

Combinatorics of traces of Hecke operators

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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.

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.), $S_{2k}^{\text{new}}(\Gamma_0(N))$] 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.

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

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

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

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*

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

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

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

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

It turns out that $\text{Tr}_{12}(\Gamma_0(3), 2) = 6T(3) = 30$, 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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Combinatorics On Traces

Andrzej Tarlecki



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Volker Diekert, 1988 [Semantics of Systems of Concurrent Processes](#)

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Gerbner is a researcher at the Alfréd Rényi Institute of Mathematics Hungarian Academy of Sciences in Budapest Hungary He holds a Ph D from Eötvös Loránd University Hungary and has contributed to numerous publications His research interests are in extremal combinatorics and search theory Balázs Patkó is also a researcher at the Alfréd Rényi Institute of Mathematics Hungarian Academy of Sciences He holds a Ph D from Central European University Budapest and has authored several research papers His research interests are in extremal and probabilistic combinatorics

Fundamentals of Computation Theory, 2001 *Automata, Languages and Programming* Javier Leach Albert, 1991 Papers presented at the 18th International Colloquium Madrid Spain July 1991 on such matters as logic and functional programming complexity concurrency graph algorithms complexity and computational geometry Annotation copyrighted by Book News Inc Portland OR

Annual Symposium on Theoretical Aspects of Computer Science, 2006 *Automata, Languages and Programming*, 2002 *Handbook of Weighted Automata* Manfred Droste, Werner Kuich, Heiko Vogler, 2009-09-18 The purpose of this Handbook is to highlight both theory and applications of weighted automata Weighted finite automata are classical nondeterministic finite automata in which the transitions carry weights These weights may model e.g. the cost involved when executing a transition the amount of resources or time needed for this or the probability or reliability of its successful execution The behavior of weighted finite automata can then be considered as the function suitably defined associating with each word the weight of its execution Clearly weights can also be added to classical automata with infinite state sets like pushdown automata this extension constitutes the general concept of weighted automata To illustrate the diversity of weighted automata let us consider the following scenarios Assume that a quantitative system is modeled by a classical automaton in which the transitions carry as weights the amount of resources needed for their execution Then the amount of resources needed for a path in this weighted automaton is obtained simply as the sum of the weights of its transitions Given a word we might be interested in the minimal amount of resources needed for its execution i.e. for the successful paths realizing the given word In this example we could also replace the resources by profit and then be interested in the maximal profit realized correspondingly by a given word

[Advances in Petri Nets](#), 1991

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