

# Combinatorics of traces of Hecke operators

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Communicated by George E. Andrews, Pennsylvania State University, University Park, PA, September 30, 2004 (received for review March 17, 2004)

We investigate the combinatorial properties of the traces of the  $n$ th 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.

**M**odular 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.),  $S_{2k}^{\text{new}}(\Gamma_0(N))$ ] 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  $\text{Tr}_{2k}(\Gamma_0(N), n)$  and  $\text{Tr}_{2k}^{\text{new}}(\Gamma_0(N), n)$  by the following:

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

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

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

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

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

$$\text{Tr}_{2k}^{\text{new}}(\Gamma_0(8), p) \equiv \mathcal{A}\left(\frac{p-1}{2}\right) \pmod{p^2}$$

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

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

*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:

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

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

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

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

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

$$\begin{aligned} \text{Tr}_{2k}(\Gamma_0(17), 3) &= -2 + 3(-2)^{k-1} \\ &\quad \cdot {}_2F_1\left(\begin{matrix} (2-k)/2, (3-k)/2 \\ 2-k \end{matrix} \middle| 9\right) \\ &\quad + (-2)^k {}_2F_1\left(\begin{matrix} (1-k)/2, (2-k)/2 \\ 1-k \end{matrix} \middle| 9\right). \end{aligned}$$

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

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

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

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

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

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

Abbreviation: resp., respectively.

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## **Table of Contents Combinatorics On Traces**

1. Understanding the eBook Combinatorics On Traces
  - The Rise of Digital Reading Combinatorics On Traces
  - Advantages of eBooks Over Traditional Books
2. Identifying Combinatorics On Traces
  - Exploring Different Genres
  - Considering Fiction vs. Non-Fiction
  - Determining Your Reading Goals
3. Choosing the Right eBook Platform
  - Popular eBook Platforms
  - Features to Look for in an Combinatorics On Traces
  - User-Friendly Interface
4. Exploring eBook Recommendations from Combinatorics On Traces
  - Personalized Recommendations
  - Combinatorics On Traces User Reviews and Ratings
  - Combinatorics On Traces and Bestseller Lists
5. Accessing Combinatorics On Traces Free and Paid eBooks
  - Combinatorics On Traces Public Domain eBooks
  - Combinatorics On Traces eBook Subscription Services
  - Combinatorics On Traces Budget-Friendly Options

6. Navigating Combinatorics On Traces eBook Formats
  - ePub, PDF, MOBI, and More
  - Combinatorics On Traces Compatibility with Devices
  - Combinatorics On Traces Enhanced eBook Features
7. Enhancing Your Reading Experience
  - Adjustable Fonts and Text Sizes of Combinatorics On Traces
  - Highlighting and Note-Taking Combinatorics On Traces
  - Interactive Elements Combinatorics On Traces
8. Staying Engaged with Combinatorics On Traces
  - Joining Online Reading Communities
  - Participating in Virtual Book Clubs
  - Following Authors and Publishers Combinatorics On Traces
9. Balancing eBooks and Physical Books Combinatorics On Traces
  - Benefits of a Digital Library
  - Creating a Diverse Reading Collection Combinatorics On Traces
10. Overcoming Reading Challenges
  - Dealing with Digital Eye Strain
  - Minimizing Distractions
  - Managing Screen Time
11. Cultivating a Reading Routine Combinatorics On Traces
  - Setting Reading Goals Combinatorics On Traces
  - Carving Out Dedicated Reading Time
12. Sourcing Reliable Information of Combinatorics On Traces
  - Fact-Checking eBook Content of Combinatorics On Traces
  - Distinguishing Credible Sources
13. Promoting Lifelong Learning
  - Utilizing eBooks for Skill Development
  - Exploring Educational eBooks
14. Embracing eBook Trends
  - Integration of Multimedia Elements

- Interactive and Gamified eBooks

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