

CONSTRUCTING ELLIPTIC CURVES OVER FINITE FIELDS WITH PRESCRIBED TORSION

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ABSTRACT. We present a method for constructing optimized equations for the modular curve $X_1(N)$ using a local search algorithm on a suitably defined graph of birationally equivalent plane curves. We then apply these equations over a finite field \mathbb{F}_q to efficiently generate elliptic curves with nontrivial N -torsion by searching for affine points on $X_1(N)(\mathbb{F}_q)$, and we give a fast method for generating curves with (or without) a point of order $4N$ using $X_1(2N)$.

1. INTRODUCTION

By Mazur's theorem [19], the order of a nontrivial torsion point on an elliptic curve over the rational numbers must belong to the set

$$\mathcal{T} = \{2, 3, 4, 5, 6, 7, 8, 9, 10, 12\}.$$

Conversely, for each $N \in \mathcal{T}$ an infinite family of elliptic curves over \mathbb{Q} containing a point of order N is exhibited by the parameterizations of Kubert [18].¹ Over a finite field \mathbb{F}_q , these parameterizations provide an efficient way to generate curves whose order $\#E(\mathbb{F}_q)$ is divisible by N . This can significantly accelerate applications that search for an elliptic curve E/\mathbb{F}_q with a desired property, such as curves with smooth order, as in the elliptic curve factorization method [1, 22], or curves with a particular endomorphism ring, as when computing Hilbert class polynomials with the Chinese Remainder Theorem [3, 6, 27].

To generate an elliptic curve E/\mathbb{F}_q with nontrivial 7-torsion, for example, we simply pick an element $r \in \mathbb{F}_q$ and use $b = r^3 - r^2$ and $c = r^2 - r$ to define

$$(1) \quad E(b, c) : \quad y^2 + (1 - c)xy - by = x^3 - bx^2.$$

Provided $E(b, c)$ is nonsingular, we obtain an elliptic curve on which the point $P = (0, 0)$ has order 7. By contrast, obtaining such a curve by trial and error is far more time consuming: testing for 7-torsion typically involves finding the roots of a degree-24 polynomial (the 7-division polynomial), and several curves may need to be tested (approximately six, on average).

Mazur's theorem limits us to $N \in \mathcal{T}$, but we may proceed further if we do not restrict ourselves to curves defined over \mathbb{Q} . Reichert treats $N \in \{11, 13, 14, 15, 16, 18\}$ over quadratic extensions of \mathbb{Q} in [24] by finding explicit equations for the modular

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¹Kubert also addresses the torsion subgroups $\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2N\mathbb{Z}$ for $N = 1, 2, 3, 4$.

curve $X_1(N)$, whose noncuspidal points parametrize elliptic curves with a distinguished point of order N . We may be able to reduce a curve defined over a quadratic field $\mathbb{Q}[\sqrt{d}]$ to \mathbb{F}_q , but only when d is a quadratic residue.

Alternatively, we can use an \mathbb{F}_q -rational point on $Y_1(N)$, the affine part of $X_1(N)$, to directly construct a curve $E(b, c)/\mathbb{F}_q$ containing a point of order N , for any sufficiently large q prime to N . For $N \in \mathcal{T}$ the curve $X_1(N)$ has genus 0 and we may use Kubert's parameterizations, but in general, we construct $E(b, c)$ from a point on $Y_1(N)(\mathbb{F}_q)$ via a birational map that depends on our choice of an explicit equation for $Y_1(N)$.

For example, to construct an elliptic curve E/\mathbb{F}_q with a point of order 13, we start by finding an \mathbb{F}_q -rational point (x, y) on the affine curve

$$(2) \quad y^2 + (x^3 + x^2 + 1)y - x^2 - x = 0,$$

which may be done by choosing $x \in \mathbb{F}_q$ at random² and attempting to solve the resulting quadratic equation for y in \mathbb{F}_q . We then apply the transformation

$$\begin{aligned} r &= 1 - xy, \\ s &= 1 - xy/(y + 1), \end{aligned}$$

set $c = s(r - 1)$ and $b = cr$, and construct $E(b, c)$. In the unlikely event that $E(b, c)$ is singular over \mathbb{F}_q , we simply look for a different point on the curve (2).

To apply this method we require a defining equation for $Y_1(N)$ and a corresponding birational map. For fast computation we seek a plane curve $f(x, y) = 0$ that minimizes the degree d of one of its variables. For $N \leq 18$ one can derive these from the results of Kubert and Reichert. Reichert's method can be applied to $N > 18$, but the resulting equation is quite large and of higher degree than necessary. More compact defining equations are given by Yang [29] for $N \leq 22$ and Baaziz [2] for $N \leq 51$, but these do not necessarily minimize d , which critically impacts the efficiency of the construction above.

The minimal $d = d(N)$ corresponds to the *gonality* of the curve $X_1(N)$, and is a topic of independent interest [11, 12, 16, 20, 23], since it implies that there are infinitely many elliptic curves containing a point of order N defined over number fields of degree $d(N)$. For $N > 18$ only a few values of $d(N)$ are known, but explicit equations provide upper bounds on $d(N)$, and can be used to define parametrized families of elliptic curves over number fields of a particular degree [14, 15].

Given a defining equation $f(x, y) = 0$, one may attempt to reduce its complexity (degree, number of terms, and coefficient size) through a judiciously chosen sequence of rational transformations [2, 24, 29]. However this procedure tends to be rather *ad hoc*, and becomes increasingly difficult as N grows. Here we treat this as a combinatorial optimization problem and apply standard search techniques to obtain a solution that is locally optimal under a metric we define.

Our results are not necessarily globally optimal, but for $N \leq 22$ we are able to match known lower bounds for $d(N)$ [11, 12, 16], and for $N \leq 50$ we are able to match or improve the best known upper bounds for $d(N)$ given by explicit equations. However, we do not achieve $d(24) = 4$, implied by the (nonexplicit) result in [11]. Optimized equations for $N \leq 30$ appear in the appendix, and are available online for $N \leq 50$. The local search strategy we describe here has recently been augmented using simulated annealing [4], extending our results to $N \leq 101$.

²For $N \in \{11, 14, 15\}$ the curve $X_1(N)$ has genus 1 and we may obtain additional points more efficiently using the elliptic curve group operation, as discussed in Section 4.

For odd N we also show how to quickly generate E/\mathbb{F}_q with a point of order $4N$, or satisfying $\#E(\mathbb{F}_q) \equiv 2N \pmod{4N}$, using our equations for $Y_1(2N)$. These techniques play an important role in [27], and we expect they have other applications.

2. COMPUTING THE “RAW FORM” OF $X_1(N)$

Following [24], we give a method to compute a defining equation $F_N(r, s) = 0$ for $Y_1(N)$ that Reichert calls the “raw form” of $X_1(N)$.³ The equation $E(b, c)$ is the Tate normal form of an elliptic curve (called a Kubert curve in [1]). Any elliptic curve with a point of order greater than 3 can be put in this form [17, §V.5]. The discriminant of $E(b, c)$ is

$$(3) \quad \Delta(b, c) = b^3(16b^2 - 8bc^2 - 20bc + b + c(c - 1)^3).$$

To ensure that $E(b, c)$ is nonsingular we require $\Delta(b, c) \neq 0$, so we assume that $b \neq 0$. Applying the group law for elliptic curves [25, III.2.3], we double the point $P = (0, 0)$ to obtain $2P = (b, bc)$, and for $n > 1$ we may compute the point $(n + 1)P = (x_{n+1}, y_{n+1})$ in terms of $nP = (x_n, y_n)$ using

$$(4) \quad x_{n+1} = by_n/x_n^2, \quad y_{n+1} = b^2(x_n^2 - y_n)/x_n^3.$$

The inverse of the point $nP = (x_n, y_n)$ is

$$(5) \quad -nP = (x_n, b + (c - 1)x_n - y_n).$$

If P is an N -torsion point and $m + n = N$, then we must have $mP = -nP$. If $m \neq n$ this implies $x_m = x_n$, and if $m = n$ we have $2y_n = b + (c - 1)x_n$. When $x_m = x_n$, either $mP = nP$ or $mP = -nP$, and in the latter case P is an N -torsion point. If we choose $m = \lceil \frac{N+1}{2} \rceil$ and $n = \lfloor \frac{N-1}{2} \rfloor$, we ensure $mP \neq nP$, obtaining a necessary and sufficient condition for N -torsion:

$$(6) \quad NP = 0_E \iff x_m = x_n,$$

valid for all $N > 3$, where 0_E denotes the neutral point on $E(b, c)$.

The first three multiples of P are:

$$\begin{aligned} P &= (0, 0), \\ 2P &= (b, bc), \\ 3P &= (c, b - c). \end{aligned}$$

None of these points is 0_E , thus P always has order greater than 3. Applying (6), we see that P is a point of order 4 if and only $c = 0$, and P is a point of order 5 if and only $b = c$. For N greater than 5 we define:

$$\begin{aligned} r &= b/c, & b &= rs(r - 1), \\ s &= c^2/(b - c), & c &= s(r - 1), \end{aligned}$$

where $r \neq 0, 1$, and $s \neq 0$, since $b \neq 0$. We may apply (4) to iteratively compute x_n as a rational function of r and s ; values for $1 \leq n \leq 10$ are listed in Table 1.

We now give an algorithm to compute $F_N(r, s)$ for $N > 5$, working in the polynomial ring $\mathbb{Z}[r, s]$. We assume that the polynomials F_M have already been computed, for $5 < M < N$, and that the rational function $x_n(r, s)$ is in the form $x_n = v_n/w_n$, where v_n and w_n are relatively prime polynomials in $\mathbb{Z}[r, s]$.

³Reichert also uses auxiliary variables $m = s(1 - r)/(1 - s)$ and $t = (r - s)/(1 - s)$. We work directly with r and s throughout.

Algorithm 1. Given an integer $N > 5$, compute $F_N(r, s)$ as follows:

1. Compute $G_N = v_m w_n - v_n w_m$, where $m = \lceil \frac{N+1}{2} \rceil$ and $n = \lfloor \frac{N-1}{2} \rfloor$.
2. Remove any powers of r , s , $(r-1)$, or F_M that divide G_N , for all $M > 5$ properly dividing N .
3. Make the remaining polynomial square-free and output the result as $F_N(r, s)$.

Example 1. For $N = 16$ we have $m = 9$ and $n = 7$. After computing $x_9 = v_9/w_9$ and $x_7 = v_7/w_7$ (which may be found in Table 1), step 1 of the algorithm constructs the polynomial

$$G_{16}(r, s) = s(r-1)(rs-2r+1)(rs^2-3rs+r+s+s^2) \cdot (r-s)^2 \\ - rs(r-1)(s-1)(rs-2r+1) \cdot (r-s^2+s-1)^2.$$

In step 2 the factors s , $r-1$, and $F_8(r, s) = rs-2r+1$ are removed, yielding the square-free polynomial

$$F_{16}(r, s) = r^3 s^2 - 4r^3 s + 2r^3 + 3r^2 s^2 + 2r^2 s - 2r^2 - r s^5 + 4r s^4 \\ - 10r s^3 + 6r s^2 - 3r s + r + s^4,$$

which appears in Table 4.

For practical implementation it is convenient to first compute x_n for all n up to some bound B , and then use these to compute F_N for $N \leq 2B-1$. The polynomials $F_N(r, s)$ for $N \leq 101$ can be found at <http://math.mit.edu/~drew>.

Proposition 1. Let $F_N(r, s)$ be the polynomial output by Algorithm 1 on input $N > 5$. Let $b = r_0 s_0 (r_0 - 1)$ and $c = s_0 (r_0 - 1)$ with $\Delta(b, c) \neq 0$, where r_0 and s_0 lie in a field whose characteristic does not divide N .

Then $P = (0, 0)$ is a point of order N on $E(b, c)$ if and only if $F_N(r_0, s_0) = 0$.

Proof. We first note that $\Delta(b, c) \neq 0$ implies $b \neq 0$, hence $r_0 \neq 0, 1$ and $s_0 \neq 0$. We thus have $c \neq 0$ and $b \neq c$, so P has order greater than 5. If $w_m(r_0, s_0) = 0$ in step 1 of the algorithm, then P is an m -torsion point with $v_m(r_0, s_0) = b^2 \neq 0$, and we must have $w_n(r_0, s_0) \neq 0$, since $m - n \leq 2$ and P has order greater than 2. Similarly, if $w_n(r_0, s_0) = 0$, then $v_n(r_0, s_0)$ and $w_m(r_0, s_0)$ are both nonzero. It follows that $G_N(r_0, s_0) = 0$ if and only if $x_m(r_0, s_0) = -x_n(r_0, s_0)$, equivalently, if and only if $NP = 0_E$. This proves the proposition in the case that N has no proper factors greater than 5, since P has order greater than 5, and it proves the forward implication in every case.

For the reverse implication we proceed by induction on the number of proper factors of N greater than 5, appealing to the moduli interpretation of $Y_1(N)$. For $N > 5$ (in fact, $N \geq 5$) the irreducible affine curve $Y_1(N)$ is a fine moduli space for equivalence classes of pairs (E, P) , where P is a point of order N on the elliptic curve E (this is classical, see, e.g., [8, §4] for a modern summary and references). Each equivalence class is represented by a curve $E(b, c)$ with the point $P = (0, 0)$ of order N , corresponding to a pair (r_0, s_0) . There is a surjective rational map from the set $\{(r_0, s_0) : G_N(r_0, s_0) = 0, r_0 \neq 0, 1, s_0 \neq 0\}$ to the union of the curves $Y_1(M)$ with $M > 5$ dividing N . By the inductive hypothesis, the inverse image of $Y_1(M)$ under this map is the zero locus of F_M , for each $M > 5$ properly dividing N . After these factors are removed in step 4, the points on the remaining curve, $F_N(r, s) = 0$, must be mapped onto $Y_1(N)$.⁴ \square

⁴This argument is essentially a formalization of the remarks in [10, pp. 88–89].

TABLE 1. x -coordinates of nP for $n \leq 10$.

$$\begin{aligned}
 x_1 &= 0 \\
 x_2 &= rs(r-1) \\
 x_3 &= s(r-1) \\
 x_4 &= r(r-1) \\
 x_5 &= rs(s-1) \\
 x_6 &= s(r-1)(r-s) / (s-1)^2 \\
 x_7 &= rs(r-1)(s-1)(rs-2r+1) / (r-s)^2 \\
 x_8 &= r(r-1)(r-s)(r-s^2+s-1) / (rs-2r+1)^2 \\
 x_9 &= s(r-1)(rs-2r+1)(rs^2-3rs+r+s^2) / (r-s^2+s-1)^2 \\
 x_{10} &= rs(r-s^2+s-1)(r^2-rs^3+3rs^2-4rs+s) / (rs^2-3rs+r+s^2)^2 \\
 x_{11} &= rs(r-1)(s-1)(rs^2-3rs+r+s^2)(r^2s-3r^2+rs+3r-s^2-1)
 \end{aligned}$$

3. OPTIMIZING PLANE CURVE EQUATIONS

We now consider how to optimize a given curve equation $F(r, s) = 0$ for fast computation. We have in mind the curves $F_N(r, s) = 0$ of the previous section, but our method can be applied more generally. We seek a birationally equivalent curve $f(x, y) = 0$ that minimizes the degree of one of its variables (say y). Subject to this constraint, we would like to make f monic in y and to minimize the degree in x , the number of terms, and the size of the coefficients (roughly in that order of priority). One technique is to attempt to remove singularities through a carefully chosen sequence of translations and inversions; see [24] for examples. Here we take a more naïve approach that allows us to completely automate the process.

There are three basic types of transformations we shall use:

- (1) Translate: $x \rightsquigarrow x + a$ or $y \rightsquigarrow y + a$.
- (2) Invert: $x \rightsquigarrow 1/x$ or $y \rightsquigarrow 1/y$.
- (3) Separate: $x \rightsquigarrow 1/x, y \rightsquigarrow y/x$ or $x \rightsquigarrow x/y, y \rightsquigarrow 1/y$.

These are clearly all invertible operations. The third type combines an inversion and a division, but we find it works well as an atomic unit. In order to bound the number of atomic operations, we let $a \in \{\pm 1\}$, giving a total of eight.

Consider the directed graph G on the set \mathcal{C} of plane curves that can be obtained from $F(r, s) = 0$ by applying a finite sequence of the transformations above, with edges labeled by the corresponding operation. A path in G defines a birational map (the composition of the operations labeling its edges), and any path can be reversed to yield the inverse map. Starting from the given curve C_0 defined by $F(r, s) = 0$, we want to find a path to a “better” curve C . To make this precise, we associate to each integer polynomial $f(x, y)$ a vector of nonnegative integers

$$v(f) = (d_y, m_y, d_x, d_{\text{tot}}, t, S),$$

whose components are defined by:

- d_x is the degree of f in x and d_y is the degree of f in y ;
- m_y is 0 if no term of f is a multiple of xy^{d_y} and 1 otherwise;
- d_{tot} is the total degree of f ;
- t is the number of terms in f ;
- S is the sum of the absolute values of the coefficients of f .

The component m_y will be zero exactly when f can be made monic as a polynomial in y . We order the vectors $v(f)$ lexicographically, and to each $C \in \mathcal{C}$ assign the vector $v(C) = \min\{v(f(x, y)), v(f(y, x))\}$, where $f(x, y) = 0$ defines C . We compare curves by comparing their vectors, obtaining a prewellordering of \mathcal{C} . In particular, any subset of \mathcal{C} contains a (not necessarily unique) minimal element.

Given a plane curve C_0 we now give a simple algorithm to search the graph G for a birationally equivalent curve C_1 that is locally optimal within a radius R . Let $\rho(C, k)$ be the set of curves connected to C by a path of length at most k in G , and call C k -optimal if $v(C) \leq v(C')$ for all $C' \in \rho(C, k)$.

Algorithm 2. *Given a plane curve C_0 defined by an integer polynomial and an integer R , output an R -optimal curve C_1 and a birational map $\varphi : C_1 \rightarrow C_0$.*

1. Set $C \leftarrow C_0$, $k = 1$, and let φ be the identity map.
2. While $k \leq R$:
 - a. Determine a minimal element C' of $\rho(C, k)$.
 - b. If $v(C') < v(C)$, then set $\varphi \leftarrow \varphi \circ \phi(C', C)$, $C \leftarrow C'$, and $k \leftarrow 0$.
 - c. Set $k \leftarrow k + 1$.
3. Output $C_1 = C$ and φ .

We note that the output curve C_1 is birationally equivalent to C_0 via the map φ , and it is clearly R -optimal. Moreover, $v(C_1) \leq v(C)$ for all $C \in \rho(C_0, R)$.

To enumerate the neighbors of the curve C defined by $f(x, y) = 0$, the algorithm applies each of the eight atomic operations. The result of applying the birational map ϕ with inverse π is computed by expanding $f(\pi_x(x, y), \pi_y(x, y))$ as a formal substitution of variables and clearing any denominators that result. Thus the translation $x \rightsquigarrow x - 1$ is obtained by expanding $f(x + 1, y)$, and the inversion $x \rightsquigarrow 1/x$ effectively replaces x^i in $f(x, y)$ with $x^{d_x - i}$. To enumerate $\rho(C, k)$ we must consider up to 8^k possible sequences of operations (this number can be reduced by eliminating obviously redundant sequences), so the bound R cannot be very large. We have tested up to $R = 10$, but find that $R = 8$ suffices to obtain the results given here. With $R = 8$ the algorithm takes less than an hour to process the curve $F_N(r, s) = 0$ for $N \leq 50$ (on a single 2.8 GHz AMD Athlon core).

Example 2. Table 2 illustrates the algorithm's execution on $F_{16}(r, s) = 0$. We start with $C = C_0$ defined by $f(x, y) = F_{16}(x, y)$. Since $v(f(y, x)) < v(f(x, y))$, the algorithm determines that $v(C) = v(f(y, x)) = (3, 1, 5, 6, 13, 40)$, indicating that $f(y, x)$ has degree 3 in y , is not monic in y , has degree 5 in x , total degree 6, 13 terms, and coefficients whose absolute values sum to 40.

No curves within a distance $k = 1$ are found that improve $v(C)$, but for $k = 2$ a curve C' is found that is monic in x (and also degree 3), which implies $v(C') < v(C)$. C' is a minimal curve in $\rho(C, 2)$, so C is replaced by C' and the map φ becomes

$$x \rightsquigarrow y/x, \quad y \rightsquigarrow 1/y.$$

This reverses the sequence of steps 5,8 (as identified in the key to Table 2), used to reach C' from C_0 (so φ maps points on C' back to points on C_0). The next improvement occurs when $k = 4$. In this case reversing the path 1,3,8,6 from C to C' yields the path 6,8,4,2 from C' back to C , and φ becomes

$$x \rightsquigarrow (y + 1)/(xy + 1), \quad y \rightsquigarrow 1/(y + 1).$$

The algorithm continues in this fashion, finding the sequence of curves listed in Table 2. Eventually, it is unable to find a better curve within the search radius $R =$

TABLE 2. Optimization of $F_{16}(r, s) = 0$.

steps	$f(x, y)$	$v(C)$
-	$x^3y^2 - 4x^3y + 2x^3 + 3x^2y^2 + 2x^2y - 2x^2 - xy^5 + 4xy^4$	(3,1,5,6,13,40)
5,8	$x^3 + x^2y^5 - 3x^2y^4 + 6x^2y^3 - 10x^2y^2 + 4x^2y - x^2 - 2xy^6$ $+ 2xy^5 + 3xy^4 + 2y^7 - 4y^6 + y^5$	(3,0,7,7,13,40)
1,3,8,6	$x^3 + x^2y^4 + 2x^2y^3 + 4x^2y^2 - 5x^2 - 2xy^4 - 8xy^3 - 13xy^2$ $+ 8x + 2y^4 + 8y^3 + 10y^2 - 4$	(3,0,4,6,13,68)
1	$x^3 + x^2y^4 + 2x^2y^3 + 4x^2y^2 - 2x^2 - 4xy^3 - 5xy^2 + x$ $+ y^4 + 2y^3 + y^2$	(3,0,4,6,11,24)
1	$x^3 + x^2y^4 + 2x^2y^3 + 4x^2y^2 + x^2 + 2xy^4 + 3xy^2 + 2y^4$	(3,0,4,6,8,16)
5,6	$2x^3 + 3x^2y^2 + 2x^2 + xy^4 + 4xy^2 + 2xy + x + y^4$	(3,0,4,5,8)
2,4,5,6,8	$-x^3 + x^2y^3 - 4x^2y^2 + 4x^2y + 2x^2 + 3xy^2 - 6xy - x + 2y$	(3,0,3,5,9,24)
3	$-x^3 + x^2y^3 - x^2y^2 - x^2y + 3x^2 + 3xy^2 - 4x + 2y + 2$	(3,3,0,5,9,18)
4,5,1,7	$-x^2y^2 - 2x^2y - x^2 + xy^3 + 2xy^2 + y^3 + 3y^2 + 2y$	(2,1,3,4,8,13)
4	$-x^2y^2 + xy^3 - xy^2 - xy + x + y^3 - y$	(2,1,3,4,7,7)
8	$-x^2 + xy^3 - xy^2 - xy + x - y^3 + y$	(2,0,3,4,7,7)
1	$-x^2 + xy^3 - xy^2 - xy - x - y^2$	(2,0,3,4,6,6)

$1 : x \rightsquigarrow x - 1, \quad 2 : x \rightsquigarrow x + 1, \quad 3 : y \rightsquigarrow y - 1, \quad 4 : y \rightsquigarrow y + 1$
 $5 : x \rightsquigarrow 1/x, \quad 6 : y \rightsquigarrow 1/y, \quad 7 : x \rightsquigarrow 1/x, \quad y \rightsquigarrow y/x, \quad 8 : x \rightsquigarrow x/y, \quad y \rightsquigarrow 1/y.$

8 and terminates. The resulting curve C_1 has minimal degree in x rather than y , so we swap variables (and adjust signs) to obtain the optimized equation

$$f_{16}(x, y) = y^2 + (x^3 + x^2 - x + 1)y + x^2 = 0,$$

which appears in Table 6. Corresponding changes to φ yield the birational map

$$r = 1 + (y + 1)/(xy + y^2), \quad s = 1 + (y + 1)/(xy - y^2),$$

listed in Table 7, which carries points on $f_{16}(x, y) = 0$ to points on $F_{16}(r, s) = 0$.

Table 5 shows the improvement in the minimal degree $d(C_i)$ and the number of terms $t(C_i)$ obtained when the initial curve C_0 is transformed to the locally optimal curve C_1 output by the algorithm. For comparison, we also list the genus of $X_1(N)$ (sequence A029937 in the OEIS [26], or see [13, Thm. 1.1] for a general formula).

The search procedure described above can, in principal, be applied to any plane curve, but its effectiveness depends largely on finding singularities with small integer coordinates. Empirically, this works well with the curves $F_N(r, s) = 0$, but other applications may wish to modify the list of atomic operations to incorporate more general translations. More sophisticated local search techniques such as simulated annealing [4] can significantly improve performance.

4. APPLICATION TO FINITE FIELDS

As described in the introduction, we may use our optimized equations for $Y_1(N)$ to efficiently generate elliptic curves containing a point of order N over a finite field \mathbb{F}_q , where q is prime to N . Here we briefly address a few topics relevant to practical implementation. We assume we have an optimized equation $f_N(x, y) = 0$ for $Y_1(N)$ with $d_y \leq d_x$, and consider how we may use $f_N(x, y)$ to efficiently generate a set of n elliptic curves over \mathbb{F}_q , each containing a point of order N .

TABLE 3. Short Weierstrass models for the genus 1 cases.

N	Weierstrass equation and birational map to $F_N(r, s) = 0$
11	$y^2 = x^3 - 432x + 8208$ $r = (y + 108)/216$ $s = 1 + (y - 108)/(6x + 72)$
14	$y^2 = x^3 - 675x + 13662$ $r = 1 + (108x - 36y + 3564)/(3x^2 - xy - 342x + 75y + 999)$ $s = (6x - 234)/(9x - y - 135)$
15	$y^2 = x^3 - 27x + 8694$ $t = (6x - 90)(18x + 6y - 918)$ $r = 1 - t/(x^2y - 189x^2 + 42xy - 4050x - 3y^2 + 441y - 1701)$ $s = 1 - t/(x^2y - 81x^2 + 6xy - 3402x - 3y^2 + 981y - 35721)$

Except for a small set of points (those leading to singular curves and those for which φ is undefined), there is a one-to-one correspondence between \mathbb{F}_q -rational points on $f_N(x, y) = 0$ and elliptic curves E/\mathbb{F}_q in Tate normal form on which the point $P = (0, 0)$ has order N (see Section 2). It follows that we can obtain a uniform distribution of pairs (E, P) from a uniformly distributed sample of the \mathbb{F}_q -rational points on $f_N(x, y) = 0$. We should note that this distribution is not uniform on E ; there is a pair (E, P) for each point P of order N in $E(\mathbb{F}_q)[N]$, and the number of such P may vary with E . The distribution on E can be precisely determined; see [7] for the case where q is prime.

When $d_y > 2$ it is not a trivial task to uniformly sample of the zero locus of f_N in an efficient manner. It is impractical to test random solutions to $f_N(x, y) = 0$, so instead we pick $x_i \in \mathbb{F}_q$ at random and compute the \mathbb{F}_q -rational roots y_{ij} of the polynomial $h_i(y) = f_N(x_i, y)$ (if any). For each such y_{ij} we include the point (x_i, y_{ij}) in our set of n points. Assuming $n \gg d_y$ this gives us an approximately uniform distribution (if we used only one root of h_i this would not be true), but the points obtained are not all independent. In practice this does not typically pose a problem. At most d points share a common x value, and after mapping the points back to $F_N(r, s) = 0$ and constructing $E(b, c)$ it is difficult to discern any relationship among the curves.⁵ With this approach we expect to compute the roots of n polynomials $h_i(y)$, on average, in order to obtain n points on $f_N(x, y) = 0$.

When $X_1(N)$ has genus 1, the projective closure of the curve $f_N(x, y) = 0$ is an elliptic curve, and we may use a more efficient approach: select a point at random and compute multiples of it via the group operation. We can generate n random multiples using a total of $O(\log q + n \log q / \log \log q)$ group operations via standard multi-exponentiation techniques [30], or we can compute multiples in an arithmetic sequence using just $n + O(\log q)$ group operations. The latter approach does not generate independent points, but it is highly efficient: only $O(1)$ operations in \mathbb{F}_q are required per point, assuming $n \gg \log q$. During this computation it is convenient to work with an elliptic curve in short Weierstrass form. These are provided in Table 3, along with the corresponding maps back to $F_N(r, s) = 0$.

⁵We could obtain a uniform independent distribution by using at most one root of each h_i , provided that we discard it with a certain probability depending on the number of roots h_i has, but this is not a very efficient solution.

Having generated a set of n points on $f_N(x, y) = 0$, we apply the appropriate birational map to obtain points on $F_N(r, s) = 0$. When doing so, we invert the denominators in parallel, via the usual Montgomery trick [5, Alg. 11.15]. We then compute (b, c) pairs, using $c = s(r - 1)$ and $b = rc$. In a field of characteristic not 2 or 3, we may convert the curve $E(b, c)$ to short Weierstrass form:

$$y^2 = x^3 + Ax + B.$$

Let $a = c - 1$ and $e = a^2 - 4b$. We may apply the admissible change of variables

$$(7) \quad u = (x - 3e)/36, \quad v = (y + 108(au + b))/216,$$

to the curve $E(b, c)$ defined by $v^2 + (1 - c)uv - bv = u^3 - bu^2$. After clearing denominators we obtain the isomorphic curve $y^2 = x^3 + Ax + B$, where

$$A = 27(24ab - e^2), \quad B = 54(e^3 - 36abe + 216b^2),$$

on which $(3e, -108b)$ is a point of order N .

At some point during the process described above, we need to check that the discriminant Δ of each curve obtained is nonzero. This is most efficiently done at the end using $\Delta = -4A^3 - 27B^2$. This may result in fewer than n curves being generated, but we can always obtain more points on $f_N(x, y) = 0$ (assuming $q \gg n$).

We remark that when $X_1(N)$ has genus 0, parameterizations that additionally provide a point of infinite order over \mathbb{Q} can be found in [1].

5. PRESCRIBING 4-TORSION

For odd N , we can use our equations for $Y_1(2N)$ to generate elliptic curves which contain a point of order $4N$ over \mathbb{F}_q in a manner that may be more efficient than using $Y_1(4N)$. We can also efficiently generate curves which contain a point of order $2N$ but do *not* contain a point of order $4N$. These results rely on efficiently computing the 4-torsion of an elliptic curve using a known a point of order 2, which we obtain from the point $P = (0, 0)$ of order $2N$. For odd N , a curve with a point of order N has a point of order $4N$ if and only if it has a point of order 4.

In fact, we only need the x -coordinate of NP , which can be computed as described in Section 2. It will be convenient to work with the short Weierstrass form, so we assume that the point NP has been translated via (7) to the 2-torsion point $\beta = (x_0, 0)$ on the curve E defined by $y^2 = f(x) = x^3 + Ax + B$.

Our strategy is to use the value x_0 to determine whether $E(\mathbb{F}_q)$ contains a point of order 4 or not. In the best case this requires only a single test for quadratic residuacity in \mathbb{F}_q , and even in the worst case, a square root and two tests for quadratic residuacity suffice. If the result is not as desired, we discard E and test another curve with a point of order $2N$. On average we expect to test two curves. This is typically faster than using $Y_1(4N)$ or using $Y_1(N)$ and computing 4-torsion without a known point of order 2.

We rely on the following lemma, which is a standard result. Lacking a suitable reference, we give a short proof here.

Lemma 1. *If $\alpha = (u, v)$ and $\beta = (x_0, 0)$ are points on a nonsingular elliptic curve E defined by $y^2 = f(x) = x^3 + Ax + B$ over a field of characteristic not 2, then*

$$2\alpha = \beta \quad \iff \quad (u - x_0)^2 = f'(x_0),$$

where $f'(x) = 3x^2 + A$.

Proof. If $2\alpha = \beta$, then the duplication formula for elliptic curves [25, p. 59] implies

$$x_0 = \frac{u^4 - 2Au^2 - 8Bu + A^2}{4(u^3 + Au + B)}.$$

Therefore u must satisfy

$$u^4 - 4x_0u^3 - 2Au^2 - (4Ax_0 + 8B)u - 4Bx_0 + A^2 = 0.$$

Since $\beta = (x_0, 0) \in E$, we have $x_0^3 + Ax_0 + B = 0$. Substituting for B yields

$$u^4 - 4x_0u^3 - 2Au^2 + (8x_0^3 + 4Ax_0)u + 4x_0^4 + 4Ax_0^2 + A^2.$$

We now set $u = z + x_0$ and rewrite this as

$$(z^2 - (3x_0^2 + A))^2 = 0.$$

Therefore

$$(u - x_0)^2 = 3x_0^2 + A = f'(x_0),$$

as desired. Reversing the argument yields the converse, provided $f(u) \neq 0$. But if u is a root of f , then one can show that $(u - x_0)^2 = f'(x_0)$ implies $D(f) = 0$, contradicting the fact that E is nonsingular. \square

There may be 1 or 3 points of order 2 in $E(\mathbb{F}_q)$. The x -coordinates of the other two (if they exist) are the roots x_1 and x_2 of $f(x)/(x - x_0)$, which we can determine with the quadratic formula. We now give our main result for treating 4-torsion.

Proposition 2. *Let $(x_0, 0)$ be a point of order 2 on a nonsingular elliptic curve E defined by $y^2 = f(x) = x^3 + Ax + B$ over the field \mathbb{F}_q , with quadratic character χ . Let n be the number of roots of $f(x)$ in \mathbb{F}_q , and for $n = 3$, let x_1 and x_2 denote the other two roots.*

For $q \equiv 3 \pmod 4$:

- (1) *If $\chi(f'(x_0)) = 1$, then $E(\mathbb{F}_q)$ contains a point of order 4.*
- (2) *Otherwise, $E(\mathbb{F}_q)$ contains a point of order 4 if and only if $n = 3$ and $\chi(f'(x_1)) = 1$.*

For $q \equiv 1 \pmod 4$:

- (1) *If $n = 1$, then $E(\mathbb{F}_q)$ contains a point of order 4 if and only if $\chi(f'(x_0)) = 1$.*
- (2) *Otherwise, if $\chi(f'(x_0)) = 1$ (resp., $\chi(f'(x_0)) = -1$), then $E(\mathbb{F}_q)$ contains a point of order 4 if and only if $\chi(x_0 - x_1) = 1$ (resp., $\chi(x_1 - x_2) = 1$).*

Proof. Note that $f(x_i) = 0$ implies $f'(x_i) \neq 0$, since E is nonsingular, hence $\chi(f'(x_i)) = \pm 1$. Let \tilde{E} denote the quadratic twist of E over \mathbb{F}_q . By Lemma 1, each root x_i of $f(x)$ for which $\chi(f'(x_i)) = 1$ yields 4 points of order 4 (two pairs of inverses), either all in $E(\mathbb{F}_q)$, all in $\tilde{E}(\mathbb{F}_q)$, or split 2-2 between them. Recall that $\#E(\mathbb{F}_q) = q + 1 - t$ and $\#\tilde{E}(\mathbb{F}_q) = q + 1 + t$, where t is the trace of Frobenius, so 4 divides $\#E(\mathbb{F}_q)$ if and only if 4 divides $\#\tilde{E}(\mathbb{F}_q)$, and for $q \equiv 3 \pmod 4$, 8 divides $\#E(\mathbb{F}_q)$ if and only if 8 divides $\#\tilde{E}(\mathbb{F}_q)$.

We first consider $q \equiv 3 \pmod 4$.

Suppose $\chi(f'(x_0)) = 1$. If $n = 1$, then $E(\mathbb{F}_q)$ and $\tilde{E}(\mathbb{F}_q)$ both have two points of order 4. If $n = 3$, then at least one of $\#E(\mathbb{F}_q)$ or $\#\tilde{E}(\mathbb{F}_q)$ is divisible by 8, but then they both are, hence $E(\mathbb{F}_q)$ (and $\tilde{E}(\mathbb{F}_q)$) must contain a point of order 4, since the 2-rank of an elliptic curve over \mathbb{F}_q is at most 2.

Suppose $\chi(f'(x_0)) = -1$. If $n = 1$, then $E(\mathbb{F}_q)$ cannot contain a point of order 4, so assume $n = 3$. By Lemma 2, for $q \equiv 3 \pmod 4$ we have $\chi(f'(x_1)) = \chi(f'(x_2))$,

and if their common value is -1 then $E(\mathbb{F}_q)$ cannot have a point of order 4. If instead it is 1, then at least one of $\#E(\mathbb{F}_q)$ or $\#\tilde{E}(\mathbb{F}_q)$ is divisible by 8, hence both are, and as above, $E(\mathbb{F}_q)$ must contain a point of order 4.

We now consider $q \equiv 1 \pmod 4$.

If $n = 1$, then $E(\mathbb{F}_q)$ contains a point of order 4 if and only if $\chi(f'(x_0)) = 1$, as above, so assume $n = 3$. It follows from Theorem 4.2 of [17] that $E(\mathbb{F}_q)$ has a point of order 4 if and only if at least two of $x_0 - x_1$, $x_1 - x_2$, and $x_2 - x_0$ are squares in \mathbb{F}_q . We have $f'(x_0) = (x_0 - x_1)(x_0 - x_2)$, so if $\chi(f'(x_0)) = 1$, then it suffices to check $\chi(x_0 - x_1)$, and if $\chi(f'(x_0)) = -1$, then it suffices to check $\chi(x_1 - x_2)$. \square

Lemma 2. *Let $f(x)$ be a monic cubic polynomial with distinct roots x_0, x_1, x_2 in \mathbb{F}_q , with q odd. We have*

$$\chi(-1)\chi(f'(x_0))\chi(f'(x_2))\chi(f'(x_2)) = 1.$$

In particular, the number of squares in the set $\{f'(x_0), f'(x_1), f'(x_2)\}$ is even when $q \equiv 1 \pmod 4$ and odd when $q \equiv 3 \pmod 4$.

Proof. Recall that for a monic f of degree $n = 3$, the discriminant of f is given by

$$D(f) = (-1)^{n(n-1)/2}R(f, f') = -R(f, f'),$$

where $R(f, f')$ is the resultant. Since f is monic, we have $R(f, f') = \prod f'(x_i)$, thus

$$D(f) = -f'(x_0)f'(x_1)f'(x_2).$$

The roots of f are distinct, so $D(f) \neq 0$. By the Stickelberger-Swan Theorem (Corollary 1 in [28]), $D(f)$ must be a square in \mathbb{F}_q , since f is degree 3 and has 3 irreducible factors. The lemma then follows, since $\chi(D(f)) = 1$. \square

We note that in Proposition 2, when (1) fails to hold it is quite likely that E has trivial 4-torsion. On average, this probability is about 90% (it can be computed precisely via [7, 9]). As a practical optimization, when seeking a point of order $4N$, if condition (1) fails we may simply discard the curve and test another. When $q \equiv 3 \pmod 4$ this reduces to a test for quadratic residuacity in \mathbb{F}_q , and we expect two tests of curves generated with $Y_1(2N)$ will suffice to produce a curve with a point of order $4N$.

As a final remark, we note the following generalization to our approach to prescribing 4-torsion. In [21], Miret et al. give an algorithm to determine a point of maximal 2-power order on an elliptic curve over a finite field. Their algorithm is based on successive halving, and can be accelerated if given as input a point of order 2^i for some $i \geq 1$. Thus we can use their algorithm to efficiently search for an elliptic curve with a point of order $2^k N$ using curves generated with $Y_1(2^i N)$, where $1 \leq i < k$. The optimal choice of i depends on k and the equations for $Y_1(2^i N)$, but will often be $i = 1$. This approach is especially effective in cases where the 2-Sylow subgroup of $E(\mathbb{F}_q)$ is cyclic, which happens more often than not.

6. APPENDIX

For reasons of space, most of the tables that follow are restricted to $N \leq 30$, and we omit some data. Complete results for $N \leq 50$ are available online at <http://math.mit.edu/~drew>.

TABLE 4. Raw equations $F_N(r, s) = 0$.

N	$F_N(r, s)$
6	$s - 1$
7	$r - s$
8	$rs - 2r + 1$
9	$r - s^2 + s - 1$
10	$rs^2 - 3rs + r + s^2$
11	$r^2 - rs^3 + 3rs^2 - 4rs + s$
12	$r^2s - 3r^2 + rs + 3r - s^2 - 1$
13	$r^3 - r^2s^4 + 5r^2s^3 - 9r^2s^2 + 4r^2s - 2r^2 - rs^3 + 6rs^2 - 3rs + r - s^3$
14	$r^2s^3 - 5r^2s^2 + 6r^2s - r^2 + rs^4 - 3rs^3 + 6rs^2 - 7rs + r + s$
15	$r^3 - r^2s^5 + 7r^2s^4 - 18r^2s^3 + 19r^2s^2 - 10r^2s - rs^5 + 4rs^4 - 5rs^2 + 5rs - s^5$ $+ s^4 - s^3 + s^2 - s$
16	$r^3s^2 - 4r^3s + 2r^3 + 3r^2s^2 + 2r^2s - 2r^2 - rs^5 + 4rs^4 - 10rs^3 + 6rs^2 - 3rs$ $+ r + s^4$
17	$r^5 - r^4s^6 + 9r^4s^5 - 31r^4s^4 + 50r^4s^3 - 39r^4s^2 + 10r^4s - 3r^4 - r^3s^6 + 3r^3s^5$ $+ 12r^3s^4 - 46r^3s^3 + 54r^3s^2 - 15r^3s + 3r^3 - r^2s^6 - 3r^2s^5 + 9r^2s^4 + r^2s^3$ $- 21r^2s^2 + 6r^2s - r^2 + rs^7 - 3rs^6 + 6rs^5 - 10rs^4 + 11rs^3 - s^3$
18	$r^4s^3 - 6r^4s^2 + 9r^4s - r^4 + r^3s^5 - 7r^3s^4 + 20r^3s^3 - 19r^3s^2 - 8r^3s + r^3 + r^2s^4$ $- 11r^2s^3 + 28r^2s^2 + rs^4 - 5rs^3 - 8rs^2 + s^4 + s^3 + s^2$
19	$r^6 - r^5s^7 + 11r^5s^6 - 48r^5s^5 + 105r^5s^4 - 121r^5s^3 + 69r^5s^2 - 20r^5s - r^5$ $- 2r^4s^7 + 12r^4s^6 - 9r^4s^5 - 60r^4s^4 + 144r^4s^3 - 105r^4s^2 + 35r^4s - 3r^3s^7$ $+ 3r^3s^6 + 21r^3s^5 - 30r^3s^4 - 41r^3s^3 + 51r^3s^2 - 21r^3s + r^2s^9 - 6r^2s^8 + 21r^2s^7$ $- 50r^2s^6 + 66r^2s^5 - 31r^2s^4 + 25r^2s^3 - 18r^2s^2 + 7r^2s + 3rs^6 - 15rs^5 + 10rs^4$ $- 6rs^3 + 3rs^2 - rs + s^6$
20	$r^5s^2 - 5r^5s + 5r^5 + 5r^4s^2 - 10r^4 - r^3s^7 + 9r^3s^6 - 35r^3s^5 + 70r^3s^4 - 85r^3s^3$ $+ 51r^3s^2 - 9r^3s + 10r^3 + 10r^2s^5 - 35r^2s^4 + 60r^2s^3 - 50r^2s^2 + 10r^2s - 5r^2$ $- rs^7 + 3rs^6 - 6rs^5 + 10rs^4 - 15rs^3 + 16rs^2 - 3rs + r - s^2$
21	$r^6 - r^5s^8 + 13r^5s^7 - 69r^5s^6 + 192r^5s^5 - 300r^5s^4 + 261r^5s^3 - 119r^5s^2$ $+ 21r^5s - 4r^5 - r^4s^9 + 10r^4s^8 - 45r^4s^7 + 141r^4s^6 - 345r^4s^5 + 576r^4s^4$ $- 551r^4s^3 + 273r^4s^2 - 49r^4s + 6r^4 - r^3s^{10} + 10r^3s^9 - 51r^3s^8 + 159r^3s^7$ $- 316r^3s^6 + 450r^3s^5 - 551r^3s^4 + 489r^3s^3 - 247r^3s^2 + 42r^3s - 4r^3 + 3r^2s^8$ $- 31r^2s^7 + 109r^2s^6 - 172r^2s^5 + 203r^2s^4 - 181r^2s^3 + 97r^2s^2 - 14r^2s + r^2$ $+ 2rs^8 - 11rs^7 + 8rs^6 + 2rs^5 - 13rs^4 + 19rs^3 - 14rs^2 + rs + s^8 - s^7 + s^6 - s^5$ $+ s^4 - s^3 + s^2$
22	$r^6s^5 - 9r^6s^4 + 28r^6s^3 - 35r^6s^2 + 15r^6s - r^6 + r^5s^8 - 12r^5s^7 + 59r^5s^6$ $- 148r^5s^5 + 205r^5s^4 - 186r^5s^3 + 133r^5s^2 - 49r^5s + 3r^5 + r^4s^8 - 6r^4s^7$ $- 8r^4s^6 + 118r^4s^5 - 260r^4s^4 + 249r^4s^3 - 164r^4s^2 + 58r^4s - 3r^4 + r^3s^8$ $- 30r^3s^6 + 34r^3s^5 + 70r^3s^4 - 106r^3s^3 + 80r^3s^2 - 30r^3s + r^3 + r^2s^8$ $+ 6r^2s^7 - 7r^2s^6 - 25r^2s^5 + 5r^2s^4 + 14r^2s^3 - 16r^2s^2 + 7r^2s - rs^9 + 3rs^8$ $- 8rs^7 + 21rs^6 - 15rs^5 + 10rs^4 - 6rs^3 + 3rs^2 - rs - s^7$
23	$r^9 - r^8s^9 + 15r^8s^8 - 94r^8s^7 + 319r^8s^6 - 636r^8s^5 + 756r^8s^4 - 520r^8s^3$ $+ 189r^8s^2 - 35r^8s - 2r^8 - 4r^7s^9 + 39r^7s^8 - 120r^7s^7 + 28r^7s^6 + 597r^7s^5$ $- 1341r^7s^4 + 1256r^7s^3 - 525r^7s^2 + 105r^7s + r^7 - 10r^6s^9 + 45r^6s^8 + 24r^6s^7$ $- 357r^6s^6 + 324r^6s^5 + 570r^6s^4 - 1130r^6s^3 + 576r^6s^2 - 126r^6s + r^5s^{13} - 14r^5s^{12}$ $+ 93r^5s^{11} - 370r^5s^{10} + 970r^5s^9 - 1827r^5s^8 + 2553r^5s^7 - 2296r^5s^6 + 1095r^5s^5$ $- 480r^5s^4 + 686r^5s^3 - 369r^5s^2 + 84r^5s + r^4s^{12} - 21r^4s^{11} + 165r^4s^{10} - 650r^4s^9$ $+ 1530r^4s^8 - 2562r^4s^7 + 2957r^4s^6 - 2046r^4s^5 + 780r^4s^4 - 415r^4s^3 + 171r^4s^2$ $- 36r^4s + r^3s^{12} - 15r^3s^{11} + 66r^3s^{10} - 84r^3s^9 - 45r^3s^8 + 402r^3s^7$ $- 833r^3s^6 + 837r^3s^5 - 351r^3s^4 + 145r^3s^3 - 48r^3s^2 + 9r^3s + r^2s^{12} - 9r^2s^{11}$ $+ 13r^2s^{10} - r^2s^9 - 24r^2s^8 + 28r^2s^7 + 42r^2s^6 - 126r^2s^5 + 56r^2s^4 - 21r^2s^3$ $+ 6r^2s^2 - r^2s + rs^{12} - 3rs^{11} + 6rs^{10} - 10rs^9 + 15rs^8 - 21rs^7 + 21rs^6 - s^6$

TABLE 5. Optimization results of Algorithm 2.

N	g	$d(C_0)$	$d(C_1)$	$t(C_0)$	$t(C_1)$	k_{\max}	$\ell(C_0, C_1)$
10	0	4	0	1	1	2	10
11	1	2	2	5	4	2	4
12	0	2	0	6	1	2	13
13	2	3	2	11	6	2	13
14	1	2	2	10	4	2	11
15	1	3	2	15	5	3	18
16	2	3	2	13	6	5	23
17	5	5	4	28	12	5	23
18	2	4	2	19	6	5	24
19	7	6	5	39	18	4	23
20	3	5	3	28	6	4	23
21	5	6	4	55	11	4	18
22	6	6	4	50	17	7	40
23	12	9	7	87	38	7	25
24	5	6	5	41	20	6	25
25	12	10	8	114	46	6	20
26	10	8	7	82	27	5	32
27	13	11	8	135	52	4	19
28	10	10	7	115	30	2	16
29	22	14	11	214	88	8	32
30	9	10	8	109	46	7	23
31	26	16	13	279	124	6	23
32	17	13	10	190	78	7	19
33	21	16	12	319	109	6	29
34	21	14	11	235	88	7	22
35	25	19	15	438	142	4	19
36	17	14	11	224	94	7	23
37	40	23	18	582	225	4	19
38	28	18	14	383	140	6	27
39	33	22	17	586	212	4	20
40	25	19	15	412	171	5	22
41	51	28	22	870	336	8	49
42	25	20	15	442	165	8	27
43	57	31	24	1065	408	6	23
44	36	24	19	654	208	3	21
45	41	29	23	960	368	4	19
46	45	26	21	791	285	6	23
47	70	37	29	1526	1768	6	33
48	37	26	19	773	257	7	23
49	69	39	31	1791	900	6	37
50	48	30	23	1040	391	8	42

The curves C_0 and C_1 are the raw and optimized forms of $Y_1(N)$, respectively, and g is the genus of $X_1(N)$. The column $d(C_i)$ lists the minimum of the degree of C_i in x or y , and $t(C_i)$ is the number of terms. The column $\ell(C_0, C_1)$ gives the length of the path traveled by the algorithm of Section 3 to reach C_1 from C_0 (typically not a shortest path), and $k_{\max} \leq R = 8$ is the maximum search radius used prior to reaching C_1 .

TABLE 6. Optimized equations $f_N(x, y) = 0$.

N	$f_N(x, y)$
11	$y^2 + (x^2 + 1)y + x$
13	$y^2 + (x^3 + x^2 + 1)y - x^2 - x$
14	$y^2 + (x^2 + x)y + x$
15	$y^2 + (x^2 + x + 1)y + x^2$
16	$y^2 + (x^3 + x^2 - x + 1)y + x^2$
17	$y^4 + (x^3 + x^2 - x + 2)y^3 + (x^3 - 3x + 1)y^2 - (x^4 + 2x)y + x^3 + x^2$
18	$y^2 + (x^3 - 2x^2 + 3x + 1)y + 2x$
19	$y^5 - (x^2 + 2)y^4 - (2x^3 + 2x^2 + 2x - 1)y^3 + (x^5 + 3x^4 + 7x^3 + 6x^2 + 2x)y^2 - (x^5 + 2x^4 + 4x^3 + 3x^2)y + x^3 + x^2$
20	$y^3 + (x^2 + 3)y^2 + (x^3 + 4)y + 2$
21	$y^4 + (3x^2 + 1)y^3 + (x^5 + x^4 + 2x^2 + 2x)y^2 + (2x^4 + x^3 + x)y + x^3$
22	$y^4 + (x^3 + 2x^2 + x + 2)y^3 + (x^5 + x^4 + 2x^3 + 2x^2 + 1)y^2 + (x^5 - x^4 - 2x^3 - x^2 - x)y - x^4 - x^3$
23	$y^7 + (x^5 - x^4 + x^3 + 4x^2 + 3)y^6 + (x^7 + 3x^5 + x^4 + 5x^3 + 7x^2 - 4x + 3)y^5 + (2x^7 + 3x^5 - x^4 - 2x^3 - x^2 - 8x + 1)y^4 + (x^7 - 4x^6 - 5x^5 - 6x^4 - 6x^3 - 2x^2 - 3x)y^3 - (3x^6 - 5x^4 - 3x^3 - 3x^2 - 2x)y^2 + (3x^5 + 4x^4 + x)y - x^2(x + 1)^2$
24	$y^5 + (x^4 + 4x^3 + 3x^2 - x - 2)y^4 - (2x^4 + 8x^3 + 7x^2 - 1)y^3 - (2x^5 + 4x^4 - 3x^3 - 5x^2 - x)y^2 + (2x^5 + 5x^4 + 2x^3)y + x^6 + x^5$
25	$y^8 + (4x^2 + 7x - 4)y^7 - (x^5 - x^4 - 14x^3 - 4x^2 + 24x - 6)y^6 - (x^7 + 4x^6 - 3x^5 - 18x^4 + 15x^3 + 33x^2 - 30x + 4)y^5 - (x^8 + 2x^7 - 8x^6 - 14x^5 + 24x^4 + 17x^3 - 41x^2 + 16x - 1)y^4 + (x^8 + 6x^7 + 3x^6 - 20x^5 - 3x^4 + 28x^3 - 19x^2 + 3x)y^3 - (3x^7 + 9x^6 - 3x^5 - 13x^4 + 11x^3 - 3x^2)y^2 + (3x^6 + 4x^5 - 4x^4 + x^3)y - x^5$
26	$y^6 + (3x^2 + 4x - 2)y^5 + (3x^4 + 10x^3 - 9x + 1)y^4 + (x^6 + 7x^5 + 8x^4 - 14x^3 - 11x^2 + 6x)y^3 + (x^7 + 4x^6 - x^5 - 13x^4 + 2x^3 + 10x^2 - x)y^2 - (x^6 - 7x^4 - 4x^3 + 2x^2)y - x^4 - x^3$
27	$y^8 + (3x^2 + 6x - 3)y^7 - (3x^5 - 18x^3 - 9x^2 + 18x - 3)y^6 - (x^8 + 8x^7 + 13x^6 - 21x^5 - 48x^4 + 20x^3 + 42x^2 - 18x + 1)y^5 - (x^{10} + 6x^9 + 12x^8 - 14x^7 - 72x^6 - 27x^5 + 93x^4 + 33x^3 - 45x^2 + 6x)y^4 + (x^{10} + 11x^9 + 40x^8 + 36x^7 - 69x^6 - 105x^5 + 33x^4 + 54x^3 - 15x^2)y^3 - (4x^9 + 30x^8 + 63x^7 + 10x^6 - 69x^5 - 24x^4 + 19x^3)y^2 + (6x^8 + 27x^7 + 27x^6 - 6x^5 - 12x^4)y - 3x^7 - 6x^6 - 3x^5$
28	$y^7 + 3xy^6 + (x^5 + 3x^4 + 5x^3 + 9x^2 + 2x)y^5 - (2x^5 - 6x^3 + 2x^2 + 2x)y^4 + (3x^6 + 16x^5 + 18x^4 - 2x^2)y^3 + (x^7 - 2x^6 - 20x^5 - 28x^4 - 12x^3 - 2x^2)y^2 - (2x^7 + 3x^6 - 5x^5 - 10x^4 - 5x^3 - x^2)y + x^7 + 2x^6 + x^5$
29	$y^{11} + (2x^3 + 5x^2 + 5x - 3)y^{10} + (x^6 + 8x^5 + 18x^4 + 11x^3 - 5x^2 - 12x + \dots$
30	$y^8 - (2x^3 + 4x^2 + x + 5)y^7 + (x^6 + 4x^5 + 6x^4 + 9x^3 + 14x^2 + 10)y^6 - (x^7 + 4x^6 + 9x^5 + 10x^4 + 4x^3 + 15x^2 - 10x + 10)y^5 + (x^8 + 4x^7 + 4x^6 - 5x^4 - 20x^3 + 5x^2 - 20x + 5)y^4 + (3x^7 + 11x^6 + 15x^5 + 9x^4 + 18x^3 - 9x^2 + 14x - 1)y^3 + (3x^6 + 9x^5 + 14x^4 + 2x^3 + 13x^2 - 3x)y^2 + (x^5 + x^4 + 4x^3 - 3x^2)y - x^3$

$f_N(x, y) = x$ for $N \in \{6, 7, 8, 9, 10, 12\}$. The polynomial f_{29} is not displayed in full. Complete polynomials for $N \leq 50$ are available at <http://math.mit.edu/~drew>.

TABLE 7. Birational maps from $f_N(x, y) = 0$ to $F_N(r, s) = 0$.

N	φ
6	$r = x, \quad s = 1$
7	$r = x, \quad s = x$
8	$r = 1/(2 - x), \quad s = x$
9	$r = x^2 - x + 1, \quad s = x$
10	$r = -x^2/(x^2 - 3x + 1), \quad s = x$
11	$r = 1 + xy, \quad s = 1 - x$
12	$r = (2x^2 - 2x + 1)/x, \quad s = (3x^2 - 3x + 1)/x^2$
13	$r = 1 - xy, \quad s = 1 - xy/(y + 1)$
14	$r = 1 - (x + y)/((y + 1)(x + y + 1)), \quad s = (1 - x)/(y + 1)$
15	$r = 1 + (xy + y^2)/(x^3 + x^2y + x^2), \quad s = 1 + y/(x^2 + x)$
16	$r = (x^2 - xy + y^2 + y)/(x^2 + x - y - 1), \quad s = (x - y)/(x + 1)$
17	$r = (x^2 + x - y)/(x^2 + xy + x - y^2 - y), \quad s = (x + 1)/(x + y + 1)$
18	$r = (x^2 - xy - 3x + 1)/((x - 1)^2(xy + 1)),$ $s = (x^2 - 2x - y)/(x^2 - xy - 3x - y^2 - 2y)$
19	$r = 1 + x(x + y)(y - 1)/((x + 1)(x^2 - xy + 2x - y^2 + y)),$ $s = 1 + x(y - 1)/((x + 1)(x - y + 1))$
20	$r = 1 + (x^3 + xy + x)/((x - 1)^2(x^2 - x + y + 1)),$ $s = 1 + (x^2 + y + 1)/((x - 1)(x^2 - x + y + 2))$
21	$r = 1 + (y^2 + y)(xy + y + 1)/((xy + 1)(xy - y^2 + 1)),$ $s = 1 + (y^2 + y)/(xy + 1)$
22	$r = (x^2y + x^2 + xy + y)/(x^3 + 2x^2 + y), \quad s = (xy + y)/(x^2 + y)$
23	$r = (x^2 + x + y + 1)/(x^2 - xy), \quad s = (x + y + 1)/x$
24	$r = (x^2 + x - y + 1)/(x^2 + xy - y^2 + y), \quad s = (x + 1)/(x + y)$
25	$r = (x^2 + xy + y^2 - y)/(x^2 + x + y - 1), \quad s = (x + y)/(x + 1)$
26	$r = (x^3y + 3x^2y - x^2 + xy^2)/((x + 1)(x^2y + x^2 + 3xy + y^2)),$ $s = (xy - x)/(xy + y)$
27	$r = (-x^3 - x^2 - x - y)/(x^2y + xy - x - y), \quad s = (-x^2 - x - y)/(xy - x - y)$
28	$r = 1 + (xy + y)/((y - 1)(xy - x + 2y - 1)),$ $s = 1 - (xy + y)/((y - 1)(x - y + 1))$
29	$r = (-x^3 - x^2 - x - y)/(x^2y + xy - x - y)$ $s = 1 - (x^2 + xy)/(xy - x - y)$
30	$r = (x^2y + x + y)/(x^2y - xy + x),$ $s = (x^2y + xy + x + y)/(x^2y + x)$

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