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Annals of Statistics, Volume 1, Issue 2 (Mar., 1973), 353-355.

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Annals of Statistics

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FERGUSON DISTRIBUTIONS VIA PÓLYA URN SCHEMES

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The Polya urn scheme is extended by allowing a continuum of colors. For the extended scheme, the distribution of colors after n draws is shown to converge as $n \rightarrow \infty$ to a limiting discrete distribution μ^* . The distribution of μ^* is shown to be one introduced by Ferguson and, given μ^* , the colors drawn from the urn are shown to be independent with distribution μ^* .

Let μ be any finite positive measure on (the Borel sets of) a complete separable metric space X . We shall say that a random probability measure μ^* on X has a *Ferguson distribution with parameter μ* if for every finite partition $(B_1, \dots, B_r)$ of X the vector $\mu^*(B_1), \dots, \mu^*(B_r)$ has a Dirichlet distribution with parameter $\mu(B_1), \dots, \mu(B_r)$ (when $\mu(B_i) = 0$, this means $\mu^*(B_i) = 0$ with probability 1). Ferguson [3] has shown that, for any μ , Ferguson μ^* exist and when used as prior distributions yield Bayesian counterparts to well-known classical nonparametric tests. He also shows that μ^* is a.s. discrete. His approach involves a rather deep study of the gamma process.

One of us [1] has given a different and perhaps simpler proof that Ferguson priors concentrate on discrete distributions. In this note we give still a third approach to Ferguson distributions, exploiting their connection with generalized Pólya urn schemes.

We shall say that a sequence $\{X_n, n \geq 1\}$ of random variables with values in X is a *Pólya sequence with parameter μ* if for every $B \subset X$

$$(1) \quad P(X_1 \in B) = \mu(B)/\mu(X)$$

and

$$(2) \quad P\{X_{n+1} \in B \mid X_1, \dots, X_n\} = \mu_n(B)/\mu_n(X),$$

where $\mu_n = \mu + \sum_{i=1}^n \delta(X_i)$ and $\delta(x)$ denotes the unit measure concentrating at x . Note that, for finite X , the sequence $\{X_n\}$ represents the results of successive draws from an urn where initially the urn has $\mu(x)$ balls of color x and, after each draw, the ball drawn is replaced and another ball of its same color is added to the urn. Note also that, without the restriction to finite X , for any (Borel measurable) function ϕ on X , the sequence $\{\phi(X_n)\}$ is a Pólya sequence with parameter $\phi\mu$, where $\phi\mu(A) = \mu\{\phi \in A\}$.

We now describe the connections between Pólya sequences and Ferguson distributions.

Received August 13, 1971.

¹ Research sponsored by the Air Force Office of Scientific Research, Office of Aerospace Research, USAF, under Grant AFOSR-71-2100.

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THEOREM. Let $\{X_n\}$ be a Pólya sequence with parameter μ . Then

- (a) $m_n = \mu_n / \mu_n(X)$ converges with probability 1 as $n \rightarrow \infty$ to a limiting discrete measure μ^* ,
- (b) μ^* has a Ferguson distribution with parameter μ and
- (c) given μ^* , the variables $X_1, X_2, \dots$ are independent with distribution μ^* .

PROOF. Suppose first that X is finite, say $X = \{1, 2, \dots, r\}$. Let $\mu^*, \{X_n\}$ be variables whose joint distribution is defined by (b) and (c). If π_n is the empirical distribution of $X_1, \dots, X_n$, it follows from the strong law of large numbers that $\pi_n \rightarrow \mu^*$ with probability 1 as $n \rightarrow \infty$. Since

$$m_n = (\mu + n\pi_n) / (\mu(X) + n),$$

(a) follows. It remains to show that $\{X_n\}$ is a Pólya sequence with parameter μ , which is equivalent to

$$(3) \quad P(A) = \prod_x \mu(x)^{[n(x)]} / \mu(X)^{[n]}$$

where $A = \{X_1 = x_1, \dots, X_n = x_n\}$, $n(x)$ denotes the number of i with $x_i = x$ and $a^{[k]} = a(a+1)\dots(a+k-1)$.

Since $P(A | \mu^*) = \prod_x \mu^*(x)^{n(x)}$, we get

$$(4) \quad P(A) = E \prod_x \mu^*(x)^{n(x)}.$$

That the right sides of (3) and (4) are equal is a standard formula [2] for the moments of Dirichlet distributions.

For general X , let $\{X_n\}$ be a Pólya sequence with parameter μ , let I_j be the indicator of the event that X_j is different from all X_i with $i < j$ and define

$$\begin{aligned} f_{nj} &= I_j m_n(X_j) & \text{for } 1 \leq j \leq n, \\ f_{nj} &= 0 & \text{for } j > n. \end{aligned}$$

We show that

$$(5) \quad \text{with probability 1, } f_{nj} \text{ converges as } n \rightarrow \infty,$$

say to f_j^* and

$$(6) \quad \sum_j f_j^* = 1 \quad \text{with probability 1}.$$

Part (a) of the Theorem, with μ^* defined by

$$\mu^*(B) = \sum_{x_j \in B} f_j^*$$

is an easy consequence of (5) and (6) since, for any B , we have, writing

$$(7) \quad \begin{aligned} s_{nr} &= \sum_{1 \leq j \leq r; x_j \in B} f_{nj}, & t_{nr} &= \sum_{1 \leq j \leq r} f_{nj} \\ s_{nr} &\leq m_r(B) \leq s_{nr} + (1 - t_{nr}) & \text{for } 1 \leq r \leq n, \end{aligned}$$

so that, letting first $n \rightarrow \infty$, then $r \rightarrow \infty$ we obtain (a).

To get (5) and (6), fix r and define

$$\begin{aligned} U_n &= j & \text{if } 1 \leq j \leq r \text{ and } I_j = 1 \text{ and } X_{r+n} = X_j \\ &= 0 & \text{otherwise.} \end{aligned}$$

Given $X_1, \dots, X_r$, the sequence $\{U_n\}$ is a Pólya sequence on $\{0, 1, \dots, r\}$ with parameter μ' defined by

$$\begin{aligned}\mu'(j) &= \mu_r(X) f_{rj} & \text{for } 1 \leq j \leq r, \\ \mu'(0) &= \mu_r(X) - \sum_{j=1}^r \mu'(j),\end{aligned}$$

and the sequence m'_n associated with $\{U_n\}$ satisfies

$$(8) \quad m'_n(j) = f_{r+n,j} \quad \text{for } 1 \leq j \leq r$$

and

$$(9) \quad m'_n(0) = 1 - \sum_{j=1}^r f_{r+n,j}.$$

We apply the finite case of our Theorem to $\{U_n\}$. From (8) and part (a) of the Theorem we get (5), and from (9) and part (b) of the Theorem we conclude

$$(10) \quad E(1 - \sum_{j=1}^r f_j^* | X_1, \dots, X_r) = \frac{\mu'(0)}{\mu_r(X)} \leq \frac{\mu(X)}{\mu(X) + r}.$$

Taking expectation in (10) and letting $r \rightarrow \infty$ gives $E(1 - \sum_{j=1}^{\infty} f_j^*) = 0$, and (6) follows.

Parts (b) and (c) are now easy consequences of the finite case. For any finite partition $B_1, \dots, B_r$ of X , define ϕ on X by $\phi = i$ on B_i , so that $\{\phi(X_n)\}$ is a Pólya sequence with parameter $\phi\mu$. We conclude that the limit of $(m_n(B_1), \dots, m_n(B_r))$, already identified as $(\mu^*(B_1), \dots, \mu^*(B_r))$, has a Dirichlet distribution with parameter $\mu(B_1), \dots, \mu(B_r)$, establishing (b). For (c), let $\{\phi_i\}$ be a sequence of functions on X , each with finitely many values, such that, if $\mathcal{F}_i$ is the (finite) field of X -sets determined by ϕ_i , we have $\mathcal{F}_{i+1} \supset \mathcal{F}_i$ and the Borel field determined by $\mathcal{F} = \bigcup \mathcal{F}_i$ consists of all Borel sets. Part (c) of the finite case of our Theorem, applied to $\{\phi_j(X_n)\}$, yields

(c') given $\phi_j\mu^*$, the sequence $\{\phi_i(X_n)\}$ is independent with distribution $\phi_i\mu^*$ for $i \leq j$.

Letting $j \rightarrow \infty$, we get

(c'') given μ^* , the sequence $\{\phi_i(X_n)\}$ is independent with distribution $\phi_i\mu^*$ for all i .

Since $\{\phi_i(X_n)\}$ is independent with distribution $\phi_i\mu^*$ for all i implies $\{X_n\}$ is independent with distribution μ^* , part (c) follows from (c''), completing the proof.

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