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The well-known fact that all elliptic curves are modular, proven by Wiles, Taylor, Breuil, Conrad and Diamond, leaves open the question whether there exists a nice representation of the modular form associated to each elliptic curve. Here we provide explicit representations of the modular forms associated to certain Legendre form elliptic curves ${}_2E_1(\lambda)$ as linear combinations of quotients of Dedekind's eta-function. We also give congruences for some of the modular forms' coefficients in terms of Gaussian hypergeometric functions.

1. Introduction and statement of results

Wiles and Taylor [1995] proved that all semistable elliptic curves over \mathbb{Q} are modular. Their result was later extended by Breuil, Conrad, Diamond and Taylor [Breuil et al. 2001] to all elliptic curves over \mathbb{Q} .

This correspondence allows facts about elliptic curves to be proven using modular forms, and vice versa. (See [Koblitz 1993] for more background on the theory of elliptic curves and modular forms.)

Let E be an elliptic curve over \mathbb{Q} . If $q := e^{2\pi iz}$, $\text{GF}(p)$ is the finite field with p elements, and $N(p)$ is the number of points on E over $\text{GF}(p)$, then the modularity theorem implies that there exists a corresponding weight-2 newform $f(z) = \sum_{n=1}^{\infty} a(n)q^n$ such that if p is a prime of good reduction, then $a(p) = 1 + p - N(p)$.

For example, if $\eta(z)$ is Dedekind's eta-function,

$$\eta(z) := q^{\frac{1}{24}} \prod_{n=1}^{\infty} (1 - q^n),$$

then the elliptic curves $y^2 = x^3 + 1$ and $y^2 = x^3 - x$ have the corresponding modular forms $\eta(6z)^4$ and $\eta(4z)^2\eta(8z)^2$, respectively; see [Martin and Ono 1997].

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It is natural to ask which elliptic curves have corresponding modular forms that are quotients of eta-functions. Martin and Ono [1997] have answered this question by listing all such *eta-quotients*

$$f(z) = \prod_{\delta} \eta(\delta z)^{r_{\delta}} \quad (\delta, r_{\delta} \in \mathbb{Z})$$

which are weight-2 newforms, and they gave corresponding modular elliptic curves.

(For more on the theory of eta-quotients, see [Ono 2004, Section 1.4].)

We show, for certain values of $\lambda \in \mathbb{Q} \setminus \{0, 1\}$, that the elliptic curves ${}_2E_1(\lambda)$ defined by

$${}_2E_1(\lambda) : y^2 = x(x-1)(x-\lambda) \quad (1-1)$$

correspond to modular forms which are linear combinations of eta-quotients.

Remark. The proof of Theorem 1.1 will make clear how one can generate many more such examples.

Let

$$f_{\lambda}(z) := \sum_{n=1}^{\infty} {}_2a_1(n; \lambda) q^n \quad (1-2)$$

be the weight-2 newform corresponding to the elliptic curve ${}_2E_1(\lambda)$. It will be convenient to express eta-quotients using the notation

$$\left[\prod_{\delta} \delta^{r_{\delta}} \right] := \prod_{\delta} \eta(\delta z)^{r_{\delta}}. \quad (1-3)$$

For example, in place of $\frac{\eta(2z)^2 \eta(4z)^2 \eta(5z) \eta(40z)}{\eta(z) \eta(8z)}$ we write $[1^{-1} 2^2 4^2 5^1 8^{-1} 40^1]$.

Theorem 1.1. *If $\lambda \in \left\{ \frac{27}{16}, 5, \frac{81}{49}, -\frac{7}{25} \right\}$, then ${}_2E_1(\lambda)$ corresponds to the modular forms given here:*

λ	conductor N	eta-quotient $f_{\lambda}(z)$
$\frac{27}{16}$	33	$[1^2 11^2] + 3 \cdot [3^2 33^2] + 3 \cdot [1^1 3^1 11^1 33^1]$
5	40	$[1^{-1} 2^2 4^2 5^1 8^{-1} 40^1] + [1^1 5^{-1} 8^1 10^2 20^2 40^{-1}]$
$\frac{81}{49}$	42	$2 \cdot [1^{-1} 2^2 3^1 7^2 14^{-1} 42^1] - 3 \cdot [3^1 6^1 21^1 42^1]$ $+ [2^1 3^2 6^{-1} 7^1 21^{-1} 42^2] + [1^1 3^{-1} 6^2 14^1 21^2 42^{-1}]$
$-\frac{7}{25}$	70	$[1^{-1} 2^2 5^2 7^{-1} 10^{-1} 14^2 35^2 70^{-1}] - [1^2 2^{-1} 5^{-1} 7^2 10^2 14^{-1} 35^{-1} 70^2]$

We show, for all $\lambda \in \mathbb{Q} \setminus \{0, 1\}$, that the Fourier coefficients of all $f_{\lambda}(z)$ satisfy an interesting hypergeometric congruence. For a prime p and an integer n , define

$\text{ord}_p(n)$ to be the power of p dividing n , and if $\alpha = \frac{a}{b} \in \mathbb{Q}$, then set $\text{ord}_p(\alpha) = \text{ord}_p(a) - \text{ord}_p(b)$. We show that with this notation, the numbers ${}_2a_1(p; \lambda)$ satisfy the following congruences.

Theorem 1.2. *Let $\lambda \notin \{0, 1\}$ be rational and let $p = 2f + 1$ be an odd prime such that $\text{ord}_p(\lambda(\lambda - 1)) = 0$. Then*

$${}_2a_1(p; \lambda) \equiv (-1)^{\frac{p+1}{2}} (p-1) \sum_{k=0}^f \binom{f+k}{k} \binom{f}{k} (-\lambda)^k \pmod{p}.$$

Remarks. In light of Theorem 1.1, this implies that the congruence in Theorem 1.2 holds for the coefficients of the linear combinations of eta-quotients given above.

- A well-known theorem of Hasse states that for every prime p ,

$$|a(p)| < 2\sqrt{p}.$$

Theorem 1.2 therefore determines ${}_2a_1(p; \lambda)$ uniquely for primes $p > 16$.

Example. Consider $\lambda = \frac{27}{16}$. Then $\lambda(\lambda - 1) = \frac{3^3 \cdot 11}{2^8}$ and so for $p \notin \{2, 3, 11\}$ prime we observe the congruence by inspecting the coefficients of ${}_2E_1\left(\frac{27}{16}\right)$ for applicable primes $p < 30$, where $B(p; \lambda)$ is defined to be the right-hand side of the congruence in Theorem 1.2:

p	${}_2a_1\left(p; \frac{27}{16}\right)$	$B\left(p; \frac{27}{16}\right)$
5	$-2 \equiv 3 \pmod{5}$	3
7	$4 \equiv 4 \pmod{7}$	4
13	$-2 \equiv 11 \pmod{13}$	11
17	$-2 \equiv 15 \pmod{17}$	15
19	$0 \equiv 0 \pmod{19}$	0
23	$8 \equiv 8 \pmod{23}$	8
29	$-6 \equiv 23 \pmod{29}$	23

2. Elliptic curves and modular forms

In this section we prove Theorem 1.1. If E is an elliptic curve over \mathbb{Q} , then its conductor N is a product of the primes p of bad reduction for E , with exponents determined by the extent to which E is singular over $\text{GF}(p)$. (An algorithm by Tate for computing conductors is given in [Cremona 1997].) Moreover, the modularity theorem implies that the modular form $f(z)$ corresponding to E is an element of $S_2(\Gamma_0(N))$. In particular, for an elliptic curve ${}_2E_1(\lambda)$, proving the correctness of any representation of $f_\lambda(z)$ in terms of eta-quotients amounts to checking that the given eta-quotients are elements of $S_2(\Gamma_0(N))$ and checking a finite number of coefficients of their Fourier expansions against those of f_λ .

We first provide a formula for the dimension of the space of cusp forms of weight 2 and level N , $S_2(\Gamma_0(N))$. We then show that the eta-quotients making up the linear combinations are elements of $S_2(\Gamma_0(N))$ and use the dimension formula to show that equality of two elements of $S_2(\Gamma_0(N))$ always depends only on some finite set of coefficients.

The linear combinations of eta-quotients in this paper were generated by the following algorithm:

- (1) Given a rational number $\lambda \notin \{0, 1\}$, compute the conductor N of ${}_2E_1(\lambda)$. (The modular form corresponding to ${}_2E_1(\lambda)$ will be an element of $S_2(\Gamma_0(N))$.)
- (2) Compute $\dim_{\mathbb{C}} S_2(\Gamma_0(N))$.
- (3) Generate eta-quotients which are elements of $S_2(\Gamma_0(N))$.
- (4) Attempt to construct a basis for $S_2(\Gamma_0(N))$ using these eta-quotients.

Of course, once one is armed with a basis of eta-quotients for $S_2(\Gamma_0(N))$, it is simple to express $f_\lambda(z)$ in terms of this basis.

Dimension of $S_2(\Gamma_0(N))$. It will be useful to know not only that $S_2(\Gamma_0(N))$ is finite-dimensional for every positive integer N , but also its exact dimension $d_N := \dim_{\mathbb{C}} S_2(\Gamma_0(N))$.

The following formula for d_N is a simplification of [Ono 2004, Theorem 1.34], which gives a formula for the quantity $\dim_{\mathbb{C}} S_k(\Gamma_0(N), \chi) - \dim_{\mathbb{C}} M_{2-k}(\Gamma_0(N), \chi)$, in the case where $k = 2$ and $\chi = \epsilon$ is the trivial character modulo N .

Proposition 2.1. *If N is a fixed positive integer and $r_p := \text{ord}_p(N)$, define*

$$\lambda_p := \begin{cases} p^{\frac{r_p}{2}} + p^{\frac{r_p}{2}-1} & \text{if } r_p \equiv 0 \pmod{2}, \\ 2p^{\frac{r_p-1}{2}} & \text{if } r_p \equiv 1 \pmod{2}. \end{cases}$$

With this notation,

$$d_N = 1 + \frac{N}{12} \prod_{p|N} (1 + p^{-1}) - \frac{1}{2} \prod_{p|N} \lambda_p - \frac{1}{4} \sum_{\substack{x \pmod{N} \\ x^2+1 \equiv 0 \pmod{N}}} 1 - \frac{1}{3} \sum_{\substack{x \pmod{N} \\ x^2+x+1 \equiv 0 \pmod{N}}} 1.$$

Proof. This follows from [Ono 2004, Theorem 1.34], noting that the conductor of the trivial character is 1 and that $M_0(\Gamma_0(N), \epsilon)$ is the space of constant functions and hence has dimension 1. \square

Proof of Theorem 1.1. Let N be the conductor of $E = {}_2E_1(\lambda)$ and let $d_N = \dim_{\mathbb{C}} S_2(\Gamma_0(N))$ as before. Conditions under which an eta-quotient is an element of $S_2(\Gamma_0(N))$ are provided in [Ono 2004, Theorems 1.64 and 1.65]: If $f(z) = \prod_{\delta|N} \eta(\delta z)^{r_\delta}$ is an eta-quotient which vanishes at each cusp of $\Gamma_0(N)$, such that the pairs (δ, r_δ) satisfy $\sum_{\delta|N} r_\delta = 4$, $\sum_{\delta|N} \delta r_\delta \equiv 0 \pmod{24}$, and $\sum_{\delta|N} \frac{N}{\delta} r_\delta \equiv 0 \pmod{24}$,

then $f(z) \in S_2(\Gamma_0(N))$. The order of vanishing of such an $f(z)$ at the cusp $\frac{c}{d}$ is given by [Ono 2004, Theorem 1.65] as

$$\frac{N}{24} \sum_{\delta|N} \frac{\gcd(d, \delta)^2 r_\delta}{\gcd(d, \frac{N}{d}) d \delta}. \quad (2-1)$$

It is straightforward to check that the formula above gives a positive order of vanishing for each eta-quotient at each cusp, that each eta-quotient satisfies the given congruence conditions, and that the r_δ of each eta-quotient sum to 4. These conditions guarantee that each eta-quotient appearing in the table above lies in $S_2(\Gamma_0(N))$.

The eta-quotients given for $\lambda = \frac{27}{16}$ form a basis for $S_2(\Gamma_0(33))$. Similarly, for $\lambda = 5$, the given eta-quotients along with $[2^2 10^2]$ form a basis; for $\lambda = \frac{81}{49}$ the given eta-quotients along with $[1^{-1} 2^2 3^2 6^{-1} 7^{-1} 14^2 21^2 42^{-1}]$ form a basis; and for $\lambda = -\frac{7}{25}$ a complete basis is

$$\begin{aligned} & \{[5^2 7^2], [1^{-1} 2^2 7^2 10^1 14^{-1} 35^1], [10^2 14^2], \\ & [1^2 2^{-1} 5^1 7^{-1} 14^2 70^1], [1^2 2^{-1} 5^{-1} 7^2 10^2 14^{-1} 35^{-1} 70^2], \\ & [1^1 5^1 7^1 35^1], [1^1 5^2 10^{-1} 14^1 35^{-1} 70^2], [5^1 10^1 35^1 70^1], [1^{-1} 2^2 5^1 7^1 35^{-1} 70^2]\}. \end{aligned}$$

To see this, let $g_{i,j}$ be the j -th Fourier coefficient of the i -th basis vector g_i and define $t_1 < \dots < t_{d_N}$ to be the first ascending set of indices for which the vectors $\{(g_{i,t_j})_{j=1}^{d_N}\}_{i=1}^{d_N}$ are linearly independent. One can find such a sequence by direct computation of the Fourier coefficients and inspection of the matrices $[g_{i,t_j}]_{i,j=1}^{d_N}$ for various choices of small $t_1 < \dots < t_{d_N}$.

Now let $v_i = (g_{i,t_1}, \dots, g_{i,t_{d_N}})$ and let b_1, \dots, b_{d_N} be a basis for $S_2(\Gamma_0(N))$. If we have $h_1, h_2 \in S_2(\Gamma_0(N))$ with equal t_i -th coefficients, then these coefficients are zero in the difference $h_1 - h_2$. But $h_1 - h_2$ can be written as a linear combination $\sum c_i b_i$ of basis elements, for constants c_i . Hence $\sum c_i v_i = 0$ in \mathbb{R}^{d_N} , so by linear independence all $c_i = 0$, and thus $h_1 - h_2 = 0$. It therefore suffices to check that the coefficients of f_λ on $q^{t_1}, \dots, q^{t_{d_N}}$ match the coefficients that result from the linear combination of eta-quotients. \square

Remark. In practice, these computations can be done using a computer algebra system such as SAGE.

Example. We show that the modular form corresponding to ${}_2E_1\left(\frac{27}{16}\right)$ is

$$g(z) := [1^2 11^2] + 3 \cdot [3^2 33^2] + 3 \cdot [1^1 3^1 11^1 33^1].$$

For convenience, let $G = \{[1^2 11^2], [3^2 33^2], [1^1 3^1 11^1 33^1]\}$ be the set of eta-quotients making up the linear combination $g(z)$. The conductor of ${}_2E_1\left(\frac{27}{16}\right)$ is 33 and so the corresponding modular form $f_{\frac{27}{16}}(z)$ is an element of $S_2(\Gamma_0(33))$.

To show that $g(z)$ is also an element of $S_2(\Gamma_0(33))$, it suffices to show that $G \subset S_2(\Gamma_0(33))$. Take $g_i(z) \in G$. By [Ono 2004, Theorem 1.64], $g_i(z)$ is a modular form of weight 2 for $\Gamma_0(33)$. By [Ono 2004, Theorem 1.65], $g_i(z)$ vanishes at all cusps of $\Gamma_0(33)$, and thus $g_i(z) \in S_2(\Gamma_0(33))$.

Since $\text{ord}_3(33) = \text{ord}_{11}(33) = 1$, we have $\lambda_3 = \lambda_{11} = 2$ and evaluation of the dimension formula in Proposition 2.1 gives

$$\begin{aligned} \dim_{\mathbb{C}} S_2(\Gamma_0(33)) &= 1 + \frac{33}{12} \prod_{p|33} (1 + p^{-1}) - \frac{1}{2} \prod_{p|33} \lambda_p - \frac{1}{4} \sum_{\substack{x \pmod{33} \\ x^2+1 \equiv 0 \pmod{33}}} 1 - \frac{1}{3} \sum_{\substack{x \pmod{33} \\ x^2+x+1 \equiv 0 \pmod{33}}} 1 \\ &= 1 + \frac{33}{12} \left(1 + \frac{1}{3}\right) \left(1 + \frac{1}{11}\right) - \frac{1}{2}(\lambda_3)(\lambda_{11}) - \frac{1}{4}(0) - \frac{1}{3}(0) \\ &= 3. \end{aligned}$$

It remains to show that G is a basis for $S_2(\Gamma_0(33))$. Any dependence relation satisfied by the elements of G would imply a dependence relation among their coefficients. It thus suffices to find a set of indices $t_1 < t_2 < t_3$ such that the 3×3 matrix formed by the t_i -th coefficients of these eta-quotients is nonsingular. For this particular λ , the first three coefficients suffice.

This implies that any two elements of $S_2(\Gamma_0(33))$ which agree on the first three coefficients are equal. In fact, we observe that the first three coefficients of the modular form corresponding to ${}_2E_1\left(\frac{27}{16}\right)$ are the same as the first three coefficients of $g(z)$. That is, the coefficients of $g(z) = q + q^2 - q^3 - q^4 + \dots$ agree with the coefficients of $f_{\frac{27}{16}}(z)$.

3. Gaussian hypergeometric functions and proof of Theorem 1.2

We recall some facts about Gaussian hypergeometric functions over finite fields of prime order and use the Gaussian hypergeometric function ${}_2F_1\left(\phi, \phi \mid \lambda\right)$ to prove Theorem 1.2.

Gaussian hypergeometric functions. Greene [1987] defined *Gaussian hypergeometric functions* over arbitrary finite fields and showed that they have properties analogous to those of classical hypergeometric functions. We recall some definitions and notation from [Ono 1998] in the case of fields of prime order.

Definition 3.1. If p is an odd prime, $\text{GF}(p)$ is the field with p elements, and A and B are characters of $\text{GF}(p)$, define

$$\binom{A}{B} := \frac{B(-1)}{p} J(A, \bar{B}) = \frac{B(-1)}{p} \sum_{x \in \text{GF}(p)} A(x) \bar{B}(1-x).$$

Furthermore, if A_0, \dots, A_n and B_1, \dots, B_n are characters of $\text{GF}(p)$, define the Gaussian hypergeometric series ${}_{n+1}F_n \left(\begin{smallmatrix} A_0, A_1, \dots, A_n \\ B_1, \dots, B_n \end{smallmatrix} \mid x \right)$ by the following sum over all characters χ of $\text{GF}(p)$:

$${}_{n+1}F_n \left(\begin{smallmatrix} A_0, A_1, \dots, A_n \\ B_1, \dots, B_n \end{smallmatrix} \mid x \right) := \frac{p}{p-1} \sum_{\chi} \binom{A_0 \chi}{\chi} \binom{A_1 \chi}{B_1 \chi} \cdots \binom{A_n \chi}{B_n \chi} \chi(x)$$

In particular, we are concerned with the Gaussian hypergeometric series ${}_2F_1(\lambda)$ defined by

$${}_2F_1(\lambda) := {}_2F_1 \left(\phi, \phi \mid \lambda \right) = \frac{p}{p-1} \sum_{\chi} \binom{\phi \chi}{\chi}^2 \chi(\lambda)$$

where ϕ is the quadratic character of $\text{GF}(p)$. It is shown in [Ono 1998] that if $\lambda \in \mathbb{Q} \setminus \{0, 1\}$, then

$${}_2F_1(\lambda) = -\frac{\phi(-1) {}_2a_1(p; \lambda)}{p} \quad (3-1)$$

for every odd prime p such that $\text{ord}_p(\lambda(\lambda-1)) = 0$.

In addition, define the generalized Apéry number $D(n; m, l, r)$ for every $r \in \mathbb{Q}$ and every pair of nonnegative integers m and l by

$$D(n; m, l, r) := \sum_{k=0}^n \binom{n+k}{k}^m \binom{n}{k}^l r^{lk}.$$

Ono also shows (ibid.) that if $p = 2f + 1$ is an odd prime and $w = l + m$, then

$$D(f; m, l, r) \equiv \left(\frac{p}{p-1} \right)^{w-1} {}_wF_{w-1} \left(\phi, \phi, \dots, \phi \mid (-r)^l \right) \pmod{p}. \quad (3-2)$$

Proof of Theorem 1.2. By (3-1) and the fact that $\phi(-1) = (-1)^{\frac{p-1}{2}}$, we have that

$$\frac{p}{p-1} {}_2F_1(\lambda) = \frac{(-1)^{\frac{p+1}{2}} {}_2a_1(p; \lambda)}{p-1}.$$

By (3-2), letting $l = m = 1$ (and thus $w = 2$) and $r = -\lambda$, we have

$$\frac{p}{p-1} {}_2F_1(\lambda) \equiv D(f; 1, 1, -\lambda) \pmod{p}.$$

Combining these two equations and rearranging, we get

$${}_2a_1(p; \lambda) \equiv (-1)^{\frac{p+1}{2}} (p-1) D(f; 1, 1, -\lambda) \pmod{p}.$$

Since

$$D(f; 1, 1, -\lambda) = \sum_{k=0}^n \binom{f+k}{k} \binom{f}{k} (-\lambda)^k,$$

we have

$${}_2a_1(p; \lambda) \equiv (-1)^{\frac{p+1}{2}} (p-1) \sum_{k=0}^f \binom{f+k}{k} \binom{f}{k} (-\lambda)^k \pmod{p}. \quad \square$$

Remark. The binomial product $\binom{f+k}{k} \binom{f}{k}$ can be combined into the multinomial coefficient $\binom{f+k}{k, k, f-k}$ and so the congruence in Theorem 1.2 can also be written as

$${}_2a_1(p; \lambda) \equiv (-1)^{\frac{p+1}{2}} (p-1) \sum_{k=0}^f \binom{f+k}{k, k, f-k} (-\lambda)^k \pmod{p}.$$

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pathakjee@wisc.edu

*Department of Mathematics,
University of Wisconsin - Madison, 480 Lincoln Drive,
Madison, WI 53706-1388, United States*

rosnbrick@wisc.edu

*Department of Mathematics,
University of Wisconsin - Madison, 480 Lincoln Drive,
Madison, WI 53706-1388, United States*

eyoong@uwaterloo.ca

*Department of Pure Mathematics, University of Waterloo,
200 University Avenue West, Waterloo, ON, N2L 3G1,
Canada*

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Johnny Henderson	Baylor University, USA johnny_henderson@baylor.edu	Filip Saidak	U of North Carolina, Greensboro, USA f_saidak@uncg.edu
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Charles R. Johnson	College of William and Mary, USA crjohnso@math.wm.edu	Andrew J. Sterge	Honorary Editor andy@ajsterge.com
Karen Kafadar	University of Colorado, USA karen.kafadar@cudenver.edu	Ann Trenk	Wellesley College, USA atrenk@wellesley.edu
K. B. Kulasekera	Clemson University, USA kk@ces.clemson.edu	Ravi Vakil	Stanford University, USA vakil@math.stanford.edu
Gerry Ladas	University of Rhode Island, USA gladas@math.uri.edu	Ram U. Verma	University of Toledo, USA verma99@msn.com
David Larson	Texas A&M University, USA larson@math.tamu.edu	John C. Wierman	Johns Hopkins University, USA wierman@jhu.edu
Suzanne Lenhart	University of Tennessee, USA lenhart@math.utk.edu	Michael E. Zieve	University of Michigan, USA zieve@umich.edu

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