



AN INTRODUCTION TO CRYPTOGRAPHIC SECURITY METHODS AND THEIR ROLE IN SECURING LOW RESOURCE COMPUTING DEVICES

*An Overview of Public-key Cryptosystems based on RSA,
Diffie-Hellman and the Next Generation of Public Key
Cryptographic Security for Low-Resource Computing Devices -
the Algebraic Eraser™*

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1. Introduction:

The need for secure communications dates back to antiquity. Whether we are looking at the 5000 year old cylinder seals of ancient Mesopotamia, which were used for authentication, or the Caesar cipher, which was used to protect military messages, a theme quickly emerges: information needs to be secured.

There are two distinct paradigms for approaching security. One is the symmetric or private key path, which can be viewed as a descendant of the very early attempts at security. Any such system assumes that, if two individuals wish to communicate securely, they must both possess a unique common secret key, which is used for both encryption and decryption. While many such systems have evolved over time, it is this very assumption, and the difficulties of sharing and distributing the common key and keeping it a secret, that leads to their vulnerability and the need for a new paradigm. By the early 1970's a significantly new and different perspective on security began to take shape contributing to the emergence of public-key cryptography.

Public-key cryptosystems themselves fall into two categories: the Diffie-Hellman protocol published by Whitfield Diffie and Martin Hellman in 1976, and the RSA protocol, as publicly described by Ron Rivest, Adi Shamir, and Leonard Adleman in 1978. Before focusing on the structure of these distinct approaches, it is worth taking a moment to consider the broader impact public-key methods have had.

As ubiquitous as the Internet is today, it was not until the 1990's that the necessary security protocols were put in place that enabled users to function securely while online. For example, the online revolution in the financial sector, e-commerce, and medical records, all rely on the security breakthrough provided by public-key cryptography. In many respects we are at a similar evolutionary point with embedded systems, wireless sensor networks, and radio frequency identification (RFID) technologies. The solutions that enabled the Internet revolution are not suitable to these low-resource environments; a new generation of public-key infrastructure needs to emerge. The basic theme, which dates back to early civilization, persists: information needs to be secured.

2. A Heuristic View of Cryptographic Structures.

When viewed diagrammatically at a high level, private key methods of encryption all take the following form. Two users, Alice and Bob, each possess the same secret key, κ , which is used for both encryption and decryption (hence the term *symmetric*). When Alice wishes to communicate securely with Bob she inputs her message (often termed the plaintext), along with her key κ , into her encryption protocol, which then outputs the message in an encrypted form, referred to as the ciphertext, as seen in Figure 1.

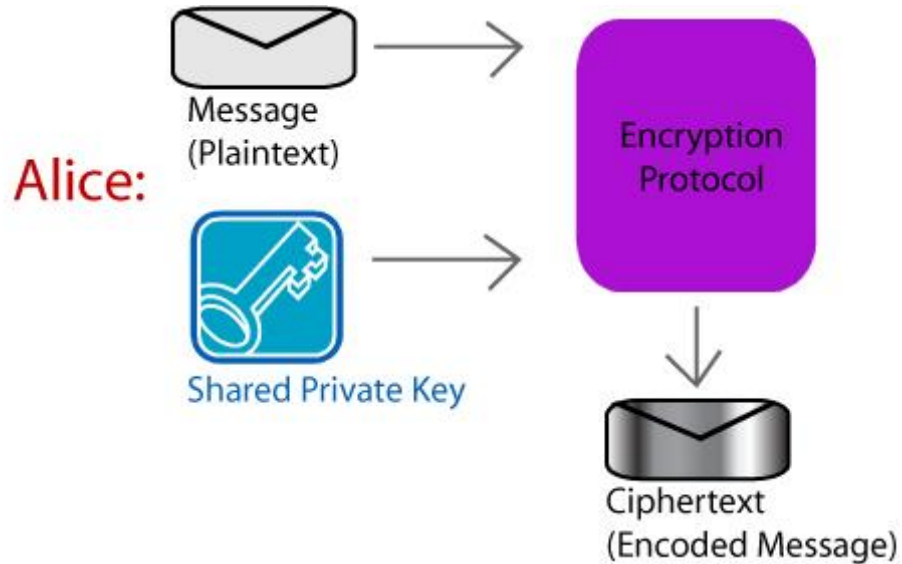


Figure 1: Alice creates an encoded message with a private key she shares with Bob.

Bob, upon receiving the Ciphertext from Alice, can obtain her original message by inputting their shared key κ along with Ciphertext into his decryption protocol, as shown in Figure 2 on the next page.

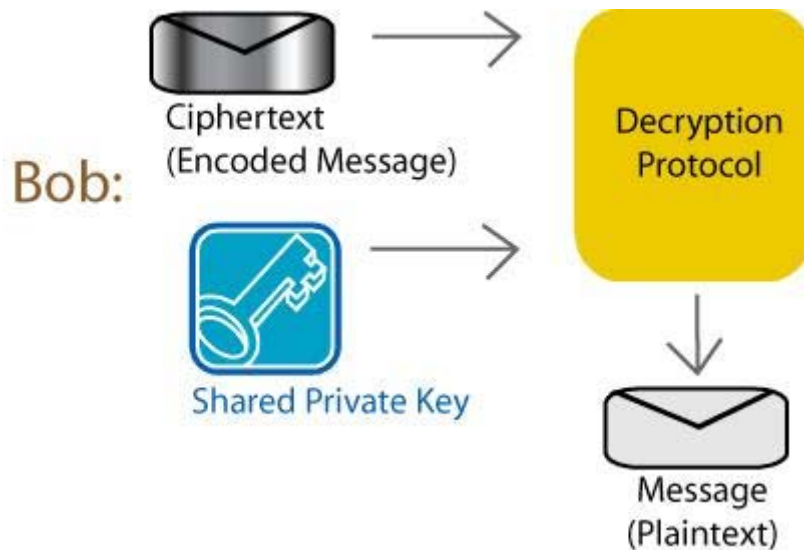


Figure 2: Bob converts encoded message from Alice into plain-text using shared private key.

As intuitive as such a private-key method is, the vulnerabilities quickly emerge. The security of the system relies on the secret key κ remaining uncompromised, at all times. In that there are many cryptographic methods to search for the secret key, a key can only remain secure for so long. With the use of a private-key solution, if one user's private key is compromised, then all users who share that key will be impacted.

As the number of users of a private key system grows (in the case of RFID - into the billions!), the need to confidentially distribute new keys on a regular basis leads to the progressively unwieldy problem of key management. While it is generally true that private-key systems have a fast running time, which perpetuates their use in many commercial systems today, their intrinsic weaknesses are ubiquitous.

Public-key (or asymmetric) cryptography frees itself from most of the above-discussed difficulties by assigning each user a specific private key, which only the user knows, and a mathematically-related public key which can be made public and freely distributed. There are two general methods for using public key cryptography, RSA and Diffie-Hellman. In both cases, the systems are designed so that the public keys do not have to be distributed to all parties prior to communicating and the security of the system is not compromised by the publication of the public keys when a session begins.

In the case of an RSA-type system, if Alice wants to send Bob a message, she uses Bob's public key to encrypt her plaintext, as seen in Figure 3.

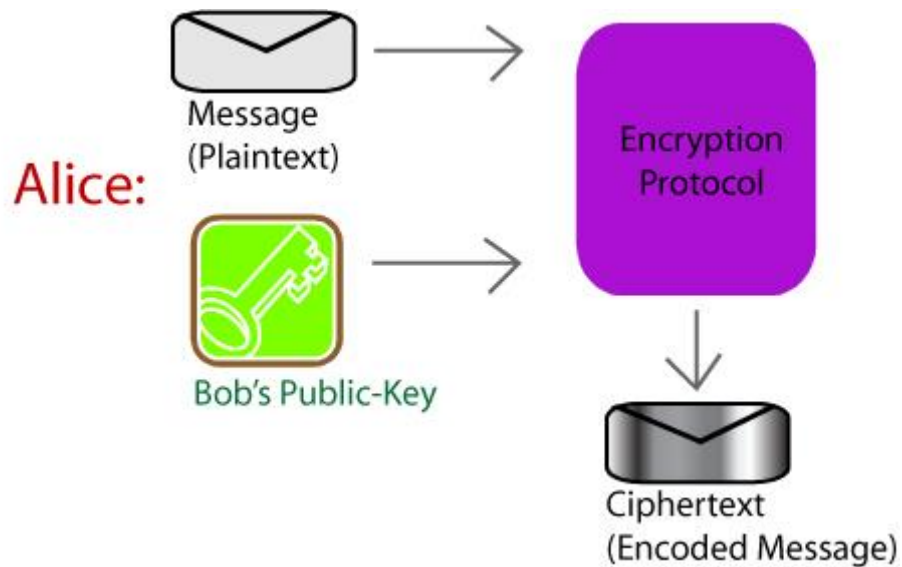


Figure 3: RSA type system: Alice uses Bob's Public Key to encrypt her message to Bob.

Bob, upon receiving the Ciphertext, can obtain Alice's original message by inputting his private key κ , along with Ciphertext into his decryption protocol, as seen in Figure 4.

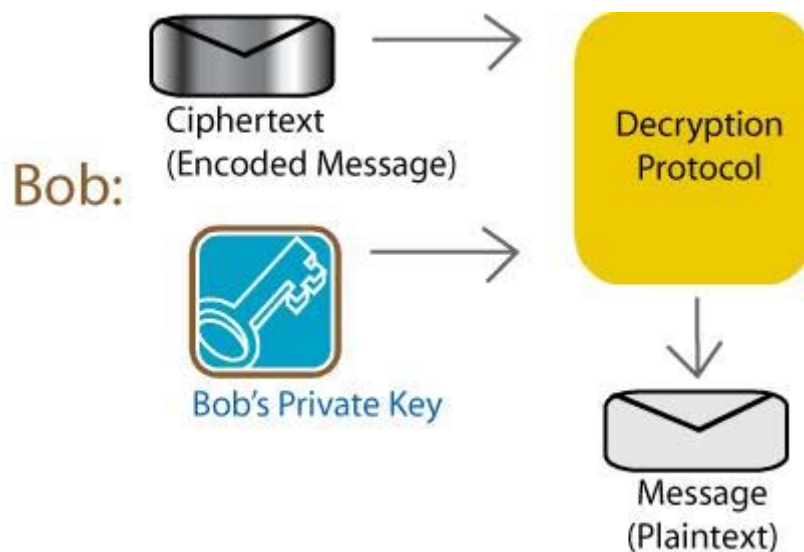


Figure 4: RSA type system: Bob uses his own private key to decrypt the encoded message.

With an RSA-type system, only Bob has a copy of his private key so anyone intercepting the encrypted message from Alice will be unable to decipher it.

In the case of a Diffie-Hellman-type system Alice and Bob use each other's public keys, together with their own respective private keys, to establish a common secret key, which can be

used for encryption and decryption of their message. Only Alice and Bob, who are participating in this session, will have access to the necessary key to encrypt or decrypt a message.

The Diffie-Hellman type systems are structurally distinct as can be seen in Figure 5.

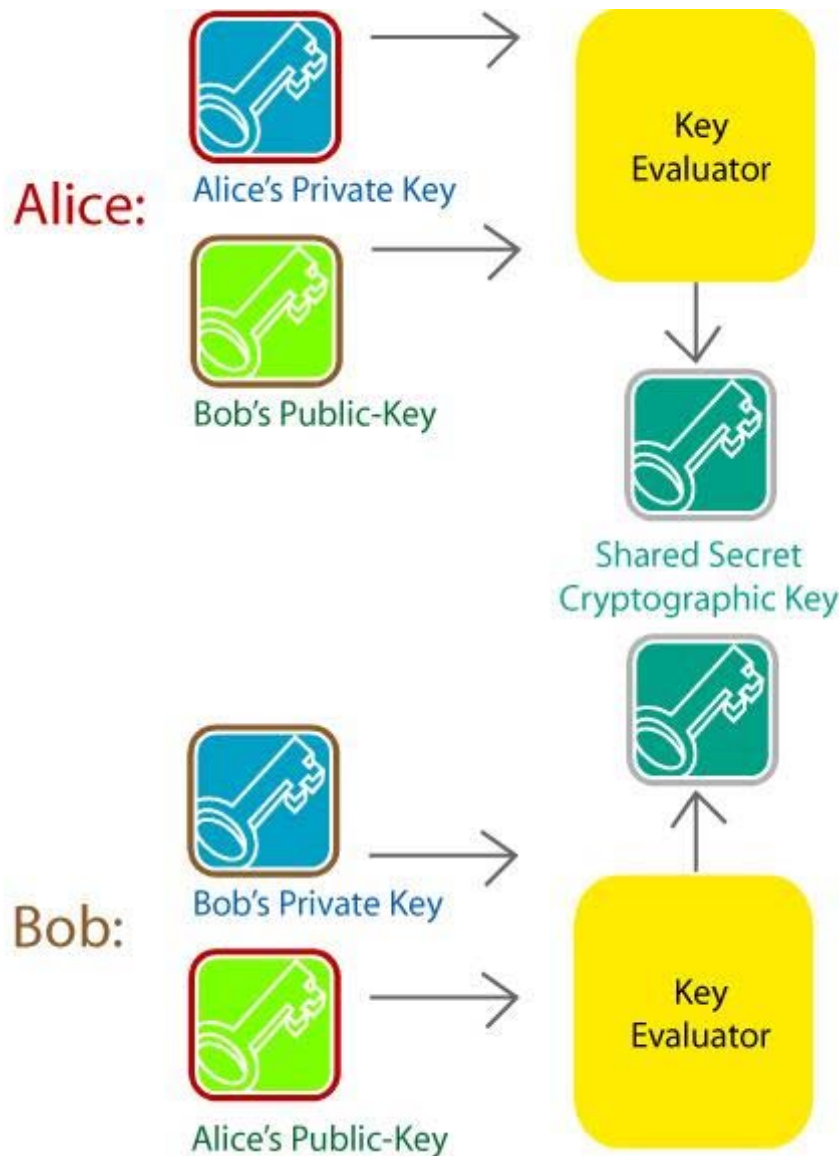


Figure 5: Diffie-Hellman type system

The output of the Diffie-Hellman type system is a shared secret cryptographic key, the value of which is the same for both Alice and Bob. This shared key can then be used for encryption and decryption of the message passed between them, similar to a private key system. In comparison, the output of an RSA type system is the encrypted text itself. In both of these asymmetric systems, each user's private key is different than another user's private key.

A succinct view of various public-key and private-key systems, including the Algebraic Eraser™ which will be discussed in the next section, is in the concept tree shown in Figure 6.

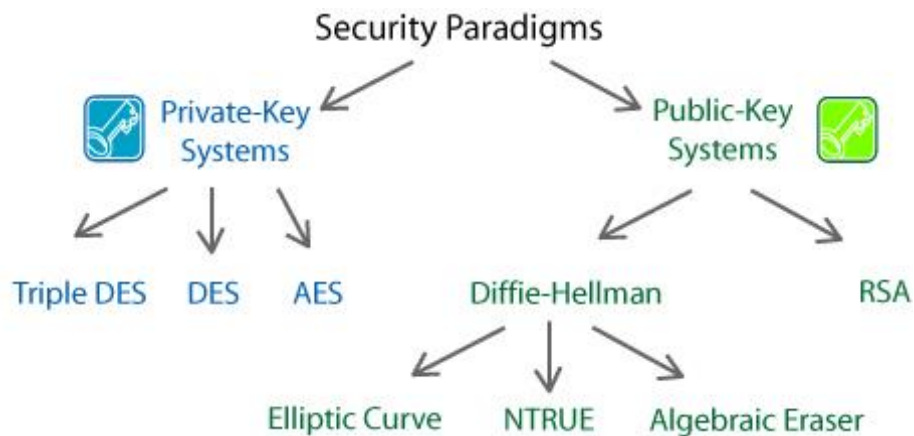


Figure 6: Categorization of private key and public key security paradigms

In a private-key situation the security of the system relies on the secret key κ remaining uncompromised at all times. In contrast, with a public-key system, if any one user's private key becomes known the other users are insulated from having their communications compromised. This is because the private key is not common across the entire system as found in a symmetric system, but rather the private key is unique to each individual. In a public key scenario the mathematical relationship between a user's private and public key is designed so that it is infeasible to derive the private key from the public key (such a relationship is referred to as a one-way function). To be able to effectively reverse engineer a public key would be as difficult as a mathematically intractable problem. That is, mathematical problems that may be solvable but are so difficult or timely to complete that the solution will provide no benefit once derived. The security of these systems lies in this intractability.

Public-key systems do have issues to overcome. Ensuring that the distributed public keys are authentic is essential to security (known as the man-in-the-middle attack). Protocols to prevent malicious use of public data also need to be put in place (preventing replay attacks). While technically challenging, these obstacles can be mitigated.

A more profound issue with today's commonly implemented RSA and Diffie-Hellman type public-key protocols, including NTRUE and Elliptic Curve Cryptography (ECC), concerns the computational footprint they entail. While memory and energy usage is not a primary concern for most environments requiring cryptographic security, these issues, along with runtime, lie at the heart of any small computing device security discussion. Every one of these cryptographic systems at its core utilizes multiplication of large numbers. As a result the computing resources required to achieve security grow rapidly as the level of security is increased.

As the market for smaller and more mobile/wireless computing devices continues to grow, so does the need for stronger and more efficient security solutions to address these markets. As a result, the need for a next generation of public-key cryptography becomes evident.

3. The SecureRF Approach.

With the goal of facilitating the security of low-resource computing platforms including RFID, NFC, Bluetooth LE, microcontrollers, wireless sensor networks and integrated circuits; SecureRF has introduced the Algebraic Eraser™ public-key cryptosystem whose characteristics are specifically suited to these low-resource environments.

The Algebraic Eraser public-key cryptosystem has as its foundation in three distinct areas of mathematics and on which its security is based: the theory of braids, the theory of matrices with polynomial entries (expressions of finite length constructed from variables), and modular arithmetic. At its core is a highly specialized function (replacing the standard system's operations), known as E-Multiplication™, which brings together these mathematical tools and enables the system to provide high-speed security without overwhelming the memory and power available. This core function is highly resistant to reverse engineering due to connections with mathematically intractable problems.

In January 2010, the United States Patent and Trademark Office granted SecureRF Corporation U.S. Patent 7,649,999, entitled "Method and apparatus for establishing a key agreement protocol," for its technology invention in the field of cryptography. The reader may learn more about the company's methods from reviewing this patent. The method is summarized in its abstract stating:

"A system and method for generating a secret key to facilitate secure communications between users. Public keys are exchanged between first and second users. Each user's private key may be iteratively multiplied by the other user's public key to produce a secret key. Secure communication may then occur between the first and second user using the secret key."

SecureRF has also received these patents:

- U.S. Patent 9,071,427: "Method and apparatus for establishing a key agreement system"
- U.S. Patent 9,071,408: "Communication System"
- U.S. Patent 8,972,715: "Cryptographic hash function"

Structurally, SecureRF's Algebraic Eraser public-key cryptosystem is of the Diffie-Hellman type. Alice and Bob each use their own private key and the other person's public key to generate a shared secret key, via the Algebraic Eraser E-multiplication function, as can be seen in Figure 7 on the following page.

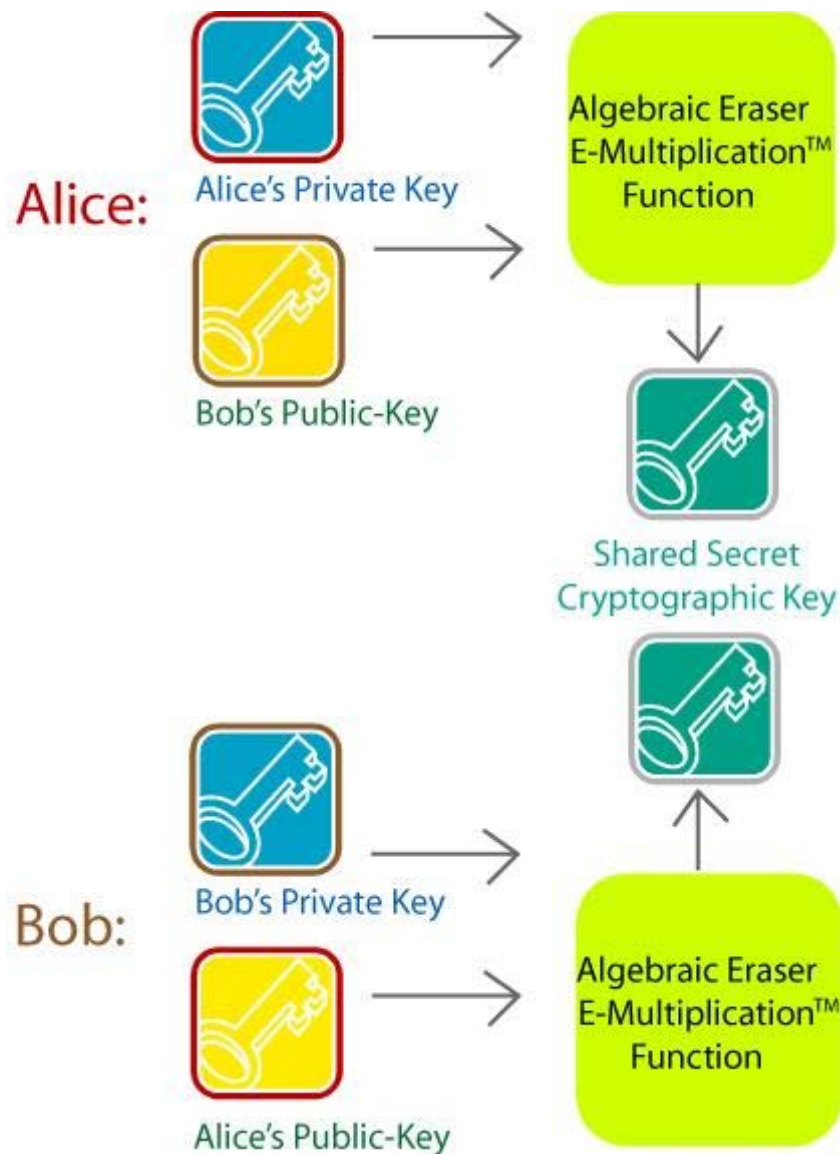


Figure 7: SecureRF's Algebraic Eraser based cryptosystem

The output of the Algebraic Eraser system is also a shared secret cryptographic key that can then be used as a private key system for encryption and decryption of the message passed between Alice and Bob.

Some of the significant features of SecureRF's approach include:

- Low power consumption for the processor, high speed implementation for real-time processing and a small computational footprint.
- Key management is mitigated because secure disposable keys can be generated for each communication session.
- Algebraic Eraser protocols are secure against replay attacks and man in the middle attacks.
- All Algebraic Eraser protocols run in linear time in the key size, while all other systems, including RSA and Diffie-Hellman protocols scale quadratically. When viewed from a

user resource perspective, the graph in Figure 8 gives a high level indication of the intrinsic benefits of the Algebraic Eraser. The Algebraic Eraser is much less resource intensive and can run on devices that have limited computing power.

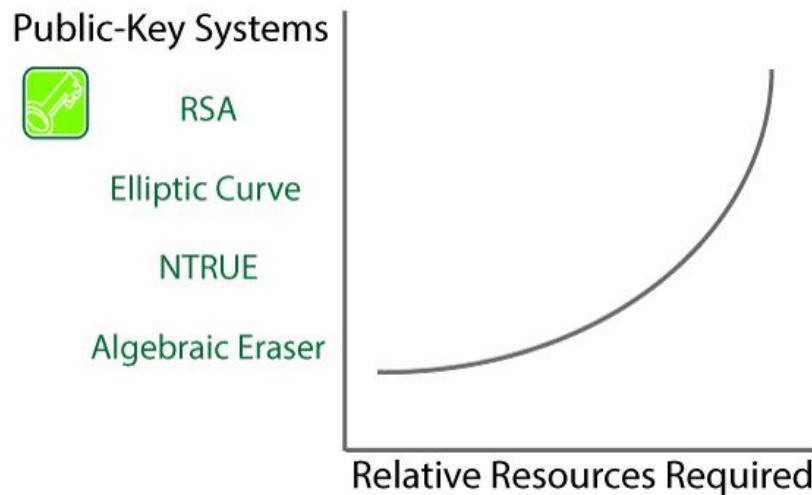


Figure 8: Public-key crypto systems vary in the amount of computing resources they require.

Security protocols which are based on secret methods are often insecure because they have not had the benefit of wide spread testing and analysis. Strong cryptographic security methods are published for peer review. Details about how the Algebraic Eraser's key agreement protocol for public key cryptography is suitable for low resource devices, such as RFID tags, have been published by The American Mathematical Society in the peer-reviewed book "[Algebraic Methods in Cryptography](#)" in the section titled *Key agreement, the Algebraic Eraser™ and Lightweight Cryptography*. A version of this paper is available on SecureRF's web site (<http://www.securerf.com/technology/papers/>).

The Algebraic Eraser key agreement protocol (AEKAP), when viewed at a high level, brings together the Braid group and a rapidly computable Algebraic Eraser based irreversible function (termed a one-way function) whose output consists of ordered pairs of specialized matrices and permutations. In the AEKAP each user is equipped with a collection of braid group elements from which the Braid element part of user's private key is constructed. Once the private key is specified the user's public key is evaluated using the above mentioned one-way functions to produce a matrix/permutation ordered pair. To execute the AEKAP the users exchange their respective public keys (over an insecure channel) and each user, by combining the received public key and their own private key can evaluate, via the same one-way function, the unique common key (which is yet again a matrix/permutation pair) that is the output of the AEKAP.

The security of the AEKAP rests on the infeasibility of reversing the Algebraic Eraser based one-way function utilized in the protocol together with the difficulty of solving certain simultaneous equations over the braid group. Among the unique features of the protocol is the fact that if there is a need to increase the security level, from 80 to 128 bit for example, the protocol execution time would scale linearly and the size of both the public and exchanged keys would not need to increase. The process of producing the user collections of braid element, which is done off-line, insures the Braid based security feature of the AEKAP is in place. There

is no possible Braid based attack on the public-key due to the fact the public keys are not themselves braid but are the outputs of a one-way function applied to braids.

There are several groups working on the mathematical security using braids. The single conjugate work of Ko-Lee, et al from Korea is a substantially different method than SecureRF's dual conjugate protocol. The security for the Ko-Lee et al Braid based key agreement protocol (KL...KAP) is based on a special case of solving a single equation in the Braid group. Each user chooses a private key, which is a braid element that commutes with the other user's private key. Each user's public key is obtained by applying a function to the private key whose output is another Braid group element. Within a more general context this function would be difficult to reverse, but the fact the inputs commute impacts the situation significantly. A specialized Braid based attack can be used and no further one-way functions are there to thwart the attack. One other contrasting point is that the size of the public key and the exchanged key grows as the size of the private key increases because the running time of the Ko-Lee et al scheme is quadratic in the length of the private key compared to a linear run time for the AEKAP. Thus a requirement of higher security would make for larger blocks of data to be transmitted and a more intensive computation would be required to obtain the exchanged key. In a resource-constrained environment this is a constant concern. There are several published papers pointing out that the attacks on the Korean's single conjugate method do not work on the dual-conjugate braid methods used by SecureRF.

More information about the Algebraic Eraser can be found in these SecureRF white papers:

- *An Introduction to the Mathematics of Braids*
- *Colored Braid Matrices, E-multiplication, and the Algebraic Eraser™ Key Agreement Protocol*
- *Security in Low Resource Environments*

These white papers, along with several technical papers, are available at <http://www.securerf.com/technology/papers/>.

4. SecureRF's Mathematician/Cryptographers

The inventors of SecureRF's public-key cryptosystem are co-founders Dr. Michael Anshel, Dr. Dorian Goldfeld and Dr. Iris Anshel.

Dr. Michael Anshel is a security thought-leader and world-class mathematician with expertise in the field of cryptography. Dr. Anshel has authored and co-authored numerous papers in the area of public-key cryptography, is the co-inventor of four patents in the area of cryptography, zeta-one-way functions, and braid group and has received numerous fellowships and honors. He is a Professor Emeritus in the Department of Computer Science at The City College of New York.

Dr. Goldfeld is a world-class mathematician who has published over 50 papers and lectured internationally on a wide range of cryptographic topics and methods including applications of elliptic curves, quadratic fields, zeta functions, public-key cryptography, and group theoretic approaches to public-key cryptography.. In 2009 he was inducted as a Fellow of the prestigious American Academy of Arts & Sciences. He is the co-inventor of three patents in the areas of multistream encryption systems, high-speed cryptography, and cryptographically secure algebraic key establishment protocols based on monoids. He has been a professor in the Faculty of Mathematics at Columbia since 1985.

Dr. Iris Anshel, SecureRF's Chief Scientist, is an accomplished mathematician and cryptographer. In addition to extensive research and publications, Dr. Anshel has experience in the commercialization of security technology. As a co-founder of Arithmetica, she was responsible for documenting methods for commercial deployment of new cryptography protocols including the AAG Braid Group Cryptosystem and supported sales and business development activity.

5. About SecureRF

SecureRF Corporation – Securing the Internet of Things® – provides security solutions for embedded systems and wireless sensor technologies used in non-traditional payment systems, secure supply chain management, cold chain management, and anti-counterfeiting applications in the pharmaceutical, fashion, spirits, defense, and homeland security sectors. The company's technology is based on a breakthrough in public-key cryptography that is computationally efficient, yet highly secure and available as a software development kit, Verilog/VHDL, or as a core for FPGAs and ASICs. SecureRF also offers the LIME Tag™ - a range of highly secure NFC, UHF and Bluetooth LE sensor tags along with its anti-counterfeiting solution – Veridify®.

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