Product formulas for the 5-division points on the Tate normal form and the Rogers-Ramanujan continued fraction

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Abstract

Explicit formulas are proved for the 5-torsion points on the Tate normal form $E_5$ of an elliptic curve having $(X,Y) = (0,0)$ as a point of order 5. These formulas express the coordinates of points in $E_5[5] - \langle(0,0)\rangle$ as products of linear fractional quantities in terms of fifth roots of unity and a parameter $u$, where the parameter $b$ which defines the curve $E_5$ is given as $b = (\varepsilon u^5 - \varepsilon^{-5})/(u^5 + 1)$ and $\varepsilon = (-1 + \sqrt{5})/2$. If $r(\tau)$ is the Rogers-Ramanujan continued fraction and $b = r^5(\tau)$, then the coordinates of points of order 5 in $E_5[5] - \langle(0,0)\rangle$ are shown to be products of linear fractional expressions in $r(5\tau)$ with coefficients in $\mathbb{Q}(\zeta_5)$.

1 Introduction.

In previous papers, several new formulas for the 3-division points on the Deuring normal form

$$E_3 : Y^2 + \alpha XY + Y = X^3,$$

and the 4-division points on the Tate normal form

$$E_4 : Y^2 + XY + bY = X^3 + bX^2,$$

have recently been given. For the curve $E_3$, the point

$$(X,Y) = \left( \frac{-3\beta}{\alpha(\beta - 3)}, \frac{\beta - 3\omega}{\beta - 3} \right)$$
represents the six points of order 3 in $E_3[(3)] - \langle(0,0)\rangle$, where $\omega$ is one of the two primitive cube roots of unity and $(\alpha, \beta)$ lies on the Fermat cubic

$$Fer_3 : \ 27X^3 + 27Y^3 = X^3Y^3.$$  

(See [8].) Setting $b = 1/\alpha^4$ in the equation for $E_4$, a point of order 4 in $E_4[4] - \langle(0,0)\rangle$ is the point

$$(X,Y) = (-\beta_1 \beta_2 \beta_3, \beta_1^2 \beta_2^2 \beta_3),$$

where

$$\beta_n = \frac{\beta + 2i^n}{2\beta}, \quad i = \sqrt{-1},$$

and the point $(\alpha, \beta)$ lies on the Fermat quartic

$$Fer_4 : \ 16X^4 + 16Y^4 = X^4Y^4.$$  

Replacing $\beta$ by $i\beta$ (so $\beta_n$ becomes $\beta_{n-1}$) and $i$ by $-i$ in the above formula yields 8 of the 12 points of order 4 in $E_4[4]$. The other points of order 4 are $(0,0), (0, -b) \in \langle(0,0)\rangle$ and the two points $(-2b, 2\beta_1 \beta_3 b)$ and $(-2b, 2\beta_2 \beta_4 b)$. (See [5], [6].)

Similar formulas have been given for the 6-torsion points on the Tate normal form $E_6$, by Lynch [5]. This normal form is

$$E_6 : \ Y^2 + aXY + bY = X^3 + bX^2, \quad b = -(a-1)(a-2).$$

Lynch’s formulas express the coordinates of 6-torsion points on $E_6$ as products of linear fractional quantities in $\alpha$ and $\beta$ and a cube root of unity $\omega$, where $(\alpha, \beta)$ is a point on the elliptic curve

$$Y^2 = X^3 + 1$$

and the parameter $a$ is given by

$$a = \frac{10\beta^2 - 18}{9(\beta^2 - 1)} = \frac{10\alpha^3 - 8}{9\alpha^3}.$$  

The exact formulas are somewhat complicated; these can be found in [5].

In this note I will prove analogous formulas for the non-trivial points of order 5 on the Tate normal form

$$E_5(b) : \ Y^2 + (1+b)XY + bY = X^3 + bX^2,$$

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on which the point \((0,0)\) is a point of order 5. (See the discussion in [7] for more on the Tate normal form.) These formulas are similar to the expressions (1.1) for the points of order 4 on the curve \(E_4\), in that they express the \(X\) and \(Y\) coordinates of points in \(E_5(b)[5] - \left\langle (0,0) \right\rangle\) as products of linear fractional quantities in a parameter \(u\), where

\[
b = \frac{\varepsilon^5 u^5 + \bar{\varepsilon}^5}{u^5 + 1}, \quad \varepsilon = \frac{-1 + \sqrt{5}}{2}, \quad \bar{\varepsilon} = \frac{-1 - \sqrt{5}}{2};
\]

and the coefficients in these linear fractional expressions lie in the field \(\mathbb{Q}(\zeta_5)\) of fifth roots of unity. These expressions are quite a bit simpler than the formulas given by Verdure [13], in which the \(Y\)-coordinates of the 5-torsion points are expressed in terms of a formal root \(x_0\) of the 5-division polynomial.

In this paper, the quantity

\[
u^5 = -\frac{b - \varepsilon^5}{b - \bar{\varepsilon}^5},
\]

which is up to sign the same as Verdure’s Kummer element (see Theorem 5 in [13]), arises naturally in the process of solving the quintic equation \(g(X) = 0\) below using Watson’s method (see [4] and Section 5 of this paper).

The expressions given in Theorem 2.1 below also allow one to check “by hand” that these points do indeed have order 5, assuming that they represent points on \(E_5\). (See Theorem 3.1 and the discussion in Section 3.) These formulas will be used in a forthcoming paper to prove the case \(p = 5\) of the conjectures stated in [9] and [10].

These formulas also have a strong connection to the Rogers-Ramanujan continued fraction, which is

\[
r(\tau) = \frac{q^{1/5}}{1 + \frac{q}{1 + \frac{q^2}{1 + \frac{q^3}{1 + \cdots}}}} = \frac{q^{1/5}}{1 + \frac{q}{1 + \frac{q^2}{1 + \frac{q^3}{1 + \cdots}}}} = \frac{q^{1/5}}{1 + \frac{q}{1 + \frac{q^2}{1 + \frac{q^3}{1 + \cdots}}}},
\]

and whose value is the modular function for \(\Gamma(5)\) given by

\[
r(\tau) = q^{1/5} \prod_{n \geq 1} (1 - q^n)^{(n/5)}, \quad q = e^{2\pi i \tau}, \quad \tau \in \mathbb{H}.
\]

(The symbol \(\left( \frac{a}{b} \right)\) in the exponent is the Legendre symbol and \(\mathbb{H}\) is the upper half-plane. See [1], [2], and [3] and the references in the latter paper.). From
the formulas of [3] it follows easily that if \( b = r^5(\tau) \), then the parameter \( u \) described above may be taken to be

\[
u = \frac{1}{\varepsilon r \left( \frac{1}{5\tau} \right)} = -\frac{r(5\tau) - \bar{\varepsilon}}{r(5\tau) - \varepsilon}.
\] (1.3)

This yields the following.

**Theorem 1.1.** If \( b = r^5(\tau) \), for \( \tau \in \mathbb{H} \), then

\[
X = -\varepsilon \frac{r^4(5\tau) - 3r^3(5\tau) + 4r^2(5\tau) - 2r(5\tau) + 1}{r^2(5\tau) + r(5\tau) + \varepsilon^2}
\] (1.4)

is the \( X \)-coordinate of a point \( P = (X, Y) \) of order 5 on the elliptic curve \( E_5(b) \), which is not in the group \( \langle (0, 0) \rangle \). The \( Y \)-coordinates of \( P \) and \( -P \) are products of linear fractional expressions in \( r(5\tau) \) with coefficients in \( \mathbb{Q}(\zeta_5) \); and the same holds for the coordinates of all points in \( E_5(b)[5] - \langle (0, 0) \rangle \).

This formula (1.4) is closely related to a well-known identity of Ramanujan:

\[
\frac{r^5(\tau)}{r(5\tau)} = \frac{r^4(5\tau) - 3r^3(5\tau) + 4r^2(5\tau) - 2r(5\tau) + 1}{r^2(5\tau) + 2r(5\tau) + 3r(5\tau) + 1}.
\]

(See [2], p. 167; also [3], equation (7.4), except that the term \( r(5\tau) \) on the left side of (7.4) should be \( r(\tau) \).) This identity allows us to express the formula for \( X \) in the following form:

\[
X = -\varepsilon \frac{r^5(\tau)}{\sqrt{5}} \left( r(5\tau) + r^2(5\tau) + \varepsilon^2 \right).
\]

One of the corresponding \( Y \)-coordinates is given by the formula

\[
Y_1 = \left( \frac{\zeta - 1}{\sqrt{5}} \right)^3 \frac{r^5(\tau)}{r(5\tau)} (r^4(5\tau) - 3r^3(5\tau) + 4r^2(5\tau) - 2r(5\tau) + 1) \cdot Z,
\]

where

\[
Z = \frac{r(5\tau) - (\zeta^3 + \zeta^4)}{(r(5\tau) - (\zeta^2 + \zeta^4))(r(5\tau) - (1 + \zeta^3))}, \quad \zeta = \zeta_5;
\]

and the other is obtained by replacing \( \zeta \) in this formula by \( \zeta^4 \). (See equations (4.3) and (4.4) below.) Replacing \( \zeta \) by \( \zeta^2 \) and interchanging \( \varepsilon \) and \( \bar{\varepsilon} \) in these
formulas yields the coordinates of the points \pm P. Thus the subgroup \langle P \rangle is determined by the action of \text{Gal}(\mathbb{Q}(\zeta)/\mathbb{Q}) on P. (See Theorem 3.1.)

In the related paper [11] this connection with \( r(\tau) \) will be applied to show the following result in the theory of complex multiplication. If \(-d = d_K f^2\) is the discriminant of the order \( R_{-d} \) of conductor \( f \) in the quadratic field \( K = \mathbb{Q}(\sqrt{-d}) \), where \( \left( \frac{-d}{5} \right) = 1 \) \( (d \neq 4f^2) \); and if \( \tau \) has the value
\[
\tau = \frac{v + \sqrt{-d}}{10}, \quad v^2 + d \equiv 0 \pmod{4 \cdot 5^2}, \quad (v, f) = 1;
\]
then the unit \( r(5\tau) = r\left(\frac{v+\sqrt{-d}}{2}\right) \) generates the field \( F = \Sigma_5 \Omega_f \) over \( \mathbb{Q} \), where \( \Sigma_5 \) is the ray class field of conductor 5 over \( K \) and \( \Omega_f = K(j(\tau)) \) is the ring class field of conductor \( f \) over \( K \). Furthermore, for some primitive 5-th root of unity \( \zeta \),
\[
\mathbb{Q}(r(\tau)) = \Sigma_{\wp_5} \Omega_f, \quad \mathbb{Q}(\zeta r\left(\frac{-1}{5\tau}\right)) = \Sigma_{\wp_5'} \Omega_f, \quad (\zeta \neq 1),
\]
where \( \wp_5 \) is the prime ideal divisor of 5 in \( K \) for which \( \wp_5 \mid 5\tau \) and \( \wp_5' \) is the conjugate prime ideal. In particular, \( \mathbb{Q}(r(5\tau)) \) is a normal extension of \( \mathbb{Q} \), while \( \mathbb{Q}(r(\tau)) \) is not normal over \( \mathbb{Q} \), though both are abelian over \( K \). At any rate, values of the Rogers-Ramanujan function \( r(\tau) \) turn out to yield generators of small height for class fields of quadratic fields \( K \) in which the prime 5 splits. The reader is referred to [11] for a list of the minimal polynomials of these values for small values of \( d \).

2 Points of order 5 on \( E_5(b) \).

The \( X \)-coordinates of points of order 5 on \( E_5(b) \) which are not in the group
\[
\langle (0, 0) \rangle = \{ O, (0, 0), (0, -b), (-b, 0), (-b, b^2) \}
\]
are roots of the polynomial
\[
D_5(x) = 5x^{10} + (5 + 25b + 5b^2)x^9 + (1 + 38b + 44b^2 + 7b^3 + b^4)x^8
+ (9b + 127b^2 + 26b^3 + 3b^4 + b^5)x^7 + (36b^2 + 248b^3 + 19b^4 + 3b^5 + b^6)x^6
+ (8b^3 + 322b^4 + 71b^5 + 3b^6 - b^7)x^5 + (126b^4 + 293b^5 + 94b^6 + 12b^7 + b^8)x^4
+ (125b^5 + 180b^6 + 50b^7 + 5b^8)x^3 + (80b^6 + 65b^7 + 10b^8)x^2
+ (30b^7 + 10b^8)x + 5b^8.
\]
This follows easily from [12], Exercise 3.7 (p. 105), applied to the curve $E_5$, after factoring out $x(x + b)$ from the polynomial $\psi_5(x)$. (But note that the formula for $b_2$ on p. 42 should be $b_2 = a_1^2 + 4a_2$.) This polynomial factors into 5 times the product of two polynomials

$$g(X) = X^5 + \frac{1}{20}(\alpha - 5)(-3 - \alpha - 7b - 3b\alpha - 2b^2)X^4$$
$$+ \frac{\alpha}{5}b(1 + 2\alpha - 11b + 4b\alpha - b^2)X^3$$
$$+ \frac{1}{10}(\alpha - 5)b^2(-9 - 2\alpha - 6b + b\alpha - b^2)X^2 + (3b^3 + b^4)X + b^4,$$

where $\alpha^2 = 5$. Using Watson’s method of solving the for the roots of a quintic equation from [4], we find that the roots of $g(X)$ are given by

$$X = \frac{(5 - \alpha)}{100}((-18 + 8\alpha - 12b + 6b\alpha - 2b^2)u^4 + (-7 + 3\alpha + 12b - 4b\alpha + 2b^2)u^3$$
$$+ (-3 + \alpha - 7b + 7b\alpha - 2b^2)u^2 + (-2 + 22b + 2b^2)u - 3 - \alpha - 7b + 3b\alpha - 2b^2)$$
$$= \frac{(5 - \alpha)}{100}(A_4u^4 + A_3u^3 + A_2u^2 + A_1u + A_0),$$

where

$$u^5 = \phi(b) = \frac{2b + 11 + 5\alpha}{-2b - 11 + 5\alpha} = \frac{b - \bar{\varepsilon}^5}{-b + \varepsilon^5},$$

$$\varepsilon = \frac{-1 + \alpha}{2} = \zeta + \zeta^4, \quad \bar{\varepsilon} = \frac{-1 - \alpha}{2} = \zeta^2 + \zeta^3,$$

and $\zeta$ is a primitive 5-th root of unity. (The details of Watson’s method applied to the polynomial $g(X)$ are given in the appendix. Note that $\varepsilon$ and $\bar{\varepsilon}$ are the quadratic Gaussian periods for $\mathbb{Q}(\zeta)$.) This may be verified on Maple by plugging the expression for $X$ into $g(X)$, and using the formula

$$b = \frac{\varepsilon^5u^5 + \varepsilon^5}{u^5 + 1} \quad (2.1)$$

for $b$ in terms of $u$.

Using this formula for $b$, the above value of $X$ can also be written as

$$X = \frac{(-7 + 3\alpha)(-2u^2 + (1 + \alpha)u - 3\alpha - 7)(2u^2 + (4 + 2\alpha)u + 3\alpha + 7)}{4(-2u^2 + (1 + \alpha)u - 2)(u + 1)^2}. \quad (2.2)$$
The formulas (2.1) and (2.2) show that there are 10 such values, since replacing $u$ by $\zeta^i u$ (and leaving $\alpha$ unchanged), or replacing $\alpha$ by $-\alpha$ and $u$ by $1/(\zeta^i u)$ gives the other X-coordinates. It is easy to see that these transformations yield distinct points in $E_5(b)[5]$, since the X-coordinates have distinct sets of poles. Setting $\alpha = \zeta - \zeta^2 - \zeta^3 + \zeta^4$, this expression factors:

$$X = -\varepsilon^4 \frac{[u - (1 + \zeta^2)][u - \zeta(1 + \zeta)][u - \zeta^2(1 + \zeta)][u - \zeta^3(1 + \zeta)]}{(u + \zeta^2)(u + \zeta^3)(u + 1)^2}.$$

The zeros and poles of this function of $u$ are all units in $Q(\zeta)$. We will now show that the corresponding Y-coordinates factor in a similar way. We derive the following theorem using calculations in an extension of the field $Q(\zeta, b)$, but the formulas themselves are valid over any field whose characteristic is different from 5.

**Theorem 2.1.** If $b = \varepsilon^5 u^{\frac{a}{5} + \varepsilon^5}$, the X-coordinates of the points of order 5 in $E_5[5] - \langle(0,0)\rangle$ are given by the formula

$$X = -\varepsilon^4 \frac{[u - (1 + \zeta^2)][u - \zeta(1 + \zeta)][u - \zeta^2(1 + \zeta)][u - \zeta^3(1 + \zeta)]}{(u + \zeta^2)(u + \zeta^3)(u + 1)^2}, \quad (2.3)$$

where $\varepsilon = \frac{-1+\alpha}{2}$, $\alpha = \pm \sqrt{5} = \zeta - \zeta^2 - \zeta^3 + \zeta^4$, and $\zeta = \zeta_5$ is a primitive 5-th root of unity. The corresponding Y-coordinates are given by

$$Y_1 = \varepsilon^7 \frac{[u - (1 + \zeta^2)][u - \zeta(1 + \zeta)][u - \zeta^2(1 + \zeta)][u - \zeta^3(1 + \zeta)]}{(u + \zeta^2)(u + \zeta^3)(u + 1)^2},$$

and

$$Y_2 = \varepsilon^7 \frac{[u - (1 + \zeta^2)][u - \zeta(1 + \zeta)][u - \zeta^2(1 + \zeta)][u - \zeta^3(1 + \zeta)]}{(u + \zeta)(u + \zeta^2)(u + \zeta^3)^2(u + 1)^3}.$$

**Proof.** Putting (2.1) and (2.2) into the equation for $E_5$ yields the following equation for $Y$:

$$AY^2 + B Y + C = 0,$$
where
\[
A = \frac{1}{8}(2u^2 + (-1 + \alpha)u + 2)(-2u^2 + (1 + \alpha)u - 2)^3(u + 1)^6;
\]
\[
B = \frac{-\varepsilon^7}{16}(-4u^3 + (3 + \alpha)u^2 - 2(1 + \alpha)u + 6 + 2\alpha)(-2u^2 + (1 + \alpha)u - 7 - 3\alpha)
\times(-2u^2 + (1 + \alpha)u - 2)(2u^2 + (4 + 2\alpha)u + 7 + 3\alpha)^2(u + 1)^3;
\]
\[
C = \frac{\varepsilon^{14}}{64}(-2u^2 + (1 + \alpha)u - 7 - 3\alpha)^3(2u^2 + (4 + 2\alpha)u + 7 + 3\alpha)^4.
\]

The discriminant of the quadratic is
\[
D = \frac{-5\alpha\varepsilon^{13}}{64}u^4(-2u^2 + (1 + \alpha)u - 7 - 3\alpha)^2(-2u^2 + (1 + \alpha)u - 2)^2
\times(2u^2 + (4 + 2\alpha)u + 7 + 3\alpha)^4(u + 1)^6,
\]
which is \(-\alpha\varepsilon = (\zeta^2 - \zeta^3)^2\) times a square. Thus, the roots of the quadratic are
\[
Y = \frac{-B \pm (\zeta^2 - \zeta^3)\alpha\varepsilon^6S}{2A} = \frac{-16B \pm 2(\zeta^2 - \zeta^3)(\zeta - \zeta^2 - \zeta^3 + \zeta^4)\varepsilon^6S}{32A},
\]
where
\[
S = u^2(-2u^2 + (1 + \alpha)u - 7 - 3\alpha)(-2u^2 + (1 + \alpha)u - 2)(2u^2 + (4 + 2\alpha)u + 7 + 3\alpha)^2(u + 1)^3.
\]
Now, \(1/\varepsilon = -\bar{\varepsilon} = -(\zeta^2 + \zeta^3)\), which gives that
\[
(\zeta^2 - \zeta^3)(\zeta - \zeta^2 - \zeta^3 + \zeta^4)\varepsilon^6 = \varepsilon^7(-\zeta^3 + 3\zeta^2 + 2\zeta + 1).
\]

The numerator in the expression for \(Y\) then becomes
\[
-16B \pm 2(-\zeta^3 + 3\zeta^2 + 2\zeta + 1)\varepsilon^7S = \varepsilon^7(-2u^2 + (1 + \alpha)u - 7 - 3\alpha)
\times(-2u^2 + (1 + \alpha)u - 2)(2u^2 + (4 + 2\alpha)u + 7 + 3\alpha)^2(u + 1)^3
\times\{(-4u^3 + (3 + \alpha)u^2 - 2(1 + \alpha)u + 6 + 2\alpha) \pm 2(-\zeta^3 + 3\zeta^2 + 2\zeta + 1)u^2\}.
\]

The quantities inside the brackets are, respectively,
\[
(-4u^3 + (3 + \alpha)u^2 - 2(1 + \alpha)u + 6 + 2\alpha) + 2(-\zeta^3 + 3\zeta^2 + 2\zeta + 1)u^2
\]
\[
= -4(u + \zeta)(u + \zeta^3)(u - (1 + \zeta)^2),
\]
and
\[
(-4u^3 + (3 + \alpha)u^2 - 2(1 + \alpha)u + 6 + 2\alpha) - 2(-\zeta^3 + 3\zeta^2 + 2\zeta + 1)u^2
= -4(u + \zeta^2)(u + \zeta^4)(u - \zeta^3(1 + \zeta)^2).
\]

On the other hand, the factors of the quantity \( A \) are
\[
2u^2 + (-1 + \alpha)u + 2 = 2(u + \zeta)(u + \zeta^4),
\]
while
\[
-2u^2 + (1 + \alpha)u - 2 = -2(u + \zeta^2)(u + \zeta^3).
\]

Now, using the factorizations
\[
-2u^2 + (1 + \alpha)u - 7 - 3\alpha = -2(u - (1 + \zeta)^2)(u - \zeta^3(1 + \zeta)^2),
\]
\[
2u^2 + (4 + 2\alpha)u + 7 + 3\alpha = 2(u - \zeta(1 + \zeta^2)(u - \zeta^2(1 + \zeta)^2),
\]
we find the two expressions \( Y_1 \) and \( Y_2 \) stated in the theorem. These factorizations also yield the factorization of the numerator and denominator of \( X \) in (2.2). □

**Remarks.** The theorem shows that the quantities \( X \) and \( Y_i \) factor in a similar way over \( \mathbb{Q}(\zeta) \) to the way that the quantity \( b \) factors:
\[
b = \varepsilon^5 \frac{[u - (1 + \zeta)^2][u - \zeta(1 + \zeta)^2][u - \zeta^2(1 + \zeta)^2][u - \zeta^3(1 + \zeta)^2][u - \zeta^4(1 + \zeta)^2]}{(u + \zeta)(u + \zeta^2)(u + \zeta^3)(u + \zeta^4)(u + 1)}.
\]

The expression for \( X \) may be written as
\[
X = -\varepsilon^4 \frac{(u - (1 + \zeta)^2)(u - \zeta(1 + \zeta)^2)(u - \zeta^2(1 + \zeta)^2)(u - \zeta^3(1 + \zeta)^2)}{u + \zeta^4} \frac{u + \zeta}{u + \zeta^2} \frac{u + \zeta^2}{u + \zeta^3} \frac{u + \zeta^3}{u + \zeta^4} \frac{u + \zeta^4}{u + 1},
\]
and the \( Y_i \) may be written in a similar form. Thus, the coordinates of \( P = (X, Y_i) \) are products of linear fractional expressions in \( u \).

### 3 Checking the formulas.

The curve \( E_5 \) is isomorphic to the curve
\[
E' : Y'^2 = X^3 + \frac{b^2 + 6b + 1}{4} X^2 + \frac{b(b + 1)}{2} X + \frac{b^2}{4},
\]
by the substitution $Y' = Y + \frac{1}{2}(1 + b)X + \frac{2}{2}$. From [12], Ex. 3.7 the doubling formula on $E'$ is given by

$$X(2P) = \frac{X^4 - (b^2 + b)X^2 - 2b^2X - b^3}{4p(X)}, \quad X = X(P),$$

with $p(X) = X^3 + \frac{b^2 + 6b + 1}{4}X^2 + \frac{b(b + 1)}{2}X + \frac{b^2}{4}$; and

$$Y'(2P) = \frac{N(X)}{16p(X)^2}Y''(P),$$

with

$$N(X) = 2X^6 + (b^2 + 6b + 1)X^5 + (5b^2 + 5b)X^4 + 10b^2X^3 + 10b^3X^2 + (b^5 + 5b^4)X + b^5.$$

Taking the expression for $X = X(P)$ from (2.2), we have

$$X(2P) = \frac{(-7 + 3\alpha)(-2u^2 + (1 + \alpha)u - 3\alpha - 7)(2u^2 + (4 + 2\alpha)u + 3\alpha + 7)}{(-2u^2 + (1 - \alpha)u - 2)(u + 1)^2},$$

which only differs from (2.2) in the denominator, where $\alpha$ has been replaced by its conjugate $-\alpha$. Notice that the numerator in this formula for $X(2P)$ is

$$(-7 + 3\alpha)(-2u^2 + (1 + \alpha)u - 3\alpha - 7)(2u^2 + (4 + 2\alpha)u + 3\alpha + 7)
= (28 - 12\alpha)u^4 + (12 - 4\alpha)u^3 + 8u^2 + (12 + 4\alpha)u + 28 + 12\alpha.$$

This expression is invariant (except for a factor of $u^4$) under the mapping $(\alpha \to -\alpha, u \to 1/u)$. From (2.1) we see that this mapping also leaves the quantity $b$ invariant, and takes the denominator of $X(2P)$ divided by $u^4$. Hence, $X(2P)$ is the $X$-coordinate in Theorem 2.1 corresponding to the pair $(-\alpha, 1/u)$, and we may state the following.

**Theorem 3.1.** If $X$ is given by (2.2), the $X$-coordinate of the double of the point $P = (X,Y_i)$ on $E_5$ is obtained by applying the mapping $(\alpha \to -\alpha, u \to 1/u)$ to the expression (2.2) or $(\zeta \to \zeta^2, u \to 1/u)$ to (2.3).

Since the mapping $(\alpha \to -\alpha, u \to 1/u)$ has order 2, it is clear that $X(4P) = X(P)$ for either of the points $P = (X,Y_i)$ in Theorem 2.1. Applying the map $\sigma = (\zeta \to \zeta^2, u \to 1/u)$ to the quantity $Y_1$ in Theorem 2.1 yields

$$Y_1^\sigma = \varepsilon^7 \frac{[1 - (1 + \zeta^2)u]^2[1 - \zeta^2(1 + \zeta^2)u]^2[1 - \zeta^4(1 + \zeta^2)u]^2[1 - \zeta^8u]}{(1 + \zeta^4u)(1 + \zeta u)(1 + \zeta^3u)(u + 1)^3}.$$
and therefore, since \( \frac{1}{1+\xi^2} = \xi^2(1+\xi)^2 \) and
\[
(\xi^2 + \xi^3)^7 \cdot (1+\xi^2)^{14} \cdot \xi = 21 + 13(\xi^2 + \xi^3) = -\varepsilon^7,
\]
we find that
\[
Y_{\sigma}^1 = \varepsilon^7 \frac{[u - (1 + \xi)^2][u - (1 + \xi^2)^2][u - \xi^2(1 + \xi)^2]^2[u - \xi^3(1 + \xi)^2]^2}{(u + \xi)^2(u + \xi^2)(u + \xi^4)(u + 1)^3}.
\]
If \( P = (X, Y_1) \), this gives an expression for \( Y_{\sigma}^1 = Y(\pm 2P) \).

Since \( \sigma^2 = (\xi \rightarrow \xi^4, u \rightarrow u) = (\xi \rightarrow \xi^{-1}, u \rightarrow u) \), we also have
\[
Y_{\sigma}^2 = \varepsilon^7 \frac{[u - (1 + \xi)^2][u - (1 + \xi^2)^2][u - \xi^2(1 + \xi)^2]^2[u - \xi^3(1 + \xi)^2]^2}{(u + \xi)(u + \xi^2)(u + \xi^3)(u + 1)^3},
\]
which coincides with \( Y_2 \). We have therefore that
\[
P_{\sigma}^2 = (X, Y_1)_{\sigma}^2 = (X, Y_2) = -P,
\]
and Theorem 3.1 yields
\[
P_{\sigma} = (X, Y_1)^{\sigma} = \pm 2P.
\]
Since \( \sigma \) is an automorphism of the extension \( \mathbb{Q}(\xi, u)/\mathbb{Q}(b) \), this shows that
\[
-P = (P_{\sigma})^{\sigma} = \pm 2P_{\sigma} = 4P,
\]
and verifies that \( 4P = -P \), i.e. \( 5P = O \).

4 The Ramanujan-Rogers continued fraction.

As in the introduction, we now set \( b = r^5(\tau) \) and \( \varepsilon = \frac{-1+\sqrt{5}}{2} \), where \( r(\tau) \) given by (1.2) is the Rogers-Ramanujan continued fraction. From equation (7.3) in [3] there is the identity
\[
r^5 \left( \frac{-1}{5\tau} \right) = \frac{-r^5(\tau) + \varepsilon^5}{\varepsilon^5 r^5(\tau) + 1} = \frac{-b + \varepsilon^5}{\varepsilon^5 b + 1}.
\]
Hence we have
\[
r^5 \left( \frac{-1}{5\tau} \right) = \frac{-b + \varepsilon^5}{\varepsilon^5(b - \varepsilon^5)} = \frac{1}{\varepsilon^5 b^5}.
\]
and we can take
\[ u = \frac{1}{\varepsilon r \left( \frac{1}{5\tau} \right)}. \]

On the other hand,
\[ r \left( \frac{-1}{5\tau} \right) = \frac{\varepsilon r (5\tau) + 1}{r(5\tau) - \bar{\varepsilon}}, \]
by (3.2) in [3]. Hence,
\[ u = \frac{r(5\tau) - \bar{\varepsilon}}{\varepsilon \varepsilon r(5\tau) + 1} = -\frac{r(5\tau) - \bar{\varepsilon}}{r(5\tau) - \varepsilon}. \]

This shows that \( u \) is a linear fractional expression in \( r(5\tau) \), proving (1.3). Hence the coordinates \( X \) and \( Y_i \) in Theorem 2.1 can be expressed as products of linear fractional expressions in \( r(5\tau) \). Since \( \varepsilon \) and the coefficients of the linear fractional expressions in Theorem 2.1 lie in \( \mathbb{Q}(\zeta_5) \) (see the remarks following Theorem 2.1), the same is true for \( X, Y_i \) in terms of \( r(5\tau) \). This also holds if \( u \) is replaced by \( \zeta^{-i} u \) in (4.1) while holding \( \alpha = \sqrt{5} \) fixed; and letting \( i \) vary yields the coordinates of 10 of the 20 points in \( E_5(b)[5] - \langle (0, 0) \rangle \).

For example, we have
\[ \frac{(u - (1 + \zeta)^2)}{u + 1} = \frac{(1 + \zeta)(1 - \zeta^3)}{\sqrt{5}}(r(5\tau) - (1 + \zeta^2)), \]
while
\[ \frac{(u - \zeta(1 + \zeta)^2)}{u + \zeta} = \zeta^2(1 + \zeta) \frac{r(5\tau) - (1 + \zeta)}{r(5\tau) + (1 + \zeta + \zeta^2)}. \]

Further,
\[ \frac{(u - \zeta^2(1 + \zeta)^2)}{u + \zeta^2} = -\zeta \frac{r(5\tau) + \zeta(1 + \zeta + \zeta^2)}{r(5\tau) - \zeta^2(1 + \zeta^2)}, \]
and
\[ \frac{(u - \zeta^3(1 + \zeta)^2)}{u + \zeta^3} = -\zeta(1 + \zeta) \frac{r(5\tau) - (1 + \zeta^3)}{r(5\tau) - \zeta(1 + \zeta^2)}. \]

Using, finally, that
\[ \frac{u + \zeta}{u + 1} = \frac{1 - \zeta}{\sqrt{5}}(r(5\tau) + (1 + \zeta + \zeta^2)), \]
we find that the $X$-coordinate in (2.3) is given by

\[
X = \frac{-\varepsilon \left[r(5\tau) - (1 + \zeta)\right][r(5\tau) - (1 + \zeta^2)][r(5\tau) - (1 + \zeta^3)][r(5\tau) - (1 + \zeta^4)]}{\sqrt{5} \left[r(5\tau) - (\zeta + \zeta^3)\right][r(5\tau) - (\zeta^2 + \zeta^4)]} = \frac{-\varepsilon \, r^4(5\tau) - 3r^3(5\tau) + 4r^2(5\tau) - 2r(5\tau) + 1}{\sqrt{5} \, r^2(5\tau) + r(5\tau) + \varepsilon^2},
\]

where, once again, all the “poles” and “zeroes” of this function of $r(5\tau)$ are units in $\mathbb{Q}(\zeta_5)$.

The numerator in the last expression coincides with the numerator in Ramanujan’s identity

\[
\frac{r^5(\tau)}{r(5\tau)} = \frac{r^4(5\tau) - 3r^3(5\tau) + 4r^2(5\tau) - 2r(5\tau) + 1}{r^4(5\tau) + 2r^3(5\tau) + 4r^2(5\tau) + 3r(5\tau) + 1},
\]

from [2], p. 167, while the denominator is a quadratic factor of the denominator in this identity. (Note that $\zeta + \zeta^2, \zeta^2 + \zeta^4, \zeta^3 + \zeta^4, \zeta + \zeta^3$ are the conjugate roots of $x^4 + 2x^3 + 4x^2 + 3x + 1$.) Therefore, we may also write the formula for $X$ as

\[
X = \frac{-\varepsilon \, r^5(\tau)}{\sqrt{5} \, r(5\tau)} \left(r^2(5\tau) + r(5\tau) + \varepsilon^2\right).
\]

The coordinates $Y_i$ in Theorem 2.1 may be computed using the above formulas, along with the formula

\[
\frac{u + \zeta}{u + \zeta^4} = -\zeta r(5\tau) + 1 + \zeta + \zeta^2 \quad (r(5\tau) - (1 + \zeta)).
\]

We find with $\eta = (\zeta - 1)/\sqrt{5}$ that

\[
Y_1 = \eta^3 \frac{r(5\tau) - (1 + \zeta)^4}{r(5\tau) - (1 + \zeta^2)^4} \frac{[r(5\tau) - (1 + \zeta^3)]^2[r(5\tau) - (1 + \zeta^4)]^2}{[r(5\tau) - (\zeta^2 + \zeta^4)]^2[r(5\tau) - (\zeta + \zeta^3)]^2[r(5\tau) - (\zeta + \zeta^2)]},
\]

or

\[
Y_1 = \eta^3 \frac{(r^4(5\tau) - 3r^3(5\tau) + 4r^2(5\tau) - 2r(5\tau) + 1)^2}{(r^4(5\tau) + 2r^3(5\tau) + 4r^2(5\tau) + 3r(5\tau) + 1)} \cdot Z, \tag{4.3}
\]

where

\[
Z = \frac{r(5\tau) - (\zeta^3 + \zeta^4)}{(r(5\tau) - (\zeta^2 + \zeta^4))(r(5\tau) - (1 + \zeta^3))}.
\]
Using (4.1) this can also be written as

\[ Y_1 = \eta^3 \frac{r^5(\tau)}{r(5\tau)}(r^4(5\tau) - 3r^3(5\tau) + 4r^2(5\tau) - 2r(5\tau) + 1) \cdot Z. \]

The formula for \( Y_2 \) can be obtained by applying the map \( \sigma^2 = (\zeta \to \zeta^4, u \to u) \) to \( Y_1 \), as in Section 3:

\[ Y_2 = \left( \frac{\zeta^4 - 1}{\sqrt{5}} \right)^3 \frac{(r^4(5\tau) - 3r^3(5\tau) + 4r^2(5\tau) - 2r(5\tau) + 1)^2}{(r^4(5\tau) + 2r^3(5\tau) + 4r^2(5\tau) + 3r(5\tau) + 1)} \cdot Z^{\sigma^2}, \quad (4.4) \]

with

\[ Z^{\sigma^2} = \frac{r(5\tau) - (\zeta + \zeta^2)}{(r(5\tau) - (\zeta + \zeta^3))(r(5\tau) - (1 + \zeta^2))}. \]

If we perform the same calculations by sending \( \zeta \) to \( \zeta^2 \) in the formula (2.3), so that \( \alpha = \sqrt{5} \) is replaced by \( -\sqrt{5} \), \( \varepsilon \) is replaced by \( \bar{\varepsilon} \), and \( u \) by \( 1/u \) in (4.1), then by Theorem 3.1 we find the \( X \)-coordinate of the double of the point \( P = (X, Y_1) \):

\[
X(2P) = \frac{\varepsilon}{\sqrt{5}} \frac{[r(5\tau) - (1 + \zeta)][r(5\tau) - (1 + \zeta^2)][r(5\tau) - (1 + \zeta^3)][r(5\tau) - (1 + \zeta^4)]}{[r(5\tau) - (\zeta + \zeta^2)][r(5\tau) - (\zeta + \zeta^3)][r(5\tau) - (\zeta + \zeta^4)]}
\]

\[
= \frac{\varepsilon}{\sqrt{5}} \frac{r^4(5\tau) - 3r^3(5\tau) + 4r^2(5\tau) - 2r(5\tau) + 1}{r^2(5\tau) + r(5\tau) + \varepsilon^2}
\]

\[
= \frac{\varepsilon}{\sqrt{5}} \frac{r^5(\tau)}{r(5\tau)}(r^2(5\tau) + r(5\tau) + \varepsilon^2).
\]

The corresponding \( Y \)-coordinates are obtained by applying \( \zeta \to \zeta^2 \) to the expressions given for \( Y_1, Y_2 \) above.

As above, if we apply \( \zeta \to \zeta^2 \) to the formulas in Theorem 2.1 and set \( u \) equal to the quantity

\[ u = -\zeta^i \frac{r(5\tau) - \varepsilon}{r(5\tau) - \bar{\varepsilon}}, \quad 0 \leq i \leq 4, \]

then we obtain the coordinates of the remaining 10 points in \( E_5(b)[5] - \langle (0, 0) \rangle \). This completes the proof of Theorem 1.1.
5 Appendix.

The roots of the equation $g(X) = 0$ in Section 2 are found using Watson’s method and the following quantities defined in [4]. First, if

$$a_1 := \frac{1}{20} (\alpha - 5)(-3 - \alpha - 7b + 3b\alpha - 2b^2)$$

is the coefficient of $X^4$ in $g(X)$, we have

$$f(x) = g(x - \frac{a_1}{5}) = x^5 + 10Cx^3 + 10Dx^2 + 5Ex + F,$$

where:

$$C = \frac{1}{4000} (-3 + \alpha)(b + 3 + \alpha)(-4b + 3 + \alpha)(-2b - 11 + 5\alpha)(2b + 11 + 5\alpha),$$

$$D = \frac{-1}{10000} (-5 + 2\alpha)(-8b^3 - 27b^2 + 11ab^2 - 41b - 19ab + 4 + 4\alpha)
\times (-2b - 11 + 5\alpha)(2b + 11 + 5\alpha)^2,$$

$$E = \frac{1}{500000} (-7 + 3\alpha)(-6b^5 - 60b^4 + 6ab^4 - 135b^3 + 47ab^3 + 505b^2 + 229ab^2
- 150b - 72ab + 12 + 6\alpha)(-2b - 11 + 5\alpha)(2b + 11 + 5\alpha)^2,$$

$$F = \frac{-1}{12500000} (-25 + 11\alpha)(-8b^7 - 133b^6 + 5ab^6 - 707b^5 + 115ab^5 + 3790b^4
+ 2900ab^4 - 15405b^3 - 6475ab^3 + 5326b^2 + 2400ab^2 - 794b - 360ab + 44 + 20\alpha)
\times (-2b - 11 + 5\alpha)(2b + 11 + 5\alpha)^2.$$

Incidentally, this shows that the polynomial $f(x)$ is irreducible over $\mathbb{Q}(\alpha, b)$, by an analogue of Eisenstein’s theorem, because of the factor $-2b - 11 + 5\alpha$ in each of the coefficients. This yields:

$$K = E + 3C^2$$

$$= \frac{1}{8000} (-9 + 4\alpha)b^2(-2b + 29 + 13\alpha)(-2b - 11 + 5\alpha)(2b + 11 + 5\alpha)^2;$$

$$L = -2DF + 3E^2 - 2C^2E + 8CD^2 + 15C^4$$

$$= \frac{1}{140800000} (-35 + 16\alpha)b^4(-2b + 1 + \alpha)(22b - 19 + 13\alpha)(-2b - 11 + 5\alpha)^2
\times (2b + 11 + 5\alpha)^4;$$
\[ M = CF^2 - 2DEF + E^3 - 2C^2DF - 11C^2E^2 + 28CD^2E - 16D^4 + 35C^4E \\
- 40C^3D^2 - 25C^6 \]

\[
= \frac{1}{512000000}(-9 + 4\alpha)b^6(-2b^4 - 20b^3 + 2\alpha b^3 - 11b^2 - 11\alpha b^2 - 35b - 13\alpha b + 3 + \alpha) \\
\times (-2b - 11 + 5\alpha)^3(2b + 11 + 5\alpha)^5.
\]

The discriminant of \( f(x) \) is

\[
\delta = \frac{1}{10240000}(123 - 55\alpha)(-2b - 11 + 5\alpha)^4(2b + 11 + 5\alpha)^8b^{14},
\]

so that

\[
\sqrt{\delta} = \frac{1}{1600}b\left(\frac{1-\alpha}{2}\right)^5(-2b - 11 + 5\alpha)(2b + 11 + 5\alpha)^4b^7.
\]

The polynomial

\[ h(x) = x^6 - K x^4 + \frac{L}{125} x^2 - \frac{\alpha \sqrt{\delta}}{390625} x + \frac{M}{3125} \]

has the quantity

\[ \theta = \frac{1}{50}b(b^2 + 11b - 1) \]

as a root. Treating \( b \) as an indeterminate, \( \theta \neq 0, \pm C \). Hence, Theorem 1 in \[4\] applies. We take

\[ T = \frac{1}{20000}(5 - \alpha)b(b - 2 + \alpha)(-2b - 11 + 5\alpha)(2b + 11 + 5\alpha)^2 \]

to be the solution of \( p(T) = q(T) = 0 \) in that theorem. Then (2.20) in \[4\] gives

\[ R_1 = \sqrt{(D - T)^2 + 4(C - \theta)^2(C + \theta)} \]

\[ = \frac{1}{4000}(3 - \alpha)b(2b - 1 + \alpha)(-2b - 11 + 5\alpha)(2b + 11 + 5\alpha)^2, \]

and

\[ R_2 = \frac{C(D^2 - T^2) + (C^2 - \theta^2)(C^2 + 3\theta^2 - E)}{R_1 \theta} \]

\[ = \frac{1}{2000}(-2 + \alpha)b(-2b + 1 + \alpha)(-2b - 11 + 5\alpha)(2b + 11 + 5\alpha)^2. \]
Next, we define the quantities
\[ X' = \frac{1}{2}(-D + T + R_1) = \frac{1}{2^{655}}(-5 + 2\alpha)(2b + 1 + \alpha)(-2b - 11 + 5\alpha)^2(2b + 11 + 5\alpha)^3, \]
\[ Y = \frac{1}{2}(-D - T + R_2) = \frac{1}{2^{155}}(-5 + 2\alpha)(-b + 2 + \alpha)^2(-2b - 11 + 5\alpha)^2(2b + 11 + 5\alpha)^2, \]
\[ Z = -C - \theta = \frac{1}{2000}(3 - \alpha)(-b + 2 + \alpha)(2b + 1 + \alpha)(-2b - 11 + 5\alpha)(2b + 11 + 5\alpha). \]
Then, according to Theorem 1 of [4], the quantity \( u_1 \) is the fifth root of the expression
\[ u_1^5 = \frac{X'^2 Y}{Z^2} = \frac{1}{2^{1118}}(-25 + 11\alpha)(-2b - 11 + 5\alpha)^4(2b + 11 + 5\alpha)^6 \]
\[ = \frac{1}{2^{10155}} \left( -\frac{5 + \alpha}{10} \right)^5 (-2b - 11 + 5\alpha)^5(2b + 11 + 5\alpha)^5 \]
\[ \times \frac{2b + 11 + 5\alpha}{-2b - 11 + 5\alpha}. \]
This shows that \( u_1 \) is a polynomial in \( b \) and \( \alpha \) times \( u \), where
\[ u^5 = \frac{2b + 11 + 5\alpha}{-2b - 11 + 5\alpha}, \]
as in Section 2; in fact, we have
\[ u_1 = \frac{-5 + \alpha}{200}(2b^2 + 22b - 2)u = \frac{5 - \alpha}{100}A_1u. \]
This gives the first degree term in \( u \) in the expression for the root \( X \) in Section 2. Similarly, the quantities
\[ \bar{X} = \frac{1}{2}(-D + T - R_1) \]
\[ = \frac{1}{1000000}(-5 + 2\alpha)(-2b - 1 + \alpha)^2(-2b - 11 + 5\alpha)(2b + 11 + 5\alpha)^2, \]
\[ \bar{Y} = \frac{1}{2}(-D - T - R_2) \]
\[ = \frac{1}{2000000}(-5 + 2\alpha)(-2b - 1 + \alpha)(2b + 1 + \alpha)^2(-2b - 11 + 5\alpha)(2b + 11 + 5\alpha)^2, \]
\[ \bar{Z} = -C + \theta = \frac{1}{4000}(3 - \alpha)(-2b - 1 + \alpha)(-2b - 11 + 5\alpha)(2b + 11 + 5\alpha), \]
yield the expressions

\[ u_2 = \frac{\bar{X}}{Z^2} u_1^2 = \frac{5 - \alpha}{100} A_2 u^2, \quad u_3 = \frac{\bar{X}Y}{Z^2Z_3^2} u_1^3 = \frac{5 - \alpha}{100} A_3 u^3, \]

\[ u_4 = \frac{\bar{X}^2Y}{Z^2Z_4} u_1^4 = \frac{5 - \alpha}{100} A_4 u^4, \]

which are the second, third, and fourth degree terms in the expression for the root \( X \), where

\[ A_2 = (b - 2 - \alpha)(-2b - 11 + 5\alpha), \]
\[ A_3 = -\frac{1}{2}(2b + 1 + \alpha)(-2b - 11 + 5\alpha), \]
\[ A_4 = -\frac{1}{2}(-2b - 1 + \alpha)(-2b - 11 + 5\alpha). \]

Together with the fact that \( \frac{(5-\alpha)}{100} A_0 = -\frac{a_1}{5} \), this yields the expression for the root

\[ X = u_1 + u_2 + u_3 + u_4 - \frac{a_1}{5} = \frac{(5 - \alpha)}{100} (A_4 u^4 + A_3 u^3 + A_2 u^2 + A_1 u + A_0) \]

of \( g(X) = 0 \) in Section 2. By replacing \( u \) by \( \zeta^i u \), for \( 0 \leq i \leq 4 \), and solving the resulting system of linear equations for the powers of \( u \), it is not hard to see that \( \mathbb{Q}(\zeta, b, X) = \mathbb{Q}(\zeta, b, u) \) is the field generated over \( \mathbb{Q}(\zeta, b) \) by the \( X \)-coordinates of the points of order 5 on \( E_5 \). This gives an alternate verification that \( u^5 \) is a Kummer element for the extension \( \mathbb{Q}(\zeta, b, X)/\mathbb{Q}(\zeta, b) \), as in [13].

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