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Samples of geometric random variables with multiplicity constraints

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We investigate the probability that a sample $\Gamma = (\Gamma_1, \Gamma_2, \dots, \Gamma_n)$ of independent, identically distributed random variables with a geometric distribution has no elements occurring exactly j times, where j belongs to a specified finite ‘forbidden set’ A of multiplicities. Specific choices of the set A enable one to determine the asymptotic probabilities that such a sample has no variable occurring with multiplicity b , or which has all multiplicities greater than b , for any fixed integer $b \geq 1$.

Keywords: Geometric random variable, Mellin transform, Poisson transform, multiplicity

1 Introduction

We study samples of independent, identically distributed (i.i.d.) random variables with a geometric distribution. Specifically, let $\Gamma_1, \Gamma_2, \Gamma_3, \dots$ be i.i.d. geometric random variables with parameter p , that is, $\mathbb{P}(\Gamma_1 = j) = pq^{j-1}$, $j \in \mathbb{N}$, with $p + q = 1$. There is now an extensive literature on the combinatorics of geometric random variables and its applications in Computer Science. We are interested in the probability that a random sample of n such variables consists of elements whose multiplicities belong to specified sets. That is, we place restrictions on the number of times any element/letter can occur in the sample.

As a simple example, we may wish to consider a sample where none of the n elements occur exactly b times. In this case $A = \{b\}$. Another example of such a forbidden set is when a letter can occur only b times or more (or not at all), i.e., $A = \{1, 2, \dots, b-1\}$, where $b \geq 2$. Note that we do not allow 0 in the forbidden set. Previously in (HK05; LP05), certain geometric samples with 0 in the forbidden set were studied under the names of ‘complete’ and ‘gap-free’ samples.

Theorem 1 *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 $n \rightarrow \infty$),*

$$p_n = 1 - \frac{T^*(0)}{\ln(1/q)} - \frac{2}{\ln(1/q)} \Re \left(\sum_{k=1}^{\infty} \exp\{\chi_k \ln(q/n)\} T^*(\chi_k) \right) + O(n^{-1}),$$

where we set $\chi_k := \frac{2k\pi i}{\ln(1/q)}$, and where

$$T^*(0) = \sum_{j \in A} p^j \sum_{n \geq 0} p_n q^n \frac{1}{n+j} \binom{n+j}{j} \quad (1.1)$$

and

$$T^*(\chi_k) = \sum_{j \in A} \frac{p^j}{j!} \sum_{n \geq 0} p_n \frac{q^n}{n!} \Gamma(n+j+\chi_k), \quad \text{for } k \in \mathbb{Z} \setminus \{0\}. \quad (1.2)$$

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2 Outline of the proof of Theorem 1

We want a recursion on the variable p_n , the probability that the sample does not have letters which appear exactly j times if j is an element of the forbidden set $A \subset \mathbb{N}$. Let \mathcal{B} represent the set of all permitted samples. If we let $p_n = \mathbb{P}(\Gamma \in \mathcal{B})$ (the probability that the sample $\Gamma = (\Gamma_1, \Gamma_2, \dots, \Gamma_n)$ has no letter occurring exactly j times for $j \in A$), then we can write

$$p_n = \sum_{\substack{j \geq 0 \\ j \notin A}} \mathbb{P}\left(\{\Gamma \in \mathcal{B}\} \cap \left\{\sum_{\ell=1}^n I_{\Gamma_\ell=1} = j\right\}\right) = \sum_{\substack{j \geq 0 \\ j \notin A}} \mathbb{P}\left(\Gamma \in \mathcal{B} \mid \sum_{\ell=1}^n I_{\Gamma_\ell=1} = j\right) \cdot \mathbb{P}\left(\sum_{\ell=1}^n I_{\Gamma_\ell=1} = j\right),$$

where the indicator function I takes values 1 for true and 0 for false. Using the law of total probability, and the memoryless property of geometric random variables, we obtain the recursion:

$$p_n = \sum_{j=0}^n p_{n-j} \binom{n}{j} p^j q^{n-j} - \sum_{j \in A} p_{n-j} \binom{n}{j} p^j q^{n-j}. \tag{2.1}$$

We would like to see how p_n behaves asymptotically as $n \rightarrow \infty$. The Poissonisation technique we use can be seen in (JS98; Szp01), but we follow more specifically the process used in (HK05; JS97). Namely, we consider the Poisson transform of the sequence (p_n) , analyse its asymptotics with Mellin transforms, then de-Poissonise to recover the asymptotics of (p_n) . To do this, we make use of the exponential generating function $P(z)$, which is the Poisson transform of (p_n) , given by $P(z) := \sum_{n \geq 0} p_n \frac{z^n}{n!} e^{-z}$. We use (2.1) to show that

$$P(z) - e^{-z} = \sum_{n \geq 1} p_n \frac{z^n}{n!} e^{-z} = P(qz) - e^{-pz} \sum_{j \in A} \frac{(pz)^j}{j!} P(qz) - e^{-z}.$$

We thus have a functional equation of the form:

$$P(z) = P(qz) - e^{-pz} \sum_{j \in A} \frac{(pz)^j}{j!} P(qz). \tag{2.2}$$

The technique we now use is the Mellin transform. A standard reference on Mellin transforms is (FGD95). We define the function (see (2.2))

$$T(z) := e^{-pz} \sum_{j \in A} \frac{(pz)^j}{j!} P(qz) \quad \left(= \sum_{n \geq 0} p_n \frac{q^n}{n!} \sum_{j \in A} \frac{p^j}{j!} z^{n+j} e^{-z} \right). \tag{2.3}$$

We note that the Mellin transform of $T(z)$ has a fundamental strip of at least $\langle -1, \infty \rangle$. Now we find the Mellin transform of (2.3) to be

$$T^*(s) = \sum_{n \geq 0} p_n \frac{q^n}{n!} \sum_{j \in A} \frac{p^j}{j!} \mathcal{M}(z^{n+j} e^{-z}) = \sum_{n \geq 0} p_n \frac{q^n}{n!} \sum_{j \in A} \frac{p^j}{j!} \Gamma(n+j+s).$$

In particular we will make use of the values $T^*(0)$ and $T^*(\chi_k)$, as given in (1.1) and (1.2). After iterating (2.2) we get

$$P(z) = P(qz) - T(z) = P(q^{m+1}z) - \sum_{j=0}^m T(q^j z),$$

for any $m \geq 0$ and thus in the limit as $m \rightarrow \infty$, $P(z) = 1 - \sum_{j=0}^{\infty} T(q^j z)$. We define $Q(z) := P(z) - 1 = -\sum_{j=0}^{\infty} T(q^j z)$. Then the corresponding Mellin transform is

$$Q^*(s) = -\sum_{j=0}^{\infty} q^{-js} T^*(s) = -\frac{T^*(s)}{1 - q^{-s}} = \frac{T^*(s)}{q^{-s} - 1},$$

where $Q^*(s)$ exists in the fundamental strip $\langle -1, 0 \rangle$. The inverse Mellin transform is

$$Q(x) = \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} Q^*(s) x^{-s} ds,$$

for any $-1 < c < 0$. The residue theorem can be used to evaluate this. This process (compare to (HK05)) results in

$$Q(x) \sim - \sum_x \operatorname{Res}_{s=\chi} (Q^*(s)x^{-s}).$$

Now, $x^{-s}Q^*(s) = x^{-s}T^*(s)/(q^{-s} - 1)$ has simple poles at $q^{-s} = 1$, i.e. at $\chi_k = 2k\pi i/\ln(1/q)$, $k \in \mathbb{Z}$, and the corresponding residues are

$$\lim_{s \rightarrow \chi_k} (s - \chi_k) \frac{x^{-s}T^*(s)}{q^{-s} - 1} = \frac{x^{-\chi_k}T^*(\chi_k)}{q^{-\chi_k} \ln(1/q)} = \left(\frac{q}{x}\right)^{\chi_k} \frac{T^*(\chi_k)}{\ln(1/q)}.$$

Of these quantities, all but the $k = 0$ term contribute oscillations of small amplitude. We need to use asymptotic de-Poissonisation to deduce that $p_n \sim P(n) = Q(n) + 1$. We consider the theorem given in Szpankowski, (Szp01, page 463), whose five conditions are met by choosing $\gamma_1(z) = 0$, $\gamma_2(z) = 1$, and $t(z) = -T(z)$. We can now deduce that

$$p_n = P(n) + O(n^{-1}) = Q(n) + 1 + O(n^{-1})$$

where

$$P(n) = Q(n) + 1 \sim 1 - \frac{T^*(0)}{\ln(1/q)} - \frac{2}{\ln(1/q)} \Re \left(\sum_{k=1}^{\infty} \exp\{\chi_k \ln(q/n)\} T^*(\chi_k) \right),$$

with $T^*(0)$ and $T^*(\chi_k)$ given in (1.1) and (1.2) respectively. This concludes the proof of Theorem 1.

3 The complementary set $\mathbb{N} \setminus A$ is finite

We consider now the complementary problem where the *permitted* set $B = \mathbb{N} \setminus A$ is finite. The de-Poissonisation method cannot be used in this case, but we can bound the probabilities by elementary means to show that $p_n \rightarrow 0$ for all finite sets B . (Consequently fluctuations are also absent in these cases.) Suppose the permitted set of multiplicities $B = \mathbb{N} \setminus A$ is finite with largest element k . The probability that all multiplicities belong to such a set B is bounded above by the case when $B = \{0, 1, 2, \dots, k\}$. Now samples where all multiplicities are at most k are themselves a subset of the set of samples with the weaker restriction that there are at most k ones.

The probability of exactly j ones in a sample of length n is $\binom{n}{j} p^j (1-p)^{n-j}$. Hence the probability of at most k ones is

$$\sum_{j=0}^k \binom{n}{j} p^j (1-p)^{n-j} \leq (k+1) \binom{n}{k} (1-p)^{n-k} = O(n^k q^n),$$

which is exponentially small.

4 Further work

We aim to continue this work by considering other examples of forbidden sets A . In addition, we would like to reconsider the results of this paper from an urn model standpoint, as was used to obtain the results in (LP05).

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