

## GROUP THEORY IN CRYPTOGRAPHY

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### Abstract

This paper is a guide for the pure mathematician who would like to know more about cryptography based on group theory. The paper gives a brief overview of the subject, and provides pointers to good textbooks, key research papers and recent survey papers in the area.

### 1 Introduction

In the last few years, many papers have proposed cryptosystems based on group theoretic concepts. Notes from a recent advanced course on the subject by Myasnikov, Shpilrain and Ushakov have recently been published as a monograph [61], and a textbook (with a rather different focus) by González Vasco, Magliveras and Steinwandt [29] is promised in 2010. Group-based cryptosystems have not yet led to practical schemes to rival RSA and Diffie–Hellman, but the ideas are interesting and the different perspective leads to some worthwhile group theory. The cryptographic literature is vast and diverse, and it is difficult for a newcomer to the area to find the right sources to learn from. (For example, there are many introductory textbooks aimed at the mathematical audience that introduce RSA. How many of these textbooks hint that the basic RSA scheme is insecure if refinements such as message padding are not used? For a discussion of these issues, see Smart [75, Chapters 17,18 and 20], for example.) Our paper will provide some pointers to some sources that, in our opinion, provide a good preparation for reading the literature on group-based cryptography; the paper will also provide a high level overview of the subject. We are assuming that our reader already has a good knowledge of group theory, and a passing acquaintance with cryptography: the RSA and Diffie–Hellman schemes have been met before, and the difference between a public key and a symmetric key cipher is known.

The remainder of the paper is structured as follows. In Section 2 we review some of the basic concepts of cryptography we will need. In Section 3 we introduce some

of the most widely studied schemes in group-based cryptography, and in Section 4 we sketch attacks on these schemes. In all these sections, we cite references that provide more details. Finally, in Section 5, we touch on some related areas and give suggestions as to where to search for current papers and preprints in the subject.

## 2 Cryptography Basics

There are innumerable books on cryptography that are written for a popular audience: they almost always take a historical approach to the subject. For those looking for a definitive historical reference book, we would recommend Kahn [40] for an encyclopedic and beautifully written account.

Technical introductions to the area written for a mathematical audience tend to concentrate (understandably, but regrettably from the perspective of a cryptographer) on the areas of cryptography that have the most mathematical content. Stinson [79] is a well written introduction that avoids this pitfall. Another good reference is Smart [75], which has the advantage of being available online for free. Once these basics are known, we suggest reading a book that looks at cryptography from the perspective of theoretical computer science and complexity theory: Katz and Lindell [43] is a book we very much enjoy. The theoretical computer science approach has had a major influence on the field, but is not without its controversial aspects: see Koblitz [46] and responses by Goldreich and others [28]. For readers who insist on falling into the mathematical pit mentioned above, the book by Washington [83] on cryptography using elliptic curves is an excellent follow-up read; elliptic curve based cryptography is becoming the norm for the current generation of public key cryptosystems. As we are writing for a mathematical audience, we also consciously aim to fall into this pit.

A standard model for a cryptographic scheme is phrased as two parties, Alice and Bob, who wish to communicate securely over an insecure channel (such as a wireless link, or a conventional phone line). If Alice and Bob possess information in common that only they know (a shared secret key) they can use this, together with a symmetric key cipher such as AES (the Advanced Encryption Standard), to communicate. If Alice and Bob do not possess a secret key, they execute a protocol such as the Diffie–Hellman key agreement protocol to create one, or use a public key cryptosystem such as RSA or ElGamal that does not need a secret key. Many of the schemes we discuss are related to the Diffie–Hellman protocol, so we give a brief description of this protocol as a reminder to the reader.

**Diffie–Hellman Key Agreement Protocol [22].** Let  $G$  be a cyclic group, and  $g$  a generator of  $G$ , where both  $g$  and its order  $d$  are publicly known. If Alice and Bob wish to create a shared key, they can proceed as follows:

1. Alice selects uniformly at random an integer  $a \in [2, d - 1]$ , computes  $g^a$ , and sends it to Bob.
2. Bob selects uniformly at random an integer  $b \in [2, d - 1]$ , computes  $g^b$ , and sends it to Alice.
3. Alice computes  $k_a = (g^b)^a$ , while Bob computes  $k_b = (g^a)^b$ .

4. The shared key is thus  $k = k_a = k_b \in G$ .

The security of the scheme relies on the assumption that, knowing  $g \in G$  and having observed both  $g^a$  and  $g^b$ , it is computationally infeasible for an adversary to obtain the shared key. This is known as the **Diffie–Hellman Problem (DHP)**. The Diffie–Hellman problem is related to a better known problem, the Discrete Logarithm Problem:

**Discrete Logarithm Problem (DLP).** Let  $G$  be a cyclic group, and  $g$  a generator of  $G$ . Given  $h \in G$ , find an integer  $t$  such that  $g^t = h$ .

Clearly, if the DLP is easy then so is the DHP and thus the Diffie–Hellman key agreement protocol is insecure. So, as a minimum requirement, we are interested in finding difficult instances of the DLP. It is clear that difficulty of the DLP depends heavily on the way the group  $G$  is represented, not just on the isomorphism class of  $G$ . For example, the DLP is trivial if  $G = \mathbb{Z}/d\mathbb{Z}$  is the additive group generated by  $g = 1$ . However, if  $G$  is an appropriately chosen group of large size, the DLP is considered computationally infeasible. In practice, one often uses  $G = \mathbb{F}_{p^l}^*$  (for appropriately selected prime  $p$  and exponent  $l$ ), or the group of points of a properly chosen elliptic curve over a finite field.

Turning from the Diffie–Hellman scheme to the more general model, there are two points we would like to emphasise:

- **Alice and Bob are computers.** So our aim is to create a protocol that is well specified enough to be implemented. In particular, a well specified scheme must describe how group elements are stored and manipulated; the scheme’s description must include an algorithm to generate any system-wide parameters; it must be clear how any random choices are made. (This last point is especially critical if we are choosing elements from an infinite set, such as a free group!) Moreover, the protocol should be efficient; the computational time required to execute the protocol is critical, but so are: the number of bits that need to be exchanged between Alice and Bob; the number of passes (exchanges of information) that are needed in the protocol; the sizes of keys; the sizes of system parameters.
- **Security is a very subtle notion.** For the last 100 years, it has become standard for cryptographers to assume that any eavesdropper knows everything about the system that is being used apart from secret keys and the random choices made by individual parties. (Claude Shannon [72, Page 662] phrased this as ‘The enemy knows the system being used’; the phrase ‘The enemy knows the system’ is known as Shannon’s maxim.). But modern security is often much more demanding. For example, in the commonly studied IND-CCA2 model, we require that an eavesdropper cannot feasibly guess (with success probability significantly greater than 0.5) which of two messages has been encrypted, when they are presented with a single challenge ciphertext that is an encryption of one of the messages. This should even be true when the eavesdropper can choose the two messages, and is allowed to request the decryption of any ciphertext not equal to the challenge ciphertext. Note that cryptographers are usually interested in the complexity in the generic case (in

other words, what happens most of the time). Worst case security estimates might not be useful in practice, as the worst case might be very rare; even average case estimates might be unduly distorted by rare but complicated events. See Myasnikov et al. [61] for a convincing argument on this point in the context of group-based cryptography.

We end the section by making the point that modern cryptography is much broader than the traditional two party communication model we have discussed here: there is a thriving community developing the theory of multi-party communication, using such beautiful concepts as zero knowledge. See Stinson [79, Chapter 13] for an introduction to zero knowledge, and see the links from Helger Lipmaa's page [52] for some of the important papers on multiparty computation.

### 3 Cryptography Using Groups

This section will discuss several ways in which group theory can be used to construct variants of the Diffie–Hellman key agreement protocol. Since the protocol uses a cyclic subgroup of a finite group  $G$ , one approach is to search for examples of groups that can be efficiently represented and manipulated, and that possess cyclic subgroups with a DLP that seems hard. Various authors have suggested using a cyclic subgroup of a matrix group in this context, but some basic linear algebra shows that this approach is not very useful: the DLP is no harder than the case when  $G$  is the multiplicative group of a finite field; see Menezes and Vanstone [59] for more details. Biggs [6] has proposed representing an abelian group as a critical group of a finite graph; but Blackburn [11] has shown that this proposal is insecure. An approach (from number theory rather than group theory) that has had more success is to consider the group of points on an elliptic curve, or Jacobians of hyperelliptic curves. See Galbraith and Menezes [23] for a survey of this area.

All the proposals discussed above use representations of abelian (indeed, cyclic) groups. What about non-abelian groups? The first proposal to use non-abelian groups that we are aware of is due to Wagner and Magyarik [82] in 1985. (See González Vasco and Steinwandt [31] for an attack on this proposal; see Levy-dit-Vehel and Perret [50, 51] for more recent related work.) But interest in the field increased with two high profile proposals approximately ten years ago. We now describe these proposals.

#### 3.1 Conjugacy and exponentiation

Let  $G$  be a non-abelian group. For  $g, x \in G$  we write  $g^x$  for  $x^{-1}gx$ , the conjugate of  $g$  by  $x$ . The notation suggests that conjugation might be used instead of exponentiation in cryptographic contexts. So we can define an analogue to the discrete logarithm problem:

**Conjugacy Search Problem.** Let  $G$  be a non-abelian group. Let  $g, h \in G$  be such that  $h = g^x$  for some  $x \in G$ . Given the elements  $g$  and  $h$ , find an element  $y \in G$  such that  $h = g^y$ .

Assuming that we can find a group where the conjugacy search problem is hard (and assuming the elements of this group are easy to store and manipulate), one can define cryptosystems that are analogues of cryptosystems based on the discrete logarithm problem. Ko et al. proposed the following analogue of the Diffie–Hellman key agreement protocol.

**Ko–Lee–Cheon–Han–Kang–Park Key Agreement Protocol [45].** Let  $G$  be a non-abelian group, and let  $g$  be a publicly known element of  $G$ . Let  $A, B$  be commuting subgroups of  $G$ , so  $[a, b] = 1$  for all  $a \in A, b \in B$ . If Alice and Bob wish to create a common secret key, they can proceed as follows:

1. Alice selects at random an element  $a \in A$ , computes  $g^a = a^{-1}ga$ , and sends it to Bob.
2. Bob selects at random an element  $b \in B$ , computes  $g^b = b^{-1}gb$ , and sends it to Alice.
3. Alice computes  $k_a = (g^b)^a$ , while Bob computes  $k_b = (g^a)^b$ .
4. Since  $ab = ba$ , we have  $k_a = k_b$ , as group elements (though their representations might be different). For many groups, we can use  $k_a$  and  $k_b$  to compute a secret key. For example, if  $G$  has an efficient algorithm to compute a normal form for a group element, the secret key  $k$  could be the normal form of  $k_a$  and  $k_b$ .

The interest in the paper of Ko et al. [45] centred on their proposal for a concrete candidate for  $G$  and the subgroups  $A$  and  $B$ , as follows. We take  $G$  to be the braid group  $B_n$  on  $n$  strings (see Artin [3], for example) which has presentation

$$B_n = \left\langle \sigma_1, \sigma_2, \dots, \sigma_{n-1} \mid \begin{array}{ll} \sigma_i \sigma_j \sigma_i = \sigma_j \sigma_i \sigma_j & \text{for } |i - j| = 1 \\ \sigma_i \sigma_j = \sigma_j \sigma_i & \text{for } |i - j| \geq 2 \end{array} \right\rangle.$$

Let  $l$  and  $r$  be integers such that  $l + r = n$ . Then we take

$$\begin{aligned} A &= \langle \sigma_1, \sigma_2, \dots, \sigma_{l-1} \rangle \text{ and} \\ B &= \langle \sigma_{l+1}, \sigma_{l+2}, \dots, \sigma_{l+r-1} \rangle. \end{aligned}$$

The braid group is an attractive choice for the underlying group (a so-called ‘platform group’) in the Ko et al. key agreement protocol: there is an efficient normal form for an element; group multiplication and inversion can be carried out efficiently; the conjugacy problem looks hard for braid groups. Note that we have not specified the cryptosystem precisely. Of course, we have not chosen the values of  $n, l$  and  $r$ . But we have also not specified how to choose the element  $g \in G$  (it emerges that this choice is critical). Finally, since the subgroups  $A$  and  $B$  are infinite, it is not obvious how the elements  $a \in A$  and  $b \in B$  should be chosen.

### 3.2 Computing a common commutator

The following beautiful key agreement protocol, due to Anshel, Anshel and Goldfeld [1], has an advantage over the Ko et al. protocol: commuting subgroups  $A$  and  $B$  are not needed.

**Anshel–Anshel–Goldfeld Key Agreement Protocol [1].** Let  $G$  be a non-abelian group, and let elements  $a_1, \dots, a_k, b_1, \dots, b_m \in G$  be public.

1. Alice picks a private word  $x$  in  $a_1, \dots, a_k$  and sends  $b_1^x, \dots, b_m^x$  to Bob.
2. Bob picks a private word  $y$  in  $b_1, \dots, b_m$  and sends  $a_1^y, \dots, a_k^y$  to Alice.
3. Alice computes  $x^y$  and Bob computes  $y^x$ .
4. The secret key is  $[x, y] = x^{-1}y^{-1}xy$ .

Note that Alice and Bob can both compute the secret commutator: Alice can premultiply  $x^y$  by  $x^{-1}$  and Bob can premultiply  $y^x$  by  $y^{-1}$  and then compute the inverse:  $[x, y] = (y^{-1}y^x)^{-1}$ .

The Anshel et al. protocol is far from well specified as it stands. In particular, we have said nothing about our choice of platform group  $G$ . Like Ko et al., Anshel et al. proposed using braid groups because of the existence of efficient normal forms for group elements and because the conjugacy search problem seems hard. See Myasnikov et al. [61, Chapter 5] for a discussion of some of the properties a platform group should have; they discuss the possibilities of using the following groups as platform groups: Thompson’s group  $F$ , matrix groups, small cancellation groups, solvable groups, Artin groups and Grigorchuk’s group.

### 3.3 Replacing conjugation

The Ko et al. scheme used conjugation in place of exponentiation in the Diffie–Hellman protocol, but there are many other alternatives. For example, we could define  $g^a = \phi(a)ga$  and  $g^b = \phi'(b)gb$  for any fixed functions  $\phi : A \rightarrow A$  and  $\phi' : B \rightarrow B$  (including the identity maps) and the scheme would work just as well. More generally, we may replace  $a$  and  $\phi(a)$  by unrelated elements from  $A$ : there are protocols based on the difficulty of the *decomposition problem*, namely the problem of finding  $a_1, a_2 \in A$  such that  $h = a_1ga_2$  where  $g$  and  $h$  are known. See Myasnikov et al. [61, Chapter 4] for a discussion of these and similar protocols; one proposal we find especially interesting is the Algebraic Eraser [2, 42]. As an example of such a protocol, we briefly describe a scheme due to Stickel.

**The Stickel Key Agreement Protocol [78].** Let  $G = \text{GL}(n, \mathbb{F}_q)$ , and let  $g \in G$ . Let  $a, b$  be elements of  $G$  of order  $n_a$  and  $n_b$  respectively, and suppose that  $ab \neq ba$ . The group  $G$  and the elements  $a, b$  are publicly known. If Alice and Bob wish to create a shared key, they can proceed as follows:

1. Alice chooses integers  $l, m$  uniformly at random, where  $0 < l < n_a$  and  $0 < m < n_b$ . She sends  $u = a^lgb^m$  to Bob.
2. Bob chooses integers  $r, s$  uniformly at random, where  $0 < r < n_a$  and  $0 < s < n_b$ . He sends  $v = a^rgb^s$  to Alice.
3. Alice computes  $k_a = a^lvb^m = a^{l+r}gb^{m+s}$ . Bob computes  $k_b = a^rub^s = a^{l+r}gb^{m+s}$ .
4. The shared key is thus  $k = k_a = k_b$ .

### 3.4 Logarithmic signatures

There is an alternative approach to generalising the Diffie–Hellman scheme: to find a more direct generalisation of the DLP for groups that are not necessarily abelian.

Let  $G$  be a finite group,  $S \subseteq G$  a subset of  $G$  and  $s$  a positive integer. For all  $1 \leq i \leq s$ , let  $A_i = [\alpha_{i1}, \dots, \alpha_{ir_i}]$  be a finite sequence of elements of  $G$  of length  $r_i > 1$ , and let  $\alpha = [A_1, \dots, A_s]$  be the ordered sequence of  $A_i$ . We say that  $\alpha$  is a *cover* for  $S$  if any  $h \in S$  can be written as a product  $h = h_1 \cdots h_s$ , where  $h_i = \alpha_{ik_i} \in A_i$ . If such a decomposition is unique for every  $g \in S$ , then  $\alpha$  is said to be a *logarithmic signature* for  $S$ . One natural way to construct a logarithmic signature for a group  $G$  is to take a subgroup chain

$$1 = G_0 < G_1 < \cdots < G_n = G,$$

and let  $A_i$  be a complete set of coset representatives for  $G_{i-1}$  in  $G_i$ . Then  $\alpha = [A_1, \dots, A_n]$  is a logarithmic signature (a so called *transversal logarithmic signature*) for  $G$ .

Given an element  $h \in S$  and a cover  $\alpha$  of  $S$ , obtaining a factorisation

$$h = \alpha_{1k_1} \cdots \alpha_{sk_s} \tag{1}$$

associated with  $\alpha$  could well be a hard problem in general. Indeed, in some situations the problem is a Discrete Logarithm Problem. For example, let  $G$  be generated by an element  $g$  of large order, and define  $A_{i+1} = [1, g^{2^i}]$ . Let  $S = \{g^a \mid 0 \leq a \leq 2^s\}$ . Then the  $i$ th bit of the discrete logarithm of  $h \in S$  is equal to 1 if and only if  $k_i = 2$  in the factorisation (1).

Though there are connections with the DLP, logarithmic signatures cannot be directly used in discrete logarithm based protocols, as there is no analogue of exponentiation. They were first used by Magliveras [53] to construct a symmetric cipher known as Permutation Group Mappings (PGM). The ideas behind PGM have inspired several public key cryptosystems based on logarithmic signatures. Qu and Vanstone [71] proposed a scheme (Finite Group Mappings, or FGM) based on transversal logarithmic signatures in elementary abelian 2-groups. Magliveras, Stinson and van Trung [56] developed two interesting schemes based on finite permutation groups,  $MST_1$  and  $MST_2$ . More recently, a public key cryptosystem based on Suzuki 2-groups (known as  $MST_3$ ) has been proposed by Lempken et al. [49].

### 3.5 Symmetric schemes

Group theory has mainly been used in proposals of public key cryptosystems and key exchange schemes, but has also been used in symmetric cryptography. We have already mentioned the block cipher PGM [53]. This cipher satisfies some nice algebraic and statistical properties (such as robustness, scalability and a large key space; see [55]). However, fast implementation becomes an issue, making it a rather inefficient cipher compared with more traditional block ciphers. (An attempt was made to improve PGM by letting the platform group be a 2-group, but again speed

remains an issue [16]). This subsection contains two more examples of group theory being used in symmetric cryptography.

A block cipher such as DES [65] or AES [68] can be regarded as a set  $\mathcal{S}$  of permutations on the set of all possible blocks, indexed by the key. The question as to whether  $\mathcal{S}$  is in fact a group has an impact on the cipher's security in some situations: if the set was a group, then encrypting a message twice over using the cipher with different keys would be no more secure than a single encryption. Other properties of the group generated by  $\mathcal{S}$  are also of interest cryptographically [35] and attacks have been proposed against ciphers that do not satisfy some of these properties [41, 70] (though good group theoretic properties are not sufficient to guarantee a strong cipher [60]). We note however that computing the group generated by a block cipher is often very difficult. For instance, it is known that the group generated by the DES block cipher is a subgroup of the alternating group  $A_{2^{64}}$  [84], with order greater than  $2^{56}$  (and thus  $\mathcal{S}$  for DES is not a group [15, 21]), however little more is known about its structure.

Block ciphers themselves are often built as iterated constructions of simpler key-dependent permutations known as *round functions*, and one can study properties of the permutation groups generated by these round functions. It has been shown, for instance, that the round function of both DES and AES block ciphers are even permutations; furthermore it can be shown that these generate the alternating group  $A_{2^{64}}$  and  $A_{2^{128}}$ , respectively [76, 84, 85].

Hash function design is a second area of symmetric cryptography where groups have been used in an interesting way. Recall [79, Chapter 7] that a hash function  $H$  is a function from the set of finite binary strings to a fixed finite set  $X$ . It should be easy to compute  $H(x)$  for any fixed string  $x$ , but it should be computationally infeasible to find two strings  $x$  and  $x'$  such that  $H(x) = H(x')$ . Hash functions are a vital component of many cryptographic protocols, but their design is still not well understood. The most widely used example of a hash function is SHA-1 (where SHA stands for Secure Hash Algorithm). See [66] for a description of this hash function. Security flaws have been found in SHA-1 (see the recent preprint [57] and the references quoted therein), and the more recent SHA-2 family of hash functions [67] are now recommended. Zémor [86] proposed using walks through Cayley graphs as a basis for hash functions; the most well known concrete proposal from this idea is a hash function of Tillich and Zémor [80]. We think this hash function deserves further study: see Steinwandt et al. [77] and the references there for comments on the security of this hash function, and see Tillich and Zémor [81] for some more recent literature.

## 4 Cryptanalysis

In this section, we briefly outline some techniques that have been developed to demonstrate the insecurity of group-based schemes.



#### 4.1 Analysis of braid based schemes

We begin with braid based schemes. The interested reader is referred to the comprehensive survey article by Garber [24] (and the extensive bibliography therein).

In 1969, Garside [26] gave the first algorithm to solve the conjugacy problem in the braid group  $B_n$ . (The conjugacy problem asks whether two braids, in other words two elements of the braid group, are conjugate.) The question of efficiency of Garside's method lay dormant until the late 1980's. Since then there has been a great deal of research, significantly motivated by cryptographic applications, into finding a polynomial time solution to the conjugacy problem. Given two braids  $x, y \in B_n$ , Garside's idea was to construct finite subsets (so called *summit sets*)  $I_x, I_y$  of  $B_n$  such that  $x$  is conjugate to  $y$  if and only if  $I_x = I_y$ . An efficient solution to the conjugacy problem via this method would yield an efficient solution to the conjugacy search problem (and hence render the braid based protocol of Ko et al. theoretically insecure). However, for a given braid  $x$ , Garside's summit set  $I_x$  may be exponentially large. The challenge has thus been to prove a polynomial bound on the size of a suitable invariant set associated with any given conjugacy class. Refinements to the summit set method (such as the *super summit set*, *ultra summit set*, and *reduced super summit set* methods) have been made over the years, but a polynomial bound remains elusive. Recent focus has been on an efficient solution to each of the three types of braids: periodic, reducible or pseudo-Anasov (according to the Nielsen–Thurston classification); see [7, 8, 9].

For the purposes of cryptography however, one need not efficiently solve the conjugacy problem in order to break a braid based cryptosystem: one is free to use the specifics of the protocol being employed; any algorithm only needs to work for a significant proportion of cases; heuristic algorithms are quite acceptable. Indeed, Hofheinz and Steinwandt [33] used a heuristic algorithm to solve the conjugacy search problem with very high success rates: their attack is based on the observation that representatives of conjugate braids in the super summit set are likely to be conjugate by a permutation braid (a particularly simple braid). Their attack demonstrates an inherent weaknesses of both the Ko et al. protocol and the Anshel et al. protocol for random instances, under suggested parameters. Around the same time, several other powerful lines of attack were discovered, and we now discuss some of the work that has been done.

**Length based attacks** Introduced by Hughes and Tannenbaum [37], length based attacks provide a neat probabilistic way of solving the conjugacy search problem in certain cases. Suppose we are given an instance of the conjugacy search problem in  $B_n$ . So we are given braids  $x, y^{-1}xy$  and want to find  $y$ . Let  $l : B_n \rightarrow \mathbb{Z}$  be a suitable length function on  $B_n$  (for example, the length of the normal form of an element). If we can write  $y = y'\sigma_i$  for some  $i$ , where  $y'$  has a shorter length than  $y$ , then  $l(\sigma_i y^{-1}xy \sigma_i^{-1})$  should be strictly smaller than  $l(\sigma_j y^{-1}xy \sigma_j^{-1})$  for  $j \neq i$ . So  $i$  can be guessed, and the attack repeated for a smaller instance  $y'$  of  $y$ . The success rate of this probabilistic attack depends on the specific length function employed. For braid groups, there are a number of suitable length functions that allow this attack to work. See the Garber et al. [25] and Miasnikov and Ushakov [62] for

convincing attacks on both the Ko et al. and Anshel et al. protocols using this approach.

**Linear algebra attacks** The idea behind this attack is quite simple: take a linear representation of the braid group and solve the conjugacy search problem using linear algebra in a matrix group. There are two well known representations of the braid group: the Burau representation (unfaithful for  $n \geq 5$ ) and the faithful Lawrence-Krammer representation. Hughes [36] and Lee and Lee [47] provide convincing attacks on the Anshel et al. protocol using the Burau representation, and Cheon and Jun [20] provide a polynomial time algorithm to break the Ko et al. protocol using the Lawrence-Krammer representation.

**Other directions** There have been many suggestions made to improve the security of schemes based on the above protocols. Themes range from changing the underlying problem (and instead investigating problems such as the decomposition problem, the braid root problem, the shifted conjugacy problem and more) to changing the platform group (Thompson's group, polycyclic groups and others have been suggested). Furthermore, cryptographers have created other cryptographic primitives based on the conjugacy search problem, for example authentication schemes and signature schemes. However, there are no known cryptographic primitives based on any of these ideas that convincingly survive the above sketched attacks. It seems to be the pattern that 'random' or 'generic' instances of either protocol lead to particularly simplified attacks. See the book by Myasnikov et al. [61] for more on this.

## 4.2 Stickel's scheme

Stickel's scheme was successfully cryptanalysed by Shpilrain [74]. We include a brief description of this attack as it is particularly simple, and illustrates what can go wrong if care is not taken in protocol design. The attack works as follows. First note that an adversary need not recover any of the private exponents  $l, m, r, s$  in order to derive the key  $k$ . Instead, it suffices upon intercepting the transmitted messages  $u$  and  $v$ , to find  $n \times n$  matrices  $x, y \in G$  such that

$$xa = ax, yb = by, u = xgy.$$

One can then compute

$$xvy = xa^r gb^s y = a^r xgyb^s = a^r ub^s = k.$$

It remains to solve these equations for  $x$  and  $y$ . The equations  $xa = ax$  and  $yb = by$  are linear, since  $a$  and  $b$  are known. The equation  $u = xgy$  is not linear, but since  $x$  is invertible we can rearrange:  $x^{-1}u = gy$ , with  $g$  and  $u$  known. Since  $xa = ax$  if and only if  $x^{-1}a = ax^{-1}$ , we write  $x_1 = x^{-1}$  and instead solve the following matrix equations involving  $x_1$  and  $y$ :

$$x_1a = ax_1, yb = by, x_1u = gy.$$

Setting  $x_1 = gy u^{-1}$  we can eliminate  $x_1$  to solve

$$gy u^{-1}a = agyu^{-1}, \quad yb = by.$$

Now only  $y$  is unknown and we have  $2n^2$  linear equations in  $n^2$  variables: a heavily overdetermined system of linear equations, and an invertible matrix  $y$  will be easily found. Shpilrain's attack is specific to the platform group  $GL(n, \mathbb{F}_q)$ . In particular, it uses the fact that  $x$  and  $u$  are invertible. Thus to thwart this attack, it makes sense to restrict the protocol to non-invertible matrices (since there is no inversion operation in the key setup). However, it is unclear whether or not this actually enhances the security of the protocol.

### 4.3 Analysis of schemes based on logarithmic signatures

How can secure logarithmic signatures be generated? The main problem with the overwhelming majority of schemes based on logarithmic signatures is a failure to specify how this should be done. (The Qu–Vanstone scheme [71] is well specified, but Blackburn, Murphy and Stern [13] showed this scheme is insecure.) Magliveras et al. [56] had the idea of restricting the logarithmic signature used in  $MST_1$  to be *totally non-transversal*, that is a logarithmic signature  $\alpha$  for a group  $G$  in which no block  $A_i$  of  $\alpha$  is a coset of a non-trivial subgroup of  $G$ . However, this condition was shown to be insufficient by Bohli et al. [14], who constructed instances of totally non-transversal logarithmic signatures that were insecure when used in  $MST_1$ . Key generation is also a problem for  $MST_2$ ; see [32] for a critique of this. As for  $MST_3$ , this was recently cryptanalysed by the authors [12]. Thus it seems that a significant new idea in this area is needed to construct a secure public key cryptosystem from logarithmic signatures.

## 5 Next Steps

Despite ten years of strong interest in group-based cryptography, a well-studied candidate for a secure, well-specified and efficient cryptosystem is yet to emerge: schemes that are more ‘number theoretic’ (such as those based on the elliptic curve DLP) currently have so many advantages. This is a disappointment (for the group theorist). However, we do not want to be overly pessimistic: we hope that the reader is already convinced that the protocols of Ko et al. and of Anshel et al. are elegant ideas, just waiting for the right platform group. *Can such a platform group be found?* We need a candidate group whose elements can be manipulated and stored efficiently, and an associated problem that is hard in the overwhelming majority of instances. There has been a great deal of attention on infinite groups (such as braid groups) that can be defined combinatorially, but we feel that finite groups deserve a much closer study; many problems disappear when we use finite groups. Note that groups with small linear representations are often problematic, as linear algebra can be used to attack such groups; groups with many normal subgroups (such as  $p$ -groups, for example) are often vulnerable to attacks based on reducing a problem to smaller quotients; groups with permutation representations

of low degree are vulnerable to attacks based on the well developed theory of computational permutation group theory. So great care must be taken in the choice of group, and the choice of supposedly hard problem. More generally, we can move beyond the Ko et al. and Anshel et al. schemes, and ask: *Is there a secure and efficient key exchange protocol based on group theoretic ideas?* There are regular proposals, but the field is still waiting for a proposal that stands up to long-term scrutiny.

We would like to point out that group-based cryptography motivates some beautiful and natural questions for the pure group theorist. Most obviously, the cryptosystems above motivate problems in computational group theory, especially combinatorial group theory. But we would like to highlight two more problems as examples of the kind of questions that can arise.

**Generic properties** The cryptosystems described in this survey require that elements and subgroups of a group  $G$  are generated *at random*. This needs to be defined precisely for this to make sense; one common method would be to select at random a sequence of integers  $\{a_1, a_2, \dots, a_l\}$  of length  $l$ , and for each  $1 \leq i \leq l$ , select at random a generator  $x_i$  of  $G$ . We then output the *random* element  $w = x_1^{a_1} x_2^{a_2} \dots x_l^{a_l}$ . Many cryptosystems run into problems because randomly generated sets of elements in the platform group behave in a straightforward way when  $l$  is large. This motivates the study of *generic* properties of groups, namely properties that hold with probability tending to 1 as  $l \rightarrow \infty$ . For example, Myasnikov and Ushakov [63] have shown that pure braid groups  $PB_n$  have the strong generic free group property: for any generating set of  $PB_n$ , when any  $k$  elements are chosen at random as above they freely generate a free group of rank  $k$  generically. An interesting and natural open problem is: does the same property hold for the braid groups  $B_n$ ? See Myasnikov et al. [61] for a discussion of this and related issues.

**Short logarithmic signatures** Let  $G$  be a finite group of order  $\prod_{j=1}^t p_j^{a_j}$ , with  $p_j$  distinct primes. Let  $\alpha = [A_1, \dots, A_s]$  be a logarithmic signature for  $G$ , with  $|A_i| = r_i$  for  $1 \leq i \leq s$ . Define the *length* of  $\alpha$  to be  $l(\alpha) := \sum_{i=1}^s r_i$ . The length of  $\alpha$  is an efficiency measure: it is the number of elements that must be stored in order to specify a typical logarithmic signature of this kind. Since  $|G| = \prod_{i=1}^s r_i$ , we must have that  $l(\alpha) \geq \sum_{j=1}^t a_j p_j$ . A logarithmic signature achieving this bound is called a *minimal logarithmic signature* for  $G$ . An attractive open problem is: Does every finite group have a minimal logarithmic signature? Now, if  $G$  has a normal subgroup  $N$  with  $G/N \cong H$  and  $H$  and  $N$  both have minimal logarithmic signatures then  $G$  has a minimal logarithmic signature. In particular, it is clear that any soluble group has a minimal logarithmic signature. Moreover, to answer the question in the affirmative it suffices to consider simple groups only. Minimal logarithmic signatures have been found for  $A_n$ ,  $\text{PSL}_n(q)$ , some sporadic groups and most simple groups of order up to  $10^{10}$ ; see [30, 32, 34, 48, 54] for further details.

Why do we attempt to propose new cryptosystems, when elliptic curve DLP systems work well? A major motivation is the worry that a good algorithm could be found for the elliptic curve DLP. This worry has increased, and the search

for alternative cryptosystems has become more urgent, with the realisation that quantum computers can efficiently solve both the integer factorisation problem and the standard variants of the DLP [73]. If quantum computers of a practical size can be constructed, classical public key cryptography is in trouble. Cryptosystems, including group-based examples, that are not necessarily vulnerable to the rise of quantum computers have become known as *post-quantum cryptosystems*. A well known example, invented well before quantum computers were considered, is the McEliece cryptosystem [58] based on the difficulty of decoding error correcting codes. Other examples include lattice based cryptosystems (such as the GGH cryptosystem [27, 64]) and cryptosystems based on large systems of multivariate polynomial equations (such as the HFE family of cryptosystems [44, 69]). Though many of these cryptosystems suffer from having large public keys, they are often computationally efficient and so we feel that these schemes are more likely than group-based cryptosystems to produce protocols that will be used in practice. For a good and recent survey of the area, that includes more details on all the cryptosystems mentioned above, see Bernstein et al. [5].

We hope the reader is keen to read more after finishing this introduction. We recommend consulting the IACR Cryptology ePrint Archive [39] or Cornell University's arXiv [4] (especially the group theory and cryptography sections) for new papers; we currently find the ePrint archive the most reliable source of high quality cryptography. Boaz Tsaban's CGC Bulletin [18] provides regular updates on the main articles and events in the area. There are many conferences dealing with cryptographic issues, see [38] for a good list; those conferences sponsored by the IACR are regarded in the field as being of top quality, though good conferences are not limited to IACR sponsored events. The *Journal of Cryptology* and *IEEE Trans. Inform. Theory* publish excellent papers in the area; *Designs, Codes and Cryptography* is a well established source. New specialist journals that publish papers on group-based cryptography include the *Journal of Mathematical Cryptology* and *Groups-Complexity-Cryptography*. For information on group-based schemes based on combinatorial group theory in particular, we would encourage the reader to consult the textbook of Myasnikov et al. [61].

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