

New Cryptosystems From CSP-Based Self-Distributive Systems

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Abstract. We propose new cryptosystems based on self-distributive systems that are defined over conjugate operations on noncommutative groups. Under certain assumptions, our basic scheme is proven to be indistinguishable against chosen plaintext attacks (IND-CPA), and the extend version is IND-CCA secure. When braid groups are taken into consideration, we derive a new braid-based encryption scheme that is directly based on the intractability assumption of the conjugator search problem in braid groups. Furthermore, we quote an analysis to manifest that our proposal has the potential to resist currently known quantum attacks.

Keywords: Self-distributive systems, provable security, braid groups, resistance to quantum attacks

1 Introduction

Most public-key cryptosystems that remain unbroken are based on the perceived difficulty of solving certain problems in large finite (abelian) groups. The theoretical foundations of these cryptosystems are related to the intractability of problems that are *closer to* number theory *than to* group theory [MST02]. In a quantum computer, most of these problems on number theory can be efficiently solved by using algorithms developed by Shor [Sho97], Kitaev [Kit95] and Proos-Zalka [PZ03]. Although quantum computing is still in its infancy, knowledge regarding their potential will soon create distrust in the current cryptographic methods [Lee04]. In order to enrich cryptography and not to put all eggs in one basket [Lee04], many attempts have been made to develop alternative public-key cryptography (PKC) based on different kinds of problems [AAG99, KLCH00, Lee04, MST02].

Under this background, some non-abelian groups gained considerable attention. One of the most popular groups in this category is the braid group. In 1999, Anshel et al. [AAG99] proposed an algebraic method for PKC. Owing to their pioneering work, braid groups gained attention in the field of modern cryptography. Shortly afterward, Ko et al. [KLCH00] published a fully fledged braid-based encryption scheme using braid groups. The security of this scheme is based on the so-called Diffie-Hellman like conjugacy problem (DHCP), which can be viewed as a *weaker* variant of the conjugator search problem (CSP). Unfortunately, Cha et al.'s algorithm [CJ03] announced the broken of Ko et al.'s braid-based encryption. After then, finding new braid-based encryption becomes an interesting challenge.

Beyond to give a direct answer for the above challenge, in this study, we propose new cryptosystems from CSP-based self-distributive systems. Our proposal is suite for arbitrary noncommutative

group G , providing that the intractability assumption of CSP in G holds. Under a further assumption, we proved that our basic scheme is indistinguishable against chosen plaintext attacks (IND-CPA). This scheme can also be converted to an IND-CCA secure one by employing the Canetti-Halevi-Katz transformation technique [CHK04]. When G is instantiated with the braid group B_n for example, we can immediately derive a new braid-based encryption scheme that is directly based on the intractability of CSP. At the time of this writing, no deterministic polynomial-time algorithm for solving CSP in braid groups has been reported yet [SU08] (cf. Section 4.4). Moreover, we quote some detailed analysis in [WWC⁺10] to argue that the resulted braid-based encryption is secure to resist currently known quantum attacks (cf. Section 4.5).

Frankly, our originality is rooted in Dehornoy’s previous work. In 2006, Dehornoy [Deh06] proposed an authentication scheme based on self-distributive systems in braid groups. Although some cryptanalysis on Dehornoy’s authentication scheme were reported [LU08], we find that Dehornoy’s work is still meaningful in at least the following two aspects: First, self-distributive systems can be defined over arbitrary noncommutative groups, rather than braid groups only; Second, self-distributive systems have the potential for building other cryptographic schemes, rather than authentication schemes only.

The rest of contents are organized as follows: In Section 2, we give a review on the concept of self-distributive system and the related assumption; In Section 3, we develop a lot of properties for a CSP-based self-distributive system that was suggested by Dehornoy; Based on these newly developed properties, a Diffie-Hellman like key agreement protocol, an ElGamal like encryption scheme and its CCA-secure extension are proposed in Section 4; Meanwhile, the provable security theorem, the efficiency, and other related issues are also provide. Concluding remarks are given in Section 5. Related proofs are arranged in Appendixes.

2 Left Self-Distributive System and the One-Wayness Assumption

Suppose S be a non-empty set, and $F : S \times S \rightarrow S$ a well-defined function. If the following rewrite formula holds,

$$F_r(F_s(p)) = F_{F_r(s)}(F_r(p)), \quad (\forall p, r, s \in S) \quad (1)$$

then we call $F(\cdot)$ a *left self-distributive system*, abbreviated as LD system (See [Deh06]). The terminology “left self-distributive” arises from the following analogical observation: If we consider $F_r(s)$ as a binary operation $r * s$, then the formula (1) becomes

$$r * (s * p) = (r * s) * (r * p), \quad (2)$$

i.e., the operation “ $*$ ” is left distributive with respect to itself.

If the LD system $F(\cdot)$ defined as (1) possesses the following one-wayness property [Deh06], it is useful for designing cryptographic protocols: It is hard to retrieve s from the pair $(p, F_s(p))$.

3 CSP-based Left Self-Distributive System and Properties

In his seminal paper, Dehornoy[Deh06] defined a non-trivial left self-distributive systems based on conjugate operation over braid groups. If we define a binary function F as follows,

$$F : B_n \times B_n \rightarrow B_n, \quad (a, b) \mapsto aba^{-1}, \quad (3)$$

and denote $F(a, b)$ by $F_a(b)$, then, we can see that F caters to the definition of the formula (1). Moreover, under the intractability assumption of conjugator search problem (CSP), this LD system is one-way, i.e., it is hard to find s for given $(p, F_s(p) = sps^{-1})$, where $s, p \in B_n$.

We have developed some properties of CSP-based LD systems. These properties should be useful from a cryptographic perspective.

Proposition 1. *Suppose F be a CSP-based LD system defined over a noncommutative group G . Then, for arbitrary $a, b, c \in G$, F satisfies the following properties:*

- (1) F is idempotent in the sense of $F_a(a) = a$;
- (2) F is mutual inverse in the sense of $F_a(b) = c \Leftrightarrow F_{a^{-1}}(c) = b$;
- (3) F is homomorphic in the sense of $F_a(bc) = F_a(b)F_a(c)$;
- (4) F is self-reflective in the sense of $F_a(b) = F_a^{-1}(b^{-1})$.

Proof. See Appendix A.

Combining all above properties together, we obtained a new property, named as *power law*, for CSP-based left self-distributive systems.

Proposition 2 (Power Law of CSP-based LD Systems). *Suppose F be a CSP-based left self-distributive system defined over a noncommutative group G . Then, for arbitrary three integers m, s, t such that $m = s + t$, we have*

$$F_a(b^m) = F_a^m(b) \quad \text{and} \quad F_{a^m}(b) = F_a(F_{a^{m-1}}(b)) = F_{a^{m-1}}(F_a(b)) = F_{a^s}(F_{a^t}(b)). \quad (4)$$

Proof. Obviously.

4 Cryptosystems from CSP-based Left Self-Distributive Systems

The power law of CSP-based LD system immediately implies a Diffie-Hellman-like key agreement protocol, which in turn implies an ElGamal-like encryption scheme. Of course, certain cryptographic assumptions and some computational issues should be taken into consideration.

4.1 Basic Ideas

Suppose F be a CSP-based left self-distributive system defined over a noncommutative group G . Let $a, b \in G$ be two public elements. Assume that Alice and Bob want to negotiate a common session key. Then, Alice (Bob) picks at random an integer s (t) (Please refer [GPV08] for exact meaning of sampling an integer from an infinite space) and then sends $F_{a^s}(b)$ ($F_{a^t}(b)$) to Bob (Alice). Finally, both of them can compute $F_{a^{s+t}}(b)$, by which a session key can be defined as

$$K_{session} = Kdf(F_{a^{s+t}}(b)), \quad (5)$$

where $Kdf(\cdot)$ is a key derivation function, such as KDF1 defined in IEEE Std 1363-2000.

The above interactive is a natural analogy of Diffie-Hellman key agreement protocol. Similarly, we can define the following encryption scheme (denoted by CSP-ElG1) that is an analogy of ElGamal cryptosystem:

- **Setup.** Picks $a, b \in G$ and publishes them as the system parameters.
- **KeyGen.** Picks an integer $s \in \mathbb{Z}$ at random. The public key is $pk = F_{a^s}(b)$, while the secret key is $sk = s$.
- **Enc.** Picks an integer $t \in \mathbb{Z}$ at random, the ciphertext on a message $m \in G$ is

$$c = (F_{a^t}(b), mF_{a^t}(pk)),$$

- **Dec.** $m = c_2 F_{a^s}^{-1}(c_1)$.

Under certain assumptions (discussed later), the above scheme is IND-CPA secure. It is easy to derive a CCS secure encryption scheme (denoted by CSP-ElG2) by employing the Canetti-Halevi-Katz transformation technique [CHK04]:

- **Setup.** Picks $a, b \in G$ and publishes them as the system parameters.
- **KeyGen.** Picks an integer $s \in \mathbb{Z}$ at random. The public key is $pk = F_{a^s}(b)$, while the secret key is $sk = s$.
- **Enc.** Picks $r \in \{0, 1\}^{k_1}$ at random, then the ciphertext on $m \in \{0, 1\}^k$ is

$$c = (F_{a^t}(b), t \oplus H(F_{a^t}(pk))),$$

where $t = (m||r)_2$ is the binary concatenation of m and r , while $H : G \rightarrow \{0, 1\}^{k+k_1}$ is a collision-resistant hash function.

- **Dec.** Computes $m' || r' = c_2 \oplus H(F_{a^s}(c_1))$, then outputs m' if $c_1 = F_{a^{(m' || r')_2}}(b)$ and \perp otherwise.

4.2 Security Requirements and Cryptographic Assumptions

Similar to the decisional Diffie-Hellman (DDH) assumption for ElGamal cryptosystem, we have to lay the security of the scheme described in the above subsection on the following assumption (denoted by CSP-DDH) over the underlying noncommutative group G : For arbitrary $a, b \in G \setminus \{1_G\}$, it is hard to distinguish the distributions

$$D_{a,b} = \{(F_{a^i}(b), F_{a^j}(b), F_{a^{i+j}}(b)) \in G^3 : i, j \xleftarrow{\$} \mathbb{Z}\},$$

and

$$\tilde{D}_{a,b} = \{(F_{a^i}(b), F_{a^j}(b), F_{a^k}(b)) \in G^3 : i, j, k \xleftarrow{\$} \mathbb{Z}\},$$

where 1_G is the identity of G , and the symbol “ $\xleftarrow{\$} \mathbb{Z}$ ” indicates the integer sampling algorithm **SampleD** defined in [GPV08].

Theorem 1. *Based on the CSP-DDH assumption, the encryption scheme CSP-ElG1 is indistinguishable against chosen plaintext attacks in the standard model.*

Proof. See Appendix B.

Theorem 2. *Based on the CSP-DDH assumption, the encryption scheme CSP-ElG2, in which H can be instantiated by arbitrary collision-resistant hash functions, is indistinguishable against chosen ciphertext attacks in the standard model.*

Proof. This is implied directly by Theorem 1 in this paper and Theorem 3 in [CHK04].

4.3 Efficiency for Computing and Representing $F_{a^t}(b)$

For computing $F_{a^t}(b)$, we should at first compute a^t , and then plus one inversion and two multiplications. Then, when t is large, say several hundreds of digits, rather than to multiply a t times, a similar successive doubling method should be employed, and thus a factor of $\log t$ would be introduced in the following performance evaluation. At present, it is enough to set t as an integer with 128 bits to resist exhaustive attacks.

It is necessary to assume that the basic group operation, i.e., multiplication of two elements, can be finished efficiently. This assume implies the lengths of the representations of all elements in G , including a, b, a^t and $F_{a^t}(b)$, should be polynomial in the system security parameters. Otherwise, the computation of a^t and $F_{a^t}(b)$ are impossible to be finished in polynomial time, since the results have to be output bit-by-bit by using classical computers.

4.4 Potential Implementations and Evaluations

Now, let us proceed to give an implementations on our proposal by using braid groups.

Intractability of CSP in braid groups. Although some algorithms for solving CSP in braid groups were proposed [EH94,GM02,FGM03,Geb05], none of them has ever been proven in polynomial time (with respect to the braid index n). As far as we know, Gebhardt’s algorithm [Geb05], which was proposed in 2003 but formally published in 2005, is the most efficient method for solving CSP in braid groups. The algorithm has not been proven to be polynomial-time, yet. After then, CSP in braid groups is classified for further study. According to Garber’s report [Gar07], at present we can merely solve CSP for periodic braids within polynomial time. From ultimate solutions for CSP in braid groups, we are still facing two kinds of challenges: one is how to solve CSP for rigid braids within polynomial time, and the other is how to find polynomial boundaries for Gebhardt’s method. (Please see [BGGM07a,BGGM07b,BGGM08] for more details.) According to [Deh04] and

[KLT08], most of known attacks against braid-based cryptosystems take advantage of the way the keys are generated, rather than solve CSP itself. So in ref. [KLT08], Ko et al. also proposed some new methods for generating hard CSP instances for braid cryptography. According to Shpilrain’s latest claim in [SU08], there is no deterministic polynomial-time algorithm for solving CSP in braid groups up to 2008. This give us certain confidence for using braid groups as the platform to implement our proposal. Especially in Section 4.5, we will quote an detailed analysis on the capability of our proposal in resiting currently known quantum attacks.

Parameter Suggestion. Note that the braid group B_n is infinite, and it is not convenient to work with an infinite group. So in practice, we always choose two positive integers n and l as the system parameters, and assume that all the braids involved in our schemes are randomly chosen from the following finite subset [KCCL02]

$$B_n(l) = \{b \in B_n | \ell(b) \leq l\} \subseteq B_n, \quad (6)$$

where $\ell(b)$ is the canonical length of b . According to ref. [KCCL02], $|B_n(l)| \leq (\lfloor \frac{n-1}{2} \rfloor!)^l$. Further, if the keys are selected properly, say by employing Ko et al.’s method [KLT08], then according to Maffre’s suggestion [Maf06], it is enough to set $n = 50$ and $l = 10$ to resist all known classical attacks.

Ciphertext Expansion. Apparently, in the CPA-secure scheme CSP-ElG1, the length of the ciphertexts is double of the length of the message to be encrypted, exactly the same situation of ElGamal cryptosystems. As for the CCA-secure extension CSP-ElG2, the ciphertext expansion factor is $(k + k_1 + \iota(G))/k$, where $\iota(G)$ indicates the length of the bit-string for representing an element in G . If G is finite, say Z_N , then in general we can assume $\iota(G) = \log |G|$. Now, new problems arise:

- First, when $\iota(G)$ is fixed, the expansion factor of the CSP-ElG2 scheme could be strictly less than 2 for sufficient large k . This in turn suggests that our CCA construction might be more efficient than our CPA construction. What is the expense for achieving this? Our answer is: computation cost. When k increase, $t = (m||r)_2$ also increase, leading to the incensement of the cost for computing a^t . Of course, when k increase *linearly*, the computation cost merely increase by a *logarithmic* factor. We must claim that this promising property *should not* be credited to ourselves. Instead, this contribution is rooted in the CHK transformation technique.
- Second, when G is infinite, what is $\iota(G)$? In fact, we never need to represent infinite elements in our proposal. We just need to represent the involved elements. For example, if G is instantiated with B_n and the canonical length of all involved braids are bounded by l , then a braid in $B_n(l)$ (cf. the previous subsection) can be represented by by a bit string of size $\iota(B_n(l)) = ln \log n$ [KLCH00,CKL⁺01].

Performance. Combining the above discussions together, let us give a performance evaluation on our proposal. Let us merely focus on braid groups, since for arbitrary group G , we have no method to evaluate the complexity of group operations, such as multiplication, inversion, etc.

According to refs. [CKL⁺01] and [Maf06], the complexities of the braid operations such as multiplication, inversion, canonical form computation, etc., are bounded by $\mathcal{O}(l^2 n \log n)$ in the sense of bit operations, where n and l are the braid index and the canonical length of involved braids, respectively. Then, taking CSP-ElG1 for example and combining the issues discussed in Section 4.3, the complexity for encryption and decryption can be concluded in Table 1.

Table 1. Computation Cost of CSP-ElG1

	Comp. content	Comp. cost	Explanation
Enc	a^t	$\log t \cdot l^2 n \log n$	successive doubling
	a^{-t}	$l^2 n \log n$	1 inversion
	$c_1 = F_{a^t}(b)$	$2 \cdot l^2 n \log n$	2 multiplications
	$c_2 = m F_{a^t}(pk)$	$3 \cdot l^2 n \log n$	3 multiplications
Dec	a^s	$\log s \cdot l^2 n \log n$	successive doubling, pre-computing
	a^{-s}	$l^2 n \log n$	1 inversion, pre-computing
	$m = c_2 F_{a^s}^{-1}(c_1)$	$4 \cdot l^2 n \log n$	3 multiplications, 1 inversion

Now, if we neglect small constant factors and the cost for pre-computations, then the encryption and decryption of the scheme CSP-ElG1 can be finished with the complexities of $\mathcal{O}(\log t \cdot l^2 n \log n)$ and $\mathcal{O}(l^2 n \log n)$, respectively. When $\log t \leq 128 = 2^7$ (cf. Section 4.3) and Maffre's suggestion [Maf06] is adopted (i.e., $n = 50$ and $l = 10$), the encryption can be implemented in $\mathcal{O}(2^{22})$ bit operations, while the decryption merely needs $\mathcal{O}(2^{15})$ bit operations. We know that at present, the modulus of a secure RSA cryptosystem should be at least 1024 bits. Then, the complexity of modular exponential operation is about $\mathcal{O}(2^{30})$. This suggests that our proposal is much efficient than RSA cryptosystem.

4.5 Can we efficiently solve CSP in braid groups by using quantum computers?

The content in this subsection was partially contained in ref. [WWC⁺10]. However, the literature [WWC⁺10] has not been published, yet. Thus, we would like to restate the related materials to support the corresponding claims in this paper.

The known quantum algorithms are roughly divided into two types, namely hidden subgroup algorithms and amplitude amplification algorithms [Röt06]. The latter can merely obtain polynomial speed-up ratios as compared to classical algorithms, while the former deals with the so-called hidden subgroup problem (HSP) and has the promise to obtain exponential speed-up ratios [Röt06]. In the HSP, one is given a black-box function $f : G \rightarrow S$ from a group G to a set S with the promise that there exists a subgroup $H \subseteq G$ such that f is constant on the cosets of H and takes distinct values for different cosets. The task is to determine H , or equivalently, to find a set of generators of H by making the minimum possible queries to f [Röt06]. HSP provides a unified framework to study problems of group theoretical nature. We have already obtained efficient solutions of the HSP for any abelian group [Kit95, Sho97, KNP07] and for some non-abelian groups [FIM⁺03, BCvD05b, BCvD05a, Bac06, KR08]. Thus, a natural question arises: Can we efficiently solve

the conjugator searching problem (CSP) by using quantum computers? This is partially equivalent to answering all of the following three sub-problems:

- (1) Can we model CSP by using the framework of HSP?
- (2) Can we solve the HSP obtained in (1) quantumly?
- (3) Can we implement the algorithm obtained in (2) efficiently in terms of elementary quantum gates?

In spite of conducting an extensive investigation on the available literatures about HSP, including surveys [Joz01,LJK02,Lom04,Röt06] and some newly proposed but not formally published results such as those mentioned in refs. [MRV07], [KR08], and [DMR09], we could not find any answers for (1), (2) or (3). Here, we present three speculations that may partially provide negative answers for the aforementioned subproblems:

- First, we have no evident solution for (1) at present. The solution (space) for a given CSP instance is not a subgroup of B_n . To understand this, we should note the following facts: (1) the identity, i.e., the empty braid, which cannot conjugate a braid x to another different braid y , is not a solution for any nontrivial CSP instance; and (2) if a braid z is a solution for some CSP instance $(x, y) \in B_n^2$, then z^2 is not necessarily a solution for (x, y) . Otherwise, we must have $z^{-1}yz = y$, which is not true in general. The simplest counterexample is $\sigma_1^{-1}\sigma_2\sigma_1 \neq \sigma_2$.
- Second, supposing (1) is solved, we still have no easy solution for (2) at present. The standard approach of a quantum algorithm for HSP is to use the oracle f to create coset states $\rho_H = \frac{1}{|G|} \sum_{z \in G} |zH\rangle\langle zH|$, where $|zH\rangle = \frac{1}{\sqrt{|H|}} \sum_{h \in H} |zh\rangle$ [DMR09]. This means that $|G|$ and $|H|$ should be finite, and thus the standard approach cannot be directly used for braid group B_n , considering $|B_n| = \infty$. (This is probably the reason because of which Shor [Sho97] worked with a finite additive cyclic group \mathbb{Z}_Q of order $Q = 2^m$ with $N^2 \leq Q < 2N^2$, where N is an integer to be factored [LJK02].) At present, we do not know how to create “coset states” in a braid group, taking into account the fact that we do not know how to define a modular operation for braids.
- Third, supposing (2) is solved, we might face new challenges in solving (3). The (quantum computational) progress on HSP in the symmetric group S_n is rather limited and so far dominated by negative results [Röt06]. It has been shown [GSVV04] that exponentially many repetitions of quantum Fourier sampling are necessary for obtaining a non-negligible probability of distinguishing between the cases $|H| = 2$ and $|H| = 1$ (where $H \subseteq S_n$). Recently, Moore et al. [MRV07,DMR09] speculated that HSP in the groups that contain the symmetric group S_n as a subgroup may be resistant to all known quantum techniques. Although S_n is not a subgroup of the braid group B_n , there is a one-to-one correspondence between the set of the permutation braids in B_n and the set of the permutations in S_n . This suggest that there might exist some HSP instances in braid groups to be intractable even by using all known quantum techniques.

In summary, the currently known quantum technique cannot break the one-wayness of the left self-distributive system based on the intractability assumption of CSP in braid groups.

We claim again that the analysis in this subsection is not our contribution. But we need to quote it in this paper for supporting the claimed advantages of our proposal.

5 Conclusion

Although CSP-based LD systems over any noncommutative groups are non-trivial, only those based on a noncommutative group with the intractability assumption of CSP are suitable for our proposal. Since the braid group is an example, even if we finally found that CSP in braid groups were tractable, CSP-based LD systems still possess their potential values in cryptography. In particular, the general linear group of degree n , i.e., the set of $n \times n$ invertible matrices, or more specially, the $GL_n(\mathbb{Z}_2)$ can be taken into account. Considering that multiplications over 0-1 matrices can be implemented much efficiently, and these matrices have a tight relation with certain lattice problems, it seems very promising to implement our proposal in $GL_n(\mathbb{Z}_2)$.

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A Proof of Proposition 1

Proof. Suppose F be a CSP-based LD system defined over noncommutative group G . Then, for arbitrary $a, b, c \in G$, we have that

- Property 1: Idempotent. Since $aaa^{-1} = a$, i.e., a will remain unchanged when it conjugates to itself. By using the notation as in the formula (1), we have $F_a(a) = a$.
- Property 2: Mutual inverse. According to the definition of F (cf. (3)), we have

$$\begin{aligned} F_a(b) = c &\Leftrightarrow c = aba^{-1} \\ &\Leftrightarrow a^{-1}ca = b \\ &\Leftrightarrow F_{a^{-1}}(c) = b. \end{aligned}$$

- Property 3: Homomorphic.

$$\begin{aligned} F_a(bc) &= a(bc)a^{-1} \\ &= (aba^{-1})(aca^{-1}) \\ &= F_a(b)F_a(c). \end{aligned}$$

- Property 4: Self-reflective.

$$\begin{aligned} F_a(b) &= aba^{-1} \\ &= (ab^{-1}a^{-1})^{-1} \\ &= (F_a(b^{-1}))^{-1} \\ &\triangleq F_a^{-1}(b^{-1}). \end{aligned}$$

This concludes the proposition. □

B Proof of Theorem 1

Proof. The proof for this theorem can be easily sketched in imitation of Jao’s[Jao08] proof for the IND-CPA security of ElGamal scheme. Of course, special cautiousness should be taken into consideration since we now work with a noncommutative group G . Assume that the CSP-DDH assumption holds for the underlying noncommutative group G . We will prove by contradiction that CSP-ElG1 is IND-CPA. Suppose that CSP-ElG1 is not IND-CPA, and let \mathcal{A} be an algorithm which, on the system parameters $a, b \in G$ and a random public key $F_{a^s}(b)$, has probability non-negligibly greater than $1/2$ of distinguishing random encryptions $Enc(m_0)$ and $Enc(m_1)$ of two messages m_0, m_1 of its choice. Let $(F_{a^s}(b), F_{a^t}(b), F_{a^u}(b)) \in G^3$ be either a random CSP-DDH triple or a random triple, with equal probability. We will produce an algorithm \mathcal{B} which can distinguish between the two cases, using \mathcal{A} as an oracle, with probability close to 1. (This result is stronger than what we need to prove.) The algorithm \mathcal{B} picks two random integers v, w and constructs the triple of group elements

$$T = (F_{a^{s+v}}(b), F_{a^{t+w}}(b), F_{a^{u+v+w}}(b)),$$

which is easy to do since \mathcal{B} knows $F_{a^s}(b), F_{a^t}(b), F_{a^u}(b), a, b, v$ and w . The algorithm \mathcal{B} then calls \mathcal{A} with the public key $F_{a^{s+v}}(b)$, which is guaranteed to be random since v is chosen randomly. Afterwards, the algorithm \mathcal{A} selects two messages $m_0, m_1 \in G$, and \mathcal{B} replies with the ciphertext $c_\beta^* = (F_{a^{t+w}}(b), m_\beta \cdot F_{a^{u+v+w}}(b))$ for randomly picked $\beta \in \{0, 1\}$. There are now two cases to consider.

1. Suppose that $u = s + t$. Then $u + v + w = (s + v) + (t + w)$, so T is a CSP-DDH triple. Moreover, all possible CSP-DDH triples w.r.t. (a, b) are equally likely to occur as T , since v and w are random. Therefore c_β^* is a valid random encryption of m_β (random since $F_{a^{t+w}}(b)$ is a random group element). Under these conditions, the algorithm \mathcal{A} by hypothesis will succeed in outputting β with probability exceeding $1/2$ by a non-negligible quantity.
2. Suppose that u is random. Then T is a random triple of group elements, and all possible triples of group elements occur with equal probability. In this situation, the probability distribution of c_0^* is *identical* to that of c_1^* , over all possible random choices of v and w . It follows that the algorithm \mathcal{A} cannot exhibit different behavior for $\beta = 0$ and $\beta = 1$. Note that we can arrive at this conclusion even though the expression c_β^* is an invalid encryption of m_β —that is, even though we have no information about how \mathcal{A} behaves on invalid inputs, we know for certain that \mathcal{A} cannot behave differently depending on the value of β .

The above analysis reveals that if $(F_{a^s}(b), F_{a^t}(b), F_{a^u}(b))$ is a CSP-DDH triple then \mathcal{A} with non-negligible probability exhibits different behavior depending on whether $\beta = 0$ or $\beta = 1$, whereas if $(F_{a^s}(b), F_{a^t}(b), F_{a^u}(b))$ is not a CSP-DDH triple then \mathcal{A} must behave identically regardless of the value of β . Hence, by repeating this process with several different choices of random integers v, w , the algorithm \mathcal{B} can determine with high probability whether or not \mathcal{A} can determine the value of β . In this way \mathcal{B} can determine whether or not $(F_{a^s}(b), F_{a^t}(b), F_{a^u}(b))$ is a CSP-DDH triple, thus violating the CSP-DDH assumption for G . \square