On the Isogeny Problem with Torsion Point Information

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Abstract. It has recently been rigorously proven (and was previously known relying on certain heuristics) that the general supersingular isogeny problem reduces to the supersingular endomorphism ring computation problem. However, in order to attack SIDH-type schemes, one requires a particular isogeny which is usually not returned by the general reduction. At Asiacrypt 2016, Galbraith, Petit, Shani and Ti presented a polynomial-time reduction of the problem of finding the secret isogeny in SIDH to the problem of computing the endomorphism ring of a supersingular elliptic curve. Their method exploits the fact that secret isogenies in SIDH are of degree approximately $p^{1/2}$. The method does not extend to other SIDH-type schemes, where secret isogenies of larger degree are used and this condition is not fulfilled.

We present a more general reduction algorithm that generalises to all SIDH-type schemes. The main idea of our algorithm is to exploit available torsion point images together with the KLPT algorithm to obtain a linear system of equations over a certain residue class ring. We show that this system will have a unique solution that can be lifted to the integers if some mild conditions on the parameters are satisfied. This lift then yields the secret isogeny. One consequence of this work is that the choice of the prime p in B-SIDH is tight.

Keywords: post-quantum · isogeny-based cryptography · supersingular isogenies · endomorphism rings · SIDH

1 Introduction

Practical large scale quantum computers pose a threat to most cryptosystems currently in use [13, 27]. Recent advances in quantum computing and the need for long-term security in cryptography has led to a surge of interest in developing quantum secure replacements for these classical cryptographic algorithms. Moreover, NIST has started a procedure to determine new cryptographic standards for a post-quantum era [22].

Most of the standardisation candidates are based on lattices, codes or multivariate polynomial systems over finite fields. A more recent but promising area of post-quantum research is isogeny-based cryptography.

Couveignes was the first one to mention isogenies for cryptographic use in 1997 [6], and the area gained traction in the following decade with new developments such as collision-resistant hashing [3] and key exchange [26, 29] based on isogeny problems. After Jao and De Feo introduced supersingular isogeny Diffie-Hellman (SIDH) [15], a predecessor of the isogeny-based submission to NIST's standardisation procedure SIKE [14], the area has enjoyed increasing popularity.

The central problem in most of isogeny-based cryptography is to find an isogeny $\varphi : E_1 \to E_2$, i.e. a morphism both in the sense of algebraic geometry and group theory, between two given supersingular elliptic curves defined over a finite field $\mathbb{F}_q$. For two supersingular elliptic curves E_1 and E_2, the problem of computing an arbitrary isogeny between them and the problem of computing their endomorphism rings $\mathrm{End}(E_1)$ and $\mathrm{End}(E_2)$ was recently proven to be equivalent under the assumption that the generalized Riemann hypothesis (GRH) holds by Wesolowski [34]. Yet, in the case where E_1 and E_2 are ordinary curves, it is usually much easier to determine $\mathrm{End}(E_i)$ of an arbitrary E_i than computing an isogeny between two arbitrary curves [19].

There are infinitely many isogenies $E_1 \to E_2$, but attacking isogeny-based primitives such as SIDH requires to recover an isogeny $\varphi : E_1 \to E_2$ of a specific degree. Generic algorithms are unlikely to return an isogeny of the correct degree given the endomorphism rings. In Section 4 of [12], it is shown how to recover secret isogenies in the case of SIDH. The attack exploits the observation that secret isogenies in SIDH are of degree $p^{1/2}$, which is relatively small. In the case where the isogeny one wishes to recover is not of particularly small degree, as is the case in B-SIDH [5], SÉTA [8] or instantiations of SIDH with secret isogenies of larger degree, this observation no longer holds and the algorithm due to Galbraith et al. no longer applies.

Our contributions. Assuming the generalized Riemann hypothesis, this paper provides a polynomial-time (in $\log p$) algorithm that recovers an isogeny with certain torsion point images between two supersingular elliptic curves of a specific degree N_1, given their endomorphism rings and some torsion point images under the isogeny. More precisely, let d be the least degree of any isogeny between two isogenous supersingular elliptic curves E_1 and E_2. Then, our algorithm solves the following problem, whenever $N_1 < dN_2/16$.

Task 1.1. *Let N_1, N_2 be coprime integers and let $\varphi : E_1 \to E_2$ be a secret isogeny of degree N_1 between two supersingular elliptic curves. Let P_B, Q_B be a basis of $E_1[N_2]$. Given End(E_1), End(E_2), $\varphi(P_B)$, and $\varphi(Q_B)$, find an isogeny $\varphi' : E_1 \to E_2$ of degree N_1 such that $\varphi_{|E_1[N_2]} = \varphi'_{|E_1[N_2]}$.*

Since SIDH-type schemes such as B-SIDH tend to use balanced parameters, where $N_1 \approx N_2$, the condition that $N_1 < dN_2/16$ is very mild.

The main idea behind the algorithm is the following. Isogenies from E_1 to E_2 form a $\mathbb{Z}$-module M of rank 4. A basis of M can be computed using an algorithm due to Kirschmer and Voight [17] (or the KLPT algorithm [18]). Then, one computes an LLL-reduced basis $\psi_1, \psi_2, \psi_3, \psi_4$ of M. We show how to evaluate $\psi_i(P_B)$, $\psi_i(Q_B)$ for $i = 1, \ldots, 4$ and we are given $\phi(P_B)$ and $\phi(Q_B)$.

Since $\phi = x_1\psi_1 + x_2\psi_2 + x_3\psi_3 + x_4\psi_4$ for some $x_i \in \mathbb{Z}$, this yields 4 linear equations in 4 variables, x_1, x_2, x_3, x_4, modulo N_2 (torsion-point images can be represented by a 2×2 matrix with entries from $\mathbb{Z}/N_2\mathbb{Z}$ and each entry corresponds to an equation). We will show that this system of equations has a unique solution for x_i modulo N_2 which we also compute. Since the ψ_i form an LLL-reduced basis, we can bound the absolute value of the coefficients x_i by $N_2/2$ for $N_1 < dN_2/16$. This leads to a solution for $x_i \in \mathbb{Z}$.

The contribution of this paper can be seen as an extension of the reductions by Kohel, Lauter, Petit, and Tignol [18] and Wesolowski [34] which allow to compute an isogeny (of no specific degree) between two supersingular elliptic curves, whenever the endomorphism rings of the curves are known. Note that Kohel et al. provide a heuristic polynomial-time algorithm for this reduction, whereas Wesolowski shows that this reduction works in polynomial-time in general assuming only GRH.

Together with known results on the computation of endomorphism rings, a consequence of this work is an answer to the open question how small the size of the prime p in B-SIDH can be chosen. More precisely, this work implies that one cannot lower the size of the prime p in B-SIDH significantly, while maintaining the same security level. Current parameter sets are not threatened because parameters were selected in a cautious way (i.e., were larger than necessary if one only accounted for existing attacks). Our algorithm has a similar classical runtime to a generic meet-in-the-middle algorithm but is essentially memory-free whereas meet-in-the-middle requires an exponential amount of memory. Furthermore, the quantum version of our attack has a much better runtime than previously known quantum attacks ($O(p^{1/4})$ [10] compared to $O(p^{1/2})$ [16]), where the authors showed that the Tani's claw algorithm has better complexity quantumly, but suffers from quantum storage issues. The running time of our algorithms is dominated by the computation of the endomorphism rings.

Outline. In Section 2, we recall some necessary mathematical background, details of the SIDH key exchange as well as some related work. In Section 3, we give algorithms to evaluate non-smooth degree isogenies and to compute an isogeny of a specific degree between two supersingular elliptic curves with known endomorphism ring, if certain torsion point information is available. Moreover, we discuss the impact of this work on isogeny-based cryptography before concluding the paper in Section 5.

2 Preliminaries

In this section, we recall some relevant background on elliptic curves and isogeny-based cryptography. For further introductory reading, we refer to Silverman [28] and De Feo [7] respectively. Furthermore, we briefly recall some consequences of the KLPT algorithm [18] and the LLL lattice reduction [20]. Moreover, we sketch a related algorithm due to Galbraith et al. [12] which computes an isogeny of specific degree between two supersingular elliptic curves with known endomorphism ring, if this degree is sufficiently small.

2.1 Elliptic curves and isogenies

Let E_1, E_2 be elliptic curves defined over a field K. An isogeny between E_1 and E_2 is a non-constant rational map which is also a group homomorphism (or equivalently, fixes the point at infinity). The *degree* of an isogeny is its degree as a finite map of curves, i.e. the degree of the extension of function fields. An isogeny is called *separable* if the corresponding field extension is separable. For a separable isogeny, the degree equals the size of its kernel. Furthermore, for every finite subgroup G of an elliptic curve E, there exists a separable isogeny whose kernel is G. Up to post-composition with an isomorphism, the isogeny is unique. We denote the codomain of this isogeny by E/G. Given a finite subgroup $G \subset E$ the corresponding isogeny from E to E/G can be computed using Vélu's formulae [32].

Let $\phi : E_1 \to E_2$ be an isogeny of degree d. Then there exists a unique isogeny $\hat{\phi}$ with the property that $\phi \circ \hat{\phi} = [d]$, where $[d]$ denotes the multiplication by d. This isogeny $\hat{\phi}$ is called the *dual* of ϕ and it is also of degree d. An isogeny from E to itself is called an *endomorphism*. Together with the zero map, endomorphisms of E form a ring under addition and composition denoted by $\mathrm{End}(E)$.

Let E be defined over a finite field of characteristic p. Then $\mathrm{End}(E)$ is either an order in an imaginary quadratic field and E is called *ordinary*, or a maximal order in the rational quaternion algebra $B_{p,\infty}$ ramified at p and at infinity in which case E is called *supersingular*. For the rest of the paper we will restrict ourselves to supersingular elliptic curves.

For an elliptic curve $E : y^2 = x^3 + Ax + B$, its *j-invariant* is given by $j(E) = 1728\frac{4A^3}{4A^3+27B^2}$ and two curves are isomorphic over $\overline{K}$ if and only if they share the same j-invariant.

Example 2.1. For the supersingular elliptic curve $E_0 : y^2 = x^3 + x$ the above formula yields the j-invariant $j(E_0) = 1728$. It is well-known that $\mathrm{End}(E_0)$ is the $\mathbb{Z}$-module generated by $1, \iota, \frac{1+\pi}{2}$ and $\frac{\iota+\iota\pi}{2}$, where ι denotes E_0's non-trivial automorphism, $(x, y) \mapsto (-x, iy)$, and π is the Frobenius endomorphism, $(x, y) \mapsto (x^p, y^p)$.

Let ℓ be a prime number and define the supersingular ℓ-isogeny *graph* as follows. The vertices of the graph are isomorphism classes of supersingular elliptic curves represented by their j-invariant and two vertices are connected by an edge if and only if they are ℓ-isogenous. The supersingular ℓ-isogeny graph is connected, $(\ell + 1)$-regular and a Ramanujan expander graph. The diameter of the graph is between $\log p$ and $2 \log p$ [25, Theorem 1]. The presumed hardness of path-finding in this graph is the hardness assumption underlying isogeny-based cryptography.

Remark 2.2. In the rest of this paper we will call an integer smooth if its smoothness bound is polynomial in $\log p$ for a fixed p.

2.2 SIDH and B-SIDH

We give a brief description of SIDH [15] and B-SIDH [5] key exchanges.

The public parameters of SIDH are two coprime smooth numbers N_1 and N_2, a prime p of the form $p = N_1N_2f - 1$, where f is a small cofactor, and a supersingular elliptic curve E_0 defined over $\mathbb{F}_{p^2}$ together with points P_A, Q_A, P_B, Q_B such that $E_0[N_1] = \langle P_A, Q_A\rangle$ and $E_0[N_2] = \langle P_B, Q_B\rangle$.

The protocol proceeds as follows:

1. Alice chooses a random cyclic subgroup of $E_0[N_1]$ as $G_A = \langle P_A + [x_A]Q_A\rangle$ and Bob chooses a random cyclic subgroup of $E_0[N_2]$ as $G_B = \langle P_B+[x_B]Q_B\rangle$.
2. Alice and Bob compute the isogeny $\phi_A : E_0 \to E_0/\langle G_A\rangle =: E_A$ and the isogeny $\phi_B : E_0 \to E_0/\langle G_B\rangle =: E_B$, respectively.
3. Alice sends the curve E_A and the two points $\phi_A(P_B), \phi_A(Q_B)$ to Bob. Mutatis mutandis, Bob sends $\big(E_B, \phi_B(P_A), \phi_B(Q_A)\big)$ to Alice.
4. Alice and Bob use the given torsion points to obtain the shared secret $j(E_0/\langle G_A, G_B\rangle)$. To do so, Alice computes $\phi_B(G_A) = \phi_B(P_A) + [x_A]\phi_B(Q_A)$ and uses the fact that $E_0/\langle G_A, G_B\rangle \cong E_B/\langle\phi_B(G_A)\rangle$. Bob proceeds analogously.

In practice N_1 and N_2 are chosen to be powers of 2 and 3, respectively, to maximize the efficiency of the scheme. However, choosing a prime of the form $N_1N_2f - 1$ with $N_1 \approx N_2$ implies that the curves E_A, E_B are much closer at E_0 than the diameter of the supersingular isogeny graph, i.e. the paths connecting E_0 with E_A and E_B are shorter than one would expect for randomly chosen isogenous curves.

In order to avoid walking only in a small subgraph and to reduce the size of the prime p, Costello introduced the variant B-SIDH [5]. The main differences between SIDH and B-SIDH are

- N_1 and N_2 are smooth coprime divisors of $p - 1$ and $p + 1$ (or vice versa) respectively. Hence, $p + 1$ and $p - 1$ both need to have large smooth factors as opposed to just one of them in SIDH.
- For the best parameter choice, we have $N_1 \approx N_2 \approx p$ as opposed to $N_1 \approx N_2 \approx \sqrt{p}$ in SIDH.
- Kernel generators are a priori $\mathbb{F}_{p^4}$-rational as opposed to $\mathbb{F}_{p^2}$-rational.

In B-SIDH the curves E_0 and E_A are no longer closer than expected in the isogeny graph, but parameter selection might be harder and it seems at first to come at the expense of working over larger field extensions. However, to every supersingular elliptic curve E defined over $\mathbb{F}_{p^2}$, there exists a quadratic twist (i.e., a curve defined over $\mathbb{F}_{p^2}$ which is isomorphic to E over $\mathbb{F}_{p^4}$ but not over $\mathbb{F}_{p^2}$). If E has $(p+1)^2$ rational points over $\mathbb{F}_{p^2}$, then its twist has $(p-1)^2$ rational points over $\mathbb{F}_{p^2}$. Thus, when computing an isogeny of degree N_1 dividing $p+1$ one can work with the curves having $p + 1$ rational points, and before computing an isogeny of degree N_2 dividing $p-1$, one switches to twists that have $p-1$ rational points. Technically, the switch makes it possible to compute the isogenies using only operations over $\mathbb{F}_{p^2}$. For more details we refer to [5].

2.3 KLPT and LLL lattice reduction

In this subsection, we recall some facts about the Kohel-Lauter-Petit-Tignol (KLPT) algorithm [18] and the Lenstra-Lenstra-Lovász (LLL) lattice reduction [20].

Let $B_{p,\infty}$ be the quaternion algebra ramified at p and at infinity. Let $\mathcal{O}_1$ and $\mathcal{O}_2$ be maximal orders in $B_{p,\infty}$. Then the quaternion isogeny problem asks for a left ideal I connecting $\mathcal{O}_1$ and $\mathcal{O}_2$, i.e., a left ideal I of $\mathcal{O}_1$ which is also a right ideal of $\mathcal{O}_2$. By [18, Lemma 8], we have the following result.

Lemma 2.3. *Let $\mathcal{O}_1$ and $\mathcal{O}_2$ be maximal orders in $B_{p,\infty}$. Then the intersection $\mathcal{O}_1 \cap \mathcal{O}_2$ has the same index M in $\mathcal{O}_1$ and $\mathcal{O}_2$. Furthermore,*

$$I(\mathcal{O}_1, \mathcal{O}_2) = \{\alpha \in B_{p,\infty} \mid \alpha \mathcal{O}_2 \overline{\alpha} \subset M\mathcal{O}_1\}$$

is a left ideal of $\mathcal{O}_1$ and a right ideal of $\mathcal{O}_2$ of reduced norm M. $I(\mathcal{O}_1, \mathcal{O}_2)$ can be computed in polynomial time.

Lemma 2.3 shows that one can compute a connecting ideal between two maximal orders efficiently. However, this ideal will not have smooth norm in general. In [18], the main algorithm shows how to compute an equivalent left ideal of $\mathcal{O}_1$ of norm ℓ^k where ℓ is some small prime number.

Let E_1, E_2 be supersingular elliptic curves with endomorphism rings $\mathcal{O}_1$ and $\mathcal{O}_2$ respectively. Then the set of isogenies from E_1 to E_2 is a left $\mathcal{O}_1$-module and a right $\mathcal{O}_2$-module. In particular, they form a $\mathbb{Z}$-lattice of rank 4 [33, Lemma 42.1.11]. The $\mathbb{Z}$-lattice is isomorphic to a connecting left ideal I as an $\mathcal{O}_1$-module by the following lemma.

Lemma 2.4. *[33, 42.2.8] Let $Hom(E_2, E_1)$ denote the set of isogenies from E_2 to E_1 and let $\mathcal{O}_1$ and $\mathcal{O}_2$ denote the endomorphism rings of E_1 and E_2 respectively. Let I be a connecting ideal of $\mathcal{O}_1$ and $\mathcal{O}_2$ and let $\phi_I : E_2 \to E_1$ denote the corresponding isogeny. Then the map $\phi_I^* : Hom(E_1, E_2) \to I$, $\psi \mapsto \psi \circ \phi_I$ is an isomorphism of left $\mathcal{O}_1$-modules.*

Since the KLPT-algorithm computes a connecting ideal between two maximal orders, Lemma 2.4 implies that one can compute a $\mathbb{Z}$-basis of $\mathrm{Hom}(E_1, E_2)$. However, the degree of these isogenies might not be smooth and it is not obvious that one can evaluate them efficiently. In Algorithm 1, we will show that one can evaluate these isogenies on points efficiently using the KLPT algorithm.

Next, we recall some basic facts about lattice reduction, which aims to transform an arbitrary input basis into a basis of "higher quality". In the following, we are interested in bases that are close to orthogonal.

Let $B := (b_1, \ldots, b_n)$ be the basis of a lattice L, let π_i denote the projection onto $\mathrm{span}(b_1, \ldots, b_{i-1})$ for $i = \{1, \ldots, n\}$ and let $B^* := (b_1^*, \ldots, b_n^*)$ be the *Gram-Schmidt orthogonalization* of B, where $b_i^* = \pi_i(b_i)$. Intuitively speaking, a good basis is one in which the sequence of Gram-Schmidt norms $\|b_1^*\|, \|b_2^*\|, \ldots, \|b_n^*\|$ does not decay too fast.

The Lenstra–Lenstra–Lovász (LLL) reduction calculates a short and nearly orthogonal lattice basis for any lattice in polynomial time [20]. We recall a more precise statement in the following proposition using the Gram-Schmidt coefficients $\mu_{i,j} := \frac{\langle b_i, b_j^* \rangle}{\langle b_j^*, b_j^* \rangle}$.

Proposition 2.5. *The LLL lattice reduction with factors (η, δ), where $\delta \in (0.25, 1)$ and $\eta \in [0.5, \sqrt{\delta}]$, provides in polynomial time a basis $B = (b_1, \ldots, b_n)$ that is size-reduced with $\mu_{i,j} < \eta$ for all $j < i$ and has Gram-Schmidt orthogonalization satisfying the Lovász condition $\delta \|b_i^*\|^2 \leq \|\mu_{i+1,i} b_i + b_{i+1}^*\|^2$.*

The default parameters for LLL-reduction in MAGMA, which we will use later in this paper, are $\delta = 0.75$ and $\eta = 0.501$. Since LLL-reduced bases are in some sense close to orthogonal, we can expect short vectors in the lattice to have rather small coefficients with respect to the basis. This is captured by the following lemma which is a consequence of [20, Equation (1.8)] and Cramer's rule.

Lemma 2.6. *Let L be a full lattice with LLL-reduced basis $b_1, \ldots, b_n$ with factors (η, δ) and let $v := \sum_{i=1}^{n} \gamma_i b_i \in L$. Then*

$$|\gamma_i| \leq \left(\frac{4}{(4\delta - 1)} \right)^{n(n-1)/4} \frac{|v|}{|b_i|}.$$

Proof. By [20, Equation (1.8)], an LLL-reduced basis $b_1, \ldots, b_n$ satisfies

$$\prod_{i=1}^{n} |b_i| \leq \left(\frac{4}{(4\delta - 1)} \right)^{n(n-1)/4} \det(L).$$

Therefore, using Cramer's rule we get

$$\begin{aligned} |\gamma_i| &= \frac{\det(b_1, \ldots, b_{i-1}, v, b_{i+1}, \ldots, b_n)}{\det(L)} \leq \frac{|b_1| \cdots |b_{i-1}| \cdot |v| \cdot |b_{i+1}| \cdots |b_n|}{\det(L)} \cdot \frac{|b_i|}{|b_i|} \\ &\leq \left(\frac{4}{(4\delta - 1)} \right)^{n(n-1)/4} \cdot \frac{|v| \cdot \det(L)}{|b_i| \cdot \det(L)} = \left(\frac{4}{(4\delta - 1)} \right)^{n(n-1)/4} \cdot \frac{|v|}{|b_i|}. \qquad \square \end{aligned}$$

2.4 GPST

In [12, §4], Galbraith, Petit, Shani and Ti describe how to compute the secret isogeny of an SIDH instance efficiently, if the endomorphism rings of both the domain and the codomain of the isogeny are known (or can be computed). We summarize their results and we recall why the algorithm does not work as such outside of an SIDH setting.

Let $\varphi : E_1 \to E_2$ be a ℓ^n-degree isogeny one wishes to recover, given the two endomorphism rings $\mathcal{O}_1$ and $\mathcal{O}_2$ of E_1 and E_2 respectively. Since E_1 and E_2 are supersingular curves, their endomorphism rings are maximal orders in the rational quaternion algebra $B_{p,\infty}$. By Lemma 2.3, one can recover an ideal connecting $\mathcal{O}_1$ and $\mathcal{O}_2$. Such an ideal corresponds to one of infinitely many isogenies between E_1 and E_2. This isogeny is in general not of degree ℓ^n and, in particular, it is not the same as φ. Yet, to attack SIDH, the isogeny needs to be of the correct degree and should also have the correct action on the torsion points.

The secret isogenies in SIDH are of degree approximately $\sqrt{p}$. However, a pair of random supersingular elliptic curves over $\mathbb{F}_{p^2}$ is unlikely to be connected by an isogeny of degree significantly smaller than $\sqrt{p}$. In [12] the authors leverage this observation to recover the sought isogeny given the endomorphism rings of E_1 and E_2 as follows.

Given a connecting ideal I for the endomorphism rings, the authors compute a Minkowski reduced basis which is used to recover an element $\alpha \in I$ of minimal norm. By [18, Lemma 5], the ideal $I' := I\overline{\alpha}/\operatorname{Norm}(I)$ is another ideal connecting $\mathcal{O}_1$ and $\mathcal{O}_2$ of minimal norm, $\operatorname{Norm}(\alpha)$. Then, one can compute the isogeny $E_1 \rightarrow E_2$ of degree $\operatorname{Norm}(\alpha)$ corresponding to this ideal using Vélu's formulae. If the shortest isogeny between E_1 and E_2 is indeed of degree ℓ^n, this algorithm allows to recover such an isogeny of correct degree from the endomorphisms. The experimental results in [12] suggest that, by trying relatively few small elements α in the previous algorithm, one recovers an isogeny that can be used to attack SIDH with overwhelming probability.

Clearly, the approach outlined above relies crucially on the fact that the degree of the isogeny one wants to recover is among the smallest possible degrees of isogenies connecting E_1 and E_2. In schemes that do not use secret isogenies of relatively small degree (e.g., B-SIDH [5] or SÉTA [8]), the GPST approach is infeasible.

3 Computing isogenies using torsion information

In this section, we describe an algorithm to evaluate non-smooth degree isogenies; and an algorithm to compute a secret isogeny $\phi : E_1 \rightarrow E_2$ of degree N_1 between supersingular elliptic curves, provided that certain torsion images and the endomorphism rings of E_1 and E_2 are known.

3.1 Evaluating non-smooth degree isogenies

In this subsection, we provide an algorithm for the following problem.

Task 3.1. *Let E_1 and E_2 be two curves with given endomorphism rings $\mathcal{O}_1$ and $\mathcal{O}_2$ respectively. Let I be an $\mathcal{O}_1$-left and $\mathcal{O}_2$-right ideal of norm N_1 and let $P \in E_1$. Evaluate $\phi_I(P)$, where ϕ_I is the isogeny corresponding to the ideal I.*

Remark 3.2. The isogeny ϕ_I corresponding to the left ideal I is only unique up to post-composition with isomorphisms. Here E_2 is a prescribed curve so one has only potential issues with automorphisms of E_2. The number of automorphisms of E_2 can be bounded by a constant (in most cases it is actually 2), so one has some slight amibguity in the end result of Task 3.1 which will eventually result in a constant overhead every time this subroutine is called.

To solve this task, we extend an algorithm due to Petit and Lauter [24, Algorithm 3] which evaluates endomorphisms. Note that a solution to Task 3.1 evaluates isogenies of non-smooth degree between curves with known endomorphism rings.

Petit-Lauter Algorithm [24, Alg. 3]: Let $(E_1, \mathcal{O}_1)$ denote a supersingular curve and its endomorphism ring, and let $w \in \mathcal{O}_1$. In order to evaluate the endomorphism $\phi_{\mathcal{O}_1 w}$ on a point $P \in E_1$, the algorithm by Petit and Lauter uses a curve $(E_0, \mathcal{O}_0)$ whose endomorphisms can be efficiently evaluated, e.g. the curve with j-invariant 1728 (see Example 2.1). The algorithm proceeds as follows.

Let $\{w_1, w_2, w_3, w_4\}$ be a basis of $\mathcal{O}_0$ and let $\{\phi_1, \phi_2, \phi_3, \phi_4\}$ be the corresponding basis of $\mathrm{End}(E_0)$. The core idea of the algorithm is to use the KLPT algorithm to compute a powersmooth isogeny $\varphi : E_1 \to E_0$ of degree N.

Then, we have $N\mathcal{O}_1 \subset \mathcal{O}_0$ and thus $Nw \in \mathcal{O}_0$. For $w = \frac{a_1w_1 + a_2w_2 + a_3w_3 + a_4w_4}{N}$ this implies

$$\phi_{w\mathcal{O}_1} = \varphi^{-1} \circ \frac{a_1\phi_1 + a_2\phi_2 + a_3\phi_3 + a_4\phi_4}{N} \circ \varphi,$$

where $\varphi^{-1} := \frac{1}{\deg \varphi}\widehat{\varphi}$. Since all the isogenies on the right-hand side can be evaluated efficiently, this allows to evaluate $\phi_{w\mathcal{O}_1}$.

Solving Task 3.1: Let $(E_2, \mathcal{O}_2)$ be a supersingular elliptic curve with its endomorphism ring, let I be an $\mathcal{O}_1$-left and $\mathcal{O}_2$-right ideal of non-smooth norm and let $P \in E_1$. We would like to evaluate the isogeny ϕ_I corresponding to the ideal I at the point P.

Using the KLPT algorithm, we compute an $\mathcal{O}_1$-right and $\mathcal{O}_2$-left ideal J whose smooth norm is coprime to that of I. Then, the ideal IJ represents an endomorphism $w \in \mathcal{O}_1$ of E_1. The element $w \in O_1$ can be recovered by computing the shortest vector in IJ. We obtain $IJ = w\mathcal{O}_1$ for some $w \in \mathcal{O}_1$. Using [24, Algorithm 3], we evaluate $Q = \phi_{w\mathcal{O}_1}(P)$, and compute $\phi_I(P) = \phi_J^{-1}(Q)$. We summarize the steps in Algorithm 1.

Lemma 3.3. *Assuming GRH, Algorithm 1 runs in polynomial time.*

Proof. The endomorphism rings of the curves E_0, E_1 and E_2 are known. For this case, Wesolowski gave a polynomial-time algorithm to compute a connecting smooth ideal in polynomial time assuming only GRH [34]. Previously, a similar (faster) polynomial-time algorithm, KLPT [18], was already known for this task, but it relies on heuristics. Thus, Steps 1 and 2 run in polynomial time.

The ideal I ($\mathcal{O}_1$-left and $\mathcal{O}_2$-right) and J ($\mathcal{O}_1$-right and $\mathcal{O}_2$-left) have coprime norms, hence the two-sided $\mathcal{O}_1$ ideal IJ corresponds to a non trivial endomorphism $w \in \mathcal{O}_1$ of E_1 that can be recovered by computing a Minkowski reduced basis of IJ. For lattices up to dimension 4, a Minkowski reduced basis can be computed in polynomial time [23]. The integers a_1, a_2, a_3 and a_4 are obtained by rewriting the quaternion Nw as an element of $\mathcal{O}_0$. Therefore, Step 3 runs in polynomial time. By hypothesis, the isogenies ϕ_1, ϕ_2, ϕ_3 and ϕ_4 can be evaluated

```
Algorithm 1: Evaluating non-smooth degree isogenies
  Input: Elliptic curves $E_1, E_2$ with endomorphism rings $\mathcal{O}_1, \mathcal{O}_2$ and an $\mathcal{O}_1$-left
         and $\mathcal{O}_2$-right ideal $I$ together with a point $P \in E_1$, an elliptic curve $E_0$
         such that its endomorphism ring $\mathcal{O}_0$ is generated by endomorphisms
         $\phi_1, \phi_2, \phi_3, \phi_4$ that can be evaluated efficiently.
  Output: $\phi_I(P)$.
1 Compute an $\mathcal{O}_1$-right and $\mathcal{O}_2$-left ideal $J$ whose smooth norm is coprime to
    that of $I$ using Wesolowski's algorithm [34] (or KLPT);
2 Compute an $\mathcal{O}_1$-left and $\mathcal{O}_0$-right ideal $K$ of powersmooth norm $N$ using
    Wesolowski's algorithm (or KLPT);
3 Set $IJ = w\mathcal{O}_1$ for some $w \in \mathcal{O}_1$ and find integers $a_1$, $a_2$, $a_3$ and $a_4$ such that
    $Nw = a_1 w_1 + a_2 w_2 + a_3 w_3 + a_4 w_4$;
4 Evaluate $Q = \phi_{IJ}(P) = \frac{\phi_K^{-1} \circ (a_1\phi_1 + a_2\phi_2 + a_3\phi_3 + a_4\phi_4) \circ \phi_K(P)}{N}$ using [24, Alg. 3];
5 return $\phi_J^{-1}(Q)$
```

efficiently. The ideals K and J have smooth norm, hence the isogenies ϕ_K, ϕ_K^{-1} and ϕ_J^{-1} have smooth degree and can also be evaluated efficiently. It follows that Step 4 and Step 5 run in polynomial time as well. □

3.2 Main algorithm

Next, we generalise Algorithm 2 of [12]. In [12], an isogeny ϕ between two curves E_1 and E_2 with known endomorphism rings $\mathcal{O}_1$ and $\mathcal{O}_2$ is computed, if its degree is minimal (i.e., ϕ is the isogeny of smallest degree connecting E_1 and E_2). The algorithm in [12] applies to the SIDH setting where the degree of the secret isogenies are minimal with non-negligible probability (or otherwise at least of particularly small degree). Meanwhile, the torsion point information available in SIDH-like schemes is not used at all.

We will show in this section how the torsion point information in SIDH-like schemes can be exploited together with the knowledge of endomorphism rings to compute secret isogenies of arbitrary (larger but fixed) degree.

The strategy is as follows. Let $\phi : E_1 \to E_2$ be a secret isogeny, let P, Q be a basis of $E_1[N_2]$ and let $\phi(P)$, $\phi(Q)$ be the torsion information provided in SIDH-like schemes. Let $I(\mathcal{O}_1, \mathcal{O}_2)$ be a connecting ideal between the maximal orders $\mathcal{O}_1$ and $\mathcal{O}_2$. Instead of solving for a minimal norm element of the ideal $I(\mathcal{O}_1, \mathcal{O}_2)$ as in [12], we compute an LLL-reduced basis $\{\psi_1, \psi_2, \psi_3, \psi_4\}$ of I.

Using Algorithm 1, the isogenies ψ_i, $i = 1, \ldots, 4$, can be evaluated at the points P and Q. Next, we want to write ϕ in terms of our LLL-reduced basis, i.e. we want to find $(x_1, \ldots, x_4) \in \mathbb{Z}^4$ such that

$$\phi = x_1\psi_1 + x_2\psi_2 + x_3\psi_3 + x_4\psi_4, \tag{1}$$

Clearly, recovering x_i allows to compute the secret isogeny ϕ.

Note that Equation 1 implies in particular

$$\sum_{i=1}^{4} x_i\psi_i(P) = \phi(P) \qquad \text{and} \qquad \sum_{i=1}^{4} x_i\psi_i(Q) = \phi(Q). \tag{2}$$

To compute x_1, x_2, x_3 and x_4, we first prove that a solution to Equation 2 is unique modulo N_2. Then, we use simple linear algebra methods to recover it. Finally, we will show that knowing the x_i modulo N_2 is enough to recover them exactly (as integers).

Lemma 3.4. *Let E_1, E_2 be supersingular elliptic curves over $\mathbb{F}_{p^2}$ and let P, Q be a basis of $E_1[N_2]$. Let $\psi_1, \psi_2, \psi_3, \psi_4$ be a $\mathbb{Z}$-basis of Hom(E_1, E_2). The system of linear equations modulo N_2 corresponding to*

$$\sum_{i=1}^{4} x_i\psi_i(P) = \phi(P) \text{ and } \sum_{i=1}^{4} x_i\psi_i(Q) = \phi(Q)$$

has a unique solution $(x_1, x_2, x_3, x_4) \in (\mathbb{Z}/N_2\mathbb{Z})^4$.

Proof. Let P', Q' be a basis of $E_2[N_2]$. Every isogeny ϕ in $\mathrm{Hom}(E_1, E_2)$ can be identified with a matrix $\begin{pmatrix} a & b \\ c & d \end{pmatrix} \in M_2(\mathbb{Z}/N_2\mathbb{Z})$ by writing its images on $E_1[N_2]$ as follows

$$\phi(P) = aP' + cQ', \ \phi(Q) = bP' + dQ'.$$

Let $A = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$ be a matrix in $M_2(\mathbb{Z}/N_2\mathbb{Z})$. First, we prove that for any matrix A, there exists an isogeny $\phi \in \mathrm{Hom}(E_1, E_2)$ such that representation of ϕ is A.

Let $\psi : E_1 \to E_2$ be an isogeny such that the degree of ψ is coprime to N_2. Note that such an isogeny exists as the ℓ-isogeny graph is connected for any prime ℓ. Let M be the matrix corresponding to ψ. Since the degree of ψ is coprime to N_2, it corresponds to an invertible matrix in $M_2(\mathbb{Z}/N_2\mathbb{Z})$.

It is known (see [33, Theorem 42.1.9.]) that $\mathrm{End}(E_1)/N_2\,\mathrm{End}(E_1)$ is isomorphic to $M_2(\mathbb{Z}/N_2\mathbb{Z})$ (the injection is clear, surjectivity is the key result). Note that the isomorphism depends on a choice of basis of $E_1[N_2]$. Consider the isomorphism corresponding to the basis P, Q. Then, there exists an endomorphism $\theta \in \mathrm{End}(E_1)$ whose matrix representation is AM^{-1}. This implies that the matrix representation of $\phi = \theta \circ \psi$ is $AM^{-1}M = A$, i.e. there exists an isogeny from E_0 to E_1 that is represented by the matrix A.

Clearly, $\sum_{i=1}^{4} x_i\psi_i$ and $\sum_{i=1}^{4} y_i\psi_i$ are represented by the same matrix if $x_i \equiv y_i \pmod{N_2}$ for $i = 1, \ldots, 4$. Thus, there are at most $N_2^4 = |(\mathbb{Z}/N_2\mathbb{Z})^4|$ different matrices that one can obtain.

Now, the Lemma follows by a simple counting argument. Since every matrix in $M_2(\mathbb{Z}/N_2\mathbb{Z})$ is represented for an isogeny, every matrix must uniquely correspond to a sum of the form $\sum_{i=1}^{4} x_i\psi_i$ modulo N_2. Consequently, if a matrix has two different representations of the form $\sum_{i=1}^{4} x_i\psi_i$, then they are the same modulo N_2 which finishes the proof. □

Remark 3.5. Essentially the main result of the proof is that $\mathrm{Hom}(E_1, E_2)$ modulo N_2 is isomorphic to $M_2(\mathbb{Z}/N_2\mathbb{Z})$ as a $\mathbb{Z}/N_2\mathbb{Z}$-module [30]. Informally, the key idea is that $\mathrm{Hom}(E_1, E_2)$ is a left ideal in $\mathrm{End}(E_1)$, hence it will be a left ideal in $M_2(\mathbb{Z}/N_2\mathbb{Z})$ modulo N_2. Since isogenies between E_1 and E_2 of degree coprime to N_2 exist, this left ideal will contain invertible matrices, hence it must be the entire matrix ring.

Now we provide details on how to recover x_1, x_2, x_3, x_4. Given $\psi_i(P)$, $\psi_i(Q)$ for $i = 1, 2, 3, 4$ and $\phi(P)$, $\phi(Q)$, where $\{\psi_1, \psi_2, \psi_3, \psi_3\}$ is the LLL-reduced basis of $\mathrm{Hom}(E_1, E_2)$, we would like to compute $(x_1, \cdots, x_4) \in (\mathbb{Z}/N_2\mathbb{Z})^4$ such that

$$\sum_{i=1}^{4} x_i\psi_i(P) = \phi(P) \qquad \text{and} \qquad \sum_{i=1}^{4} x_i\psi_i(Q) = \phi(Q).$$

Note that N_2 is a smooth integer and that $\phi(P)$ and $\phi(Q)$ form a basis of $E_2[N_2]$ as $\deg(\phi)$ and N_2 are coprime. For $i = 1, 2, 3, 4$, we can compute the integers $a_i, b_i, c_i, d_i \in \mathbb{Z}/N_2\mathbb{Z}$ such that $\psi_i(P) = [a_i]\phi(P) + [b_i]\phi(Q)$ and $\psi_i(Q) = [c_i]\phi(P) + [d_i]\phi(Q)$ by using the Weil pairing and solving discrete logarithms in a group of smooth order. Now, the integers $(x_1, \cdots, x_4) \in (\mathbb{Z}/N_2\mathbb{Z})^4$ satisfy

$$\phi(P) = \left[\sum_{i=1}^{4} x_i a_i\right] \phi(P) + \left[\sum_{i=1}^{4} x_i b_i\right] \phi(Q)$$

and

$$\phi(Q) = \left[\sum_{i=1}^{4} x_i c_i\right] \phi(P) + \left[\sum_{i=1}^{4} x_i d_i\right] \phi(Q).$$

We obtain

$$\begin{pmatrix} 1 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} x_1 & x_2 & x_3 & x_4 \end{pmatrix} \cdot \begin{pmatrix} a_1 & b_1 & c_1 & d_1 \\ a_2 & b_2 & c_2 & d_2 \\ a_3 & b_3 & c_3 & d_3 \\ a_4 & b_4 & c_4 & d_4 \end{pmatrix}.$$

By Lemma 3.4, there exists a unique solution $\begin{pmatrix} x_1 & x_2 & x_3 & x_4 \end{pmatrix}$ to the previous equation. Hence the matrix

$$M := \begin{pmatrix} a_1 & b_1 & c_1 & d_1 \\ a_2 & b_2 & c_2 & d_2 \\ a_3 & b_3 & c_3 & d_3 \\ a_4 & b_4 & c_4 & d_4 \end{pmatrix}$$

is invertible and the solution is given by $\begin{pmatrix} x_1 & x_2 & x_3 & x_4 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 1 \end{pmatrix} \cdot M^{-1}$. The latter operation corresponds to adding the first and the fourth row of M^{-1}. We summarize this process in Algorithm 2.

Lemma 3.6. *Algorithm 2 is correct and runs in polynomial time provided that N_2 is smooth.*

Algorithm 2: Computing the linear system

```
Input: $\psi_i(P)$ and $\psi_i(Q)$ for $i = 1, \ldots, 4$, where $\psi_i$ are a $\mathbb{Z}$-basis of
       $\mathrm{Hom}(E_1, E_2)$; $\phi(P)$ and $\phi(Q)$ of smooth order $N_2$.
Output: $x_1$, $x_2$, $x_3$, $x_4$ such that $\sum_{i=1}^{4} x_i\psi_i(P) = \phi(P)$, and
        $\sum_{i=1}^{4} x_i\psi_i(Q) = \phi(Q)$.
for $i = 1, \cdots, 4$ do
    Compute $a_i, b_i, c_i, d_i \in \mathbb{Z}/N_2\mathbb{Z}$ such that $\psi_i(P) = [a_i]\phi(P) + [b_i]\phi(Q)$ and
      $\psi_i(Q) = [c_i]\phi(P) + [d_i]\phi(Q)$;
Set $M$ to be the $4 \times 4$ matrix whose rows are $\begin{pmatrix} a_i & b_i & c_i & d_i \end{pmatrix}$ for $i = 1, 2, 3, 4$;
Compute the inverse matrix $M^{-1}$ of $M$;
Set $\begin{pmatrix} x_1 & x_2 & x_3 & x_4 \end{pmatrix}$ to be the sum of the first and the fourth rows of $M^{-1}$;
return $x_1$, $x_2$, $x_3$, $x_4$ such that $|x_i| < N_2/2$.
```

Proof. Follows from the previous discussion. □

Lemma 3.7 gives a condition under which the solution computed in Algorithm 2 gives a solution to Equation 1.

Lemma 3.7. *Let $d := \min\{\deg(\varphi) \mid \varphi : E_1 \to E_2$ is isogeny$\}$. If $\frac{N_1}{N_2} < \frac{d}{16}$, then given the solution $x_1, \ldots, x_4$ to the system of linear equations modulo N_2 returned by Algorithm 2 $\sum_{i=1}^{4} x_i\psi_i(P) = \phi(P)$, $\sum_{i=1}^{4} x_i\psi_i(Q) = \phi(Q)$, we have $\phi = \sum_{i=1}^{4} x_i\psi_i$ in Hom(E_1, E_2).*

Proof. By Lemma 2.6, setting $\delta = 0.75$ and $n = 4$, we have that $\phi = \sum_{i=1}^{4} \gamma_i\psi_i$ where $|\gamma_i| \leq \frac{8\deg(\phi)}{\deg(\psi_i)} \leq \frac{8N_1}{d}$. It follows that $|\gamma_i| \leq \frac{8N_1}{d} < \frac{N_2}{2}$ since $\frac{N_1}{N_2} < \frac{d}{16}$ by hypothesis.

The solution (x_1, x_2, x_3, x_4) returned by Algorithm 2 satisfies $|x_i| < \frac{N_2}{2}$ for $i = 1, 2, 3, 4$. Moreover, by Lemma 3.4, this solution is unique modulo N_2. Thus, $\phi = \sum_{i=1}^{4} x_i\psi_i$ in $\mathrm{Hom}(E_1, E_2)$. □

The entire process of computing isogenies of a specific but arbitrary degree between two supersingular curves with known endomorphism ring is summarised in Algorithm 3.

Finally, we prove that Algorithm 3 succeeds in polynomial time.

Theorem 3.8. *Let $d := \min\{\deg(\phi) \mid \phi : E_1 \to E_2$ is isogeny$\}$. Assuming GRH, Algorithm 3 solves Problem 1.1 in polynomial time, whenever $\frac{N_1}{N_2} < \frac{d}{16}$.*

Proof. Correctness of the algorithm follows from Lemma 3.7 and the preceding discussion. We are left to show the polynomial running time. Step 1 could use the KLPT algorithm [18] or in fact the algorithm due to Kirschmer–Voight [17], as the connecting ideal does not need to have a smooth norm. This runs in polynomial time (to avoid heuristics we can also use the algorithm from [34]). Step 2 is the LLL lattice reduction algorithm which also runs in polynomial time. Step 3 and Step 4 run in polynomial time by Lemma 3.3 and Lemma 3.6 respectively. □

Algorithm 3: Computing isogeny with torsion-point information

```
Input: Supersingular elliptic curves $E_1, E_2$ with known endomorphism rings
       $\mathcal{O}_1, \mathcal{O}_2$ which are connected by an isogeny $\phi$ of degree $N_1$ and
       $\phi(P), \phi(Q)$, where $P, Q$ are a basis of $E_1[N_2]$, such that $\frac{N_1}{N_2} < \frac{d}{16}$.
Output: $\phi$.
Compute a basis of an $\mathcal{O}_1$-left and $\mathcal{O}_2$-right ideal $I$;
Compute an LLL-reduced basis $\psi_1, \psi_2, \psi_3, \psi_4$ of $I$;
Compute $\psi_i(P), \psi_i(Q)$ using Algorithm 1;
Use Algorithm 2 to solve for $|x_i| < N_2/2$ such that
  $\sum_{i=1}^4 x_i\psi_i(P) = \phi(P),\ \sum_{i=1}^4 x_i\psi_i(Q) = \phi(Q)$;
Compute isogeny from the relation $\phi = \sum_{i=1}^4 x_i\psi_i$;
return $\phi$
```

Remark 3.9. We could also have required the condition $\frac{N_1}{N_2} \leq \frac{d}{16}$ and in that case we get the condition that $|x_i| \leq N_2/2$. However, when N_2 is even and x_i is congruent to $N_2/2$, then the lift to the above range is not unique (as $-N_2/2$ and $N_2/2$ represent the same residue class). This is not issue for Algorithm 3 as one will have multiple candidates (16 of them in the worst case) for ψ that can be tested. By looking at the degrees, the correct one can be chosen efficiently. More generally, one can actually relax the statement of Theorem 3.8 further by allowing non-unique lifts and adding a check step at the end of Algorithm 3.

Remark 3.10. As was shown in Lemma 3.7, Algorithm 3 requires an amount of torsion point information that depends on the degree d of the shortest isogeny between the supersingular elliptic curves E_1 and E_2.

For many applications of cryptographic interest balanced parameters are used where $N_1 \approx N_2$. Taking $\frac{N_1}{N_2} \approx 1$, the procedure above works whenever the two curves are not connected by an isogeny of degree smaller than 16. This can be checked easily with an exhaustive search.

Remark 3.11. One does not use the fact that N_1 is smooth in Algorithm 3. If one wants to retrieve the secret isogeny as a rational map (as a composition of small degree maps), then this is still important. However, if one wants only to be able to evaluate the secret isogeny at any point, then this can be accomplished by Algorithm 3 even if N_1 is not smooth.

3.3 Example

We will illustrate the attack with an example.
Consider the prime $p = 83701957499$, where we have $p + 1 = 2^2 \cdot 3^{14} \cdot 5^4 \cdot 7$. Let B be the quaternion algebra ramified at p and ∞ and generated over the rationals by i, j, k where $i^2 = -p$, $j^2 = -1$, and $k = ij$. Fix the finite field $\mathbb{F}_{p^2}$ where $\alpha^2 = -1$ generates $\mathbb{F}_{p^2}$ over $\mathbb{F}_p$.

Consider the elliptic curve given by $E_0 : y^2 = x^3 + x$ which has j-invariant 1728. The endomorphism ring of E_0 is generated by:

$$1, j, \frac{j+k}{2}, \frac{1+i}{2}.$$

We let the secret isogeny be a 3^{14}-isogeny $\theta : E_0 \to E$. We use θ to recover the endomorphism ring of E which is generated by

$$\frac{5159993 + i + 10319986j + 11800766447346k}{9565938}, \frac{2i + 6291065j + 7411685041437k}{9565938}, \frac{3j + 196249k}{2}, 1594323k.$$

Note that in the real attack, we have made the assumption that $\mathrm{End}(E)$ is known, so we have only used the secret to calculate a known quantity.

Now, using the knowledge of both endomorphism rings, we are able to compute a connecting ideal between them and also compute the reduced basis of the ideal to be

$$\frac{227049 + i + 154612j}{2}, \frac{154612 - 227049j + k}{2}, \frac{121127 - 9i + 4995744j + 14k}{2}, \frac{4995744 - 14i - 121127j - 9k}{2}.$$

We can interpret these endomorphisms and map the generators of the $E_0[5^4]$ through them.

We have chosen the points

$$P_5 = (75854242840\alpha + 62002351922, 51107649030\alpha + 19190692821),$$
$$Q_5 = (17857458337\alpha + 504604508, 77775481527\alpha + 25718537048)$$

to be the generators of $E_0[5^4]$.

In particular, by naming the reduced basis elements as $\psi_1', \psi_2', \psi_3', \psi_4'$, we have that

$$\begin{aligned}
\psi_1'(P_5) &= (9049577476\alpha + 26838535531, 9532248787\alpha + 18861270144)\\
\psi_1'(Q_5) &= (14085392798\alpha + 75272963133, 35152660085\alpha + 3705843319)\\
\psi_2'(P_5) &= (54148936824\alpha + 29574813, 27904476482\alpha + 79581351851)\\
\psi_2'(Q_5) &= (6218706354\alpha + 14437916419, 19897519544\alpha + 26853032937)\\
\psi_3'(P_5) &= (27253519435\alpha + 63921648196, 55371710596\alpha + 3587102479)\\
\psi_3'(Q_5) &= (6221393886\alpha + 23453138168, 81414672111\alpha + 63571818133)\\
\psi_4'(P_5) &= (20904892135\alpha + 45099774747, 32347928248\alpha + 14718113311)\\
\psi_4'(Q_5) &= (16837240041\alpha + 11444980635, 5815630261\alpha + 82050564219)
\end{aligned}$$

Furthermore, we have the images of P_5 and Q_5 through the secret isogeny θ as given as part of the problem. Note that these ψ_i are not the same as the ones defined in the previous section as they are endomorphisms of E_0. However, they are just the original ψ_i composed with the isogeny between E_1 and E_0 coming from KLPT. We will denote the actual isogenies corresponding to them by ψ_i. They can be evaluated at P_5 and Q_5 by applying the connecting isogeny to them and multiplying it with the inverse of its degree modulo 5^4. These are points in

E, and in particular, they are in the subgroup $E[5^4]$. This allows us to express them in terms of $\theta(P_5)$ and $\theta(Q_5)$ which we are given.

This results in the following 4×4 matrix

$$\begin{pmatrix} 222 & 128 & 484 & 474 \\ 311 & 363 & 337 & 12 \\ 184 & 477 & 307 & 574 \\ 344 & 566 & 191 & 132 \end{pmatrix}$$

whose first row represents the four coefficients that expresses $\psi_1(P_5)$ as a linear combination of $\theta(P_5)$ and $\theta(Q_5)$, and $\psi_1(Q_5)$ as a linear combination of $\theta(P_5)$ and $\theta(Q_5)$. For example,

$$\psi_2(Q_5) = [337]\theta(P_5) + [12]\theta(Q_5).$$

Inverting this matrix and summing the first and fourth rows allow us to recover the coefficients x_i's providing the expression of the secret isogeny as a linear combination of ψ_1, ψ_2, ψ_3 and ψ_4. The result of the computation is that

$$\theta = 14\psi_1 + 9\psi_2 + \psi_4.$$

One can check that this is correct without actually computing the ψ_i by computing that the degree of this linear combination is indeed 3^{14} (as the action on the 5^4-torsion is already correct).

Remark 3.12. As one can see in this example, the secret isogeny is not the isogeny between E_0 and E of smallest degree, hence the algorithm from [12] would not have been sufficient for finding θ. However, the secret isogeny in this setting is still the smallest degree isogeny with the given action on the N_2-torsion.

4 Relevance to isogeny-based cryptography

We use this section to summarize how Algorithm 3 impacts different isogeny-based constructions.

First, we recall the current state-of-the-art regarding endomorphism ring computations as it is clearly the most time consuming part when attacking an isogeny-based cryptosystem using the reduction given by this paper.

Given a supersingular elliptic curve E defined over a finite field of characteristic p, the problem is to find $\mathrm{End}(E)$. The first algorithm to solve this is described in Kohel's thesis [19] and was later improved by Delfs-Galbraith [9] to a running time of $\tilde{O}(p^{1/2})$. The most recent algorithm is due to Eisenträger, Hallgren, Leonardi, Morrison, and Park [10] which runs in time $O(\log(p)^2 p^{1/2})$. The best known quantum algorithm is due to Biasse, Jao and Sankar [2] and has a running time of $\tilde{O}(p^{1/4})$.

The isogeny-based community for a long time considered the meet in the middle attack (MiTM) [11] as best attack when addressing the security level of isogeny-based schemes. Meanwhile, this MiTM attack requires exponential storage, hence may be unrealistic. Recently, [1] and [4] considered the van Oorschot-Wiener (vOW) parallel collision finding algorithm [31] for the isogeny computation problem. The vOW collision search allows for a space-time trade-off in the generic MiTM, leading to a larger time complexity when limited storage is used.

Estimating the security level of isogeny-based schemes using vOW, suggests that one can reduce the size of parameters that where previously fixed considering the generic MiTM attack with unrealistic memory requirements. For an SIDH-like scheme in which the secret isogenies have degree roughly N, the scheme is secured against the MiTM attack if $2^{2\lambda} < N$, where λ is the desired security level. When considering the vOW attack, N may be considerably smaller compared to $2^{2\lambda}$. See for instance a recent proposal for the reduction of parameters in SIKE by Cotello, Longa, Naehrig, Renes, and Virdia. [21].

However, one also needs to take the attack into account where the endomorphism ring of curves is computed and then Algorithm 3 is used to attack the secret isogeny. Given the classical and quantum complexity $O(\log(p)^2 p^{1/2})$ and $\tilde{O}(p^{1/4})$ respectively, this implies that the parameter p must also satisfy $2^{2\lambda} < p$.

The complexity of our attack applied against SIDH instances is similar to the attack by Galbraith et al [12]. It does not effect parameter choices, as SIDH isogenies are of small degrees and thus pathfinding algorithms are more efficient.

Our algorithm has more impact when isogeny degrees are larger relative to the size of the underlying finite field $\mathbb{F}_p$ (as the complexity of our algorithms depends on p and not on N_1).

For B-SIDH, the proposed prime p is roughly $2^{2\lambda}$. Provided the new analysis of the vOW collision search attack in [21], one may be tempted to propose smaller B-SIDH primes in order to improve on B-SIDH's efficiency. However, doing so would make the scheme vulnerable to attacks that compute endomorphism rings and use the results of this paper. This is because p would be smaller than $2^{2\lambda}$.

Hence, one consequence of this paper is that the current choice of the parameter p in B-SIDH is tight. Furthermore, one can also interpret this result differently. Namely, any SIDH-like construction has to use parameters at least as large as B-SIDH, otherwise they become vulnerable. In other words, proposing schemes with longer isogeny walks than in B-SIDH does not provide any security benefit. This is not unexpected, as walks in B-SIDH have lengths which are comparable to the diameter of the supersingular isogeny graph.

Another interpretation of our result is that when torsion point images are provided, then the problem of finding one isogeny between two supersingular elliptic curves becomes equivalent to finding an isogeny of a specific degree for a wide range of parameters.

5 Conclusion

In this paper, we showed how to compute an isogeny of a specific degree between two supersingular elliptic curves, given their endomorphism rings and the images of some torsion points under the isogeny. This can be seen as an extension of an algorithm due to Galbraith et al. [12] which did not use torsion point information but required the isogeny to be of small degree.

As a consequence, this paper allows us to estimate the security of schemes like B-SIDH, SÉTA and SIDH instantiated with larger degree isogenies, when considering an attack that computes endomorphism rings. In particular, our work provides a significant speed-up to existing quantum attacks on B-SIDH. We stress that this work does not allow to break any of the recommended parameter sets. However, our work shows that the prime chosen in B-SIDH cannot be lowered for the given security levels and also implies that any (reasonable) scheme that provides torsion point images has to use a 2λ-bit prime for security level λ.

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