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Formulae are presented that give the content of a simplex in Euclidean n-space: (i) in terms of the lengths of and the angles between the vectors from a fixed point to the vertices of the simplex; (ii) in terms of the lengths of and the angles between the perpendiculars from a fixed point to the bounding faces of the simplex. We then determine the largest simplex whose vertices are given distances from a fixed point and we determine the smallest simplex whose faces are given distances from a fixed point. As special cases we find that the regular simplex is the largest simplex contained in a given sphere and is also the smallest simplex containing a given sphere.

1. Introduction and results. The n-dimensional simplex S_n in Euclidean n-space is the general term in the sequence of figures S_0 , $S_1, S_2, S_3 \cdots$ known respectively otherwise as point, line segment, triangle, tetrahedron, \cdots . S_n is determined by n+1 points, P_1 , P_2, \cdots, P_{n+1} , — its vertices —, which we assume do not lie in any (n-1)-dimensional hyperplane. Taken n at a time, these vertices determine (n-1)-dimensional hyperplanes $H_1, H_2, \cdots, H_{n+1}$, where H_i contains all vertices except P_i . We choose the normal of H_i so that P_i lies on the negative side of H_i . S_n can be regarded as the intersection of these n+1 nonpositive half spaces; it can also be regarded as the convex hull of its vertices.

Let Q be an arbitrary point. For $i=1, 2, \dots, n+1$, let $d_i>0$ be the distance from Q to P_i and let $e_i>0$ be the distance from Q to H_i . Let a_i be the unit vector in the direction from Q to P_i and let b_i be the unit vector from Q along the perpendicular to H_i . Let $r_{ij}=a_i\cdot a_j, s_{ij}=b_i\cdot b_j, i, j=1, 2, \dots, n+1$.

In this paper, we first show that the content, V_n , of S_n is given by

(1)
$$n! \ V_n = \left| \sum_{i,j} R_{ij} \frac{1}{d_i} \frac{1}{d_j} \right|^{1/2} \prod_{i=1}^{n+1} d_i$$

$$= \left| \sum_{i,j} S_{ij} e_i e_j
ight|^{n/2} \!\! / \prod_1^{n+1} S_{ii}^{1/2}$$

for $n=1,2,\cdots$, where R_{ij} is the cofactor of r_{ij} in the $(n+1)\times (n+1)$ matrix $r=(r_{ij})$ and S_{ij} is the cofactor of s_{ij} in $s=(s_{ij})$. Next we determine the largest simplex with given d values and the smallest simplex containing Q with given e values. We find

$$(\,3\,) \hspace{1cm} n! \; V_{ ext{max}} = \, heta^{-1/2} \prod_{1}^{n+1} \, (heta \, + \, d_i^2)^{1/2}, \, r'_{ij} = \, - rac{ heta}{d_i d_i} \; ,$$

$$(4) \hspace{1cm} n! \; V_{ ext{min}} = n^n \psi^{-1/2} \prod_{1}^{n+1} (\psi + e_i^2)^{1/2}, s_{ij}' = -rac{\psi}{e_i e_i} \; ,$$

 $i, j = 1, 2, \dots, n+1$ where θ and ψ are respectively the unique positive roots of

$$\theta \prod_{1}^{n+1} \frac{1}{\theta + d_{i}^{2}} = 1$$

and

$$\psi \sum_{1}^{n+1} \frac{1}{\sqrt{y + e_{i}^{2}}} = 1$$

and where the r'_{ij} are the maximizing values of r_{ij} and the s'_{ij} are the minimizing values of s_{ij} . Q lies inside the simplex given by (3).

If not all the d_i are the same, (5) has a negative real root of smallest absolute value. The simplex (3) corresponding to this root is the largest simplex with given d values having Q on the negative side of exactly one bounding face. Similarly if not all the e_i are the same, (6) has a negative real root of smallest absolute value. The simplex given by (4) corresponding to this root is the smallest simplex with given e values having Q on the positive side of exactly one bounding face.

A special case of these results states that: (a) the largest simplex contained in a given sphere is a regular simplex; (b) the smallest simplex containing a given sphere is a regular simplex.

2. Derivation of volume formula (1). Let (x_1, x_2, \dots, x_n) be the coordinates of a general point in Euclidean n-space referred to rectangular coordinate axes. We denote by r the vector from the origin to this general point. Consider the simplex whose vertices are the origin and the termini of the n vectors y_1, y_2, \dots, y_n from the origin. The simplex is described by

$$r = \sum_{1}^{n} \xi_{i} y_{i}$$

(8)
$$\sum_1^n \xi_i \leqq 1 \\ \xi_1 \geqq 0, \, \xi_2 \geqq 0, \, \cdots, \, \xi_n \geqq 0 \; .$$

The volume of the simplex is given by

$$V = \int_{S_n} \! dx_1 \cdots \int \! dx_n = \int_{R} \! d \hat{\xi}_1 \cdots \int \! d \hat{\xi}_n \mid J \mid 0$$

where R is the ξ -region defined by (8) and J is the Jacobian of the

transformation (7). If $y_i = (y_{i1}, y_{i2}, \dots, y_{in}), i = 1, 2, \dots, n$, then (7) is explicitly $x_i = \sum \xi_i y_{ji}$, whence

$$J = egin{bmatrix} y_{\scriptscriptstyle 11} & \cdots & y_{\scriptscriptstyle 1n} \ dots & & dots \ y_{\scriptscriptstyle n1} & \cdots & y_{\scriptscriptstyle nn} \ \end{pmatrix}$$

which is independent of the ξ 's. The integral in (9) is readily evaluated to give the formula

$$n! V = |J|$$
.

To obtain the content of a simplex not located at the origin, we translate the coordinates along the vector \mathbf{x}_{n+1} . Set $\mathbf{y}_i = \mathbf{x}_i - \mathbf{x}_{n+1}$, $i = 1, 2, \dots, n$. Then the content of a simplex with vertices given by the termini of \mathbf{x}_i , $i = 1, \dots, n+1$, is

(10)
$$n! \ V = \left\| \begin{array}{ccc} x_{11} - x_{n+1} & \cdots & x_{1n} - x_{n+1} & n \\ \vdots & & \vdots & & \vdots \\ x_{n1} - x_{n+1} & \cdots & x_{nn} - x_{n+1} & n \end{array} \right\| \\ = \left\| \begin{array}{ccc} x_{11} & \cdots & x_{1n} & 1 \\ \vdots & \vdots & \vdots & \vdots \\ x_{n+1} & \cdots & x_{n+1} & 1 \end{array} \right\| ,$$

a well-known formula [1, p. 124]. Here the double line denotes absolute value of a determinant. The equality shown in (10) can easily be established by subtracting the last row of the second determinant shown from each of the first n rows and evaluating the result by the cofactor expansion of the last column.

Squaring (10) we find $[n! \ V]^2 = || x_i \cdot x_j + 1 ||$ where the determinant is obtained by multiplying the last matrix of (10) by its transpose and we exhibit the element in the i th row and j th column of the result. Introducing the notation of § 1, we set $x_i \cdot x_j = d_i d_j r_{ij}$ with Q located at the origin. We have then

$$(11) \hspace{1cm} n! \hspace{1mm} V = ||\hspace{1mm} d_i d_j r_{ij} \hspace{1mm} + \hspace{1mm} 1 \hspace{1mm}||^{1/2} = \left\| r_{ij} \hspace{1mm} + \hspace{1mm} \frac{1}{|\hspace{1mm} d_i d_j|} \right\|^{1/2} \prod\limits_{1}^{n+1} d_i \hspace{1mm}.$$

Now the *i*th row of $||r_{ij} + 1/d_id_j||$ is the sum of the two rows $(r_{i1}, \dots, r_{in+1})$ and $1/d_i(1/d_1, 1/d_2, \dots, 1/d_{n+1})$. The determinant can thus be written as the sum of the 2^{n+1} determinants obtained by taking for each row either a row of the matrix (r_{ij}) or a row of the matrix $(1/d_id_j)$. But any determinant having two or more rows taken from $(1/d_id_j)$ vanishes, and $|r_{ij}|$ also vanishes since the n+1 n-vectors a_i

are linearly dependent. The determinant $|r_{ij} + 1/d_id_j|$ can therefore be expressed as the sum of n+1 determinants, the k th term being $|r_{ij}|$ with row k replaced by $1/d_k(1/d_1, 1/d_2, \dots, 1/d_{n+1})$. Expanding this determinant by the k th row gives $\sum_j R_{kj}(1/d_k)(1/d_j)$ and formula (1) then follows directly.

3. Derivation of volume formula (2). Consider the volume, V_n , of the region S_n defined by

(12)
$$r \cdot b_i = \sum_{j=1}^n b_{ij} x_j \leq e_i, i = 1, 2, \cdots, n+1$$
.

Let

$$b = \begin{pmatrix} b_{11} & \cdots & b_{1n} \\ \vdots & & \vdots \\ b_{n1} & \cdots & b_{nn} \end{pmatrix}$$

and let B_{ij} be the cofactor of b_{ij} in b. Set $b_{ij}^{-1}=B_{ji}/|b|, i,j=1$, $2,\cdots,n$. Define new variables y_1,\cdots,y_n by

$$y_i = \sum_{j=1}^n b_{ij} x_j$$
, $i = 1, \dots, n$

so that

$$x_i = \sum_{j=1}^{n} b_{ij}^{-1} y_j, \ i = 1, \ \cdots, \ n$$
.

In the new variables, the inequalities (12) are

(14)
$$y_i \leq e_i, i = 1, 2, \dots, n$$
 $\sum\limits_k \left(\sum\limits_j b_{n+1} \ _j b_{jk}^{-1}\right) y_k \leq e_{n+1} \ .$

If we now regard the y's as rectangular coordinates, we see that (14) defines a simplex S'_n in this new space. If S'_n has y-volume V'_n , then

$$(15) V_n = V_n'/|b|$$

since $dx_1 \cdots dx_n = dy_1 \cdots dy_n/|b|$. We proceed by finding V'_n . The bounding hyperplanes of S'_n are

(16)
$$\begin{aligned} H_1 \colon & y_1 = e_1 \\ \vdots & \vdots \\ H_n \colon & y_n = e_n \end{aligned}$$

(17)
$$H_{n+1}: \sum_{k} \left(\sum_{l} b_{n+1} b_{la}^{-1} \right) y_{k} = e_{n+1}.$$

The vertex P_{n+1} of this simplex, given by $H_1 \cap H_2 \cap \cdots \cap H_n$, has coordinates

(18)
$$P_{n+1}$$
: (e_1, e_2, \dots, e_n) .

Consider the vertex P_i given by $H_1 \cap \cdots \cap H_{i-1} \cap H_{i+1} \cap \cdots \cap H_{n+1}$, $i = 1, 2, \dots, n$. For the j th coordinate of P_i we find

(19)
$$y_{ij} = e_i, j \neq i, i, j, = 1, 2, \dots, n$$

from (16). The i th coordinate y_{ii} is found from (17) as the solution of

$$y_{ii} \sum_{l} b_{n+1\, l} b_{l\, i}^{-1} + \sum_{k
eq i} \sum_{l} b_{n+1\, l} b_{l\, k}^{-1} e_k = e_{n+1}$$

or

$$(20) y_{ii} \sum_{l} b_{n+1} B_{il} + \sum_{k \neq i} \sum_{l} b_{n+1} B_{kl} e_{k} = |b| e_{n+1}.$$

Now let

(21)
$$c = \begin{pmatrix} b_{11} & b_{1n} & e_1 \\ \vdots & \vdots & \vdots \\ b_{n+11} \cdots b_{n+1n} & e_{n+1} \end{pmatrix} = (c_{ij})$$

and write C_{ij} for the cofactor of c_{ij} in c. Equation (20) now becomes

$$-\,y_{ii}C_{i\,n+1} - \sum\limits_{k
eq i} C_{k\,n+1} e_k = C_{n+1\,n+1}e_{n+1}$$

or

$$-y_{ii}C_{i\,n+1} = \sum_{k
eq i}^{n+1} C_{k\,n+1}e_k = |c| - C_{i\,n+1}e_i$$
 .

Thus

(22)
$$y_{ii} = e_i - \frac{|c|}{C_{i,n+1}}, i = 1, 2, \dots, n$$
.

Formulas (18), (19) and (22) provide us with the coordinates of the vertices of S'_n . Using the first equality of (10) with the substitution $x_{ij} = y_{ij}$, $i, j = 1, 2, \dots, n, x_{n+1j} = e_j, j = 1, 2, \dots, n$, we find

$$n! \ V'_n = \left| \operatorname{diag} \left(-\frac{\mid c \mid}{C_{1 \, n+1}}, -\frac{\mid c \mid}{C_{2 \, n+1}}, \ \cdots, \ \frac{-\mid c \mid}{C_{n \, n+1}} \right) \right| = \frac{\mid\mid c \mid\mid^n}{\prod\limits_{i \, n+1}^n C_{i \, n+1}} \, .$$

From (15), then

(23)
$$n! \ V_n = \frac{|| c ||^n}{\left| \prod_{n=1}^{n+1} C_{j n+1} \right|}.$$

Next we note from (21), by multiplying c by its transpose, that $|c|^2 = |s_{ij} + e_i e_j|$ where as before $s_{ij} = b_i \cdot b_j$. An argument analogous to that given after equation (11) then shows that $|c|^2 = \sum S_{ij} e_i e_j$ with S_{ij} the cofactor of s_{ij} in (s_{ij}) . Finally, we see from (21) that $|C_{jn+1}|$ is (apart from sign) the determinant of the $n \times n$ matrix whose rows are the b vectors, b_j being omitted. Multiplying this matrix by its transpose gives $|C_{jn+1}|^2 = S_{jj}$. This quantity is positive since we assume every n of the b's are independent and hence, as a matrix S_{jj} is positive definite. Formula (2) then follows by substitution in (23).

4. The largest simplex whose i th vertex is distant d_i from a given point. We choose the origin as the special point Q and denote by a_id_i the vector from Q to the vertex P_i . Here $a_i = (a_{i1}, a_{i2}, \dots, a_{in})$ is a unit vector. Equation (10) then gives

$$(24) \hspace{1cm} n! \; V = \prod_{1}^{n+1} d_i \left\| egin{array}{cccc} a_{1n} & rac{1}{d_1} \ dots & dots & dots \ a_{n+11} a_{n+1 \; n} & rac{1}{d_{n+1}} \end{array}
ight\|.$$

The vectors a_i are linearly dependent. We write

$$a_{n+1} = \sum_{j=1}^{n} \alpha_j a_j.$$

The determinant D displayed in (24) can now be expressed easily in other terms. Multiply the jth row of D by α_j and subtract from the last row, $j=1,2,\dots,n$. Because of (25), all elements of the last row except the diagonal entry are zero. On expanding by this last row, we then find

(26)
$$D = |a| \left[\frac{1}{d_{n+1}} - \sum_{i=1}^{n} \frac{\alpha_{i}}{d_{i}} \right]$$

where

$$a = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix}.$$

We have also $|a|^2 = |\rho|$ where

(27)
$$\rho = (\rho_{ij}) = \begin{pmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & & \vdots \\ r_{n1} & \cdots & r_{nn} \end{pmatrix}$$

and as before $a_i \cdot a_j = r_{ij}$. Finally, defining

$$(28) x_i = d_{n+1}/d_i, i = 1, 2, \cdots, n$$

equation (24) becomes

$$\frac{n! \ V_n}{\prod\limits_{i=1}^n d_i} = |\rho|^{1/2} \left| \left[1 - \sum\limits_{i=1}^n \alpha_i x_i \right] \right| .$$

The condition that a_{n+1} is a unit vector becomes from (25)

$$(30) \qquad \qquad \prod_{i=1}^{n} \rho_{ij} \alpha_i \alpha_j = 1.$$

We now seek to maximize (29), subject to (30), over all values of $\alpha_1, \alpha_2, \dots, \alpha_n$ and over all symmetric $n \times n$ nonsingular matrices ρ having

(31)
$$\rho_{ii} = 1, i = 1, 2, \dots, n$$

Introducing the Lagrange multiplier λ , we seek the stationary values of

$$J=|\,
ho\,|^{\scriptscriptstyle 1/2}\!\Big[1-\sum\limits_{\scriptscriptstyle 1}^{\scriptscriptstyle n}lpha_{\scriptscriptstyle j}x_{\scriptscriptstyle j}\Big]-\lambda\sum\limits_{i,j}
ho_{ij}lpha_{i}lpha_{\scriptscriptstyle j}$$
 .

We have

(32)
$$\frac{\partial J}{\partial \alpha_i} = -|\rho|^{1/2} x_i - 2\lambda \sum_j \rho_{ij} \alpha_j = 0, i = 1, 2, \dots, n$$

$$egin{align} rac{\partial J}{\partial
ho_{ij}} &= rac{1}{2}
ho_{ji}^{-1} \left|
ho
ight|^{1/2} \left[1 - \sum lpha_l x_l
ight] - \lambda lpha_i lpha_j = 0, \ i
eq j, \, i, \, j = 1, \, 2, \, \cdots, \, n \; . \end{aligned}$$

Multiply (32) by α_i and sum. By (30) one finds

(34)
$$2\lambda = + |\rho|^{1/2}/u$$

where we have written

$$(35) u = -\frac{1}{\sum_{i=1}^{n} \alpha_{i} x_{i}}.$$

Equations (32) and (33) then become

(36)
$$\sum_{j=1}^{n} \rho_{ij} \alpha_{j} = -u x_{i}, i = 1, 2, \dots, n$$

(37)
$$\rho_{ij}^{-1} = \frac{1}{1+u} \alpha_i \alpha_j, i \neq j, i, j = 1, 2, \dots, n.$$

Our task now is to solve the non-linear system (31), (35), (36), (37) for the α 's and ρ_{ij} .

Multiply (36) by α_i to obtain

$$egin{aligned} -ulpha_{i}x_{i} &= \sum_{j}
ho_{ij}lpha_{i}lpha_{j} \ &= lpha_{i}^{2} + \sum_{j
eq i}
ho_{ij}lpha_{i}lpha_{j} \ &= lpha_{i}^{2} + (1+u)\sum_{j
eq i}
ho_{ij}
ho_{ji}^{-1} \ &= lpha_{i}^{2} + (1+u)[1-
ho_{ii}^{-1}] \ . \end{aligned}$$

Here (31) was used to obtain the second line and (37) was used to obtain the third line. We have then

(38)
$$ho_{ii}^{-1} = 1 + rac{1}{1+u} [lpha_i^2 + ulpha_i x_i]$$
 .

From (36) we also have

$$lpha_i=\,-u\sum\limits_i
ho_{ij}^{\scriptscriptstyle -1}x_j,\,i=1,\,2,\,\cdots,\,n$$
 .

We now use (37) and (38) to replace ho_{ij}^{-1} in this sum. There results

$$\begin{array}{ll} -\alpha_{i}/u = \rho_{ii}^{-1}x_{i} + \sum\limits_{j \neq i} \rho_{ij}^{-1}x_{j} \\ &= x_{i} + \frac{x_{i}}{1+u}[\alpha_{i}^{2} + u\alpha_{i}x_{i}] + \frac{\alpha_{i}}{1+u}\sum\limits_{j \neq i} \alpha_{j}x_{j} \\ &= x_{i} + \frac{x_{i}}{1+u}[\alpha_{i}^{2} + u\alpha_{i}x_{i}] + \frac{\alpha_{i}}{1+u}\left[-\frac{1}{u} - \alpha_{i}x_{i}\right]. \end{array}$$

To obtain the last line we have employed (35). The quadratic terms in α_i cancel in (39) and the equation yields

Therefore

$$\sum_{i=1}^{n} \alpha_{i} x_{i} = -(1+u) \sum_{i=1}^{n} \frac{x_{i}^{2}}{1+u x_{i}^{2}}$$

$$= -\frac{1}{u}$$

by (35). The parameter u must therefore satisfy

(41)
$$\sum_{i=1}^{n} \frac{x_{i}^{2}}{1 + ux_{i}^{2}} = \frac{1}{u(1 + u)}.$$

We now write (38) in the form

(42)
$$\rho_{ii}^{-1} = \frac{1}{1+u} [\alpha_i^2 + q_i], i = 1, 2, \dots, n$$

where

(43)
$$q_i = 1 + u + u\alpha_i x_i, i = 1, 2, \dots, n$$
.

It is easy to invert the matrix ρ^{-1} whose elements are given by (37) and (42). One finds

(44)
$$|
ho^{-1}| = rac{1}{(1+u)^n} [1+\sum lpha_i^2/q_i] \prod q_i$$

(45)
$$\rho_{ii} = \frac{(1+u)\left[1 + \sum_{j \neq i} \alpha_j^2/q_j\right]}{q_i[1 + \sum_{j \neq i} \alpha_j^2/q_j]}, i = 1, 2, \dots, n$$

$$\rho_{ij} = -\frac{(1+u)}{1+\sum \alpha_j^2/q_j} \cdot \frac{\alpha_i \alpha_j}{q_i q_j}, \, i \neq j, \, i, j = 1, \, 2, \, \cdots, \, n \; .$$

Using (40), (41) and (43) in these expressions, one verifies that $\rho_{ii}=1$ and finds

(47)
$$\rho_{ij} = -ux_ix_j, i \neq j, i, j = 1, 2, \dots, n.$$

We note that from (25)

(48)
$$r'_{n+1i} = \boldsymbol{a}_{n+1} \cdot \boldsymbol{a}_i = \sum_{1}^{n} \alpha_{j} \rho_{ij}$$
$$= \alpha_i + \sum_{j \neq 1} \alpha_j (-ux_i x_j)$$
$$= \alpha_i - ux_i \left(-\frac{1}{u} - \alpha_i x_i \right)$$
$$= -ux_i.$$

Here we have used (47) to obtain the second line, (35) to obtain the third line and (40) to obtain the final line. From (44), using (40), (41) and (43), one finds

(49)
$$|\rho| = \frac{u}{1+u} \prod_{i=1}^{n} (1+ux_i^2).$$

We now symmetrize the formulae thus far obtained by introducing

$$\theta = ud_{n+1}^2.$$

With the help of (28), (41) becomes

(51)
$$heta \sum_{1}^{n+1} \frac{1}{\theta + d_{j}^{2}} = 1$$
.

Equations (47) and (48) can be written jointly as

(52)
$$r'_{ij} = -\frac{\theta}{d_i d_j}, \, i \neq j, \, i, j = 1, 2, \, \cdots, \, n+1 \; .$$

Finally, (29), (35) and (49) give us

$$n! \; V = |\, heta \,|^{-1/2} \prod_{i=1}^{n+1} |\, heta \, + \, d_i^2 \,|^{1/2}$$
 .

To complete our demonstration of (3) and (5), we must show that θ must be chosen as the unique positive root of (51).

Let us suppose that the distances d_i are all distinct and that $0 < d_1 < d_2 < \cdots < d_{n+1}$. The modifications of our argument necessary when several d's are identical are easily made. It is readily seen from (51) that θ is the root of a polynomial of degree n+1 whose n+1 roots are real and can be labelled so that

$$heta_1>0>-d_1^2> heta_2>-d_2^2>\cdots> heta_{n+1}>-d_{n+1}^2$$
 .

We shall show that the roots θ_3 , θ_4 , \cdots , θ_{n+1} do not correspond to a realizable simplex. Let $H(\theta)=\theta^{-1}\prod^{n+1}(\theta+d_i^2)$ so that $n!\ V=|H(\theta)|^{1/2}$. We shall also show that $H(\theta_1)>H(\theta_2)>0$ which will then complete the proof.

Consider the $(n+1) \times (n+1)$ matrix r whose elements are given by (52) and $r_{ii} = 1, i = 1, 2, \dots, n+1$. The elements $r_{ij} = \mathbf{a}_i \cdot \mathbf{a}_j$ of this matrix are scalar products of the optimal \mathbf{a} 's and since for arbitrary real numbers γ_i ,

$$|\sum \gamma_i a_i|^2 = \sum \gamma_i a_i \cdot \sum \gamma_j a_j = \sum_{i,j} r_{ij} \gamma_i \gamma_j \ge 0$$

it follows that r must be nonnegative definite. The determinant of r and all the principal minors of r must then also be nonnegative. One readily finds

(53)
$$|r| = \left[1 - \theta \sum_{1}^{n+1} \frac{1}{\theta + d_{j}^{2}} \prod_{1}^{n+1} \frac{\theta + d_{j}^{2}}{d_{j}^{2}} \right].$$

An expression for the principal minor of r obtained by deleting rows and columns j_1, j_2, \dots, j_l is given by (53) by omitting the terms and factors involving $d_{j_1}, d_{j_2}, \dots, d_{j_l}$.

Suppose now $\theta = \theta_3$. Since θ_3 is a root of (51),

$$0 = 1 - heta_3 \sum\limits_{1}^{n+1} rac{1}{ heta_3 + d_j^2} < 1 - heta_3 \sum\limits_{2}^{n+1} rac{1}{ heta_3 + d_j^2}$$

since $\theta_3/(\theta_3 + d_j^2) > 0$. The principal minor of r obtained by deleting the first row and column has value

$$R_{\scriptscriptstyle 11} = \left[1 - heta_{\scriptscriptstyle 3} \sum\limits_{\scriptscriptstyle 2}^{\scriptscriptstyle n+1} rac{1}{ heta_{\scriptscriptstyle 3} + d_{\scriptscriptstyle i}^{\scriptscriptstyle 2}}
ight] \prod\limits_{\scriptscriptstyle 2}^{\scriptscriptstyle n+1} rac{ heta_{\scriptscriptstyle 3} + d_{\scriptscriptstyle i}^{\scriptscriptstyle 2}}{d_{\scriptscriptstyle i}^{\scriptscriptstyle 2}} \; .$$

We have seen that the bracketed expression is positive. Of the factors, $\theta_3 + d_2^2$ is negative, and all others positive. R_{11} is therefore negative and we must reject the root θ_3 .

In a similar manner one sees that for $\theta=\theta_k,\,k>2$ the principal minor obtained by deleting rows and columns $1,\,2,\,\cdots,\,k-2$ is negative. We complete the proof by showing $H(\theta_1)>H(\theta_2)>0$. Since $\theta_1>0$ while $0>-d_1^2>\theta_2>-d_2^2\cdots$

$$rac{d_{\scriptscriptstyle \perp}^2}{ heta_{\scriptscriptstyle \perp}}>rac{d_{\scriptscriptstyle \perp}^2}{ heta_{\scriptscriptstyle \perp}}$$

so

$$1+rac{d_{\scriptscriptstyle 1}^{\scriptscriptstyle 2}}{ heta_{\scriptscriptstyle 1}}>1+rac{d_{\scriptscriptstyle 1}^{\scriptscriptstyle 2}}{ heta_{\scriptscriptstyle 2}}$$

or

$$rac{ heta_{\scriptscriptstyle 1}+d_{\scriptscriptstyle 1}^2}{ heta_{\scriptscriptstyle 1}}>rac{ heta_{\scriptscriptstyle 2}+d_{\scriptscriptstyle 1}^2}{ heta_{\scriptscriptstyle 2}}>0$$
 .

Now

$$heta_{\scriptscriptstyle 1} + d_{\scriptscriptstyle j}^{\scriptscriptstyle 2} > heta_{\scriptscriptstyle 2} + d_{\scriptscriptstyle j}^{\scriptscriptstyle 2} > 0 \quad ext{for} \quad j \geqq 2$$

so that

$$H(heta_{\scriptscriptstyle 1}) = rac{ heta_{\scriptscriptstyle 1} + d_{\scriptscriptstyle 1}^2}{ heta_{\scriptscriptstyle 1}} \prod_{\scriptscriptstyle 2}^{\scriptscriptstyle n-1} (heta_{\scriptscriptstyle 1} + d_{\scriptscriptstyle j}^2) > rac{ heta_{\scriptscriptstyle 2} + d_{\scriptscriptstyle 1}^2}{ heta_{\scriptscriptstyle 2}} \prod_{\scriptscriptstyle 2}^{\scriptscriptstyle n+1} (heta_{\scriptscriptstyle 2} + d_{\scriptscriptstyle j}^2) = H(heta_{\scriptscriptstyle 2}) > 0$$
 .

We close this section with the remark that the origin and P_j lie on the same side of H_j if and only if $(\theta + d_j^2)/\theta$ is positive. We omit the direct demonstration of this fact here. Corresponding to the root $\theta_1 > 0$ of (51) we obtain a simplex containing the special point Q. For the root θ_2 , satisfying $-d_1^2 > \theta_2 > -d_2^2$, we see that Q lies outside the simplex, since $(\theta_2 + d_2^2)/\theta_2 < 0$ for example.

5. The smallest simplex whose i th bounding plane is distant e_i from a given interior point. We choose the origin as the given interior point. Let b_i be the unit vector from the origin along the perpendicular to boundary H_i , $i = 1, 2, \dots, n + 1$. The volume of the simplex is given by (23) with c defined in (21). Now the vectors b_i are linearly dependent. We write

$$\boldsymbol{b}_{n+1} = \sum_{j=1}^{n} \beta_j \boldsymbol{b}_j$$

in analogy with (25). Making an obvious association between |c| and the determinant in (24), we find from (26) that

$$\mid c \mid = \mid b \mid \left[e_{n+1} - \sum\limits_{1}^{n} eta_{j} e_{j}
ight]$$

where b is the $n \times n$ matrix given in (13). We note that $|C_{jn+1}| = |\alpha_j|b|$, $j = 1, \dots, n$ while $C_{n+1,n+1} = |b|$. Equation (23) then gives us

(55)
$$n! \ V_n = \left| \frac{|b|^n \left[e_{n+1} - \sum_{1}^n \beta_j e_j \right]^n}{|b|^{n+1} \prod_{1}^n \beta_j} \right| = \frac{\left| e_{n+1} - \sum_{1}^n \beta_j e_j \right|^n}{|\sigma|^{1/2} \left| \prod_{1}^n \beta_j \right|}$$

where

$$\sigma = (\sigma_{ij}) = \begin{pmatrix} s_{11} & \cdots & s_{1n} \\ \vdots & & \vdots \\ s_{n1} & \cdots & s_{nn} \end{pmatrix}$$

where as before $s_{ij} = \boldsymbol{b}_i \cdot \boldsymbol{b}_j$. Finally, defining

(56)
$$y_i = e_i/e_{n+1}, i = 1, \dots, n$$

(55) becomes

$$\frac{n! \ V_n}{e_{n+1}^n} = \frac{|1 - \sum \beta_j y_j|^n}{|\sigma|^{1/2} \left|\prod_{j=1}^n \beta_j\right|}.$$

The condition that b_{n+1} is a unit vector becomes from (54)

(58)
$$\sum_{1}^{n}\sigma_{ij}eta_{i}eta_{j}=1$$
 .

We now seek to minimize (57), subject to (58), over all values of β_1, \dots, β_n and all symmetric $n \times n$ nonsingular matrices σ having

(59)
$$\sigma_{ii} = 1, i = 1, 2, \dots, n$$
.

Introducing the Lagrange multiplier μ , we seek the stationary values of

$$K = n \log \left[1 - \sum eta_j y_j
ight] - rac{1}{2} \log |\sigma| - \sum \log eta_j - \mu \sum \sigma_{ij} eta_i eta_j$$
 .

We have

$$(60) \qquad rac{\partial K}{\partial eta_i} = rac{-ny_i}{1-\sumeta_jy_j} - rac{1}{eta_i} - 2\mu\sum\sigma_{ij}eta_j = 0,\, i=1,2,\,\cdots,\, n\;,$$

$$(61) \qquad \frac{\partial K}{\partial \sigma_{i,i}} = -\frac{1}{2}\,\sigma_{ji}^{\scriptscriptstyle -1} - \mu\beta_i\beta_j = 0,\, i \neq j,\, i,j = 1,\, 2,\, \cdots,\, n\;.$$

Multiply (60) by β_i and sum. By (58) one finds

(62)
$$2\mu = -\frac{n}{1 - \sum_{i} \beta_{i} y_{i}} = -\frac{1}{1 + v}$$

where we have set

(63)
$$v = -\frac{1}{n} \left[n - 1 + \sum_{j=1}^{n} \beta_j y_j \right].$$

Equations (60) and (61) then become

(64)
$$\sum_{j} \sigma_{ij} \beta_{j} = y_{i} + \frac{1+v}{\beta_{i}}, i = 1, 2, \dots, n$$

(65)
$$\sigma_{ij}^{-1} = \frac{1}{1+v} \beta_i \beta_j, \ i \neq j, \ i, j = 1, 2, \ \cdots, \ n.$$

Our task now is to solve the nonlinear system (59), (63), (64), (65) for the β 's and σ_{ij} .

Multiply (64) by β_i to obtain

$$egin{aligned} eta_i y_i + 1 + v &= eta_i^2 + \sum\limits_{j
eq i} \sigma_{ij} eta_i eta_j \ &= eta_i^2 + (1 + v) \sum\limits_{j
eq i} \sigma_{ij} \sigma_{ji}^{-1} \ &= eta_i^2 + (1 + v) (1 - \sigma_{ii}^{-1}) \end{aligned}$$

whence

(66)
$$\sigma_{ii}^{-1} = \frac{1}{1+v} [\beta_i^2 - \beta_i y_i]$$
 .

From (64)

$$eta_i = \sum\limits_{j=1}^n \sigma_{ij}^{-1} \! \left[y_j + rac{1+v}{eta_i}
ight]$$
 .

Replace σ_{ij}^{-1} by values given in (65) and (66). Use (63). There results

$$eta_i = -rac{(1+v)y_i}{v+y_i^2},\, i=1,2,\, \cdots,\, n$$
 .

Multiply by y_i and sum. Insert the result in (63). One finds that v must satisfy

$$\sum rac{1}{v+y_j^2} = rac{1}{v(1+v)}$$
 .

The analogy between (37) and (65) and between (42) and (66) permits us to use (44), (45) and (46) directly to obtain

$$||\,\sigma\,|| = rac{v\prod\limits_{_{_{1}}}^{^{n}}(v+y_{j}^{_{2}})}{(v+1)\prod\limits_{_{_{1}}}^{^{n}}y_{j}^{_{2}}} \ \sigma_{ij} = -rac{v}{y_{i}y_{j}} \ .$$

The substitution

$$v = \psi/e_{n+1}^2$$

now yields (4) and (6). We omit the details.

In analogy with (5), the roots of (6) are all real and can be labelled so that $\psi_1 > 0 > -e_1^2 > \psi_2 > -e_2^2 > \cdots > \psi_{n+1} > -e_{n+1}^2$, if $e_1 < e_2 \cdots < e_{n+1}$. Only ψ_1 and ψ_2 correspond to realizable simplexes and the content corresponding to ψ_1 is greater than the content of the simplex corresponding to the root ψ_2 . It is not difficult to show that P_j and the origin lie on the same side of H_j if and only if $\psi + e_j^2 > 0$. For the solution corresponding to ψ_1 , then, Q lies within the simplex; for the solution corresponding to ψ_2 , Q and the simplex lie on opposite sides of H_1 .

REFERENCE

1. D. M. Y. Sommerville, An Introduction to the geometry of N dimensions, Dutton & Co., New York, 1930.

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