

# Synopsys PUFs in a Post-Quantum World

## Introduction

In July 2022, NIST announced the first batch of to-be-standardized algorithms for post-quantum cryptography.<sup>1</sup> This announcement has security professionals worldwide scrambling to assess the status of their systems and to evaluate the need for transitioning to these algorithms in the future. Security is critical to all systems, so this has led to some nervousness and uncertainty. Moreover, the discussions around applying post-quantum cryptography are highly technical, making it challenging for security professionals to make well-informed decisions.

Unfortunately, this current situation of temporary uncertainty also creates a brief opening for opportunistic actors to push their “solutions” through tactics of fearmongering (warning against non-existent problems which they claim to solve) and deception (claiming to solve real problems while in fact they do not). This can lead to well-intentioned but misguided investments, and worst-case even to vulnerable systems. In this white paper, we want to address two important questions with the goal of helping embedded security architects and engineers weather the current uncertain stage of this evolution by arming them with the right information:

1. Why should I (not) be concerned about using post-quantum cryptography?
2. What is the status of Synopsys hardware-based security PUF products in a post-quantum world?

## The Need for Post-Quantum Cryptography

### The Quantum Threat

Before diving into post-quantum cryptography, we first need to clarify the quantum threat, i.e., what precisely will post-quantum cryptography protect us from?<sup>2,3,4</sup> Understanding this is paramount in evaluating one’s need for post-quantum cryptography.

The quantum threat is brought about by a combination of two important evolutions in the last couple of decades:

1. The development of quantum computing technology since the 1980s, with gradually improving operational quantum computers since the 2010s.
2. The discovery in the 1990s of quantum algorithms that affect the security of certain traditional cryptographic techniques.

Let's look a little more into the details of these developments.

A quantum computer is a computing system which uses quantum mechanical phenomena like superposition and entanglement to perform basic operations. Based on this, it can in theory perform certain very specific computations much more efficiently than any traditional computer could. However, the development of a meaningful quantum computer, i.e., one that can in practice outperform a modern traditional computer is exceptionally difficult. For the moment there is still ongoing debate as to whether this is just an incredibly complex engineering problem to be solved, or if there are more fundamental limitations at play which could prevent this altogether. Assuming the former case, enormous investments and significant research and development time will still be needed to bring quantum computing technology to a meaningful level. Taking the current state of the art and extrapolating its development into the future, assuming an exponential improvement equivalent to Moore's law for traditional computers, it is estimated by experts that it will still take at least 15 to 20 years before a meaningful quantum computer can become reality. <sup>2,3</sup>

Contrary to popular belief, a quantum computer is not a very fast general-purpose supercomputer, nor can it magically operate in a massively parallel manner. Instead, it presents a different paradigm to computing, because it is able to efficiently execute so-called quantum algorithms for which there are sometimes no known efficient equivalents on a traditional computer. Today, two known quantum algorithms are of concern to us, because they affect the security of classical cryptography:

1. Shor's algorithm, invented in 1994 by Peter Shor, is an efficient (polynomial-time) quantum algorithm for factoring large integers, and for solving a few related number-theoretical problems. There are currently no known efficient factoring algorithms for traditional computers, a problem which lies at the basis of several classic public-key cryptographic techniques.
2. Grover's algorithm, invented in 1996 by Lov Grover, is a quantum algorithm which can search for the inverse of a generic function quadratically faster than a traditional computer can. In cryptographic terms, searching for inverses is equivalent to a brute-force attack (e.g., on an unknown secret key value), and its difficulty lies at the basis of security for most symmetric cryptography primitives.

It is clear that these quantum algorithms if they can be executed on a meaningful quantum computer, will have an impact on the security of current cryptographic techniques.

## Impact on Public-Key Cryptography

By far the most important and most widely used public-key primitives today are based on RSA (for encryption and signing), and discrete-logarithm or elliptic curve cryptography (for key exchange and signing). All these primitives are based on number-theoretic problems which can be efficiently solved by Shor's algorithm. This has major implications. At the point in time when meaningful quantum computers become operational, Shor's algorithm can be used to break

these primitives on a practical level. This will make virtually all public-key cryptography in current use insecure.

For the affected public-key encryption and key exchange primitives, this problem is already real today. An attacker can capture, and store encrypted messages exchanged now and break their decryption in the future when meaningful quantum computers are operational. Highly sensitive and/or long-term secrets communicated today (or in the past) are hence already at risk to be disclosed in the future.

For the affected signing primitives, the problem is a little less problematic when used in short-term commitments. However, if meaningful quantum computers become available, then valid signatures can be forged, which hence voids the value of any signature at that point in time. It is, therefore, not recommended to use the affected primitives for signing long-term commitments which still need to be verifiable in 15-20 years or more.

Due to Shor's algorithm, the impact of quantum computers on current-day public-key cryptography is problematic and needs to be fixed. For some use cases, there is already a real risk now due to the capture-and-store scenario, but the situation becomes globally impactful if meaningful quantum computers become available in an estimated 15-20 years from now. Over the last decade, the cryptographic community has worked hard on solving this problem by designing new public-key primitives based on mathematical problems that cannot be solved by Shor's algorithm (or any other known efficient algorithm, quantum or otherwise). These algorithms are generally referred to as post-quantum cryptography. After years of public scrutiny, NIST's announcement on a selection of these algorithms for standardization<sup>1</sup> is the latest culmination of that field-wide exercise.

## Impact on Symmetric Cryptography

Nearly all applications of symmetric cryptography are based on the use of block cyphers (e.g., AES) and hash functions (e.g., SHA-256) and to a lesser extent, stream cyphers. or a well-designed symmetric key primitive, its security level is equivalent to the effort needed for brute-forcing the used secret key or exhaustively searching for collisions. On a traditional computer, the effort of brute-forcing a secret key is directly exponential in the key's length:  $O(2^n)$ . However, when a meaningful quantum computer can be used, Grover's algorithm can speed up the brute-force attack quadratically. The needed effort remains exponential, though only in half of the key's length:  $O(\sqrt{2^n})=2^{n/2}$ . In terms of the security level of a symmetric primitive expressed in a number of bits, Grover's algorithm can be said to reduce it by 50%.

However, there are some important remarks to be made regarding the potential impact of Grover's algorithm on symmetric cryptography:

- It was shown that Grover's algorithm is an optimal brute-force strategy (quantum or otherwise)<sup>5</sup>, so the quadratic speed-up is the worst-case security impact that needs to be considered. No future developments in quantum computing or quantum algorithms will lead to better brute-force attacks on symmetric crypto.
- There are strong indications that it is not possible to meaningfully parallelize the execution of Grover's algorithm.<sup>3,6,7,8</sup> In a traditional brute-force attack, doubling the number of computers used will cut the computation time in half. Such a scaling is not possible for Grover's algorithm on a quantum computer, which makes its use in a brute-force attack very impractical.

- Before Grover's algorithm can be used to perform practical brute-force attacks, e.g., on 128-bit keys, so with an effort of  $O(2^{128/2} = 2^{64})$ , the performance of quantum computers needs to improve tremendously. Very modern traditional (non-quantum) supercomputers can barely perform computations with a complexity of  $O(2^{64})$  in a practically feasible time (several months). Based on their current state and rate of progress, it will still take a very long time – much, much more than 20 years – before quantum computers could be at that same level.<sup>7</sup>

Despite Grover's algorithm, the practical impact of quantum computers on symmetric cryptography is, for the moment, very limited. Worst-case, the security strength of currently used primitives is reduced by 50% (of their key length), but due to the mentioned limitations of Grover's algorithm, that is an overly pessimistic assumption for the near future. The natural conclusion that the solution is to double the length of symmetric keys to withstand quantum brute-force attacks is a very broad blanket measure that will certainly solve the problem but is too conservative. At this point in time, there are no mandated recommendations for quantum-hardening symmetric-key cryptography, and 128-bit security strength primitives like AES-128 or SHA-256 are considered safe to use now and in the foreseeable future (also see, e.g., reference <sup>8</sup>, for the standpoint of NIST about this).

## Impact on Information-Theoretical Security

In addition to public-key and symmetric cryptography, we also want to take a short look at the impact of quantum computing on information-theoretic security. Information-theoretically secure methods are algorithmic techniques for which security claims are proven mathematically, without any further assumptions on the complexity of functions or the hardness of mathematical problems (hence, it is also called unconditional or perfect security). Some important information-theoretically secure constructions and primitives are:

- The Vernam cypher, also called the one-time pad, is an information-theoretically secure encryption method. While highly secure, the Vernam cypher is not very practical for most use cases.
- Shamir's secret sharing, a method for securely sharing a secret among multiple parties. It is used in scenarios where high-security secret sharing is needed.
- Quantum key distribution<sup>9</sup> (unrelated to, and not to be confused with post-quantum cryptography) is a secure method for establishing a shared secret between two parties based on quantum-mechanical effects in communication, e.g., using entangled photons.
- Entropy sources and PUFs will generate outputs with guaranteed entropy levels based on validated stochastic models underpinning their physical operation. They are generally used as secure sources of randomness and for generating root secrets.
- Fuzzy commitment schemes<sup>10</sup> will reliably generate high-entropy secrets from noisy sources (e.g., PUFs or quantum channels) without leaking any information on that secret.

It is important to realize that all information-theoretical security claims for these constructions remain fully valid in the presence of quantum computers. An information-theoretical proof basically shows that an adversary does not have sufficient information to break the security claim, regardless of its computing power, quantum or otherwise. Hence, the quantum threat does not impact information-theoretically secure constructions.

## Executive Summary

Why should I (not) be concerned about using post-quantum cryptography?

The quantum threat to information security is fueled by the development of quantum computing technology and the discovery of quantum algorithms that affect the security of currently used cryptographic primitives. This threat will become imminent once meaningful quantum computers become available, which is at the earliest expected, about 15 to 20 years from now. However, quantum computing and quantum algorithms will not break all of cryptography, and the real impact of the quantum threat differs between different primitives:

- Popular public-key primitives (e.g., RSA, Diffie-Hellman, elliptic-curve crypto) are severely impacted and must be fixed. This has led to the development of post-quantum cryptography, and several alternative public-key crypto candidates exist today. The standardization process for these new candidates is ongoing.<sup>1</sup>
- Symmetric cryptography (e.g., AES, SHA-256) is, in theory, affected as well, but in practice, the impact is very limited. For the moment, there is no need for quantum-hardening existing symmetric-key primitives<sup>8</sup>. If ever needed in the future, a doubling of the used key lengths is guaranteed to solve any known issues.
- Information-theoretically secure primitives are not impacted at all and will remain fully secure in the face of quantum computers.

## Synopsys PUFs and PUF-Based Key Generation

### SRAM PUF

The core technology underpinning all Synopsys PUF products is that of an SRAM physically unclonable function or SRAM PUF. Like other PUFs, an SRAM PUF generates device-unique responses that stem from unpredictable variations originating in the production process of silicon chips. The operation of an SRAM PUF is based on a conventional SRAM circuit and is, hence, readily available in virtually all digital chips.

The behavior of an SRAM PUF is fundamentally physical in nature. However, as a component in a security solution, it is essential to have this physical behavior captured in a stochastic model that describes the important statistical metrics of the PUF and enables us to quantify them accurately.<sup>11</sup> Based on years of continuous measurements and analysis, Synopsys has developed stochastic models that describe the behavior of SRAM PUFs very accurately, and that go much further than traditional, generic PUF evaluation metrics. Using these models, we can determine tight bounds on the unpredictability of SRAM PUFs, both in terms of uniqueness (how unpredictable is one SRAM PUF instance from any other), and in terms of noisiness (how unpredictable is one SRAM PUF evaluation from another). These unpredictability bounds are expressed in terms of entropy, and are fundamental in nature, i.e., they cannot be overcome by any amount of computation, quantum or otherwise.

### Synopsys Hardware-based PUF IP

Synopsys offers a hardware security solution based on SRAM PUF technology in the form of its Hardware-based PUF IP product. Figure 1 shows, on a high level, the basic internal architecture of Synopsys Hardware-based PUF IP.

The central component of Synopsys Hardware-based PUF IP is a fuzzy commitment scheme<sup>10</sup> that protects a root key with an SRAM PUF response and produces public helper data. The operation of a fuzzy commitment scheme is such that the root key can always be reliably

regenerated later based on the helper data and a noisy version of the PUF response. It is information-theoretically proven that the helper data discloses zero information on the root key, so the fact that the helper data is public has no impact on the root key's security. This no-leakage proof relies on the unpredictability bounds of the PUF employed by the system, as expressed by its stochastic model. Over the years, Synopsys has spent significant effort on optimizing the fuzzy commitment scheme to robustly deal with the stochastic behavior of SRAM PUFs in a very broad sense, always with a focus on keeping the no-leakage proof intact.<sup>12</sup>

Where the goal of a fuzzy commitment scheme is to be able to securely regenerate the same root secret, the goal of an entropy source is rather to generate guaranteed fresh entropy every time it is evaluated.<sup>13</sup> The actual entropy which is collected by an entropy source needs to originate from a physically noisy process. Synopsys Hardware-based PUF IP implements an entropy source that relies on an SRAM PUF acting as a physical noise source. In this case, it is the noisiness of the SRAM PUF that plays an important role, and the PUF's stochastic model is seminal for assessing the amount of generated noise entropy. Very importantly, Synopsys Hardware-based PUF IP uses its entropy source to initialize its root key for the first time, which is subsequently protected by the fuzzy commitment scheme.

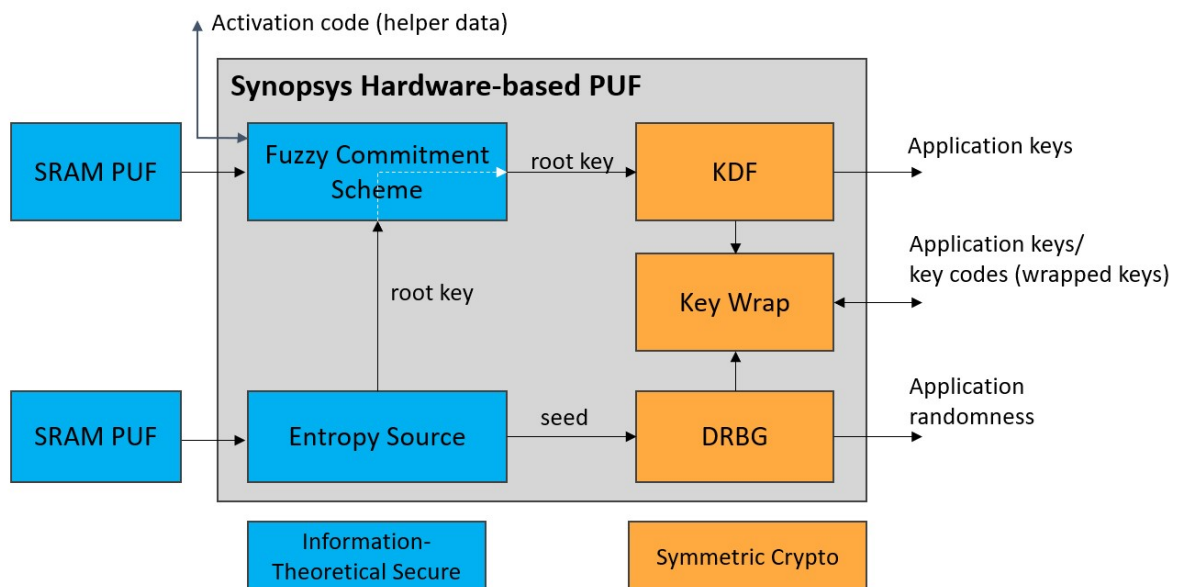


Figure 1 – High-level Architecture of Synopsys Hardware-based PUF

In addition to the fuzzy commitment scheme and the entropy source, Synopsys Hardware-based PUF IP also implements several cryptographic operations for conveniently serving an application. These include:

- A key derivation function (KDF) which uses the root key protected by the fuzzy commitment scheme as a key derivation key. The KDF is accessible to an application for the reproducible generation of device-unique, cryptographically secure application keys.
- A deterministic random bit generator (DRBG) is initially seeded by a high-entropy seed coming from the entropy source. The DRBG is accessible to an application to generate cryptographically secure randomness.

- Key wrapping functionality, essentially a form of authenticated encryption, protects externally provided application keys using a key-wrapping key derived from the root key protected by the fuzzy commitment scheme.

All these application-accessible cryptographic operations are based on certified standard-compliant constructions using standard symmetric crypto primitives, particularly AES and SHA-256.<sup>14</sup>

## Post-Quantum Assessment of Synopsys Hardware-based PUF IP (and Synopsys FPGA PUF IP)

As schematically shown in Figure 1, all security components of Synopsys Hardware-based PUF IP are either backed by information theory or based on symmetric cryptography. In that sense, the impact of the quantum threat described in the previous section on the security of Synopsys Hardware-based PUF IP is very limited.

All the core components leading up to the generation and protection of the Synopsys Hardware-based PUF root key are shown to be information-theoretically secure and are, hence, impervious to quantum attacks. Essential elements which back this information-theoretical security are: the accurate stochastic model of the SRAM PUF, which describes and quantifies its unpredictability in terms of entropy; the noise entropy assessment of the entropy source based on that model; and the no-leakage proof of the fuzzy commitment scheme, also based on that model.

All application-accessible functionality of Synopsys Hardware-based PUF IP is based on established symmetric cryptography. As discussed in the previous section, in theory, symmetric cryptography is mildly affected by quantum attacks due to Grover's algorithm, but in practice, the impact is very limited, and no remediation is required nor recommended. In addition, Synopsys Hardware-based PUF IP can be delivered in several variants, including a 256-bit security strength variant, which reflects on the length of the root key. This 256-bit variant of Synopsys Hardware-based PUF IP will offer strong quantum resistance, even in the near future when Grover's algorithm becomes feasible. However, it should be reiterated that for now and the foreseeable future, 128-bit symmetric cryptography remains safe to use,<sup>8</sup> which includes the 128-bit variant of Synopsys Hardware-based PUF IP.

The Synopsys FPGA PUF IP solution is constructed following a similar architecture and using identical building blocks. All the post-quantum assessments above for Synopsys Hardware-based PUF IP equally hold for Synopsys FPGA PUF IP.

Importantly, Synopsys Hardware-based PUF IP and Synopsys FPGA PUF IP do not deploy any public-key cryptography primitives for which a near-future update would be imminent.

## Executive Summary

What is the status of Synopsys Hardware-based PUF Security products in a post-quantum world? The security architecture of Synopsys Hardware-based PUF IP is completely based on information-theoretically secure components for the generation and protection of a root key and on established symmetric cryptography for the application-accessible functionality. As discussed in the previous section, information-theoretically secure constructions are impervious to

quantum attacks. The impact of the quantum threat on symmetric cryptography is limited and does not require any remediation now or in the foreseeable future. Importantly, Synopsys Hardware-based PUF IP does not deploy any quantum-vulnerable public-key cryptographic primitives.

Concluding, all variants of Synopsys Hardware-based PUF IP are quantum-secure and in accordance with recommended post-quantum guidelines. The use of the 256-bit security strength variant of Synopsys Hardware-based PUF IP will offer strong quantum resistance, even in the distant future, but also, the 128-bit variant is considered perfectly safe to use now and in the foreseeable future.

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