encrypt a message $m \in \mathbb{Z}/N\mathbb{Z}$, we calculate

$$c := m^e \mod N$$

The typical word size on computers is now 64 bits. Because of this, to do arithmetic modulo N , we need a Big Number library to work with these large numbers, as well as to provide optimized implementations of operations like modular exponentiation, which aren't natively supported.

DSA [8] also relies on modular arithmetic, this time using a large prime p of around 2048 bits, and working in the multiplicative group $(\mathbb{Z}/p\mathbb{Z})^*$.

Elliptic Curve Cryptography [6] relies on complex formulas for adding points on an elliptic curve, built over a finite field K . This field is usually either a prime field $\mathbb{Z}/p\mathbb{Z}$, in which case arithmetic modulo p is used, or a binary extension field $\text{GF}(2^n)$, in which case binary arithmetic in combination with polynomial addition and multiplication are used.

For prime fields, a Big Number library is once again necessary, because the size of the prime is greater than 200 bits.

In summary, large modular arithmetic is a cornerstone of Public Key cryptosystems, requiring Big Numbers in some form.

2.1.1 Big Numbers in go/crypto

Go [1] provides implementations of numerous cryptographic algorithms as part of its standard library, including the aforementioned Public Key systems, in the go/crypto package.

Unfortunately [2], the general purpose `big.Int` type gets used in this package for Cryptography, despite its potential vulnerability to timing attacks.

For DSA [8], Go uses `big.Int` for all operations, including key generation, signing, and verification.

For RSA [7], Go uses `big.Int` for all operations, and fixes this type as part of the API for this package. Key generation, encryption, decryption, signing, and verification all use `big.Int`.

For ECC [6], Go defines a general interface for Elliptic Curves, requiring operations like point addition, scalar multiplication, etc. All of these are defined in terms of `big.Int`. Some of the curves have specialized implementations of their prime field, only converting from `big.Int` to satisfy the interface curves. The remaining curves directly make use `big.Int` for their field arithmetic.

2.2 Timing Attacks

Explain the concept of side-channels in cryptography, and give some of the fundamental types we're concerned with.

2.2.1 Actual Attacks

Explain how these concerns actually lead to vulnerabilities in systems.

2.2.2 Our Threat-Model

Explain the threat model we have, and what side-channels we aren't concerned about.

2.3 Vulnerabilities in `big.Int`

Explain what vulnerabilities are potentially lurking in `big.Int`.

2.3.1 Padding and Truncation

Explain how `big.Int` truncates numbers internally.

Explain potential issues with padding in cryptography.

2.3.2 Leaky Algorithms

Explain how most algorithms are potentially leaky.

2.3.3 Mitigations

Explain what mitigations are deployed in Go.

3 Implementation

Describe at a high level what we've done.

3.1 Strategies for numbers in Cryptography

Describe different strategies in place for providing numbers for Cryptography.

3.2 The `safenum` library

Describe at a high level what the library provides.

3.2.1 Handling Size

Describe how we handle sizing of numbers.

3.3 Some Basic Techniques

Describe some basic techniques for constant-time operation.

3.4 Some Algorithm Choices

Describe the algorithm choices we've used for different things.

4 Results

Describe what results we've managed to perform.

4.1 Comparison with `big.Int`

Describe the final performance results we've managed to achieve.

4.2 Comparison with `go/crypto`

Describe the benchmarks on actual code.

5 Further Work

5.1 Upstreaming to `go/crypto`

Describe our work in providing a patch for RSA, and what results we've managed to achieve.

6 Conclusion

Summarize the things we put in the introduction.

Acknowledgements

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