APPENDIX I
A Glossary for Geometric Morphometrics

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INTRODUCTION

This glossary provides definitions for terms, concepts, and methods frequently encountered in morphometric literature and discussions. It includes entries for technical terms with more-or-less special meaning in shape analysis and biological morphometrics (e.g., preshape, warps, anisotropy) and some of the casual jargon that may be completely foreign to newcomers to the field (e.g., books of various color – Red, Blue, Orange, and Black). Many definitions provide the general idea behind each entry instead of a technically or mathematically rigorous treatment. As such, they are intended to give readers an intuitive understanding of a particular entry that will allow them to follow the main ideas in the literature without becoming unduly distracted, at first, with technical details. Unless otherwise indicated, the following general notation has been used: n—number of specimens; p—number of points/landmarks; k—number of dimensions; and A' will refer to the transpose of the matrix A. Members of the morphometrics community, especially the subscribers to the MORPHMET electronic mailing list, have helped greatly in the selection of terms to be included in the glossary.

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Glossary

\( \alpha \) – In a relative warps analysis, \( \alpha \) is the exponent used to rescale partial warps before computing their principal components, the relative warps (see Rohlf’s chapter in the Black Book). Scale-invariant multivariate analyses using rescaled principal warp scores, such as canonical variates analysis, are not affected by the choice of \( \alpha \) (see Rohlf, this volume).

\( \otimes \) – The Kronecker tensor product or direct product. The Kronecker tensor product of matrices \( X \) and \( Y \), written as \( X \otimes Y \), results in a large matrix formed by taking all possible products of the elements of \( X \) and those of \( Y \). For example, if \( X \) and \( Y \) are 2\( \times \)2 then \( X \otimes Y \) results in a 4\( \times \)4 matrix:

\[
\begin{bmatrix}
x_{11} & x_{12} \\
x_{21} & x_{22}
\end{bmatrix}
\otimes
\begin{bmatrix}
y_{11} & y_{12} \\
y_{21} & y_{22}
\end{bmatrix}
= \\
\begin{bmatrix}
x_{11}y_{11} & x_{11}y_{12} & x_{12}y_{11} & x_{12}y_{12} \\
x_{11}y_{21} & x_{11}y_{22} & x_{12}y_{21} & x_{12}y_{22} \\
x_{21}y_{11} & x_{21}y_{12} & x_{22}y_{11} & x_{22}y_{12} \\
x_{21}y_{21} & x_{21}y_{22} & x_{22}y_{21} & x_{22}y_{22}
\end{bmatrix}
\]

accuracy – The closeness of a measurement or estimate to its true value. See precision.

affine superimposition – A superimposition for which the associated transformations are all affine. See affine transformation.

affine transformation - A transformation for which parallel lines remain parallel. Affine transformations of the plane take squares into parallelograms and take circles into ellipses of the same shape and orientation. Affine transformations of a three-dimensional space take cubes into parallelepipeds (sheared bricks) and spheres into ellipsoids all of the same shape and orientation. Similar results are produced in higher dimensional spaces. Equivalent to “uniform transformation” or “shear.”

allometry – Any change of shape with size. It describes any deviation of the bivariate relation from the simple functional form \( y/x = c \), where \( c \) is a constant and \( x \) and \( y \) are size measures in units of the same dimension. See Klingenberg, this volume.

anisotropy – An Anisotropy is a descriptor of one aspect of an affine transformation. In two dimensions, it is the ratio of the axes of the ellipse into which a circle is transformed by an affine transformation. In general, it is the maximum ratio of extension of length in one direction to extension in a perpendicular direction.

asymptotically unbiased estimator – An estimator, \( \hat{\theta}_n \), with an expected value that converges in probability on the parametric value it is estimating, \( \theta \), as sample size goes to infinity: \( E(\hat{\theta}_n) \rightarrow \theta \) as \( n \rightarrow \infty \). See unbiased estimator and consistent estimator.
baseline — For a system of two-point shape coordinates (see below) for landmarks in a plane, the baseline is the line connecting the pair of landmarks that are assigned to fixed locations (0,0) and (1,0) in the construction. In general, baselines work better if they are closely aligned with the long axis of the mean landmark shape and pass near the centroid of that mean shape (see the Orange Book).

bending energy — Bending energy is a metaphor borrowed for use in morphometrics from the mechanics of thin metal plates. Imagine a configuration of landmarks that has been printed on an infinite, infinitely thin, flat metal plate, and suppose that the differences in coordinates of these same landmarks in another picture are taken as vertical displacements of this plate perpendicular to itself, one Cartesian coordinate at a time. The bending energy of one of these out-of-plane “shape changes” is the (idealized) energy that would be required to bend the metal plate so that the landmarks were lifted or lowered appropriately.

Whereas in physics bending energy is a real quantity, measured in appropriate units (g cm² sec⁻²), there is an alternate formula that remains meaningful in morphometrics. Bending energy is proportional to the integral of the summed squared second derivatives of the “vertical” displacement—the extent to which the vertical displacement varies from a uniform tilt. The bending energy of a shape change is the sum of the bending energies that apply to any two perpendicular coordinates in which the metaphor is evaluated. The bending energy of an affine transformation is zero because it corresponds to a tilting of the plate without any bending. The value obtained for the bending energy corresponding to a given displacement is inversely proportional to scale. Such quantities should not be interpreted as measures of dissimilarity (e.g., taxonomic or evolutionary distance) between two forms.

bending energy matrix — The formula for bending energy (see above)—the formula whose value is proportional to that integral of those summed squared second derivatives—is a quadratic form (usually written \( L^T_{x} h \)) determined by the coordinates of the landmarks of the reference form. That is, if \( h \) is a vector describing the heights of a plate above a set of landmarks, then bending energy is \( h^T L^x_k h \). In morphometrics, the bending energy of a general transformation is the sum \( x^T L^x_k x + y^T L^y_k y \) of the bending energy of its horizontal \( x \)-component, modeled as a “vertical” plate, plus the bending energy of its vertical \( y \)-component, modeled similarly as a “vertical” plate. See \( L \).

biplot — A single diagram that represents two separate scatterplots on the same pair of axes. One scatter is of some pair of columns of the matrix \( U \) of the singular value decomposition of a matrix \( S \), and the other scatter is of the matching pair of columns of \( V \). When \( S \) is a centered data matrix, the effect is to plot principal component loadings and scores on the same diagram. See Marcus (Black Book) for an in-depth discussion.


Bookstein coordinates — See two-point shape coordinates.

canonical — A canonical description of any statistical situation is a description in terms of extracted vectors that have especially simple ordered relationships. For instance, a canonical correlations analysis describes the relation between two lists of variables in terms of two lists of linear combinations that show a remarkable pattern of zero correlations. Each score
(linear combination) from either list is correlated with no other combination from its list and with only one score from the other list.

**canonical correlation analysis** — A multivariate method for assessing the associations between two sets of variables within a data set. The analysis focuses on pairs of linear combinations of variables (one for each set) ordered by the magnitude of their correlations with each other. The first such pair is determined so as to have the maximal correlation of any such linear combinations. Subsequent pairs have maximal correlation subject to the constraint of being orthogonal to those previously determined.

**canonical variates analysis** — A method of multivariate analysis in which the variation among groups is expressed relative to the pooled within-group covariance matrix. Canonical variates analysis finds linear transformations of the data that maximize the among-group variation relative to the pooled within-group variation. The canonical variates then may be displayed as an ordination to show the group centroids and scatter within groups. Canonical variates analysis may be thought of as a “data reduction” method in the sense that one wants to describe among-group differences in few dimensions. The canonical variates are uncorrelated, however the vectors of coefficients are not orthogonal as in principal component analysis. The method is closely related to multivariate analysis of variance (MANOVA), multiple discriminant analysis, and canonical correlation analysis. A critical assumption is that the within-group variance–covariance structure is similar, otherwise the pooling of the data over groups is not very sensible.

**centroid size** — Centroid size is the square root of the sum of squared distances of a set of landmarks from their centroid, or, equivalently, the square root of the sum of the variances of the landmarks about that centroid in x- and y-directions. Centroid size is used in geometric morphometrics because it is approximately uncorrelated with every shape variable when landmarks are distributed around mean positions by independent noise of the same small variance at every landmark and in every direction. Centroid size is the size measure used to scale a configuration of landmarks so they can be plotted as a point in Kendall’s shape space. The denominator of the formula for the Procrustes distance between two sets of landmark configurations is the product of their centroid sizes.

**cluster analysis** — A method of analysis that represents multivariate variation in data as a series of sets. In biology, the sets are often constructed in a hierarchical manner and shown in the form of a treelike diagram called a dendrogram.

**coefficient** — A coefficient, in general, is a number multiplying a function. In multivariate data analysis, usually the “function” is a variable measured over the cases of the analysis, and the coefficients multiply these variable values before we add them up to form a score. A coefficient is not the same as a loading.

**complex numbers** — Complex numbers are an algebraic way of coding points in the ordinary Euclidean plane so that translation (shift of position) corresponds to the addition of complex numbers and both rescaling (enlargement or shrinking) and rotation correspond to multiplication of complex numbers. In this system of notation, invented by Gauss, the x-axis is identified with the “real numbers” (ordinary decimal numbers) and the y-axis is identified with “imaginary numbers” (the square roots of negative numbers). When you multiply points on this latter axis by themselves according to the rules, you get negative points on the “real” axis just defined. Many operations on data in two dimensions can be proved valid more directly if they are written out as operations on complex numbers.
consensus configuration — A single set of landmarks intended to represent the central
tendency of an observed sample for the production of superimpositions, a weight matrix, or
some other morphometric purpose. Often a consensus configuration is computed to optimize
some measure of fit to the full sample: in particular, the Procrustes mean shape is computed
to minimize the sum of squared Procrustes distances from the consensus landmarks to those
of the sample.

consistent estimator — An estimator, \( \hat{\theta}_n \), that converges in probability on the parametric
value it is estimating, \( \theta \), as sample size goes to infinity:

\[
\lim_{n \to \infty} P ( | \hat{\theta}_n - \theta | < \varepsilon ) = 1
\]

for any positive \( \varepsilon \). Asymptotically unbiased estimators are consistent estimators if their
variance goes to zero as sample size goes to infinity. See unbiased estimator.

coordinates — A set of parameters that locate a point in some geometrical space. Cartesian
coordinates, for instance, locate a point on a plane or in physical space by projection onto
perpendicular lines through one single point, the origin. The elements of any vector may be
thought of as coordinates in a geometric sense.

correlation — Relation between two or more variables. Frequently the word is used for
Pearson’s product-moment correlation, which is the covariance divided by the product of the
standard deviations,

\[
r_{XY} = \frac{s_{XY}}{s_X s_Y}
\]

This correlation coefficient is \( \pm 1 \) when all values fall on a straight line, not parallel to either
axis. However, there are also for example Kendall, Spearman, and tetrachoric correlations
that measure other aspects of the relation between two variables.

covariance — A measure of the degree to which two variables vary together. Computed as

\[
s_{xy} = \frac{1}{n} \sum_{i=1}^{n} (X_i - \bar{X})(Y_i - \bar{Y})
\]

for two variables \( X \) and \( Y \) in a sample of size \( n \). See correlation.

covariant — A covariant of a particular shape change is a shape variable whose gradient
vector as a function of changes in any complete set of shape coordinates lies precisely along
the change in question. For transformations of triangles, the relation between invariants and
covariants is a rotation by 90 degrees in the shape-coordinate plane. For more than three
landmarks, a given transformation has only one direction of covariants; but has a full plane
(four landmarks) or hyperplane (five or more landmarks) of invariants (see the Orange Book).
See invariant.

curved space — A space with coordinates and a distance function such that the area of
circles, volume of spheres, etc., are not proportional to the appropriate power of the radius,
e.g., Kendall’s shape space. In curved spaces, the usual intuitions about what “straight lines”
can be expected to do will be faulty. For instance, corresponding to every triangular shape
in Kendall’s shape space, there is another that is “as far from it as possible,” just as there is a point on the surface of the earth as far as possible from where you now sit.

**D** – See (1) generalized distance or (2) fractal dimension.

**D^2** – Squared Mahalanobis, or generalized, distance.

**deficient coordinate** – In addition to landmark locations, a digitizer can be used to supply information of other sorts. For example, a point can be used to encode part of the information about a curving arc by identifying the spot at which the arc lies farthest from some other image structure (perhaps another such curving arc). The null model of independent Gaussian noise does not apply to position along the tangent direction of the curve that is digitized in this way, and so that Cartesian coordinate is “deficient.” The usual model of independent Gaussian noise is inapplicable in principle for such points. See Type III landmark.

**degrees of freedom** – Given a set of parameters estimated from the data, the “degrees of freedom” of some statistic is the number of independent observations required to compute the statistic. For example, the variance has n-1 degrees of freedom because only n-1 of the observations are needed for its computation given the sample mean. The missing observation can be computed as

\[ X_n = n \bar{y} - \sum_{i=1}^{n-1} X_i \]

**dilation** – Increase of length in a particular direction or along a particular interlandmark segment.

**discriminant analysis** – A broad class of methods concerned with the development of rules for assigning unclassified objects or specimens to previously defined groups. See discriminant function.

**discriminant function** – A discriminant function is used to assign an observation to one of a set of groups. Linear discriminant functions take a vector of observations from a specimen and multiply it by a vector of coefficients to produce a score that can be used to classify the specimen as belonging to one or another predefined group. See discriminant analysis.

**distance** – This term has several meanings in morphometrics; it should never be used without a prefixed adjective to qualify it, e.g., Euclidean distance, Mahalanobis distance, Procrustes distance, or taxonomic distance.

**edgel** – An extension of the notion of landmark to include partial information about a curve through the landmark. An edgel specifies rotation of a direction through a landmark, extension along a direction through a landmark, or both. The formula for thin-plate splines on landmarks can be extended to encompass data about edgels as well. They are intended eventually to circumvent any need for deficient coordinates in multivariate morphometric analysis. See Little (this volume) and Bookstein and Green (1993).

**EDMA** – See Euclidean distance matrix analysis.
Appendix I

**eigenshapes** — Principal components for outline data. An eigenshape analysis begins with the selection of a distance function between pairs of outlines. At the end one gets “eigenshapes,” which have the properties of principal component vectors (uncorrelated, describing the sample in decreasing order of variance) and also are outline shapes themselves, so that the scores for each specimen of the sample can be combined to produce a new outline shape that approximates it in some possibly useful way. Eigenshapes apply to curves as relative warps apply to landmark shape. See the chapter by Lohmann and Schweitzer in the Blue Book and that by Sampson, this volume.

**eigenvalues** — Eigenvalues, $\lambda_i$, are the diagonal elements of the diagonal matrix $\Lambda$ in the equation: $SE = EA$. In the common data analysis case, $S$ is a symmetrical variance–covariance matrix, $E$ is a matrix of eigenvectors, $\lambda_i \geq 0$, and

$$\sum \lambda_i = \sum s_i^2,$$

The order of the columns of $E$ and $\Lambda$ is arbitrary, but by convention they are usually sorted from largest to smallest eigenvalue. See eigenvectors and singular value decomposition.

**eigenvectors** — In the equation given to define eigenvalues, $E$ contains the eigenvectors. In the common data analysis case, $E$ is an orthonormal matrix (i.e., $E' E = I$ and $EE' = I$). When sorted by descending eigenvalues, the first eigenvector is that linear combination of variables that has the greatest variance. The second eigenvector is the linear combination of variables that has the greatest variance of such combinations orthogonal to the first, and so on. See eigenvalues and singular value decomposition.

**elliptic Fourier analysis** — A type of outline analysis in which differences in $x$ and $y$ (and possibly $z$) coordinates of an outline are fit separately as a function of arc length by Fourier analysis. The chapter by Rohlf in the Blue Book provides an overview of various methods of fitting curves to outline data.

**Euclidean distance** — Euclidean distance is defined as:

$$d_{lm} = \left( \sum_{i=1}^{k} (x_{li} - x_{mi})^2 \right)^{1/2}$$

for coordinates of points $x_l$ and $x_m$ on the axes of a $k$-dimensional space. This can be expressed in matrix notation as

$$d_{lm} = \left( (x_l - x_m)(x_l - x_m)' \right)^{1/2},$$

where $x_l$ and $x_m$ are the $1 \times k$ row vectors of the coordinates of points $l$ and $m$ in some coordinate system.

**Euclidean distance matrix analysis (EDMA)** — A method for the statistical analysis of full matrices of all interlandmark distances, by averaging elementwise within samples, and then comparing those averages between samples by computing the ratios of corresponding mean distances. See Lele and Richtsmeier (1991).

**Euclidean space** — A space in which distances between two points are defined as Euclidean distances in some system of coordinates.
factor analysis — Factor analysis is a multivariate technique for describing a set of measured variables in terms of a set of causal or underlying variables. A factor model can be characterized in terms of path diagrams to show relations between measured variables and factors. See the chapter by Marcus in the Blue Book and Reyment and Jöreskog (1993).

FESA — see finite element scaling analysis.

fiber — In geometric morphometrics, the set of preshapes (configurations that have been centered at the origin and scaled to unit centroid size) that differ only by a rotation. It is the path, through preshape space, followed by a centered and scaled configuration under all possible rotations.

figure — A representation of an object by the coordinates of a specified set of points, for instance, its landmarks.

figure space — For landmark data, the $2p$- or $3p$-space of figures, i.e., the original coordinate data vectors.

finite element scaling analysis (FESA) — Without the word “scaling,” finite element analysis is a computational system for continuum mechanics that estimates the deformation (fully detailed changes of position of all component particles) which are expected to result from a specified pattern of stresses (forces) upon a mechanical system. As applied in morphometrics, FESA solves the inverse problem of estimating the strains representing the hypothetical forces that deformed one specimen into another. These results are a function of the “finite elements” into which the space between the landmarks is subdivided. Finite element scaling analysis can be compared with the thin-plate spline, which interpolates a set of landmark coordinates under an entirely different set of assumptions.

form — In morphometrics, we represent the form of an object by a point in a space of form variables, which are measurements of a geometric object that are unchanged by translations and rotations. If you allow for reflections, forms stand for all the figures that have all the same interlandmark distances. A form is usually represented by one of its figures at some specified location and in some specified orientation. When represented in this way, location and orientation are said to have been “removed.”

form space — The space of figures with differences due to location and orientation removed. It is of $2p$–3 dimensions for two-dimensional coordinate data and $3p$–6 dimensions for three-dimensional coordinate data.

Fourier analysis — In morphometrics, the decomposition of an outline into a weighted sum of sine and cosine functions. The chapter by Rohlf in the Blue Book provides an overview of this and other methods of analyzing outline data.

fractal dimension $(D)$ — A measure of the complexity of a structure, assuming a consistent pattern of self-similarity (structural complexity at smaller scales is mathematically indistinguishable from that at larger-scales) over all scales considered. See the chapter by Slice in the Black Book.

generalized distance $(D)$ — A synonym for Mahalanobis distance. Defined by the equation for two row vectors $x_i$ and $x_j$ for two individuals, and $p$ variables as
\[ \left( (x_i - x_j) S^{-1} (x_i - x_j) \right)^{\frac{1}{2}}, \]

where S is the \( p \times p \) within group, variance-covariance matrix. Generalized distance takes into consideration the variance and correlation of the variables in measuring distances between points, i.e., differences in directions in which there is less variation within groups are given greater weight than are differences in directions in which there is more variation.

**generalized superimposition** — The superimposition of a set of configurations onto their consensus configuration.

**geodesic distance** — The length of the shortest path between two points in a suitable geometric space (one for which curving paths have lengths). On a sphere, it is the distance between two points as measured along a great circle. In a Euclidean space, geodesic distance is ordinary (straight-line) Euclidean distance.

**geometric morphometries** — Geometric morphometries is a collection of approaches for the multivariate statistical analysis of Cartesian coordinate data, usually (but not always) limited to landmark point locations. The “geometry” referred to by the word “geometric” is the geometry of Kendall’s shape space: the estimation of mean shapes and the description of sample variation of shape based on the geometry of Procrustes distance. The multivariate part of geometric morphometries is usually carried out in a linear tangent space to the non-Euclidean shape space in the vicinity of the mean shape.

More generally, it is the class of morphometric methods that preserve complete information about the relative spatial arrangements of the data throughout an analysis. As such, these methods allow for the visualization of group and individual differences, sample variation, and other results in the space of the original specimens.

**great circle** — A circle on a sphere with a diameter equal to that of the sphere. The shortest path connecting two points on the surface of a sphere lies along the great circle passing through the points. See geodesic distance.

**homology** — The notion of homology bridges the language of geometric morphometrics and the language of its biological or biomathematical applications. In theoretical biology, only the explicit entities of evolution or development, such as molecules, organs or tissues, can be “homologous.” Following D’Arcy Thompson, morphometricians often apply the concept instead to discrete geometric structures, such as points or curves, and, by a further extension, to the multivariate descriptors (e.g., partial warp scores) that arise as part of most multivariate analyses. In this context, the term “homologous” has no meaning other than that the same name is used for corresponding parts in different species or developmental stages. To declare something “homologous” is simply to assert that we want to talk about processes affecting such structures as if they had a consistent biological or biomechanical meaning. Similarly, to declare an interpolation (such as a thin-plate spline) a “homology map” means that one intends to refer to its features as if they had something to do with valid biological explanations pertaining to the regions between the landmarks, about which we have no data.

**Hotelling’s \( T^2 \)** — See \( T^2 \) statistic.

**hyperplane** — A \( k-1 \)-dimensional subspace of a \( k \)-dimensional space. A hyperplane is typically characterized by the vector to which it is orthogonal.
hyperspace — A space of more than three dimensions.

hypersphere — In any space, the set of all points at a fixed distance (the radius) from some fixed point (the center).

hypervolume — A generalization of the idea of volume to a space of more than three dimensions.

invariant — An invariant, generally speaking, is a quantity that is unchanged (even though its formula may have changed) when one changes some inessential aspect of a measurement. For instance, Euclidean distance is an invariant under translation or rotation of one’s coordinate system, and ratio of distances in the same direction is an invariant under affine transformations. In the morphometrics of triangles, the invariants of a particular transformation are the shape variables that do not change under that transformation (see the Orange Book). See covariant.

isometry — An isometry is a transformation of a geometric space that leaves distances between points unchanged. If the space is the Euclidean space of a picture or an organism, and the distances are distances between landmarks, the isometries are the Euclidean translations, rotations, and reflections. If the distances are Procrustes distances between shapes, the isometries (for the simplest case, landmarks in two dimensions) are the rotations of Kendall’s shape space. For triangles, these can be visualized as ordinary rotations of Kendall’s “spherical blackboard.”

isotropic — Invariant with respect to direction. Isotropic errors have the same statistical distribution in all directions, implying equal variance and zero correlation between the original variables (e.g., axis coordinates).

Kendall’s shape space — The fundamental geometric construction, developed by David Kendall, underlying geometric morphometrics. Kendall’s shape space provides a complete geometric setting for analyses of Procrustes distances among arbitrary sets of landmarks. Each point in this shape space represents the shape of a configuration of points in some Euclidean space, irrespective of size, position, and orientation. In shape space, scatters of points correspond to scatters of entire landmark configurations, not merely scatters of single landmarks. Most multivariate methods of geometric morphometrics are linearizations of statistical analyses of distances and directions in this underlying space.

Kronecker product — See ⊗.

L — The crucial matrix for computing the thin-plate spline interpolant between two landmark configurations. In this entry, $k$ stands for the number of landmarks, for historical reasons.

The equation of the thin-plate spline has coefficients $L^{-1}h$, where $h$ is a vector of the $x$- or $y$-coordinates of the landmarks in a target form, followed by three 0’s (for two dimensional data, four 0’s for three-dimensional data). The entries in the matrix $L$ are wholly functions of the starting or reference form for the spline.

Bending energy is the upper left $k \times k$ square of $L^{-1}$. For the complete formula for $L$, see the Orange Book or Rohlf (Black Book).

landmark — A specific point on a biological form or image of a form located according to some rule. Landmarks with the same name, homologues in the purely semantic sense, are
presumed to correspond in some sensible way over the forms of a data set. See Type I, Type II, and Type III landmarks.

**least-squares estimates** - Parameter estimates that minimize the sum of squared differences between observed and predicted sample values.

**likelihood ratio test** - A test based on the ratio of the likelihood (the probability of the data given the parameters) under a general model to the likelihood when another, specified hypothesis is true. Many of the commonly used statistical tests are likelihood ratio tests, e.g., the $t$-test for comparisons of means, Hotelling’s $T^2$, and the analysis of variance $F$-test.

**linear combination** - A sum of values each multiplied by some coefficient. A linear combination can be expressed as the inner product of two vectors, one representing the data and the other a vector of coefficients.

**linear transformation** - In multivariate statistics, a linear transformation is the construction of a new set of variables that are all linear combinations of the original set. In geometric morphometrics, one linear transformation takes Procrustes-fit coordinates to partial warp scores; another takes them to relative warp scores. A linear transformation of a matrix $A$ can be written in the form $y = Ax$, where $y$ is the resulting linear combination of $x$, a column vector, with the rows of $A$.

**linear vector space** - In morphometrics, the most common $k$-dimensional linear vector space is the set of all real $k$-dimensional vectors, including all sums of these vectors and their scalar multiples. More generally, but informally, a linear vector space is a set of elements, usually bits of geometry or whole functions, that can be added together and can be multiplied by real numbers in an intuitive way. The points of a plane don’t form a linear vector space (what is “five times a point”?), but lines (vectors) connecting all the points to the origin do form such a space.

**loading** - The correlation or covariance of a measured variable with a linear combination of variables. A loading is not the same as a coefficient. In general, coefficients supply formulas for the computation of scores, whereas loadings are used for the biological interpretation of the linear combination.

**Mahalanobis distance** - Also $D$ or Mahalanobis $D$. See generalized distance.

**MANOVA** - See multivariate analysis of variance.

**maximum likelihood estimate** - A likelihood function is a probability or density function for a set of data and given estimates of its parameters. A maximum likelihood estimate is the set of parameter values that maximize this function. In some cases, such as the arithmetic mean of a sample used as an estimate of the parameter $\mu$ for a normally distributed population, the maximum likelihood estimate may be identical to the least-squares estimate.

**median size** - A size measure based on the repeated median of interlandmark distances. Used in resistant-fit methods.

**metric** - A nonnegative function, $d_{ij}$, of two points, $i$ and $j$, satisfying the following conditions: $d_{ii} = d_{jj} = 0$, if $i \neq j$ then $d_{ij} > 0$, $d_{ij} = d_{ji}$, and $d_{ik} \leq d_{ij} + d_{jk}$. The last condition is known as the “triangle inequality.” The value of the function is referred to as the “distance”
between the two points. A space is called "semimetric" if \( d_{ij} \) can be equal to zero when \( i \neq j \).

**metric space** — A space and a distance function defined on every pair of points that meets the requirements of the definition of "metric" above.

**morphometrics** — From the Greek: "morphē, " meaning "shape," and "metron," meaning "measurement." Schools of morphometrics are characterized by what aspects of biological "form" they are concerned with, what they choose to measure, and what kinds of biostatistical questions they ask of the measurements once those measurements are made. The methods of this book emphasize configurations of landmarks from whole organs or organisms analyzed by appropriately invariant biometric methods (covariances of taxon, size, cause or effect with position in Kendall's shape space) in order to answer biological questions. Another sort of morphometrics studies tissue sections, measures the densities of points and curves, and uses these patterns to answer questions about the random processes that may be controlling the placement of cellular structures. A third, the method of "allometry," measures sizes of separate organs and asks questions about their correlations with each other and with measures of total size. There are many others.

**multiple discriminant analysis** — Discriminant analysis involving three or more a priori-defined groups. See discriminant analysis.

**multiple regression** — The prediction of a dependent variable by a linear combination of two or more independent variables by means of least-squares methods for parameter estimation. See multivariate regression and multivariate multiple regression.

**multivariate analysis of variance (MANOVA)** — An analysis of variance of two or more dependent variables considered simultaneously.

**multivariate morphometrics** — A term historically used for the application of standard multivariate techniques to measurement data for the purposes of morphometric analysis. Somewhat confusing now as any morphometric technique must be multivariate in nature. See traditional morphometrics.

**multivariate multiple regression** — The prediction of two or more dependent variables based on two or more independent variables. See multiple regression and multivariate regression.

**multivariate regression** — The prediction of two or more dependent variables based on one independent variable. See multiple regression and multivariate multiple regression.

**normalize** — To normalize a geometric object is to transform it so that some function of its coordinates or other parameters has a prespecified value. For example, vectors are often normalized by transformation into unit vectors, which have a length of one.

**nuisance parameters** — Parameters of a model that must be fit but that are not of interest to the investigator. In morphometrics, the parameters for translation and rotation are usually nuisance parameters.

**null model** — The simplest model under consideration. The null model for shape is the distribution in Kendall's shape space which arises from landmarks that are distributed by
independent circular normal noise of the same variance in the original digitizing plane or space and are drawn from a single, homogeneous population. It is exactly analogous to the usual assumption of “independent identically distributed error terms” in conventional linear models (regression, analysis of variance).

**oblique** — At an angle that is not a multiple of 90 degrees.


**ordination** — A representation of objects with respect to one or more coordinate axes. There are many kinds of ordinations depending upon the goals of the ordination and criteria used. For example, plotting objects according to their scores on the first two principal component axes provides the two-dimensional ordination best summarizing the total variability of the objects in the original sample space. Biplots combine an ordination of specimens and an ordination of variables.

**orthogonal** — At right angles. In linear algebra, being “at right angles” is defined relative to a symmetric matrix \( P \), such as the bending-energy matrix; two vectors \( x \) and \( y \) are orthogonal with respect to \( P \) if \( x'Py = 0 \).

Principal warps are orthogonal with respect to bending energy, and relative warps are orthogonal with respect to both bending energy and the sample covariance matrix.

**orthogonal superimposition** — A superimposition using only transformations that are all Euclidean similarities, i.e., that involve only translation, rotation, scaling, and, possibly, reflection.

**orthonormal** — A set of vectors is orthonormal if each has length unity and all pairs are orthogonal with respect to some relevant matrix, \( P \), such as the identity matrix. A matrix is orthogonal if its rows (columns) are orthonormal as a set of vectors.

**outline** — A mathematical curve that stands for the two-dimensional image of a physical boundary. Outline data can be archived as a sequence of point coordinates, but such points do not share the notion of homology associated with landmarks (but see Sampson, this volume).

**parameter** — In general, a parameter is a number (an integer, a decimal) indexing a function. For instance, the \( F \)-distribution used to test decompositions of variance has two parameters, both integers: the counts of the degrees of freedom for the two variances whose ratio is being tested. In morphometrics, there are four main kinds of parameters: nuisance parameters, which must be estimated to account for differences not of particular scientific interest; the geometric parameters, such as shape coordinates, in which landmark shape is expressed; statistical parameters, such as mean differences or correlations, by which biological interpretation is confronted with that data; and another set of geometric parameters, such as partial warp scores or Procrustes residuals, in which the findings of the statistical analysis are expressed.

**partial least squares** — Partial least squares is a multivariate statistical method for assessing relationships among two or more sets of variables measured on the same entities. Partial least squares analyses the covariances between the sets of variables rather than optimizing linear
combinations of variables in the various sets. Partial least squares computations usually do not involve the inversion of matrices (see the Orange Book).

**partial warp scores** — Partial warp scores are the quantities that characterize the location of each specimen in the space of the partial warps. They are a rotation of the Procrustes residuals around the Procrustes mean configuration. For the nonuniform partial warps, the coefficients for the rotation are the principal warps, applied first to the x-coordinates of the Procrustes residuals, then to the y-coordinates and, for three-dimensional data, then the z-coordinates. Coefficients for the uniform partial warps are produced by special formulas (see Bookstein's "Uniform" chapter, this volume).

**partial warps** — Partial warps are an auxiliary structure for the interpretation of shape changes and shape variation in sets of landmarks. Geometrically, partial warps are an orthonormal basis for a space tangent to Kendall's shape space. Algebraically, the partial warps are eigenvectors of the bending-energy matrix that describes the net local information in a deformation along each coordinate axis. Except for the largest-scale partial warp, the one for uniform shape change, they have an approximate location and an approximate scale.

**precision** — The closeness of repeated measurements to the same value. See accuracy.

**preform space** — The space corresponding to centered figures, i.e., differences in location have been removed. It is of \( k(p-1) \) dimensions.

**preshape space** — The space corresponding to figures that have been centered and scaled but not rotated to alignment. It is of \( k(p-1)-1 \) dimensions.

**principal axes and strains** — A change of one triangle into another, or of one tetrahedron into another, can be modeled as an affine transformation that can be parameterized by its effect on a circle or sphere. An affine transformation takes circles into ellipses. The principal axes of the shape change are the directions of the diameters of the circle that are mapped into the major and minor axes of the ellipse. The principal strains of the change are the ratios of the lengths of the axes of the ellipse to the diameter of the circle. In the case of the tetrahedron, there are three principal axes, the axes of the ellipsoid into which a sphere is deformed. One has the greatest principal strain (ratio of axis length to diameter of sphere) and one the least, and there is a third perpendicular to both, having an intermediate principal strain.

**principal components analysis** — The eigenanalysis of the sample covariance matrix. Principal components (PCs) can be defined as the set of vectors that are orthogonal both with respect to the identity matrix and the sample covariance matrix. They can also be defined sequentially: the first is the linear combination with the largest variance of all those PCs with coefficients summing in square to 1; the second has the largest variance (when normalized that way) of all PCs that are uncorrelated with the first one; and so on. One way to compute PCs is to use a singular value decomposition. Relative warps are principal components of partial warp scores. There is a lot to be said about PCs; see any of the colored books.

**principal warps** — Principal warps are eigenfunctions of the bending-energy matrix interpreted as actual warped surfaces (thin-plate splines) over the picture of the original landmark configuration. Principal warps are like the harmonics in a Fourier analysis (for circular shape) or Legendre polynomials (for linear shape) in that together they decompose the relation of any sample shape to the sample average shape as a unique summation of multiples of
eigenfunctions of bending energy. They differ from these more familiar analogues in that there are only \( k-3 \) of them for a set of \( k \) landmarks—they form a finite series. Together with the uniform terms, the partial warps, which are projections (shadows) of the principal warps, supply an orthonormal basis for a space that is tangent to Kendall’s shape space in the vicinity of a mean form.

**Procrustes distance** — Approximately (see Bookstein’s “Combining” chapter, this volume) the square root of the sum of squared differences between the positions of the landmarks in two optimally (by least squares) superimposed configurations at centroid size. This is the distance that defines the metric for Kendall’s shape space.

**Procrustes mean** — The shape that has the least summed squared Procrustes distance to all the configurations of a sample; the best choice of consensus configuration for most subsequent morphometric analyses (see Bookstein’s “Combining” chapter, this volume).

**Procrustes methods** — A term for least-squares methods for estimating nuisance parameters. The adjective “Procrustes” refers to the Greek giant who would stretch or shorten victims to fit a bed and was first used in the context of superimposition methods by Hurley and Cattell (1962). Modern workers have often cited Mosier (1939), a psychometrician, as the earliest known developer of these methods. However, Cole (in press) reports that Franz Boas in 1905 suggested the “method of least differences” (ordinary Procrustes analysis) as a means of comparing homologous points to address obvious problems with the standard point-line registrations (Boas, 1905). Cole further points out that one of Boas’ students extended the method to the construction of mean configurations from the superimposition of multiple specimens using either the standard registrations or Boas’ method (Phelps, 1932). The latter being essentially a Generalized Procrustes Analysis.

**Procrustes residuals** — The set of vectors connecting the landmarks of a specimen to corresponding landmarks in the consensus configuration after a Procrustes fit. The sum of squared lengths of these vectors is approximately the squared Procrustes distance between the specimen and the consensus in Kendall’s shape space. The partial warp scores are an orthogonal rotation of the full set of these residuals.

**Procrustes scatter** — A collection of forms all superimposed by ordinary orthogonal Procrustes fit over one single consensus configuration that is their Procrustes mean; a scatter of all the Procrustes residuals each centered at the corresponding landmark of the Procrustes mean shape.

**Procrustes superimposition** — The construction of a two-form superimposition by least squares based on orthogonal or affine transformations.


**reference configuration** — In the context of superimposition methods, this is the configuration to which data are fit. It may be another specimen in the sample, an estimated consensus configuration, or an hypothetical ancestor. The construction of two-point shape coordinates does not involve a reference specimen, though the intelligent choice of baseline for the construction usually does. In shape space itself, the reference specimen is a shape in the vicinity of which the linear tangent space is constructed. When splines or warps are part of the analysis, the reference configuration usually serves as the “starting form.”
regression — A model for predicting one variable from another. Coined by Francis Galton, the term derives from the fact that when measurements of offspring, whether peas or people, were plotted against the same measurements for their parents, the offspring measurements "went back," or regressed, towards the mean.

relative warps — Relative warps are principal components of a distribution of shapes in a space tangent to Kendall's shape space. They are the axes of the "ellipsoid" occupied by the sample of shapes in a geometry in which spheres are defined by Procrustes distance. Each relative warp, as a direction of shape change about the mean form, can be interpreted as specifying multiples of one single transformation, a transformation that can often be usefully drawn out as a thin-plate spline. In a relative warps analysis, the parameter \( \alpha \) (see above) can be used to weight shape variation by the geometric scale of shape differences. Relative warps can be computed from Procrustes residuals or from partial warps (see Bookstein's "Combining" article, this volume).

repeated median — A median of medians. Repeated medians are used to estimate some superimposition parameters in the resistant-fit methods. For example, the resistant-fit rotation estimate is the median of the estimates obtained for each landmark, which is, in turn, the median of angular differences between the reference configuration and the configuration being fit of the line segments defined by that landmark and the other \( n-1 \) landmarks. Repeated medians are insensitive to larger subsets of extremely deviant values than are simple medians.

residual — The deviations of an observed value or vector of values from some expectation, e.g., the differences between a shape and its prediction by an allometric regression expressed in any set of shape coordinates.

resistant-fit superimposition — Superimposition methods that use median- and repeated-median-based estimates of fitting parameters rather than least-squares estimates. Resistant-fit procedures are less sensitive to subsets of extreme values than are those of comparable least-squares methods. As such, their results may provide a simple description of differences in shape that are due to changes in the positions of just a few landmarks. However, resistant-fit methods lack the well-developed distributional theory associated with the least-squares fitting methods. See Slice, this volume.

resolution — The smallest scale distinguishable by a digitizing, imaging, or display device.


ridge curve — Ridge curves are curves on a surface along which the curvature perpendicular to the curve is a local maximum. For instance, on a skull the line of the jaw or the rim of an orbit are ridge curves. See Dean, this volume.

rigid rotation — An orthogonal transformation of a real vector space with respect to the Euclidean distance metric. Such transformations leave distances between points and angles between vectors unchanged. A principal components analysis represents a rigid rotation to new orthogonal axes. A canonical variates analysis does not.

score — A linear combination of an observed set of measured variables. The coefficients for the linear combination are usually determined by some matrix computation. Multivariate statistical findings in the form of coefficient vectors can usually be more easily interpreted
if scores are also shown case by case—in the form of scatters of scores, their loadings (correlations of the scores with the original variables), and so on.

shape — The geometric properties of a configuration of points that are invariant to changes in translation, rotation, and scale. In morphometrics, we represent the shape of an object by a point in a space of shape variables, which are measurements of a geometric object that are unchanged under similarity transformations. For data that are configurations of landmarks, there is also a representation of shapes per se, without any nuisance parameters (position, rotation, scale), as single points in a space, Kendall’s shape space, with a geometry given by Procrustes distance. Other sorts of shapes (e.g., those of outlines, surfaces, or functions) correspond to quite different statistical spaces.

shape coordinates — In the past, any system of distance ratios and perpendicular projections permitting the exact reconstruction of a system of landmarks by a rigid trusswork. Now, more generally, coordinates with respect to any basis for the tangent space to Kendall’s shape space in the vicinity of a mean form. See Procrustes residuals, partial warp scores, and two-point shape coordinates.

shape space — A space in which the shape of a figure is represented by a single point. It is of $2p-4$ dimensions for two-dimensional coordinate data and $3p-7$ dimensions for three-dimensional coordinate data. See Kendall’s shape space.

shape variable — Any measure of the geometry of a biological form, or the image of a form, that does not change under similarity transformations: translations, rotations, and changes of geometric scale (enlargements or reductions). Useful shape variables include angles, ratios of distances, and any of the sets of shape coordinates that arise in geometric morphometrics.

shear — In a general sense, an affine transformation. For example (see Bookstein’s “Uniform” chapter, this volume), a transformation that leaves one Cartesian coordinate, $y$, invariant and alters $x$ by a translation that is a multiple of $y$: for instance, what happens when you slide the top of a square sideways without altering its vertical position or the length of the horizontal edges. The score for such a translation, together with a separate score for dilation of the vertical axis, supplies one orthonormal basis for the subspace of uniform shape changes of two-dimensional data.

similarity transformation — A change in a Cartesian coordinate system that leaves all ratios of distances unchanged. The term proper or special similarity group of similarities is sometimes used when the transformations do not involve reflection. Similarities are arbitrary combinations of translations, rotations, and changes of scale. Compare affine transformation.

singular value decomposition — Any $m \times n$ matrix $X$ may be decomposed into three matrices, $U$, $D$, and $V$ (with dimensions $m \times m$, $m \times n$, and $n \times n$, respectively), in the form: $X = UDV^t$, where the columns of $U$ are orthogonal, $D$ is a diagonal matrix of singular values, and the columns of $V$ are orthogonal. The singular value decomposition of a variance–covariance matrix $S$ is written as $S = EAE^t$, where $A$ is the diagonal matrix of eigenvalues and $E$ the matrix of eigenvectors.

size measure — In general, some measure of a form (i.e., an invariant under the group of isometries) that scales as a positive power of the geometric scale of the form. Interlandmark lengths are size measures of dimension one, areas are size measures of dimension two, and so on.
space — In statistics, a collection of objects or measurements of objects treated as if they were points in a plane, a volume, on the surface of a sphere, or on any higher-dimensional generalization of these intuitive structures. Examples are Euclidean spaces, sample spaces, shape spaces, and linear vector spaces.

superimposition — The transformation of one or more figures to achieve some geometric relationship to another figure. The transformations are usually affine transformations or similarities. They can be computed by matching two or three landmarks, by least-squares optimization of squared residuals at all landmarks, or in other ways. Sometimes informally referred to as a “fit” or “fitting,” e.g., a resistant fit.

SVD — See singular value decomposition.

\( T^2 \) statistic — A multivariate generalization of the univariate \( t^2 \) statistic. It is the square of the ratio of the group mean difference to the standard error of that difference. Used in the \( T^2 \)-test.

\( T^2 \)-test — A test developed by Hotelling for comparing an observed mean vector with a parametric mean or comparing the difference between two mean vectors to a parametric difference (usually the zero vector). If the observations are independently multivariate normal, then the \( T^2 \)-test may be used to test null hypotheses using the \( F \)-distribution. The \( T^2 \) statistic is also closely related to Mahalanobis \( D^2 \). See Marcus (Black Book).

tangent space — Informally, if \( S \) is a curving space and \( P \) a point in it, the tangent space to \( S \) at \( P \) is a linear space \( T \) having points with the same “names” as the points in \( S \) and in which the metric on \( S \) “in the vicinity of \( P \)” is very nearly the ordinary Euclidean metric on \( T \). One can visualize \( T \) as the projection of \( S \) onto a “tangent plane” “touching” at \( P \) just like a map is a projection of the surface of the earth onto flat paper.

In geometric morphometrics, the most relevant tangent space is a linear vector space that is tangent to Kendall’s shape space at a point corresponding to the shape of a reference configuration (usually taken as the mean of a sample of shapes). If variation in shape is small then Euclidean distances in the tangent space can be used to approximate Procrustes distances in Kendall’s shape space. Because the tangent space is linear, it is possible to apply conventional statistical methods to study variation in shape. See Rohlf (this volume) and Bookstein’s “Combining” chapter (this volume).

tensor — An example of a tensor in morphometrics is the representation of a uniform component of shape change as a transformation matrix. The transformation matrix assigns to each vector in a starting (or average) form a vector in a second form. A rigorous, general definition of a tensor would be beyond the scope of this glossary, but a reasonably intuitive characterization comes from Misner, Thorne, and Wheeler (1973): a tensor is a “geometric machine” that is fed one or more vectors in an arbitrary Cartesian coordinate system and that produces scalar values (ordinary decimal numbers) which are independent of that coordinate system. In morphometrics, these “numbers” will be ordinary geometric entities such as lengths, areas, or angles: anything that doesn’t change when the coordinate system changes. For the representation of a uniform component as a transformation matrix, the “scalars” of the Misner–Thorne–Wheeler metaphor are the lengths of the resulting vectors and the angles among them.

A different tensor representing the same uniform transformation is the relative metric tensor, which you probably know as the ellipse of principal axes and principal strains. This tensor produces the necessary numerical invariants (distances in the second form as a
function of coordinates on the first form) directly. Other tensors include the metric tensor of a curving surface, which expresses distance on the surface as a function of the parameters in which surface points are expressed, and the curvature tensor of the same surface, which expresses the way in which the surface “falls away” from its tangent plane at any point.

**thin-plate spline** – In continuum mechanics, a thin-plate spline models the form taken by a metal plate that is constrained at some combination of points and lines and is otherwise free to adopt the form that minimizes bending energy. (The extent of bending is taken as so small that elastic energy—stretches and shrinks in the plane of the original plate—can be neglected.) One particular version of this problem—an infinite, uniform plate constrained only by displacements at a set of discrete points—can be solved algebraically by a simple matrix inversion. In that form, the technique is a convenient general approach to the problem of surface interpolation for computer graphics and computer-aided design. In morphometrics, the same interpolation (applied once for each Cartesian coordinate) provides a unique solution to the construction of D’Arcy Thompson-type deformation grids for data in the form of two landmark configurations.

**traditional morphometrics** – Application of multivariate statistical methods to arbitrary collections of size or shape variables such as distances and angles. “Traditional morphometrics” differs from the geometric morphometrics discussed here in that even though the distances or measurements are defined to record biologically meaningful aspects of the organism, the geometrical relationships between these measurements are not taken into account. Traditional morphometrics makes no reference to Procrustes distance or any other aspect of Kendall’s shape space. See multivariate morphometrics.

**transformation** – In general, a replacement of landmark coordinates by another set purporting to pertain to the same landmarks. For example, a matrix of landmark coordinates might be transformed by multiplication by another matrix to produce a new set of coordinates that have been scaled, rotated, and translated with respect to the original data.

**two-point shape coordinates** – A convenient system of shape coordinates, originally proposed by Francis Galton and rediscovered by Bookstein, consisting (for two-dimensional data) of the coordinates of landmarks 3, 4, and so on after forms are rescaled and repositioned so that landmark 1 is fixed at (0,0) and landmark 2 is fixed at (1,0) in a Cartesian coordinate system. Also referred to as Bookstein coordinates or Bookstein’s shape coordinates.

**Type I landmark** – A mathematical point whose claimed homology from case to case is supported by the strongest evidence, such as a local pattern of juxtaposition of tissue types or a small patch of some unusual histology.

**Type II landmark** – A mathematical point whose claimed homology from case to case is supported only by geometric, not histological, evidence: for instance, the sharpest curvature of a tooth.

**Type III landmark** – A landmark having at least one deficient coordinate, for instance, either end of a longest diameter or the bottom of a concavity. Type III landmarks characterize more than one region of the form. The multivariate machinery of geometric morphometrics permits them to be treated as landmark points in some analyses, but the deficiency they embody must be kept in mind in the course of any geometric or biological interpretation.
unbiased estimator — An estimator, \( \hat{\theta} \), that has as its expected value the parametric value, \( \theta \), it is intended to estimate: \( E(\hat{\theta}) = \theta \). See consistent estimator and asymptotically unbiased estimator.

uniform shape component — That part of the difference in shape between a set of configurations that can be modeled by an affine transformation. Once a metric is supplied for shape space one can ascertain which such transformation takes a reference form closest to a particular target form. For the Procrustes metric (the geometry of Kendall’s shape space), that uniform transformation is computed by a formula based in Procrustes residuals or by another based in two-point shape coordinates (see Bookstein’s “Uniform” chapter, this volume). Together with the partial warps, the uniform component defined in this way supplies an orthonormal basis for all of shape space in the vicinity of a mean form. In this setting, the uniform shape component may also be interpreted as the projection of a shape difference (between two group means or between a mean and a particular specimen) into the plane (or hyperplane for data of dimension greater than two) through that mean form and all nearby forms related to it by affine transformations. For descriptive purposes, the uniform component is parameterized not by a vector, like the partial warps, but by a representation as a tensor, in terms of sets of shears and dilations with respect to a fixed, orthogonal set of Cartesian axes.

weight matrix, W matrix — The matrix of partial warp scores, together with the uniform component, for a sample of shapes. The weight matrix is computed as a rotation of the Procrustes residual shape coordinates; like them, partial warp scores are a set of shape coordinates for which the sum of squared differences is the squared Procrustes distance between any two specimens.

Wright factor analysis — A version of factor analysis, due to Sewall Wright, in which a path model is used to describe the relation between the measured variables and the factors of interest. It is usually exploratory, in that one fits a simple one-factor model iteratively to explain maximally the correlations among variables and then proceeds to find additional factors to fit to the residuals, and so on until the data is adequately fit. See the Orange Book for examples and discussion of the application of this approach to the analysis of size and group factors for morphometric data.

z — Notation for complex numbers in two-dimensional Procrustes formulas.

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REFERENCES

Appendix I


APPENDIX II

Morphometric Resources Available on the Internet

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INTRODUCTION

This appendix is prepared with some trepidation as the descriptions given below are guaranteed to be out of date by the time this volume is published!

Becerra (1993) provides an excellent introductory description and tutorial of list-servers (electronic discussion groups), FTP (a protocol for transferring files across the Internet), TELNET (terminal emulation to allow one to log onto another computer across the Internet), and ARCHIE (a program that allows one to search for files across the Internet). The purpose of this paper is to update some of the information given in that paper and to describe some of the newer developments—such as Gopher and World Wide Web (WWW) servers.

THE MORPHMET LISTSERVER

The MORPHMET listserver is a forum for exchange of ideas, references and queries about morphometrics. E-mail messages sent to the server (morphmet@cunyvm.cuny.edu) are automatically redistributed to all subscribers to the MORPHMET listserver. See Appendix III for instructions on how to use this facility.

FTP

File transfer protocol (FTP) programs allow you to transfer files (both text files and binary files such as computer software) to or from a remote computer located anywhere on the Internet. Becerra's (1993) detailed tutorial on the use of FTP is now largely out of date because there are now friendly FTP programs that allow you to select files by clicking on their names in a file list, setting options for text or binary, and then to transfer the files to a directory on your computer by clicking on a button. In many cases the owner of the directory provides a "readme" or index file that gives some descriptive information about the files to
Morphometrics
at SUNY Stony Brook

This server contains news and files related to the field of geometric morphometrics. Please contact F. James Rohlf with suggestions for improvements and with additional contributions to the morphmet archive.

Notices of meetings and workshops related to morphometrics

- **Morphometrics and Evolution**
  Symposium to be held at the Fifth International Congress of Systematic and Evolutionary Biology, Budapest, Hungary, August 17-24, 1996. [More info.]

- **Image Fusion and Shape Variability Techniques**

- **Geometric Morphometrics course**
  The graduate level course on geometric morphometrics is planned to be offered again at the State University of New York at Stony Brook by F. James Rohlf for the Fall 1996 semester. Participants from other institutions are welcome. [Course description.]

Please send notices of any meetings!

Morphometric listservers

- **MORPHMET**
  This a listserver managed by Les Marcus (lamqc@cunyvm.cuny.edu). If you subscribe to it you will be able to take part (or just listen in) on discussions of various issues related to morphometrics. [More information.]

- **MORPHOLOGY**
  This is a listserver managed by Henk Heijmans (henkh@cwi.nl). [FTP archive.]

Morphometrics Archive

This contains both software and data files. "Hotlinks" are provided so that one can view the readme files for many of the programs.

- **Software**
  Various software packages related to geometric morphometrics. There are programs both for the PC and the Mac (as well some Unix systems).

- **Datasets**
  A collection of several well-known datasets. Useful for checking prior analyses and for testing new methods.

- **FTP**
  FTP access to MORPHMET directory for those whose WWW software does not permit downloading.

Morphometrics publications

- **Books**
  A list of books, workshop proceedings, and similar documents concerned with geometric morphometrics.

- **Primer**
  A contribution by Richard Reyment containing a "Multivariate Statistical Primer for Geologists."
help you determine which files you need. The speed of transmission is limited by the speed of the slowest link in the network between you and the remote computer.

The principle limitation of FTP is that the interface provides the user with only a simple directory listing of file names, which may be somewhat cryptic. The new Gopher and WWW servers (described below) are designed to provide descriptive information about the files. Even with these new developments, FTP is still used because, if you know the name of the file and its location, FTP provides the fastest and most direct way to transfer a file.

Note: The address of the SUNY Stony Brook morphometrics FTP directory listed in Becerra (1993) has changed. It is now the *morph* directory at *Life.Bio.SUNYSB.edu*. Its contents have greatly expanded over the last two years.

**GOPHER SERVERS**

Gopher is a campus wide information server developed at the University of Minnesota. With the use of special software on your local computer, Gopher provides a hierarchical system of menus leading to files and documents that can be downloaded. There are also search utilities that help you locate files in “Gopher space.” Having descriptive menu entries makes Gopher much easier to use than simple FTP programs. The menus can also provide links to other Gopher directories on the same or other computers.

Even though Gopher was a development that became popular after the Becerra (1993) paper was written, its function has already been largely replaced by the World Wide Web (see below).

**THE WORLD WIDE WEB**

CERN, the European high-energy physics center, developed a new information system it called the World Wide Web (WWW). They made the WWW and “browser” software to access it, publicly available in January 1992. The WWW is based on the concept of displaying information graphically as documents with hypertext links to related documents (whether they are documents on the same computer or around the world).

The hypertext links to documents are of the following format: “http://computer/directory/file,” where “computer” is the Internet address of the computer containing the document and “directory/name” gives the name and the subdirectory containing the desired document. This is called a uniform resource locator, or URL. If the directory and file name are not given, then a default document for that site is displayed. In place of the code “http” one sometimes sees other protocol codes, such as “FTP” (which will cause a directory to be displayed or a file downloaded using the FTP protocol described above), “Gopher” (uses the Gopher protocols to display a hierarchical system of menus), “telnet” (which will try to establish a telnet session to a remote computer), “mailto” (allows one to

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**Return to Biological Sciences Home Page**

You are the 385th person to access this page since 9/30/95

Revised by F. James Rohlf, Rohlf@Life.Bio.SUNYSB.edu, October 28, 1995. e-mail comments?

Figure 1. Opening page of the SUNY at Stony Brook morphometrics WWW page as of the end of October 1995. Note: The underlined words correspond to hypertext links to other WWW documents, FTP directories or files that can be downloaded.
Morphometric software

The purpose of this directory is to make available programs useful for morphometric analysis. Contributions of additional software are welcome. Contact us with suggestions for improvements and with additional contributions to the morphmet archive.

WWW viewers such as Netscape or Mosaic can download these files. Most of the programs in the archive are for PC compatible computers as indicated by the ".ibmpc" suffix on the names of the files. FTP software for the PC will automatically remove this suffix leaving a valid DOS name. In Mosaic set the "Load to disk" option and then click on the file name shown in "[ ]". Netscape will pop-up a window asking you if you want to save a file to disk.

There are also links to directories on other servers (such as the edgewarp directory on Bookstein's server. These names are shown without the "[ ]" characters. If you select one of these links a directory will be displayed from which you can select files to transfer via FTP. No dates are furnished with these entries since they can be updated independently.

Dates indicate the date of the last upload of the file to this server. For many of the programs there is a link to the readme file which may be selected to get additional information about the software.

Software

Click on the categories below to obtain lists of available software.

- Software based on thin-plate splines
- Superimposition methods
- Analysis of outlines
- Support routines
- Misc. collections of programs

Notes:

- The files with types of "exe.ibmpc" are self-extracting archive files for the IBM PC. Download them in binary and give them an extension of "EXE" on a PC.
- The files with a type of "zip ibmpc" are IBM PC ZIP files that require the PKUNZIP program to unpack. They are also binary files.
- DPMI = DOS protected mode interface that allows programs to use all of memory and not have the normal 640K limitation. Requires computer using 80386 or better CPU. Not compatible with all clone computers.

Modified: October 25, 1995 by F. James Rohlf. Please send comments, suggestions, and contributions by e-mail.

Figure 2. Listing of the software page from the SUNY at Stony Brook morphometrics WWW Server.

send e-mail to a specified account without having to leave the browser), "news" (allows one to read recent news from an Internet newsgroup) and "WAIS" (allows one to search a WAIS database), as well as variations on the above formats. Most browsers display these URLs somewhere on the screen when you pass the mouse cursor over a hypertext field in a document.

World Wide Web has proven to be a very flexible format for many types of information. The WWW grew even faster after the end of 1993 when the U. S. National Center for Supercomputing Applications (NCSA) released the first browsing software (Mosaic) for the Apple Macintosh, for computers using Microsoft Windows, and for Unix computers supporting
Appendix II

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X–Windows. There are now many choices of software for browsing the WWW (Netscape is currently popular, but there are many competitors). Some of these browsers support extensions that allow WWW documents to contain tables, pictures, forms, access to databases, animations, sound and interactions with other software running on the host computer. There is also a text-only browser called Lynx (developed at the University of Kansas). Lynx can be used from text-mode terminals, and it is usually quite fast because it does not have to download images in order to display the information on a WWW page. Many individuals and organizations are putting considerable effort into making information available via the WWW. (I hope comparable effort is spent keeping the information up to date.)

SUNY at Stony Brook Morphometrics WWW Pages

An extensive set of WWW pages is available from the URL address http://life.bio.sunysb.edu/morph/morph.html. The opening page is

Software based on thin-plate splines

- **[TPS]: Thin-plate spline (Windows)**  
  Program to compare pairs of specimens by displaying a D'arcy Thompson style transformation grid based on a thin-plate spline. The program has a limit of 50 landmarks. By F. James Rohlf. Version 1.02 2/19/96. This program replaces the **[TPSPLINE]** program (a DOS program with a limit of 40 landmarks and required the **[BG1]** Graphics drivers) and its DPMI version **[TPSPLINEP]** (with a limit of 60 landmarks). Readme. By F. James Rohlf.

- **[TPSREGR]: Regression of partial warp scores (DOS)**  
  Performs a regression of partial warp scores onto an independent variable. Can be used to study allometry. 12/2/94. **[TPSREGRP]** DPMI version of TPSREGR which can be used to process larger datasets. Requires the Graphics drivers. By F. James Rohlf. Readme

- **[TPSRW]: Relative warps (DOS)**  
  Performs a relative warp analysis. This corresponds to a principal components analysis of variation in a sample (relative to bending energy if the alpha parameter is not equal to zero). Requires the **[BG1]** Graphics drivers. 10/17/94. **[TPSRWP]** DPMI version of the TPSRW program which can process larger datasets. 10/17/94. Readme. By F. James Rohlf.

- **Edgewarp: Thin-plane splines with edgels (HP, HP901, Solaris, Sun, Stellar, Ultrix)**  
  This entry points to a FTP directory containing software and documentation for the edgewarp program. Readme. By Bill Green and Fred L. Bookstein.

- **JSPLINE & VECTOR: Thin-plate spline programs (DOS & Windows)**  
  This entry points to a FTP directory containing the file SPLINE.ZIP that contains the programs JSPLINE and VECTOR. These compute thin-plate splines, principal and partial warps, etc., to compare two specimens. The VECTOR program displays principal and partial warps as vector diagrams. 1/20/94. By Julian M. Humphries.

Revised: February 19, 1996 by F. James Rohlf. Please send comments, suggestions, and contributions by e-mail.

Figure 3. Listing of the thin-plate spline software page from the SUNY Stony Brook morphometrics WWW server. Selecting the underlined “Readme” fields brings up WWW pages that give additional information about a program. The fields corresponding to the underlined names of programs are used to download the binary files containing the software or to transfer to another directory in which where one can use FTP to transfer the files.
shown in Fig. 1. The underlined words correspond to links to other WWW documents, FTP directories or files that can be downloaded. If you click on them, your WWW browser will take an appropriate action (display a WWW page, display a directory or popup a window that allows you to download a file). For example, clicking on the word "software" under the Morphometrics Archive heading leads to the display shown in Fig. 2 which lists various categories of software. Figure 3 shows the current list of available software that is based on the use of thin-plate splines. If you click on "[TPSPLINE]", a browser such as Netscape will popup a window to allow you to save the file to disk (you will be presented with another window in which you can enter a file name and select the drive and directory where the file is to be saved on your local computer). The name of this particular file is tpsz.exe.ibmpc. For use on a PC it should be saved as tpsz.exe. After you click the "OK" button the file will be transferred to your computer.

As explained in Fig. 2, most of the entries correspond to files that have been grouped together (e.g., the program itself plus sample data files and documentation) and then compressed to save both space and the time it takes to download the file. As a convenience to the user, most files have been archived as self-extracting files. To retrieve the original files one executes the file as if it were a program, and the files will be extracted and expanded into their original form.

The entry in Fig. 3 for the edgewarp software is an example of a FTP link to another computer (in this case to the directory /pub/edgewarp on the computer brainmap.med.umich.edu. Figure 4 shows the contents of this directory using the text-only browser Lynx.

A limitation of the WWW is that there is currently no way for a user to know when the WWW pages have been updated. Dates of last revision are shown at the end of all the WWW pages and a "NEW!" graphic is inserted next to each new item, but users still must access the pages from time to time. For this reason, notices are usually sent to the MORPHMET listserver whenever new or updated programs are added or when other significant changes are made.

<table>
<thead>
<tr>
<th>edgewarp directory</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Up to pub</strong></td>
</tr>
<tr>
<td>Sep 8 02:04 text/plain arg.l 1Kb</td>
</tr>
<tr>
<td>Sep 8 02:04 text/plain COPYRIGHT 1Kb</td>
</tr>
<tr>
<td>Sep 8 02:04 text/plain data.l 3Kb</td>
</tr>
<tr>
<td>Sep 8 02:04 Tar File demo.oct94.tar 888Kb</td>
</tr>
<tr>
<td>Sep 8 02:04 text/plain display.l 6Kb</td>
</tr>
<tr>
<td>Sep 8 02:04 text/plain edgewarp.l 5Kb</td>
</tr>
<tr>
<td>Sep 8 02:04 text/plain edgewarp@aiix 576Kb</td>
</tr>
<tr>
<td>Sep 8 02:04 text/plain edgewarp@hp 616Kb</td>
</tr>
<tr>
<td>Sep 8 02:04 text/plain edgewarp@hp901 344Kb</td>
</tr>
<tr>
<td>Sep 8 02:04 text/plain edgewarp@sun 904Kb</td>
</tr>
<tr>
<td>Sep 8 02:04 text/plain edgewarp@ultrix 713Kb</td>
</tr>
<tr>
<td>Sep 8 02:04 text/plain MANUAL 46Kb</td>
</tr>
<tr>
<td>Sep 8 02:04 text/plain README.EDGEWARP 2Kb</td>
</tr>
<tr>
<td>Sep 8 02:04 text/plain SOURCE 4Kb</td>
</tr>
<tr>
<td>Sep 8 02:04 text/plain xhand.l 2Kb</td>
</tr>
</tbody>
</table>

Commands: Use arrow keys to move, '?' for help, 'q' to quit, '<-' to go back

Figure 4. Listing of the pub/edgewarp directory at brainmap.med.umich.edu using the Lynx WWW browser. Versions of the edgewarp software are available for several types of computers that use the Unix operating system.
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REFERENCE

APPENDIX III

Morphmet: The On-Line Bulletin Board on Morphometrics

Leslie F. Marcus

The on-line LISTSERV list MORPHMET provides a forum for exchange of ideas, references and queries about morphometrics, the study of form—shape and size—in organisms. Appropriate contributions are queries and statements about morphometric methods and philosophy; new references or queries about the literature; announcements for relevant meetings and relevant job announcements or needs. Because the list is not monitored, it is up to the users to define the content and frequency of use.

In order to subscribe, send a one-line message to the list without a subject or signature. Send the request to LISTSERV@CUNYVM.CUNY.EDU and include the following single line in the body of the message (leave the subject line blank because LISTSERV will send you an error message and ignore what you say if you write anything at all there):

• subscribe morphmet [your name]

For example, I would subscribe by saying

• subscribe morphmet Leslie F. Marcus

The system is smart enough to know your user ID and node from the received message. Please DO NOT send the request to morphmet@cunyvm.cuny.edu!

When you first sign up, LISTSERV will send you further instructions about signing off, getting an index for the archives (all contributions are archived monthly), retrieving archived monthly files and obtaining further information about LISTSERV lists. The earliest archive is LOG9103 and contains all mail for March of 1991.

In order to retrieve the index of MORPHMET archived files send to LISTSERV@CUNYVM.CUNY.EDU the single line message:

• INDEX MORPHMET

You will receive only a list of monthly log files, and you will have to search a number of them to find out what was said during that period. It is easier and faster than it sounds.

Note that when you answer a query or want to enter a discussion on MORPHMET and you use REPLY on your local mail software, the answer will go back only to the PERSON initiating the mail. If you want to send something to everybody on the MORPHMET list then address it to:
• MORPHMET@CUNYVM.CUNY.EDU

You need not be a member of the list to send a query or comment. All further queries to:

Leslie F. Marcus

Snail Mail to:

Department of Invertebrates
American Museum of Natural History
CPW at 79th
New York, NY 10024, USA

Telephone: 212-769-5721 (answering service after 4 rings)
FAX: 212-769-5842
E-mail: LAMQC@CUNYVM.CUNY.EDU or MARCUS@AMNH.ORG

SOME OTHER COMMANDS OF POSSIBLE INTEREST TO SEND TO LISTSERV AT CUNYVM

All of these are single-line commands to LISTSERV@CUNYVM.CUNY.EDU in the body of the message—no signature or subject. I have indicated what they do with an asterisk (*) after the command—don’t type this part of the line. The commands are not case sensitive.

help
index morphmet *
signoff morphmet *
subscribe morphmet *
get log9404 morphmet *
review morphmet *

sends you a short list of commands
already mentioned above
takes you off the list
puts you on morphmet
gets the April 1994 archive that contains discussion of phylogenetics; this was conveniently broken into three files by my mail system—remember everything from that month is archived in this file, so the file will contain all entries for that month, which includes other information than the phylogenetic discussion
gets a list of the user ids and nodes of all of the persons currently on the list

You may send more than one command in an e-mail message.
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