SQUARE q, t-LATTICE PATHS AND ∇(p_n)

NICHOLAS A. LOEHR AND GREGORY S. WARRINGTON

Abstract. The combinatorial q, t-Catalan numbers are weighted sums of Dyck paths introduced by J. Haglund and studied extensively by Haglund, Haiman, Garsia, Loehr, and others. The q, t-Catalan numbers, besides having many subtle combinatorial properties, are intimately connected to symmetric functions, algebraic geometry, and Macdonald polynomials. In particular, the n'th q, t-Catalan number is the Hilbert series for the module of diagonal harmonic alternants in 2n variables; it is also the coefficient of s_1^n in the Schur expansion of ∇(e_n). Using q, t-analogues of labelled Dyck paths, Haglund et al. have proposed combinatorial conjectures for the monomial expansion of ∇(e_n) and the Hilbert series of the diagonal harmonics modules.

This article extends the combinatorial constructions of Haglund et al. to the case of lattice paths contained in squares. We define and study several q, t-analogues of these lattice paths, proving combinatorial facts that closely parallel corresponding results for the q, t-Catalan polynomials. We also conjecture an interpretation of our combinatorial polynomials in terms of the nabla operator. In particular, we conjecture combinatorial formulas for the monomial expansion of ∇(p_n), the “Hilbert series” ⟨∇(p_n), h_1^n⟩, and the sign character ⟨∇(p_n), s_1^n⟩.

1. Introduction

In 1996, A. Garsia and M. Haiman introduced a two-variable analogue of the Catalan numbers called the q, t-Catalan numbers [7]. Garsia and Haiman’s definition of the q, t-Catalan, which arose from their study of Macdonald polynomials and diagonal harmonics, was quite complicated. Several years later, J. Haglund [8] conjectured an elementary combinatorial definition of the q, t-Catalan numbers as weighted sums of Dyck paths relative to two statistics called area and bounce. Shortly thereafter, Haiman proposed an equivalent combinatorial interpretation involving area and a third statistic called div. Garsia and Haglund eventually proved that the two combinatorial definitions were equivalent to the original definition of Garsia and Haiman [5, 6]. Haiman proved many of the conjectures relating the q, t-Catalan numbers to the representation theory of diagonal harmonics modules and the algebraic geometry of the Hilbert scheme [17, 18]. Meanwhile, various authors studied the subtle combinatorial properties of the combinatorial q, t-Catalan numbers and their generalizations [4, 9, 13, 14, 19, 20, 21, 22, 23, 24]. Surveys of different aspects of this research can be found in [15, 16, 19], and especially in [11].
This article discusses a generalization of the combinatorial $q,t$-Catalan numbers in which Dyck paths are replaced by lattice paths inside squares. We develop the combinatorial theory of these “square $q,t$-lattice paths,” which closely parallels the corresponding theory for the $q,t$-Catalan numbers. We also conjecture analogs of the $q,t$-Catalan numbers. We also prove algebraic interpretations for our combinatorial and algebraic results associated with the combinatorial $q,t$-Catalan numbers. The main body of the paper discusses the corresponding results and conjectures for our square $q,t$-lattice paths.

1.1. Combinatorial aspects of the $q,t$-Catalan numbers. This section reviews the essential definitions and combinatorial results involving the $q,t$-Catalan numbers.

1. Lattice paths and Dyck paths. A lattice path in a $c \times d$ rectangle is a path from $(0,0)$ to $(c,d)$ consisting of $c$ east steps and $d$ north steps of length 1. Such a path can be represented as a word $w = w_1 \cdots w_{c+d}$ with $d$ zeros (encoding north steps) and $c$ ones (encoding east steps). Let $\mathcal{R}_{c,d}$ be the set of lattice paths from $(0,0)$ to $(c,d)$. A Dyck path of order $n$ is a lattice path in an $n \times n$ rectangle that never visits any point $(x,y)$ with $y < x$. Let $\mathcal{D}_n$ be the set of Dyck paths of order $n$.

2. Classical statistics on paths. For any logical statement $A$, write $\chi(A) = 1$ if $A$ is true, and $\chi(A) = 0$ if $A$ is false. Let $P \in \mathcal{R}_{c,d}$ be encoded by the word $w = w_1 w_2 \cdots w_{c+d}$. Define the major index, inversions, and lower area of $P$ by the formulas $\text{maj}(P) = \sum_{i < c+d} i \chi(w_i > w_{i+1})$, $\text{inv}(P) = \sum_{i<j} \chi(w_i > w_j)$, and $\text{ar}(P) = cd - \text{inv}(P)$. The $q$-binomial coefficient is given by any of the following formulas:

\[
\begin{bmatrix} c+d \\ c, d \end{bmatrix}_q = \sum_{P \in \mathcal{R}_{c,d}} q^{\text{ar}(P)} = \sum_{P \in \mathcal{R}_{c,d}} q^{\text{inv}(P)} = \sum_{P \in \mathcal{R}_{c,d}} q^{\text{maj}(P)}.
\]

For $D \in \mathcal{D}_n \subset \mathcal{R}_{n,n}$, let $g_i(D)$ be the number of complete lattice squares between $D$ and the line $y = x$ in the $i$'th row from the bottom ($0 \leq i < n$). Define the area vector of $D$ to be $g(D) = (g_0(D), \ldots, g_{n-1}(D))$. Set $\text{area}(D) = \sum_{i=0}^{n-1} g_i(D) = \text{ar}(D) - \binom{n+1}{2}$.

3. The statistics dinv and bounce. Given $D \in \mathcal{D}_n$, Haiman defined the $d$-inversions of $D$ by setting

\[
\text{dinv}(D) = \sum_{i<j} \chi(g_i(D) - g_j(D) \in \{0,1\}).
\]

Haglund defined a bounce path and bounce statistic for $D$ as follows. A ball starts at $(n,n)$ and makes a succession of alternating horizontal and vertical moves $H_0(D), V_0(D), H_1(D), V_1(D), \ldots, H_n(D), V_n(D)$ leading west and south to $(0,0)$. The moves $H_i(D)$ and $V_i(D)$ will consist of $h_i(D)$ west steps and $v_i(D) = h_i(D)$ south steps, respectively. After the first $i$ pairs of moves, the ball has reached the point $(n_i, n_i)$ on the main diagonal, where $n_i = n - \sum_{j<i} h_j(D)$. At the next step, the ball moves west $h_i(D)$ units until it is “blocked” by the north step of $D$ ending at $(n_i - h_i(D), n_i)$. The ball then moves south $v_i(D) = h_i(D)$ units to
numbers by the equivalent formulas
\[ \sum \]

sketch the definition of 
\[ g \]

north steps, the last of which is a blocking north step. To determine the substring
\[ (\text{area, } \text{dinv, } \text{bounce}) \]

that maps the ordered pair of statistics (area, dinv, bounce) to (dinv, area). We briefly
define bounce(D) = \sum_{i \geq 0} iv_i(D) = \sum_{i \geq 0} ih_i(D), which is the number
of lattice squares in the rows west of the blocking north steps.

For example, if \( n = 8 \) and \( D \) is the Dyck path represented by the word \( w = 0010010011101101 \), then \( \text{maj}(D) = 34, \text{inv}(D) = 18, \text{g}(D) = (0, 1, 1, 2, 3, 1, 0), \)
area(D) = 10, dinv(D) = 10, \( s = 3, v_0 = h_0 = 1, v_1 = h_1 = 2, v_2 = h_2 = 3, \)
v_3 = h_3 = 2, and bounce(D) = 14. See Figure I where the cells contributing to bounce(D)
marked by X’s, and the blocking north steps are cross-hatched.

4. Combinatorial q, t-Catalan numbers. We define the combinatorial q, t-Catalan
numbers by the equivalent formulas
\[ C_n(q, t) = \sum_{D \in \mathcal{D}_n} q^{\text{dinv}(D)} t^{\text{area}(D)} = \sum_{D \in \mathcal{D}_n} q^{\text{area}(D)} t^{\text{bounce}(D)}. \]

The equivalence of these definitions is proved by exhibiting a bijection \( \alpha : \mathcal{D}_n \rightarrow \mathcal{D}_n \)
that maps the ordered pair of statistics (area, bounce) to (dinv, area). We briefly
sketch the definition of \( \alpha \). Given \( D \in \mathcal{D}_n \), compute bpath(D) and \( (h_0, v_0, \ldots, h_s, v_s) \)
as above. We construct \( D' = \alpha(D) \) by specifying its area vector \( g(D') \). This vector
consists of \( v_i \) copies of \( i, \) for \( 0 \leq i \leq s \). For each \( i \leq s \), the portion of \( D \) located
west of \( V_{i-1} \) and north of \( H_i \) is used to determine the relative order of the \( i-1 \)'s
and \( i \)'s in \( g(D') \). Note that this portion of \( D \) consists of \( h_i = v_i \) east steps and \( v_{i-1} \)
north steps, the last of which is a blocking north step. To determine the substring of
\( g(D') \) involving the \( (i-1)'s \) and \( i \)'s, we read this portion of \( D \) backwards,
interpreting a north step as an \( i-1 \) and an east step as an \( i \). This information about
substrings of \( g(D') \) does suffice to determine \( g(D') \) uniquely, because \( g_0(D') = 0 \)
and \( g_{j+1}(D') \leq g_j(D') + 1 \) for all \( j \). Moreover, the passage from \( D \) to \( g(D') \) to
\( D' \) is reversible, and one checks that it has the desired effect on the statistics. For
example, if \( D \) is the path shown in Figure I then \( g(D') = (0, 1, 2, 3, 2, 2, 3, 1), \)
area(D') = 14 = bounce(D), and dinv(D') = 10 = area(D).

5. Symmetry properties. We have the univariate symmetry \( C_n(q, 1) = C_n(1, q), \)
which says that the statistics area, dinv, and bounce are equidistributed on \( \mathcal{D}_n \).
In fact, we even have the joint symmetry \( C_n(q, t) = C_n(t, q), \) which follows from
Garsia and Haglund’s long proof linking \( C_n(q, t) \) to the nabla operator \( [5, 6] \). The

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{dyck_path}
\caption{Bouncing through a Dyck path.}
\end{figure}
map $\alpha$ provides a bijective proof of univariate symmetry; giving a bijective proof of joint symmetry is an open problem.

6. Recursion. For $0 \leq k \leq n$, let $D_{n,k}$ consist of all Dyck paths $D \in D_n$ ending with exactly $k$ east steps; $D \in D_{n,k}$ iff $h_0(D) = k$. Set

$$C_{n,k}(q,t) = \sum_{D \in D_{n,k}} q^{\text{area}(D)} t^{\text{bounce}(D)}.$$ 

By classifying paths based on $r = h_1(D)$, Haglund proved the recursion

$$C_{n,k}(q,t) = q^{k(k-1)/2} n^{-k} \sum_{r=0}^{n-k} \binom{r+k-1}{r,k-1} q^{n-k} r(q,t)$$

with initial conditions $C_{n,0}(q,t) = \chi(n = 0)$ for all $n \geq 0$ [8]. Since $C_n(q,t) = t^{-n} C_{n+1,1}(q,t)$, this recursion uniquely determines the $q,t$-Catalan numbers.

7. Fermionic formula. Haglund also derived an explicit “fermionic” formula for $C_n(q,t)$ [8]:

$$C_n(q,t) = \sum_{w_0, \ldots, w_s = n \atop w_i > 0} q^{\text{maj}(w)} t^{\text{area}(w)} \prod_{i=0}^{s-1} \left[ w_{i+1} + w_i - 1 \right]_q \left[ w_i + 1, w_i - 1 \right]_q.$$ 

The summand indexed by $(w_0, \ldots, w_s)$ enumerates those Dyck paths $D$ such that $v_i(D) = w_i$ for $0 \leq i \leq s$.

8. Specialization at $t = 1/q$. Haglund [8] and Loehr [24] gave algebraic and bijective proofs (respectively) of the respective formulas

$$q^{(\frac{n}{2})} C_{n,k}(q,1/q) = \left[ \frac{k}{n} \right]_q \binom{2n - k - 1}{n-k, n-1} q^{(k-1)n},$$

$$q^{\left(\frac{n+1}{2}\right)-nk} C_{n,k}(q,1/q) = \left[ \frac{2n - k - 1}{n-k, n-1} \right]_q - q^k \left[ \frac{2n - k - 1}{n-1, n} \right]_q.$$ 

It follows that $q^{(\frac{n}{2})} C_n(q,1/q)$ is given by the formulas

$$\frac{1}{n+1}_q 2n \left\{ \begin{array}{c} n+n \\ n \end{array} \right\}_q = q \left\{ \begin{array}{c} 2n \\ n-1,n+1 \end{array} \right\}_q = \sum_{D \in D_n} q^{\text{maj}(D)}.$$ 

Using completely different methods, Garsia and Haiman [7] proved the same result for their original version of the $q,t$-Catalan numbers.

9. Statistics for labelled paths. The area and $\text{dinv}$ statistics for Dyck paths extend naturally to labelled Dyck paths. A labelled Dyck path of order $n$ is a path $D \in D_n$ in which each vertical step is assigned a label between 1 and $n$. We require that the labels of vertical steps in the same column strictly increase from bottom to top. Let $P_n$ denote the set of all such objects with distinct labels; let $Q_n$ denote the set of all such objects where labels may be repeated (subject to the increasing-column condition). An object $Q \in Q_n$ is uniquely determined by the pair $(g(Q), r(Q))$, where $g(Q) = (g_0(Q), \ldots, g_{n-1}(Q))$ is the area vector of the path $Q$ (ignoring labels), and $r(Q) = (r_0(Q), \ldots, r_{n-1}(Q))$ is the sequence of labels in $Q$ from bottom to top. We call $r(Q)$ the label vector of $Q$. Define $c_Q(j)$ to be the number of $j$’s in the label vector $r(Q)$. Define $\text{area}(Q) = \sum_{i=0}^{n-1} g_i(Q)$ and

$$\text{dinv}(Q) = \sum_{i<j} \chi(g_i = g_j \text{ and } r_i < r_j) \text{ or } (g_i = g_j + 1 \text{ and } r_i > r_j)).$$
Finally, define generating functions
\[ H_n(q, t) = \sum_{P \in \mathcal{P}_n} q^{\text{area}(P)} t^{\text{dinv}(P)}, \quad F_n(\tilde{z}; q, t) = \sum_{Q \in \mathcal{Q}_n} q^{\text{area}(P)} t^{\text{dinv}(P)} \prod_{j \geq 1} z_{c_j^q}(j). \]

Many combinatorial properties of the \( q, t \)-Catalan numbers extend to these polynomials \([13, 14, 21]\), including: univariate symmetry in \( q \) and \( t \), conjectural joint symmetry, definitions via bounce-like statistics, fermionic formulas, recursions, and specializations at \( t = 1/q \). For example, \( q^{(2)} H_n(q, 1/q) = [n + 1]_q^{n-1} \) \([21]\).

### 1.2. Algebraic aspects of the \( q, t \)-Catalan numbers

This section reviews the principal theorems and conjectures connecting Haglund’s combinatorial \( q, t \)-Catalan numbers (and their extensions \( H_n \) and \( F_n \)) to the theory of Macdonald polynomials, diagonal harmonics modules, and symmetric functions. We first recall some standard definitions and results in symmetric function theory and representation theory; see \([25, 29]\) for more details.

1. **Partitions.** Let \( \mu = (\mu_1 \geq \cdots \geq \mu_s > 0) \) be a partition. Define \( |\mu| = \mu_1 + \cdots + \mu_s, \mu \vdash n \) if \( |\mu| = n \), \( \ell(\mu) = s, n(\mu) = \sum_{i=1}^s (i-1)\mu_i, \mu_i = 0 \) for all \( i > s \), and write \( \mu' \) for the transpose of \( \mu \). If \( \lambda, \mu \vdash n \), write \( \lambda \geq \mu \) if \( \lambda \) dominates \( \mu \) iff \( \lambda_1 + \cdots + \lambda_i \geq \mu_1 + \cdots + \mu_i \) for all \( i \). We draw the Ferrers diagram \( D(\mu) \) in the first quadrant of the \( xy \)-plane, left-justified, with the longest row appearing at the bottom. With this convention, for each cell \( c \in D(\mu) \) we define the arm, coarm, leg, and coleg of \( c \) (denoted \( a(c), a'(c), l(c), \) and \( l'(c) \)) to be the number of cells strictly east, strictly west, strictly north, and strictly south of \( c \) in \( D(\mu) \). We define

\[
M = (1-q)(1-t), \quad B_\mu = \sum_{c \in D(\mu)} q^{a'(c)} t^{l'(c)}, \quad \Pi_\mu = \prod_{c \in D(\mu)} (1-q^{a(c)} t^{l(c)}),
\]

\[
T_\mu = q^{a(\mu')} t^{n(\mu)}, \quad w_\mu = \prod_{c \in D(\mu)} [q^{a(c)} t^{l(c)+1} (t^{l(c)} - q^{a(c)+1})].
\]

For example, if \( \mu = (3, 2) \), then \( |\mu| = 5, \ell(\mu) = 2, n(\mu) = 2, \mu' = (2, 2, 1), n(\mu') = 4, B_\mu = 1 + q + q^2 + t + qt, \Pi_\mu = (1-q)(1-q^2)(1-t)(1-qt), T_\mu = q t^2, \) and 

\[
w_\mu = (q^2 - t^2)(q - t^2)(1-t)(q-t)(1-t)(t-q^2)(t-q^2)(1-q)(1-q^2)(1-q).
\]

2. **Symmetric functions.** We will work in the vector space \( \Lambda^F_n \) consisting of symmetric functions homogeneous of degree \( n \) in the variables \( z_1, \ldots, z_n \) with coefficients in \( F = \mathbb{Q}(q, t) \). We write \( m_\mu, h_\mu, e_\mu, p_\mu, \) and \( s_\mu \) to denote (respectively) the monomial, homogeneous, elementary, power-sum, and Schur symmetric functions indexed by \( \mu \vdash n \). These all form bases of \( \Lambda^F_n \). The **Hall scalar product** is defined by requiring that the Schur basis be orthonormal. The power-sum basis is orthogonal relative to this scalar product, while the monomial basis is dual to the homogeneous basis.

3. **Macdonald polynomials and nabla.** The modified Macdonald polynomials \( \{ H_\mu : \mu \vdash n \} \) form another basis for \( \Lambda^F_n \) \([12, 15, 16, 25]\). These can be defined from scratch as follows. Let \( \phi_q \) be the unique \( F \)-linear map on \( \Lambda^F_n \) defined on the basis \( \{ p_\mu \} \) by \( \phi_q(p_\mu) = (\prod_{i=1}^{\ell(\mu)} (1 - q^{\mu_i})) p_\mu \). Similarly, define a linear map \( \phi_t \) by requiring that \( \phi_t(p_\mu) = (\prod_{i=1}^{\ell(\mu')} (1 - t^{\mu_i})) p_\mu \). Then there exists a unique basis \( \{ \tilde{H}_\mu : \mu \vdash n \} \) of \( \Lambda^F_n \) characterized by the axioms:

\[
\begin{align*}
(1) \quad & \phi_q(\tilde{H}_\mu) = \sum_{\lambda \geq \mu} \lambda_{\geq \mu} a_{\lambda, \mu} s_\lambda \quad \text{for some } a_{\lambda, \mu} \in F, \\
(2) \quad & \phi_t(\tilde{H}_\mu) = \sum_{\lambda \geq \mu} \lambda_{\geq \mu} b_{\lambda, \mu} s_\lambda \quad \text{for some } b_{\lambda, \mu} \in F, \\
(3) \quad & \langle \tilde{H}_\mu, s_n \rangle = 1.
\end{align*}
\]
An explicit combinatorial description of $\tilde{H}_\mu$ was recently discovered by Haglund \cite{10} and proved by Haglund, Haiman, and Loehr in \cite{12}.

The nabla operator, introduced by F. Bergeron and Garsia \cite{1 \cite{2} \cite{3}}, is the unique $F$-linear map on $\Lambda^n_F$ defined on the basis $\{H_\mu\}$ by $\nabla(H_\mu) = T_\mu H_\mu$. For example, Theorem 2.4 in \cite{7} gives the following expansion of $e_n$ in terms of modified Macdonald polynomials: $e_n = \sum_{\mu \vdash n} MB_\mu \Pi_\mu / w_\mu H_\mu$. Therefore, the definition of nabla gives $\nabla(e_n) = \sum_{\mu \vdash n} (MT_\mu B_\mu \Pi_\mu / w_\mu) H_\mu$.

4. **Diagonal harmonics.** For $n \geq 1$, the symmetric group $S_n$ acts diagonally on the polynomial ring $R_n = \mathbb{Q}[x_1, \ldots, x_n, y_1, \ldots, y_n]$, which is doubly graded by total degree in the $x$-variables and in the $y$-variables. The **diagonal harmonics module** $DH_n$ consists of all $f \in R_n$ such that $\sum_{i=1}^n \partial x_i^h \partial y_i^k f = 0$ for all $h, k$ with $h + k \geq 1$. The **diagonal harmonic alternants** $DHA_n$ is the submodule of $DH_n$ consisting of all $f$ such that $\pi f = \text{sgn}(\pi) f$ for $\pi \in S_n$. We write $\text{Hilb}(DH_n)$ and $\text{Hilb}(DHA_n)$ for the Hilbert series of these doubly-graded $S_n$-modules, which are elements of $\mathbb{N}[q,T]$.

Write $\text{Frob}(DH_n)$ for the Frobenius series of $DH_n$: note that $\text{Frob}(DH_n) \in \Lambda^n_F$.

5. **Master theorem for the $q,t$-Catalan numbers.** For $n \geq 1$, the following five elements of $\mathbb{Q}[q,T]$ are all equal (and are, therefore, elements of $\mathbb{N}[q,T]$):

(a) $\sum_{\rho \in P_n} q^{\text{area}(P)} (\text{Haglund’s combinatorial formula} \cite{8}),$
(b) $\sum_{\rho \in P_n} q^{\text{dim}(P)} (\text{Haiman’s combinatorial formula}),$
(c) $\langle \nabla(e_\rho), h_{1^n} \rangle$ (nabla formula),
(d) $\sum_{\mu \vdash n} T_\mu^2 MB_\mu \Pi_\mu / w_\mu$ (Garsia-Haiman rational-function formula \cite{7}),
(e) $\text{Hilb}(DHA_n)$ (representation-theoretical formula).

The bijection $\alpha$ shows that (a) = (b). Using the formula for $\nabla(e_n)$ in terms of $\tilde{H}_\mu$, together with the identity $(H_\mu, h_{1^n}) = T_\mu$, we see that (c) = (d). The fact that (d) = (e) follows from a difficult theorem due to Mark Haiman giving a complete character formula for $DH_n$. \cite{17} \cite{15}. Finally, the equality (a) = (d) is also a hard result, due to Garsia and Haglund, whose long proof requires many intricate plethystic manipulations and subtle identities from the theory of Macdonald polynomials \cite{5} \cite{6}.

6. **Hilbert series conjecture** \cite{14}. For $n \geq 1$, the following six elements of $\mathbb{Q}[q,T]$ are all equal (and are, therefore, elements of $\mathbb{N}[q,T]$):

(a) $\sum_{\rho \in P_n} q^{\text{dim}(P)}$ (first combinatorial formula),
(b) $\sum_{\rho \in P_n} q^{\text{area}(P)} (\text{second combinatorial formula} \cite{21}),$
(c) $\langle \nabla(e_\rho), h_{1^n} \rangle$ (nabla formula),
(d) $\sum_{\mu \vdash n} (H_\mu, h_{1^n}) T_\mu MB_\mu \Pi_\mu / w_\mu$ (Macdonald polynomial formula),
(e) $\sum_{\mu \vdash n+1} M \Pi_\mu B_{\mu+1} / w_\mu$ (rational-function formula),
(f) $\text{Hilb}(DHA_n)$ (representation-theoretical formula).

The following equalities have already been proved: (a) = (b) holds by a bijection in \cite{21} \cite{23}; (c) = (d) follows immediately from the formula for $\nabla(e_n)$ in terms of $\tilde{H}_\mu$; (c) = (e) was proved by Haglund in \cite{9}; (d) = (f) follows from Haiman’s results on the character of $DH_n$. \cite{17} \cite{15}. The open conjecture states that the combinatorial formulas (a) and (b) equal the algebraic formulas (c) through (f).

7. **Frobenius series conjecture** \cite{13}. For $n \geq 1$, the following five elements of $\Lambda^n_F$ are all equal (and are, therefore, Schur-positive):

(a) $\sum_{Q \in Q_n} q^{\text{dim}(Q)} z^{\text{area}(Q)} z_1^{q(1)} \cdots z_n^{q(n)}$ (combinatorial formula),
(b) $\nabla(e_n)$ (nabla formula),
(c) $\sum_{\mu \vdash n} \tilde{H}_\mu T_\mu MB_\mu \Pi_\mu / w_\mu$ (Macdonald polynomial formula),
(d) $\sum_{\lambda\vdash n} s_\lambda \left( \sum_{\mu\vdash n+1} M_{\mu\lambda} B_\mu s_\lambda(B_\mu) / w_\mu \right)$ (Schur expansion),
(e) $\text{Frob}(DH_n)$ (representation-theoretical formula).

Here, $s_\lambda(B_\mu)$ denotes the value of the Schur function $s_\lambda(z_1, \ldots, z_n)$ at $z_i = q^{a_i(c_i)} t^{l_i(c_i)}$, where $c_1, \ldots, c_n$ are the cells of $D(\mu)$ in any order. It is clear that (b)=(c), (b)=(d) by a result of Haglund [9], and (c)=(e) by results of Haiman [17, 18]. The conjecture states that these four algebraic quantities are given by the combinatorial formula (a). It has been proved that (a) is a symmetric function in the variables $z_1, \ldots, z_n$ [13].

2. Combinatorics of square $q, t$-lattice paths

2.1. Statistics for square paths. A square lattice path of order $n$ is a lattice path in an $n \times n$ square. Let $\mathcal{SQ}_n$ denote the set of square lattice paths of order $n$. We now define three statistics on paths in $\mathcal{SQ}_n$ generalizing the area, dinv, and bounce statistics defined in [11, 12].

1. Square area statistic. For $S \in \mathcal{SQ}_n$, let $\ell = \ell(S)$ be the minimum possible value such that $S$ stays weakly above the line $y = x - \ell$. We call $\ell$ the deviation of the path $S$. Since $S$ begins at the origin and ends at $(n, n)$, we see that $0 \leq \ell \leq n$. Define the area vector $g(S) = (g_0(S), \ldots, g_{n-1}(S))$ by requiring that $g_i(S) + n - i$ be the number of complete boxes in the $i$th row from the bottom between $S$ and the line $x = n$. Note that the entries of this vector can be negative, but that this area vector reduces to the area vector in [11, 12] when $S$ is a Dyck path. We define $\text{area}(S) = \sum_{i=0}^{n-1} (\ell + g_i(S))$. This can be interpreted as the number of complete boxes to the right of $S$ and to the left of the line $y = x - \ell$.

2. Square dinv statistic. Suppose $S \in \mathcal{SQ}_n$ has $(g_0(S), \ldots, g_{n-1}(S))$ as its area vector. Define

$$\text{dinv}(S) = \sum_{i < j} \chi(g_i(S) - g_j(S) \in \{0, 1\}) + \sum_i \chi(g_i(S) < -1).$$

If $S$ is a Dyck path, then the condition $g_i(S) < -1$ never holds, and this formula for dinv$(S)$ reduces to the formula given in [11, 12].

3. Square bounce statistic. Let $S \in \mathcal{SQ}_n$ have deviation $\ell$. The break point of $S$, $(\ell_x(S), \ell_y(S))$, is the leftmost point along the path $S$ lying on the line $y = x - \ell$.

We now proceed to define a bounce path $bpath(S)$ in analogy with the bounce paths defined for Dyck paths. The bounce path for $S$ consists of two pieces: a positive part located northeast of the break point, and a negative part located southwest of the break point. First consider the positive part. A ball starts at $(n, n)$ and makes an initial vertical move $V_{-1}$ of length $v_{-1} = \ell$ ending at $(n, n - \ell)$. The ball then makes alternating horizontal and vertical moves $H_0, V_0, H_1, V_1, \ldots, H_s, V_s$ until it reaches the break point. We let $h_i$ and $v_i$ denote the length of the moves $H_i$ and $V_i$, respectively. We determine $h_i$ and $v_i$ for each $i \geq 0$ as follows. First, the ball moves west $h_i$ units until it is blocked by the north step of $S$ ending at the horizontal level occupied by the ball. Second, the ball moves south $v_i = h_i$ units to return to the line $y = x - \ell$. As before, the steps that block the ball’s westward motion are called blocking north steps.

The negative part of the bounce path traces the motion of a second bouncing ball that starts at the origin and moves northeast towards the break point. This ball makes an initial horizontal move $H_{-1}$ of length $h_{-1} = \ell$ from $(0, 0)$ to $(\ell, 0)$. It then
makes alternating vertical and horizontal moves $V_{-2}, H_{-2}, V_{-3}, H_{-3}, \ldots, V_u, H_u$ until it reaches the break point. For each $i < -1$, the ball moves north $v_i$ units until it is blocked by the east step of $S$ ending at the vertical line occupied by the ball. (Note that this is not just a reflected version of the bounce algorithm in the positive part.) The ball then moves east $h_i = v_i$ units to return to the line $y = x - \ell$. The east steps that block the ball’s northward motion are called blocking east steps.

Finally, we define the bounce statistic for any path $S \in SQ_n$. Let $V_u, \ldots, V_s$ be the nonzero vertical moves in $bpath(S)$, where $u \leq 0 \leq s$. Set $\text{bounce}(S) = \sum_{i=u}^s (i - u)v_i$. Also set $\text{bmin}(S) = u$ and $\text{bmax}(S) = s$.

For a Dyck path $D$, the deviation $\ell$ is 0, the break point is $(0,0)$, the positive part of the bounce path coincides with the bounce path described in §1.1, and the negative part of the bounce path is empty. In this case, we set $\text{bmin}(D) = 0$ (ignoring the empty moves $V_{-1}$ and $H_{-1}$), and the bounce statistic just defined reduces to the formula used in §1.1.

For example, Figure 2 illustrates a path $S \in SQ_{15}$ and its bounce path. For this path, $\ell(S) = 3$, the break point is $(8,5)$, $g(S) = (0, -1, -2, -1, -1, -3, -2, -2, -3, -2, -1, -1, 0, 1)$, $\text{area}(S) = 25$, $\text{dinv}(S) = 52$, $\text{bmin}(S) = -4$, $\text{bmax}(S) = 2$, $(v_{-4}, \ldots, v_2) = (h_{-4}, \ldots, h_2) = (1, 2, 2, 3, 3, 2, 2)$, and $\text{bounce}(S) = 49$.

2.2. Comparison of the statistics.

**Theorem 1.** There is a bijection $\phi : SQ_n \rightarrow SQ_n$ such that $\text{area}(\phi(S)) = \text{dinv}(S)$ and $\text{bounce}(\phi(S)) = \text{area}(S)$. The deviation of $\phi(S)$ is the number of $-1$’s in $g(S)$,
the break point of \( \phi(S) \) is

\[
(\ell_x(\phi(S)), \ell_y(\phi(S))) = (|\{j : g_j(S) < 0\}|, |\{j : g_j(S) < -1\}|),
\]

\( \min(\phi(S)) = \min_j g_j(S) \), and \( \max(\phi(S)) = \max_j g_j(S) \). Moreover, \( \phi(S) \) ends with an east step iff \( S \) begins with a north step.

**Proof.** Fix \( S \in \mathcal{SQ}_n \) with deviation \( \ell \). We begin our construction of \( \phi(S) \) by specifying its bounce path. Let \( u \) be the minimal value appearing in \( g(S) \), and let \( s \) be the maximal value appearing in \( g(S) \). It is easy to see that \( u = -\ell \). For \( u \leq i \leq s \), define \( v_i \) to be the number of \( g_j(S) \)'s equal to \( i \), and define \( h_i = v_i \). These data uniquely determine a bounce path \( B(S) \) according to the rules above. We will construct \( \phi(S) \) so that \( \phi(\phi(S)) = B(S) \), \( h_i(\phi(S)) = h_i \), and \( v_i(\phi(S)) = v_i \).

It suffices to specify how the north and east steps of \( \phi(S) \) are interleaved between successive bounces of \( B(S) \). The ordering of the steps west of \( V \) and north of \( H_{i+1} \) is determined by the relative order of the entries \( i \) and \( i+1 \) in the area vector for \( S \). However, the details depend on whether we are considering the positive or negative part of the bounce path.

First, we identify the break point of \( \phi(S) \) as the point \((\sum_{j<i} h_j, \sum_{j<i} v_j)\). The path \( \phi(S) \) must pass through this point. Also, note that \( \phi(S) \) runs east for \( h_i \) steps just before the break point and north for \( v_i \) steps just after the break point.

Second, for each \( i \geq 0 \), we describe the subpath of \( \phi(S) \) located north of \( H_i(\phi(S)) \) and west of \( V_{i-1}(\phi(S)) \). Our description starts with the step just after (northeast of) the blocking north step that terminates the horizontal bounce \( H_i \). Scanning \( g(S) \) from right to left, going north in \( \phi(S) \) we encounter a \( g_j(S) \) equal to \( i - 1 \), and going east in \( \phi(S) \) we encounter a \( g_j(S) \) equal to \( i \). Note that this process generates \( v_i = h_i \) east steps and \( v_{i-1} \) north steps, so the subpath ends where it should. Moreover, for \( i > 0 \), the last step generated by this scan must be a north step, since \( g_0(S) \leq 0 \) and \( g_{i+1}(S) \leq g_i(S) + 1 \) imply that the leftmost \( i \) in \( g(S) \) must be immediately preceded by an \( i - 1 \). This last step is the blocking north step that terminates the horizontal bounce \( H_{i-1} \). On the other hand, for \( i = 0 \), the subpath ending at \((n,n)\) may or may not end in a north step, and this fact does not influence the bounce path. Note that this last subpath ends in an east step if \( g_0(S) = 0 \). Conversely, if \( g_0(S) < 0 \), then the leftmost \( -1 \) in \( g(S) \) must occur to the left of the leftmost \( 0 \), so that the last subpath ends in a north step. Since \( g_0(S) = 0 \) iff \( S \) begins with a north step, these comments show that \( \phi(S) \) ends in an east step iff \( S \) begins with a north step. (If \( S \) is a Dyck path, there is no subpath corresponding to \( i = 0 \). In this case, \( \phi(S) \) is also a Dyck path, and the italicized statement is obviously true. The restricted map \( \phi|_{\mathcal{D}_n} : \mathcal{D}_n \rightarrow \mathcal{D}_n \) coincides with the inverse of the bijection \( \alpha \) mentioned in \([1,1]\) For all paths \( S \), it follows that the positive part of the bounce path for \( \phi(S) \) coincides with the positive part of \( B(S) \), as desired.

Third, for each \( i < 0 \), we describe the subpath of \( \phi(S) \) located north of \( H_i(\phi(S)) \) and west of \( V_{i-1}(\phi(S)) \). Our description starts at the step just after (northeast of) the blocking east step that terminates the vertical bounce \( V_i \), or at \((0,0)\) for \( i = -1 \). Scan \( g(S) \) from right to left, ignoring the first occurrence of a \( g_j(S) \) equal to \( i \). Continuing the scan, we go north in \( \phi(S) \) when we encounter a \( g_j(S) \) equal to \( i - 1 \), and we go east in \( \phi(S) \) when we encounter a \( g_j(S) \) equal to \( i \). At the end of the scan, we append one more east step to \( \phi(S) \), which is the blocking east step.
terminating the vertical bounce $V_{i-1}$. As before, this process guarantees that the negative part of $bpath(\phi(S))$ equals the negative part of $B(S)$.

It is easily checked that $\phi$ is invertible. To compute $T = \phi^{-1}(S')$, first draw $\text{bounce}(S')$. Next, for each $i$, use the subpaths of $S'$ between the blocking steps to recover the substrings of $g(T)$ consisting of $i$’s and $i - 1$’s. This is done by reversing the two scanning procedures just described for the positive and negative regions of the bounce path. Finally, these substrings suffice to determine $g(T)$ (and hence $T$) uniquely, because of the condition $g_{j+1}(T) \leq g_j(T) + 1$.

Finally, we check that $\phi$ has the desired effect on statistics. By construction, the bounce path of $\phi(S)$ is indeed $B(S)$, and the break point does lie at the coordinates given earlier. The statements in the theorem giving the deviation of $\phi(S)$ and the coordinates of the break point of $\phi(S)$ now follow from the formula $v_i = h_i = |\{j : g_j(S) = i\}|$. The same formula shows that

$$\text{bounce}(\phi(S)) = \sum_{i=u}^{s} (i - u)v_i = \sum_{i=u}^{s} (i + \ell)v_i = \sum_{j=0}^{n-1} (\ell + g_j(S)) = \text{area}(S).$$

Next, recall that $\text{area}(\phi(S))$ can be interpreted as the number of complete lattice squares east of $\phi(S)$ and west of the line $y = x - v_{-1}$, where $v_{-1}$ is the deviation of $\phi(S)$. These cells can be partitioned into the following disjoint sets:

- the set $B_i$ of cells east of $V_i$ and west of $y = x - v_{-1}$, for all $i$;
- the set $P_i$ of cells east of $\phi(S)$, north of $H_i$, and west of $V_{i-1}$, for all $i \geq 0$;
- the set $N_i$ of cells east of $\phi(S)$, north of $H_i$, and west of $V_{i-1}$, for all $i < 0$.

Using the definition of $\phi$, the following identities are easily verified:

$$|B_i| = \binom{v_i}{2} = \sum_{j<k} \chi(g_j(S) = g_k(S) = i),$$

$$|P_i| = \sum_{j<k} \chi(g_j(S) = i, g_k(S) = i - 1),$$

$$|N_i| = \sum_{j<k} \chi(g_j(S) = i, g_k(S) = i - 1) + \sum_{k} \chi(g_k(S) = i - 1).$$

The last summand in the formula for $|N_i|$ accounts for the area cells above $\text{bounce}(\phi(S))$ in the column below the blocking east step that terminates $V_{i-1}$. Adding these formulas over all $i$, we see that $\text{dinv}(S) = \text{area}(\phi(S))$. 

For example, let $S$ be the path from Figure 2. Figure 3 shows $\phi(S)$ along with its bounce path. Note that $g(S)$ has two $-3$’s, five $-2$’s, five $-1$’s, two $0$’s, and one $1$, so that

$$(v_{-3}(\phi(S)), \ldots, v_1(\phi(S))) = (2, 5, 5, 2, 1).$$

Furthermore, $\text{area}(S) = 25 = \text{bounce}(\phi(S))$ and $\text{dinv}(S) = 52 = \text{area}(\phi(S))$.

### 2.3. Symmetry properties.

For all $n \geq 1$, define

$$S_n(q, t) = \sum_{S \in \mathcal{Q}_n} q^{\text{area}(S)} t^{\text{bounce}(S)}.$$

Using the bijection $\phi$, it follows that

$$S_n(q, t) = \sum_{S \in \mathcal{Q}_n} q^{\text{dinv}(S)} t^{\text{area}(S)}.$$
Figure 3. Image of the path $S$ under $\phi$.

Letting $q = 1$ or $t = 1$ here, we obtain the following \textit{univariate symmetries}.

\textbf{Corollary 2.}  \[ \sum_{S \in SQ_n} q^{\text{dinv}(S)} = \sum_{S \in SQ_n} q^{\text{bounce}(S)} = \sum_{S \in SQ_n} q^{\text{area}(S)}. \]

\textbf{Conjecture 3.} The joint symmetry $S_n(q, t) = S_n(t, q)$ holds for all $n$.

This conjecture has been confirmed by computer for $1 \leq n \leq 11$.

Computing $S_n(q, t)$ for small values of $n$, one sees that the polynomial $S_n(q, t)$ is always divisible by 2. Our next goal is to explain this property. Define $SQ_n^N$, $SQ_n^E$, $NSQ_n$, and $ESQ_n$ to be the paths in $SQ_n$ that end with a north step, end with an east step, begin with a north step, and begin with an east step, respectively. Set

\begin{align*}
S_n^N(q, t) &= \sum_{S \in SQ_n^N} q^{\text{area}(S)}t^{\text{bounce}(S)}, \\
S_n^E(q, t) &= \sum_{S \in SQ_n^E} q^{\text{area}(S)}t^{\text{bounce}(S)}, \\
NS_n(q, t) &= \sum_{S \in NSQ_n} q^{\text{dinv}(S)}t^{\text{area}(S)}, \\
ES_n(q, t) &= \sum_{S \in ESQ_n} q^{\text{dinv}(S)}t^{\text{area}(S)}.
\end{align*}

We will show that $S_n^N(q, t) = S_n^E(q, t) = S_n(q, t)/2$. Since $\phi$ sends paths with initial north steps to paths with terminal east steps and vice versa, it also follows that $NS_n(q, t) = ES_n(q, t) = S_n(q, t)/2$. We call these identities \textit{pair-symmetries}. 

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To prove the pair-symmetries, it suffices to construct a bijection \( \psi : SQ^E_n \rightarrow SQ^N_n \) preserving area and bounce. We begin by introducing a cyclic shift map cyc : \( SQ_n \rightarrow SQ_n \). Let \( S \in SQ_n \) be encoded by the word \( w_1 w_2 \cdots w_{2n} \in \{0,1\}^{2n} \). Define cyc(S) to be the path encoded by the word \( w_{2n} w_1 w_2 \cdots w_{2n-1} \).

**Lemma 4.** For \( S \in SQ_n \), area\((S) = \text{area}(\text{cyc}(S)) \) for all integers \( i \).

**Proof.** It suffices to prove the equality for \( i = 1 \). Let \( S' = \text{cyc}(S) \), and let the deviation of \( S \) be \( \ell \). First consider the case where the last step of \( S \) is a north step. Then \( \ell \geq 1 \) and the deviation of \( \text{cyc}(S) \) is \( \ell' = \ell - 1 \). Furthermore, \( g_0(S') = 0 \), \( g_{n-1}(S) = -1 \), and \( g_j(S') = g_{j-1}(S) + 1 \) for \( 1 \leq j < n \). So, by definition,

\[
\text{area}(S') = (\ell' + g_0(S')) + \sum_{j=1}^{n-1} (\ell' + g_j(S')) = (\ell - 1 + 0) + \sum_{j=0}^{n-2} (\ell - 1 + g_j(S) + 1) = \sum_{j=0}^{n-1} (\ell + g_j(S)) = \text{area}(S).
\]

Now suppose \( S \) ends in an east step. In this case, \( \ell' = \ell + 1 \), and \( g_j(S') = g_j(S) - 1 \) for each \( 0 \leq j < n \). It follows immediately that \( \text{area}(S') = \text{area}(S) \) for this case as well. \( \square \)

**Theorem 5.** There is a bijection \( \psi : SQ^E_n \rightarrow SQ^N_n \) preserving area and bounce. Consequently,

\[
SN^N_n(q,t) = SE^E_n(q,t) = S_n(q,t)/2 = NS_n(q,t) = ES_n(q,t).
\]

**Proof.** Let \( S \in SQ^E_n \). Let \( A \) denote the east step at the end of the path \( S \), and let \( B \) denote the blocking north step terminating the initial horizontal move \( H_0 \) (of length \( h_0 \)) in the positive part of the bounce path for \( S \). Define \( S' = \psi(S) \) to be \( \text{cyc}^{v_1(S)+h_0(S)}(S) \), and let \( A' \) and \( B' \) denote the steps corresponding to \( A \) and \( B \) under this cyclic shift. Since the north step \( B' \) is the last step of \( S' \), we have \( S' \in SQ^N_n \). By the lemma, \( \text{area}(S') = \text{area}(S) \). Let \( \ell \) and \( \ell' \) be the deviations of \( S \) and \( S' \), respectively. Note that \( \ell = v_{-1}(S) \). Recall that applying cyc to a path in \( SQ^E_n \) increases the deviation by 1, while applying cyc to a path in \( SQ^N_n \) decreases the deviation by 1. Therefore, \( v_{-1}(S') = \ell' = \ell + h_0(S) - v_{-1}(S) = h_0(S) = v_0(S) \). Now, the bounce \( V_0(S) \) begins at \( B \), while the bounce \( V_{-1}(S') \) begins at \( B' \). Since \( v_{-1}(S') = v_0(S) \), it follows easily that \( v_i(S') = v_{i+1}(S) \) for \( -1 \leq i < s \). See Figure 3 for an example.

In the negative part of the bounce path for \( S' \), we have \( h_{-1}(S') = \ell' = h_0(S) \). It follows that \( A' \) will be the blocking east step that terminates \( V_{-2}(S') \), and hence \( v_{-2}(S') = v_{-1}(S) \). Tracing the bounce paths upward, we easily see that \( v_i(S') = v_{i+1}(S) \) for \( u - 1 \leq i \leq -2 \). Therefore,

\[
\text{bounce}(S') = \sum_{i=0}^{s-1} (i - (u - 1))v_i(S') = \sum_{i=0}^{s-1} (i + u)v_{i+1}(S) = \sum_{i=u}^{s} (i - u)v_i(S) = \text{bounce}(S).
\]
Finally, \( \psi \) is a bijection: to invert it, we just cyclically shift \( S' \) backwards so that the first blocking east step \( A' \) becomes the final east step of the path. \( \square \)

We close this section with an alternate formula for \( E_S^n(q,t) = S^n(q,t)/2 \). Define \( \text{dinv}_0(S) = \sum_{i<j} \chi(g_i(S) - g_j(S) \in \{0, 1\}) + \sum_i \chi(g_i(S) < 0) \).

**Theorem 6.** For all \( n \geq 1 \),

\[
E_S^n(q,t) = \sum_{S \in E \mathcal{S}_n} q^{\text{dinv}(S)} t^{\text{area}(S)} = \sum_{U \in \mathcal{S}_n^E} q^{\text{dinv}_0(U)} t^{\text{area}(U)}.
\]

**Proof.** The map \( \text{cyc}^{-1} \) is a bijection \( E \mathcal{S}_n \to \mathcal{S}_n^E \) that preserves area. Letting \( U = \text{cyc}^{-1}(S) \), we see that \( \text{area}(U) = \text{area}(S) \) and \( g_i(U) = g_i(S) + 1 \) for all \( i \). This implies that \( g_i(U) - g_j(U) = g_i(S) - g_j(S) \) for all \( i < j \), while \( g_i(U) < 0 \) iff \( g_i(S) < -1 \). Hence, \( \text{dinv}_0(U) = \text{dinv}(S) \), and the theorem follows. \( \square \)

### 2.4. Recursion for square paths.

In §1.1, we saw that the generating functions \( C_n,k(q,t) \) for Dyck paths of order \( n \) with \( h_0 = k \) satisfied the recursion (3). Now we prove a similar recursion for square \( q,t \)-lattice paths. The idea is to remove the “earliest” bounce in a square \( q,t \)-lattice path, namely the negative bounce arriving at the break point.

Formally, for \( n > 0 \) and \( 1 \leq k \leq n \), we set

\[
R_{n,k}(q,t) = \sum_{S \in \mathcal{S}_n} q^{\text{area}(S)} t^{\text{bounce}(S)} \chi(h_{\text{bmin}}(S) = k, \ell(S) > 0).
\]

The condition \( \ell(S) > 0 \) means that \( S \) is not a Dyck path, while \( h_{\text{bmin}}(S) = k \) means that the last horizontal move in the negative part of the bounce path (arriving at the break point) has length \( k \). To take care of the Dyck paths in \( \mathcal{S}_n \), we define \( R_{n,0}(q,t) = C_n(q,t) = t^{-n}C_{n+1,1}(q,t) \) for \( n \geq 0 \). For \( k = n \geq 0 \), we have \( R_{n,n}(q,t) = q^{\binom{n}{2}} \) since the only path that contributes is the one that goes east \( n \) steps and then north \( n \) steps. Clearly, \( S_n(q,t) = \sum_{k=0}^n R_{n,k}(q,t) \).
Theorem 7. For \(0 < k < n\),

\[
R_{n,k}(q,t) = q^k t^{n-k} \sum_{r=1}^{n-k} \binom{r+k}{r,k} C_{n-k,r}(q,t)
\]

\[
+ q^k t^{n-k} \sum_{r=1}^{n-k} q^r \binom{r+k}{r-1,k} R_{n-k,r}(q,t).
\]

Proof. Any path \(S\) contributing to \(R_{n,k}\) either has its break point on the bottom row (i.e., \(t_y = 0\)), or has the break point above the bottom row (i.e., \(t_y > 0\)). These two cases will correspond to the two summations on the right side of (8).

First consider the case where the break point is on the bottom row. This implies that \(S\) is encoded by \(1^k w_{k+1} \cdots w_{2n}\). Letting \(r = h_0(S)\) so that \(1 \leq r \leq n-k\), it follows from our description of bouncing for square lattice paths that the northeast end of bpath\((S)\) is encoded by \(01^r 0^k\), regardless of what \(S\) does in its last \(r+k\) steps. Hence, the path \(D\) encoded by \(w_{k+1} w_{k+2} \cdots w_{2n-r-k+1}\) is a Dyck path of order \(n-k\) with \(h_0(D) = r = h_0(S)\). This accounts for the factor \(C_{n-k,r}(q,t)\). The factor \(\binom{r+k}{r-1,k} q^r\) corresponds to choosing the subpath \(S'\) consisting of the final \(r+k\) steps of \(S\). The power of \(q\) in this factor records \(ar(S')\), which is the number of area squares between \(S'\) and bpath\((S)\). We have now obtained the summand in the first summation of (8). The total power of \(q\) is correct, thanks to the identity \(bounce(S) = \sum_{i=0}^{\text{bmax}(S)} (i+1) v_i(S) = \sum_{i=0}^{\text{bmax}(D)} iv_i(D) + \sum_{i \geq 0} v_i(S)\)

\[
= \text{bounce}(D) + n - k,
\]

so the power of \(t\) is correct as well. Note that every triple \((r, S', D)\) counted by the first summation arises from a unique path \(S\) in the manner described.

Now consider the case where the break point does not lie on the bottom row. We then have \(u = \text{bmin}(S) \leq -2\), \(v_u(S) = h_u(S) = k\), and \(v_{u+1}(S) = h_{u+1}(S) = r\) for some \(r > 0\). Let \(S'\) be the subpath of \(S\) starting just after the blocking east step that terminates \(V_{u+1}\) and ending just before the blocking east step that terminates \(V_u\). Note that \(S'\) is an arbitrary lattice path consisting of \(r-1\) east steps and \(k\) north steps. This accounts for the term \(\binom{r+k-1}{r-1,k} q^r\) in the second summation.

Next, let \(S_0\) be obtained from \(S\) by deleting \(S'\) and the \(k+1\) east steps following \(S'\) and by replacing them by \(r\) east steps. (Intuitively, we are excising the \(k\) rows of the figure immediately below the break point, and then sliding the break point \(k\) units down and \(k\) units left along the line \(y = x - \ell(S)\).) One easily checks that \(S_0\) is one of the paths enumerated by \(R_{n-k,r}(q,t)\), that \(\text{bmin}(S_0) = u+1\), and that \(h_i(S_0) = v_i(S_0) = v_i(S) = h_i(S)\) for \(\text{bmin}(S_0) \leq i \leq \text{bmax}(S_0) = \text{bmax}(S)\). As above, it easily follows that \(\text{bounce}(S) = \text{bounce}(S_0) + n - k\). Moreover, since \(ar(S')\) is the number of area squares below \(S'\) and above \(\text{bpath}(S)\), we see that \(\text{area}(S) = \text{area}(S_0) + ar(S') + \binom{k}{2} + k\). Here, the \(k\) added at the end accounts for the extra area cells below the blocking east step immediately following \(S'\). Since the passage from \(S\) and \(k\) to the triple \((r, S', S_0)\) is reversible, the proof of the recursion is complete. \(\square\)
Note that recursions (3) and (5), and the initial conditions, uniquely determine the quantities \( R_{n,k}(q,t) \) and \( S_n(q,t) \) and provide an efficient method for computing them.

2.5. Fermionic formula. We now obtain a fermionic formula for \( S_n(q,t) \) in analogy with (4).

**Theorem 8.** For \( n \geq 1 \),

\[
S_n(q,t) = 2q^{\binom{n}{2}} + \sum_{w_0 + \cdots + w_s = n, \ w_i > 0, s \geq 1} q^{p_1 \cdot p_2} \prod_{j=0}^{s-1} \left[ \frac{w_j + w_{j+1} - 1}{w_j - 1, w_{j+1}} \right]_q \\
+ \sum_{a=0}^{s-1} q^{p_3} \left[ \frac{w_a + w_{a+1}}{w_a, w_{a+1}} \right] \prod_{j=0}^{a-1} \left[ \frac{w_j + w_{j+1} - 1}{w_j, w_{j+1} - 1} \right]_q \prod_{j=a+1}^{s-1} \left[ \frac{w_j + w_{j+1} - 1}{w_j - 1, w_{j+1}} \right]_q,
\]

where \( p_1 = \sum_{j=0}^{s} \binom{w_j}{2}, \ p_2 = \sum_{j=0}^{s} jw_j, \) and \( p_3 = p_1 + \sum_{0 \leq j < a} w_j \).

**Proof.** One can deduce this formula by simply examining the picture of a path \( S \) counted by \( R_{n,k} \) and its bounce path \( \text{bpath}(S) \). The paths \( S_0 \) and \( S_1 \) encoded by \( 0^a 1^n \) and \( 1^a 0^n \) account for the initial term \( 2q^{\binom{n}{2}} \) in (9). Of the two primary summands in (9), the first gives the contributions of all Dyck paths other than \( S_0 \), as can be checked by comparing with (4). Here, \( w_i = v_i(D) \) for \( 0 \leq i \leq s = \text{bmax}(D) \), and the \( q \)-binomial coefficients account for the subpaths of \( D \) above \( \text{bpath}(D) \), keeping in mind the blocking north steps.

The second summand accounts for all non-Dyck paths \( S \) in \( \mathcal{SQ}_n \) other than \( S_1 \). To translate a particular term in this summand into a path \( S \), take \( \text{bmin}(S) = -(a+1) \), \( \text{bmax}(S) = \text{bmin}(S) + s \), and \( v_i(S) = w_{i-\text{bmin}(S)} \) for \( \text{bmin}(S) \leq i \leq \text{bmax}(S) \). In particular, \( v_0(S) = w_{a+1} \) and \( h_{-1}(S) = w_a \). One checks that \( p_3 \) counts the area squares between \( \text{bpath}(S) \) and \( y = x - \ell(S) \), plus the extra area squares above \( \text{bpath}(S) \) in the columns below the blocking east steps. It is also clear that \( p_2 = \text{bounce}(S) \). The first \( q \)-binomial coefficient on the second line of (9) accounts for the subpath of \( S \) above the zeroth horizontal bounce move, which is an arbitrary lattice path with \( w_{a+1} \) east steps and \( w_a \) north steps. The product of \( q \)-binomial coefficients for \( 0 \leq j < a \) accounts for the subpaths of \( S \) above the bounces in the negative part of the bounce path, keeping in mind the blocking east steps. The product of \( q \)-binomial coefficients for \( a < j < s \) accounts for the subpaths of \( S \) above the bounces in the positive part of the bounce path, keeping in mind the blocking north steps.

For \( 0 < k < n \), there is a similar fermionic formula for \( R_{n,k}(q,t) \). We simply use the second line of (9), summing over all \( (w_0, \ldots, w_s) \) and all \( a \) such that \( w_0 + \cdots + w_s = n, \ w_i > 0, \ s \geq 1, \ 0 \leq a \leq s - 1, \) and fixing \( w_0 = k \).

2.6. Specialization at \( t = 1/q \). Our next goal is to derive explicit formulas for \( R_{n,k}(q,1/q) \) and \( S_n(q,1/q) \) similar to the formulas for \( C_{n,k}(q,1/q) \) and \( C_n(q,1/q) \)
We shall need the following standard identities:

\begin{align}
\left(\begin{array}{c} c + d \\ c, d \end{array}\right)_q &= q^d \left(\begin{array}{c} c + d - 1 \\ c - 1, d \end{array}\right)_q + \left(\begin{array}{c} c + d - 1 \\ c, d - 1 \end{array}\right)_q, \\
\left(\begin{array}{c} c + d \\ c, d \end{array}\right)_q &= \left(\begin{array}{c} c + d - 1 \\ c - 1, d \end{array}\right)_q + q^c \left(\begin{array}{c} c + d - 1 \\ c, d - 1 \end{array}\right)_q, \\
\left(\begin{array}{c} c + d + e + 1 \\ c, d + 1 + e \end{array}\right)_q &= \sum_{u=0}^{c} \left[\begin{array}{c} u + d \\ u, d \end{array}\right] q^{c - u - e} \left(\begin{array}{c} c + e - u \\ c - u, e \end{array}\right)_q, \\
\left(\begin{array}{c} c + d \\ c, d \end{array}\right)_q &= \sum_{v=0}^{d} q^{cv} \left(\begin{array}{c} c + d - v - 1 \\ c - 1, d - v \end{array}\right)_q.
\end{align}

As in [24], the reader may give computation-free bijective proofs of these identities by drawing suitable pictures and using (11). For instance, (12) classifies paths in a $d \times c$ rectangle based on the number $v$ of east steps following the final north step.

**Theorem 9.** For $1 \leq k \leq n$,

\begin{equation}
q^{\left(\binom{n+k+1}{2} - \binom{k}{2}\right)} R_{n,k}(q,1/q) = \left[\begin{array}{c} 2n - k - 1 \\ n - 1, n - k \end{array}\right]_q + q^k \left[\begin{array}{c} 2n - k - 1 \\ n, n - k - 1 \end{array}\right]_q.
\end{equation}

For $k = 0$, $q^{(\binom{n}{2})} R_{n,0}(q,1/q) = q^{(\binom{n}{2})} C_n(q,1/q)$ is given by the formulas

\begin{equation}
\left[\begin{array}{c} 2n \\ n, n \end{array}\right]_q - q \left[\begin{array}{c} 2n \\ n - 1, n + 1 \end{array}\right]_q = \frac{1}{[n + 1]_q} \left[\begin{array}{c} 2n \\ n, n \end{array}\right]_q.
\end{equation}

**Proof.** Recall from (11) that

\begin{equation}
q^{\left(\binom{n+1}{2} - uv\right)} C_{u,v}(q,1/q) = \left[\begin{array}{c} 2u - v - 1 \\ u - v, u - 1 \end{array}\right]_q - q^{v} \left[\begin{array}{c} 2u - v - 1 \\ u - v - 1, u \end{array}\right]_q.
\end{equation}

This identity can be proved from (3) by manipulations similar to those given in this proof; see [19] for details. The formulas for $C_n(q,1/q) = R_{n,0}(q,1/q)$ now follow easily from the fact that $C_n(q,t) = t^{-n} C_{n+1,1}(q,t)$.

Now we prove (14) by induction on $n$, the cases $n \leq 1$ and $n = k$ being easy. Using the induction hypothesis and (15) on the right side of (8), we see that $q^{\left(\binom{n+k+1}{2} - \binom{k}{2}\right)} R_{n,k}(q,1/q)$ equals

\begin{equation}
q^{n-k} \sum_{r=1}^{n-k} \left\{ \left[\begin{array}{c} r + k \\ r, k \end{array}\right] q^{p_2} (\alpha - q^{\rho} \beta) + q^k \left[\begin{array}{c} r + k - 1 \\ r - 1, k \end{array}\right]_q q^{p_3} (\alpha + q^{\rho} \beta) \right\},
\end{equation}

where $\alpha = \left[\begin{array}{c} 2(n-k)-r-1 \\ n-k-r-n-k-1 \end{array}\right]_q$, $\beta = \left[\begin{array}{c} 2(n-k)-r-1 \\ n-k-r-1, n-k \end{array}\right]_q$, $p_1 = \binom{n+k+1}{2} - (n-k)$, $p_2 = (n-k)r - \binom{n-k+1}{2}$, and $p_3 = \binom{n}{2} - \binom{n-k+r+1}{2}$.

To continue simplifying (16), we proceed in seven steps.

**Step 1:** we simplify the powers of $q$. One easily calculates that $p_1 + p_2 = (n-k)(r-1)$ and $p_1 + p_3 + k = n(r-1) - k(r-2)$.

**Step 2:** we break (16) into several smaller sums. To do this, use (10) to rewrite \(\left[\begin{array}{c} r+k \\ r,k \end{array}\right]_q\) as $q^{k} \left[\begin{array}{c} r+k-1 \\ r-1,k \end{array}\right]_q + \left[\begin{array}{c} r+k-1 \\ r,k-1 \end{array}\right]_q$ and then expand the contents of the curly braces in (10) using the distributive law. What results is a sum of six terms. Two of
these terms are equal, and two others cancel. After cancelling and grouping, we can rewrite \(16\) as a sum \(A + B + C\), where

\[
(17)\quad A = 2q^k \sum_{r=1}^{n-k} q^{(n-k)(r-1)} \left[ \frac{r + k - 1}{r - 1, k}_q \left[ \frac{2n - 2k - r - 1}{n - k - r, n - k - 1}_q \right] \right],
\]

\[
(18)\quad B = q^{k-n} \sum_{r=1}^{n-k} q^{(n-k)r} \left[ \frac{r + k - 1}{r, k - 1}_q \left[ \frac{2n - 2k - r - 1}{n - k - r, n - k - 1}_q \right] \right],
\]

\[
(19)\quad C = -q^{k-n} \sum_{r=1}^{n-k} q^{(n-k+1)r} \left[ \frac{r + k - 1}{r, k - 1}_q \left[ \frac{2n - 2k - r - 1}{n - k - r, n - k - 1}_q \right] \right].
\]

Step 3: we evaluate \(A\). Using \(12\) with \(c = n - k - 1\), \(d = k\), \(e = n - k - 1\), and \(u = r - 1\), we find that

\[
A = 2q^k \left[ \frac{2n - k - 1}{n - k - 1, n}_q \right].
\]

Step 4: we evaluate \(B\). We use \(12\) with \(c = n - k\), \(d = k - 1\), \(e = n - k - 1\), and \(u = r\). Since the \(u = 0\) summand is missing in \(B\), we must add and subtract it. We find that

\[
B = q^{k-n} \left[ \frac{2n - k - 1}{n - k - 1, n}_q - \frac{2n - 2k - 1}{n - k - 1, n - k}_q \right].
\]

Step 5: we evaluate \(C\). We use \(12\) with \(c = n - k - 1\), \(d = k - 1\), \(e = n - k\), and \(u = r\). Since the \(u = 0\) summand is missing in \(C\), we must add and subtract it. Also note that the \(r = n - k\) term is 0. We find that

\[
C = -q^{k-n} \left[ \frac{2n - k - 1}{n - k - 1, n}_q - \frac{2n - 2k - 1}{n - k - 1, n - k}_q \right].
\]

Step 6: we compute \(B + C\). The second terms in the preceding formulas for \(B\) and \(C\) cancel; using \(10\) and \(11\), we find that

\[
B + C = q^{k-n} \left[ \frac{2n - k - 1}{n - k - 1, n}_q - \frac{2n - k - 1}{n - k - 1, n}_q \right]
= \left[ \frac{2n - k - 1}{n - k - 1, n}_q \right] - q^k \left[ \frac{2n - k - 1}{n - k - 1, n}_q \right].
\]

Step 7: We combine steps 3 and 6 to obtain

\[
q^{(n-k)/2} R_{n,k}(q,1/q) = A + B + C = \left[ \frac{2n - k - 1}{n - k - 1, n}_q \right] + q^k \left[ \frac{2n - k - 1}{n - k - 1, n}_q \right],
\]

completing the induction. \(\square\)

**Theorem 10.** For all \(n \geq 1\),

\[
q^{(n)} S_n(q, 1/q) = 2 \left[ \frac{2n - 1}{n, n - 1}_q \right] = \frac{2}{1 + q^n} \left[ \frac{2n}{n, n}_q \right].
\]
Proof. Recall that $S_n(q, 1/q) = \sum_{k=0}^{n} R_{n,k}(q, 1/q)$. Using the formulas in the previous theorem for $R_{n,k}(q, 1/q)$, and writing $p_1 = \binom{n}{2} + \binom{k}{2} - \binom{n-k+1}{2}$, $p_2 = \binom{n-k+1}{2} - \binom{k}{2}$, we get

\[ q^{\binom{n}{2}} S_n(q, 1/q) = q^{\binom{n}{2}} R_{n,0}(q, 1/q) + \sum_{k=1}^{n} q^{p_1} [q^{p_2} R_{n,k}(q, 1/q)] \]

\[ = q^{-n} \left\{ \binom{2n}{n,n}_q - \binom{2n}{n-1,n+1}_q + D + E \right\}, \text{ where} \]

\[ D = \sum_{k=1}^{n} q^{2n-k-1} \binom{n-1,n-k}_q, \]

\[ E = \sum_{k=1}^{n} q^{(n+1)k} \binom{2n-k-1}{n,n-k-1}_q. \]

We evaluate $D$ by using (13) with $c = d = n$ and $v = k$ (adding and subtracting the missing $v = 0$ summand), which gives

\[ D = \binom{2n}{n,n}_q - \binom{2n}{n-1,n}_q. \]

We evaluate $E$ by using (13) with $c = n+1$, $d = n-1$ and $v = k$ (adding and subtracting the missing $v = 0$ summand), which gives

\[ E = \binom{2n}{n+1,n-1}_q - \binom{2n}{n,n-1}_q. \]

Inserting these expressions into (21) and simplifying, we get

\[ q^{\binom{n}{2}} S_n(q, 1/q) = 2q^{-n} \left( \binom{2n}{n,n}_q - \binom{2n}{n-1,n}_q \right). \]

Finally, since $\binom{2n}{n,n}_q = q^n \binom{2n-1}{n-1,n}_q + \binom{2n-1}{n,n-1}_q$ by (10), we see that

\[ q^{\binom{n}{2}} S_n(q, 1/q) = 2 \binom{2n-1}{n-1,n}_q. \]

The identity $2 \binom{2n-1}{n,n-1}_q = 2 \binom{2n}{n,n}_q / (1 + q^n)$ follows from a simple algebraic manipulation. \[ \square \]

We remark that the methods in [24] can be used to mechanically translate the preceding algebraic manipulations into bijective proofs of the same results. However, because of all the subtractions involved, the bijections will be extremely complicated.

3. ALGEBRAIC CONJECTURES FOR SQUARE PATHS

We now give some conjectures connecting square $q,t$-lattice paths to Macdonald polynomials and the nabla operator.
3.1. Unlabelled paths. Master conjecture for square $q,t$-lattice paths: For all $n \geq 1$, the following elements of $\mathbb{Q}(q,t)$ are all equal (and are, therefore, elements of $\mathbb{N}(q,t)$):

(a) $\sum_{S \in SQF_n} q^{\text{area}(S)} t^{\text{bounce}(S)}$
(b) $\sum_{S \in SQF_n} q^{\text{area}(S)} t^{\text{bounce}(S)}$
(c) $\sum_{S \in SQF_n} q^{\text{dinv}(S)} t^{\text{area}(S)}$
(d) $\sum_{S \in SQF_n} q^{\text{dinv}(S)} t^{\text{area}(S)}$
(e) $\sum_{S \in SQF_n} q^{\text{dinv}(S)} t^{\text{area}(S)}$
(f) $(-1)^{n-1} (\nabla(p_n), s_{1^n})$
(g) $\sum_{\mu+n}(1 - t^n)(1 - q^n)\prod_{\mu} T_{\mu}/w_{\mu} = \sum_{\mu+n} MB_{(n^n)} \prod_{\mu} T_{\mu}/w_{\mu}$.

We have already seen that (a) through (c) are equal, using the bijections $\psi$, $\phi$, and $\text{cyc}^{-1}$. To see that (f) equals (g), we use the expansion

$$p_n = \sum_{\mu+n} ((-1)^{n-1}(1 - t^n)(1 - q^n)\prod_{\mu} T_{\mu}/w_{\mu}) \hat{H}_{\mu},$$

which follows immediately from Corollary 2.4 in [7] and the definition of plethysm. Applying $\nabla$ gives

$$(-1)^{n-1} \nabla(p_n) = \sum_{\mu+n} ((1 - t^n)(1 - q^n)\prod_{\mu} T_{\mu}/w_{\mu}) \hat{H}_{\mu}.$$

Taking the scalar product with $s_{1^n}$ turns $\hat{H}_{\mu}$ into another factor $T_{\mu}$. Hence, (f) equals (g). The main conjecture, (a) = (f), has been tested for $1 \leq n \leq 8$.

3.2. Labelled paths. Fix $n$ and $N$ with $n \leq N \leq \infty$. Let $SQF_n$ denote the set of all pairs $(S, r)$, where $S$ is a path in $SQF_n$ (so that $S$ ends with an east step), and $r = r_0 \cdots r_{n-1}$ is a label vector with $r_i \in \{1, 2, \ldots, N\}$ such that $g_i + 1$ implies $r_i < r_{i+1}$. If we attach the labels $r_i$ to the vertical steps of $S$ as we did for Dyck paths, then the last condition means that labels in each column must strictly increase from bottom to top. Let $SQH_n$ denote the subset of $SQF_n$ such that $r_0 \cdots r_{n-1}$ is a permutation of $\{1, 2, \ldots, n\}$. Given $(S, r) \in SQF_n$, define $\text{area}(S, r) = \text{area}(S)$ and $\text{dinv}_0(S, r) = \sum_{i<j} \chi \{ (g_i(S) - g_j(S) = 0 \text{ and } r_i < r_j) \text{ or } (g_i(S) - g_j(S) = 1 \text{ and } r_i > r_j) \} + \sum_{i=0}^{n-1} \chi(g_i(S) < 0)$.

(It is equivalent to use all labelled paths beginning with an east step, replacing $\chi(g_i(S) < 0)$ by $\chi(g_i(S) < -1)$ in the definition of $\text{dinv}_0$.)

**Hilbert series conjecture for square $q,t$-lattice paths:** For all $n \geq 1$,

$$(-1)^{n-1} \langle \nabla(p_n), h_{1^n} \rangle = \sum_{(S, r) \in SQH_n} q^{\text{area}(S, r)} t^{\text{dinv}_0(S, r)}.$$

**Frobenius series conjecture for square $q,t$-lattice paths:** For all $n \geq 1$,

$$(-1)^{n-1} \nabla(p_n[z_1, \ldots, z_N]) = \sum_{(S, r) \in SQF_n} q^{\text{area}(S, r)} t^{\text{dinv}_0(S, r)} \prod_{i=0}^{n-1} z_{r_i}.$$
We remark that the same arguments used in [13] show that the Frobenius series conjecture implies the Hilbert series conjecture and the master conjecture for unlabelled square paths, along with shuffle-type formulas for any scalar product of the form $(\nabla(p_n), h_\mu e_\eta)$. It is an open problem to find a naturally occurring doubly-graded $S_n$-module $M_n$ that has $(-1)^{n-1}\nabla(p_n)$ as its Frobenius series. Since elements of $\mathcal{SQH}_n$ encode functions $f : \{1, 2, \ldots, n\} \rightarrow \{1, 2, \ldots, n\}$ in the obvious way $(f^{-1}\{i\})$ is the set of labels in column $i$, we should have $\dim(M_n) = |\mathcal{SQH}_n| = n^n$.

3.3. More nabla conjectures. So far, we have seen combinatorial formulas that are conjectured to give the monomial expansions of $\nabla(e_n)$ and $(-1)^{n-1}\nabla(p_n)$. Since $e_n = m_{(1^n)}$ and $p_n = m_{(n)}$, these results suggest that $\nabla(m_\mu)$ may have a nice monomial expansion for any $\mu \vdash n$. In fact, an even stronger statement appears to be true.

**Conjecture 11.** For all $n \geq 1$ and $\mu, \nu \vdash n$,$$
(-1)^{n-\ell(\mu)}\langle \nabla(m_\mu), s_\nu \rangle \in \mathbb{N}[q, t].
$$

The conjecture has been tested for $1 \leq n \leq 8$. If the conjecture is true, it readily follows that $\nabla(m_\mu)|_{m_\nu} \in \mathbb{N}[q, t]$ for all $\mu$ and $\nu$. In [3], Bergeron, Garsia, Haiman, and Tesler made the analogous conjecture

$$
i(\mu')(\nabla(s_\nu), s_\mu) \in \mathbb{N}[q, t],$$

where $i(\mu) = \binom{\ell(\mu)}{2} + \sum_{\ell(\mu),<i(\mu)}(i - 1 - \mu_i)$. This second conjecture implies that $\nabla(s_\mu)|_{m_\nu} \in \mathbb{N}[q, t]$ for all $\mu$ and $\nu$. Because of the signs, it is not clear whether either conjecture easily implies the other.

**Added in proof**

M. Can and N. Loehr (in A proof of the q,t-square conjecture, Journal of Combinatorial Theory, Series A, in press) have proved the Master conjecture for square $q, t$-lattice paths of §3.1 by proving the equality $(a) = (f)$.

**References**


SQUARE q,t-LATTICE PATHS AND $\nabla(p_n)$


DEPARTMENT OF MATHEMATICS, COLLEGE OF WILLIAM & MARY, WILLIAMSBURG, VIRGINIA 23187
E-mail address: nick@math.wm.edu

DEPARTMENT OF MATHEMATICS, WAKE FOREST UNIVERSITY, WINSTON-SALEM, NORTH CAROLINA 27109
E-mail address: warrnings@wfu.edu