Frequency Moments in Streams

Edo Liberty
Algorithms in Data mining

Frequency Moments

Assume we have a stream A, of length N which is composed of m different types of items $a_1, \ldots, a_m$ each of which repeats itself $n_1, \ldots, n_m$ times (in arbitrary order) We define the frequency moments f_k as:

$$f_k = \sum_{i=1}^{m} n_i^k$$

Our aim is to process the stream one element at a time and attain an (ϵ, δ)-approximation. That is, a multiplicative factor $(1 \pm \epsilon)$ with probability at least $1 - \delta$. Note that f_0 is the number of distinct elements in the stream m and that f_1 is the number of elements N. f_2 is also an important quantity which represents how "skewed" the distribution of the elements in stream is.

Estimating f_0

Here we describe an algorithm for estimating f_0 which merges (and hopefully simplifies) ideas from [1] and [2]. First, assume a hash function $h : a \to [0, 1]$ uniformly. Let us define a random variable $X = min_i h(a_i)$. Intuitively, X should be roughly $1/m$ and therefore $1/X$ should be a fair estimate of m. This is almost true. In what comes next we make this into an exact statement.

Let us first compute the expectation of X. The distribution function f_X of the random variable X is $f_X(x) = m(1 - x)^{m-1}$. This is because, we have m different choices for the minimal element and for every value it takes, x, all the rest $m - 1$ values need to be higher than it (w.p $(1 - x)^{m-1}$). Therefore:

$$\begin{aligned} E[X] &= \int_0^1 xm(1-x)^{m-1}dx \\ &= \int_0^1 (1-y)my^{m-1}dy \\ &= \int_0^1 my^{m-1}dy - \int_0^1 my^m dy \\ &= 1 - \frac{m}{m+1} = \frac{1}{m+1} \end{aligned}$$

This is after the substitution $y = 1 - x$. We now compute the variance of X. For that we first compute $E[X^2]$.

$$\begin{aligned} E[X^2] &= \int_0^1 x^2 m(1-x)^{m-1} dx \\ &= \int_0^1 (1-y)^2 m y^{m-1} dy \\ &= \int_0^1 m y^{m-1} dy - \int_0^1 2my^m dy + \int_0^1 m y^{m+1} dy \\ &= 1 - \frac{2m}{m+1} + \frac{m}{m+2} \leq \frac{2}{(m+1)^2} \end{aligned}$$

Thus, the standard deviation of $\sigma(X)$ is in the same order of magnitude as its expectation $E[X]$. To reduce this ratio we again define $Y = \frac{1}{s}\sum_{i=1}^{s} X_i$ for which $E[Y] = \frac{1}{m+1}$. and $Var[Y] \leq \frac{2}{s(m+1)^2}$.

Using Chebyshev's inequality we get that

$$\Pr[|Y - \frac{1}{m+1}| \geq \frac{\varepsilon/2}{m+1}] \leq \frac{8}{\varepsilon^2 s} \leq \delta$$

if $s \geq \frac{8}{\varepsilon^2 \delta}$. Therefore, multiplying this procedure $\frac{8}{\varepsilon^2\delta}$ different hash function and taking their mean minimal value guaranties that with probability at least $1-\delta$ we have $\frac{1}{m+1}(1-\varepsilon/2) \leq Y \leq \frac{1}{m+1}(1+\varepsilon/2)$. In other words: $(m+1)\frac{1}{1+\varepsilon/2} \leq \frac{1}{Y} \leq (m+1)\frac{1}{1-\varepsilon/2}$. But, since $\frac{1}{1-\varepsilon/2} \leq 1+\varepsilon$ and $1-\varepsilon \leq \frac{1}{1+\varepsilon/2}$ we get the desired results that $(m+1)(1-\varepsilon) \leq \frac{1}{Y} \leq (m+1)(1+\varepsilon)$

Estimating f_1

This is basically counting the N elements in the stream. A trivial solution therefore requires $O(\log(n))$ bits of memory. It is also possible to store an approximate counter in the space $O(\log\log(n))$ (see [3]) but we will not discuss this here.

Estimating all Frequency Moments $k > 0$

We follow the derivation in [1]. For now, assume we know N in advance. This is not necessary and we will fix it later. Let us first define a random variable X. We choose an index $q \in [1, \ldots, N]$ uniformly at random. Let a be the element in place q in the stream, i.e. $a = A_q$. Define by r the number of times a appears in the stream after location q, including. In other words $r = |\{i | A_i = a\ ,\ i \geq q\}|$. We define X:

$$X = N(r^k - (r-1)^k)$$

We claim that $E[X] = f_k$. Let us define the variable $e_{i,j}$ which indicates the event that the index q is such that $A_q = a_i$ and a_i appears exactly j times after the location q. Note that the events $e_{i,j}$ are disjoint and that if $e_{i,j}$ happens than r takes the value j. Therefore, $X = \sum_{i,j} e_{i,j} N(j^k - (j-1)^k)$. Moreover, $\Pr[e_{i,j}] = \frac{n_i}{N}\frac{1}{n_i} = \frac{1}{N}$ since the probability of choosing a_i is $\frac{n_i}{N}$ and given that this happens the probability of each index (out of the locations of a_i) is equal to $\frac{1}{n_i}$.

$$\begin{aligned} E[X] &= \sum_{i,j} E[e_{i,j} N(j^k - (j-1)^k)] \\ &= \sum_{i=1}^{m}\sum_{j=1}^{n_i} \Pr[e_{i,j}] N(j^k - (j-1)^k) \\ &= \sum_{i=1}^{m}\sum_{j=1}^{n_i} (j^k - (j-1)^k) \\ &= \sum_{i=1}^{m} n_i^k = f_k \quad . \end{aligned}$$

It is somewhat complicated and tedious to compute the variance of X. Citing from [1] we have that:

$$Var[X] \le k m^{1-1/k} f_k^2 \ .$$

We define Y as the mean of s different copies of X, $Y = \frac{1}{s}\sum_{i=1}^{s} X_i$. Clearly, $E[Y] = E[X] = f_k$ and $Var[Y] \le Var[X]/s = km^{1-1/k} f_k^2/s$. Using Chebyshev's inequality we have that

$$\Pr[|Y - f_k| > \varepsilon f_k] \le \frac{Var[Y]}{\varepsilon^2 f_k^2} \le \frac{km^{1-1/k}}{\varepsilon^2 s}$$

Demanding that $s \ge \frac{km^{1-1/k}}{\varepsilon^2 \delta}$ gives that $\Pr[|Y - f_k| > \varepsilon f_k] \le \delta$ which concludes the construction.

Estimating f_2

We will give here a better estimator of f_2. Assume a hash function $h : a \to \{-1, 1\}$ with probability 1/2 each. Define $Z = \sum_{i=1}^{N} h(A_i) = \sum_{i=1}^{m} n_i h(a_i)$. Consider the variable $X = Z^2$. As usual, we will begin with computing the expectation and variance of X.

$$\begin{aligned}
E[X] &= E[Z^2] = E[\sum_{i=1}^{m} n_i h(a_i)^2] \\
&= E[(\sum_{i=1}^{m} n_i h(a_i))(\sum_{i'=1}^{m} n_{i'} h(a_{i'}))] \\
&= \sum_{i=1}^{m}\sum_{i'=1}^{m} n_i n_{i'} E[h(a_i)h(a_{i'})] \\
&= \sum_{i=1}^{m} n_i^2 = f_2
\end{aligned}$$

Similarly,

$$\begin{aligned}
E[X^2] &= E[Z^4] = \sum_{i=1}^{m} n_i^4 + 6 \sum_{1 \le i < i' \le m} n_i^2 n_{i'}^2 \\
Var[X] &= E[X^2] - E^2[X] \le 4 \sum_{1 \le i < i' \le m} n_i^2 n_{i'}^2 \le 2 f_2
\end{aligned}$$

Finally, defining $Y = \frac{1}{s}\sum_{i=1}^{s} X_i$, where each X_i is an independent copy of X we have that:

$$\Pr[|Y - f_2| \ge \varepsilon f_2] \le \delta$$

if $s \ge \frac{2}{\varepsilon^2 \delta}$.

Connection to random projections (next class)

Consider the s hash functions $h_i : a \to \{-1, 1\}$ we used in estimating the second frequency moment. Consider the matrix $H \in \mathbb{R}^{s \times m}$ such that $H(i,j) = h_i(j)$. Also, consider representing each input element a_i by $\vec{a_i}$, the i'th standard basis vector in $\mathbb{R}^m$ (the vector whose i'th entry is equal to 1 and the rest are zero). Analogously, $\vec{A}_i$ is the vector representing the i'th element in the stream. Remember that our estimate Y of f_2 was $\frac{1}{s}\sum_{i=1}^{s} Z_i^2 = ||\frac{1}{\sqrt{s}}\vec{Z}||^2$. Moreover, from the definition of $\vec{Z}$, H, and $\vec{A}_i$ we have that $\vec{Z} = \sum_{i=1}^{N} H\vec{A}_i = H\sum_{i=1}^{N}\vec{A}_i = H\vec{A}$. Here, $\vec{A} = \sum_{i=1}^{N}\vec{A}_i = [n_1, n_2, \ldots, n_m]$. Note however, that $f_2 = ||\vec{A}||^2$ by definition of the second frequency moment. We get that for any stream and any element frequencies $||\frac{1}{\sqrt{s}}H\vec{A}||^2 \approx_{(\varepsilon,\delta)} ||\vec{A}||^2$. In other words, multiplying the vector $\vec{A}$ by the matrix $\frac{1}{\sqrt{s}}H$ is very likely to preserve its ℓ_2 norm. We will see that this phenomenon is in fact more overreaching and has some serious consequences on point ensembles in high dimensional euclidian spaces.

References

[1] Noga Alon, Yossi Matias, and Mario Szegedy. The space complexity of approximating the frequency moments. In *Proceedings of the twenty-eighth annual ACM symposium on Theory of computing*, STOC '96, pages 20–29, New York, NY, USA, 1996. ACM.

[2] Edith Cohen. Size-estimation framework with applications to transitive closure and reachability. *J. Comput. Syst. Sci.*, 55:441–453, December 1997.

[3] Philippe Flajolet, G. N. Martin, and G. Nigel Martin. Probabilistic counting algorithms for data base applications, 1985.