Combinatorics of traces of Hecke operators

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We investigate the combinatorial properties of the traces of the nth Hecke operators on the spaces of weight 2k cusp forms of level N. We establish examples in which these traces are expressed in terms of classical objects in enumerative combinatorics (e.g., tilings and Motzkin paths). We establish in general that Hecke traces are explicit rational linear combinations of values of Gegenbauer (also known as ultraspherical) polynomials. These results arise from "packaging" the Hecke traces into power series in weight aspect. These generating functions are easily computed by using the Eichler–Selberg trace formula.

Modular forms play many roles in mathematics. For example, they often occur as generating functions for interesting quantities in arithmetic, combinatorics, and number theory. The theory of Hecke operators then often applies and leads to results of interest. Here, we examine the combinatorial properties of the action of Hecke operators on spaces of modular forms.

1. Introduction and Statement of Results

Throughout this article, let k be a positive integer, and let $S_{2k}(\Gamma_0(N))$ [respectively (resp.), $S_{2k}^{new}(\Gamma_0(N))$] denote the space generated by the weight $2k$ cusp forms (resp. newforms) on the congruence subgroup $\Gamma_0(N)$ (see refs. 1 and 2 for background on modular forms). For positive integers n and N, which are coprime, define the integers $\mathrm{Tr}_{2k}(\Gamma_0(N), n)$ and $\mathrm{Tr}_{2k}^{new}(\Gamma_0(N), n)$ by the following:

$$\mathrm{Tr}_{2k}^{new}(\Gamma_0(N), n) := \text{trace of the } n\text{th Hecke}$$
$$\text{operator on } S_{2k}^{new}(\Gamma_0(N)); \qquad [1.1]$$

$$\mathrm{Tr}_{2k}(\Gamma_0(N), n) := \text{trace of the } n\text{th Hecke}$$
$$\text{operator on } S_{2k}(\Gamma_0(N)). \qquad [1.2]$$

Recent works (for example, see refs. 3–7) have proven congruences between such traces and combinatorial numbers, such as the Apéry numbers.

$$A(n) := \sum_{j=0}^{n} \binom{n+j}{j}^2 \binom{n}{j}^2.$$

For example, Ahlgren and K.O. (3) confirmed the following conjecture of Beukers:

$$\mathrm{Tr}_4^{new}(\Gamma_0(8), p) \equiv A\left(\frac{p-1}{2}\right) \pmod{p^2}$$

for every odd prime p. Many more such congruences for traces are obtained in ref. 4.

In view of these congruences, it is natural to investigate the intrinsic combinatorial properties of these traces. In the n aspect (i.e., where $2k$ and N are fixed), one does not expect to find a simple combinatorial description of these traces. However, in the weight aspect, these traces are combinatorial numbers. We begin by presenting four examples of this phenomenon.

There are many instances in which these traces are combinatorial numbers analogous to the Apéry numbers. For example, we establish the following fact.

Theorem 1.1. If $k \geq 2$, then

$$\mathrm{Tr}_{2k}(\Gamma_0(7), 2) = -2 - \sum_{r=0}^{k-1} \binom{k+r-1}{2r} 4(-2)^{k-r-1}.$$

Theorem 1.1 provides a combinatorial formula for the trace of T_2 on the space of cusp forms for the congruence subgroup $\Gamma_0(7)$. Such formulas are often connected closely to hypergeometric functions. First, we recall the traditional notation for these functions. If n is a positive integer, then define $(a)_n$ by the following:

$$(a)_n := a(a+1)(a+2)\cdots(a+n-1). \qquad [1.3]$$

If $n = 0$, then let $(a)_n := 1$. Gauss' $_2F_1$ hypergeometric functions are defined by the following:

$$_2F_1\left(\begin{array}{c} a, b \\ c \end{array}\middle| x\right) := \sum_{n=0}^{\infty} \frac{(a)_n (b)_n}{(c)_n n!} \cdot x^n. \qquad [1.4]$$

We establish the following formula involving $_2F_1$ functions (which are Gegenbauer polynomials).

Theorem 1.2. If $k \geq 3$, then

$$\mathrm{Tr}_{2k}(\Gamma_0(17), 3) = -2 + 3(-2)^{k-1}$$
$$\cdot\, _2F_1\left(\begin{array}{c} (2-k)/2, (3-k)/2 \\ 2-k \end{array}\middle| 9\right)$$
$$+ (-2)^k \,_2F_1\left(\begin{array}{c} (1-k)/2, (2-k)/2 \\ 1-k \end{array}\middle| 9\right).$$

In general, we will demonstrate that, apart from certain simple summands, Hecke traces are almost always sums of such $_2F_1$ evaluations.

In view of the combinatorial formulas in *Theorems 1.1* and *1.2*, it is natural to wonder whether these traces are connected to classical topics in enumerative combinatorics. The next two examples confirm this speculation.

If n is a nonnegative integer, then let

$$T(n) := \#\{\text{tilings of a } 3 \times n \text{ rectangle using}$$
$$1 \times 1 \text{ and } 2 \times 2 \text{ tiles}\}. \qquad [1.5]$$

For example, Fig. 1 shows the five tilings when $n = 3$.

It turns out that $\mathrm{Tr}_{12}(\Gamma_0(3), 2) = 6 \cdot T(3) = 30$, which is an example of the following more general result.

Theorem 1.3. If $k \geq 3$, then

$$\mathrm{Tr}_{2k}(\Gamma_0(3), 2) = 6(-1)^k \cdot T(k-3).$$

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