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Compositions and samples of geometric random variables with constrained multiplicities

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\textbf{Abstract.} We investigate the probability that a random composition (ordered partition) of the positive integer $n$ has no parts occurring exactly $j$ times, where $j$ belongs to a specified finite ‘forbidden set’ $A$ of multiplicities. This probability is also studied in the related case of samples $\Gamma = (\Gamma_1, \Gamma_2, \ldots, \Gamma_n)$ of independent, identically distributed random variables with a geometric distribution.

\textbf{Keywords:} compositions, generating functions, geometric random variable, Mellin transform, Poisson transform, multiplicity

\section{Introduction}

In this paper we derive generating functions for random compositions (ordered partitions) of a positive integer $n$ in which no parts occur exactly $j$ times, where $j$ belongs to a specified finite ‘forbidden set’ $A$ of multiplicities. For notational convenience we shall refer to such compositions as being ‘A-avoiding’. We go on to find the probabilities that compositions and samples of geometric random variables are A-avoiding.

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As a simple example of a forbidden set, we may wish to consider a sample where none of the \( n \) elements occur exactly \( a \) times. In this case \( A = \{a\} \). Another example is when a letter can occur only \( a \) times or more (or not at all), i.e., \( A = \{1, 2, \ldots, a - 1\} \), for \( a \geq 2 \). Note that we do not allow 0 in the forbidden set.

Previously in [6,12], geometric samples with the multiplicity constraint that certain values must occur at least once were studied. These were called ‘gap-free’ and ‘complete’ samples. A gap-free sample has elements whose values form an interval, namely if elements 2 and 6 are in the sample, then so are 3, 4 and 5. A complete sample is gap-free with minimal element 1.

In this paper we drop the ‘interval’ restriction, hence no value 0 in our forbidden sets. Here we are more interested in the number of times the elements do occur than in the values of the elements. However, in Section 2 the idea of forbidden sets is generalised even further when we allocate each value a different forbidden set. For example, one could provide the restriction that the value 2 is not allowed to occur once, but that the number of times that 5 can occur is anything except 2, 3 or 6 times. We denote the forbidden set for the value \( i \) by \( A_i \), so in this case, we have \( A_2 = \{1\} \) and \( A_5 = \{2, 3, 6\} \).

The paper begins with a discussion on compositions (Section 2), where explicit generating functions are derived for \( A \)-avoiding compositions and particular forbidden sets are highlighted. In Section 3 the link between compositions and samples of geometric random variables is explained. Section 4 is devoted to geometric samples, and Theorem 2 gives the probability that a geometric sample is \( A \)-avoiding, along with some further examples of specific forbidden sets. Finally in Section 5 we state the result for compositions - i.e., the probability that a random composition of \( n \) is \( A \)-avoiding. Some of the longer proofs, in particular, the proof of Theorem 2 in Section 4 will be detailed in the full version of this paper.

2 Compositions

In this section we investigate the generating function for the number of \( A \)-avoiding compositions of \( n \), that is the number of compositions of \( n \) such that each part does not appear exactly \( j \) times, where \( j \in A \). We then go on to generalise this by allowing a different forbidden set for each value, as described in the introduction.

Let \( C_{A,d}(x; m) \) be the generating function for the number of \( A \)-avoiding compositions of \( n \) with exactly \( m \) parts from the set \([d] = \{1, 2, \ldots, d\} \). If \( \sigma \) is any \( A \)-avoiding composition with \( m \) parts in \([d]\), then \( \sigma \) contains the part \( d \) exactly \( j \) times with \( j \not\in A \) and \( 0 \leq j \leq m \). Deleting the parts that equal to \( d \) from \( \sigma \) we get an \( A \)-avoiding composition \( \sigma' \) of \( m - j \) parts in \([d - 1]\). Thus, rewriting the above rule in terms of generating functions we get that

\[
C_{A,d}(x; m) = \sum_{j=0}^{m} \binom{m}{j} x^j C_{A,d-1}(x; m-j),
\]

which is equivalent to

\[
\frac{C_{A,d}(x; m)}{m!} = \sum_{j=0}^{m} \frac{x^j}{j!} \binom{m-j}{(m-j)!} \frac{C_{A,d-1}(x; m-j)}{(m-j)!}.
\]
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We denote the exponential generating function for the sequence \( C_{A,d}(x; m) \) by \( C_{A,d}(x, y) \), that is,

\[
C_{A,d}(x, y) = \sum_{m \geq 0} C_{A,d}(x; m) \frac{y^m}{m!}.
\]

Therefore, the recurrence in (1) can be written as

\[
C_{A,d}(x, y) = C_{A,d-1}(x, y) \left( e^{x^d y} - \sum_{j \in A} \frac{x^{d_j} y^j}{j!} \right),
\]

which implies that

\[
C_{A,d}(x, y) = \prod_{k \geq 1} \left( e^{x^k y} - \sum_{j \in A} \frac{x^{k_j} y^j}{j!} \right),
\]

for all \( d \geq 1 \). Hence, we can state the following result.

**Proposition 1** The generating function \( C_A(x, y) = \sum_{m \geq 0} C_A(x; m) \frac{y^m}{m!} \) is given by

\[
C_A(x, y) = \prod_{k \geq 1} \left( e^{x^k y} - \sum_{j \in A} \frac{x^{k_j} y^j}{j!} \right),
\]

where \( C_A(x; m) \) is the generating function for the number of \( A \)-avoiding compositions of \( n \) with exactly \( m \) parts in \( \mathbb{N} \).

Let \( C_A(n, m) \) be the number of \( A \)-avoiding compositions of \( n \) with \( m \) parts and \( C_A(n) = \sum_{m \geq 1} C_A(n, m) \) be the number of \( A \)-avoiding compositions of \( n \).

**Corollary 1** The generating function \( C_A(x) = \sum_{n \geq 0} C_A(n) x^n \) is given by

\[
C_A(x) = \int_0^\infty e^{-y} \prod_{k \geq 1} \left( e^{x^k y} - \sum_{j \in A} \frac{x^{k_j} y^j}{j!} \right) \, dy.
\]

**Proof:** We use the fact that \( \int_0^\infty e^{-y} y^m \, dy = m! \). Then

\[
\int_0^\infty e^{-y} C_A(x, y) \, dy = \sum_{n \geq 0} x^n \sum_{m \geq 0} \frac{C_A(n, m)}{m!} \int_0^\infty y^m e^{-y} \, dy = \sum_{n \geq 0} C_A(n) x^n.
\]

**Example 1** Let \( A_i = \{1\} \) for all \( i \), then the above proposition gives that

\[
C_{\{1\}}(x, y) = \prod_{k \geq 1} \left( e^{x^k y} - x^k y \right).
\]

and Corollary 1 gives

\[
C_{\{1\}}(x) = \int_0^\infty e^{-y} \prod_{k \geq 1} \left( e^{x^k y} - x^k y \right) \, dy.
\]
Proposition 2 The generating function $D_{A_1, A_2, \ldots}(x, y) = \sum_{m \geq 0} D_{A_1, A_2, \ldots}(x; m) \frac{y^m}{m!}$ is given by

$$D_{A_1, A_2, \ldots}(x, y) = \prod_{k \geq 1} \left( e^{x+y} - \sum_{j \in A_k} \frac{x^j y^j}{j!} \right),$$

where $D_{A_1, A_2, \ldots}(x; m)$ is the generating function for the number of compositions $\sigma$ of $n$ with exactly $m$ parts in $\mathbb{N}$ such that if $\sigma$ contains the part $i$ exactly $d_i$ times, then $d_i \notin A_i$. Furthermore,

$$D_{A_1, A_2, \ldots}(x) = \int_0^\infty e^{-y} \prod_{k \geq 1} \left( e^{x+y} - \sum_{j \in A_k} \frac{x^j y^j}{j!} \right) dy.$$

Example 2 For instance, let $A_1 = \{1\}$ and $A_i = \emptyset$ for $i \geq 2$, then the above proposition gives that

$$F(x, y) = D_{\{1\}, \emptyset, \emptyset, \ldots}(x, y) = (e^{xy} - xy) e^{\frac{x^2 y}{2}}.$$

If we expand $F(x, y)$ as a power series at $x = y = 0$, then we obtain that

$$F(x, y) = \sum_{j \geq 0} \frac{x^j y^j}{j!(1-x)^j} - xy \sum_{j \geq 0} \frac{x^j y^j}{j!(1-x)^j},$$

which implies that

$$D_{\{1\}, \emptyset, \emptyset, \ldots}(x; m) = \frac{x^m}{(1-x)^m} - m \frac{x^{2m-1}}{(1-x)^{m-1}}.$$

Summing over all $m \geq 0$, we get that the ordinary generating function for the number of compositions $\sigma$ of $n$ such that the number occurrence of the part 1 in $\sigma$ does not equal 1 is given by

$$\frac{1-x}{1-2x} - \frac{x(1-x)^2}{(1-x-x^2)^2}.$$

Note that it is not hard to generalize the above enumeration to obtain that the ordinary generating function for the number of compositions $\sigma$ of $n$ such that the number occurrence of the part 1 in $\sigma$ does not equal $\ell$ is given by

$$\frac{1-x}{1-2x} - \frac{x^\ell(1-x)^{\ell+1}}{(1-x-x^2)^{\ell+1}}.$$

Example 3 For instance, let $A_1 = A_2 = \{1\}$ and $A_i = \emptyset$ for $i \geq 3$, then the above proposition gives that

$$G(x, y) = D_{\{1\}, \{1\}, \emptyset, \emptyset, \ldots}(x, y) = (e^{xy} - xy)(e^{x^2 y} - x^2 y)e^{\frac{x^3 y}{3}}.$$

If we expand $G(x, y)$ as a power series at $x = y = 0$, then we find that

$$D_{\{1\}, \{1\}, \emptyset, \emptyset, \ldots}(x; m) = \frac{x}{(1-x)^m} - m \frac{x^{m+1}(1-x+x^2)^{m-1}}{(1-x)^{m-1}} - m \frac{x^{2m-1}}{(1-x)^{m-1}} - m(m-1) \frac{x^{3m-3}}{(1-x)^{m-2}}.$$
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Summing over all \( m \geq 0 \), we get that the ordinary generating function for the number of compositions \( \sigma \) of \( n \) such that the number occurrence of the part \( i, i = 1, 2, \) in \( \sigma \) does not equal 1 is given by

\[
\frac{1 - x}{1 - 2x} - \frac{x(1-x)^2}{(1-x-x^2)^2} - \frac{x^2(1-x)^2}{(1-2x+x^2-x^3)^2} + \frac{2x^3(1-x)^3}{(1-x-x^3)^3}.
\]

**Theorem 1** Fix \( a \in \mathbb{N} \). Let \( A_i = \{a\} \) for all \( i = 1, 2, \ldots, \ell \) and \( A_{i+1} = \emptyset \) for all \( i \geq 1 \). The ordinary generating function for the number of compositions \( \pi \) of \( n \) such that \( \pi \) does not contain part \( i \) exactly \( a \) times for all \( i = 1, 2, \ldots, \ell \) is given by

\[
\sum_{m \geq 0} D_{A_1, A_2, \ldots}(x; m) = \frac{1 - x}{1 - 2x} + \sum_{j=1}^{\ell} \sum_{1 \leq i_1 < i_2 < \cdots < i_j \leq \ell} (-1)^j \frac{j! a^a \sum_{k=1}^{i_k} i_k}{\left(1 - \frac{x}{1-x} + \sum_{k=1}^{\ell} x^{a_k}\right)^{j+1}}.
\]

The proof of this result will be given in the full version of this paper. From the theorem we can deduce the following result.

**Corollary 2** The ordinary generating function for the number of \( \{a\} \)-avoiding compositions of \( n \) is given by

\[
\frac{1 - x}{1 - 2x} + \sum_{j \geq 1} \sum_{B \subseteq \mathbb{N}, |B| = j} \left((-1)^j \frac{(aj)! (x^a/a!)^\sum_{b \in B} b}{\left(1 - \frac{x}{1-x} + \sum_{b \in B} x^b\right)^{aj+1}}\right).
\]

Even in this simple case of \( A = \{a\} \) it does not seem easy to find asymptotic estimates for the coefficients from the generating functions appearing in either Corollary 1 or Corollary 2. Instead we will exploit the correspondence between compositions and geometric random variables of parameter \( p = 1/2 \), as detailed in the next section.

# 3 Reduction of compositions to geometric samples

In order to derive asymptotic estimates, it will be convenient to adopt a probabilistic viewpoint. That is, rather than think of the proportion of \( A \)-avoiding compositions we will equip the set of all compositions of \( n \) with the uniform probability measure and will be interested in the probability that a randomly chosen composition of \( n \) is \( A \)-avoiding. In that setting, compositions of \( n \) are closely related to the special case for geometric random variables when \( p = 1/2 \), as shown in [7, 8] and again in this section.

The starting point for reducing compositions to samples of geometric random variables is the following representation of compositions of \( n \) (see e.g., [2]). Consider sequences of \( n \) black and white dots subject to the following constraints

1. the last dot is always black
2. each of the remaining \( n - 1 \) dots is black or white.

Then there is a 1-1 correspondence between all such sequences and compositions of \( n \). Namely, part sizes in a composition correspond to “waiting times” for occurrences of black dots. For example, the sequence

```
  1  3  2  2  1  1  2  2
```
represents the composition of 12 into parts \((1, 3, 2, 1, 1, 2, 2)\). As discussed e.g. in [7, 8] this leads to the following representation of random compositions. Let \(p = 1/2\) and define

\[ \tau = \tau_n = \inf\{ k \geq 1 : \Gamma_1 + \Gamma_2 + \cdots + \Gamma_k \geq n \}. \]

Then a randomly chosen composition \(\kappa\) of \(n\) has distribution given by

\[ \kappa = (\Gamma_1, \Gamma_2, \ldots, \Gamma_{\tau - 1}, n - \sum_{j=1}^{\tau - 1} \Gamma_j) := (\tilde{\Gamma}_1, \tilde{\Gamma}_2, \ldots, \tilde{\Gamma}_\tau). \]

Furthermore, \(\tau\) has known distribution, namely,

\[ \tau \overset{d}{=} 1 + \text{Bin}(n - 1, \frac{1}{2}), \]

where \(\text{Bin}(m, p)\) denotes a binomial random variable with parameters \(m\) and \(p\) and \(\overset{d}{=}\) stands for equality in distribution. Hence, \(\tau\) is heavily concentrated around its mean. Specifically, since \(\text{var}(\tau) = \text{var}(\text{Bin}(n - 1, 1/2)) = (n - 1)/4\), for every \(t > 0\) we have (see [1, Section A.1])

\[ \mathbb{P}(|\tau - E\tau| \geq t) \leq 2 \exp\{-\frac{2t^2}{n - 1}\}. \]

In particular, for \(t_n \sim \sqrt{cn \ln n}\),

\[ \mathbb{P}(|\tau - E\tau| \geq t_n) = O\left(\frac{1}{n^{2c}}\right), \]

for any \(c > 0\).

Let \(\mathbb{P}(\kappa \in C)\) be the probability that a random composition is \(A\)-avoiding. We proceed by series of refinements exactly as in [6]. Set \(m_n^-\) to be

\[ m_n^- = \left\lfloor \frac{n + 1}{2} - t_n \right\rfloor. \]

As shown in [6], with overwhelming probability, \(\kappa\) is \(A\)-avoiding if and only if the first \(m_n^-\) of its parts are \(A\)-avoiding. In [6] the property considered is “complete” rather than “\(A\)-avoiding”, but the arguments remain unchanged.

Ultimately we obtain, exactly as in [6],

\[ \mathbb{P}(\kappa \in C) = \mathbb{P}((\Gamma_1, \ldots, \Gamma_{m_n^-}) \in C) + O\left(\frac{\ln^{3/2} n}{\sqrt{n}}\right), \]

thereby reducing the problem to samples of geometric random variables.
4 Geometric random variables

Following the discussion in Section 3 above it is natural to start the investigation for the probability that a composition is $A$-avoiding with samples of geometric random variables with arbitrary parameter $p$, where $0 < p < 1$. There is now an extensive literature on the combinatorics of geometric random variables and its applications in Computer Science which includes [3, 5, 6, 11, 12, 13, 14].

Let $\Gamma = (\Gamma_1, \Gamma_2, \ldots, \Gamma_n)$ be a sample of independent identically distributed (i.i.d.) geometric random variables with parameter $p$, that is, $\mathbb{P}(\Gamma_i = k) = pq^{k-1}$, with $p + q = 1$, where $k = 1, 2, \ldots$ and $i = 1, 2, \ldots, n$. We shall restrict the multiplicity of elements in a sample of length $n$ by prohibiting any occurrences of exactly $j$ entries of a given size, for $j$ a natural number belonging to a specified finite set of excluded numbers $A$, the forbidden set. We also call such a random sample of $n$ geometric variables $A$-avoiding.

The method used in [6] can be applied to the problem described above. We start with a recursion for the probabilities that depends on the set $A$ and then use Poissonisation and Mellin transforms followed by de-Poissonisation to obtain our asymptotic estimates.

Using this approach, the following main result for geometric random variables will be proved in the full version of this paper. We define $\chi_k := \frac{2k\pi i}{\ln(1/q)}$.

**Theorem 2** Let $A$ be any finite set of positive integers. The probability $p_n$ that a geometric sample of length $n$ has no letter appearing with multiplicity $j$, for any $j \in A$ is (asymptotically as $n \to \infty$)

$$p_n = 1 - \frac{T^*(0)}{\ln(1/q)} - \delta\left(\log_{1/q}(n/q)\right) + O(n^{-1}),$$

with

$$T^*(0) = \sum_{j \in A} p^j \sum_{n \geq 0} p_n q^n \frac{1}{n+j} \binom{n+j}{j}$$

and

$$\delta(x) = \frac{1}{\ln(1/q)} \sum_{k \neq 0} T^*(\chi_k) e^{-2k\pi ix}$$

where

$$T^*(\chi_k) = \sum_{j \in A} \frac{p^j}{j!} \sum_{n \geq 0} p_n q^n \frac{q^n}{n!} \Gamma(n+j+\chi_k), \quad \text{for} \quad k \in \mathbb{Z}\setminus\{0\}.$$ (3)

Here $\delta(x)$ is a periodic function of $x$ with period 1, mean 0 and small amplitude.

The corresponding result for compositions of $n$ is given in Section 5.

4.1 Examples of finite forbidden sets $A$

In the sections above we mentioned a few specific examples that would satisfy this definition of the forbidden set. Here we simplify the $T^*(0)$ and $T^*(\chi_k)$ formulae from Theorem 2 for a few specific cases. The simplest case for $A$ is a singleton set consisting of one value $a$. If $A = \{a\}$, then

$$T^*(0) = p^a \sum_{n \geq 0} p_n q^n \frac{1}{n+a} \binom{n+a}{a} \quad \text{and} \quad T^*(\chi_k) = \frac{p^a}{a!} \sum_{n \geq 0} p_n q^n \frac{q^n}{n!} \Gamma(n+a+\chi_k).$$

Here $\delta(x)$ is a periodic function of $x$ with period 1, mean 0 and small amplitude.
If we consider the case where $A = \{1, \ldots, a - 1\}$, then

\[
T^*(0) = \sum_{j=1}^{a-1} p^j \sum_{n \geq 0} p_n q^n \frac{1}{n+j} \binom{n+j}{j} \quad \text{and} \quad T^*(\chi_k) = \sum_{j=1}^{a-1} p^j \sum_{n \geq 0} p_n q^n \frac{n!}{n!} \Gamma(n+j+\chi_k).
\]

In particular if we want the probability that no element occurs exactly once (all elements must occur at least twice if they occur at all), we have a main term for $p_n$ of

\[
1 - \frac{p}{\ln(1/q)} \sum_{n \geq 0} p_n q^n.
\]

This main term is plotted as a function of $p$ in Figure 1.

![Fig. 1: Plot of the non-oscillating limit term for $p_n$ for $0 \leq q \leq 1$.](image)

The corresponding picture for the probability that no element occurs exactly twice is given in Figure 2.

![Fig. 2: Plot of the non-oscillating limit term for $p_n$ for $0 \leq q \leq 1$.](image)

In spite of what the Figures 1 and 2 tend to suggest for $q$ near 1, the main term here is strictly greater...
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than zero for every $0 < p < 1$ as

$$T^*(0) = p^a \sum_{n \geq 0} p_n q^n \frac{1}{n + a} \left( \frac{n + a}{a} \right)$$

$$\leq p^a \sum_{n \geq 0} q^n \frac{1}{n + a} \left( \frac{n + a}{a} \right) = p^a \left(1 - q^a\right)$$

$$\leq 1 < \ln(1/q).$$

We observe also that the sequences $(p_n)$ in this section do not have a limit, but exhibit small oscillations where both the period and amplitude of the oscillations depend on $p$. Such oscillations are almost ubiquitous in problems solved using Mellin transform techniques. For example, Figures 3 and 4 (Section 5) show these oscillations in the case that no element occurs exactly once (twice) when $p = 1/2$.

5 Compositions revisited

From Section 3, we conclude that probabilities for compositions can be reduced to probabilities for samples of geometric random variables. This result together with the special case $p = q = \frac{1}{2}$ in Theorem 2 leads to the following corollary.

**Corollary 3** Let $A$ be any finite set of positive integers. The probability $p_n$ that a composition of $n$ has no part appearing with multiplicity $j$, for any $j \in A$ is (asymptotically as $n \to \infty$)

$$p_n = 1 - \frac{T^*(0)}{\ln 2} - \delta(\log_2 n) + O \left( \frac{\ln^{3/2} n}{\sqrt{n}} \right),$$

with

$$T^*(0) = \sum_{j \in A} \left(\frac{1}{2}\right)^j \sum_{n \geq 0} p_n \left(\frac{1}{2}\right)^n \frac{1}{n + j} \left(\frac{n + j}{j}\right)$$

and

$$\delta(x) = \frac{1}{\ln 2} \sum_{k \neq 0} T^*(\chi_k)e^{-2\pi k\pi x}$$

where $\chi_k = \frac{2k\pi i}{\ln 2}$ and

$$T^*(\chi_k) = \sum_{j \in A} \frac{1}{j!} \left(\frac{1}{2}\right)^j \sum_{n \geq 0} \frac{p_n}{n!} \left(\frac{1}{2}\right)^n \Gamma(n + j + \chi_k), \quad \text{for} \quad k \in \mathbb{Z}\setminus\{0\}.$$

As in Theorem 2, $\delta(x)$ is a periodic function of $x$ with period 1, mean 0 and small amplitude. In Figures 3 and 4, we plot the probabilities that no element occurs exactly once (twice) in compositions of $n$.

In particular, we see that the probabilities $p_n$ that a composition is $A$-avoiding, do not converge to a limit as $n \to \infty$, but instead oscillate around the value $1 - \frac{T^*(0)}{\ln 2}$.
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References


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