Geometric Morphometrics and Archaeology

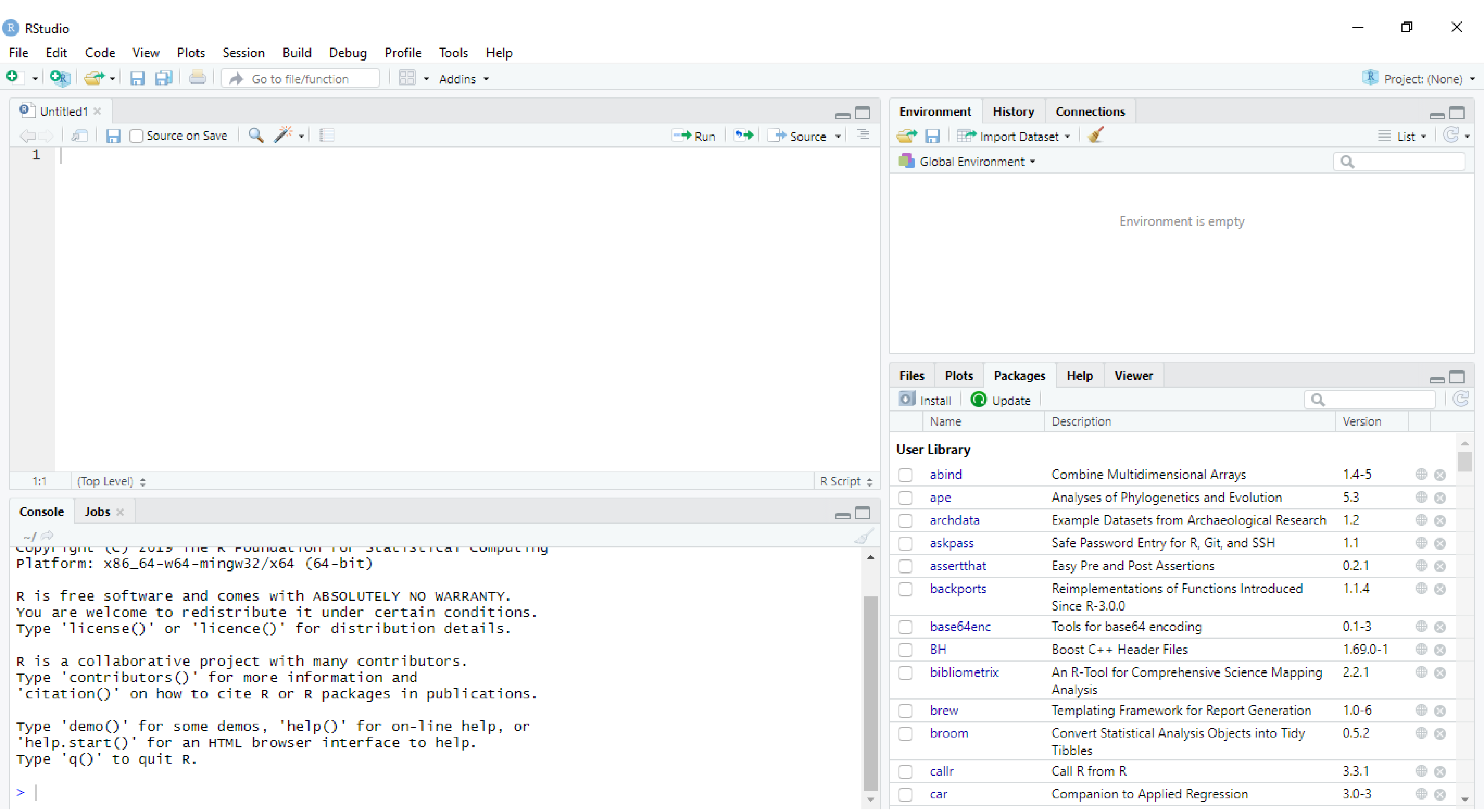
Dr. Christian Hoggard

CSHoggard

MORPH 2019
A conference on the Archaeological Applications of Morphometrics
13–15 September | Sendai, Japan

いらっしゃいませ! (Welcome!)

1. Get connected to the Wi-Fi
2. Get the workshop materials
   https://github.com/CSHoggard/-Morph2019
3. Ensure R/Rstudio and packages are on your laptop
   Follow instructions in **setup.R**
4. Stuck? Please ask for help!


RStudio
File Edit Code View Plots Session Build Debug Profile Tools Help
Go to file/function
Addins
Project: (None)
Untitled1
Source on Save
Run
Source
1
1:1
(Top Level)
R Script
Console
Jobs
~/
Platform: x86_64-w64-mingw32/x64 (64-bit)
R is free software and comes with ABSOLUTELY NO WARRANTY.
You are welcome to redistribute it under certain conditions.
Type 'license()' or 'licence()' for distribution details.
R is a collaborative project with many contributors.
Type 'contributors()' for more information and
'citation()' on how to cite R or R packages in publications.
Type 'demo()' for some demos, 'help()' for on-line help, or
'help.start()' for an HTML browser interface to help.
Type 'q()' to quit R.
>
Environment
History
Connections
Import Dataset
List
Global Environment
Environment is empty
Files
Plots
Packages
Help
Viewer
Install
Update
Name
Description
Version
User Library
abind
Combine Multidimensional Arrays
1.4-5
ape
Analyses of Phylogenetics and Evolution
5.3
archdata
Example Datasets from Archaeological Research
1.2
askpass
Safe Password Entry for R, Git, and SSH
1.1
assertthat
Easy Pre and Post Assertions
0.2.1
backports
Reimplementations of Functions Introduced Since R-3.0.0
1.1.4
base64enc
Tools for base64 encoding
0.1-3
BH
Boost C++ Header Files
1.69.0-1
bibliometrix
An R-Tool for Comprehensive Science Mapping Analysis
2.2.1
brew
Templating Framework for Report Generation
1.0-6
broom
Convert Statistical Analysis Objects into Tidy Tibbles
0.5.2
callr
Call R from R
3.3.1
car
Companion to Applied Regression
3.0-3

Dr. Christian S. Hoggard

Position: Visiting Fellow (University of Southampton)
Previous: Postdoctoral Researcher (Aarhus University)

Interests: R Stats / GMM (2D) / Palaeolithic / Cultural Taxonomies

Recent publications

Vestergaard, C. and Hoggard, C.S. (2019). A Novel Geometric Morphometric (GMM) Application to the Study of Bronze Age Tutuli. Danish Journal of Archaeology.

Riede, F., Hoggard, C.S. and Shennan, S. (2019). Reconciling material cultures in archaeology with genetic data requires robust cultural evolutionary taxonomies. Nature: Palgrave Communications..

Hoggard, C.S., McNabb, J. and Cole, J.N. (2019). The application of elliptic Fourier analysis in understanding biface shape and symmetry through the British Acheulean. Journal of Paleolithic Archaeology.

Hoggard, C.S. and Stade, C.M. (2018). The efficiency Of Middle Palaeolithic technological blade strategies: an experimental investigation. Lithics: the journal of the Lithic Studies Society.

Format for today…

- An introduction to GMM (c. 45 minutes)
- **Practical #1**: Landmark analysis (c. 60 minutes)
- Outline analysis (c. 45 minutes)
- **Practical #2**: Elliptic Fourier Analysis (EFA) (c. 60 minutes)
- Session wrap-up (c. 15 minutes)

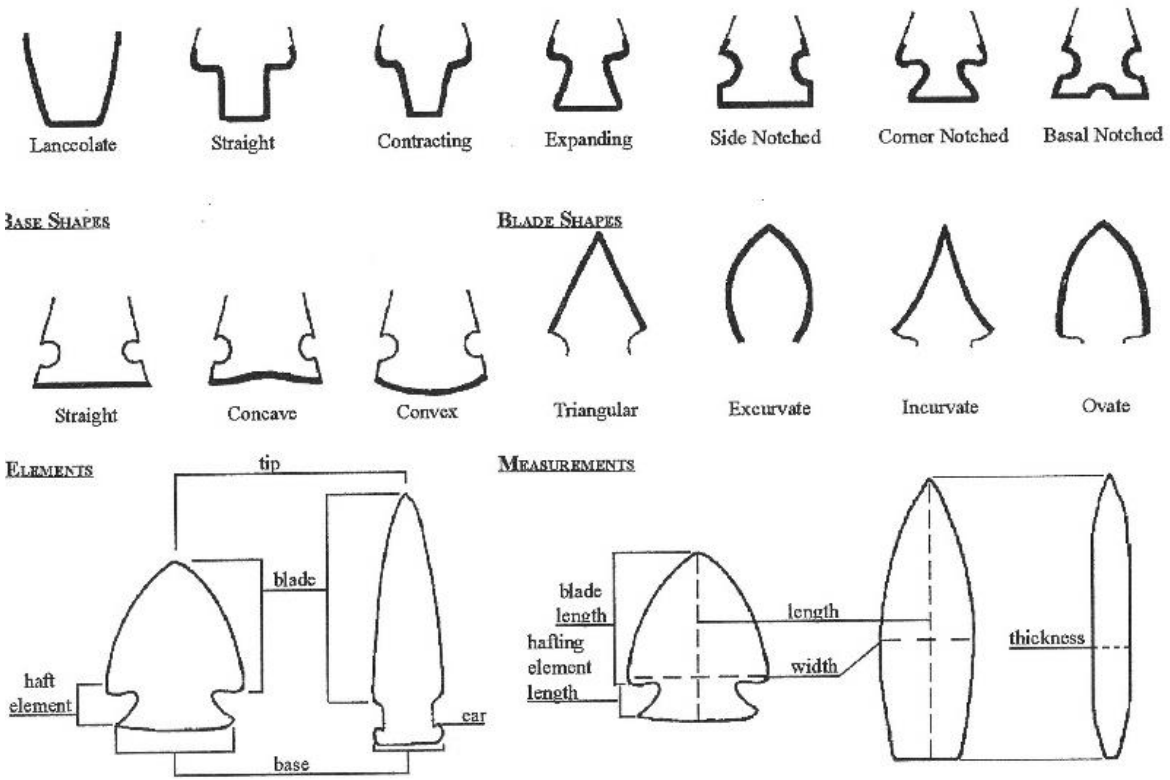
“Art of the possible”

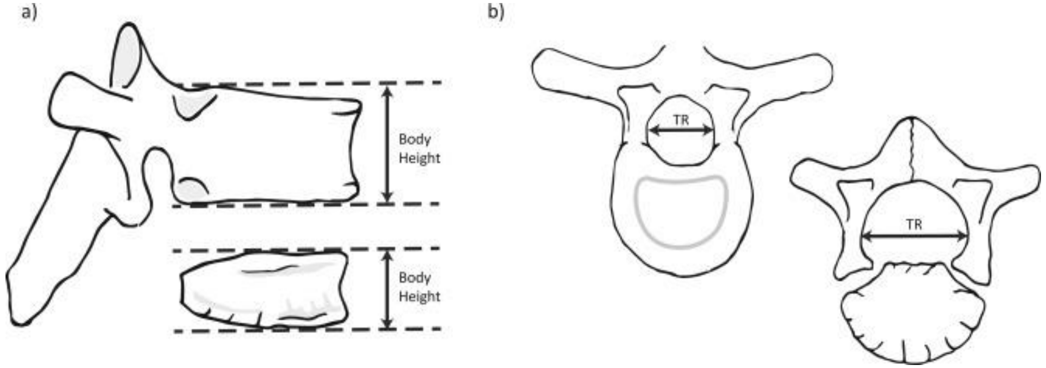
Morphometrics and Geometric Morphometrics…

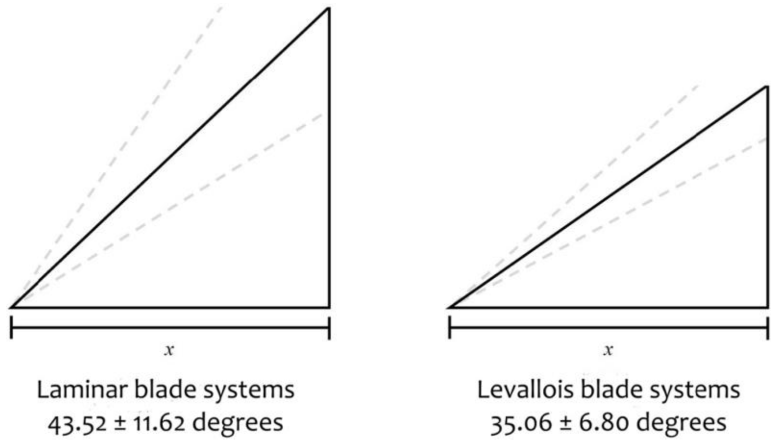
Morphometrics 101

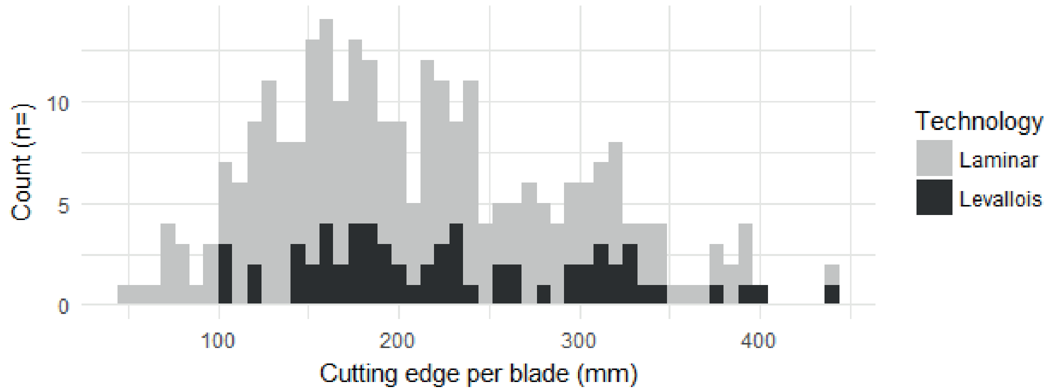
- First coined by Professor of Zoology (UCD) Robert Blackith in 1957
- **Quantitative study of shape, shape variation and shape covariation**
- Two types of morphometric studies:
  - **Traditional morphometrics** (e.g. length measurements, angles, ratios…)
  - **Geometric morphometrics** (e.g. landmarks, outlines and curves, surfaces…)
- Note: Geometric Morphometrics $\ngtr$ Traditional Morphometrics

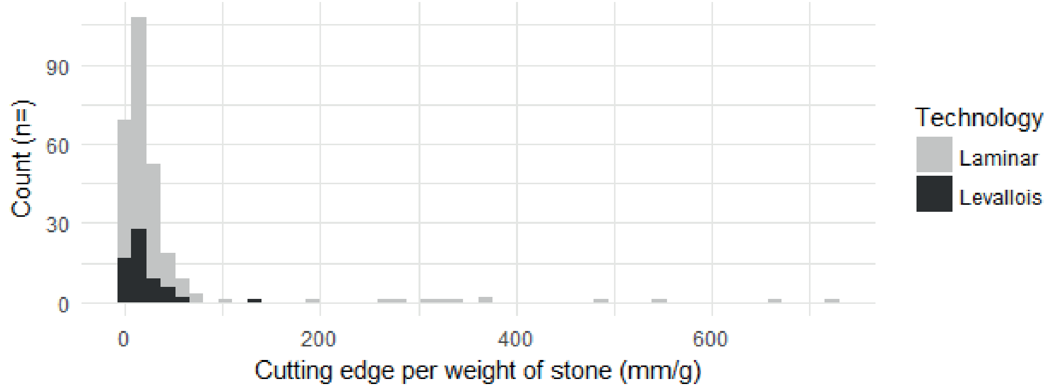
Blackith, E.R. (1957). Polymorphism in Some Australian Locusts and Grasshoppers. Biometrics., 13.: 183.

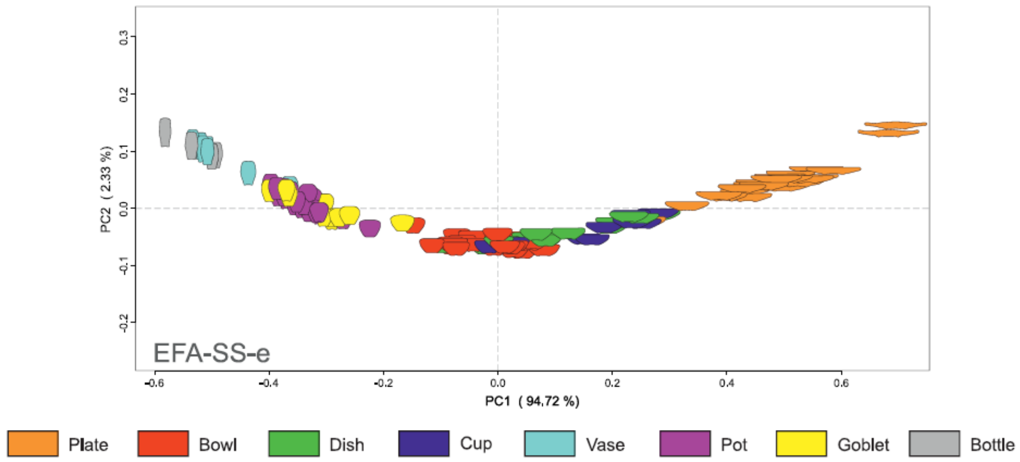

Lanceolate
Straight
Contracting
Expanding
Side Notched
Corner Notched
Basal Notched
Base Shapes
Blade Shapes
Straight
Concave
Convex
Triangular
Excurvate
Incurvate
Ovate
Elements
tip
blade
haft element
ear
base
Measurements
blade length
hafting element length
length
width
thickness

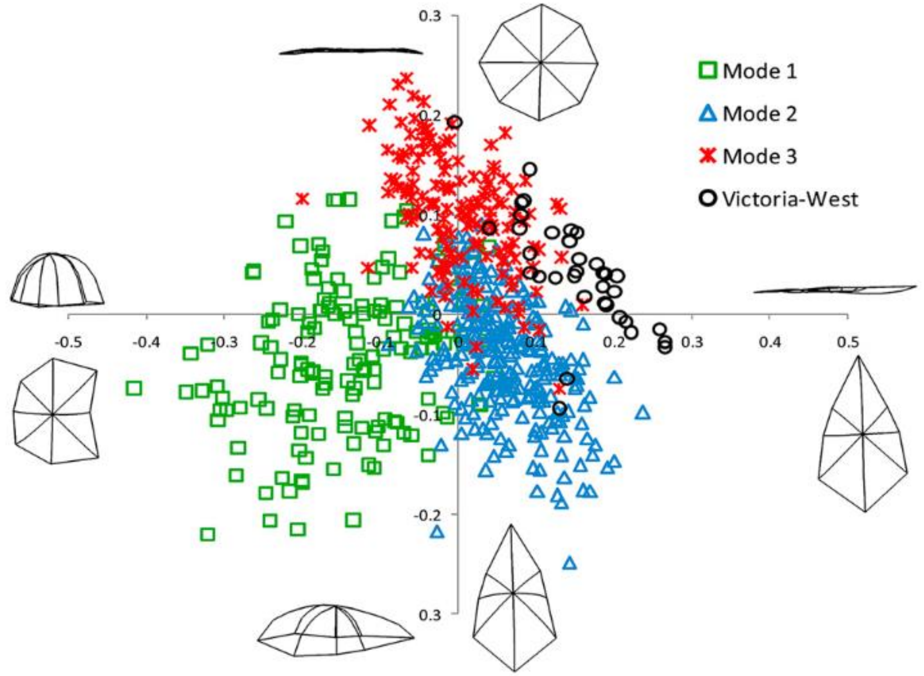

a)
b)
Body Height
Body Height
TR
TR

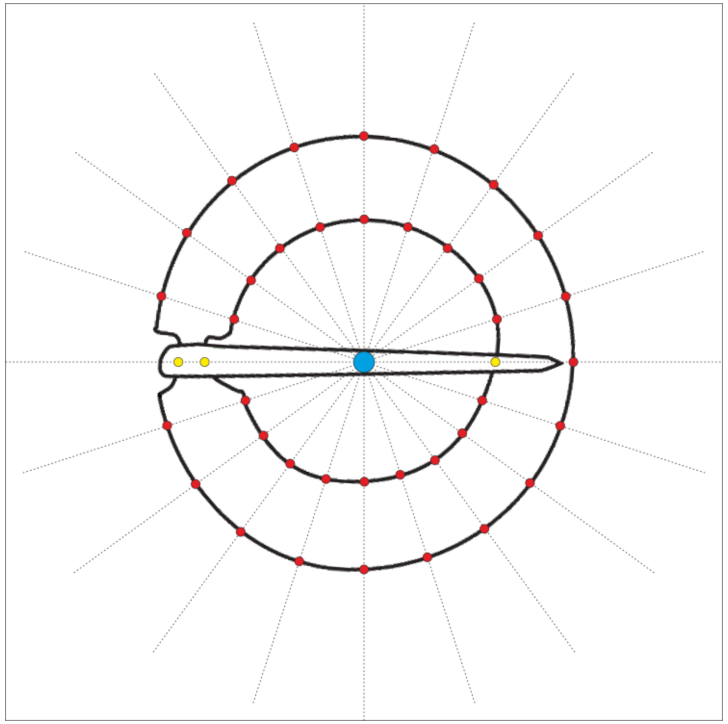

x
x
Laminar blade systems
43.52 ± 11.62 degrees
Levallois blade systems
35.06 ± 6.80 degrees

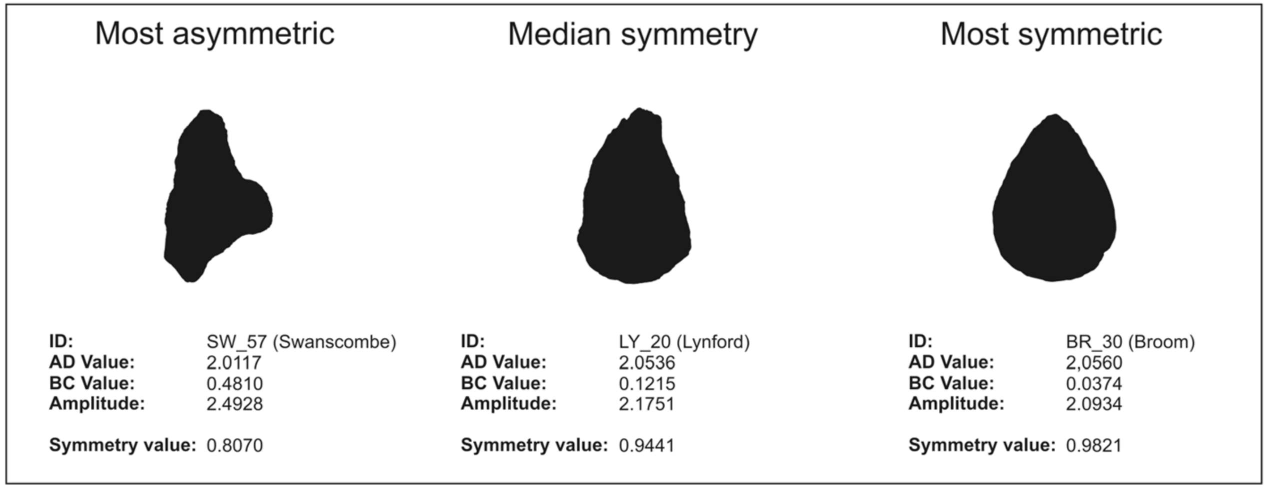

Count (n=)
0
5
10
100
200
300
400
Cutting edge per blade (mm)
Technology
Laminar
Levallois


Count (n=)
0
30
60
90
0
200
400
600
Cutting edge per weight of stone (mm/g)
Technology
Laminar
Levallois


EFA-SS-e
PC1 (94.72 %)
PC2 (2.33 %)
Plate
Bowl
Dish
Cup
Vase
Pot
Goblet
Bottle


Mode 1
Mode 2
Mode 3
Victoria-West




Most asymmetric
Median symmetry
Most symmetric
ID: SW_57 (Swanscombe)
AD Value: 2.0117
BC Value: 0.4810
Amplitude: 2.4928
Symmetry value: 0.8070
ID: LY_20 (Lynford)
AD Value: 2.0536
BC Value: 0.1215
Amplitude: 2.1751
Symmetry value: 0.9441
ID: BR_30 (Broom)
AD Value: 2,0560
BC Value: 0.0374
Amplitude: 2.0934
Symmetry value: 0.9821

What do we mean by shape and size

Shape

“In general terms, the shape of an object, dataset or image that can be defined as the **total of all information is invariant under translation, rotation, and isotropic rescalings**”

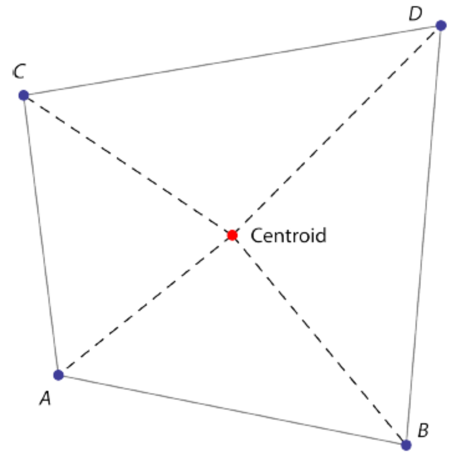
Small, C. (1996). The statistical theory of shape. New York: Springer.

Size

Vague term: what to use? Length? Circumference?

Preferred term...

Centroid size: square root of the summed squared lengths of the dashed lines



Mitteroecker, P., Gunz, P., Windhager, S., Schaefer, K. (2013). A brief review of shape, form, and allometry in geometric morphometrics, with applications to human facial morphology. Hysterix, the Italian Journal of Mammalogy. pp. 59-66.

Aim of Geometric Morphometrics

1. Determine whether two assemblages are different in terms of their shape?
2. Determine how are these related to size? time? raw material? hominin?
3. Determine whether differences correspond to a hypothesis or a model?
4. Determine on an assemblage level: what is the mean shape?
5. Determine, with respect to size: is there an allometric relationship?

Advantages

Powerful method of documenting shape change

Less information is lost in comparison to lineal measurements

Can easily be collected from a variety of methods (e.g. photographs)

Abstraction and registration method permits an analysis of exclusively shape

Disadvantages

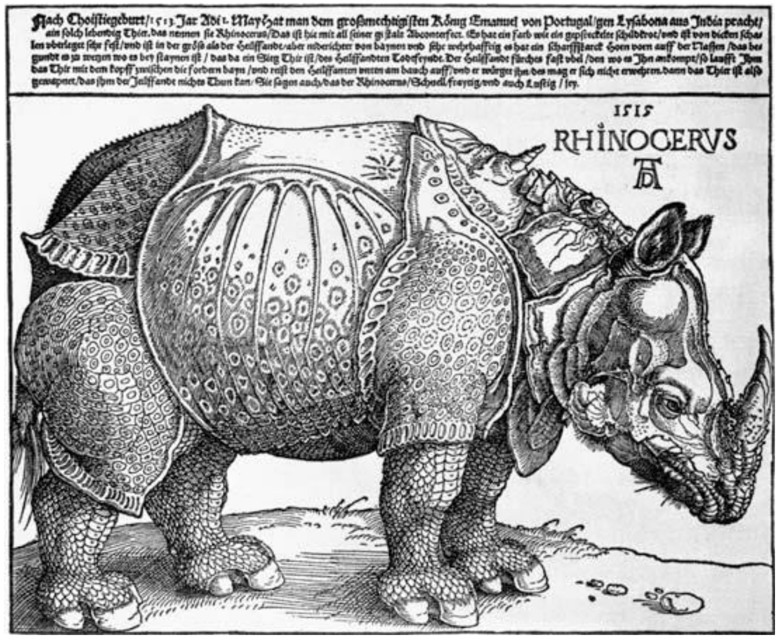
Size is often removed which may be of biological importance (can be reintegrated)

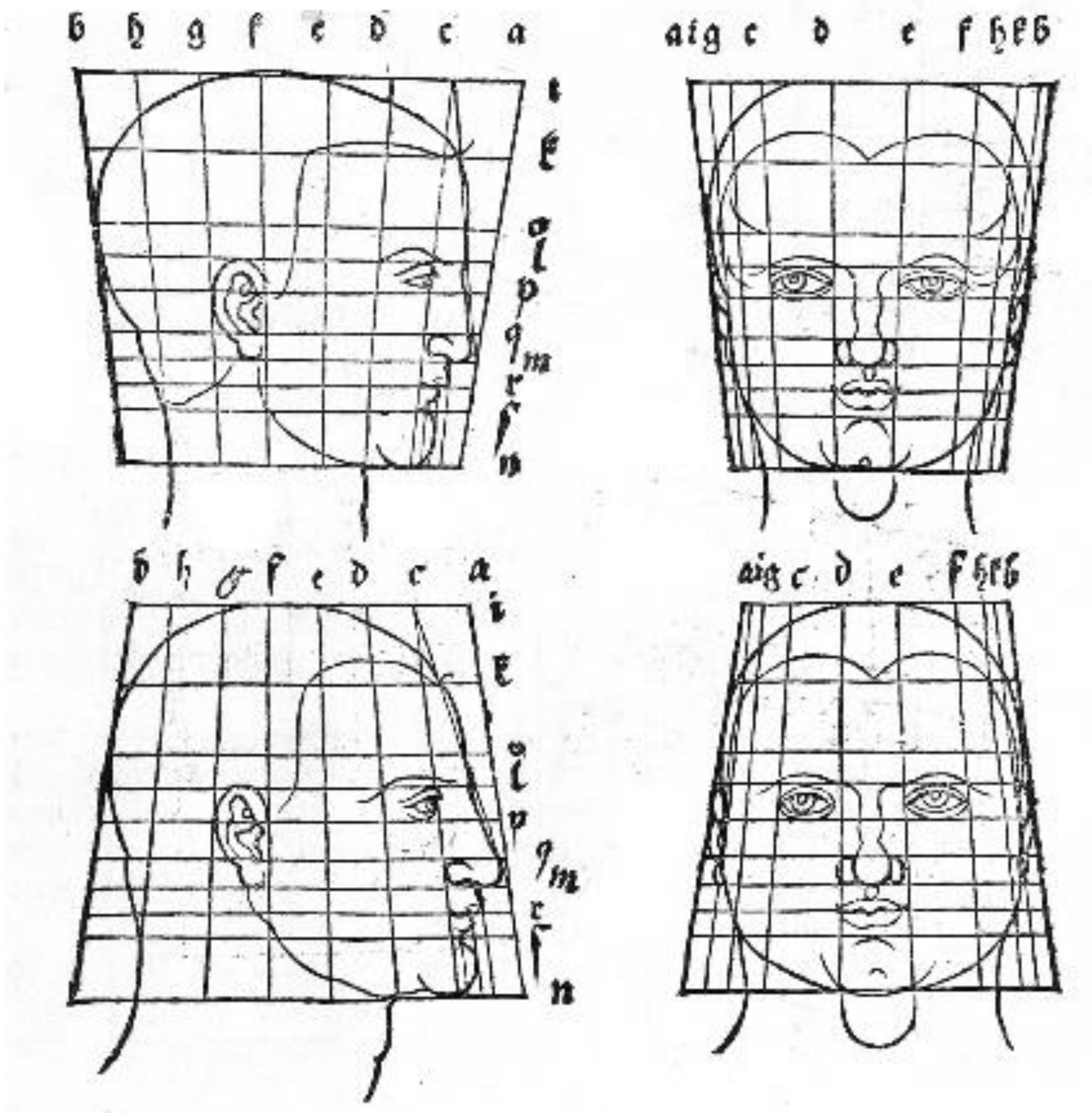
Skill competency: often requires specialised software and knowledge

A short history of geometric morphometrics…

Albrecht Dürer (1471-1528)

- Painter, printmaker and theorist
- Founder of descriptive geometry working on helices, conchoids and epicycloids
- Investigated the Delian Problem (doubling the cube)
- Used shape transformations of the human head in his studies on human proportions (providing the basis of determining shape change)





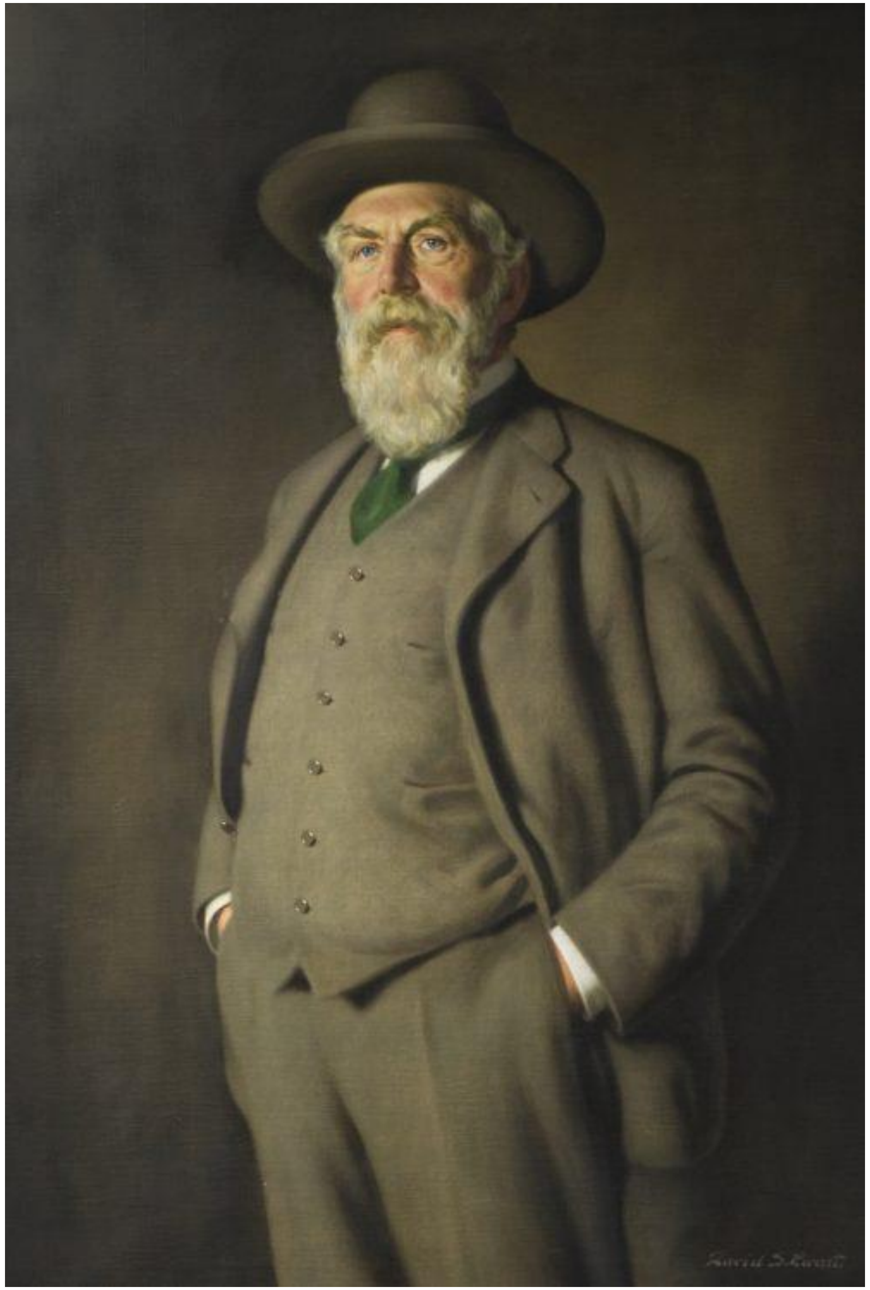
Dü rer, A. (1528). De Symetria Partium in Rectis Formis Humanorum Corporum Libri, German edn. Patav. Nuremberg: Parisiis Curvi ac recti proportio.

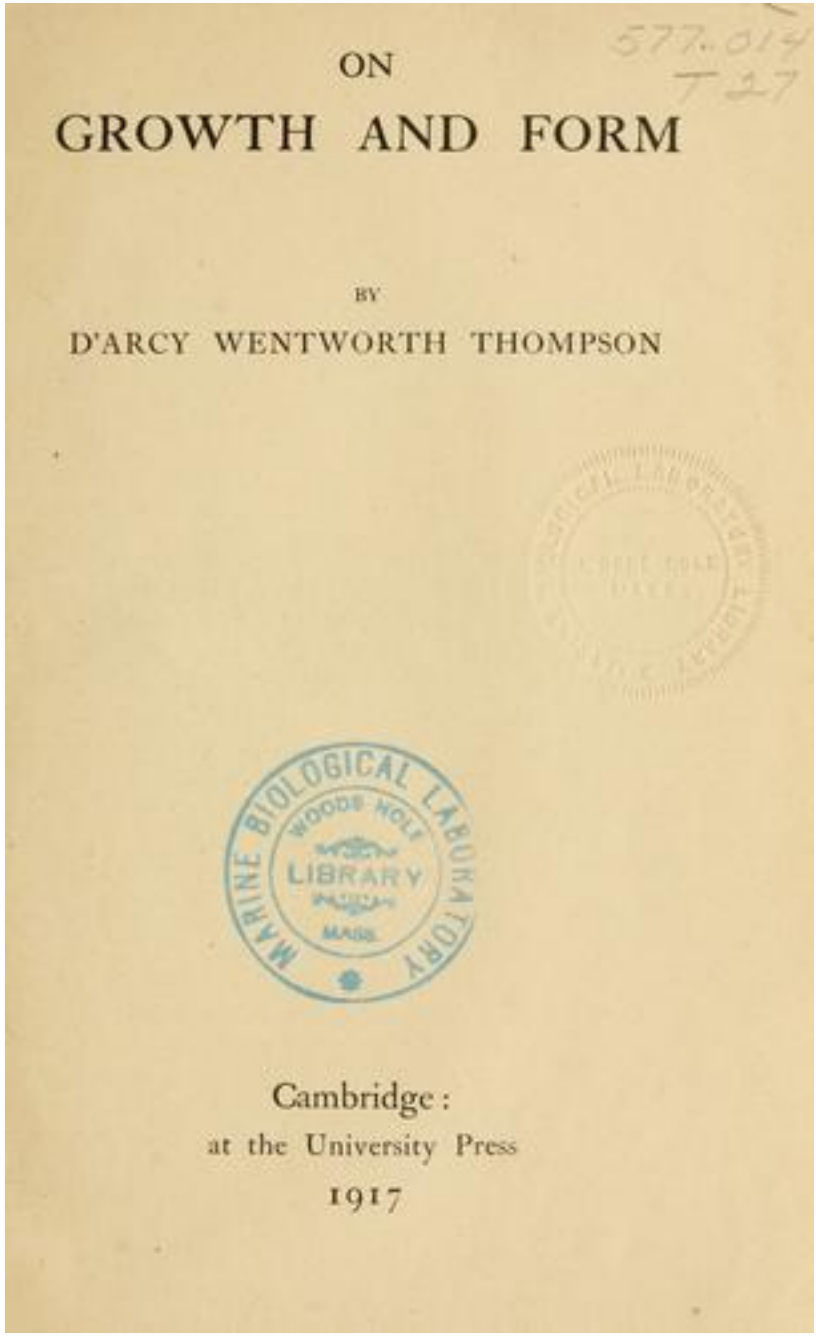
Sir D’Arcy Wentworth Thompson (1860-1948)

- Biologist, mathematician and classics scholar
- Famous for his quotes on the mathematical beauty of nature (inspired Huxley, Turing, Lévi-Straussand van der Rohe)

On Growth and Form (1917)

- Fundamental book documenting the process of body structures formed in plants and animals
- Emphasis on mathematical structures accounting for biological diversity





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ON

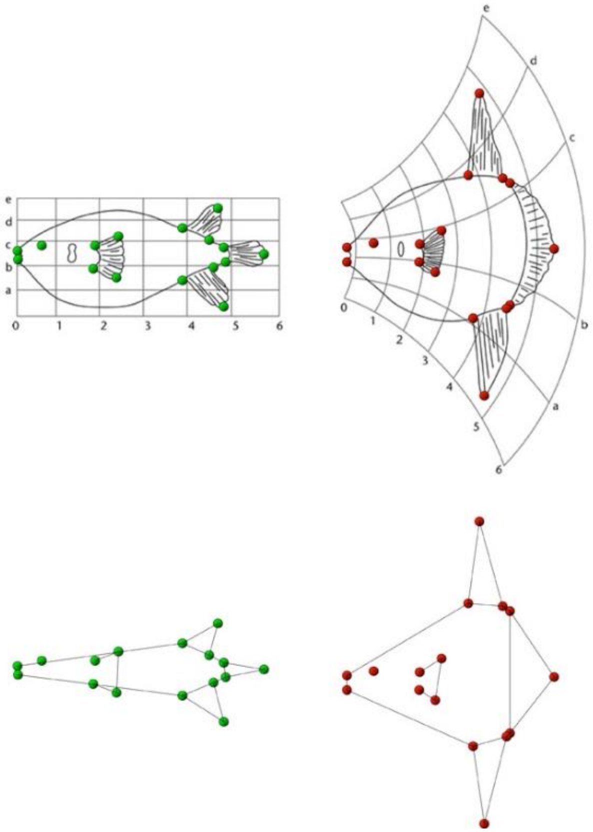
GROWTH AND FORM

BY

D'ARCY WENTWORTH THOMPSON

MARINE BIOLOGICAL LABORATORY
WOODS HOLE
LIBRARY
MASS.

Cambridge:
at the University Press
1917



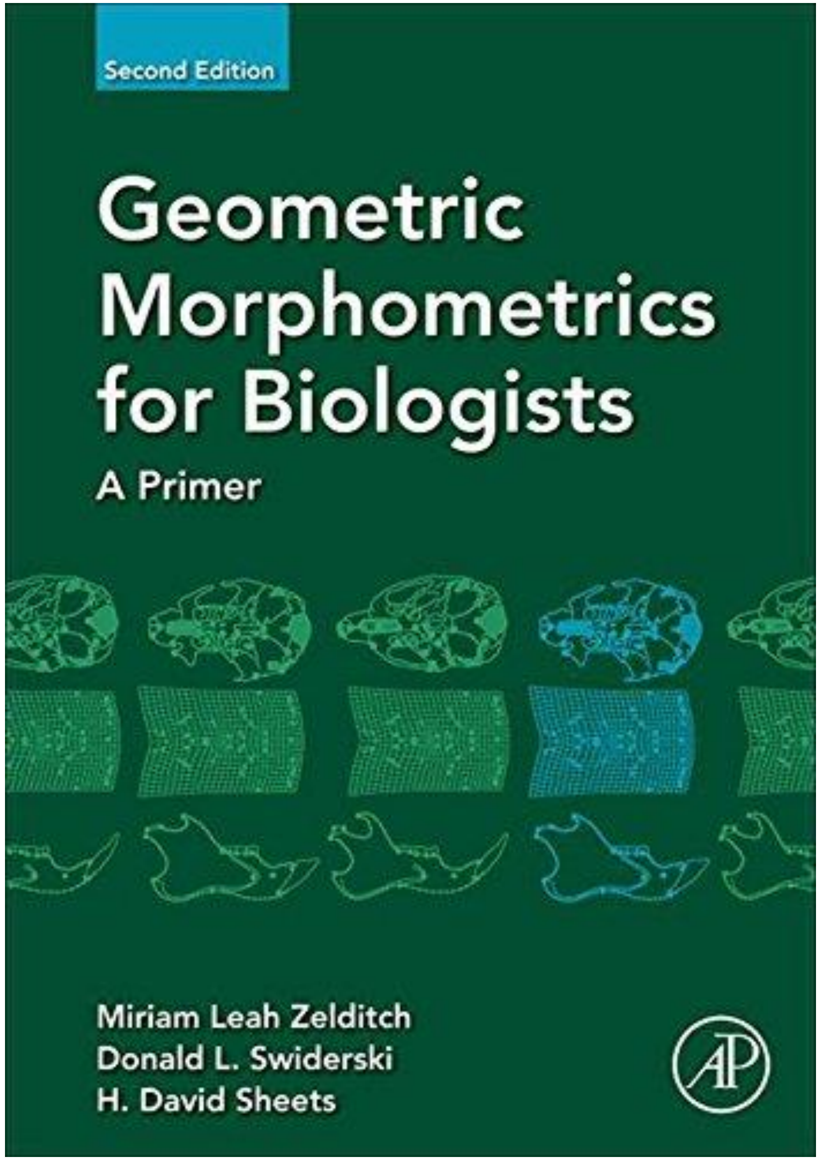
"The harmony of the world is made manifest in Form and Number, and the heart and soul and all the poetry of Natural Philosophy are embodied in the concept of mathematical beauty."

Thompson, D.W. (1917). On Growth and Form. Cambridge University Press.

Towards a statistical framework…

From the 1960s onwards…

- Fred Bookstein
- Dennis Slice
- Miriam Zelditch
- Norman MacLeod
- Ian Dryden and Kanti Mardia
- James Rohlf



How do we ‘do’ geometric morphometrics

(Following the design study)

Stage 1: Dataset creation

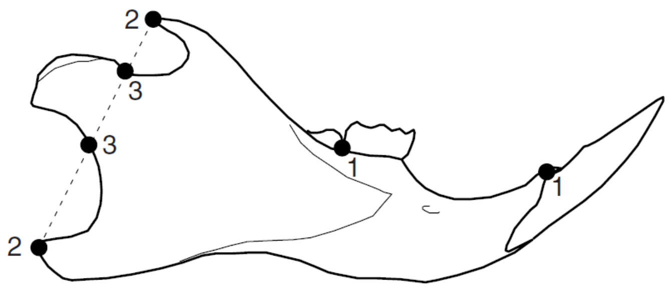
Methods include...

- **CT scanning**
- **Photogrammetry** and structure from motion (**SfM**) recording
- **Microphotogrammetry**
- **Microscribe**
- **3D scanners** (e.g. NextEngine)
- Data obtained from **drawings** and **photographs**

Note: Considered the error associated with each technique

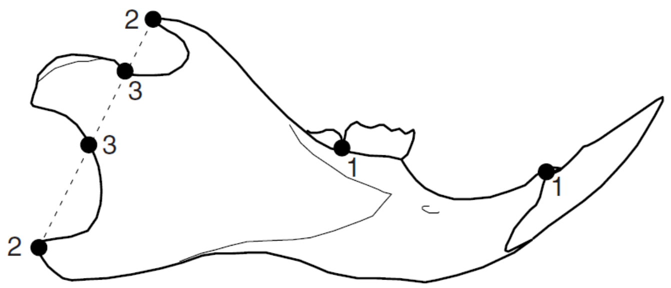
Stage 2: Landmark choice

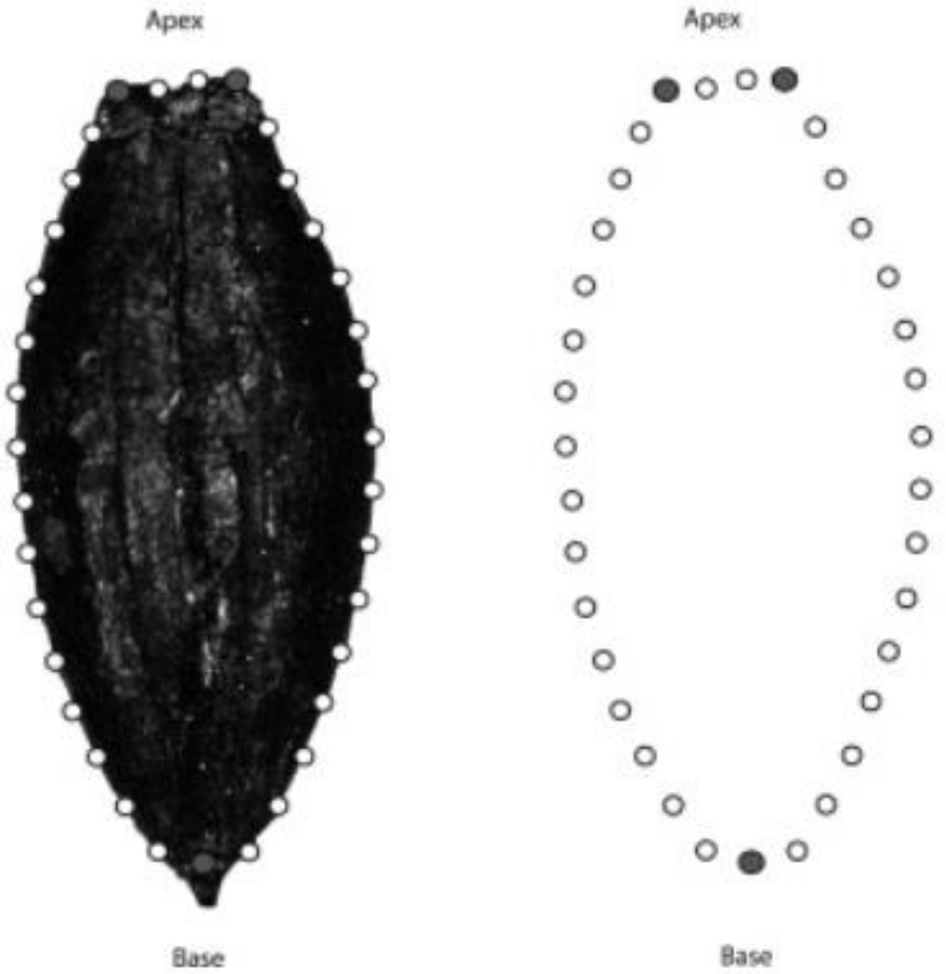
- Central to geometric morphometrics are landmarks
- **Landmark**: coordinate point used to represent a shape and/or a homologous point on a structure
- Quantifiable as Cartesian coordinates (x , y / z coordinates)
- Variety of different ways of approaching what type of landmarks are necessary
- Can be treated as individual points or converted (using various techniques) into curves and outlines



Stage 2: Landmark choice (types)

- **Various types of landmarks**
  - **Type I**: Homologous biological structures
  - **Type II**: Geometric definition e.g. greatest curvature
  - **Type III**: Point with reference to another point
- A special example: **semilandmarks**
  - Placed using an algorithm
  - Equidistant and placed between one or two end-points
  - A special **Type III landmark**
  - See also sliding semilandmarks





Ros, J., Evin, A., Bouby, L. & Marie-Pierre, R. (2013). Geometric morphometric analysis of grain shape and the identification of two-rowed barley (Hordeum vulgare subsp. distichum L.) in southern France. Journal of Archaeological Science. 41.

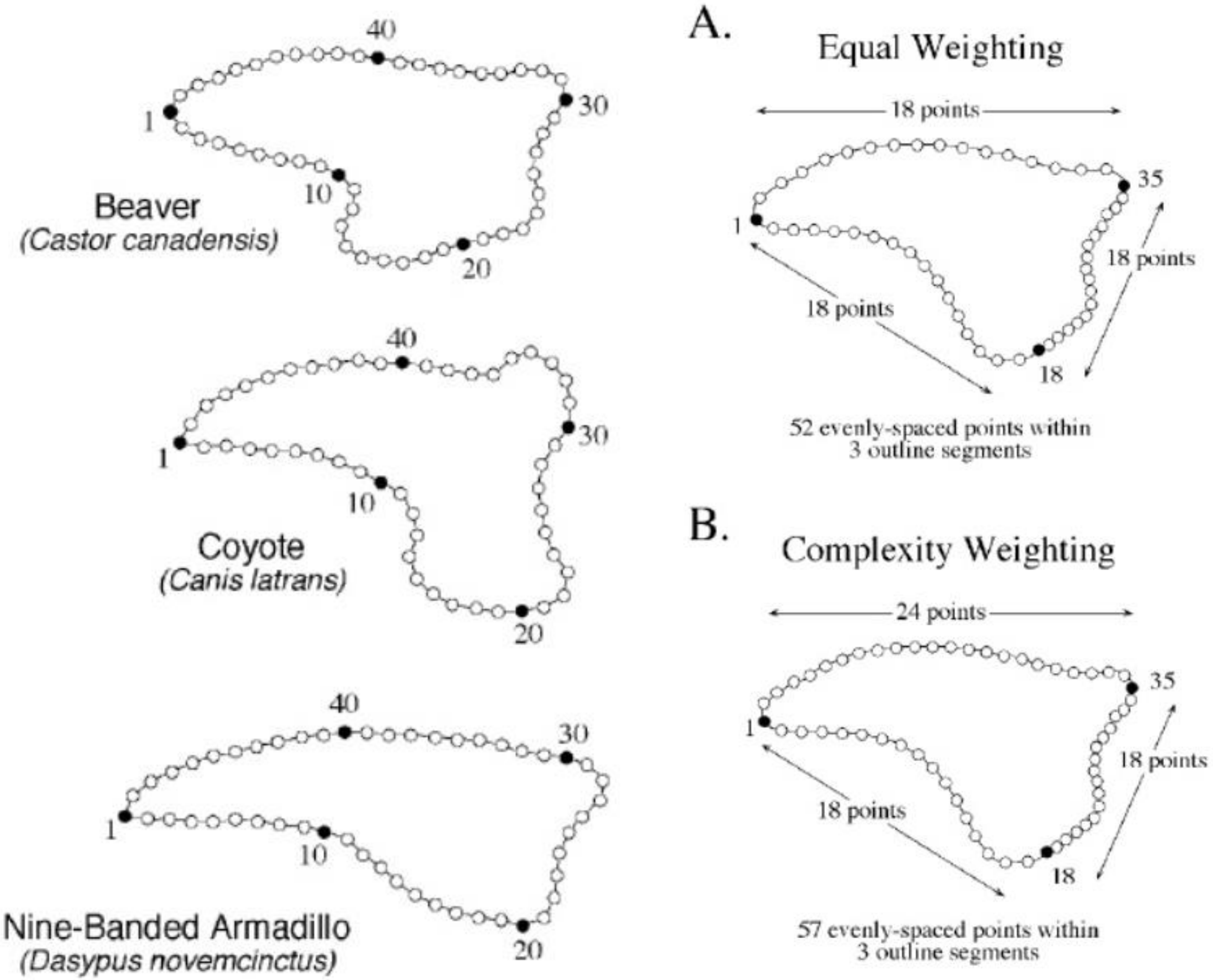
Stage 2: Landmark choice (position)

Quantity and coverage of landmarks:

- Landmarks should sample aspects of shape which are of **archaeological interest**
- Landmarks should be **repeatable** and **identifiable** on all examples if possible
- Landmarks should cover **as much of the shape as possible** (issues of distortion during GPA)
- Sufficient as to **not increase the 'weighting of areas'**
- Combination of **both landmarks and semilandmarks considered 'optimal'**

Ordering:

- Landmarks should always be **plotted in the same order** (otherwise the math wouldn't work!)



Norman MacLeod's PalaeoMath 101 Series
(http://www.palass.org/publications/newsletter/palaeomath-101)

Stage 2: Landmark choice (final comments)

For…

Bioarchaeologists

- Greater number of points of morphological correspondence on specimens
- Easier to study three-dimensional shape (orientation is less of an issue)

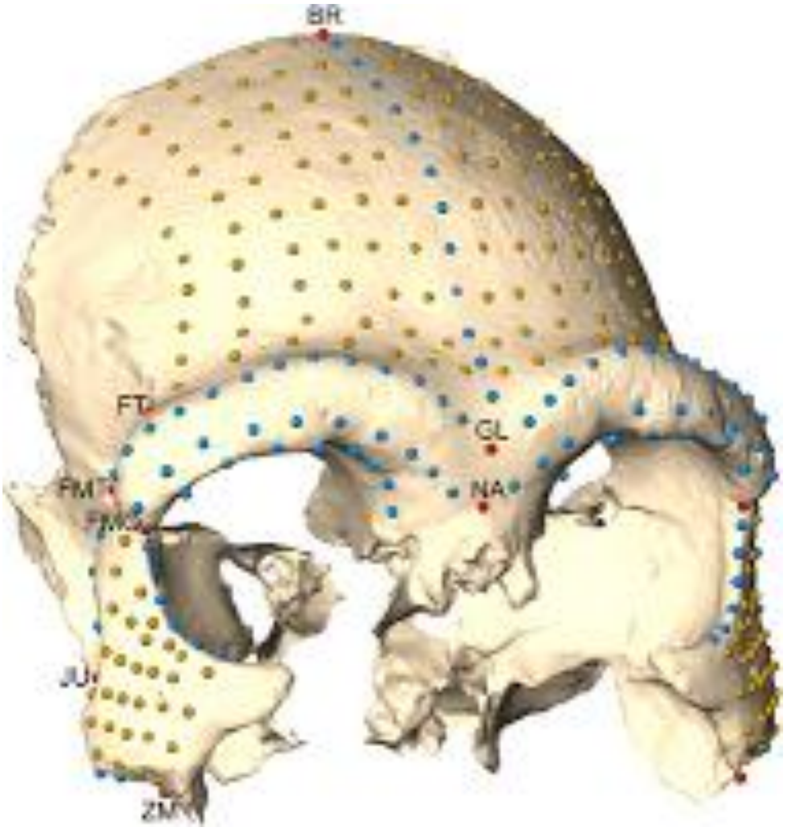
Archaeologists studying non-biological material

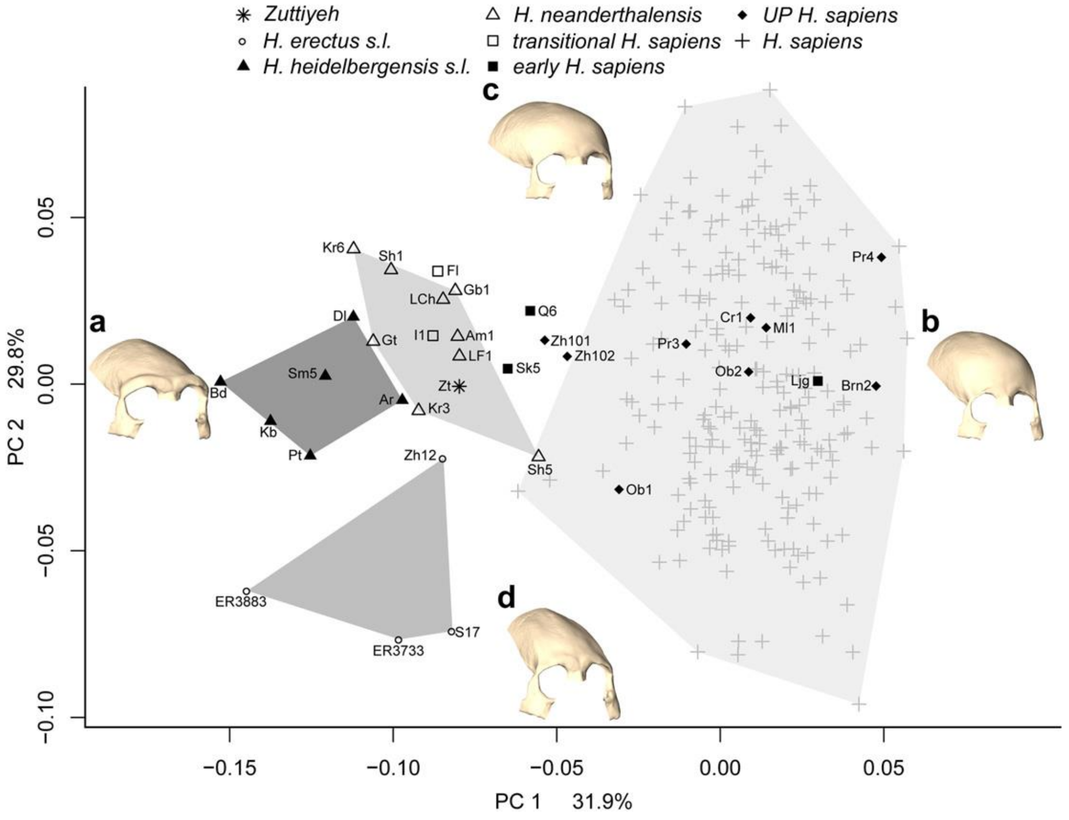
- Greater creativity and thought is needed in orienting specimens and placing landmarks
- Fewer case studies to compare geometric morphometric methodologies

All archaeologists

- Fragmentation and sample size (representation of a population) need to be considered

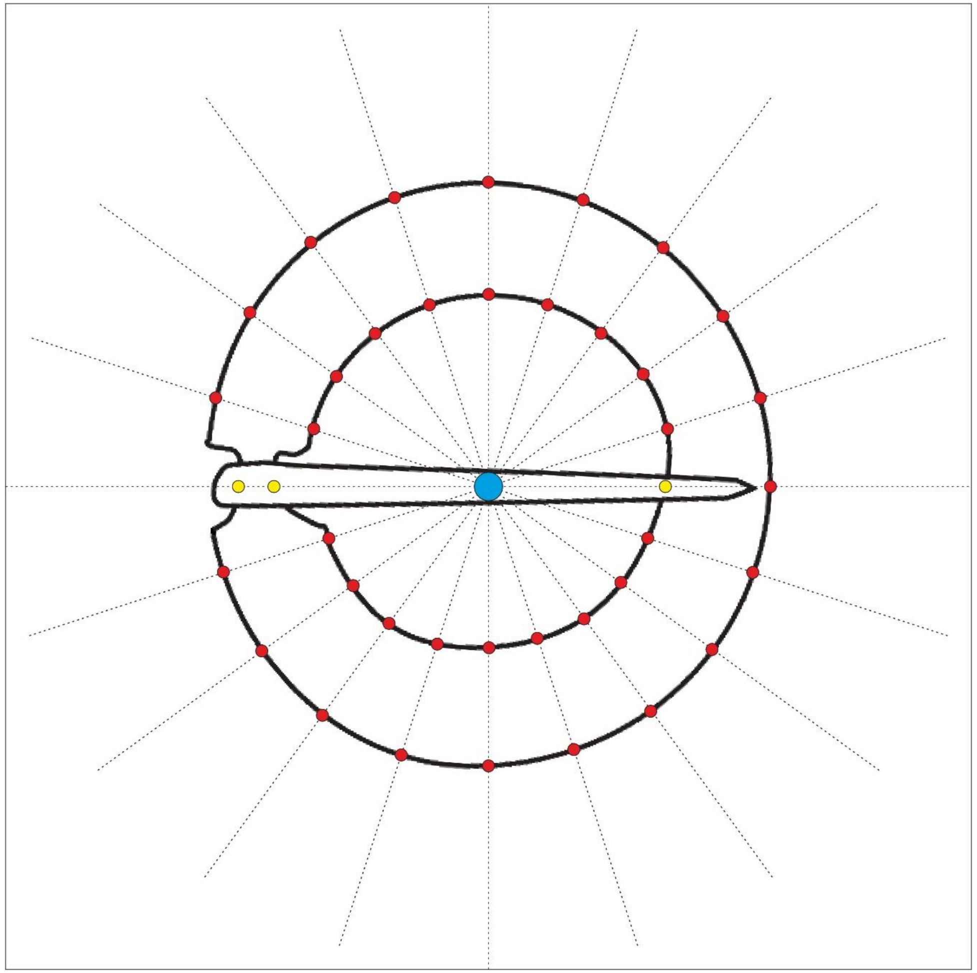
Freidline S.E, Gunz P., Janković I., Harvati K., Hublin J-J. (2012). A comprehensive morphometric analysis of the frontal and zygomatic bone of the Zuttiyeh fossil from Israel.. Journal of Human Evolution: 225-241.





Hoggard, C.S., Lauridsen, L. and Witte, K.B. (2019). The Potential of Geometric Morphometrics for Danish Archaeology: Two Case Studies. *Arkæologisk Forum*, 40: 30-42.

Article: (http://www.archaeology.dk/16738/Nr.%2040%20-%202019).
OSF: https://osf.io/en5d2/.



Stage 3: Landmark digitisation

Variety of different programs including:

- TPS Suite (TpsUtil and TpsDig2)*
- R Packages (geomorph, StereoMorph and GUImorph)*
- Landmark Editor (IDAV)
- PhyloNimbus

Variety of different output files created including:

- .tps*
- .nts
- .csv
- .text

*using in today's practicals

Stage 3: Landmark digitisation

Ask yourself…

1. Do all my specimens have the correct number of points?
2. Are all my landmarks in the correct order?
3. Are the ID labels correct?
4. Are they to scale? (For size-integrated analyses)

```
LM=28
66.00000 340.00000
72.00000 318.00000
75.00000 297.00000
78.00000 274.00000
84.00000 253.00000
86.00000 232.00000
88.00000 209.00000
83.00000 187.00000
80.00000 166.00000
76.00000 155.00000
75.00000 147.00000
57.00000 144.00000
37.00000 146.00000
34.00000 155.00000
33.00000 166.00000
32.00000 187.00000
32.00000 209.00000
30.00000 231.00000
30.00000 253.00000
30.00000 274.00000
33.00000 296.00000
37.00000 318.00000
46.00000 340.00000
50.00000 350.00000
52.00000 357.00000
57.00000 361.00000
61.00000 355.00000
63.00000 350.00000
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ID=Abri_Mannlefels_R
SCALE=0.105240
```
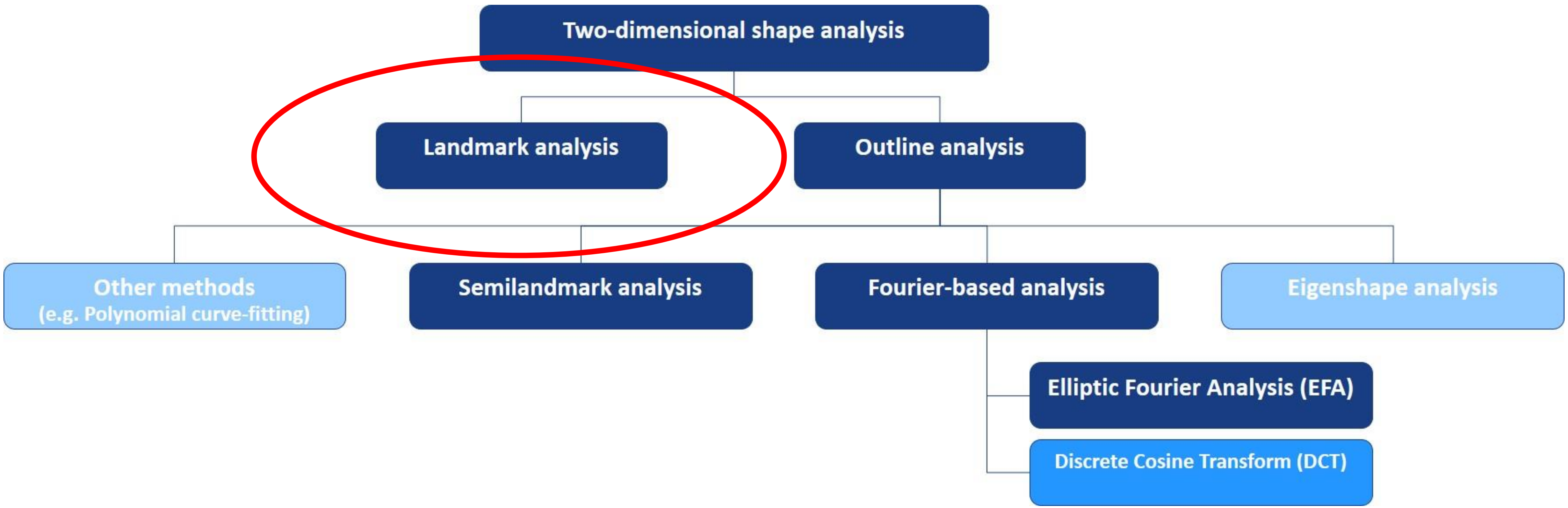


Two-dimensional shape analysis
Landmark analysis
Outline analysis
Other methods
(e.g. Polynomial curve-fitting)
Semilandmark analysis
Fourier-based analysis
Eigenshape analysis
Elliptic Fourier Analysis (EFA)
Discrete Cosine Transform (DCT)

Landmark analysis:
Generalised Procrustes Analysis (GPA)

Also known as...

- Procrustes Superimposition
- Procrustes Analysis
- Procrustes Fitting
- Generalised Least Squares

Procedure to isolate shape from a number of sometimes related variables, specifically **rotation, size and translation**

Generalised Procrustes Analysis (GPA)

- In Greek Mythology…
  - Procrustes was a son of Poseidon and lived on a sacred way between Athens and Eleusis
  - There he had a bed, in which he invited every passer-by to spend the night, and where he set to work on them with his blacksmith's hammer, to stretch them to fit
  - In later tellings, if the guest proved too tall, Procrustes would amputate the excess length; nobody ever fitted the bed exactly
  - Procrustes continued his reign of terror until he was captured by Theseus, travelling to Athens along the sacred way, who "fitted" Procrustes to his own bed

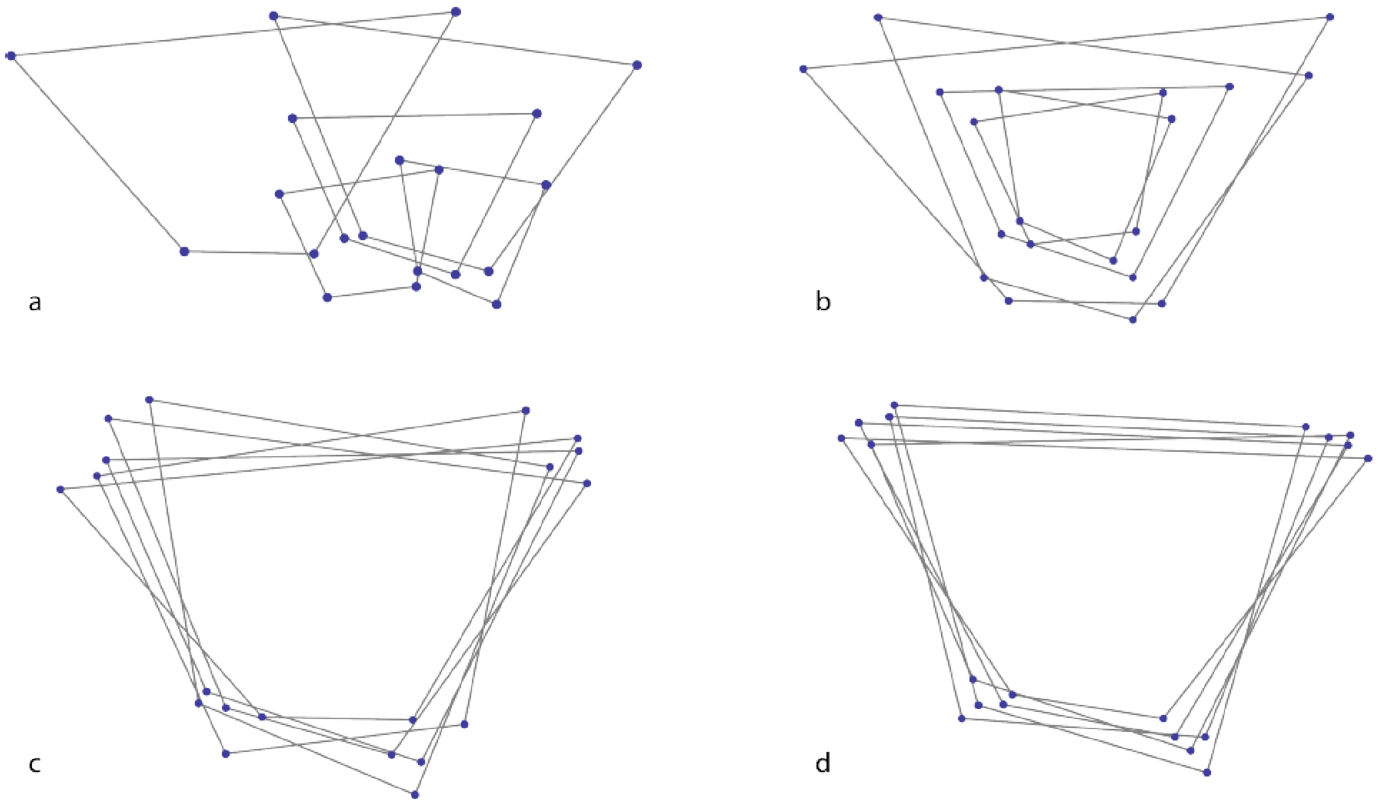
Generalised Procrustes Analysis (GPA)

- The raw coordinates are…
  - Translated to a **common centroid**
  - Scaled to the **same centroid size**
  - Rotated to **minimise the summed square distances** between corresponding landmarks

- Outcome: **Procrustes coordinates**

- The Procrustes coordinates describe shape *per se*
- The **Procrustes distance**: sum of distance between corresponding transformed landmarks
- These are used in subsequent statistical analyses

Generalised Procrustes Analysis (GPA)



Mitteroecker, P., Gunz, P., Windhager, S. & Schaefer, K. (2013). A brief review of shape, form, and allometry in geometric morphometrics, with applications to human facial morphology. Hysterix, the Italian Journal of Mammalogy. pp. 59-66.

Analysis

Methods include…

PCA: to explore the main sources of variation in shape among a dataset

LDA/CVA: to explore and assign specimens based on maximum between-group variance

Correlation and regression: shape and size (e.g. PC1 vs. centroid size)

Procrustes ANOVA: Statistical testing of difference (MANOVA)

Cluster analysis: task of grouping objects with similar shapes

Maximum likelihood (ML): permutation method of identifying trends/cluster (useful in phylogenetic studies)

Software

Programs include…

PCA: Eigenshape, PAST, tpsRelw, MorphoJ, R (geomorph, shapes, Momocs)

LDA/CVA: Statistica, tpsRel, MorphoJ, PAST, R (geomorph, Momocs)

Correlation and regression: Statistica, tpsRel, MorphoJ, PAST, R (geomorph, Momocs)

Procrustes ANOVA: R (geomorph)

Cluster analysis: PAST, R (Geomorph, Momocs)

Maximum likelihood: RPhylip

Practical #1: Landmark analysis

Step 1: Download all files on GitHub (https://github.com/CSHoggard/-Morph2019) and save in an appropriate directory

Step 2: Load "practical_one.R" in Rstudio and set the working directory as appropriate

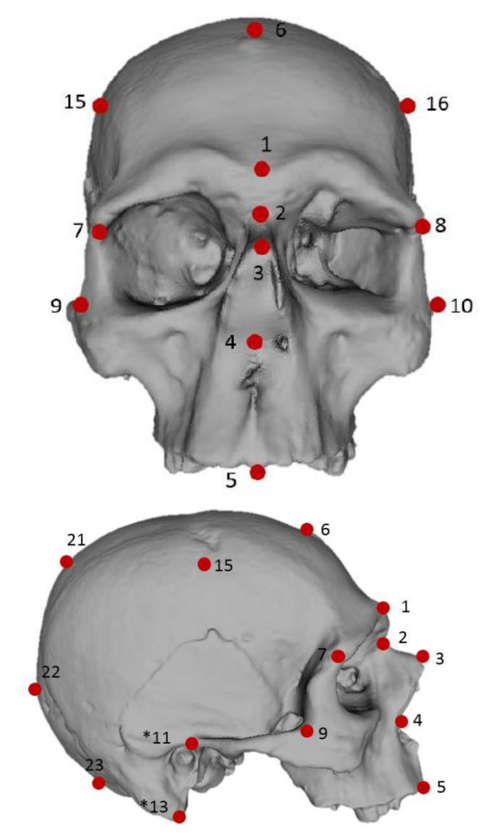
Step 3: Follow through the instructions and guidance in the script

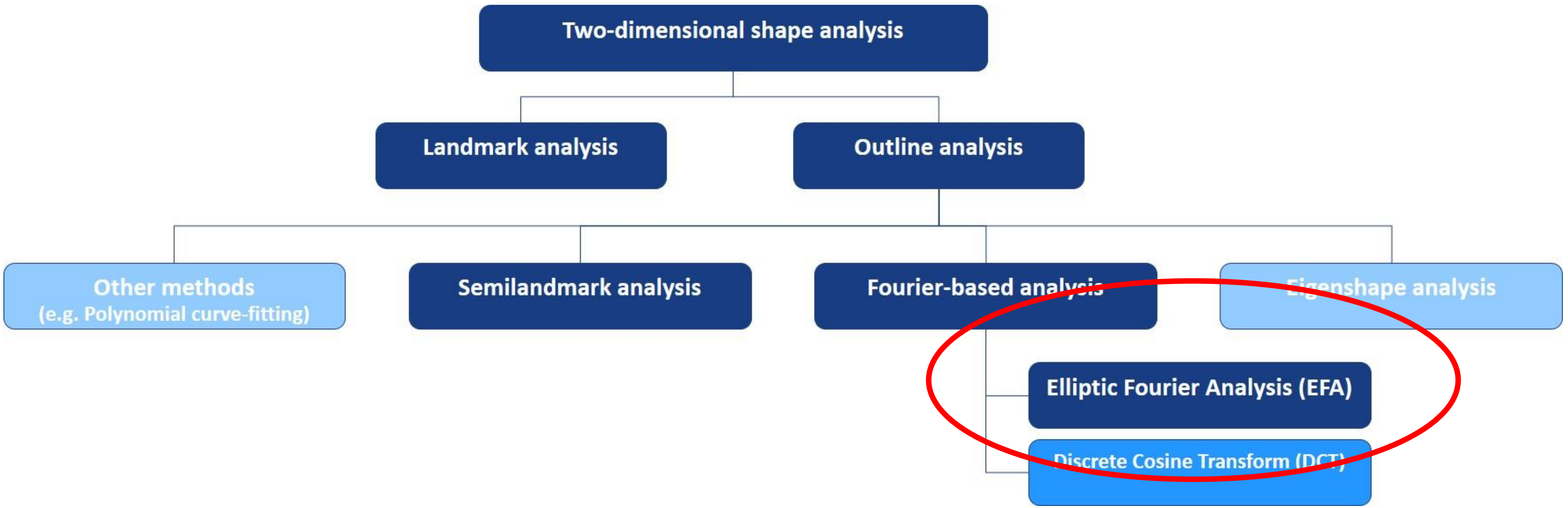
Dataset used in this practical:

- **Six skulls (3d mesh files)**
- **Two factors: sex and location**

Methodology:

- **Creation of a template (23 landmarks and 200 surface semilandmarks)**
- **Digitsation of landmarks**
- **Generalised Procrustes Analysis**
- **Principal Component Analysis**
- **Procrustes ANOVA (MANOVA)**




Two-dimensional shape analysis
Landmark analysis
Outline analysis
Other methods
(e.g. Polynomial curve-fitting)
Semilandmark analysis
Fourier-based analysis
Eigenshape analysis
Elliptic Fourier Analysis (EFA)
Discrete Cosine Transform (DCT)

Outline analysis

- **Outline coordinates:** XY coordinates along an open or closed curve
- Useful for structures which are comparable in a geometric sense but where individual homologous landmarks are difficult to pinpoint e.g. tooth perimeters
- Three main types of outline or curve analysis:
  - **Semilandmark analysis**
  - **Eigenshape analysis** (not as widely used)
  - **Fourier-based analyses (EFA/DCT)**

About the data used in outline analysis

- For **semilandmark** analysis **we need the same** amount of points (the process is the same as with landmark analysis)
- For **Fourier-based** analysis **we do not need the same** amount of points

- For semilandmark analysis **we need to start** at exactly the same position
- For Fourier-based analysis **we do not need to start** at exactly the same position

Elliptical Fourier Analysis (EFA)

- One of a number of ‘Fourier’ based methods of **curve (de-)composition**
  - Derived from the first series by **Jean Baptiste Joseph Fourier** (1768-1830)

- EFA was developed during the Cold War, partly by Giardina and Kuhl (1977) and Kuhl and Giardina (1982): used as a method of categorising enemy aircraft

- Grounded on a set of **parametric equations to fit a curve (Fourier harmonic amplitudes) from x and y Cartesian landmarks**

- Math: **sine and cosine transformations**

- Product: **Fourier coefficients**

Elliptical Fourier Analysis (EFA)

$$A_n = \frac{T}{2n^2\pi^2}\sum_{p=1}^{k}\frac{\Delta x_p}{\Delta t_p}\left[\cos\left(\frac{2\pi n t_p}{T}\right) - \cos\left(\frac{2\pi n t_{p-1}}{T}\right)\right]$$

$$B_n = \frac{T}{2n^2\pi^2}\sum_{p=1}^{k}\frac{\Delta x_p}{\Delta t_p}\left[\sin\left(\frac{2\pi n t_p}{T}\right) - \sin\left(\frac{2\pi n t_{p-1}}{T}\right)\right]$$

$$C_n = \frac{T}{2n^2\pi^2}\sum_{p=1}^{k}\frac{\Delta y_p}{\Delta t_p}\left[\cos\left(\frac{2\pi n t_p}{T}\right) - \cos\left(\frac{2\pi n t_{p-1}}{T}\right)\right]$$

$$D_n = \frac{T}{2n^2\pi^2}\sum_{p=1}^{k}\frac{\Delta y_p}{\Delta t_p}\left[\sin\left(\frac{2\pi n t_p}{T}\right) - \sin\left(\frac{2\pi n t_{p-1}}{T}\right)\right]$$

Where: k = the total number of steps around the outline
n = the harmonic number
Δx = the displacement along the x axis between point p and $p+1$
Δt = the length of the step between point p and $p+1$
t_p = accumulated length of step segments at point p
T = sum of lengths of all steps around outline

When **summed** together, these transformations represent an **approximation of an artefact form**

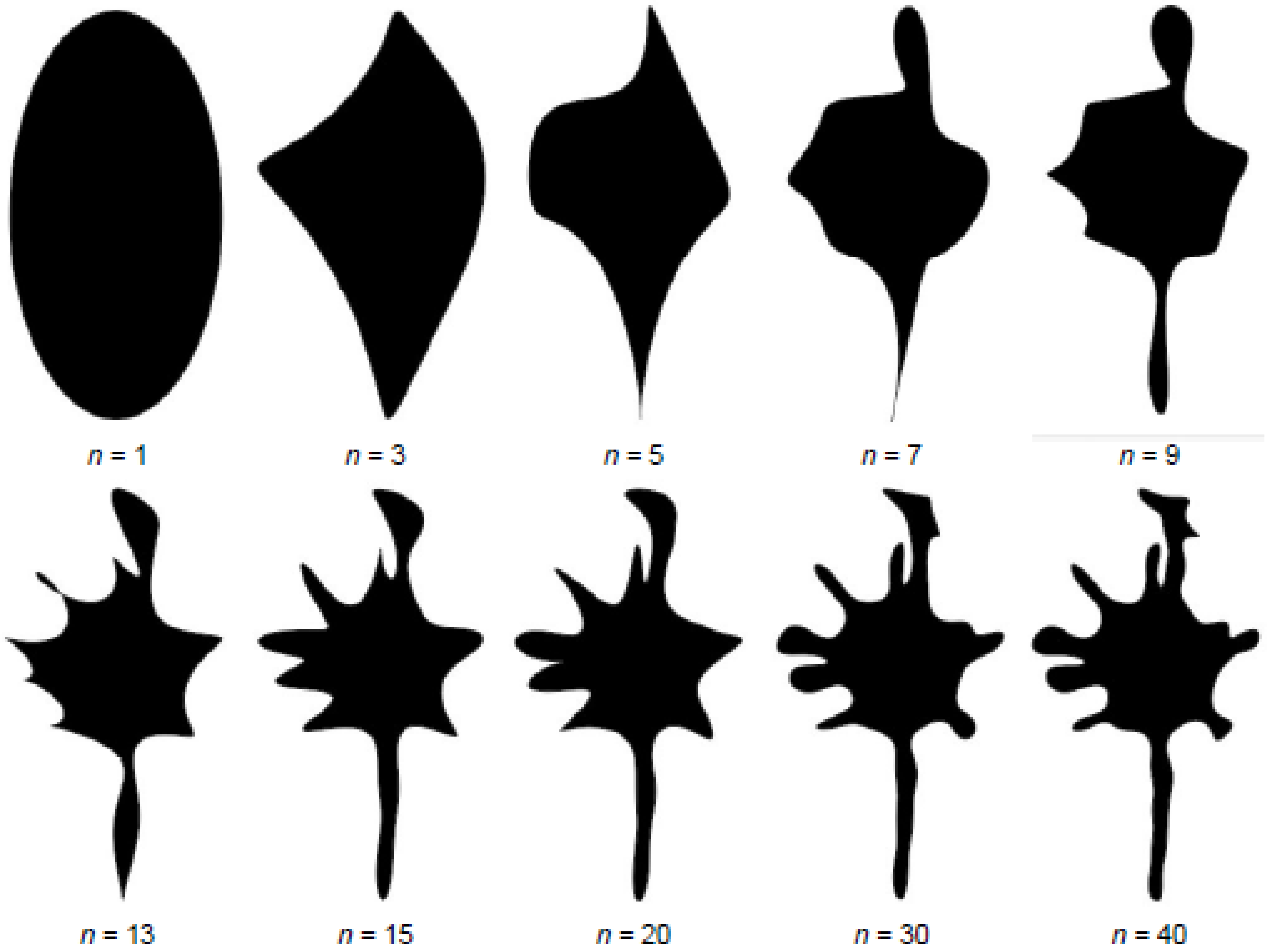
Elliptical Fourier Analysis (EFA)

- Outline estimation process that can provide a shape of varying detail depending on the number of harmonics you used.

- **Greater number of harmonics = greater detail**
(and more closely resembling the shape)

- **Too much detail = too much statistical noise**

- So the right level of harmonics are necessary



Norman MacLeod's PalaeoMath 101 Series
(http://www.palass.org/publications/newsletter/palaeomath-101)

Calculating harmonic power

1. ‘Eyeing it’: see at what harmonic the shape looks right
2. Calculating 99% harmonic power
3. Calculating deviation in % of the centroid size
4. Calculating deviation in coefficients

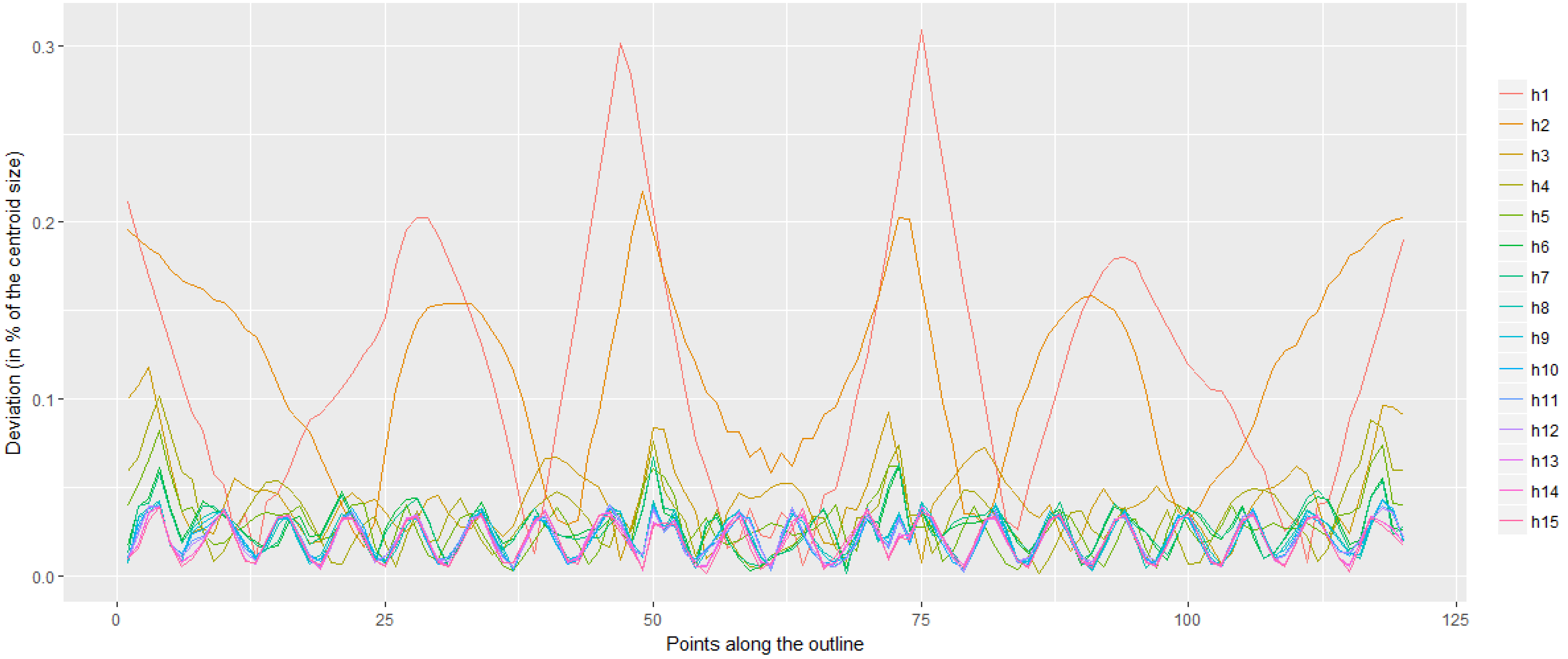
For 2-4:

R/Momocs: `calibrate()` functions

Norman MacLeod’s PalaeoMath 101 Series
(http://www.palass.org/publications/newsletter/palaeomath-101)

Calculating harmonic power

`calibrate_deviations_efourier()`



The output: Fourier coefficients

Similarly to landmarks a number of analyses can be performed including…

1. Principal Component Analysis (PCA)
2. Discriminant (LDA/DF/CVA) Analysis
3. Regression and correlation frameworks
4. MANOVA and statistical testing
5. Cluster and Maximum Likelihood (ML) methodologies

Note: coefficients can also be used to calculate symmetry, roundness and rectilinearity

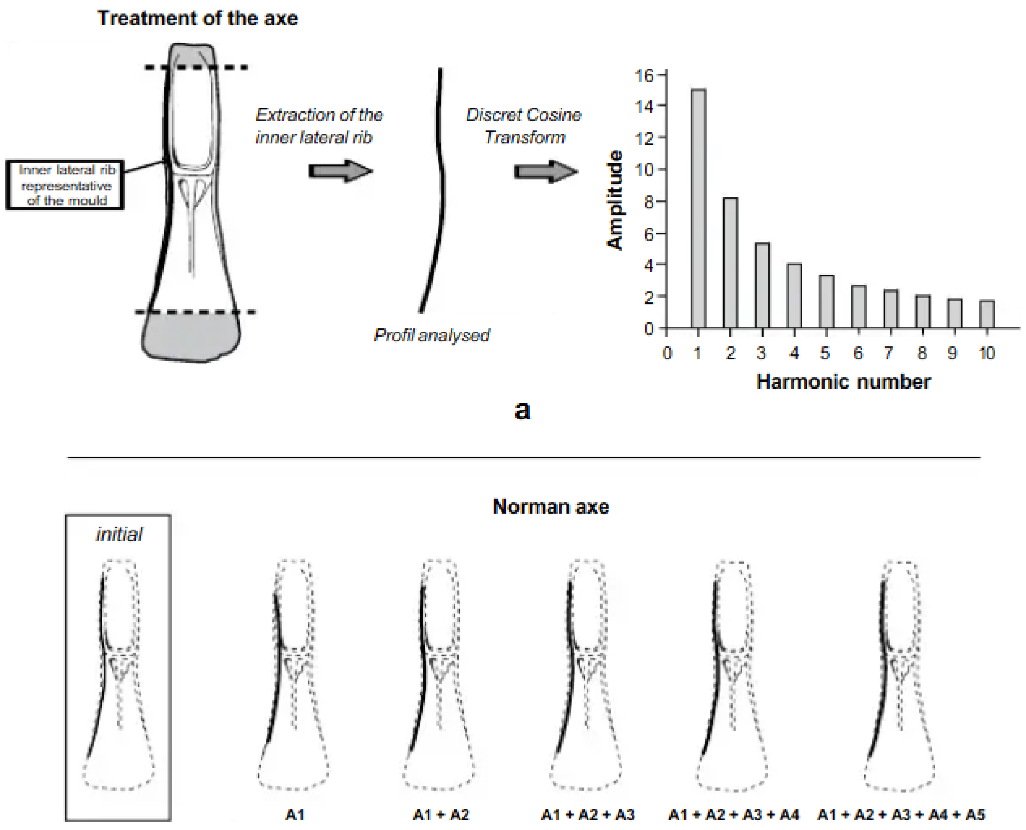
Discrete Cosine Transform (DCT)

An alternative method to EFA using cosine transformations to calculate the shape.

Useful for open outlines.

See Dommergues et al. (2007).

Note: can be performed in Momocs using the `dfourier()` functions.



Dommergues, C. H., Dommergues, J.-L., & Verrecchia, E. P. (2007). The Discrete Cosine Transform, a Fourier-related Method for Morphometric Analysis of Open Contours. Mathematical Geology, 39(8), 749-763.

Forel, B. et al. (2009). Morphometry of Middle Bronze Age palstaves by Discrete Cosine Transform. Journal of Archaeological Science., 36. 721-729.

Practical #2: Outline analysis

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The Application of Elliptic Fourier Analysis in Understanding Biface Shape and Symmetry Through the British Acheulean

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Practical #2: Outline analysis

RQ1: How does biface shape change throughout the British Acheulean and can increasing standardisation in biface shape be observed?

RQ2: How does biface symmetry change throughout the British Acheulean and can increasing standardisation in biface symmetry be observed?

RQ3: How are the main sources of biface shape variation linked to variations in symmetry, and how does biface size relate to both biface shape and symmetry?

Dataset used in this practical:
- Silhouettes of handaxes (silhouettes made using photographs in Photoshop CS6)
- Handaxes created throughout the Acheulean period (MIS 13 onwards)
- Control dataset: Lynford (MIS 4/3)

Methodology:
- Elliptic Fourier Analysis of the raw coordinates to create coefficients
- Extraction of symmetry values
- Principal Component Analysis (and visual summaries) of shape data
- Discriminant Analysis and MANOVA of shape data (shape vs. MIS)
- Visual summaries of symmetry data
- Statistical testing of symmetry (symmetry vs. MIS)
- Correlation analysis

Practical #2: Outline analysis

Table 1 The British Lower and Middle Palaeolithic assemblages used for this study (total: 468)

Marine Isotope Stage	*Context*	*Sample size*	*Source*	*Collection*
13 (528–474 kya)	Warren Hill	49	Marshall et al. (2002)	–
	Boxgrove	50	Marshall et al. (2002)	–
11 (427–364 kya)	Bowman's Lodge	28	Marshall et al. (2002)	–
	Elveden	29	Author (JNC)	BM (Sturge Collection)
	Swanscombe	58	Author (JM)	BM (Marston Collection)
9 (334–301 kya)	Broom	50	Marshall et al. (2002)	–
	Furze Platt	69	Author (JM)	BM (Treacher Collection)
7 (242–186 kya)	Cuxton	50	Marshall et al. (2002)	–
	Pontnewydd Cave	37	Author (JNC)	NMW
4/3 (57 kya)	Lynford	48	Author (JNC)	NAU

Practical #2: Outline analysis

Step 1: Download all files on GitHub (https://github.com/CSHoggard/-Morph2019) and save in an appropriate directory

Step 2: Load “practical_two.R” in Rstudio and set the working directory as appropriate

Step 3: Follow through the instructions and guidance in the script (we’ll work through it together after!)

GMM and Archaeology: The Future

1. **Greater application** of GMM in a variety of new (non biological) archaeologies
2. **Methodological applications**: automisation (recording and landmarking)
3. **Coding developments:** towards a replicable, reproducible and Shiny GMM…
4. **More powerful analytics**: e.g. Bayesian and Machine Learning techniques

Thank you for attending!

Enjoy Morph2019!
Enjoy Sendai!

MORPH 2019
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