

q -Identities related to overpartitions and divisor functions

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Abstract. We generalize and prove two conjectures of Corteel and Lovejoy related to overpartitions and divisor functions.

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1. Introduction

In this paper, for any pair positive integers m, n , we prove the following two identities:

$$\sum_{i=1}^n \begin{bmatrix} n \\ i \end{bmatrix} \frac{(-1)^{i-1} (x+1) \cdots (x+q^{i-1})}{(1-q^i)^m} q^{mi} \\ = \sum_{i=1}^n \frac{(-1)^{i-1} (x^i - (-1)^i)}{1-q^i} q^i \sum_{i \leq i_2 \leq \cdots \leq i_m \leq n} \frac{q^{\sum_{j=2}^m i_j}}{\prod_{j=2}^m (1-q^{i_j})}, \quad (1.1)$$

$$\frac{(z; q)_{n+1}}{(q; q)_n} \sum_{i=0}^n \begin{bmatrix} n \\ i \end{bmatrix} \frac{(-1)^{i-1} (x+1) \cdots (x+q^{i-1})}{1-zq^i} q^i = \sum_{i=0}^n (-1)^{i-1} \frac{(z; q)_i}{(q; q)_i} x^i q^i, \quad (1.2)$$

using the classical notations $(z; q)_i = (1-z) \cdots (1-zq^{i-1})$, and $\begin{bmatrix} n \\ i \end{bmatrix} = \frac{(q; q)_n}{(q; q)_i (q; q)_{n-i}}$.

In the next section, we shall show that (1.1) and (1.2) can be obtained from the Newton interpolation in points $\{-1, -q, -q^2, \dots\}$, using the complete symmetric function in the variables $\{q/(1-q), q^2/(1-q^2), \dots\}$.

Given $\mathbb{X} = \{x_1, x_2, \dots\}$, Newton gave the following interpolation formula, for any function $f(x)$:

$$f(x) = f(x_1) + f\partial_1(x - x_1) + f\partial_1\partial_2(x - x_1)(x - x_2) + \cdots,$$

where ∂_i , acting on its left, is defined by

$$f(x_1, \dots, x_i, x_{i+1}, \dots) \partial_i = \frac{f(\dots, x_i, x_{i+1}, \dots) - f(\dots, x_{i+1}, x_i, \dots)}{x_i - x_{i+1}}.$$

Taking $f(x) = x^n$, we have,

$$x_1^n \partial_1 \cdots \partial_i = h_{n-i}(x_1, x_2, \dots, x_{i+1}), \quad (1.3)$$

where h_k is the complete symmetric function of degree k defined by

$$h_k(x_1, x_2, \dots, x_n) = \sum_{1 \leq i_1 \leq i_2 \leq \dots \leq i_k \leq n} x_{i_1} x_{i_2} \cdots x_{i_k}.$$

Recall the following properties of h_k :

1. Given an alphabet $\mathbb{X}$, the generating function of h_k is

$$\sum_{k=0}^{\infty} h_k(\mathbb{X}) t^k = \frac{1}{\prod_{x \in \mathbb{X}} (1 - xt)}. \quad (1.4)$$

In particular, Take $\mathbb{X} = \{z, zq, zq^2, \dots\}$, $\mathbb{X}_n = \{z, zq, zq^2, \dots, zq^{n-1}\}$. We have

$$\sum_{k=0}^{\infty} h_k(z, zq, zq^2, \dots) t^k = \frac{1}{\prod_{i=0}^{\infty} (1 - tzq^i)},$$

and

$$\sum_{k=0}^{\infty} h_k(z, zq, zq^2, \dots, zq^{n-1}) t^k = \frac{1}{\prod_{i=0}^{n-1} (1 - tzq^i)}.$$

In consequence of the q -binomial theorem

$$\sum_{i=0}^{\infty} \frac{(a; q)_i}{(q; q)_i} t^i = \frac{(at; q)_{\infty}}{(t; q)_{\infty}},$$

it follows that

$$h_k(z, zq, zq^2, \dots) = \frac{z^k}{(q; q)_k}. \quad (1.5)$$

Putting $a = q^n$ in the q -binomial theorem gives

$$\sum_{i=0}^{\infty} \begin{bmatrix} n+i-1 \\ i \end{bmatrix} t^i = \frac{1}{(t; q)_n}.$$

Thus we have

$$h_k(z, zq, zq^2, \dots, zq^{n-1}) = \begin{bmatrix} n+k-1 \\ k \end{bmatrix} z^k. \quad (1.6)$$

2. More generally, given two alphabets $\mathbb{X}$ and $\mathbb{Y}$, the generating functions of $h_k(\mathbb{X} + \mathbb{Y})$ and $h_k(\mathbb{X} - \mathbb{Y})$ are

$$\begin{aligned}\sum_{k=0}^{\infty} h_k(\mathbb{X} + \mathbb{Y})t^k &= \frac{1}{\prod_{x \in \mathbb{X}}(1 - xt) \prod_{y \in \mathbb{Y}}(1 - yt)}, \\ \sum_{k=0}^{\infty} h_k(\mathbb{X} - \mathbb{Y})t^k &= \frac{\prod_{y \in \mathbb{Y}}(1 - yt)}{\prod_{x \in \mathbb{X}}(1 - xt)}.\end{aligned}\tag{1.7}$$

As a consequence, one has

$$h_n(\mathbb{X} + \mathbb{Y}) = \sum_{k=0}^n h_k(\mathbb{X})h_{n-k}(\mathbb{Y}).\tag{1.8}$$

3. Given $\{x_1, x_2, \dots, x_n\}$, and a positive integer m , we have

$$\sum_{i=1}^n x_i h_{m-1}(x_i, x_{i+1}, \dots, x_n) = h_m(x_1, x_2, \dots, x_n).\tag{1.9}$$

Taking $\mathbb{X} = \{-1, -q, -q^2, \dots\}$, it is easy to check from (1.3) and (1.6):

$$x_1^n \partial_1 \cdots \partial_i = h_{n-i}(-1, -q, \dots, -q^i) = (-1)^{n-i} \begin{bmatrix} n \\ i \end{bmatrix}.$$

2. Proofs of (1.1) and (1.2)

The Gauss polynomials $\begin{bmatrix} n \\ k \end{bmatrix}$ satisfy the following recursion (cf.[1]):

$$\sum_{j=0}^n \begin{bmatrix} m+j \\ m \end{bmatrix} q^j = \begin{bmatrix} n+m+1 \\ m+1 \end{bmatrix}.\tag{2.1}$$

In this paper, we need the following more general relations.

Lemma 2.1 *Let k, m and n be nonnegative integers. Then we have the following formulas:*

$$\sum_{i=k}^n \begin{bmatrix} i \\ k \end{bmatrix} \frac{q^i}{1 - q^i} \sum_{i \leq i_2 \leq \dots \leq i_m \leq n} \frac{q^{\sum_{j=2}^m i_j}}{\prod_{j=2}^m (1 - q^{i_j})} = \begin{bmatrix} n \\ k \end{bmatrix} \frac{q^{km}}{(1 - q^k)^m},\tag{2.2}$$

and

$$\sum_{i=0}^n \frac{(z; q)_i}{(q; q)_i} q^i = \frac{(zq; q)_n}{(q; q)_n}.\tag{2.3}$$

Proof.

Taking $\mathbb{X} = \{1, q, \dots, q^l\}$ and $\mathbb{Y} = \{q^{l+1}, q^{l+2}, \dots\}$, we obtain from (1.5), (1.6) and (1.8):

$$\frac{1}{(q; q)_n} = h_n(\mathbb{X} + \mathbb{Y}) = \sum_{i=0}^n h_i(\mathbb{Y}) h_{n-i}(\mathbb{X}) = \sum_{i=0}^n \frac{1}{(q; q)_i} \begin{bmatrix} n-i+l \\ l \end{bmatrix} q^{(l+1)i}. \quad (2.4)$$

Letting $f(m)$ be the left side of (2.2), we have

$$\begin{aligned} \sum_{m=1}^{\infty} f(m) z^m &= \sum_{m=1}^{\infty} \sum_{i=k}^n \begin{bmatrix} i \\ k \end{bmatrix} \frac{q^i}{1-q^i} h_{m-1} \left(\frac{q^i}{1-q^i}, \frac{q^{i+1}}{1-q^{i+1}}, \dots, \frac{q^n}{1-q^n} \right) z^m \\ &\stackrel{(1.4)}{=} z \sum_{i=k}^n \begin{bmatrix} i \\ k \end{bmatrix} \frac{q^i}{1-q^i} \frac{1}{(1-q^i z/(1-q^i)) \cdots (1-q^n z/(1-q^n))} \\ &= z \sum_{i=k}^n \begin{bmatrix} i \\ k \end{bmatrix} \frac{q^i}{1-q^i} \sum_{l=0}^{\infty} (q^i; q)_{n-i+1} \begin{bmatrix} n-i+l \\ l \end{bmatrix} (q^i(1+z))^l \\ &= z \begin{bmatrix} n \\ k \end{bmatrix} \sum_{i=k}^n \frac{(q; q)_{n-k}}{(q; q)_{i-k}} \sum_{l=0}^{\infty} \begin{bmatrix} n-i+l \\ l \end{bmatrix} q^{(l+1)i} \sum_{m=0}^l \binom{l}{m} z^m \\ &= z \begin{bmatrix} n \\ k \end{bmatrix} \sum_{l=0}^{\infty} \sum_{m=0}^l \binom{l}{m} z^m \sum_{i=k}^n \frac{(q; q)_{n-k}}{(q; q)_{i-k}} \begin{bmatrix} n-i+l \\ l \end{bmatrix} q^{(l+1)i} \\ &\stackrel{(2.4)}{=} \begin{bmatrix} n \\ k \end{bmatrix} \sum_{l=0}^{\infty} \sum_{m=0}^l \binom{l}{m} z^{m+1} q^{(l+1)k} \\ &= \begin{bmatrix} n \\ k \end{bmatrix} \frac{q^k z}{1-q^k(1+z)} \\ &= \sum_{m=1}^{\infty} \begin{bmatrix} n \\ k \end{bmatrix} \frac{q^{km}}{(1-q^k)^m} z^m. \end{aligned}$$

Taking $\mathbb{X} = \{1\}$, $\mathbb{Y} = \{q, q^2, \dots\}$ and $\mathbb{Z} = \{zq, zq^2, \dots\}$, from (1.7), (1.8) and the q -binomial theorem, we get the proof of (2.3):

$$\begin{aligned} \frac{(zq; q)_n}{(q; q)_n} &= h_n((\mathbb{X} + \mathbb{Y}) - \mathbb{Z}) \\ &= h_n(\mathbb{X} + (\mathbb{Y} - \mathbb{Z})) = \sum_{i=0}^n h_i(\mathbb{Y} - \mathbb{Z}) h_{n-i}(\mathbb{X}) = \sum_{i=0}^n \frac{(z; q)_i}{(q; q)_i} q^i. \end{aligned}$$

■

Taking

$$f(x) = \sum_{i=1}^n \frac{(-1)^{i-1} (x^i - (-1)^i)}{1-q^i} q^i \sum_{i \leq i_2 \leq \dots \leq i_m \leq n} \frac{q^{\sum_{j=2}^m i_j}}{\prod_{j=2}^m (1-q^{i_j})},$$

and

$$\mathbb{X} = \{-1, -q, -q^2, \dots\},$$

we have,

$$\begin{aligned} f(x) &= f(x_1) + \sum_{k=1}^n f(x_1) \partial_1 \cdots \partial_k (x+1) \cdots (x+q^{k-1}) \\ &= \sum_{k=1}^n \sum_{i=k}^n (-1)^{k-1} \begin{bmatrix} i \\ k \end{bmatrix} \frac{q^i}{1-q^i} \sum_{i \leq i_2 \leq \cdots \leq i_m \leq n} \frac{q^{\sum_{j=2}^m i_j}}{\prod_{j=2}^m (1-q^{i_j})} (x+1) \cdots (x+q^{k-1}) \\ &= \sum_{k=1}^n (-1)^{k-1} (x+1) \cdots (x+q^{k-1}) \sum_{i=k}^n \begin{bmatrix} i \\ k \end{bmatrix} \frac{q^i}{1-q^i} \sum_{i \leq i_2 \leq \cdots \leq i_m \leq n} \frac{q^{\sum_{j=2}^m i_j}}{\prod_{j=2}^m (1-q^{i_j})} \\ &= \sum_{k=1}^n \begin{bmatrix} n \\ k \end{bmatrix} \frac{(-1)^{k-1} (x+1) \cdots (x+q^{k-1})}{(1-q^k)^m} q^{mk}, \end{aligned}$$

as stated in (1.1). ■

Taking

$$f(x) = \sum_{i=0}^n (-1)^{i-1} \frac{(z; q)_i}{(q; q)_i} x^i q^i, \quad \text{and} \quad \mathbb{X} = \{-1, -q, -q^2, \dots\},$$

we have,

$$\begin{aligned} f(x) &= \sum_{k=0}^n f(x_1) \partial_1 \cdots \partial_k (x+1) \cdots (x+q^{k-1}) \\ &= \sum_{k=0}^n (x+1) \cdots (x+q^{k-1}) \sum_{i=k}^n (-1)^{k-1} \begin{bmatrix} i \\ k \end{bmatrix} \frac{(z; q)_i}{(q; q)_i} q^i \\ &= \sum_{k=0}^n (-1)^{k-1} (x+1) \cdots (x+q^{k-1}) q^k \frac{(z; q)_k}{(q; q)_k} \sum_{i=k}^n \frac{(zq^k; q)_{i-k}}{(q; q)_{i-k}} q^{i-k} \\ &= \sum_{k=0}^n (-1)^{k-1} (x+1) \cdots (x+q^{k-1}) q^k \frac{(z; q)_k}{(q; q)_k} \frac{(zq^{k+1}; q)_{n-k}}{(q; q)_{n-k}} \\ &= \frac{(z; q)_{n+1}}{(q; q)_n} \sum_{k=0}^n \begin{bmatrix} n \\ k \end{bmatrix} \frac{(-1)^{k-1} (x+1) \cdots (x+q^{k-1})}{1-zq^k} q^k, \end{aligned}$$

which implies (1.2). ■

3. Special Cases

In their study of overpartitions [3, Theorem 4.4], Corteel and Lovejoy obtained a combinatorial interpretation of the identity:

$$\sum_{i=1}^{\infty} (-1)^{i-1} \frac{(-1; q)_i}{(q; q)_i} \frac{q^i}{1-q^i} = \sum_{i=1}^{\infty} \frac{2q^{2i-1}}{1-q^{2i-1}} = \sum_{i=1}^{\infty} \frac{2q^i}{1-q^{2i}},$$

and formulated, as conjectures, the following finite forms (private communication):

$$\sum_{i=1}^{2n-1} \begin{bmatrix} 2n-1 \\ i \end{bmatrix} \frac{(-1)^{i-1}(-1; q)_i}{(1-q^i)^m} q^{mi} = \sum_{i=1}^n \frac{2q^{2i-1}}{1-q^{2i-1}} \sum_{2i-1 \leq i_2 \leq \dots \leq i_m \leq 2n-1} \frac{q^{\sum_{j=2}^m i_j}}{\prod_{j=2}^m (1-q^{i_j})}, \quad (3.1)$$

and

$$\sum_{i=1}^{2n} \begin{bmatrix} 2n \\ i \end{bmatrix} \frac{(-1)^{i-1}(-1; q)_i}{1-q^{i+2}} q^i = \sum_{i=1}^n \frac{2q^{2i-1}(1-q)}{(1+q^2)(1-q^{2i-1})(1-q^{2i+1})}. \quad (3.2)$$

In fact, (3.1) is the special case of (1.1) when $x = 1$. Taking $x = 1$, $z = q^2$, (1.2) can be deduced to (3.2).

The case $x = 0$, $m = 1$ of (1.1) is due to Van Hamme [6] (see also [2], [5], [8]):

$$\sum_{i=1}^n \begin{bmatrix} n \\ i \end{bmatrix} \frac{(-1)^{i-1} q^{\binom{i+1}{2}}}{1-q^i} = \sum_{i=1}^n \frac{q^i}{1-q^i}.$$

Taking $x = 0$, and (1.9), we get the formula of Dilcher [4]:

$$\sum_{i=1}^n \begin{bmatrix} n \\ i \end{bmatrix} (-1)^{i-1} \frac{q^{\binom{i}{2} + mi}}{(1-q^i)^m} = \sum_{1 \leq i_1 \leq i_2 \leq \dots \leq i_m \leq n} \frac{q^{i_1}}{1-q^{i_1}} \cdots \frac{q^{i_m}}{1-q^{i_m}}.$$

When $x = 0$ and $z = q^m$ in (1.2), we get Uchimura's identity [9]:

$$\sum_{i=1}^n \begin{bmatrix} n \\ i \end{bmatrix} \frac{(-1)^{i-1} q^{\binom{i+2}{2}}}{1-q^{i+m}} = \sum_{i=1}^n \frac{q^i}{1-q^i} \Big/ \begin{bmatrix} i+m \\ i \end{bmatrix}.$$

Note added in proof: Two different approaches to prove (1.1) and (1.2) were recently given by Prodinger [7] and Zeng [10].

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