

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.

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

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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Combinatorics On Traces

**Manfred Droste, Werner Kuich, Heiko
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Combinatorics On Traces:

Combinatorics on Traces Volker Diekert, 2014-03-12 Parallelism or concurrency is one of the fundamental concepts in computer science. But in spite of its importance, theoretical methods to handle concurrency are not yet sufficiently developed. This volume presents a comprehensive study of Mazurkiewicz trace theory from an algebraic combinatorial point of view. This theory is recognized as an important tool for a rigorous mathematical treatment of concurrent systems. The volume covers several different research areas and contains not only known results but also various new results published nowhere else. Chapter 1 introduces basic concepts. Chapter 2 gives a straight path to Ochmanski's characterization of recognizable trace languages and to Zielonka's theory of asynchronous automata. Chapter 3 applies the theory of traces to Petri nets. A kind of morphism between nets is introduced which generalizes the concept of synchronization. Chapter 4 provides a new bridge between the theory of string rewriting and formal power series. Chapter 5 is an introduction to a combinatorial theory of rewriting on traces which can be used as an abstract calculus for transforming concurrent processes.

The Book of Traces Volker Diekert, Grzegorz Rozenberg, 1995 The theory of traces employs techniques and tackles problems from quite diverse areas which include formal language theory, combinatorics, graph theory, algebra, logic, and the theory of concurrent systems. In all these areas, the theory of traces has led to interesting problems and significant results. It has made an especially big impact in formal language theory and the theory of concurrent systems. In both these disciplines, it is a well-recognized and dynamic research area. Within formal language theory, it yields the theory of partially commutative monoids and provides an important connection between languages and graphs. Within the theory of concurrent systems, it provides an important formal framework for the analysis and synthesis of concurrent systems. This monograph covers all important research lines of the theory of traces; each chapter is devoted to one research line and is written by leading experts. The book is organized in such a way that each chapter can be read independently, and hence it is very suitable for advanced courses or seminars on formal language theory, the theory of concurrent systems, the theory of semigroups, and combinatorics. An extensive bibliography is included. At present, there is no other book of this type on trace theory.

Combinatorics on traces with applications to Petri nets and replacement systems Volker Diekert, 1988

Semantics of Systems of Concurrent Processes Irene Guessarian, Laboratoire informatique théorique et programmation (France), 1990-11-28 This volume contains the proceedings of the 1990 Spring School of Theoretical Computer Science devoted to the semantics of concurrency. The papers are of two kinds: surveys and tutorials introducing the subject to novices and students, and giving updates of the state of the art; research papers presenting recent achievements in the semantics of concurrency. The contributions explicate the connections, similarities, and differences between various approaches to the semantics of concurrency, such as pomsets and metric semantics, event structures, synchronization trees, fixpoints, and languages, traces, CCS, and Petri nets, and categorical models. They also cover and compare the various notions of observation and bisimulation, equivalences, logics for concurrency, and

applications to distributed systems

STACS 91 Christian Choffrut, Matthias Jantzen, 1991-02-08 Annotation The Symposium on Theoretical Aspects of Computer Science is organized jointly by the Special Interest Group for Applied Mathematics of AFCET Association Française de Cybernétique Economique et Technique and the Special Interest Group for Theoretical Computer Sciences of GI Gesellschaft für Informatik It is held alternately in France and in Germany This volume contains two invited papers on combinatorial methods in computer science and on the complexity of local optimization and 24 contributions on theoretical aspects of computer science Some software systems are presented showing the possibilities of applying theoretical research to the realization of software tools

Combinatorial Image Analysis Valentin E. Brimkov, Reneta P. Barneva, 2017-05-15 This book constitutes the proceedings of the 18th International Workshop on Combinatorial Image Analysis IW CIA 2017 held in Plovdiv Bulgaria in June 2017 The 27 revised full papers presented were carefully reviewed and selected from 47 submissions The workshop is organized in topical sections of theoretical foundations and theory of applications namely discrete geometry and topology tilings and patterns grammars models and other technical tools for image analysis image segmentation classification reconstruction compression texture analysis bioimaging

Discrete Geometry for Computer Imagery Nicolas Normand, Jeanpierre Guédon, Florent Autrusseau, 2016-04-08 This book constitutes the refereed proceedings of the 19th IAPR International Conference on Discrete Geometry for Computer Imagery DGCI 2016 held in Nantes France in April 2016 The 32 revised full papers presented together with 2 invited talks were carefully selected from 51 submissions The papers are organized in topical sections on combinatorial tools discretization discrete tomography discrete and combinatorial topology shape descriptors models for discrete geometry circle drawing morphological analysis geometric transforms and discrete shape representation recognition and analysis

Structures in Concurrency Theory Jörg Desel, 1995-10-13 This is the latest volume in the Workshops in Computing series and contains the papers presented at the International Workshop on Structures in Concurrency Theory STRICT held in Berlin from 11-13 May 1995 Concurrency theory deals with formal aspects of concurrent systems It uses partly competing and partly complementary formalisms and structures This workshop was jointly organised by the Humboldt Universität zu Berlin and the ESPRIT Basic Research Working Group CALIBAN CALIBAN and its predecessor DEMON are ESPRIT Basic Research projects with the aim of developing design methodologies based on causal models such as Petri nets The workshop marked the third year of the project and surveyed the results of CALIBAN and DEMON since 1989

Paradigms of Concurrency Ryszard Janicki, Jetty Kleijn, Maciej Koutny, Łukasz Mikulski, 2022-06-06 Paradigms of Concurrency Observations Behaviours and Systems a Petri Net View Ryszard Janicki McMaster University CA Jetty Kleijn Leiden University NL Maciej Koutny Newcastle University UK Łukasz Mikulski Nicolaus Copernicus University PL Concurrency can be studied at different yet consistent levels of abstraction from individual behavioural observations via more abstract concurrent histories that can be represented by causality structures capturing invariant dependencies between

executed actions to system level constructs such as Petri nets or process algebra expressions Histories can then be understood as sets of closely related observations Depending on the nature of the observed relationships between executed actions involved in a single concurrent history one may identify different concurrency paradigms underpinned by different kinds of causality structures such as partial orders This book studies fundamental mathematical abstractions to capture and relate observations histories and systems In particular taking a Petri net view we present system models fitting various concurrency paradigms and their associated causality structures

Mathematics From the Birth of Numbers Jan

Gullberg,1997-01-07 An illustrated exploration of mathematics and its history beginning with a study of numbers and their symbols and continuing with a broad survey that includes consideration of algebra geometry hyperbolic functions fractals and many other mathematical functions Mathematical Foundations of Computer Science 1993 Andrzej M.

Borzyszkowski,1993-08-18 This volume contains the proceedings of the 18th International Symposium on Mathematical Foundations of Computer Science MFCS 93 held in Gdansk Poland August September 1993 The MFCS symposia organized annually in Poland and the former Czechoslovakia since 1972 have a long and well established tradition Over the years they have served as a meeting ground for specialists from all branches of theoretical computer science in particular algorithms and complexity automata theory and theory of languages concurrent distributed and real time systems the theory of functional logic and object oriented programming lambda calculus and type theory semantics and logics of programs and others The volume contains 12 invited lectures and 56 contributed papers selected from 133 submissions *Mathematical Foundations of Computer Science* ,2003 **Extremal Finite Set Theory** Daniel Gerbner,Balazs Patkos,2018-10-12

Extremal Finite Set Theory surveys old and new results in the area of extremal set system theory It presents an overview of the main techniques and tools shifting the cycle method profile polytopes incidence matrices flag algebras etc used in the different subtopics The book focuses on the cardinality of a family of sets satisfying certain combinatorial properties It covers recent progress in the subject of set systems and extremal combinatorics Intended for graduate students instructors teaching extremal combinatorics and researchers this book serves as a sound introduction to the theory of extremal set systems In each of the topics covered the text introduces the basic tools used in the literature Every chapter provides detailed proofs of the most important results and some of the most recent ones while the proofs of some other theorems are posted as exercises with hints Features Presents the most basic theorems on extremal set systems Includes many proof techniques Contains recent developments The book s contents are well suited to form the syllabus for an introductory course About the Authors Daniel 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 **Annual Symposium on Theoretical Aspects of Computer Science** ,2006

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 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

Automata, Languages and Programming ,2002 **Inquiry-Based Enumerative Combinatorics** T. Kyle Petersen,2019-06-28 This textbook offers the opportunity to create a uniquely engaging combinatorics classroom by embracing Inquiry Based Learning IBL techniques Readers are provided with a carefully chosen progression of theorems to prove and problems to actively solve Students will feel a sense of accomplishment as their collective inquiry traces a path from the basics to important generating function techniques Beginning with an exploration of permutations and combinations that culminates in the Binomial Theorem the text goes on to guide the study of ordinary and exponential generating functions These tools underpin the in depth study of Eulerian Catalan and Narayana numbers that follows and a selection of advanced topics that includes applications to probability and number theory Throughout the theory unfolds via over 150 carefully selected problems for students to solve many of which connect to state of the art research Inquiry Based Enumerative Combinatorics is ideal for lower division undergraduate students majoring in math or computer science as there are no formal mathematics prerequisites Because it includes many connections to recent research students of any level who are interested in combinatorics will also find this a valuable resource *Mathematical Reviews* ,2005

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