Sainte-Laguë's chi-square divergence for the rounding of probabilities and its convergence to a stable law

Lothar Heinrich, Friedrich Pukelsheim, Udo Schwingenschlögl

Sainte-Laguë's chi-square divergence for the rounding of probabilities and its convergence to a stable law

Lothar Heinrich, Friedrich Pukelsheim, Udo Schwingenschlögl

Summary: For rounding arbitrary probabilities on finitely many categories to rational proportions, the multiplier method with standard rounding stands out. Sainte-Laguë showed in 1910 that the method minimizes a goodness-of-fit criterion that nowadays classifies as a chi-square divergence. Assuming the given probabilities to be uniformly distributed, we derive the limiting law of the Sainte-Laguë divergence, first when the rounding accuracy increases, and then when the number of categories grows large. The latter limit turns out to be a Lévy-stable distribution.

1 Introduction

Let $W = (W_1, \ldots, W_c)$ be some "arbitrary" probability vector, for a fixed number of *categories c*. We model "arbitrariness" by taking W to follow a uniform distribution on the probability simplex

$$\mathcal{S}_c = \left\{ (w_1, \ldots, w_c) \in [0, 1]^c : \sum_{j \leq c} w_j = 1 \right\}.$$

When quoting the *weights* W_j in print, or when processing them otherwise, it is common practice to round them to rational proportions of the form N_j/n, for some prescribed integer *accuracy n*. For instance, in contingency table analysis the weights, often relative frequencies of some raw data, are usually rounded to multiples of a percent ($n = 100$), or to multiples of a tenth of a percent ($n = 1000$). Of course, in order that the proportions N_j/n again form a valid probability vector, the numerators $N_1, \ldots, N_c$ must sum to n.

The individual rounding of each of the scaled weights nW_j in a standard fashion to integers $\langle nW_j \rangle$ does *not*, however, guarantee that these integers achieve the correct total n.

Instead, there may remain a nonzero *discrepancy*

$$D_{c,n} = \left(\sum_{j \leq c} \langle n W_j \rangle \right) - n,$$

see Happacher (2001) and the references given there. For this reason many statistical publications include a salvatory clause that "percentages may not sum to 100 due to rounding errors" or the like.

There are other spheres of life, though, that do not tolerate such a liberal attitude towards rounding errors. Most noticeably this concerns apportionment methods for proportional representation in electoral systems. There, the *c* categories signify the political bodies participating in the apportionment process, and the accuracy *n* is the number of seats to be apportioned among them. For instance, the $n = 435$ seats of the US House of Representatives are apportioned to the $c = 50$ States, proportionally to their population. Or the $n = 598$ seats in the German Bundestag are apportioned among $c = 5$ eligible parties, proportionally to their electoral votes. In the political arena it is plainly *not* acceptable that an apportionment procedure would terminate with a nonzero discrepancy, leaving some seats unaccounted for or creating surplus seats, "due to rounding errors". In fact, the field of politics abounds with *apportionment methods* properly partitioning the total *n* into integers $N_1, \ldots, N_c$. The seminal monograph of Balinski and Young (1982) is an excellent source for the political history of proportional representation, as well as for the mathematical theory of apportionment methods that flows from the historical experience.

One of the early contributors to the subject was the French mathematician André Sainte-Laguë [sɛ̃t laˈgy] (1882–1950), see the bibliographical note in Marshall, Olkin and Pukelsheim (2002, p. 888). Sainte-Laguë (1910a, b) set out to minimize a Gaussian-type squared-error goodness-of-fit criterion, determining the values $N_1, \ldots, N_c$ so as to satisfy

$$\sum_{j \leq c} \frac{(N_j - nW_j)^2}{W_j}$$
$$= \min \left\{ \sum_{j \leq c} \frac{(n_j - nW_j)^2}{W_j} : n_1, \ldots, n_c \in \{0, 1, \ldots, n\}, \sum_{j \leq c} n_j = n \right\}.$$

This approach gives rise to a well-defined apportionment method, the *multiplier method with standard rounding*. We will call

$$S_{c,n} = \sum_{j \leq c} \frac{(N_j - nW_j)^2}{W_j}$$

the *Sainte-Laguë divergence*, for *c* categories and accuracy *n*.

Sainte-Laguë (1910a, b) motivated his criterion from the viewpoint of electoral applications. If party *j* gains weight $W_j = V_j/V$, calculated from their vote count V_j and the vote total $V = \sum_{i \leq c} V_i$, then

$$S_{c,n} = \frac{n^2}{V} \sum_{j \leq c} V_j \left(\frac{N_j/n}{V_j/V} - 1 \right)^2$$

is the sum, for each of the V_j voters, of the squared difference between the voter's *realized success values* $\frac{N_j/n}{V_j/V}$ and the common *ideal success value* 1. These numerical quantities directly relate to the qualitative requirements that the German Federal Constitutional Court demands of electoral equality, see Pukelsheim (2000). By mapping qualitative, constitutional principles into a quantitative, operational formula, the Sainte-Laguë divergence $S_{c,n}$ provides a measure for assessing the goodness of an apportionment method that is particularly persuasive from the viewpoint of constitutional law and political sciences.

Because of the striking similarity of the Sainte-Laguë divergence $S_{c,n}$ with the χ^2-statistics, the multiplier method with standard rounding may well be the apportionment method that is most appropriate also for contingency table analysis, see Wainer (1998), Pukelsheim (1998). However, the statistical assumptions underlying the χ^2-analysis do not apply. This raises the question as to the distributional properties of $S_{c,n}$, which is the topic of the present paper.

In Section 2 we review the multiplier method with standard rounding, and set it up for the ensuing asymptotic analysis. Section 3 singles out the case of two categories, because it is particularly transparent. The main step is to show that the rounding residuals $U_{1,n} = nW_1 - \langle nW_1 \rangle$ are, asymptotically, uniformly distributed and independent of W_1. Section 4 derives the asymptotic distribution of the Sainte-Laguë divergence $S_{c,n}$ for a fixed number of categories $c \geq 3$, as the accuracy n tends to infinity:

$$S_{c,n} \quad \xrightarrow[n\to\infty]{\text{D}} \quad S_c.$$

Though not of any known type, the distribution of the limiting random variable S_c can be simulated by computer, as shown in Figure 3.1. Section 5 tackles the asymptotics when the number of categories, c, grows large, assuming that the weight vector W follows a uniform distribution on the probability simplex $\mathcal{S}_c$. With appropriate scale constants a_c and shift constants b_c we obtain convergence,

$$a_c S_c - b_c \quad \xrightarrow[c\to\infty]{\text{D}} \quad S,$$

where S has a Lévy-stable distribution. Figure 5.1 shows that the (simulated) densities of $a_c S_c - b_c$ converge to the density of S, though rather slowly. In Section 6 we indicate some possible generalizations, such as assuming a Dirichlet distribution $\mathcal{D}(\alpha)$ for W, with form parameter $\alpha \in (0, 2]$.

2   The multiplier method with standard rounding

The idea underlying Sainte-Laguë's apportionment method is simple: Given a set, w_1, ..., w_c, each weight w_j is first scaled by some common *multiplier* $\mu > 0$ and then rounded in a standard fashion, $N_j = \langle \mu w_j \rangle$, where the multiplier μ is adjusted so as to achieve the correct total, $\sum_{j \leq c} N_j = n$. Despite its simplicity we need to take a closer look at the method, in order to set it up for our asymptotic analysis.

As a prerequisite we consider the rounding of individual numbers. *Standard rounding* maps a real number $x \in \mathbb{R}$ into its nearest integer $\langle x \rangle \in \mathbb{Z}$ (Abramowitz and Stegun 1970, p. 223; Garfunkel 2003, p. 523). More precisely, if $x \in [z, z+1]$ lies in an interval delimited by two neighboring integers, z and $z+1$, then

$$\langle x \rangle = \begin{cases} z+1 & \text{for} \quad x > z + 1/2, \\ z & \text{for} \quad x \le z + 1/2. \end{cases}$$

Standard rounding enjoys the important *stationarity property* that $\langle x + z \rangle = \langle x \rangle + z$, for all $x \in \mathbb{R}$ and $z \in \mathbb{Z}$.

There is no general agreement in the literature on where to round the dividing points $z + 1/2$. We have chosen to always round down, $\langle z + 1/2 \rangle = z$. In order to evade a downward trend, one could alternatively round $z + 1/2$ to the nearest *even* integer, see Wallis and Roberts (1956, p. 175), Bronstein and Semendjajew (1991, Sect. 2.1.1.2). Balinski and Young (1982, p. 99) resolve a tie $x = z + 1/2$ by rounding x either up or down, thus generating multiple apportionment solutions. For our subsequent stochastic analysis, the distributional assumptions make ties disappear in Lebesgue nullsets (Happacher and Pukelsheim 1996, p. 378), and hence are of no further concern.

Now we turn to *apportionment methods*, that is, the rounding of sets of numbers subject to achieving a prespecified total n. Depending on the weights $w_1, \ldots, w_c$ there exists a multiplier $\mu > 0$ such that the individual roundings $N_j = \langle \mu w_j \rangle$ satisfy $\sum_{j \le c} N_j = n$. The multiplier μ is thus used as a degree of freedom for the individual roundings to correctly sum to the desired total. In this way any procedure for individual roundings gives rise to a multiplier method of apportionment. The method of Sainte-Laguë is the specific method built on standard rounding.

The definition of standard rounding entails $N_j - 1/2 < \mu w_j < N_j + 1/2$ (neglecting ties). Therefore the relation between the final apportionment $N_1, \ldots, N_c$ and an appropriate multiplier μ is captured by the max-min inequality

$$\max_{j \le c} \frac{N_j - 1/2}{w_j} < \mu < \min_{j \le c} \frac{N_j + 1/2}{w_j},$$

see Balinski and Young (1982, p. 100). However, initially neither the numbers N_j nor a multiplier μ are given. Hence all apportionment methods make use of an algorithmic approach of some sort or other.

The following Adjustment Algorithm is tailored to our asymptotic needs. In essence it dates back to the computational scheme proposed by Hagenbach-Bischoff (1905, p. 9), and it is akin to the rank-index methods of Balinski and Young (1982, p. 142), or to the two-step algorithm of Happacher and Pukelsheim (1996, p. 378) and Dorfleitner and Klein (1999, p. 147). Since n is a reasonable choice to initialize the multiplier (Happacher and Pukelsheim 1996, 2000), this initialization is used to first jump to $\langle n w_j \rangle$ and then adjust these numbers if need be. Let $\operatorname{sgn}(d) = -1, 0, 1$ according as d is negative, zero, or positive.

Lemma 2.1 (Adjustment Algorithm) *For Lebesgue almost all weight vectors* $(w_1, \ldots, w_c) \in \mathcal{S}_c$ *and for all prespecified totals* n, *the multiplier method with standard round-*

ing (Sainte-Laguë) yields a unique apportionment $(N_1, \ldots, N_c)$, which may be obtained as follows. With initial multiplier $\mu_0 = n$, first calculate the "discrepancy" $d = (\sum_{j \le c} \langle n w_j \rangle) - n$, which is an integer satisfying $|d| \le \langle (c-1)/2 \rangle$. Then, for $j = 1, \ldots, c$, adjust the roundings $\langle n w_j \rangle$ to obtain

$$N_j = \langle n w_j \rangle - \mathrm{sgn}(d) m_{j,n}(d),$$

where $m_{j,n}(d)$ is the count how often index j appears among the $|d|$-smallest quotients

$$\frac{k - \mathrm{sgn}(d) \langle n w_i \rangle + 1/2}{w_i}, \qquad i = 1, \ldots, c, \quad k = 0, \ldots, |d|.$$

Proof: The event that one of the weights is zero, $w_j = 0$, or that, for a given multiplier $\mu > 0$, a scaled component μw_j hits a dividing point $z + 1/2$, is a Lebesgue nullset, see Happacher and Pukelsheim (1996, p. 378). In all other cases, the Sainte-Laguë apportionment $N_1, \ldots, N_c$ is unique, and the max-min inequality is strict,

$$\max_{j \le c} \frac{N_j - 1/2}{w_j} < \mu < \min_{j \le c} \frac{N_j + 1/2}{w_j}.$$

The discrepancy d is an integer, with values in the interval $[-c/2, c/2]$; when c is even, the event that d hits a boundary point $\pm c/2$ is a Lebesgue nullset (Happacher 2001, p. 173). Hence the discrepancy d equals one of the whole numbers $-\langle (c-1)/2 \rangle, \ldots, \langle (c-1)/2 \rangle$.

In case of a negative discrepancy, $d < 0$, the initial multiplier $\mu_0 = n$ is too small and additional assignments are called for, $m_{j,n}(d) := N_j - \langle n w_j \rangle \ge 0$. Upon defining the quotients

$$Q(k, z, w) = \frac{k + z + 1/2}{w},$$

the max-min inequality gives $\mu_0 < \min_{i \le c} Q(0, \langle n w_i \rangle, w_i) = Q(0, \langle n w_{i_1} \rangle, w_{i_1}) = \mu_1$, say. As μ grows past μ_1, a first additional unit is apportioned to i_1. Another, second unit is assigned when μ next passes the smallest among the quotients $Q(0, \langle n w_i \rangle, w_i)$ for $i \ne i_1$ and $Q(1, \langle n w_{i_1} \rangle, w_{i_1})$, etc. In other words, $m_{j,n}(d)$ is the count of how often index j appears among the $|d|$-smallest values, of the quotients $Q(k, \langle n w_i \rangle, w_i)$ for $i = 1, \ldots, c$ and $k = 0, \ldots, |d|$. We obtain $N_j = \langle n w_j \rangle + m_{j,n}(d) = \langle n w_j \rangle - \mathrm{sgn}(d) m_{j,n}(d)$.

In case of a vanishing discrepancy, $d = 0$, no adjustment is needed and $N_j = \langle n w_j \rangle = \langle n w_j \rangle - \mathrm{sgn}(0) m_{j,n}(0)$.

In case of a positive discrepancy, $d > 0$, the multiplier $\mu_0 = n$ is too large, and we need to remove $m_{j,n}(d) := \langle n w_j \rangle - N_j \ge 0$ units. The first unit is removed from i_1 as soon as μ falls below $\max_{i \le c} (\langle n w_i \rangle - 1/2)/w_i = (\langle n w_{i_1} \rangle - 1/2)/w_{i_1}$, say. It transpires that now $m_{j,n}(d)$ is the count of how often index j ranks among the d-largest values of the quotients $(\langle n w_i \rangle - k - 1/2)/w_i$. Reversing the sign of the quotients, we may equivalently count occurrences among the d-smallest quotients $Q(k, -\langle n w_i \rangle, w_i)$. Now we obtain $N_j = \langle n w_j \rangle - m_{j,n}(d) = \langle n w_j \rangle - \mathrm{sgn}(d) m_{j,n}(d)$. $\square$

3   Two categories

We now turn to the stochastic behavior and hence assume that we no longer have a deterministic weight vector w, but a random weight vector W. For $c = 2$ categories, the multiplier $\mu_0 = n$ works for almost all weight vectors $W = (W_1, W_2)$ (Happacher and Pukelsheim, 1996, p. 379). Theorem 3.1 shows that the rounding residuals $nW_1 - \langle nW_1 \rangle$ are, asymptotically, stochastically independent of W_1 and uniformly distributed, for a wide class of distributions of W_1.

Theorem 3.1 *If W_1 has a Riemann integrable Lebesgue density on $(0, 1)$, then*

$$\begin{pmatrix} nW_1 - \langle nW_1 \rangle \\ W_1 \end{pmatrix} \quad \xrightarrow[n \to \infty]{D} \quad \begin{pmatrix} U_1 \\ W_1 \end{pmatrix},$$

where the random variable U_1 is uniformly distributed on $(-1/2, 1/2)$ and independent of W_1. Moreover, we have

$$S_{2,n} \quad \xrightarrow[n \to \infty]{D} \quad S_2 := \frac{U_1^2}{W_1} + \frac{U_1^2}{1 - W_1}.$$

Proof: Let f be a Riemann integrable density of W_1. In the joint Fourier transform of $U_{1,n} = nW_1 - \langle nW_1 \rangle$ and W_1 we substitute $nw = u$ to obtain, for $s, t \in \mathbb{R}$,

$$\begin{aligned} \mathrm{E}e^{isU_{1,n}+itW_1} &= \int_0^1 \exp\Big(is\,(nw - \langle nw \rangle) + itw\Big) f(w)\,dw \\ &= \int_0^n \exp\Big(is\,(u - \langle u \rangle) + it\frac{u}{n}\Big) f\Big(\frac{u}{n}\Big) \frac{du}{n} \\ &= \int_0^1 \frac{1}{n} \sum_{k=0}^{n-1} \exp\Big(is\,(u - \langle u \rangle) + it\frac{u+k}{n}\Big) f\Big(\frac{u+k}{n}\Big)\,du, \end{aligned}$$

where the last step uses the stationarity property $u + k - \langle u + k \rangle = u - \langle u \rangle$. Dominated convergence and Riemann integrability entail

$$\begin{aligned} \lim_{n \to \infty} \mathrm{E}e^{isU_{1,n}+itW_1} &= \int_0^1 \int_0^1 \exp\Big(is\,(u - \langle u \rangle) + itw\Big) f(w)\,dw\,du \\ &= \int_{-1/2}^{1/2} e^{isu}\,du \cdot \int_0^1 e^{itw} f(w)\,dw \\ &= \mathrm{E}e^{isU_1} \cdot \mathrm{E}e^{itW_1}, \end{aligned}$$

since any integrable function h fulfills

$$\int_0^1 h\,(u - \langle u \rangle)\,du = \int_0^{1/2} h(u)\,du + \int_{1/2}^1 h(u-1)\,du = \int_{-1/2}^{1/2} h(u)\,du.$$

Moreover, in $S_{2,n}$ we substitute $W_2 = 1 - W_1$, and $nW_2 - \langle nW_2 \rangle = \langle nW_1 \rangle - nW_1 = -U_{1,n}$. Convergence of $S_{2,n}$ to S_2 now follows from the Continuous Mapping Theorem (Pollard 2002, p. 175).   □

When W_1 is uniformly distributed on $(0, 1)$, the density of S_2 is given by the following, where $I_A(s)$ is the usual indicator function of the set A.

Corollary 3.2 *If $W = (W_1, W_2)$ is uniformly distributed on the probability simplex $\mathcal{S}_2$, then the Sainte-Laguë divergences $S_{2,n}$ converge to a random variable S_2 with Lebesgue density g_2 given by, for $s > 0$,*

$$g_2(s) = \frac{\pi}{8\sqrt{s}} - \frac{1}{4\sqrt{s}}\left(\frac{\sqrt{s-1}}{s} + \arctan\sqrt{s-1}\right)I_{[1,\infty)}(s).$$

Proof: If W is uniformly distributed on $\mathcal{S}_2$, then W_1 is uniform on $(0, 1)$. We have $S_2 = U_1^2/[(W_1(1 - W_1)]$. The variables $X = U_1^2$ and $Y = W_1(1 - W_1)$ have densities $f_X(x) = 1/\sqrt{x}$ and $f_Y(y) = 2/\sqrt{1 - 4y}$ on $(0, 1/4)$. The quotient $S_2 = X/Y$ then has density $g_2(s) = \int f_X(sy) f_Y(y)|y|\, dy$ which, after some calculations, takes the form given above. $\qquad\square$

The density g_2 is continuous, and is strictly decreasing from infinity at $s = 0$ to zero at $s = \infty$. For large s it behaves like $1/(6s^2)$, that is, $\lim_{s\to\infty} g(s)/(6s^2) = 1$. Hence S_2 has all moments of order less than one finite, while its expectation is infinite. See Figure 3.1.
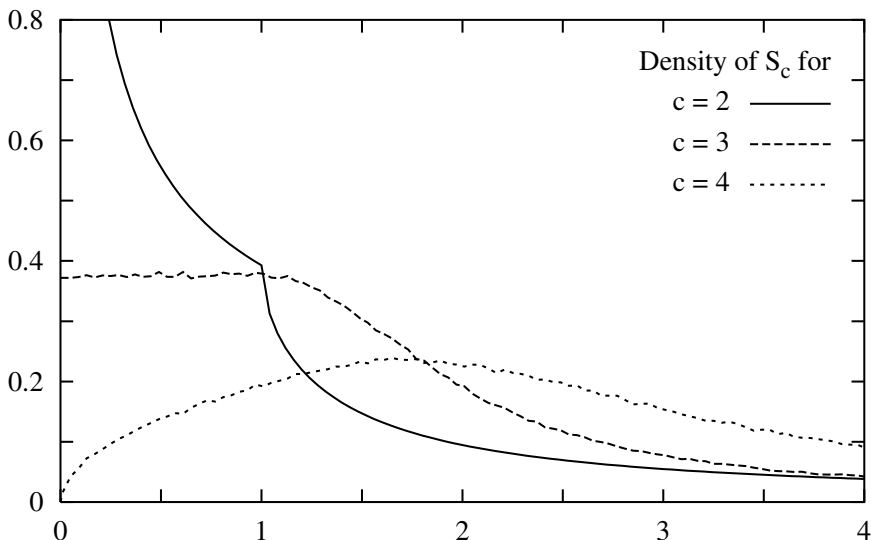

Figure 3.1 Limiting density g_c, for $c = 2, 3, 4$ categories, of the Sainte-Laguë divergences $S_{c,n}$ as $n \to \infty$. The density g_2 is given in Corollary 3.2, while g_3 and g_4 are obtained by simulating one million replicates according to Theorem 4.1. The starting points are $g_2(0) = \infty$, $g_3(0) = 0.376$, and $g_c(0) = 0$ for $c \geq 4$. The tails for $s \to \infty$ are of order s^{-2}, whence the moment of order p is finite if and only if $p < 1$.

4   Three or more categories

For $c \geq 3$ categories the rounding residuals $nW_j - \langle nW_j \rangle$ again become independent of W_j and uniform as n grows large. Convergence of the Sainte-Laguë divergences $S_{c,n}$ builds on the Adjustment Algorithm from Lemma 2.1.

Theorem 4.1 *If the weight vector* $W_{(c-1)} := (W_1, \dots, W_{c-1})$ *has a Riemann integrable Lebesgue density on* $\{(w_1, \dots, w_{c-1}) \in [0, 1]^{c-1} : \sum_{j<c} w_j < 1\}$, *then*

$$
\begin{pmatrix} nW_1 - \langle nW_1 \rangle \\ \vdots \\ nW_{c-1} - \langle nW_{c-1} \rangle \\ W_{(c-1)} \end{pmatrix} \xrightarrow[n \to \infty]{\mathrm{D}} \begin{pmatrix} U_1 \\ \vdots \\ U_{c-1} \\ W_{(c-1)} \end{pmatrix},
$$

where the random variables $U_1, \dots, U_{c-1}$ *are uniformly distributed on* $(-1/2, 1/2)$, *and independent of each other as well as independent of* $W_{(c-1)}$. *Moreover, we have*

$$
S_{c,n} \xrightarrow[n \to \infty]{\mathrm{D}} S_c := \sum_{d=-\langle(c-1)/2\rangle}^{\langle(c-1)/2\rangle} I\left\{ \left\langle \sum_{j<c} U_j \right\rangle = -d \right\} \sum_{j \leq c} \frac{\left(U_j + \mathrm{sgn}(d)m_j(d) \right)^2}{W_j},
$$

where $U_c := \langle \sum_{j<c} U_j \rangle - \sum_{j<c} U_j$, *and* $m_j(d)$ *is the count how often index* j *appears among the* $|d|$-*smallest quotients*

$$
\frac{k - \mathrm{sgn}(d)U_i + 1/2}{w_i}, \qquad i = 1, \dots, c, \quad k = 0, \dots, |d|.
$$

Proof: The first convergence result follows from a multivariate extension of the Fourier transform argument used in the proof of Theorem 3.1.

Convergence of $S_{c,n}$ is established by re-expressing it in terms of W_j and $U_{j,n} := nW_j - \langle nW_j \rangle$ for $j < c$. We set $W_c = 1 - \sum_{j<c} W_j$, as usual, and define

$$
U_{c,n} := \left\langle \sum_{j<c} U_{j,n} \right\rangle - \sum_{j<c} U_{j,n} = nW_c - \langle nW_c \rangle.
$$

The last equality is a straightforward consequence of the stationarity property of standard rounding. Thus $U_{c,n}$ itself is a rounding residual, of the negative cumulative sum of the rounding residuals $U_{j,n}$ for $j < c$, or of nW_c.

In case $D_{c,n} = d$, the Adjustment Algorithm from Lemma 2.1 yields

$$
nW_j - N_j = U_{j,n} + \mathrm{sgn}(d)m_{j,n}(d),
$$

for all $j \leq c$, where $m_{j,n}(d)$ counts the occurrences of index j among the $|d|$-smallest quotients $Q(k, -\mathrm{sgn}(d)\langle nW_i \rangle, W_i)$, with $Q(k, z, w)$ defined as in the proof of Lemma 2.1.

The latter equal $Q(k, \, \text{sgn}(d)U_{i,n}, \, W_i) - \text{sgn}(d)n$, from which the common shift $\text{sgn}(d)n$ may be dropped since it does not affect the ranking. This establishes the representation

$$S_{c,n} = \sum_{d=-\langle(c-1)/2\rangle}^{\langle(c-1)/2\rangle} 1\left\{D_{c,n} = d\right\} \sum_{j \leq c} \frac{\left(U_{j,n} + \text{sgn}(d)m_{j,n}(d)\right)^2}{W_j}.$$

By definition, we have $\langle \sum_{j<c} U_{j,n} \rangle = \sum_{j \leq c} U_{j,n} = -D_{c,n}$; see also Diaconis and Freedman (1979, p. 361), Happacher and Pukelsheim (2000, p. 155). Now an appeal to the Continuous Mapping Theorem completes the proof. □

For three categories and uniform weights $W = (W_1, W_2, W_3)$ on the probability simplex $\mathcal{S}_3$, the density $g_3(s)$ of S_3 may be shown to satisfy

$$g_3(0) = \lim_{\epsilon \to 0} \frac{1}{\epsilon} \, \mathrm{P}\left(\frac{U_1^2}{W_j} + \frac{U_2^2}{W_2} + \frac{(U_1 + U_2)^2}{1 - W_1 - W_2} \leq \epsilon\right) = \frac{4\pi^2}{105} = 0.376.$$

From $c \geq 4$ categories on the densities start out from $g_c(0) = 0$. See Figure 3.1.

In Theorem 4.1, $U_c = \langle \sum_{j<c} U_j \rangle - \sum_{j<c} U_j$ is evidently not independent of $U_1, \ldots,$ U_{c-1}, but it shares their distribution by also being uniformly distributed on the interval $(-1/2, 1/2)$. This follows from Theorem 3.1, or by a direct Fourier transform argument using the uniform convolution density formula $f_{c-1}(v) = \int_{v-1/2}^{v+1/2} f_{c-2}(x)\,dx$:

$$\mathrm{E}e^{it\left(\langle \sum_{j<c} U_j \rangle - \sum_{j<c} U_j\right)} = \sum_{d=-\langle(c-1)/2\rangle}^{\langle(c-1)/2\rangle} \int_{d-1/2}^{d+1/2} e^{it(d-x)} f_{c-1}(x)\,dx$$

$$= \int_{-1/2}^{1/2} e^{itu} C\,du,$$

with

$$C := \sum_{d=-\langle(c-1)/2\rangle}^{\langle(c-1)/2\rangle} f_{c-1}(d-u) = \sum_{d=-\langle(c-1)/2\rangle}^{\langle(c-1)/2\rangle} \int_{d-u-1/2}^{d-u+1/2} f_{c-2}(x)\,dx$$

$$= \int_{\mathbb{R}} f_{c-2}(x)\,dx = 1.$$

Section 5 will show that the asymptotic behavior of S_c is determined by the sum over the leading terms U_j^2/W_j. To this end we provide the following bounds.

Corollary 4.2 *With the assumptions and notations of Theorem 4.1, we have*

$$0 \leq S_c - \sum_{j \leq c} \frac{U_j^2}{W_j} \leq c \left|\left\langle \sum_{j<c} U_j \right\rangle\right|.$$

Proof: Expanding the squares $\big(U_j + \text{sgn}(d)m_j(d)\big)^2$ we get

$$S_c - \sum_{j \le c} \frac{U_j^2}{W_j} = \sum_{d=-\langle(c-1)/2\rangle}^{\langle(c-1)/2\rangle} I\left\{\left\langle \sum_{j<c} U_j \right\rangle = -d\right\} \sum_{j \le c} \frac{2\text{sgn}(d)U_j + m_j(d)}{W_j} m_j(d).$$

All terms in the last sum are nonnegative, which is evident for $m_j(d) = 0$, and which for $m_j(d) \ge 1$ follows from $2\text{sgn}(d)U_j + m_j(d) \ge 0$. This verifies the lower bound zero.

To establish the upper bound we consider the case $\langle \sum_{j<c} U_j \rangle = -d$, and characterize the adjustment counts $m_j(d)$ using a multiplier ρ, see Balinski and Young (1982, p. 100). That is, one has $m_j(d) = \langle \rho W_j - \text{sgn}(d)U_j \rangle$ for all $j \le c$ if and only if

$$\max_{j \le c} \frac{\text{sgn}(d)U_j + m_j(d) - 1/2}{W_j} < \rho < \min_{j \le c} \frac{\text{sgn}(d)U_j + m_j(d) + 1/2}{W_j}.$$

By construction we have $\sum_{j \le c} U_j = -d$ and $\sum_{j \le c} m_j(d) = |d|$, whence the right inequality yields

$$\rho = \sum_{j \le c} \rho W_j < -\text{sgn}(d)d + |d| + \frac{c}{2} = \frac{c}{2}.$$

The left inequality is invoked only when $m_j(d) \ge 1$, giving

$$\frac{2\text{sgn}(d)U_j + m_j(d)}{W_j} \le 2\frac{\text{sgn}(d)U_j + m_j(d) - 1/2}{W_j} < 2\rho < c.$$

Now $c \sum_{d=-\langle(c-1)/2\rangle}^{\langle(c-1)/2\rangle} I\{\langle \sum_{j<c} U_j \rangle = -d\}|d| = c|\langle \sum_{j<c} U_j \rangle|$ completes the proof. $\square$

5   Infinitely many categories

The behavior of S_c for a large number of categories c is studied under the assumption that, for c fixed, the weight vector $W = (W_1, \dots, W_c)$ is uniformly distributed on the probability simplex $\mathcal{S}_c$. By casting out some negligible terms we approximate the distribution of S_c by an average over stochastically independent and identically distributed random variables. This does away with the dependencies, of W_c on $W_1, \dots, W_{c-1}$, and of U_c on $U_1, \dots, U_{c-1}$.

Lemma 5.1 *Suppose the distribution of W on $\mathcal{S}_c$ is uniform, and let the random variables $V_1, E_1, V_2, E_2, \dots$ be independent such that every V_j is uniformly distributed on $(-1/2, 1/2)$ and every E_j is exponentially distributed with mean one. Then the differences*

$$\frac{1}{c^2} S_c - \frac{1}{c} \sum_{j \le c} \frac{V_j^2}{E_j}$$

converge in probability to zero, as c tends to infinity.

Proof: Firstly we get, from Corollary 4.2 and using $\langle \sum_{j<c} U_j \rangle \leq (\sum_{j<c} U_j) + 1/2$,

$$0 \leq \frac{1}{c^2} S_c - \frac{1}{c^2} \sum_{j \leq c} \frac{U_j^2}{W_j} \leq \left| \frac{1}{c} \sum_{j<c} U_j \right| + \frac{1}{2c}.$$

The latter converges in probability to zero, by the law of large numbers. Hence we may approximate $c^{-2} S_c$ by $c^{-2} \sum_{j \leq c} U_j^2 / W_j$.

Secondly we replace the dependent variable U_c by the independent variable V_c. Happacher and Pukelsheim (2000, p. 153) show that $P(W_c \leq t) = 1 - (1 - t)^{c-1}$. From $|U_c^2 - V_c^2| \leq 1/4$ we get, for $\epsilon > 0$,

$$\lim_{c \to \infty} P\left(\frac{1}{c^2} \left| \frac{U_c^2}{W_c} - \frac{V_c^2}{W_c} \right| \geq \epsilon \right) \leq \lim_{c \to \infty} P\left(\frac{1}{4c^2 W_c} \geq \epsilon \right)$$

$$= 1 - \lim_{c \to \infty} \left(1 - \frac{1}{4\epsilon c^2} \right)^{c-1} = 0.$$

Hence we may approximate $c^{-2} \sum_{j \leq c} U_j^2 / W_j$ by $c^{-2} \sum_{j \leq c} V_j^2 / W_j$.

Thirdly we represent the uniform distribution on $\mathcal{S}_c$ through $W_j = E_j / \sum_{i \leq c} E_i$, see Aitchison (1986, p. 59). Thus the random variables

$$\frac{1}{c^2} \sum_{j \leq c} \frac{V_j^2}{W_j} \quad \text{and} \quad \frac{\sum_{i \leq c} E_i}{c^2} \sum_{j \leq c} \frac{V_j^2}{E_j}$$

have the same distribution. The average $c^{-1} \sum_{i \leq c} E_i$ converges in probability to one, by the law of large numbers. Hence we may approximate $c^{-2} \sum_{j \leq c} V_j^2 / W_j$ by $c^{-1} \sum_{j \leq c} V_j^2 / E_j$. The proof is complete. $\qquad \square$

The random variables $Z_j := V_j^2 / E_j$ live on $[0, \infty)$, and their common density f satisfies

$$f(z) = \frac{1}{\sqrt{z}} \int_0^{1/(4z)} e^{-x} \sqrt{x} \, dx = \frac{1}{12z^2} - \frac{1}{80z^3} + \frac{1}{2688z^4} \mp \cdots$$

Clearly Z_j has infinite expectation, and the averages $c^{-1} \sum_{j \leq c} Z_j$ do *not* obey the law of large numbers. Instead, Z_j lies in the domain of attraction of a stable distribution, see Ibragimov and Linnik (1971, p. 76). Let S be a random variable with Fourier transform given by

$$\mathrm{E} e^{itS} = \exp\left(-|t| - \frac{2it}{\pi} \log |t| \right),$$

for $t \in \mathbb{R}$. That is, S has a Lévy-stable distribution with characteristic exponent $\alpha = 1$ and skewness parameter $\beta = 1$, see Zolotarev (1986, p. 9). With Euler's constant $\gamma = \lim_{k \to \infty}(1 + 1/2 + \cdots + 1/k - \log k) = 0.5772 \cdots$, the limiting distribution of the suitably scaled and shifted statistics S_c is now given by the following.

Theorem 5.2 *Suppose the distribution of W on $\mathcal{S}_c$ is uniform. Then we have*

$$a_c S_c - b_c \xrightarrow[c\to\infty]{\text{D}} S,$$

with scale constants $a_c = \dfrac{24}{\pi c^2}$ and shift constants $b_c = \dfrac{2}{\pi}\left(\dfrac{5}{3} - 2\gamma + \log\dfrac{\pi c}{6}\right)$.

Proof: In view of Lemma 5.1 and using Slutzky's Theorem (Pollard 2002, p. 175) it suffices to show that $\frac{24}{\pi c}(\sum_{j\le c} Z_j) - b_c$ converges in distribution to S. To this end we consider their Fourier transforms

$$\psi_c(t) := \mathrm{E}\exp\left(i\frac{24t}{\pi c}\left(\sum_{j\le c} Z_j\right) - itb_c\right) = \left(\mathrm{E}e^{isZ_1 - \frac{it}{c}b_c}\right)^c,$$

with $t \in \mathbb{R}$ fixed, and upon setting $s := 24t/(\pi c)$. For a passage to the limit as c tends to infinity, that is, as s tends to zero, we shall establish the following approximation (*):

$$\mathrm{E}e^{isZ_1} = 1 - \frac{\pi|s|}{24} + \frac{is}{12}\left(\frac{5}{3} - 2\gamma + \log 4 - \log|s|\right) + O\left(|s|^{3/2}\right) \tag{*}$$

$$= 1 - \frac{|t|}{c} + \frac{2it}{\pi c}\left(\frac{5}{3} - 2\gamma + \log\frac{\pi c}{6} - \log|t|\right) + o\left(\frac{1}{c}\right).$$

We multiply by $e^{-\frac{it}{c}b_c} = 1 - \frac{it}{c}b_c + o(1/c)$ and collect lower order terms to conclude

$$\lim_{c\to\infty}\psi_c(t) = \lim_{c\to\infty}\left(1 - \frac{|t| + \frac{2it}{\pi}\log|t|}{c} + o\left(\frac{1}{c}\right)\right)^c = \mathrm{E}e^{itS}.$$

In order to establish the approximation (*), we set $a := 1/\sqrt{s}$ and split the pertinent integral into two:

$$\mathrm{E}e^{isZ_1} - 1 = \int_0^a \left(e^{isz} - 1\right)f(z)\,dz + \int_a^\infty \left(e^{isz} - 1\right)f(z)\,dz =: I_1(a) + I_2(a).$$

In the integral $I_1(a)$, we use the inequality $\left|e^{isz} - 1 - isz\right|f(z) \le s^2/24$, substitute $1/(4z) = y$, and integrate by parts, to obtain the first three of the following equalities:

$$I_1(a) = is\int_0^a \sqrt{z}\int_0^{1/(4z)} e^{-x}\sqrt{x}\,dxdz + O\left(as^2\right)$$

$$= \frac{is}{8}\int_{1/(4a)}^\infty y^{-5/2}\int_0^y e^{-x}\sqrt{x}\,dxdy + O\left(as^2\right)$$

$$= \frac{is}{12}\left((4a)^{3/2}\int_0^{1/(4a)} e^{-x}\sqrt{x}\,dx + \int_{1/(4a)}^\infty \frac{e^{-x}}{x}\,dx\right) + O\left(as^2\right)$$

$$= \frac{is}{12}\left(\frac{2}{3} - \gamma + \log 4 + \log a\right) + O\left(\frac{|s|}{a}\right) + O\left(as^2\right).$$

The last equality follows from $\int_0^{1/(4a)} e^{-x}\sqrt{x}\,dx = (2/3)(4a)^{-3/2} + O(1/a)$, while the exponential integral is evaluated from

$$\int_\epsilon^\infty \frac{e^{-x}}{x}\,dx = -\gamma - \log\epsilon + \int_0^\epsilon \frac{1-e^{-x}}{x}\,dx = -\gamma - \log\epsilon + O(\epsilon)$$

for $\epsilon \in (0,1]$, see Abramowitz and Stegun (1970, Eq. 5.1.11).

In the integral $I_2(a)$, the inequality $|e^{isz} - 1| \leq |s|z$ implies that the remainder $\int_a^\infty (e^{isz} - 1)\big(f(z) - 1/(12z^2)\big)\,dz$ is bounded of order $|s|/a$. We substitute $sz = x$ and $e^{ix} = \cos x + i\sin x$, combine the two cases $s > 0$ and $s < 0$ into one, use $\int_0^\infty (1-\cos x)/x^2\,dx = \pi/2$, and integrate by parts, to obtain the first three of the following equalities:

$$\begin{aligned}
I_2(a) &= \frac{1}{12}\int_a^\infty \frac{e^{isz}-1}{z^2}\,dz + O\left(\frac{|s|}{a}\right) \\
&= -\frac{|s|}{12}\int_{a|s|}^\infty \frac{1-\cos x}{x^2}\,dx + \frac{is}{12}\int_{a|s|}^\infty \frac{\sin x}{x^2}\,dx + O\left(\frac{|s|}{a}\right) \\
&= -\frac{|s|}{12}\left(\frac{\pi}{2} - \int_0^{a|s|}\frac{1-\cos x}{x^2}\,dx\right) \\
&\quad + \frac{is}{12}\left(\frac{\sin(a|s|)}{a|s|} + \int_{a|s|}^\infty \frac{\cos x}{x}\,dx\right) + O\left(\frac{|s|}{a}\right) \\
&= -\frac{\pi|s|}{24} + \frac{is}{12}(1 - \gamma - \log a - \log|s|) + O(as^2) + O\left(\frac{|s|}{a}\right).
\end{aligned}$$

For the last equality, we use $1 - \cos x \leq x^2/2$ to obtain $\int_0^{a|s|}(1-\cos x)/x^2\,dx = O(a|s|)$. From $1 - (\sin x)/x \leq x^2/6$ for $x > 0$ we get $(\sin a|s|)/(a|s|) = 1 + O(a^2s^2)$. And the formulas for the sine integral in Abramowitz and Stegun (1970, Eqs. 5.2.2+27) lead to

$$\int_\epsilon^\infty \frac{\cos x}{x}\,dx = -\gamma - \log\epsilon + \int_0^\epsilon \frac{1-\cos x}{x}\,dx = -\gamma - \log\epsilon + O(\epsilon^2)$$

for $\epsilon \in (0,1]$, whence $\int_{a|s|}^\infty(\cos x)/x\,dx = -\gamma - \log a - \log|s| + O(a^2s^2)$. In view of $a = 1/\sqrt{|s|}$ all remainder terms are seen to be bounded of order $|s|^{3/2}$. Now $1 + I_1(a) + I_2(a)$ sums to (*), thus completing the proof. $\qquad\square$

The density of S can be calculated numerically, see Nolan (1997, 1998). It is known to be positive over the whole real line, smooth, and unimodal, with mode in the negative axis, at about -0.435. See Figure 5.1.
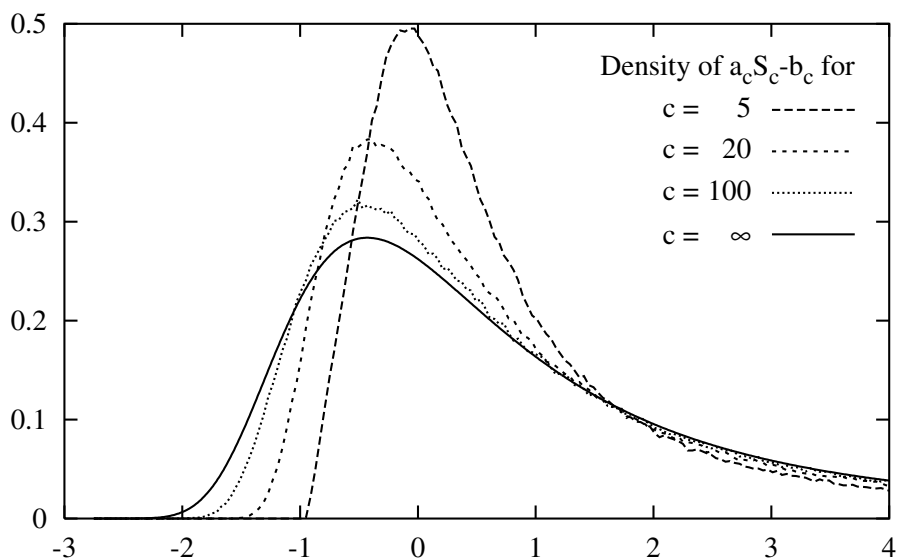
Figure 5.1 Convergence of $a_c S_c - b_c$ to a Lévy-stable law when $c \to \infty$. Theorem 5.2, specifying the scale constants a_c and the shift constants b_c, only establishes convergence in distribution, while the figure exhibits convergence of the associated densities. For $c = 5, 20, 100$, the density of S_c is obtained by simulating one million replicates according to Theorem 4.1. The density of the limiting law ($c = \infty$) is calculated using the program of Nolan (1997).

6   Concluding remarks

Our approach suggests generalizations in various directions. Thus we may assume that the random variables E_j from Lemma 5.1 possess a Gamma density with form parameter $\alpha \in (0, 2]$ and scale parameter 1,

$$\frac{1}{\Gamma(\alpha)} \, x^{\alpha-1} \, e^{-x}, \qquad x > 0.$$

That is, on the simplex $\mathcal{S}_c$ the weight vector W, with exchangeable components $W_j = E_j / \sum_{i \le c} E_i$ for $j = 1, \ldots, c$, follows a Dirichlet distribution $\mathcal{D}(\alpha)$, see Aitchison (1986, p. 59). Specifically, $\alpha = 1$ is the uniform case discussed in Section 5.

Generalizing Lemma 5.1, we find that now, as c tends to infinity,

$$\frac{1}{\alpha c^{1+1/\alpha}} \, S_c - \frac{1}{c^{1/\alpha}} \sum_{j \le c} \frac{V_j^2}{E_j}$$

vanishes in probability when $\alpha \in (0, 2)$, while for $\alpha = 2$ convergence takes place for

$$\frac{1}{2c\sqrt{c \log c}} \, S_c - \frac{1}{1\sqrt{c \log c}} \sum_{j \le c} \frac{V_j^2}{E_j}.$$

The density f of the random variables $Z_j = V_j^2/E_j$ becomes

$$f(z) = \frac{1}{\Gamma(\alpha)\sqrt{z}} \int_0^{1/(4z)} e^{-x} x^{\alpha-1/2}\, dx = \frac{1}{(1+2\alpha)4^\alpha \Gamma(\alpha) z^{1+\alpha}} + r(z).$$

It remains bounded of order $z^{-1/2}$ as z tends to zero, and the remainder $r(z)$ is bounded of order $z^{-(2+\alpha)}$ as z tends to infinity. For $\alpha > 1$, we obtain $E[Z_1] = 1/(12(\alpha-1))$.

For $\alpha \in (0, 2)$, Z_1 thus belongs to the domain of normal attraction of a stable distribution with characteristic exponent α. For $\alpha = 2$, Z_1 lies in the non-normal domain of attraction of the Gaussian law. See Ibragimov and Linnik (1971) for details. After some lengthy calculations, similar to those in the proof of Theorem 5.2, it transpires that the appropriate norming constants turn out to be

$$a_c = \begin{cases} \left(\dfrac{\Gamma(1+\alpha)\,(1+2\alpha)\,(1-\alpha)}{\Gamma(2-\alpha)\,\sin(\pi(1-\alpha)/2)}\right)^{1/\alpha} \dfrac{4}{\alpha c^{1+1/\alpha}} & \text{for} \quad \alpha \in (0,1) \cup (1,2), \\[4mm] \dfrac{4\sqrt{5}}{c\sqrt{c}\,\log c} & \text{for} \quad \alpha = 2; \end{cases}$$

$$b_c = \begin{cases} 0 & \text{for} \quad \alpha \in (0,1), \\[4mm] \dfrac{\alpha c^2 a_c}{12(\alpha-1)} & \text{for} \quad \alpha \in (1,2]. \end{cases}$$

Then $a_c S_c - b_c$ is found to converge in distribution to the stable law with Fourier transform φ_α given by, for $\alpha \neq 1$,

$$\varphi_\alpha(t) = \exp\left(-|t|^\alpha \left(1 - i\, \text{sgn}(t) \tan\frac{\pi\alpha}{2}\right)\right).$$

Other generalizations are possible. With $f(x) = x^2$ the Sainte-Laguë divergence takes the form

$$S_{n,c} = n^2 \sum_{j \le c} W_j f\left(\frac{N_j/n}{W_j} - 1\right).$$

This is just one choice out of many for generating meaningful statistical distances, see Liese and Vajda (1987). Other choices would entail a similar analysis as the one presented here, though their bearing on the rounding problem would need to be explored.

References

[1] M. Abramowitz and I. A. Stegun. *Handbook of Mathematical Functions. Seventh Printing.* New York: Dover, 1970.

[2] J. Aitchison. *The Statistical Analysis of Compositional Data.* London: Chapman and Hall, 1986.

[3] M. L. Balinski and H. P. Young. *Fair Representation–Meeting the Ideal of One Man, One Vote.* New Haven CT: Yale University Press, 1982. [Second Edition (with identical pagination): Washington DC: Brookings Institution Press, 2001.]

[4] I. N. Bronstein and K. A. Semendjajew. *Taschenbuch der Mathematik, 25. Auflage.* Stuttgart: Teubner, 1991.

[5] P. Diaconis and D. Freedman. On rounding percentages. *Journal of the American Statistical Association*, 74:359–364, 1979.

[6] G. Dorfleitner and T. Klein. Rounding with multiplier methods: An efficient algorithm and applications in statistics. *Statistical Papers*, 40:143–157, 1999.

[7] S. Garfunkel. *For All Practical Purposes–Mathematical Literacy in Today's World, Sixth Edition*. New York: W. H. Freeman, 2003.

[8] E. Hagenbach-Bischoff. *Die Verteilungsrechnung beim Basler Gesetz nach dem Grundsatz der Verhältniswahl.* Basel: Buchdruckerei zum Basler Berichthaus, 1905.

[9] M. Happacher. The discrepancy distribution of stationary multiplier rules for rounding probabilities. *Metrika*, 53:171–181, 2001.

[10] M. Happacher and F. Pukelsheim. Rounding probabilities: Unbiased multipliers. *Statistics & Decisions*, 14:373–382, 1996.

[11] M. Happacher and F. Pukelsheim. Rounding probabilities: Maximum probability and minimum complexity multipliers. *Journal of Statistical Planning and Inference*, 85:145–158, 2000.

[12] I. A. Ibragimov and Yu. V. Linnik. *Independent and Stationary Sequences of Random Variables.* Groningen: Wolters-Nordhoff, 1971.

[13] F. Liese and I. Vajda. *Convex Statistical Distances.* Leipzig: Teubner, 1987.

[14] A. W. Marshall, I. Olkin and F. Pukelsheim. A majorization comparison of apportionment methods in proportional representation. *Social Choice and Welfare*, 19:885–900, 2002.

[15] J. P. Nolan. Numerical calculation of stable densities. *Stochastic Models*, 13:759–774, 1997.

[16] J. P. Nolan. Parametrizations and modes of stable densities. *Statistics & Probabilities Letters*, 38:187–195, 1998.

[17] F. Pukelsheim. Rounding tables on my bicycle. *Chance*, 11:57–58, 1998.

[18] F. Pukelsheim. Mandatszuteilungen bei Verhältniswahlen: Erfolgswertgleichheit der Wählerstimmen. *Allgemeines Statistisches Archiv*, 84:447–459, 2000.

[19] D. Pollard. *A User's Guide to Measure Theoretic Probability*. Cambridge UK: Cambridge University Press, 2002.

[20] A. Sainte-Laguë. La représentation proportionnelle et la méthode des moindres carrés. *Annales scientifiques de l'École normale supérieure, Troisième série*, 27:529–542, 1910a.

[21] A. Sainte-Laguë. La représentation proportionnelle et les Mathématiques. *Revue Générale des Sciences Pures et Appliquées*, 21:846–852, 1910b.

[22] H. Wainer. Rounding tables. *Chance*, 11:46–50, 1998.

[23] W. A. Wallis and H. V. Roberts. *Statistics–A New Approach*. London: Methuen, 1956.

[24] V. M. Zolotarev. *One-Dimensional Stable Distributions*. Providence RI: American Mathematical Society, 1986.

Lothar Heinrich
Institut für Mathematik
Universität Augsburg
86135 Augsburg, Germany
heinrich@math.uni-augsburg.de

Friedrich Pukelsheim
Institut für Mathematik
Universität Augsburg
86135 Augsburg, Germany
pukelsheim@math.uni-augsburg.de

Udo Schwingenschlögl
Institut für Physik
Universität Augsburg
86135 Augsburg, Germany
schwingenschloegl@physik.uni-augsburg.de