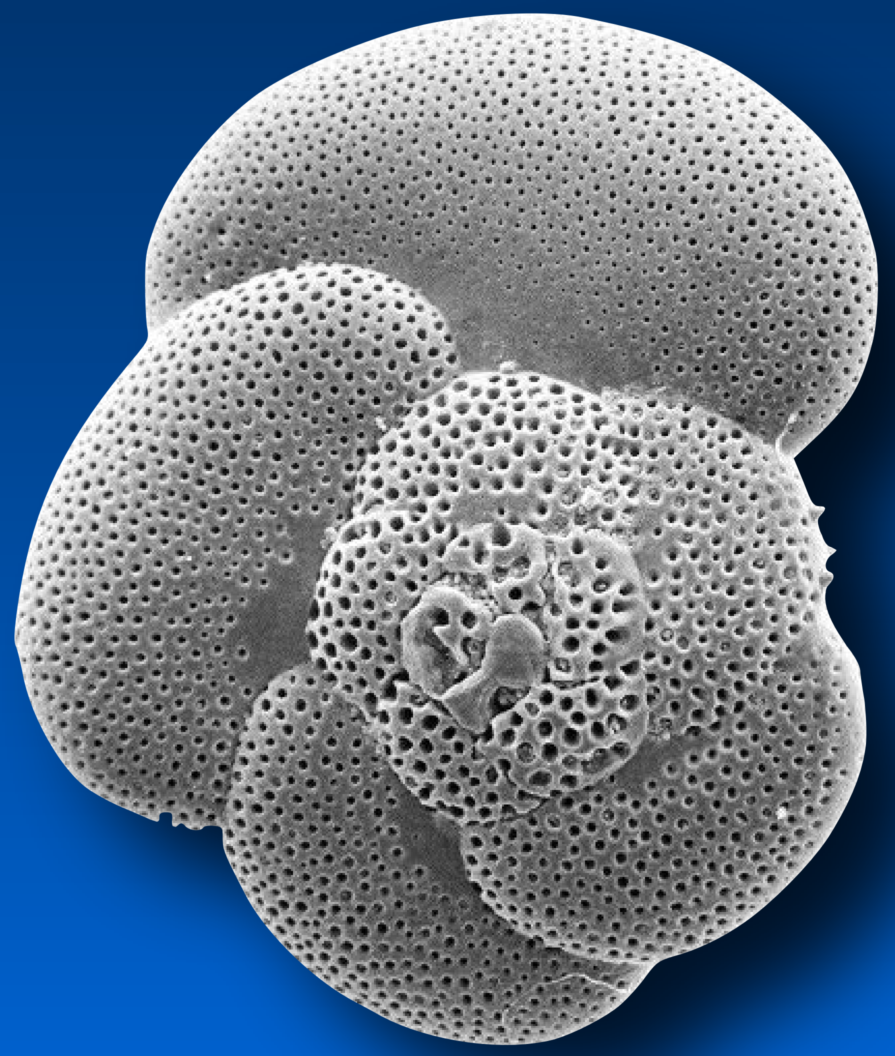
NJU Course

Principles of Paleobiology

Description & Analysis of Morphology

Description & Analysis of Morphology

The basic data of paleontology is, and always will be, morphology. Therefore, paleontologists, uniquely among the earth scientists, have a special interest, and need to develop expertise, in the description and analysis of morphology. This requires the acquisition of advanced observational and quantitative skills.




Description & Analysis of Morphology

Description: Characters & Character States

Characters - attributes that can be used to provide the evidence from which both unique aspects and relationships between taxa are inferred (e.g., amniote egg).

Character states - variant forms of the character (e.g., eyes: blue, green) that provide evidence of either anagenetic or cladogenetic modification of the character. Because of its ambiguity “none” or “absent” should not be regarded as a valid character state.

Types of Characters	
Morphology	Behavior
Physiology	Ecology
Molecular	Geography

Description & Analysis of Morphology

Taxonomic Description

A formal paleontological taxonomic description should provide all the morphological information necessary for any qualified researcher to identify a fossil taxon (e.g., species, genus, family) in terms of a standard set of characters and character states, including an explicit discussion of how the taxon might be distinguished from closely related or morphologically similar taxa.

In addition, taxonomic descriptions should provide information regarding:

- Where the specimen(s) was/were collected (both geographic location and stratigraphic position);
- Where any types have been deposited;
- The taxon's stratigraphic range;
- A summary of any incorrect published identifications (= a synonymy).

Description & Analysis of Morphology

How to Describe a New/Revised Species

Name:
Scientific name w/ citation or original author (if appropriate).

Figure/Plate reference:
Callout for photograph(s) or drawing(s) of (a) representative specimen(s).

Diagnosis:
Description of character states that allow this taxon to be distinguished from similar taxa.

Description:
Complete description of all the taxon's characters and character states.

Remarks:
Any information you believe might be helpful for readers to understand the taxon's concept.

Etymology:
Origin and/or meaning of the taxon's name.

Measurements:
Reference to a table containing any quantitative measurements collected from the specimens.

Description & Analysis of Morphology

How to Describe a New/Revised Species (cont.)

Measurements:
Reference to a table containing any quantitative measurements collected from the specimens.

(Type) Locality:
Description of the geographic locality from which specimen(s) was/were collected.

Deposition of types:
Name of the institution where the specimens/samples are housed.

Stratigraphic range:
Position of the specimen/sample within the local biostratigraphy.

Occurrence:
Description of the taxon's geographic range.

Description & Analysis of Morphology

Description

Perispyridium robustum MacLeod, **n. sp.**
Plate 1, figures 7, 9, 10; plate 2, figure 8; plate 5, figures 3, 6, 9

Diagnosis: Cephalis small, subspherical to ellipsoidal in shape with subcircular to elliptical pores. Peripheral shell subcircular in frontal view with thick pore frames enclosing subcircular to elliptical pores. Apical and primary lateral spines thick and stout with crown structure at spine tips.

Description: Cephalis small; spherical in shape with strongly elliptical pores. Cephalic pore frames thick, pentagonal to hexagonal with simple pore frame vertices. Five to six moderately large, subcircular pericephalic pores. Peripheral shell subcircular in frontal view with broadly concave frontal surface and planar to slightly rounded marginal surfaces. Peripheral shell moderately thick and robust. Peripheral shell pore frames pentagonal to hexagonal, relatively thick with weakly nodose pore frame vertices. Peripheral shell pores subcircular to weakly elliptical. Apical spine noticeably longer than primary lateral spines. All spines triradiate throughout with blunt tips that exhibit crown structure. Spine bases relatively wide. All spines taper at relatively constant rates giving rise to uniformly straight to slightly concave spine profiles. Spine grooves deep, broad and continuous throughout the length of the spines. Width of spine grooves and ridges approximately equal. Spine ridges smooth and rounded with weak proximate bifurcations.

Remarks: Distinguishing features of *P. robustum*, n. sp. with respect to *P. dobzhanskyi*, n. sp. have been listed under the discussion of the latter. *P. robustum*, n. sp. differs from *P. facetum* Pessagno and Blome by exhibiting a thicker, more robust peripheral shell, smaller pericephalic pores, and thicker spines that terminate in the crown structure.

Etymology: Robustum (Latin, adjective) = hard and strong like an oak.

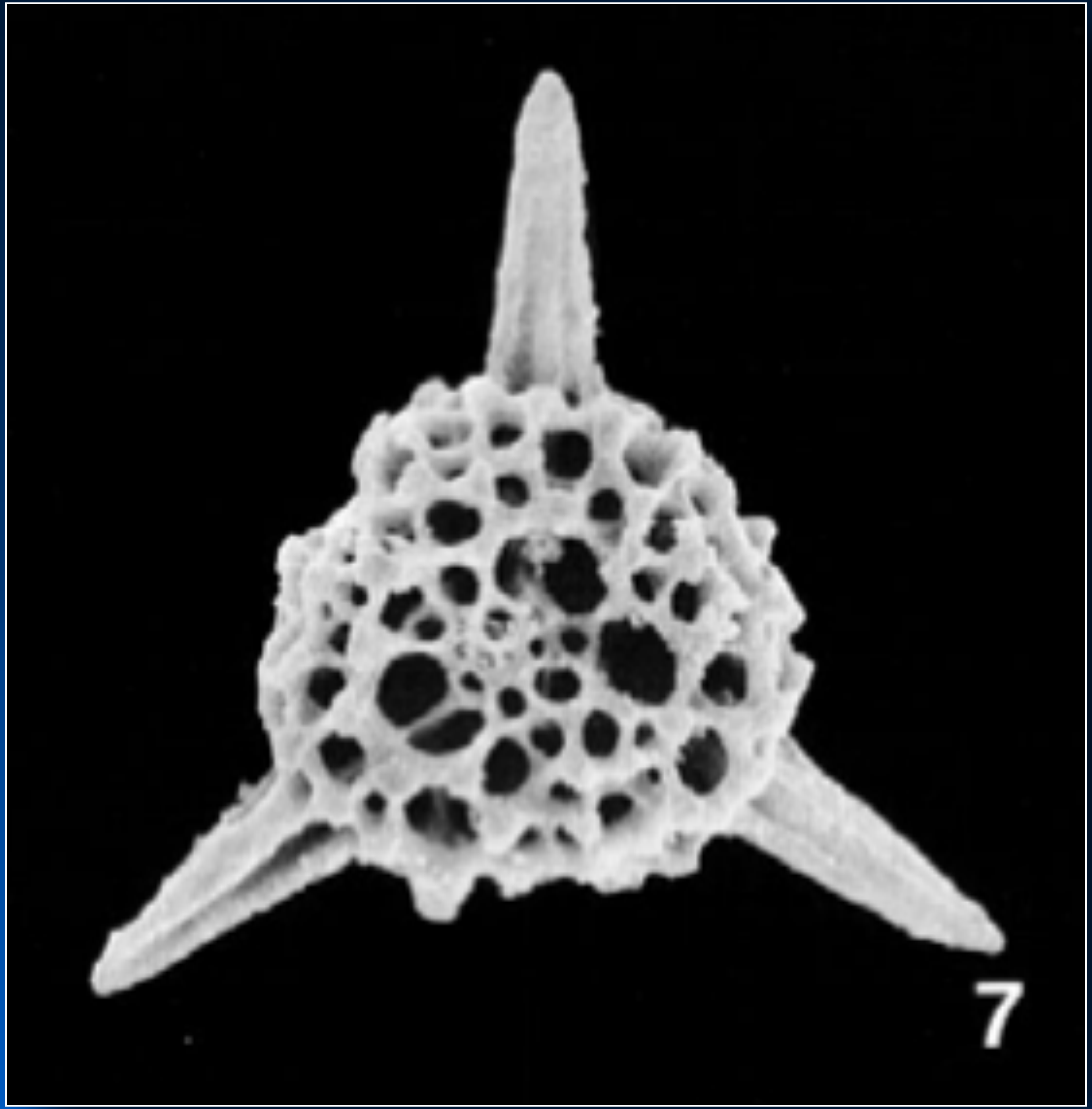
Measurements: See Table 9.

Type locality: MF-84(11)19 (see Appendix).

Deposition of types: Holotype, USNM 416156. Paratypes, USNM 416157.

Stratigraphic range: Lower–Middle Jurassic (upper Toarcian–upper Bajocian); Zone $1A_2$–Zone 1D (see Pessagno et al. 1987).

Occurrence: Snowshoe Formation, east-central Oregon.



MacLeod (1988)

Description & Analysis of Morphology

Issues with Taxonomic Descriptions

Advantages

- Traditional.
- Required by international commissions of zoological and botanic nomenclature.
- Level of complexity can be graded on the project's needs/ requirements.

Disadvantages

- Inherently subjective.
- Text often a poor way of describing geometrically complex structures.
- Descriptions often fail to include all characters exhibited by the taxon.

Perispyridium robustum MacLeod, **n. sp.**
Plate 1, figures 7, 9, 10; plate 2, figure 8; plate 5, figures 3, 6, 9

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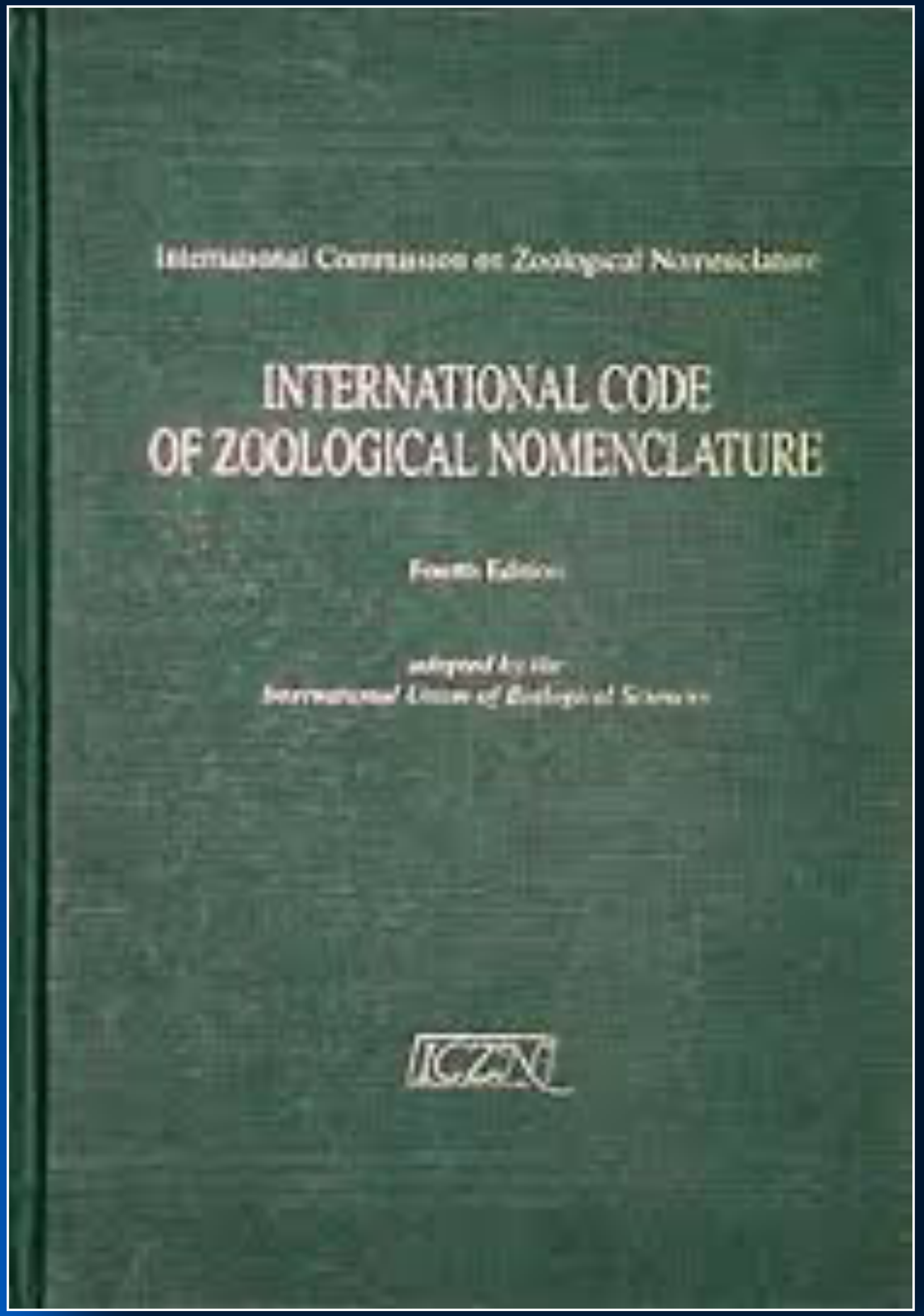
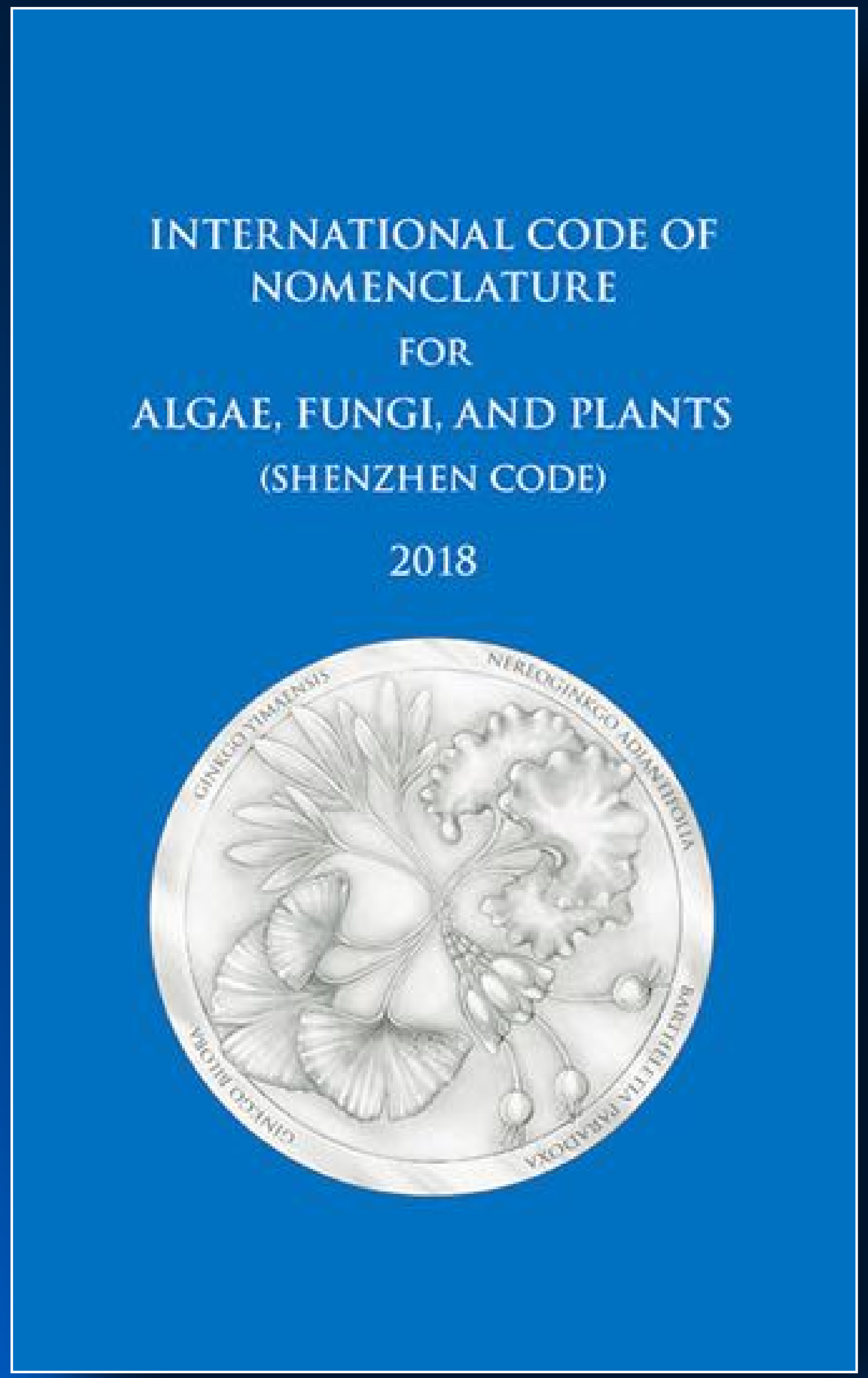
Description & Analysis of Morphology

International Nomenclature Commissions/Guides



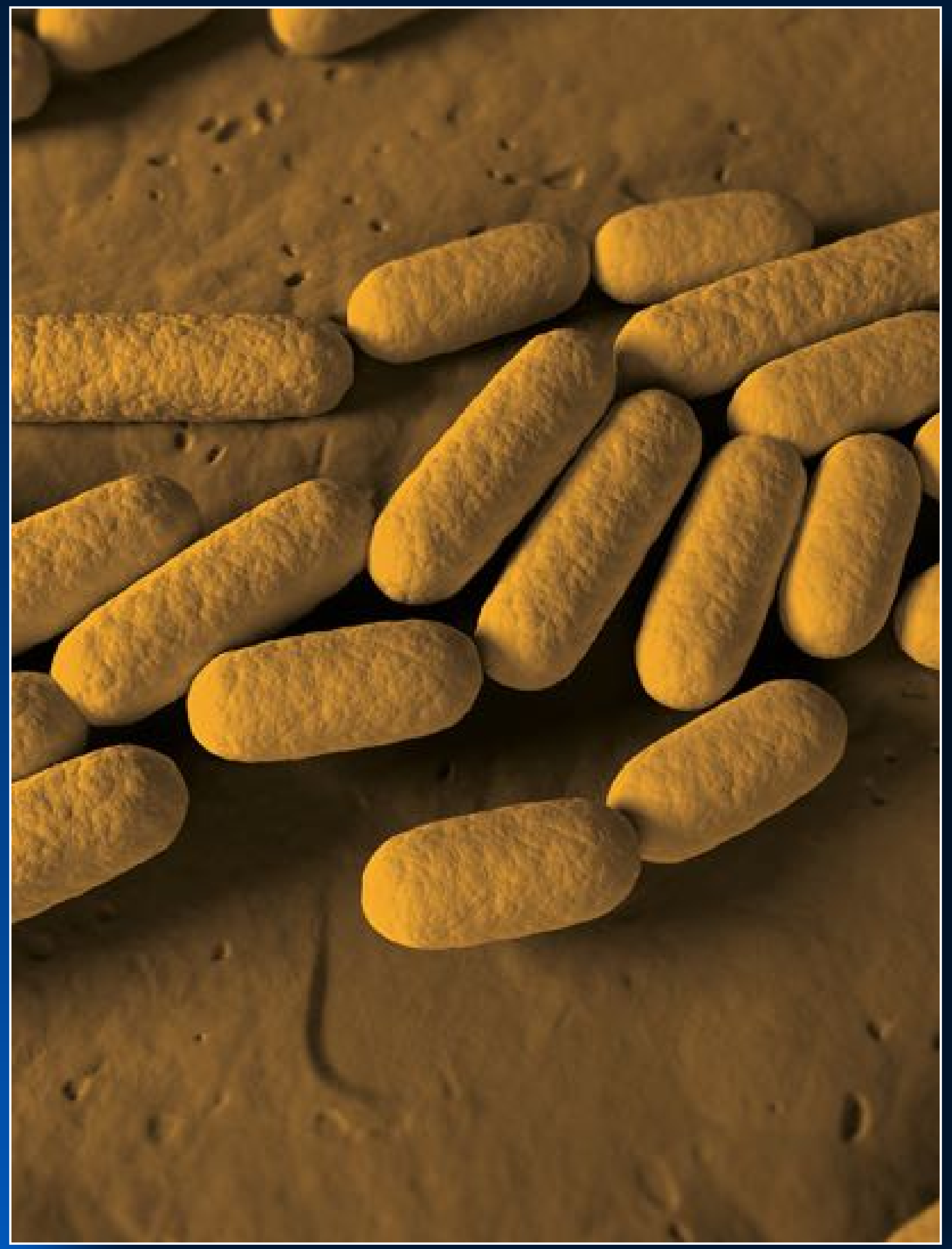
International Commission on Zoological Nomenclature (1999)

https://www.iczn.org



International Association for Plant Taxonomy (2018)

https://www.iapt-taxon.org/nomen/main.php



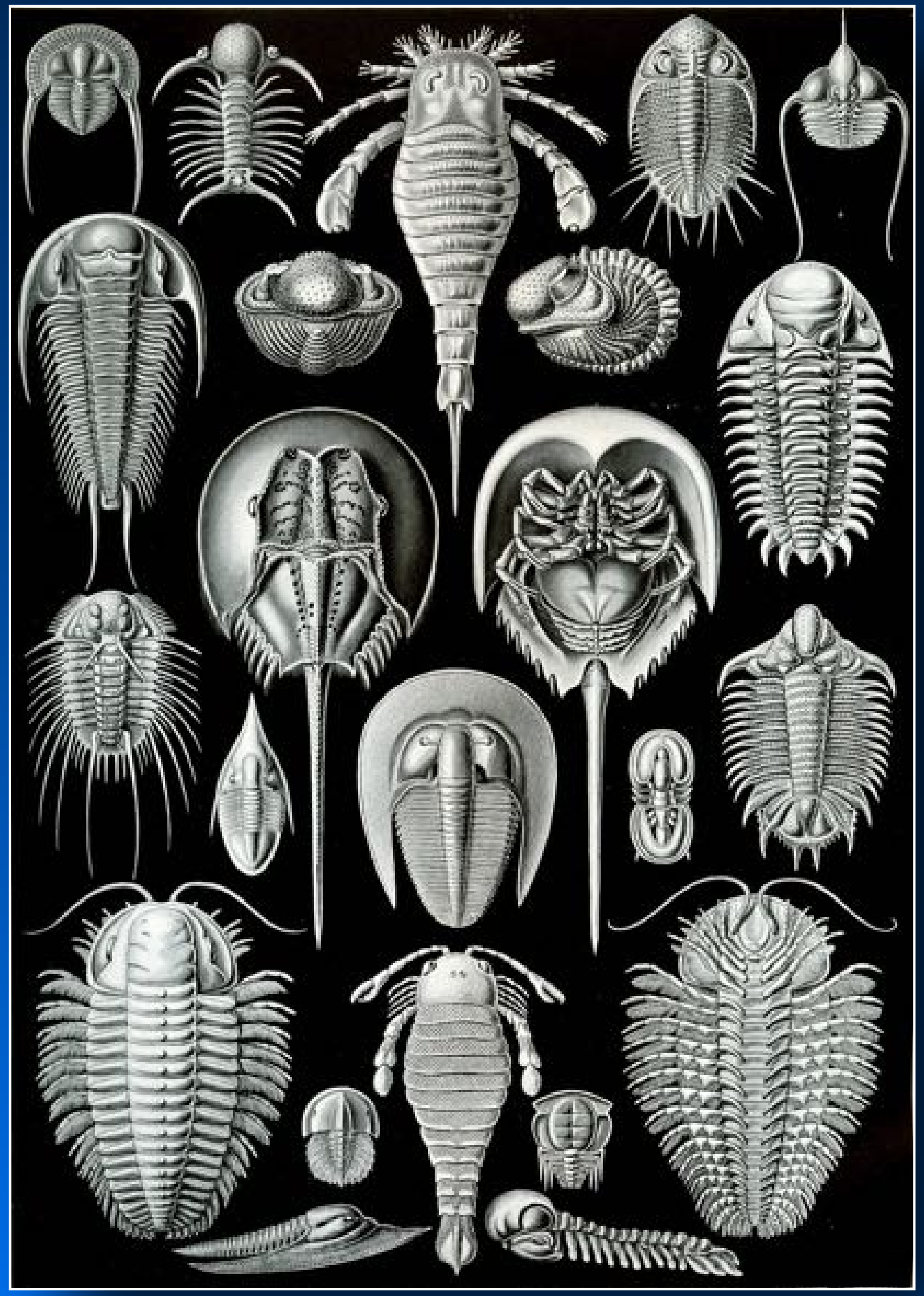
International Code of Nomenclature of Prokaryotes (2022)

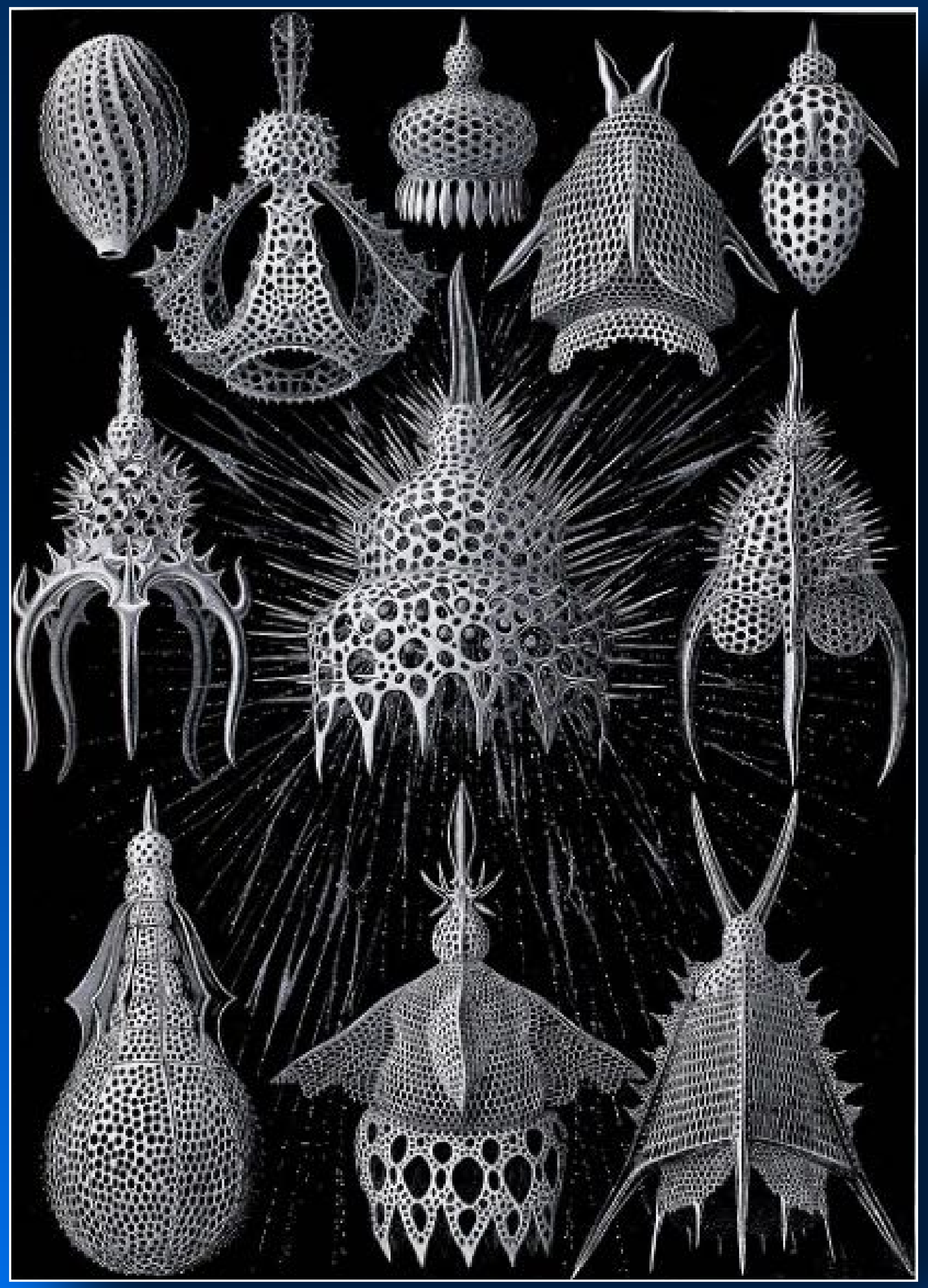
https://www.the-icsp.org/index.php/code-of-nomenclatur

Description & Analysis of Morphology

Illustration: Drawing/Painting

The oldest form of visual art which uses instruments to mark paper or other two-dimensional surface in order to create an image of an object. Digital drawing is the act of drawing on graphics software in a computer.

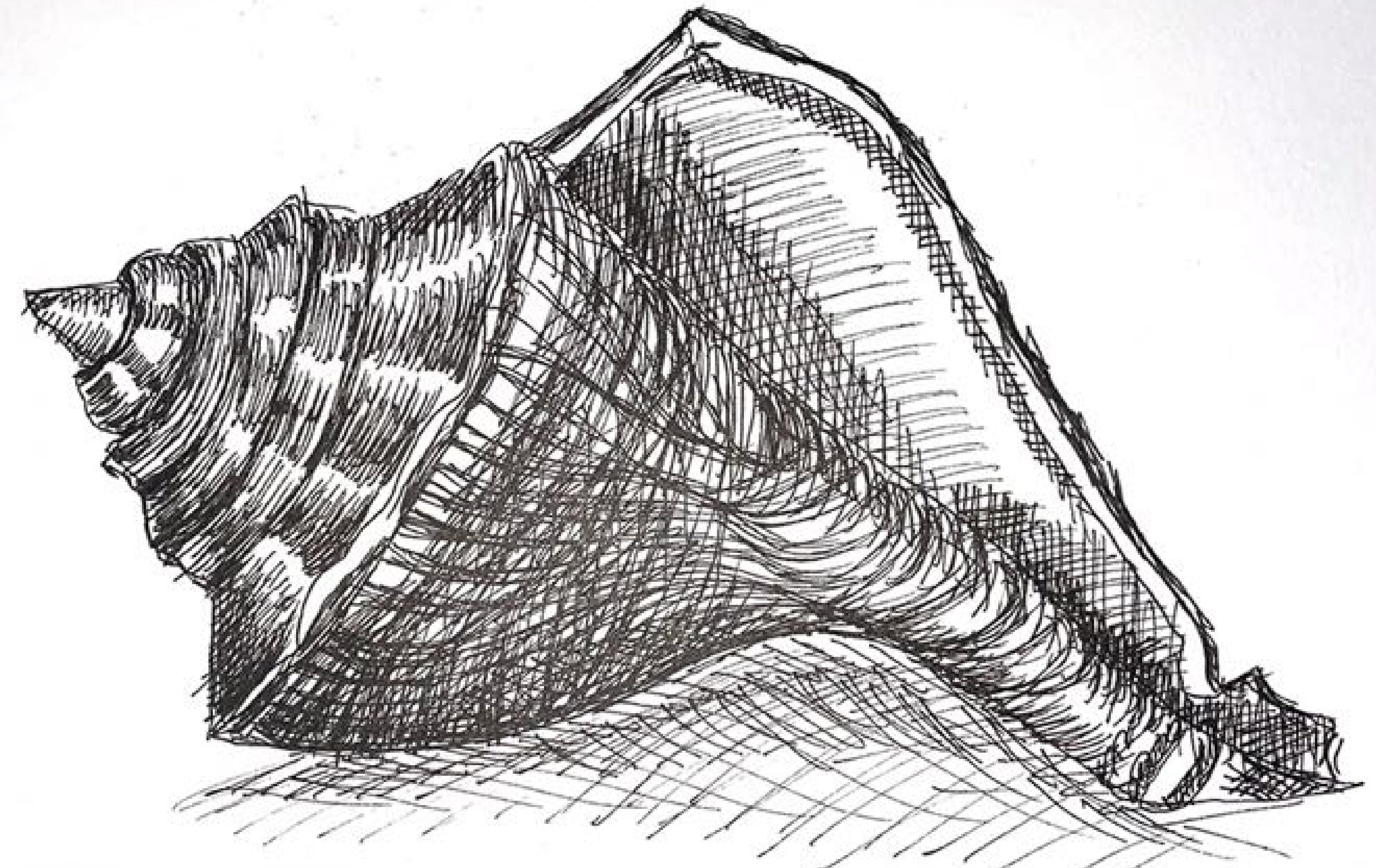




Description & Analysis of Morphology

Illustration: Drawing/Painting

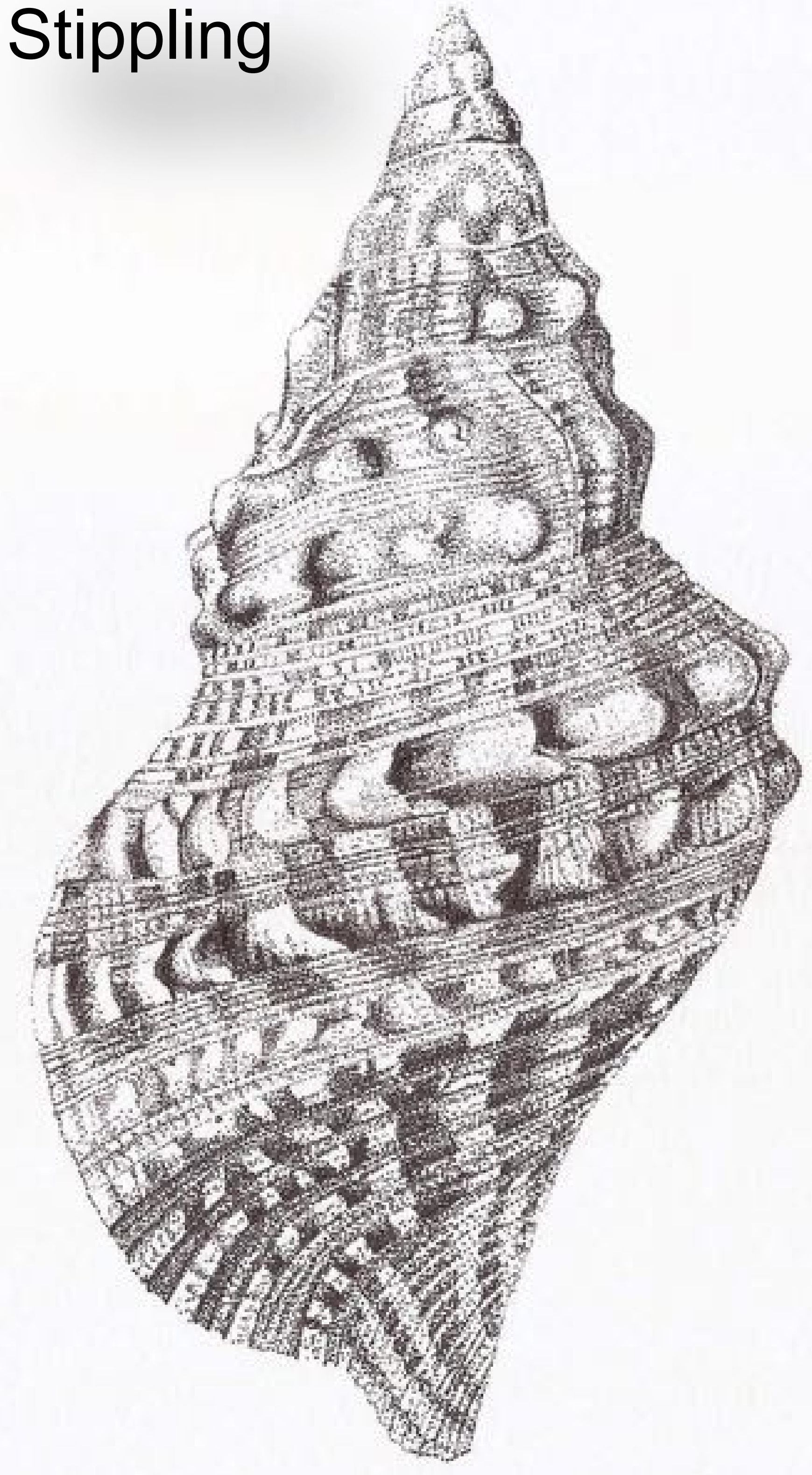
Shading Techniques



Crosshatching

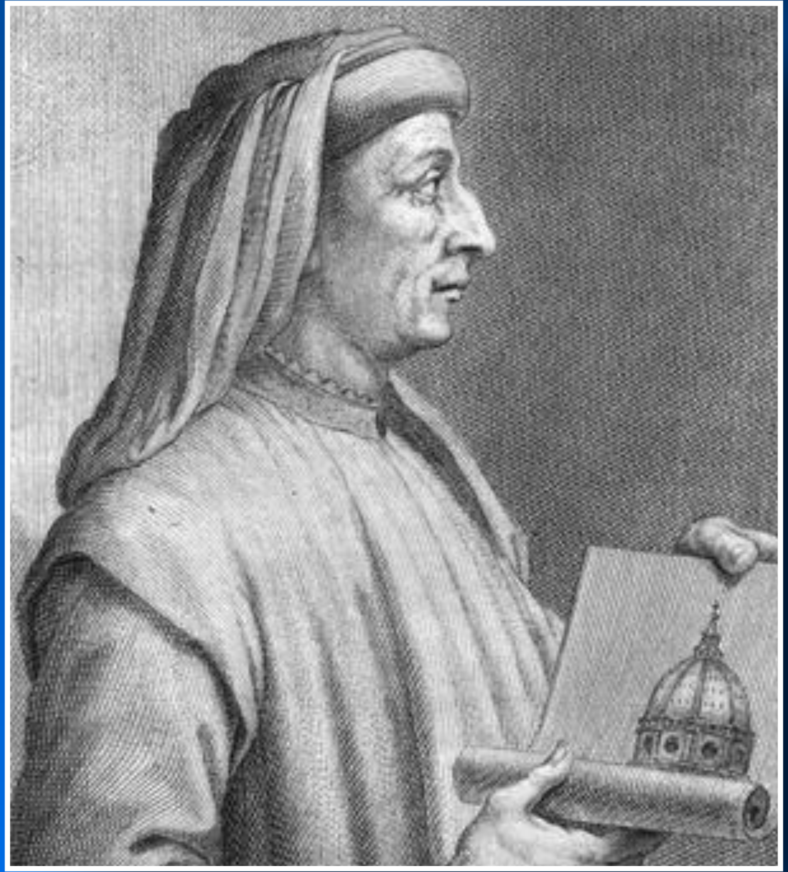
Shading methods can be used to emphasize certain features and/or represent fine details, but often creates a conflict between represent-ation and interpretation.

Stippling



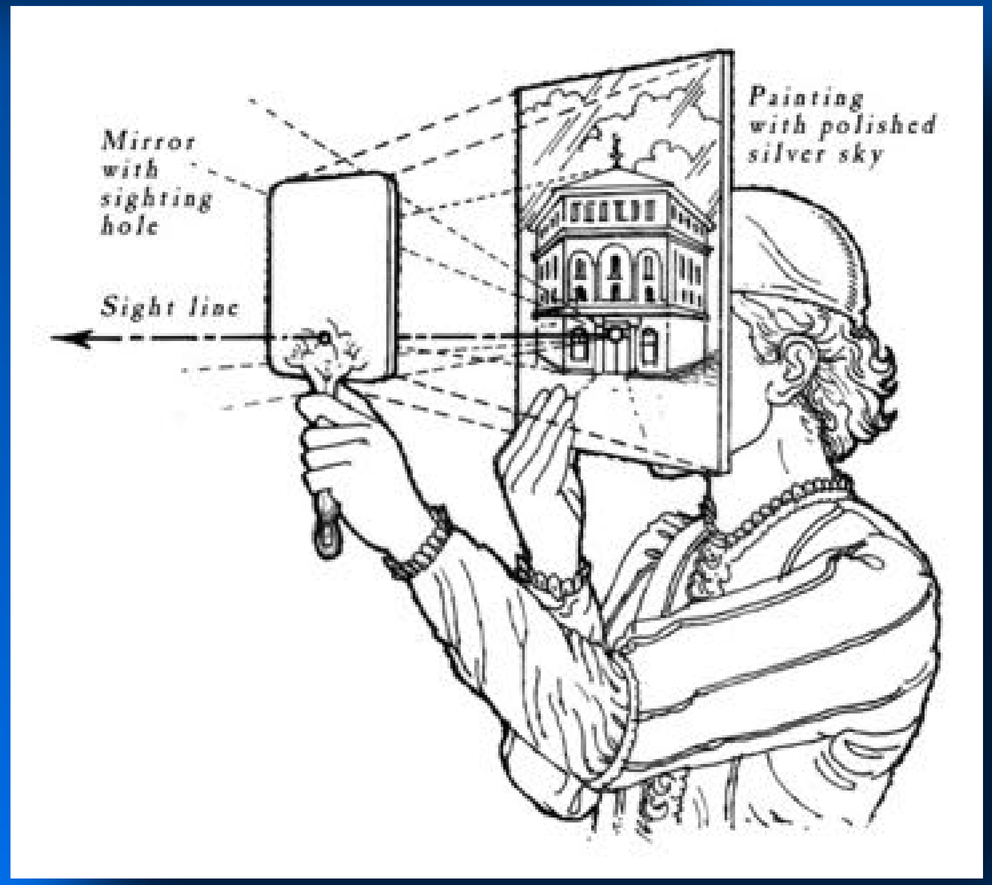
Description & Analysis of Morphology

Artistic & Architectural Origins



Filippo Brunelleschi (1377–1446)

Discovered that lines which were known to be parallel appeared to converge to a single (vanishing) point and recognized his principle could be used to calculate depth either for representational or analytic purposes.



Description & Analysis of Morphology

Issues with Scientific Illustration by Drawing/Painting

Advantages

- Fast, flexible and inexpensive.
- Reproduces well in publications.
- Level of complexity can be graded on the project's needs/ requirements.

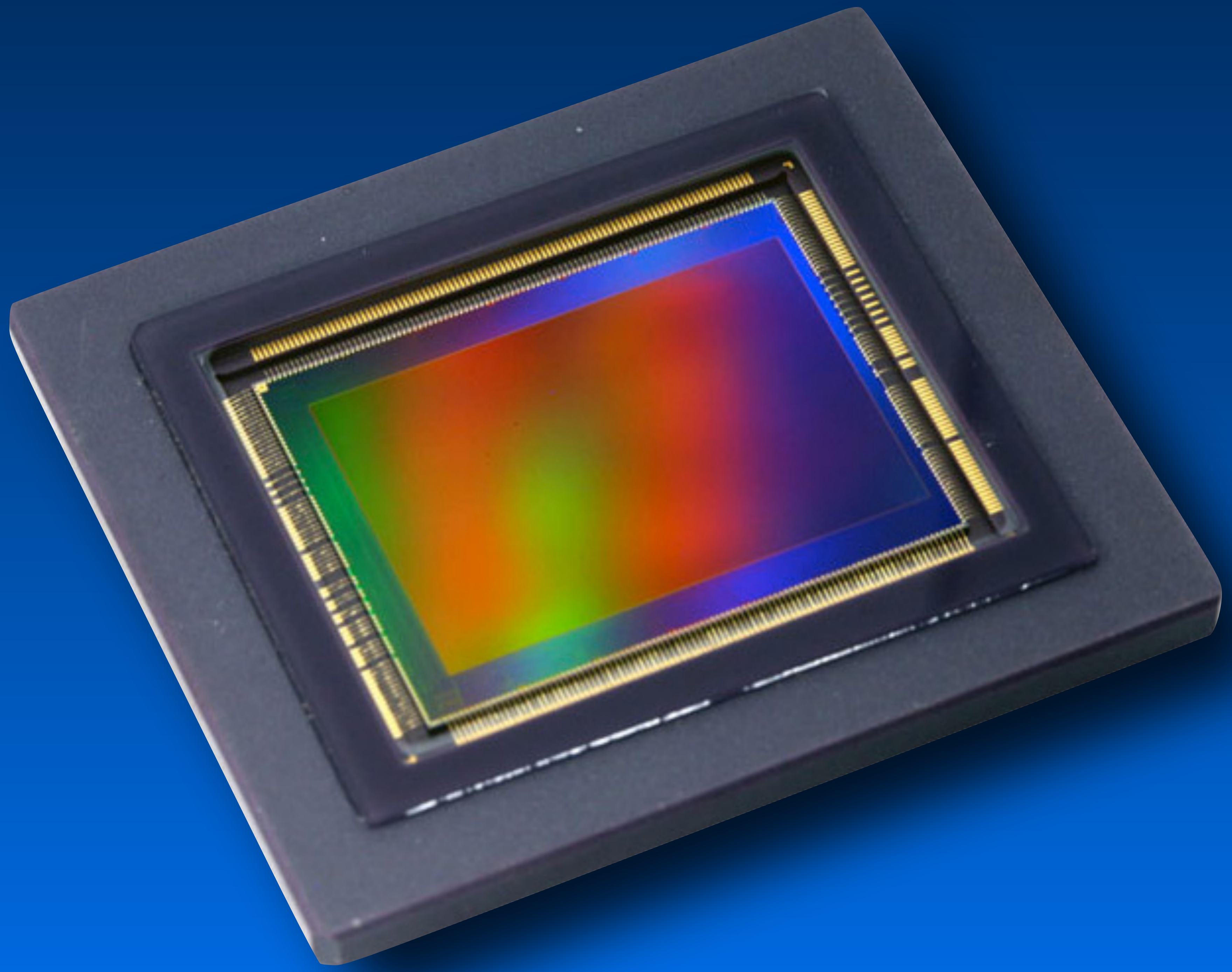
Disadvantages

- Inherently subjective.
- Often involves a collaboration between a scientist and an artist which, in turn, raises issues of communication and control.
- Standards for a "good" scientific illustration are quite different from standards for a "good" artwork.

Description & Analysis of Morphology

Illustration: Photography

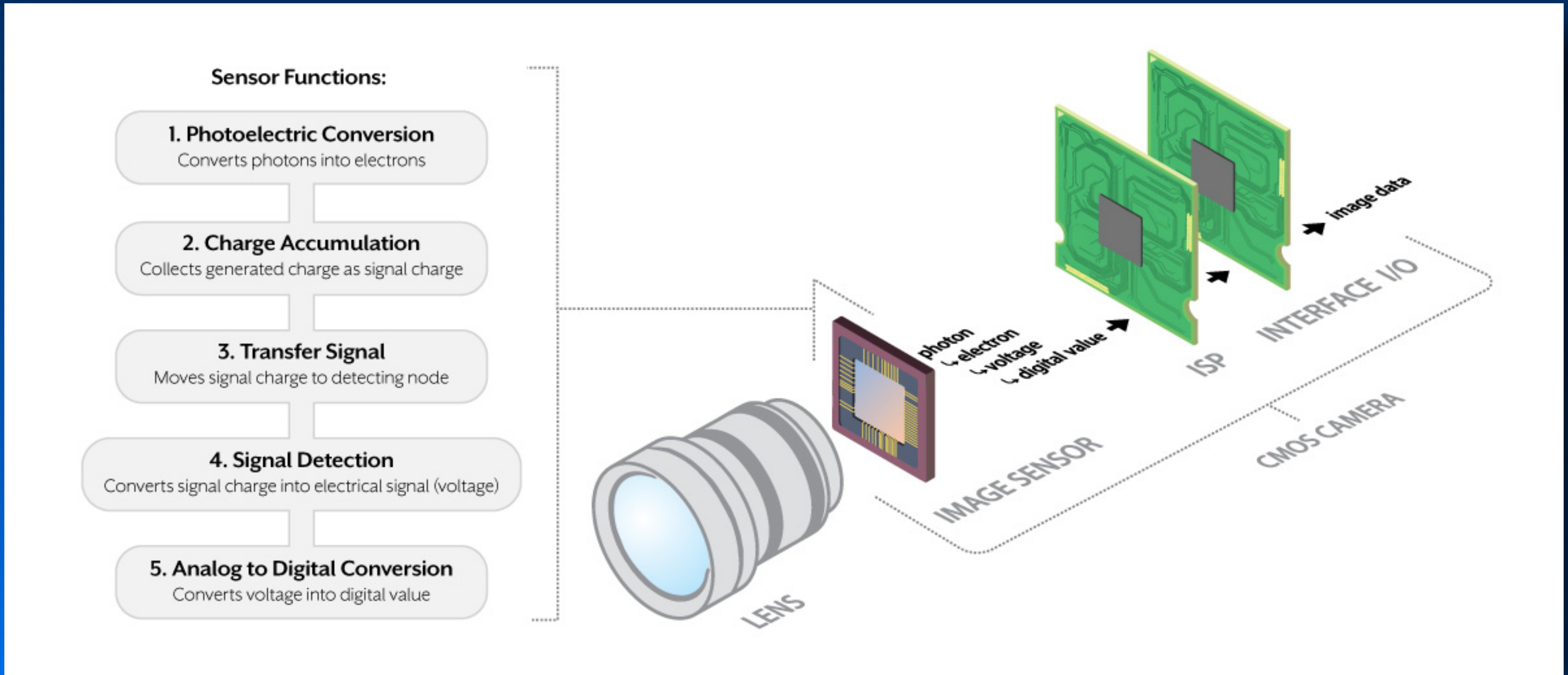
The art, application, and practice of creating durable images by recording light, either electronically by means of an image sensor, or chemically by means of a light-sensitive material such as photographic film.



Description & Analysis of Morphology

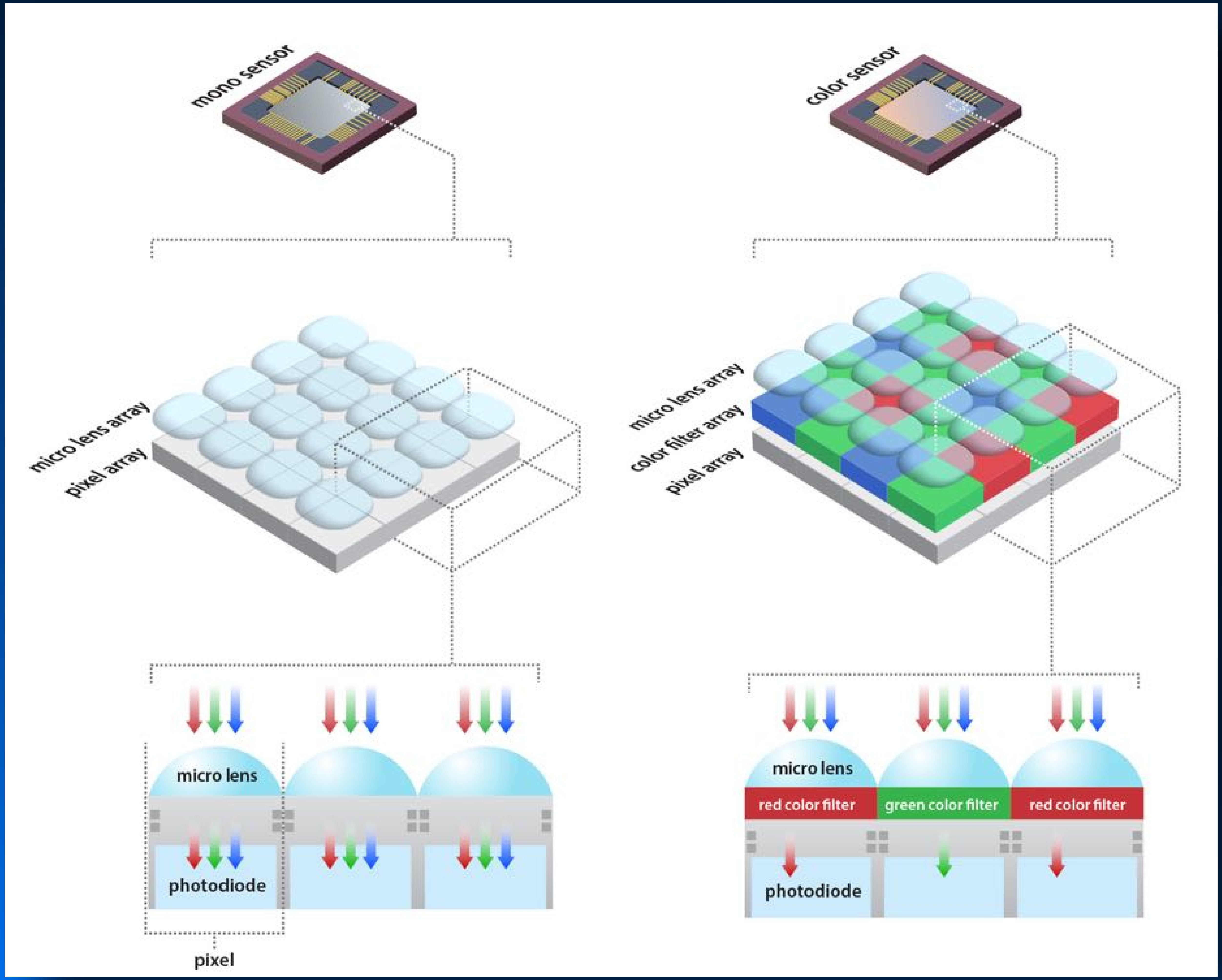
Illustration: Digital Photography

The art, application, and practice of creating durable images by recording light, either electronically by means of an image sensor, or chemically by means of a light-sensitive material such as photographic film.



Description & Analysis of Morphology

Illustration: Digital Photography

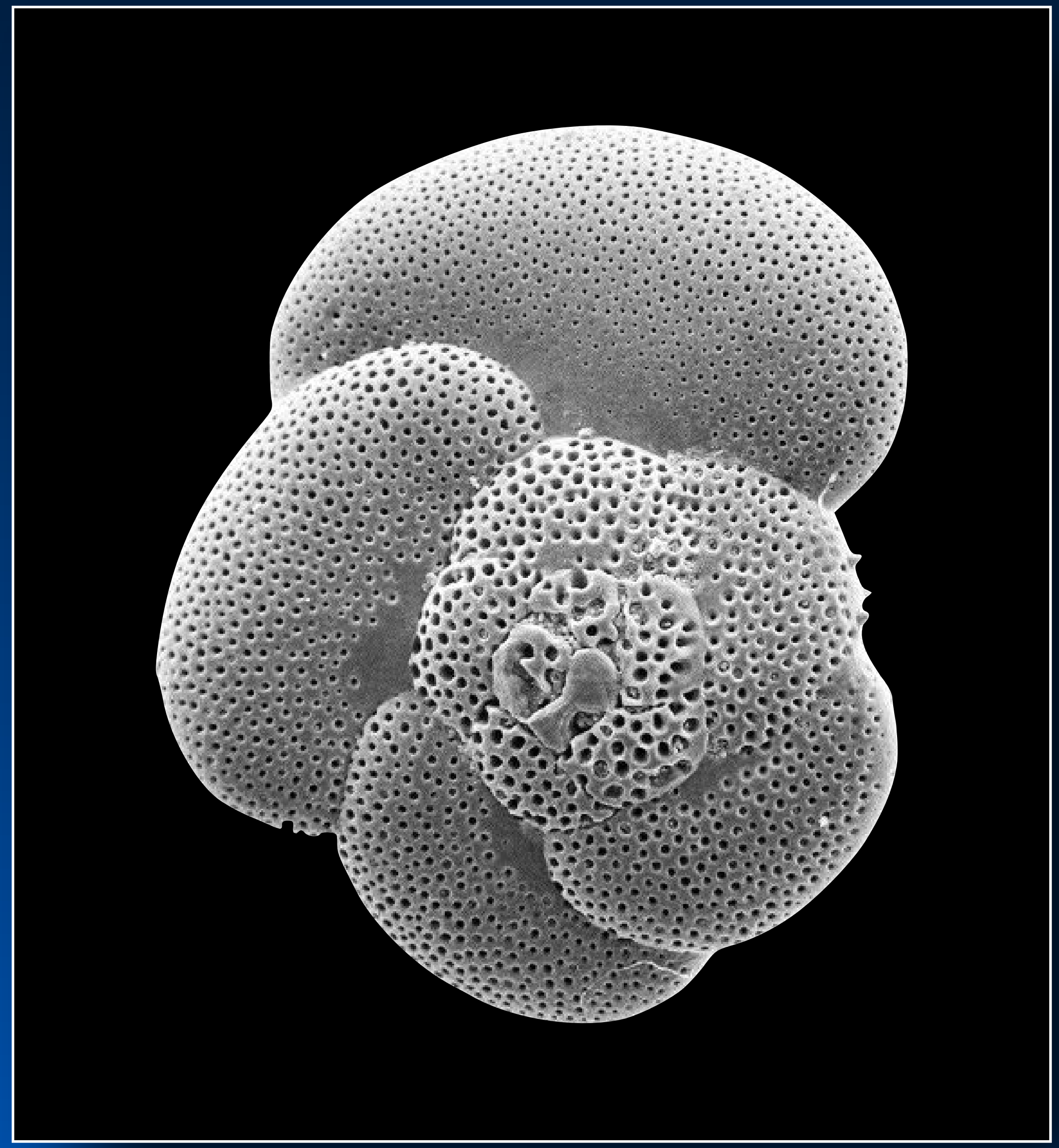


Description & Analysis of Morphology

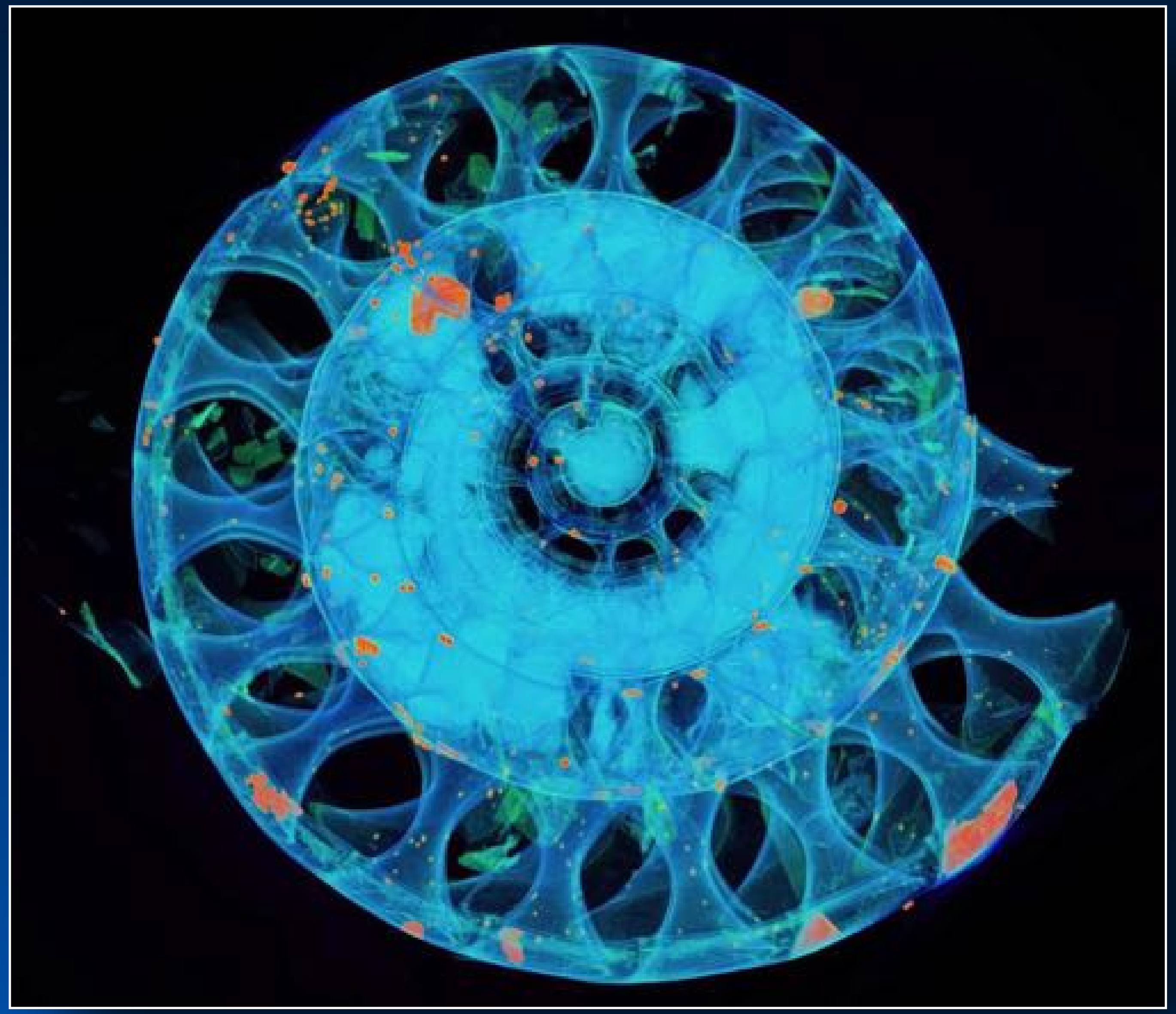
Illustration: Types of Images

Monochrome
Image

Color (RGB)
Image



Scanning Electron
Micrograph (SEM)

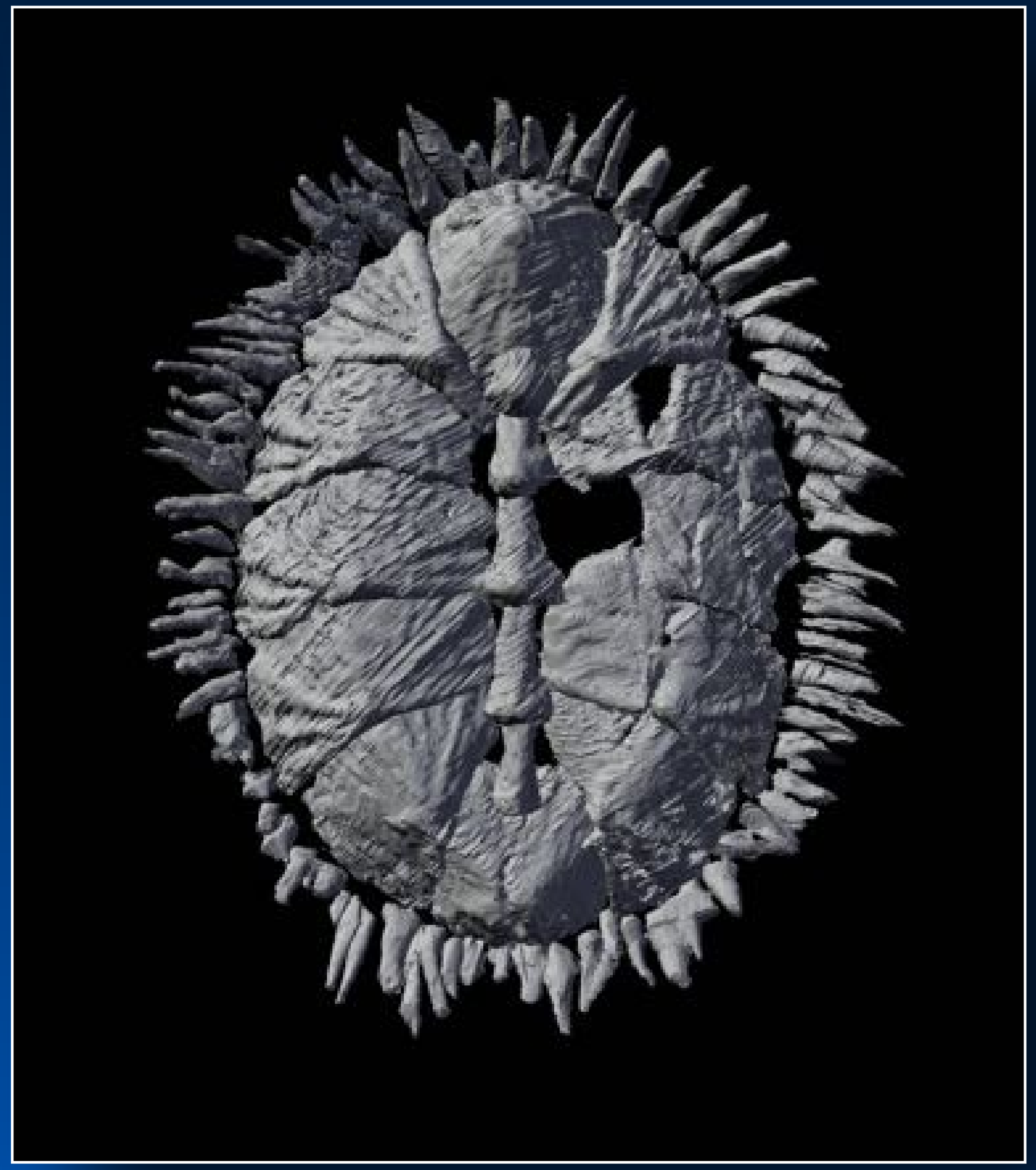


X-Ray
Image

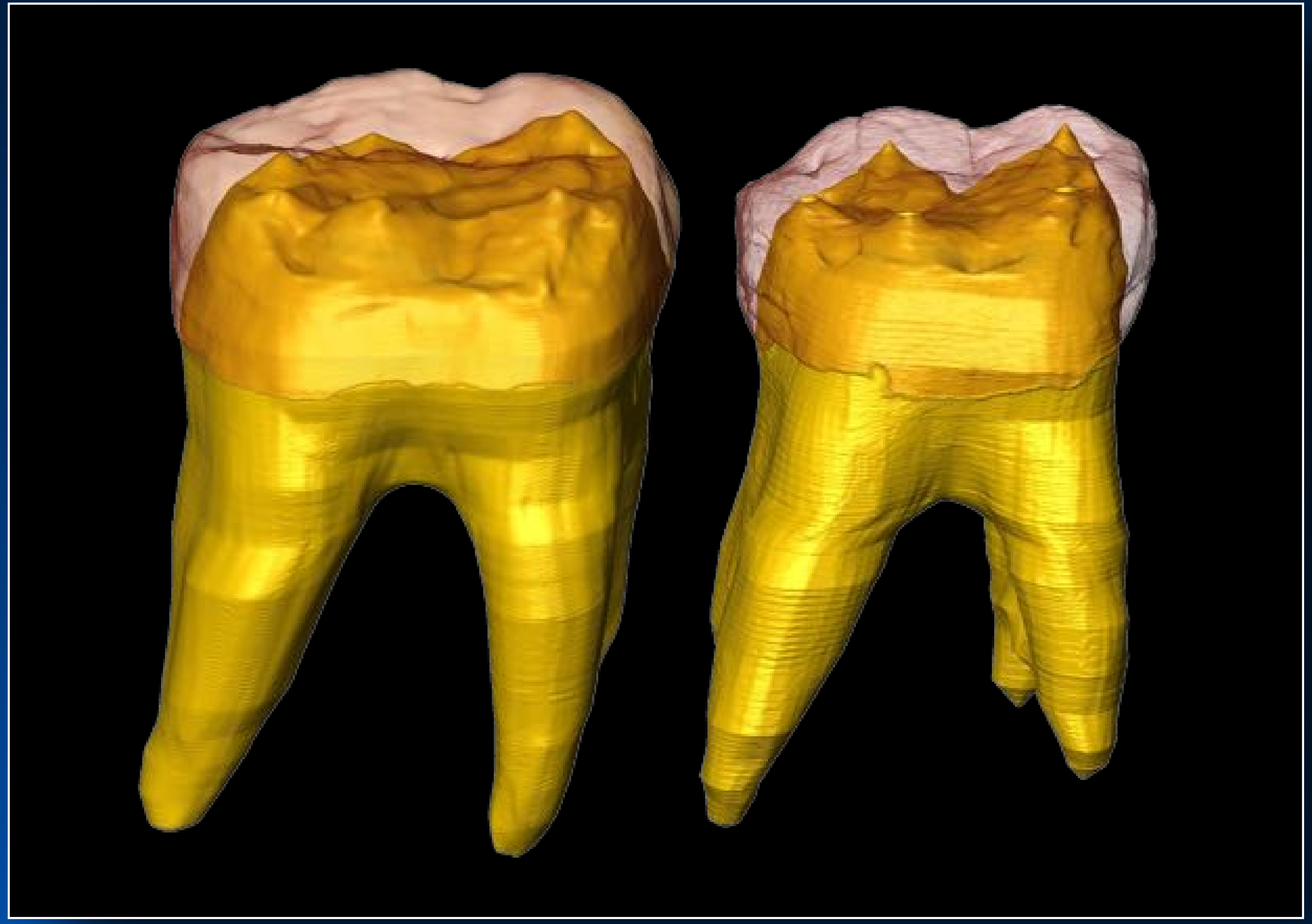
Description & Analysis of Morphology

Illustration: Types of Images

X-Ray (CT)
Tomograph



Magnetic
Resonance Image



Synchrotron
(n-µCT) Tomograph

Description & Analysis of Morphology

Issues with Scientific Illustration by Photography

Advantages

- Fast, flexible.
- Inherently objective.
- Reproduces well in publications.
- Often can be accomplished by researcher.
- Technology can be used to extend researcher’s level of perception.

Disadvantages

- Often involves a collaboration between a scientist and an artist which, in turn, raises issues of communication and control.
- Level of complexity cannot be graded based on the project’s needs/ requirements.
- Standards for a “good” scientific photograph quite different from standards for a “good” photograph.

Description & Analysis of Morphology

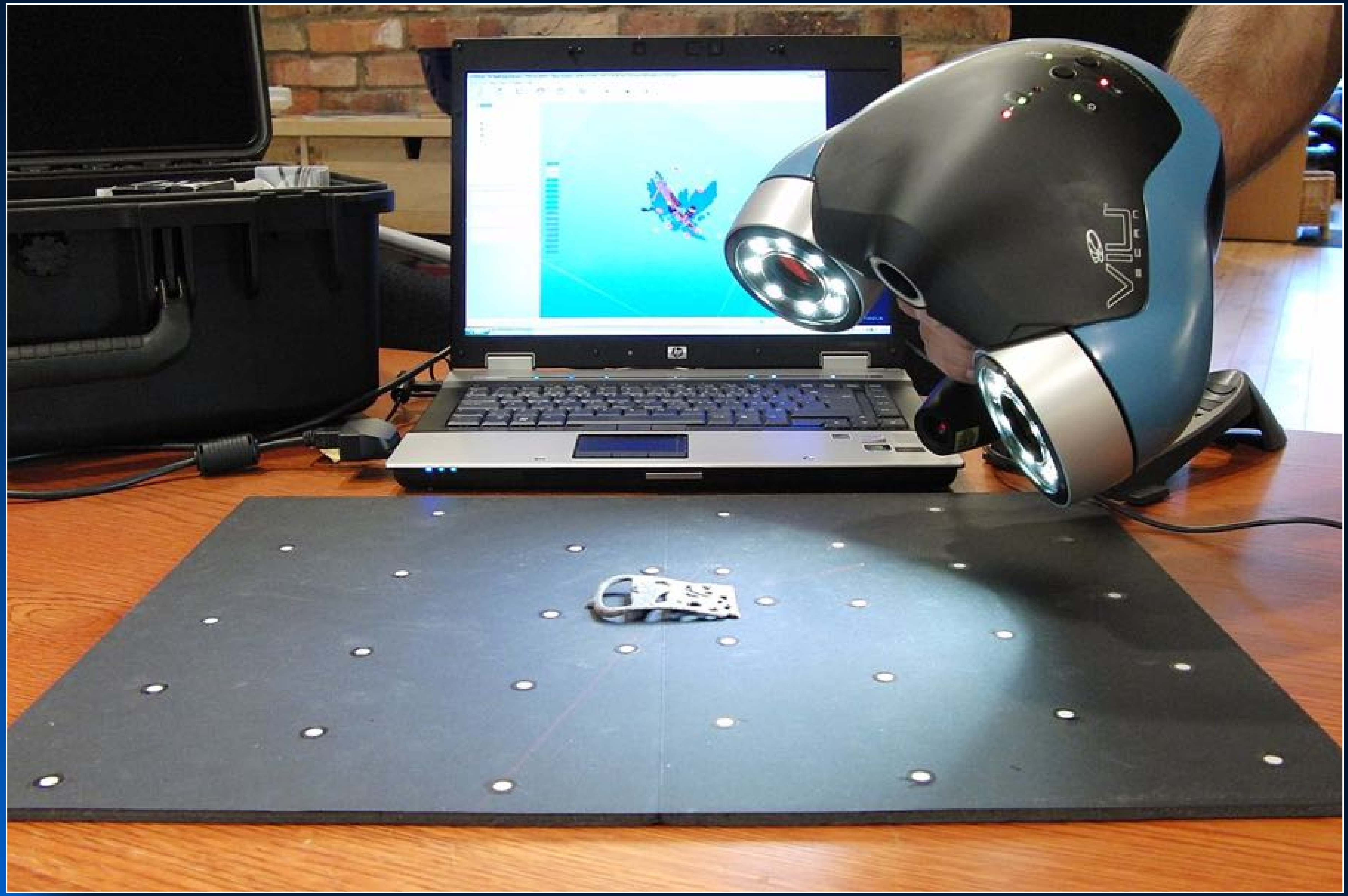
Illustration: 3D Digitzation/Scanning

The process of collection three-dimensional data from the surface of a real-world object or set of objects in order to represent, model and/or analyze its/their shape and/or appearance (e.g. color).

Description & Analysis of Morphology

Illustration: 3D Digitzation/Scanning

Contact Digitizers
(Microscribe)

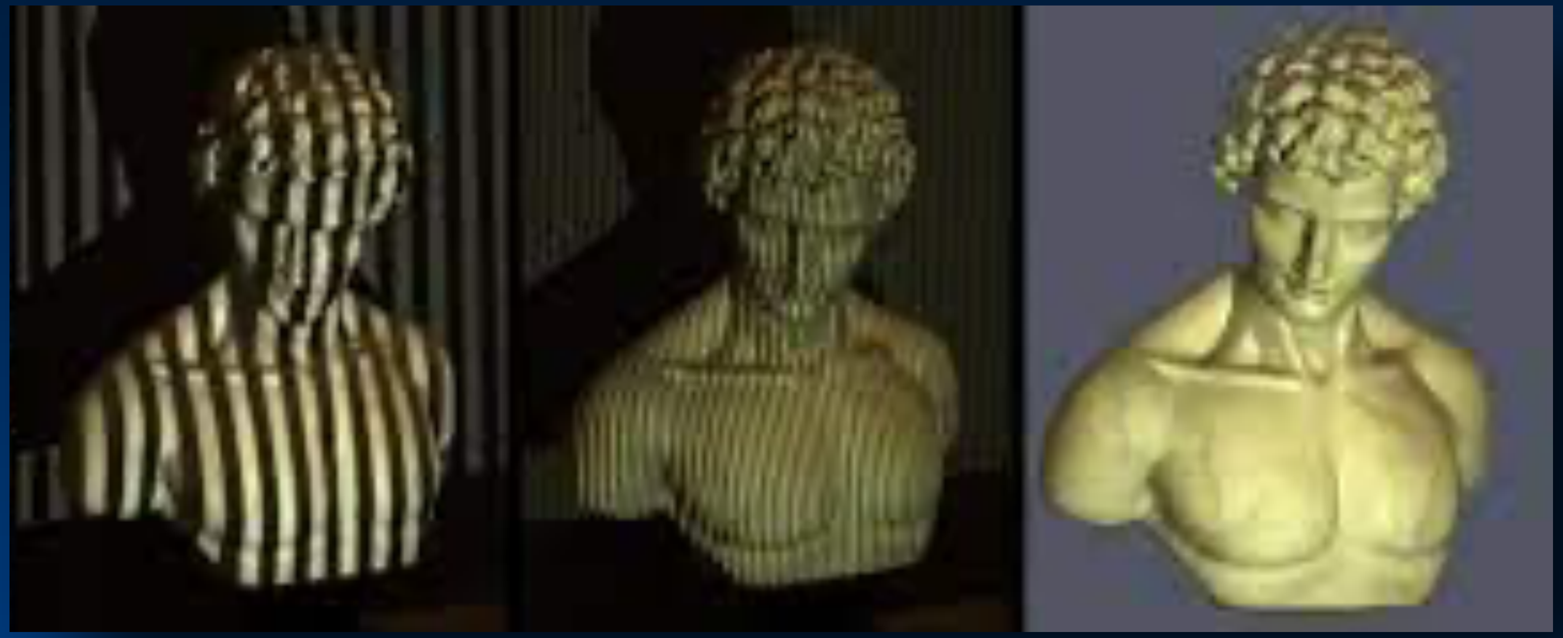


Non-Contact Digitizers
(VIUScan 3D)

Description & Analysis of Morphology

Illustration: Non-Contact 3D Digitzation/Scanning

Time-of-Flight
3D Digitizers

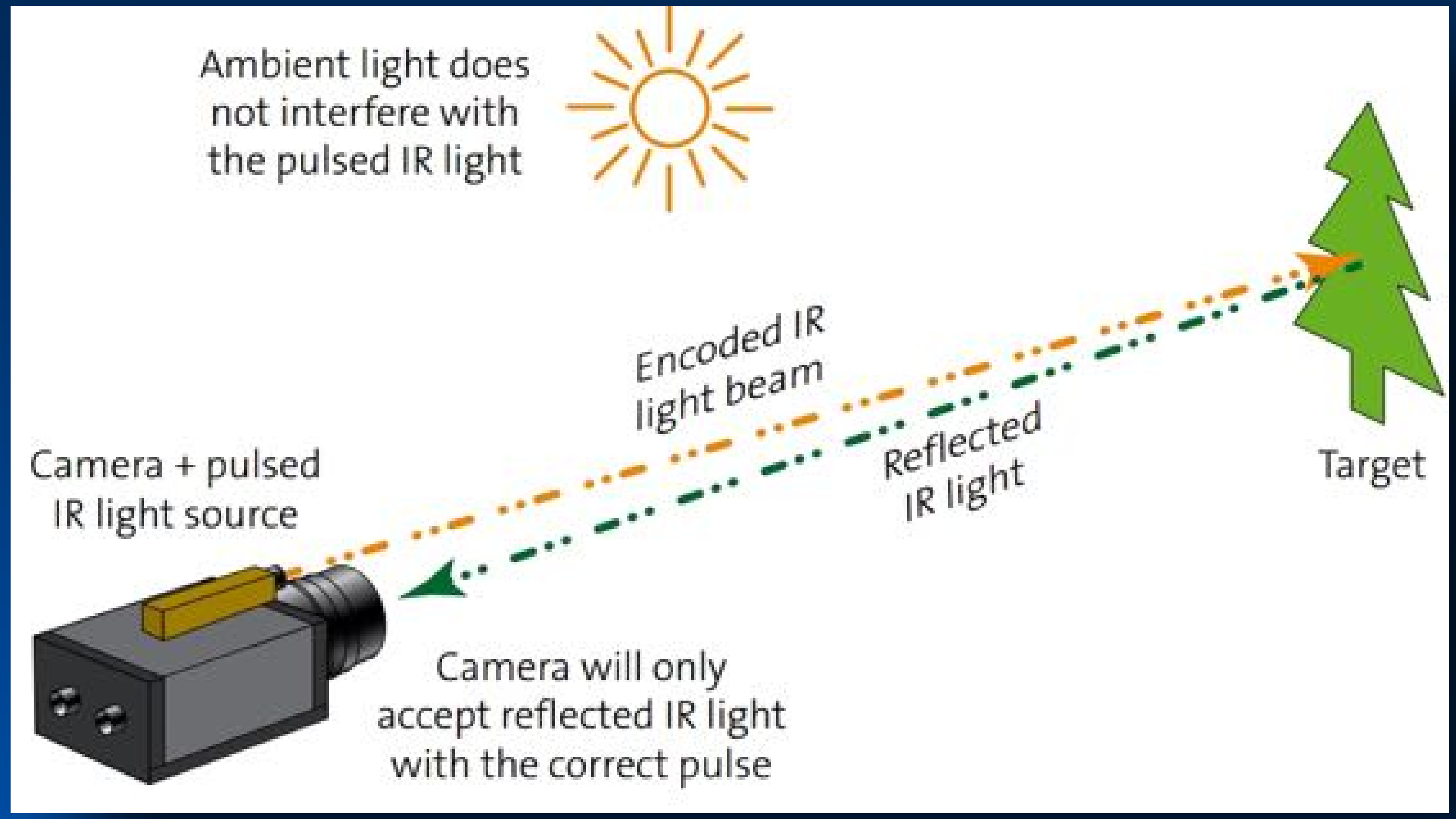


Structured- Light
3D Digitizers

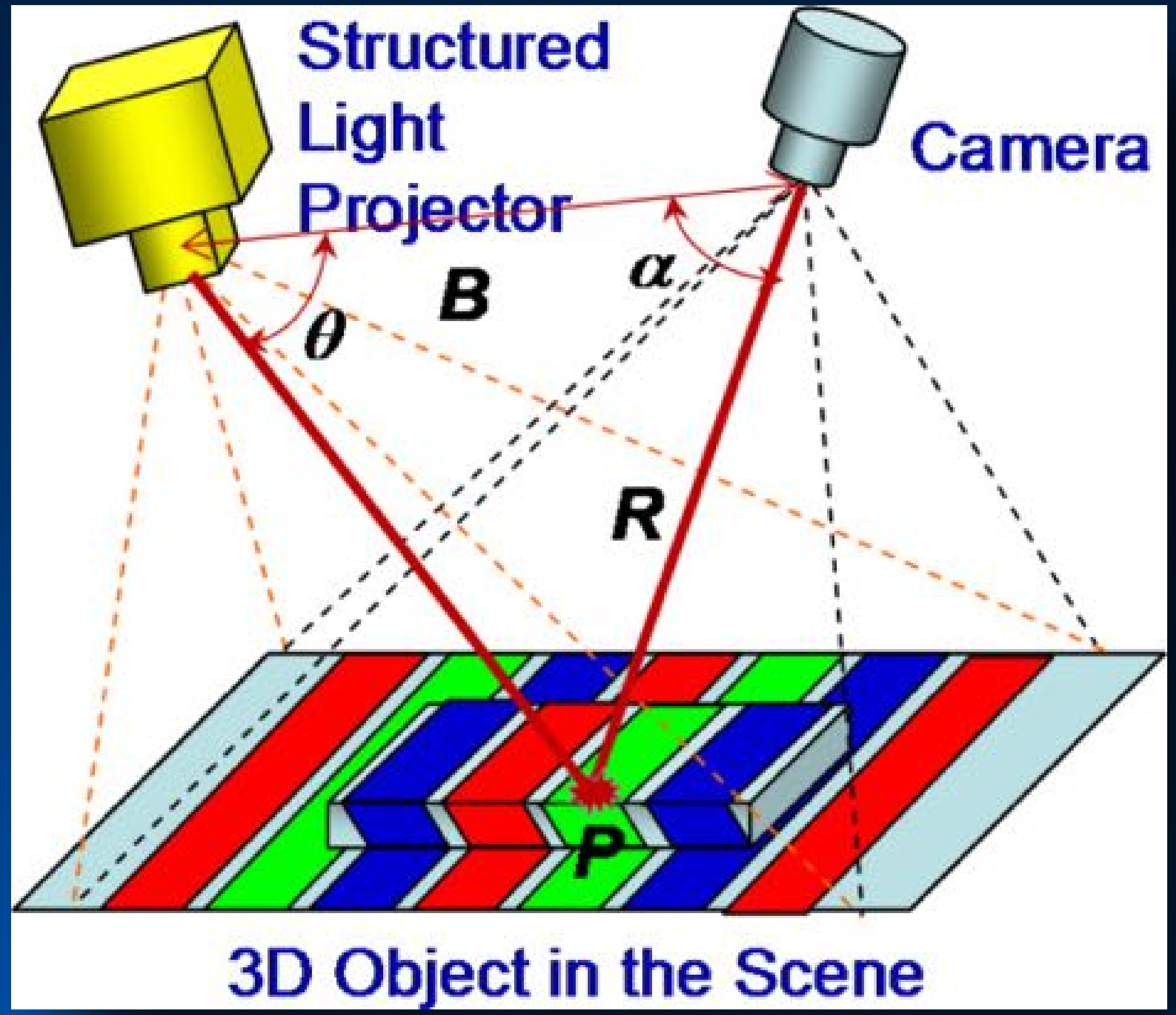
Phase-Shift
3D Digitizers

Description & Analysis of Morphology

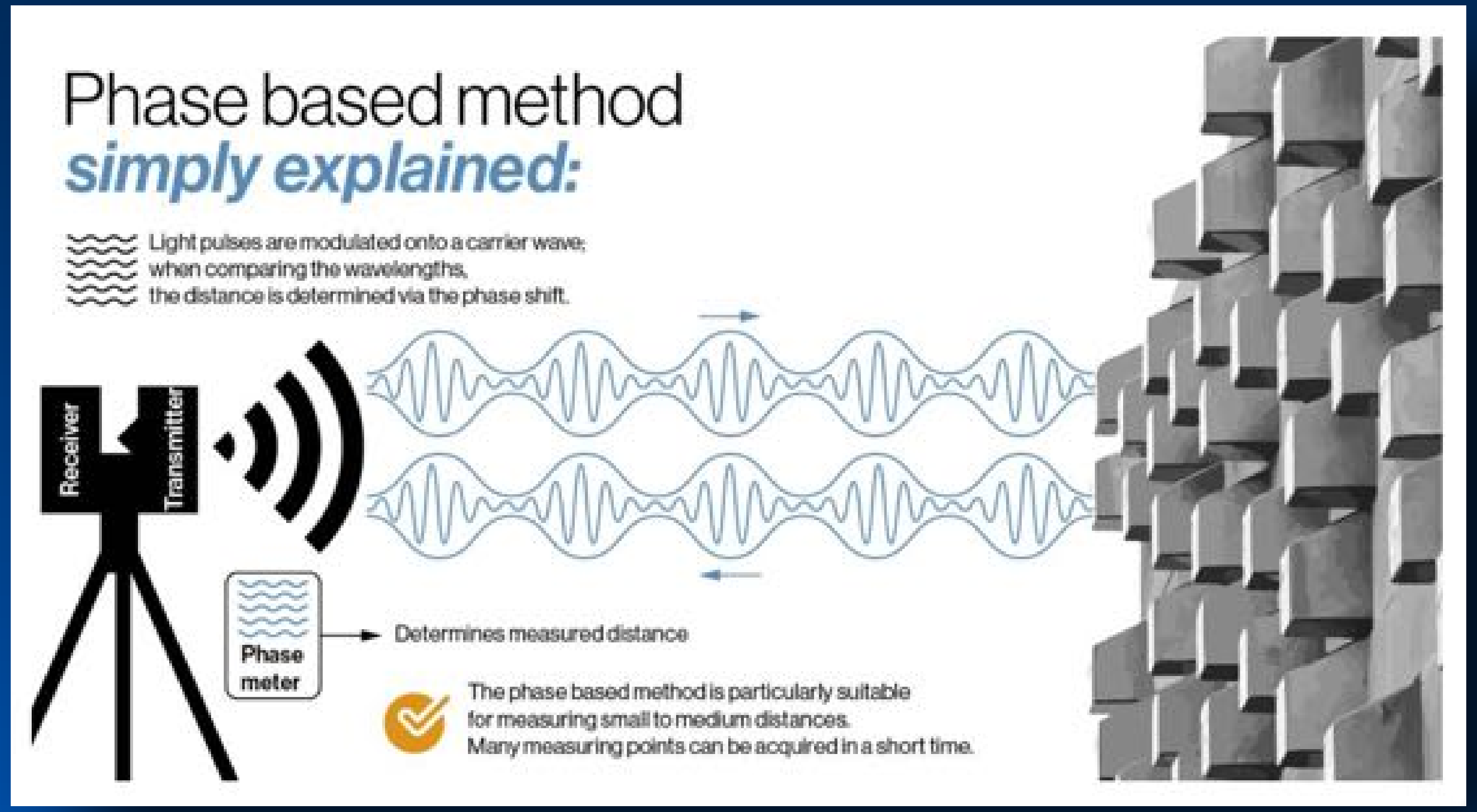
Illustration: Non-Contact 3D Digitzation/Scanning



Time-of-Flight
3D Digitizers



Structured- Light
3D Digitizers



Phase-Shift
3D Digitizers

Description & Analysis of Morphology

Issues with Scientific Illustration by 3D Digitization

Advantages

- Inherently objective.
- Technology can be used to extend researcher's level of perception.
- Fairly good results can be obtained with a minimum of training.

Disadvantages

- Slow & cumbersome.
- Expensive.
- Not suitable for print publications.
- Level of complexity cannot be graded based on the project's needs/ requirements.
- Complete "watertight" models of fossils difficult and time-consuming to achieve.

Description & Analysis of Morphology

Analysis: Morphometrics

Central tendency (mean)?
Modal Shape(s)?
Distribution of modes?
Continuous or discontinuous variation?

Covariance with environment?
Covariance with ecology?
Covariance with geography?
Covariance with genotype?

Description & Analysis of Morphology

Morphometrics

Zoological Systematics, 42(1): 4–33 (January 2017), DOI: 10.11865/zs.201702

REVIEW

Morphometrics: History, development, methods and prospects

Norman MacLeod

The Natural History Museum, Cromwell Road, London SW7 5BD, UK; E-mail: N.MacLeod@nhm.ac.uk

Abstract Morphometrics has been pursued by graphical and computational means since the European Renaissance, drawing on core geometric principles first discovered in China and Classical Greece. Through the late 1800s, two distinct approaches to such analyses were pursued: a deformationist approach, epitomized by D'Arcy Thompson's graphical trans-formation grids and the statistical approach popularized by Francis Galton, Karl Pearson, and Julian Huxley in which Cartesian spaces were employed to summarize patterns of variation in size and/or shape variables. Unification of these approaches was an oft-stated goal throughout the 20th century, but proved elusive until the mid-1980s when David Kendall, Fred Bookstein, and Colin Goodall proposed a radically new way of understanding form — as the locations of configurations of landmarks on the surfaces of a nested series of hyperdimensional manifolds. Once this new mathematics of form was understood development of basic concepts, procedures, graphical tools, and statistical tests followed quickly such that the core of the long-hoped for synthesis took less than a decade to achieve. The result — geometric morphometrics — continues to develop into an ever-more extensive toolkit that can be used by researchers to describe and understand a wide range of problems involving the characterization of morphological similarities and differences in all of their many and varied contexts. In particular, the new approaches involving the direct analysis of image pixels and new tools such as machine learning and artificial intelligence are set to reinvigorate (and possibly to revolutionize) the field once again.

Key words Morphometrics, form, size, shape, biology, geometry.

1 Introduction

Morphology is a critical source of information throughout the natural sciences, materials sciences, and engineering. Across all these fields an object's form consists of two primary components: size and shape. Size is the physical scale of an object, usually determined by comparing one or more of its spatial dimensions (e.g., diameter, height, length, width, perimeter, area, volume, mass) to a reference which serves as a basis for measurement. Shape is also usually conceptualized via comparison to some reference (e.g., circle, triangle, mean distance, mean point configuration) and has been defined operationally as that component of form which remains after differences in size, position and rotation between two or more objects have been discarded (Kendall, 1977). Morphometrics, then, is the quantitative analysis of form and covariances with form (Bookstein, 1991). While this domain overlaps strongly with that of geometry, to date morphometrics has been pursued in descriptive biological contexts of far more restricted scope than those of geometry, biometry and/or spatial analysis, despite the fact that all these fields share a common origin.

The Chinese philosopher Mozi (470-390 BC) authored the earliest known description of a mathematical point which he defined as the part of a line which cannot be divided into smaller parts (Needham, 1959). Mozi, like Plato and Euclid who established geometry as the foundation of mathematics in western Europe, noted that a line segment is a one-dimensional figure joining two mathematical points in space and that the length of a line segment records the separation between its defining endpoints. These concepts of point and separation are fundamental to morphometrics where point

Special Issue: Geometric morphometrics: Current shape and future directions
Received 6 October 2016, accepted 6 January 2017
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MacLeod, N., 2017, Morphometrics: history, development methods and prospects: Zoological Systematics, v. 42, p. 4–33, doi:10.11865/zs.201702.

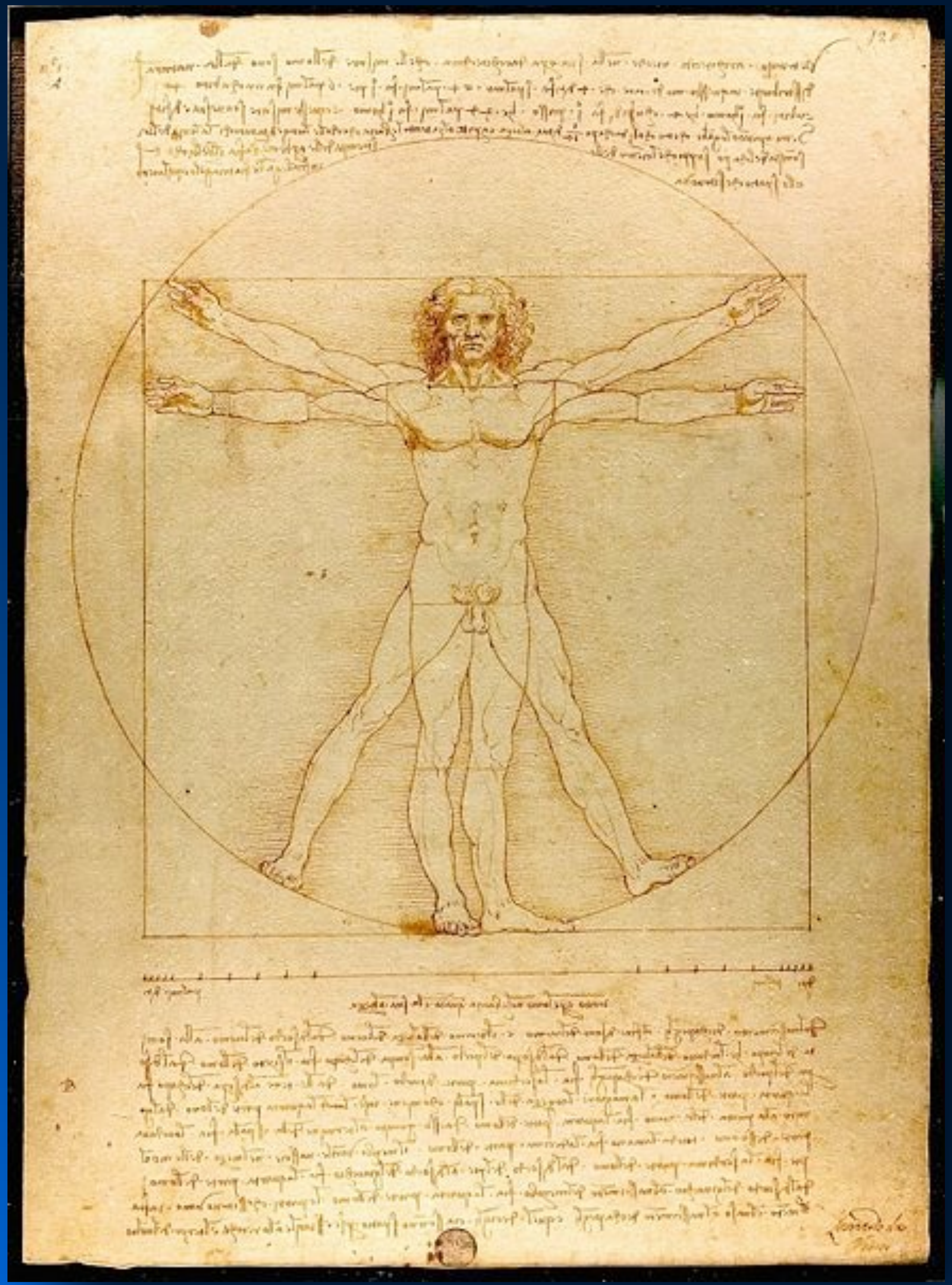
Topics

- Traditional approaches to morphometric data collection
  - Linear Distances
  - Landmarks
  - Boundary Outlines
- The geometric morphometric synthesis
- Example analyses
- Post-synthesis developments
- Future directions

Description & Analysis of Morphology

Artistic & Architectural Origins

Leonardo da Vinci
(1452 - 1519)



Vitruvian Man
(c. 1487)

Diagram illustrating ideal proportions of the human form (male version) as a guide to architectural design.

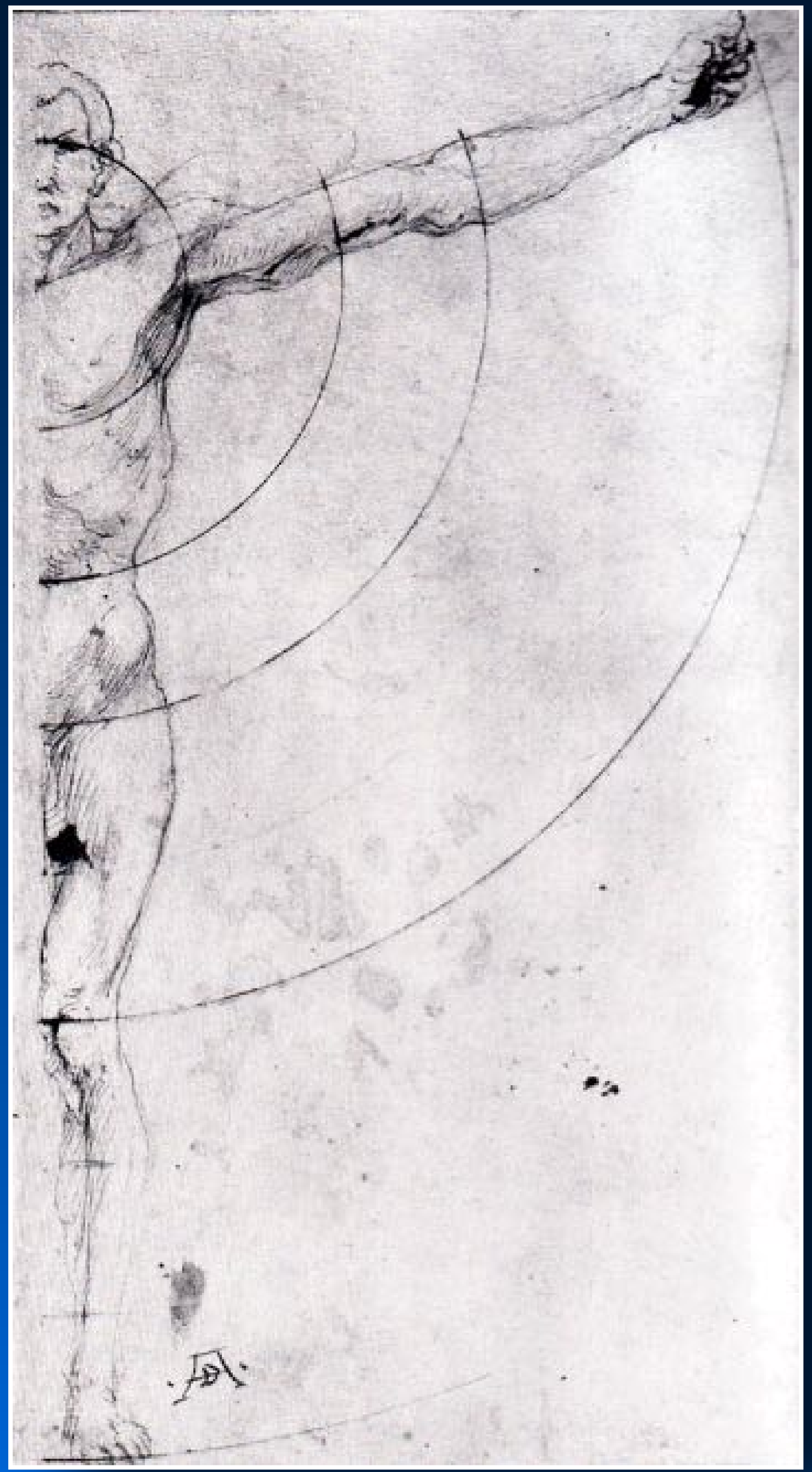
- Palm = 4 fingers
- Foot = 4 palms
- Cubit = 6 palms
- Pace = 4 cubits
- Man = 4 cubits or 24 palms

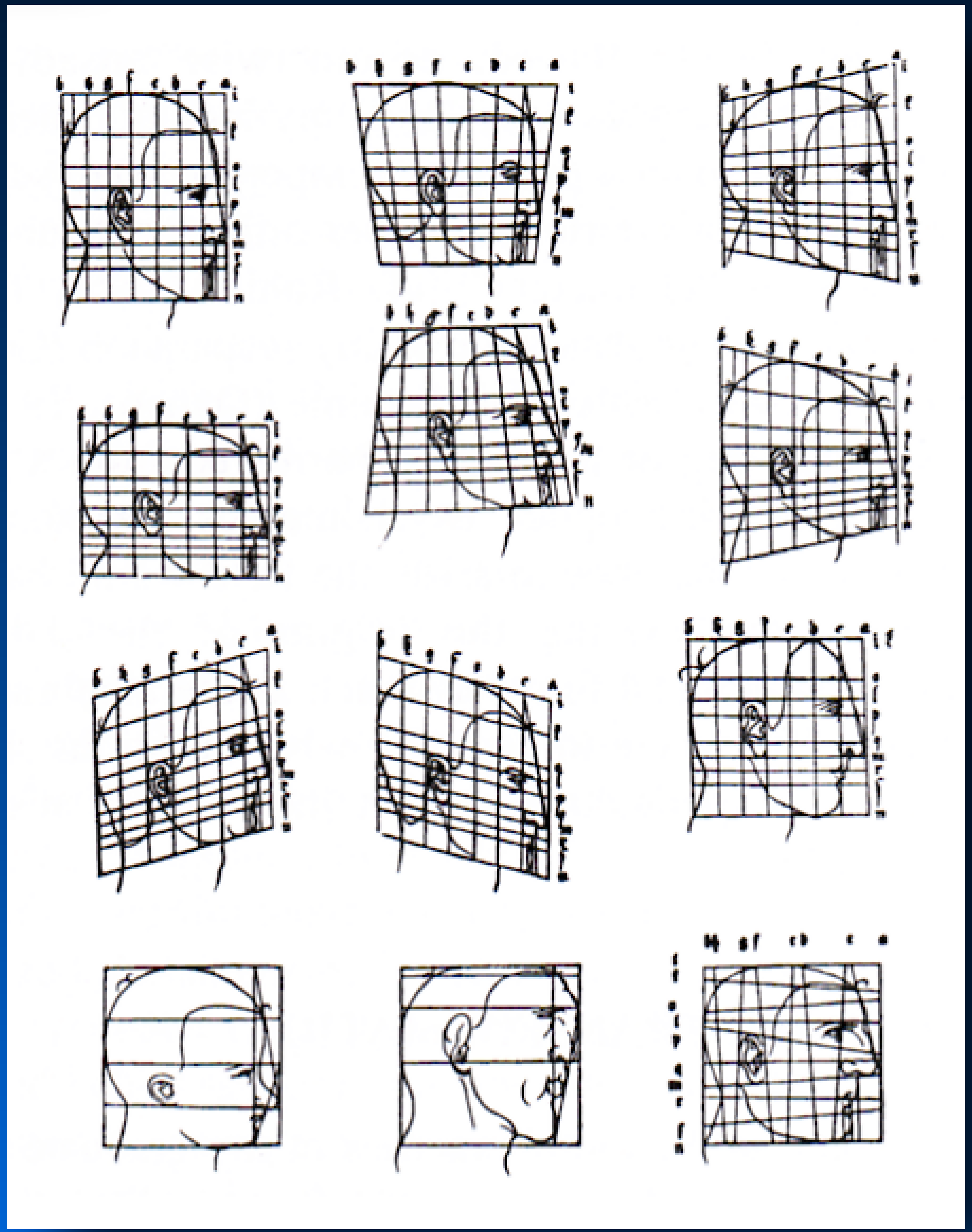
If you open your legs enough that your head is lowered by one-fourteenth of your height and raise your hands enough that your extended fingers touch the line of the top of your head, know that the centre of the extended limbs will be the navel, and the space between the legs will be an equilateral triangle.

Description & Analysis of Morphology

Artistic & Architectural Origins

Albrecht Dürer
(1471 - 1528)





Vire Bücher von Menchlicher
Proportion (1524)

Description & Analysis of Morphology

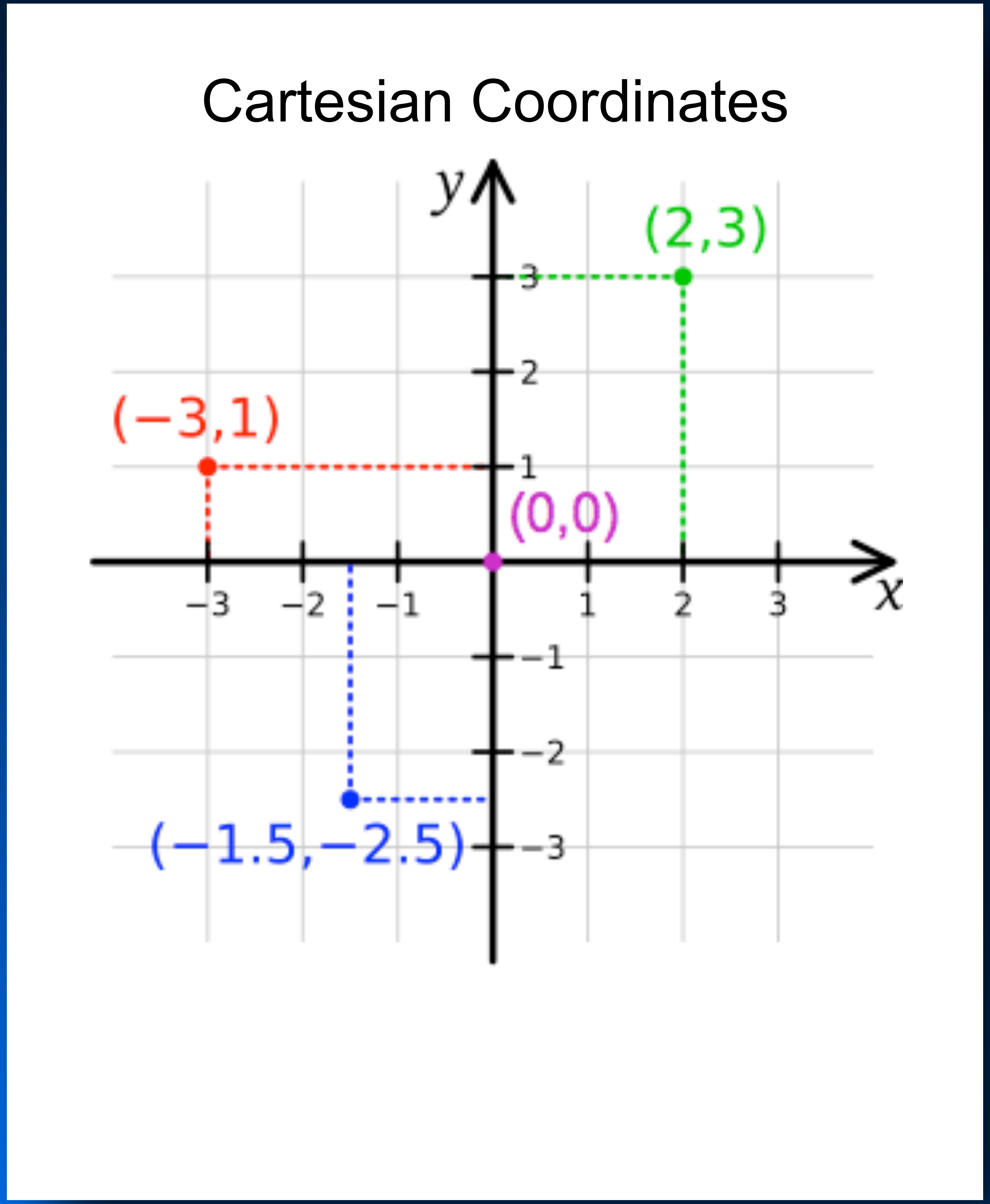
Mathematical Origins

Description & Analysis of Morphology

Mathematical Origins

René Descartes
(1596 - 1650)

Developed a graphic system within which any shape could be represented and any geometry ordinated. This formed the basis of analytic geometry which forged a critical link between algebra and geometry



Discours de la Methode
(1637)

Description & Analysis of Morphology

Mathematical Origins

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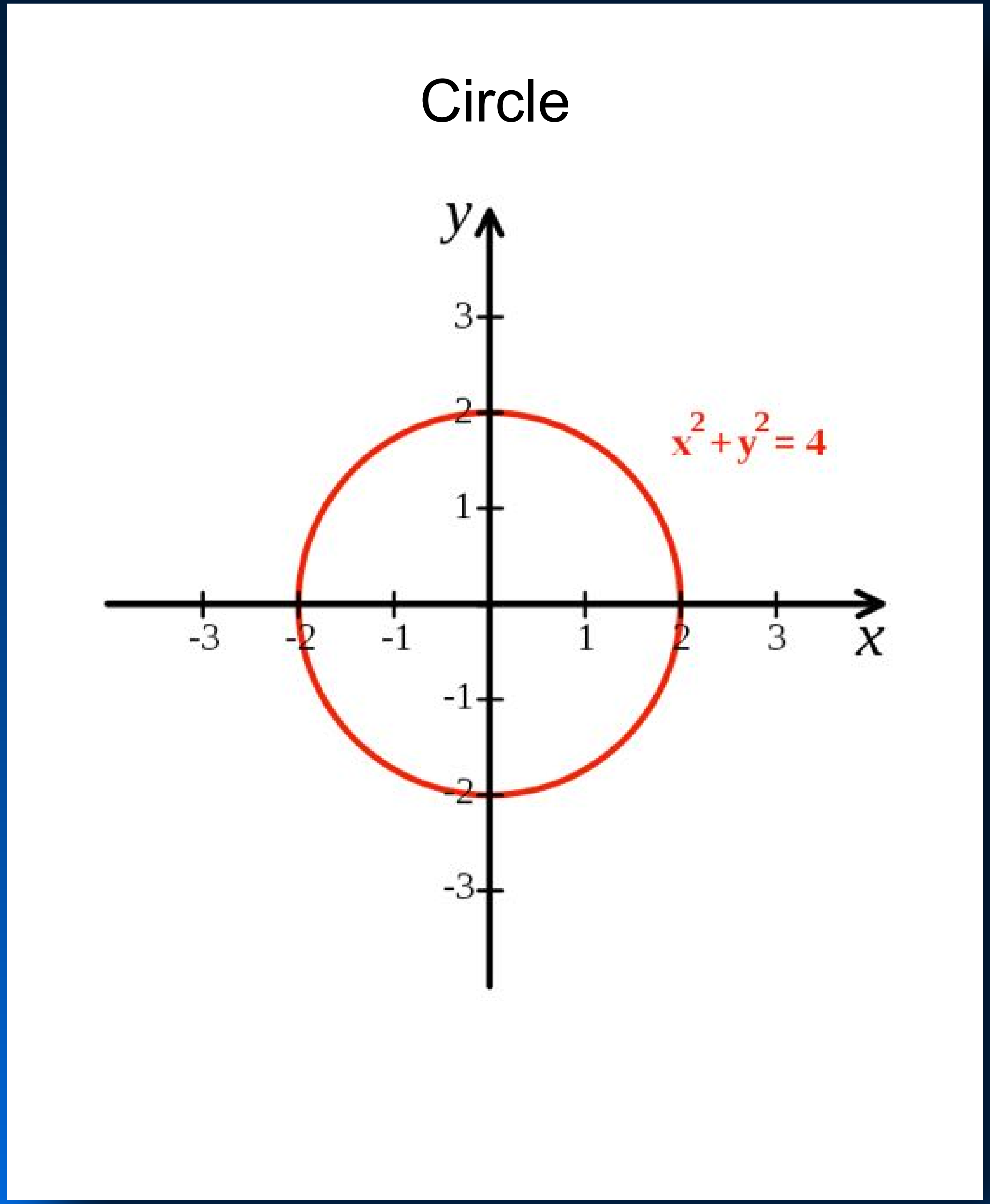

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Description & Analysis of Morphology

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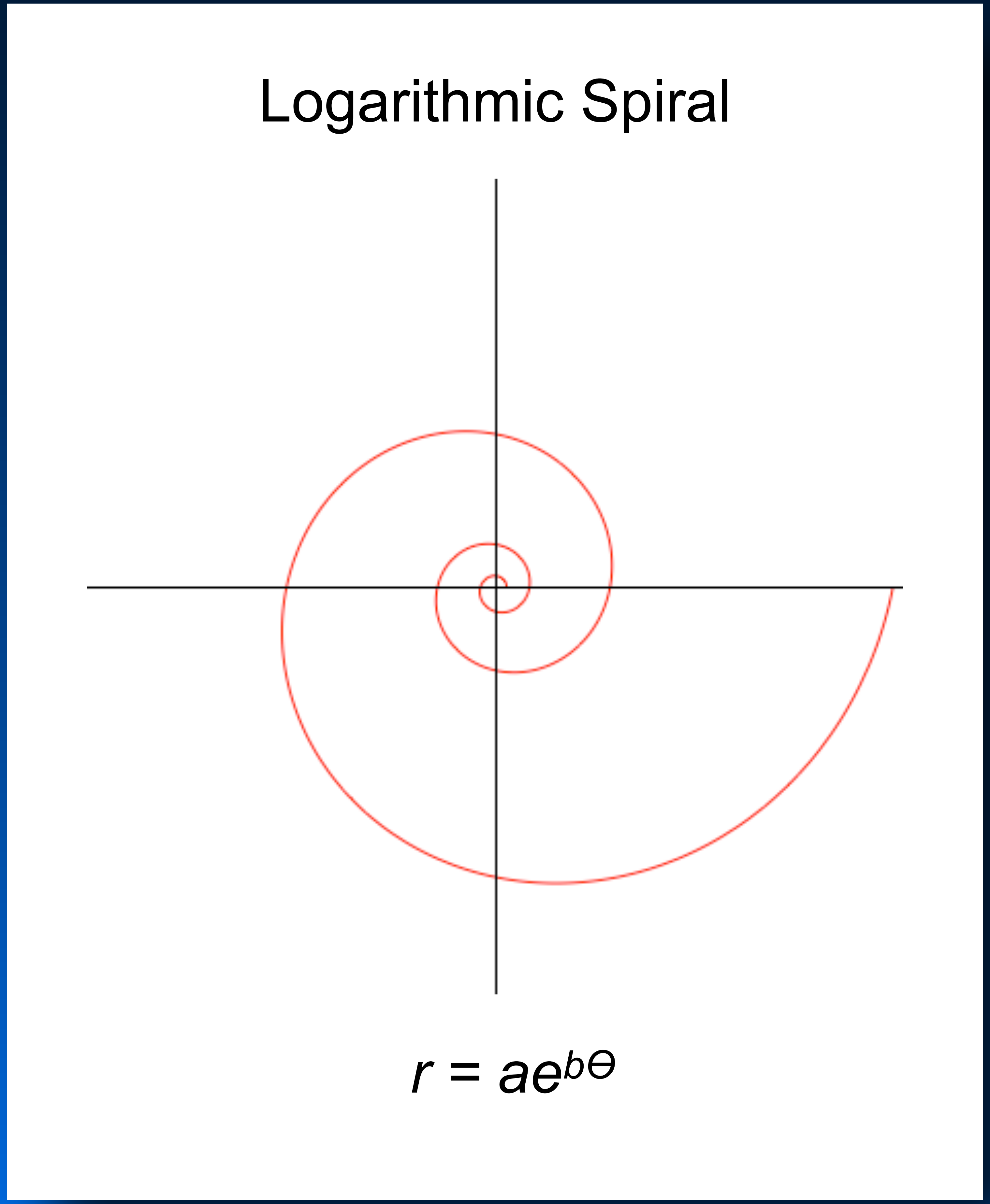
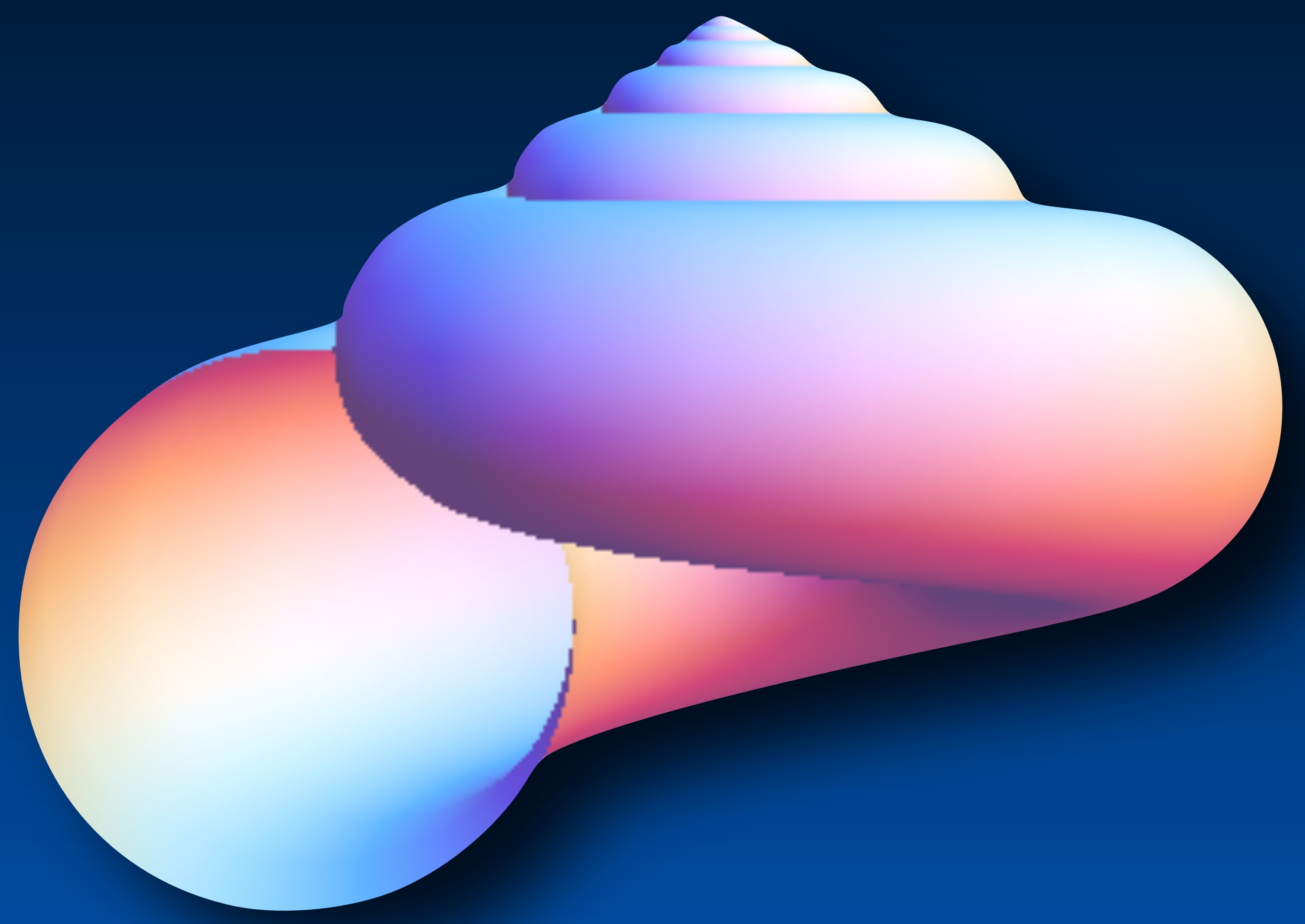
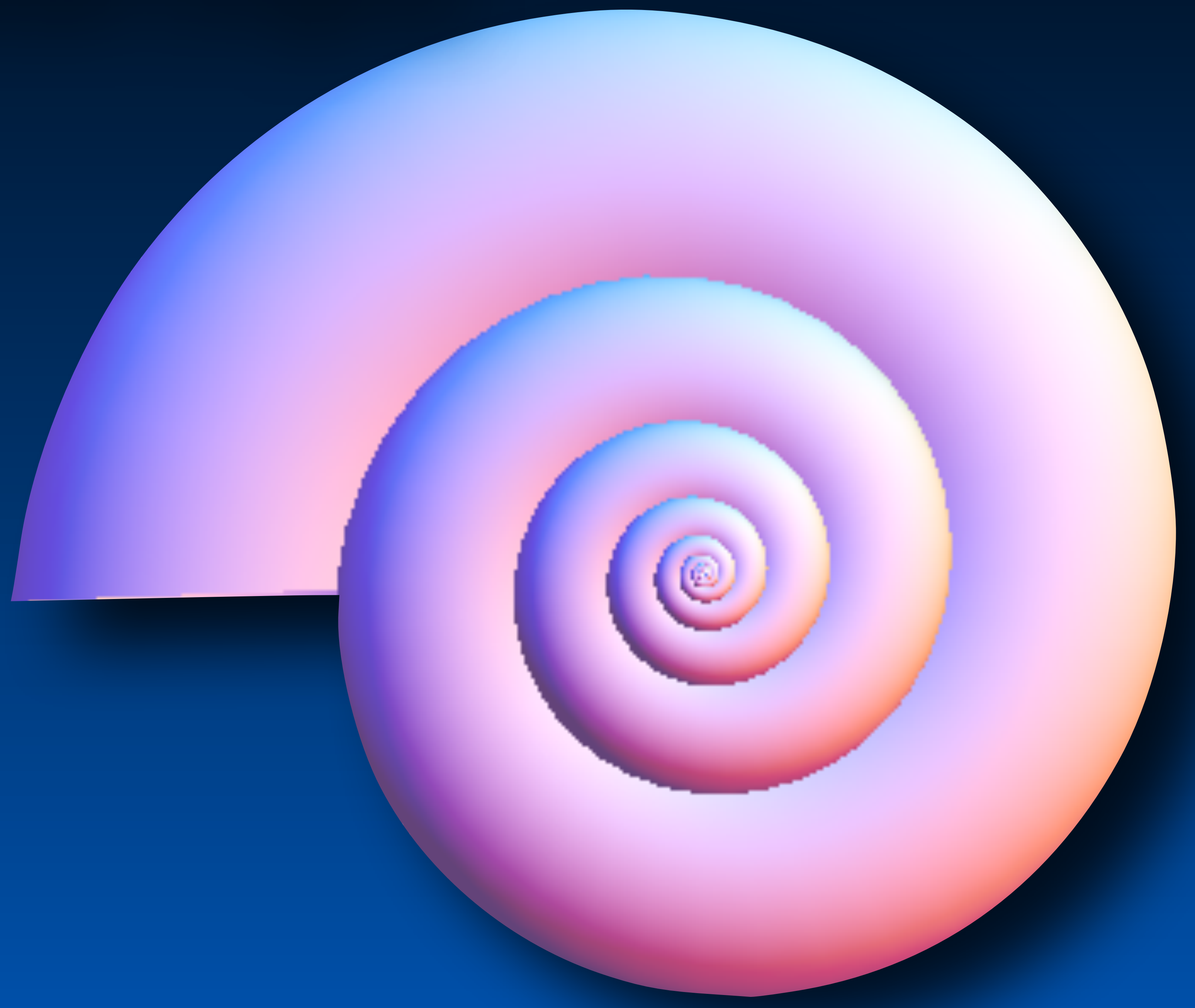


Discours de la Methode
(1637)

Description & Analysis of Morphology

Mathematical Origins





$$r_{\theta,\phi} = w^{\theta/2\pi}\left\{\cos\theta\left(1+\frac{1-d}{1+d}\cos\phi\right),\sin\theta\left(1+\frac{1-d}{1+d}\cos\phi\right),-t\left(1+\frac{1-d}{1+d}\sin\phi\right)\right\}$$

Description & Analysis of Morphology

Morphometric Data


Anisotremus virginicus


Anthias anthias


Anthias argus


Archosargus rhomboidalis


Chelmon rostratus


Conodon nobilis


Epinephelus merra

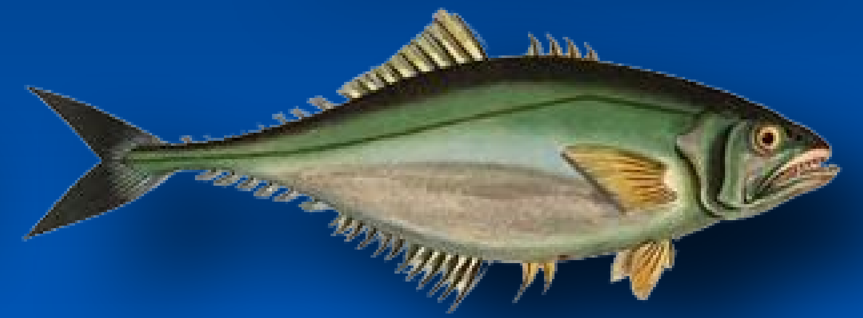

Gerres erythrourus


Holacanthus ciliaris


Holocentrus ascensionis


Johnius carutta


Lonchurus lanceolatus


Oligoplites saliens


Ophiocara macrolepidota


Perca fluviatilis


Pomacentrus pavo


Pomadasys furcatus

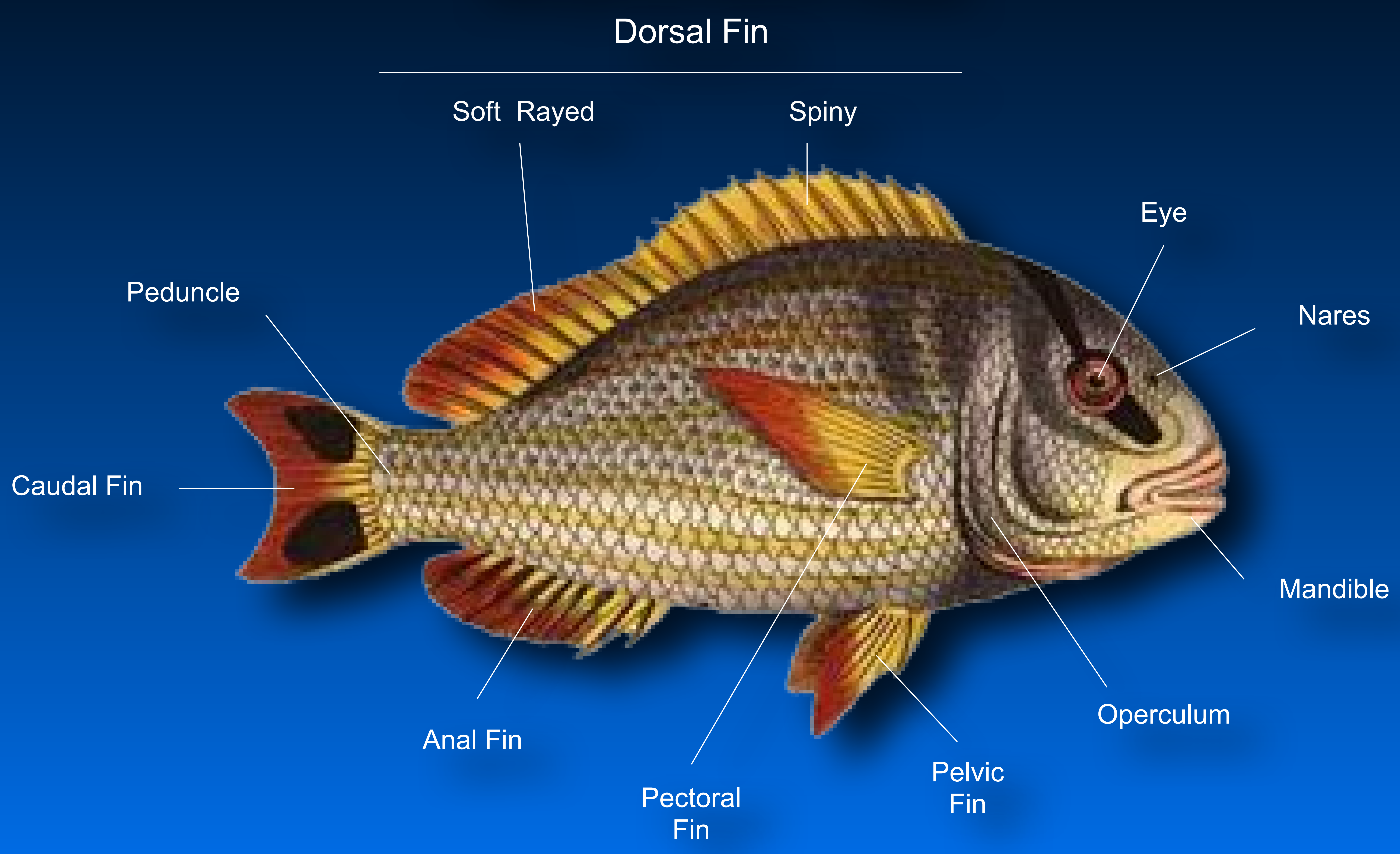

Sparisoma chrysopterum


Trachichthys australis


Umbrina cirrosa

Description & Analysis of Morphology

Morphometric Data

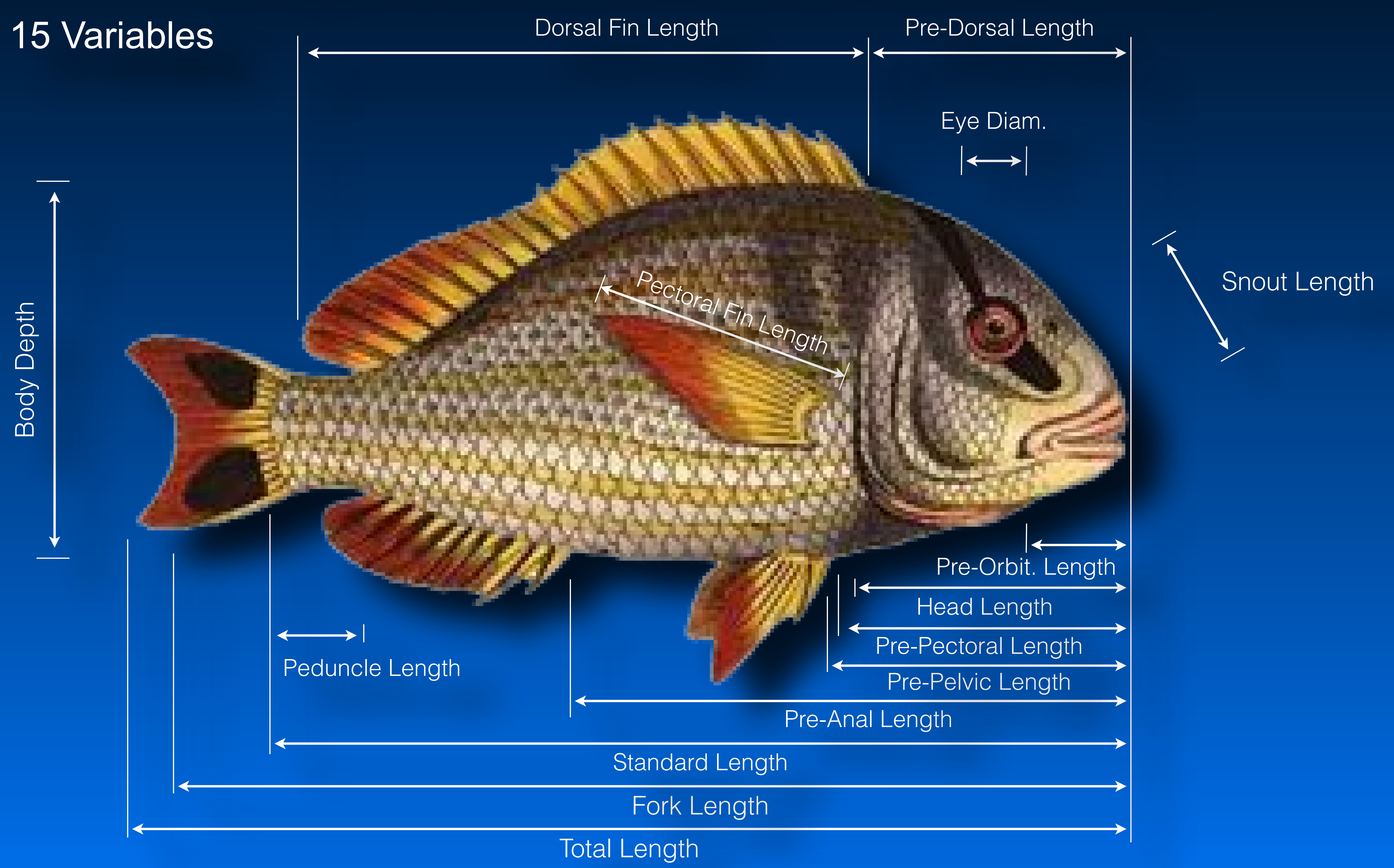


Anisotremus virginicus

Description & Analysis of Morphology

Morphometric Data: Linear Distances

15 Variables



Anisotremus virginicus

Description & Analysis of Morphology

Morphometric Data: Linear Distances

15 Variables

Total Length
Fork Length
Standard Length
Dorsal Fin Length
Pre-Anal Length
Body Depth
Pre-Pelvic Length
Pre-Pectoral Length
Head Length
Pre-Dorsal Length
Pectoral Fin Length
Snout Length
Pre-Orbit. Length
Peduncle Length
Eye Diam.

However, no aspect of geometry is recorded by these lengths

Anisotremus virginicus

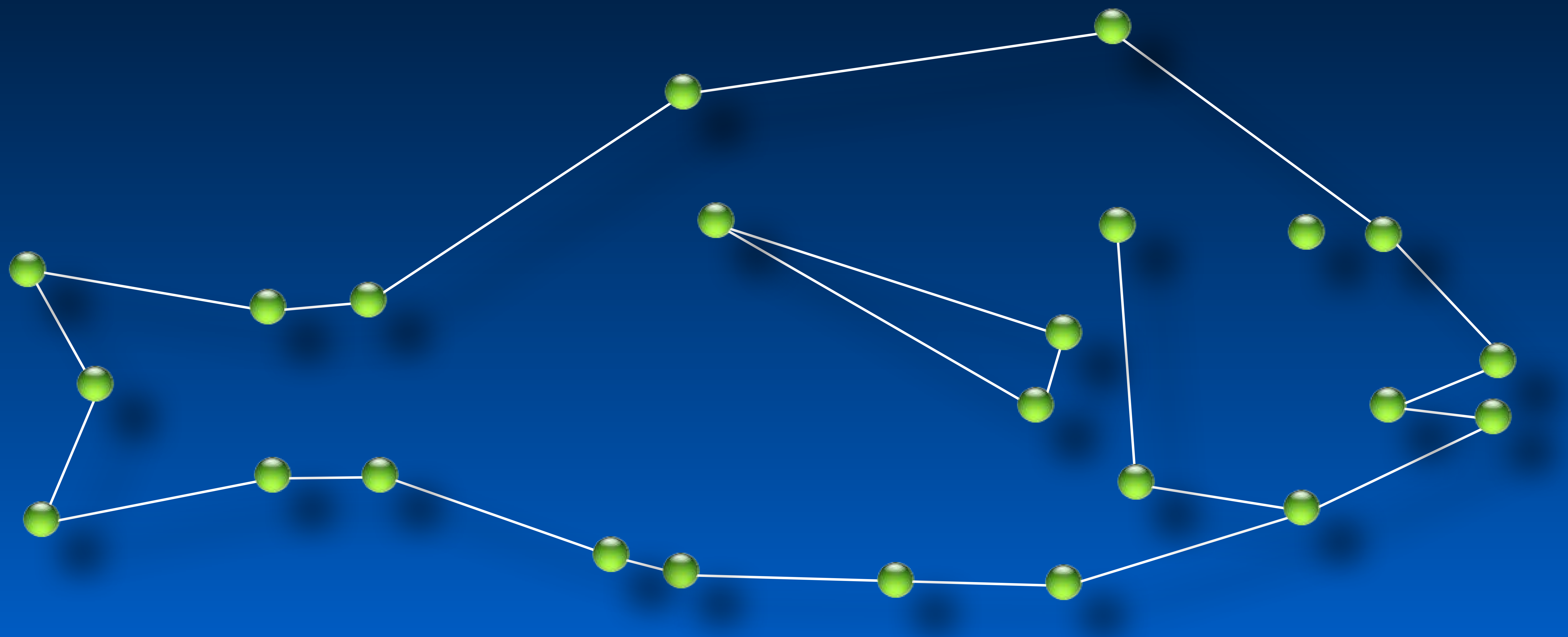
Description & Analysis of Morphology

Morphometric Data: Landmarks

Anisotremus virginicus

Description & Analysis of Morphology

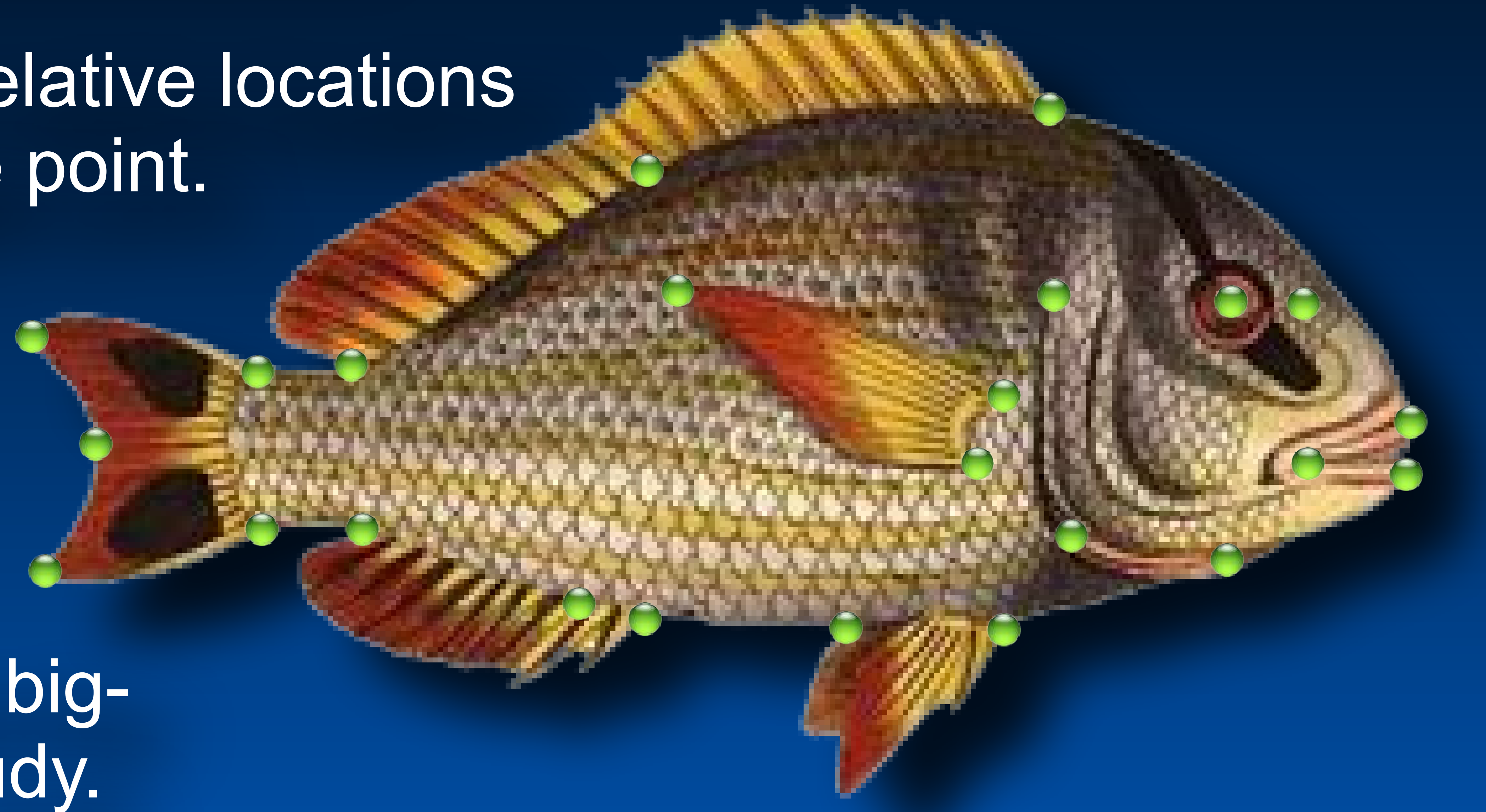
Morphometric Data: Landmarks



Anisotremus virginicus

Description & Analysis of Morphology

When to Use Landmarks



- When an object is composed of multiple parts the relative locations of which can be represented adequately by a single point.
- When the object is rigid (*e.g.*, bone, shell) such that the relative positions of its parts don't change.
- When all of the landmarks can be recognized unambiguously on all objects within the population under study.
- When the hypothesis of interest pertains to, or can be reasonably supposed to involve, positions that can be represented by landmark points.

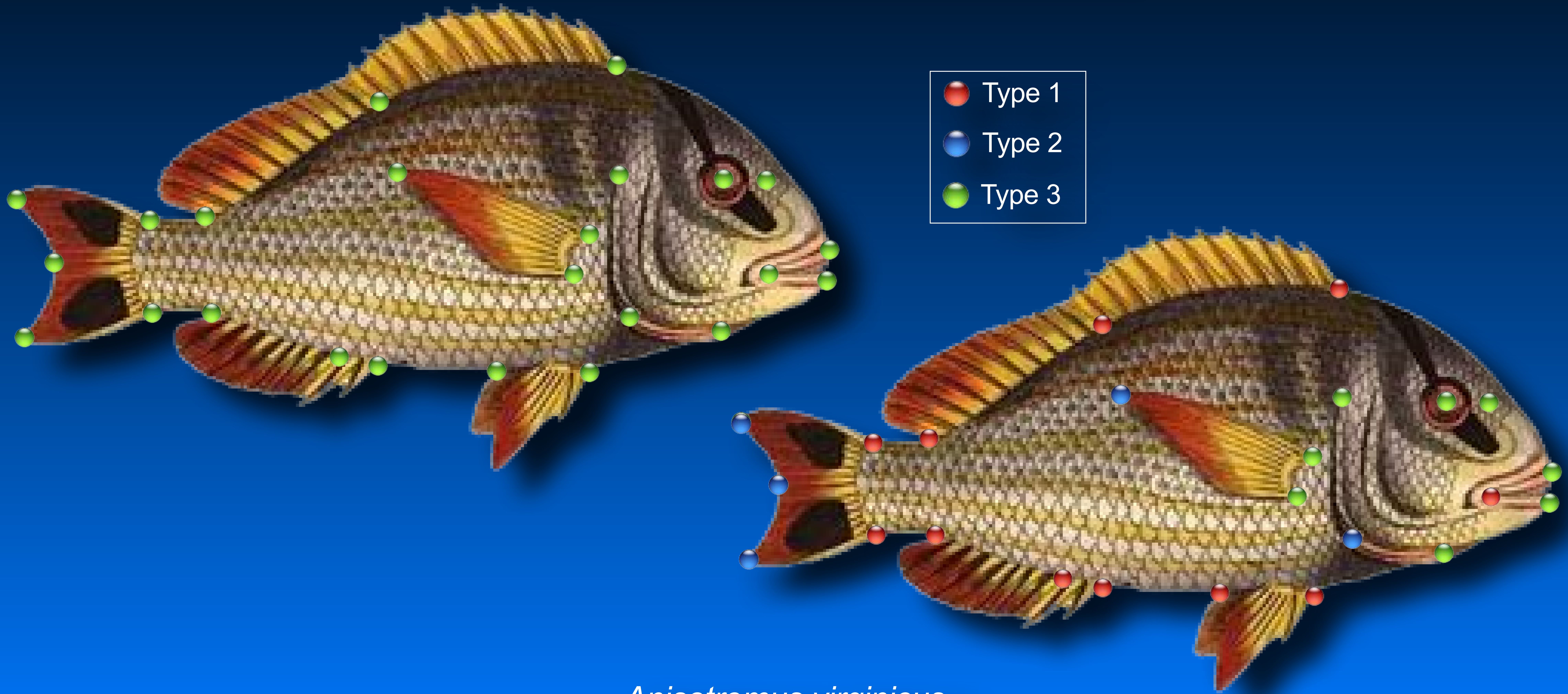
Description & Analysis of Morphology

Types Landmarks

- Type 1 - a mathematical point that represents the juxtaposition of different tissues, organs, bones, sutures, or other unified component part of the form.
- Type 2 - a mathematical point that represents some geometric aspect of the form (e.g., maxima of curvature).
- Type 3 - a mathematical point whose location contains at least one ‘deficient’ or ‘dependent’ coordinate (e.g., points that are ‘farthest’ from other points, extremal points, centroids, endpoints of diameters, etc.).

Description & Analysis of Morphology

Morphometric Data: Landmarks

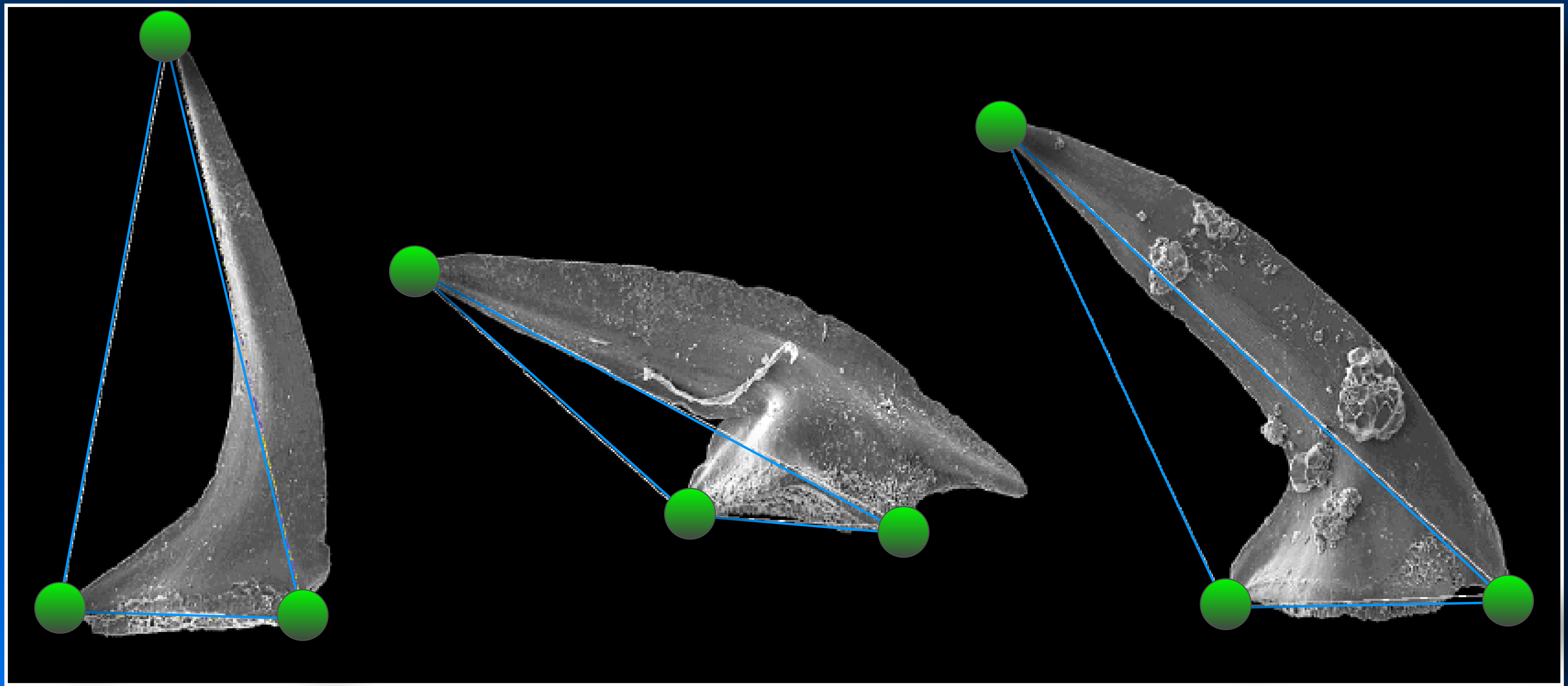


Anisotremus virginicus

Description & Analysis of Morphology

Issues with Landmarks

Landmarks facilitate the detailed tracking of specific locations on the form and preserves the geometry of those locations. But their uninformed use often leads to gross oversimplifications and/or misrepresentations of the forms in question.



Description & Analysis of Morphology

Morphometric Data: Outline Semilandmarks

Anisotremus virginicus

Description & Analysis of Morphology

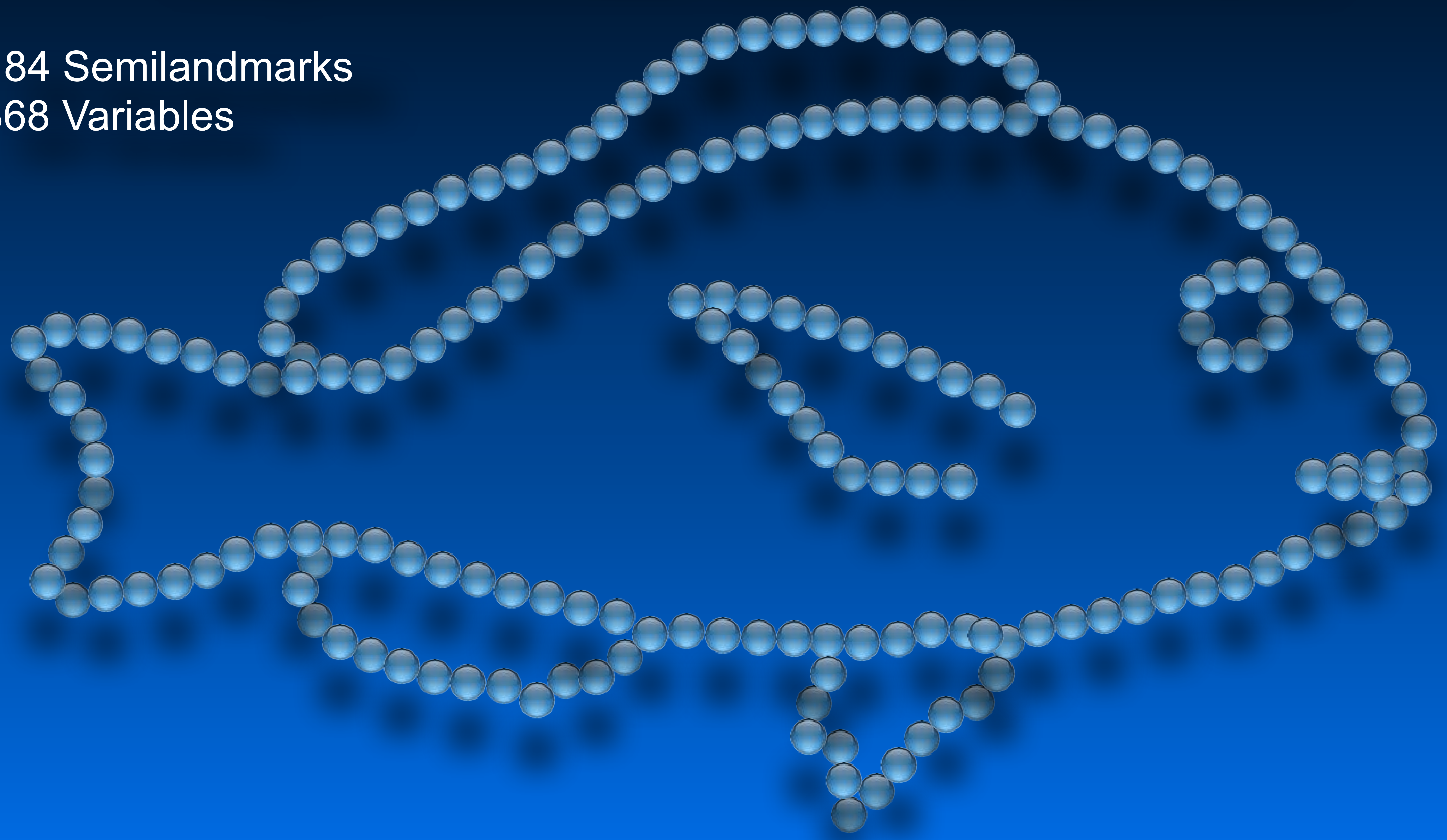
Types Landmarks

- Type 1 - a mathematical point that represents the juxtaposition of different tissues, organs, bones, sutures, or other unified component part of the form.
- Type 2 - a mathematical point that represents some geometric aspect of the form (e.g., maxima of curvature).
- Type 3 - a mathematical point whose location contains at least one ‘deficient’ or ‘dependent’ coordinate (e.g., points that are ‘farthest’ from other points, extremal points, centroids, endpoints of diameters, etc.).
- Semilandmarks - a special form of Type 3 landmark in which its location is referenced to the preceding (semi)landmark position in a unified geometric sequence.

Description & Analysis of Morphology

Morphometric Data: Outline Semilandmarks

184 Semilandmarks
368 Variables

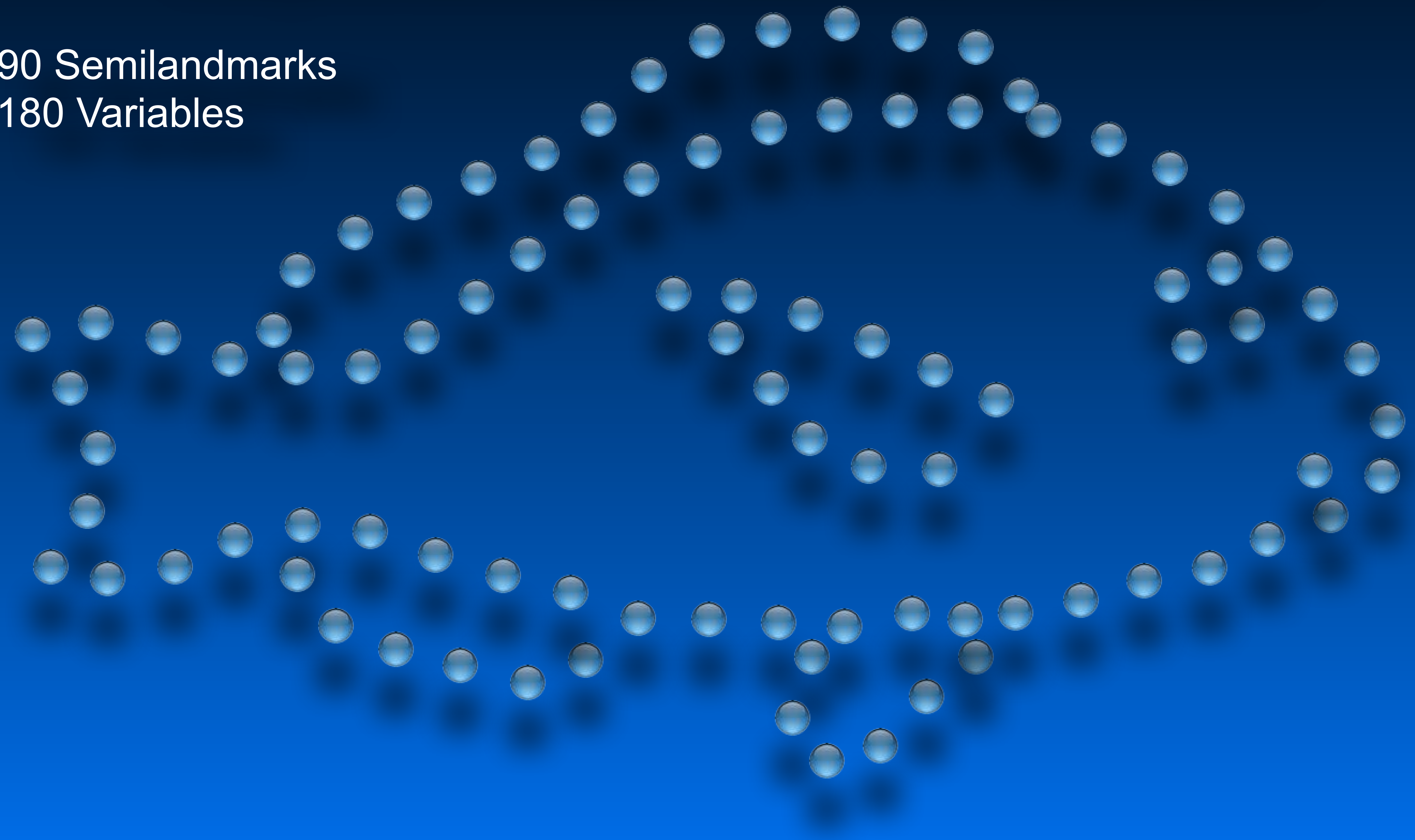


Anisotremus virginicus

Description & Analysis of Morphology

Morphometric Data: Outline Semilandmarks

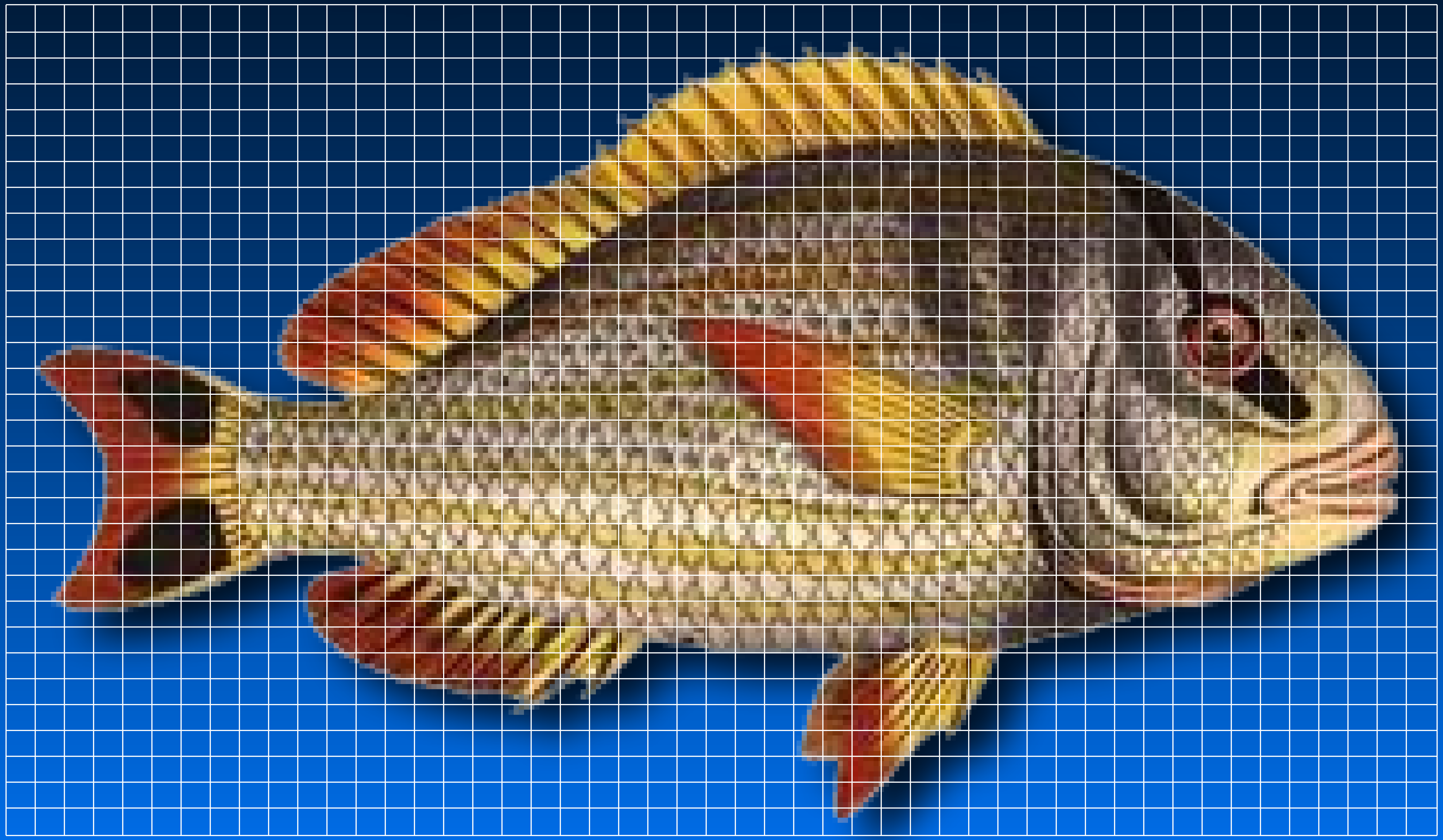
90 Semilandmarks
180 Variables



Anisotremus virginicus

Description & Analysis of Morphology

Morphometric Data: Image Pixels



Anisotremus virginicus

Description & Analysis of Morphology

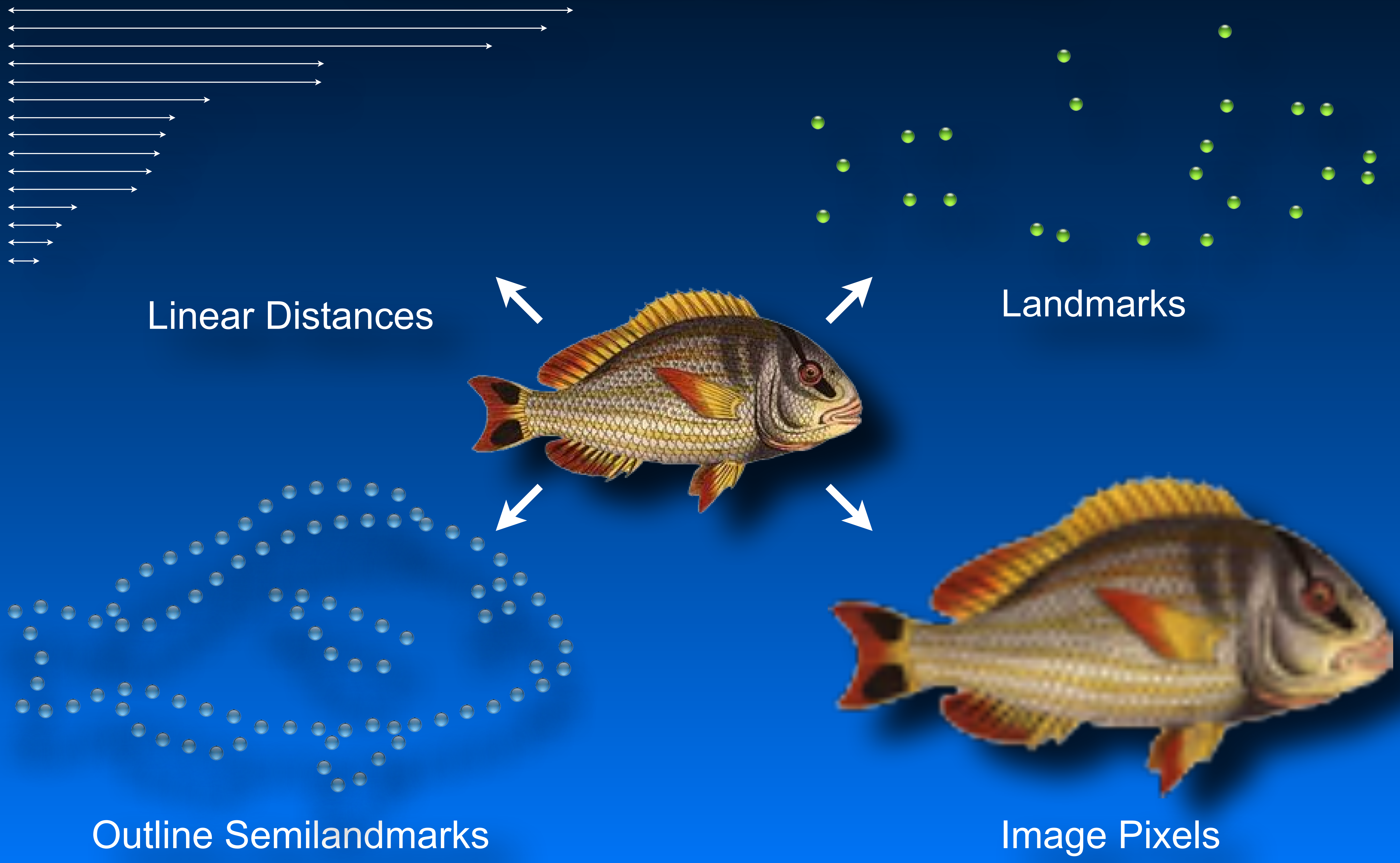
Morphometric Data: Image Pixels

5,625 pixels
16,875 variables

Anisotremus virginicus

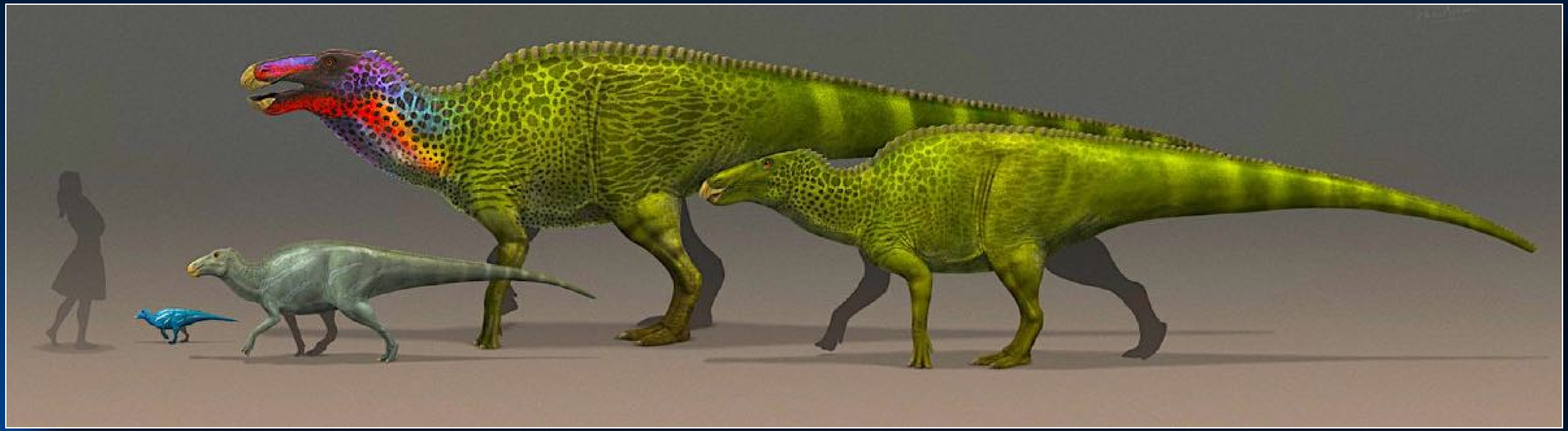
Description & Analysis of Morphology

Morphometric Data: Summary



Description & Analysis of Morphology

Morphometric Data Analysis: Allometry

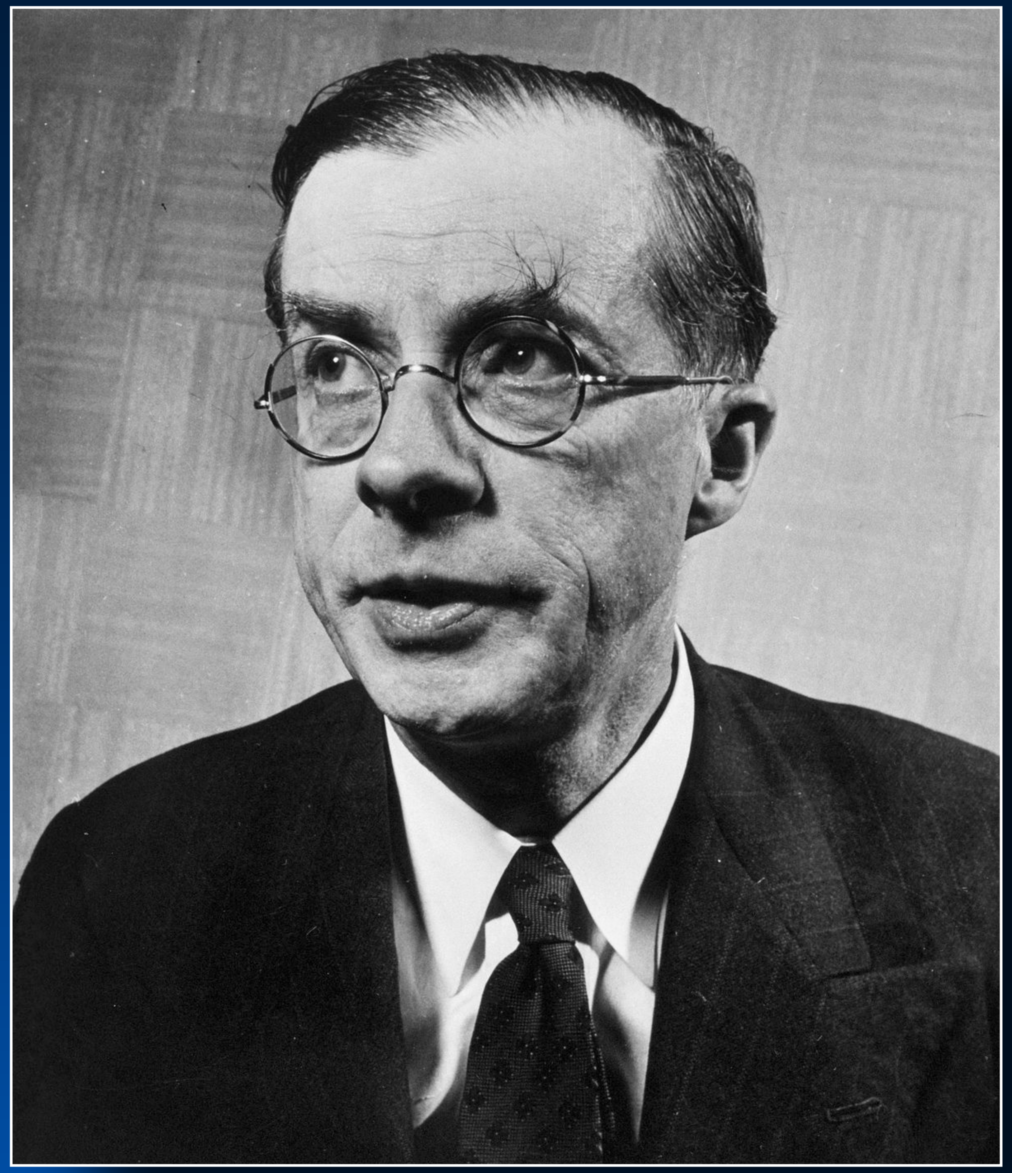


The study of the influence of body size on form and function.

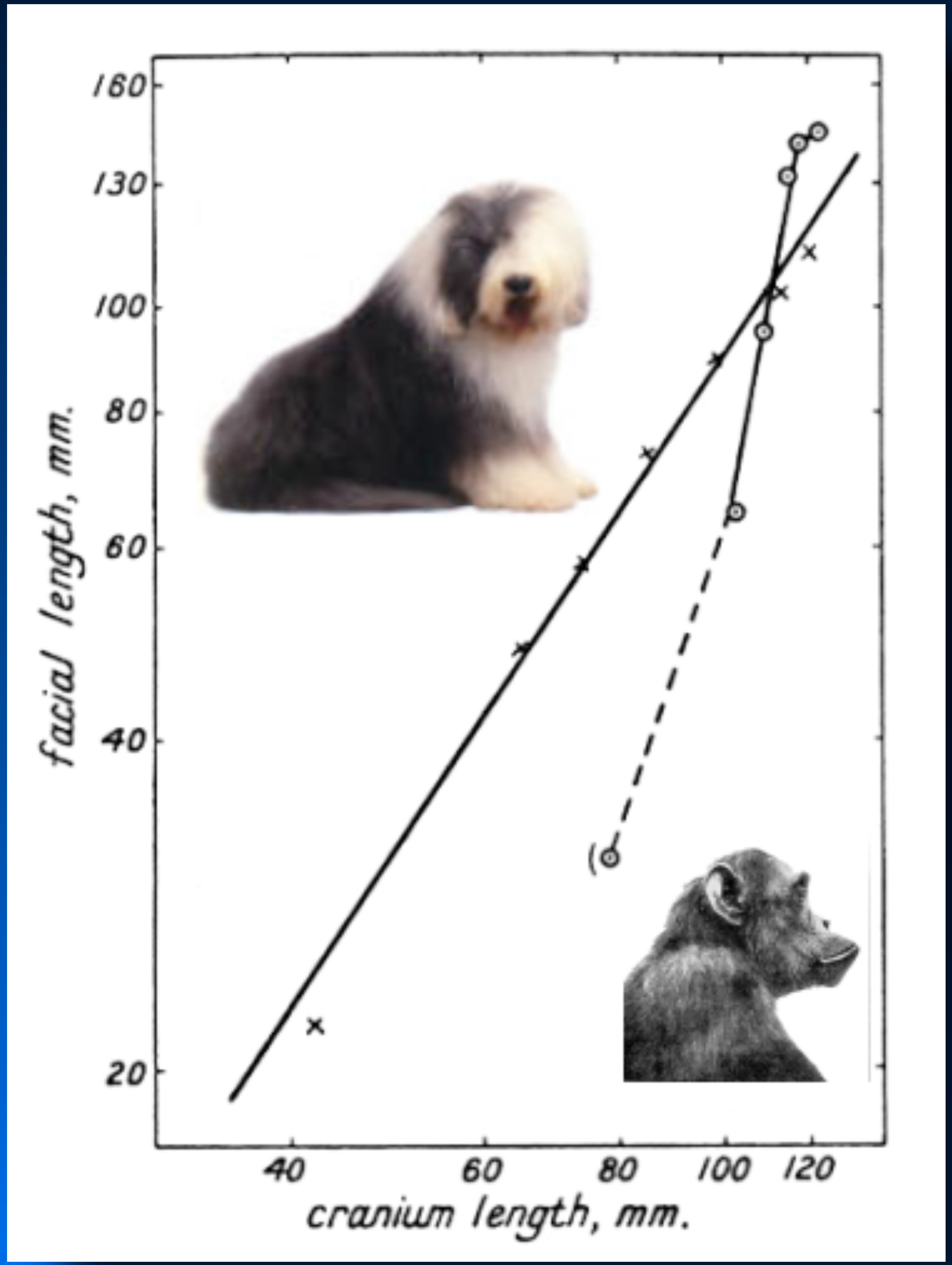
- Ontogenetic - allometry between different individuals of the same species at different stages of development.
- Static - allometry between different individuals of the same species at comparable developmental stages.
- Phylogenetic - allometry between individuals of different sister species, or system taxa, at comparable developmental stages.

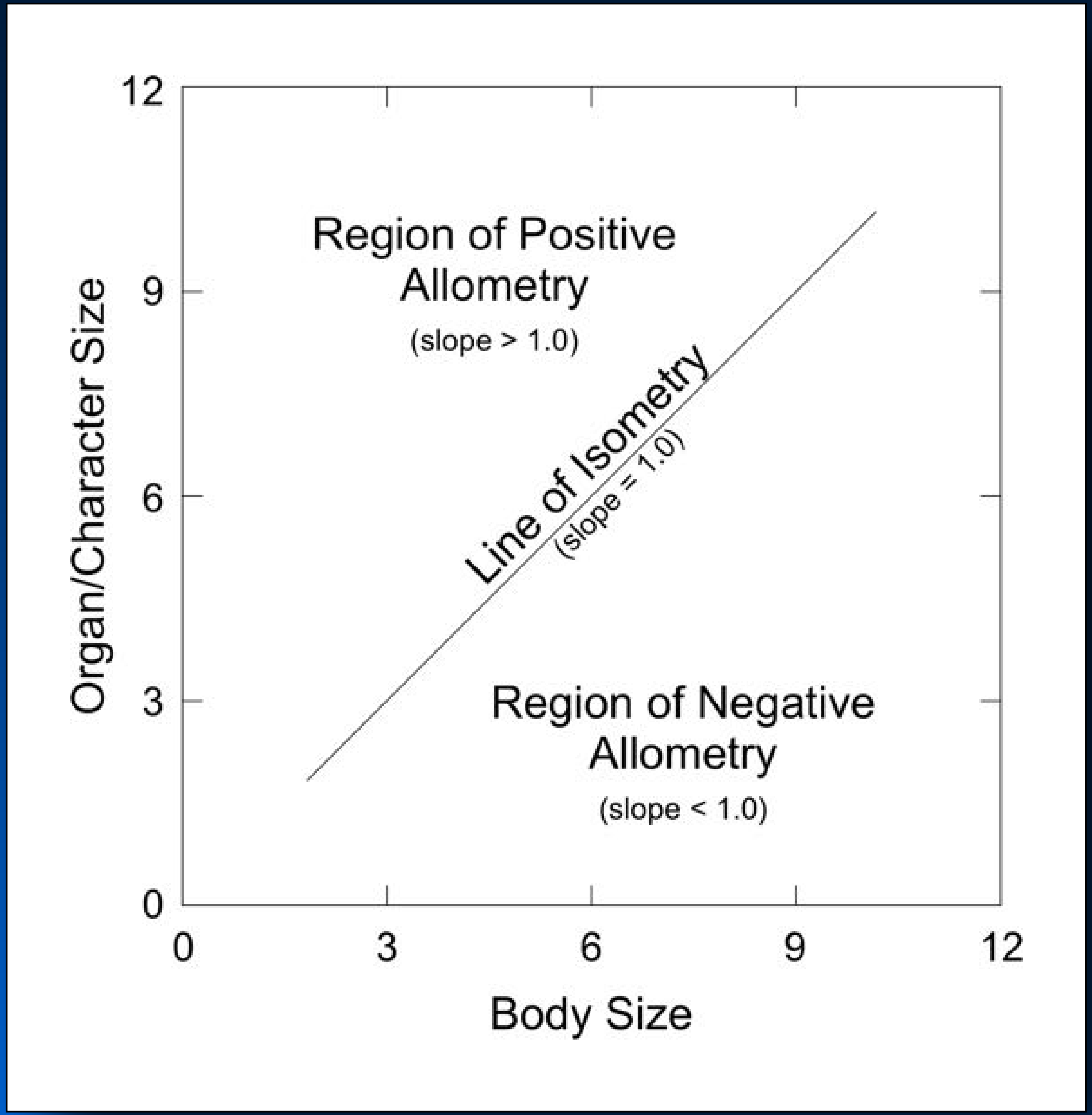
Description & Analysis of Morphology

Morphometric Data Analysis: Allometry



In the early 1900s Julian Huxley noticed that, when plotted on logarithmically ruled paper, the pattern of size increase for structures in a large number of animals and plants looked remarkably simple.

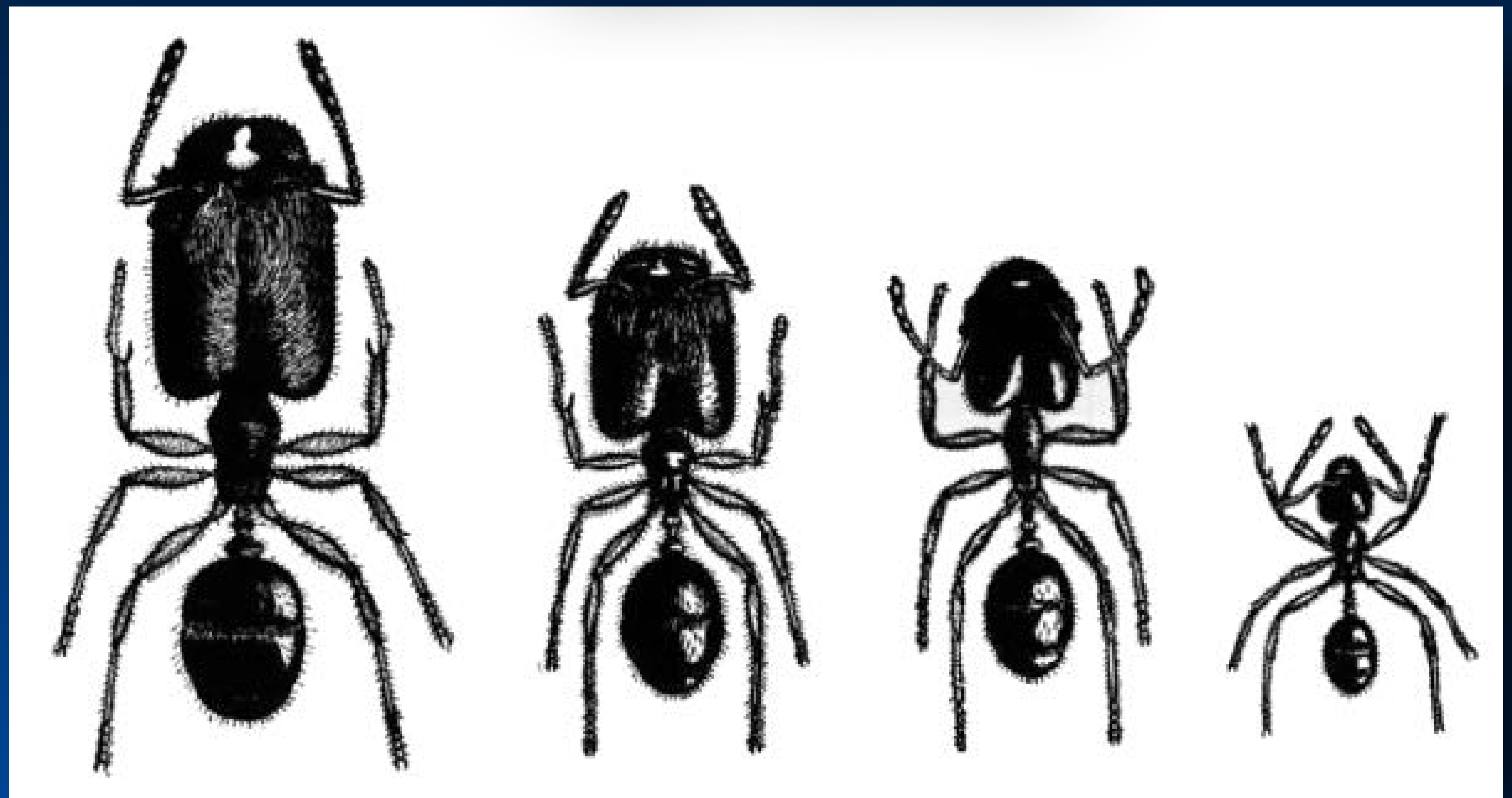




Description & Analysis of Morphology

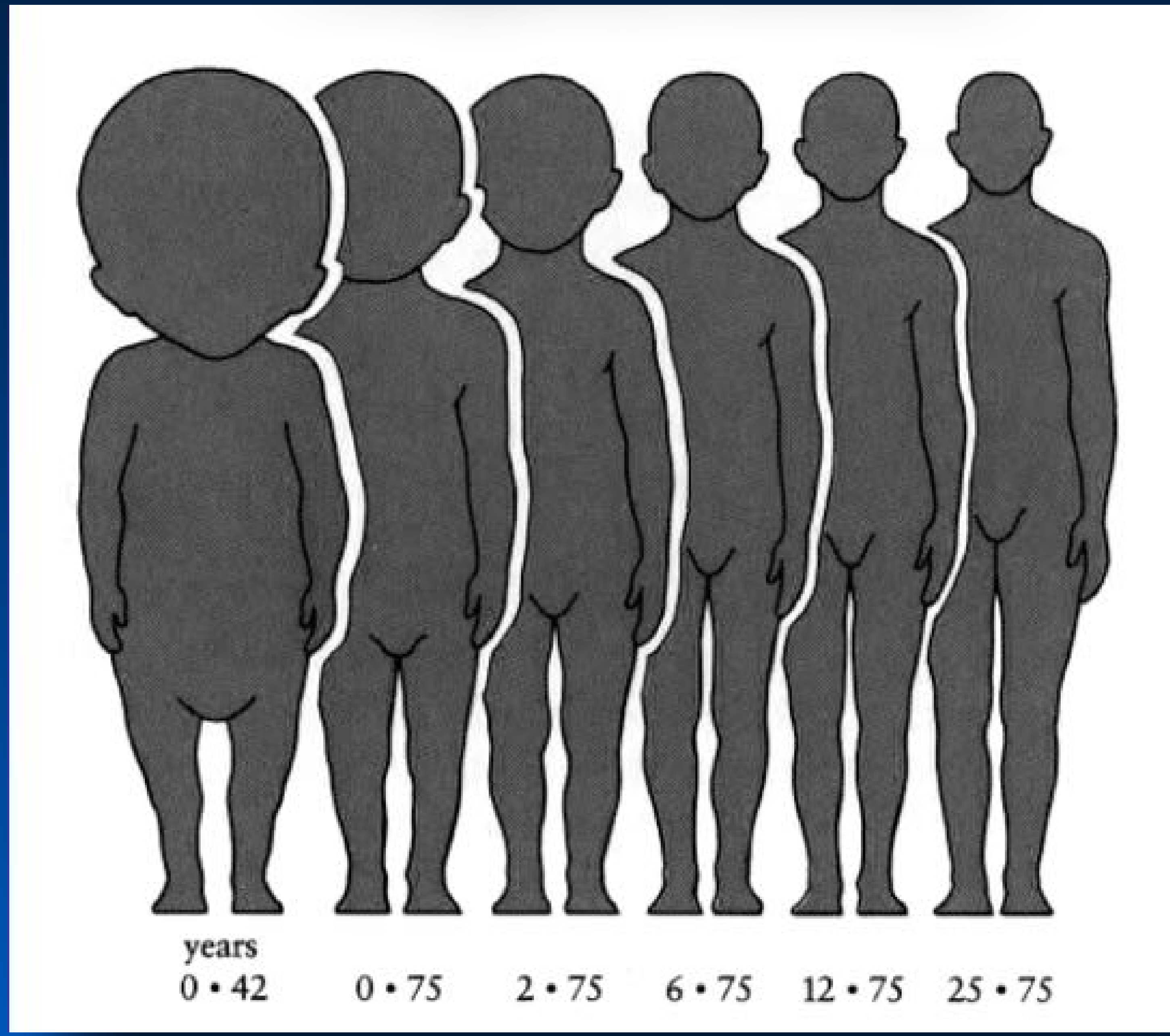
Morphometric DataAnalysis: Types of Allometry

Static Allometry



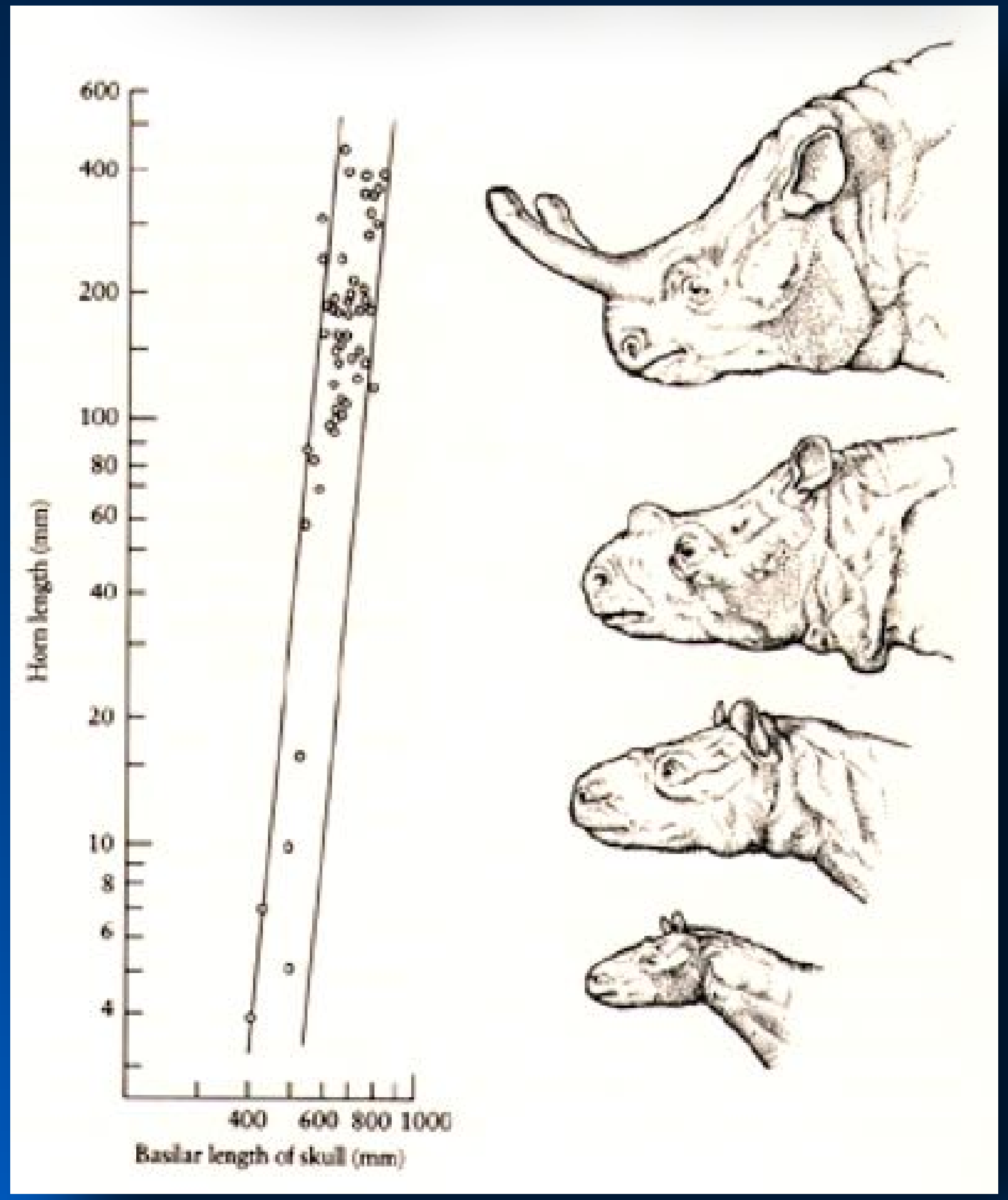
Allometry between different individuals of the same species at comparable levels of development.

Ontogenetic Allometry



Allometry in the same individuals at different stages of development.

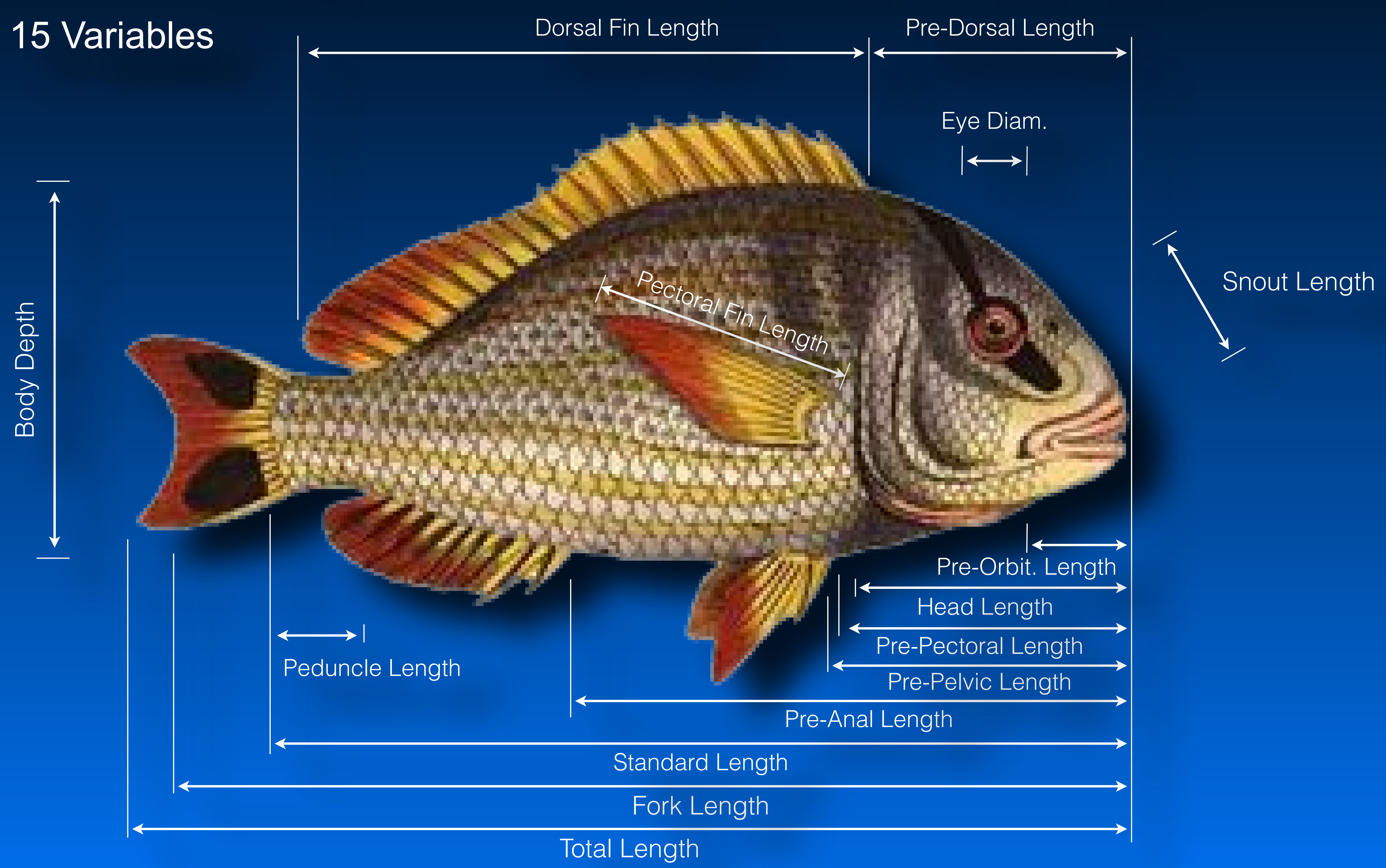
Phylogenetic Allometry



Allometry between sister taxa at comparable levels of development.

Description & Analysis of Morphology

Morphometric Data: Linear Distances



Anisotremus virginicus

Description & Analysis of Morphology

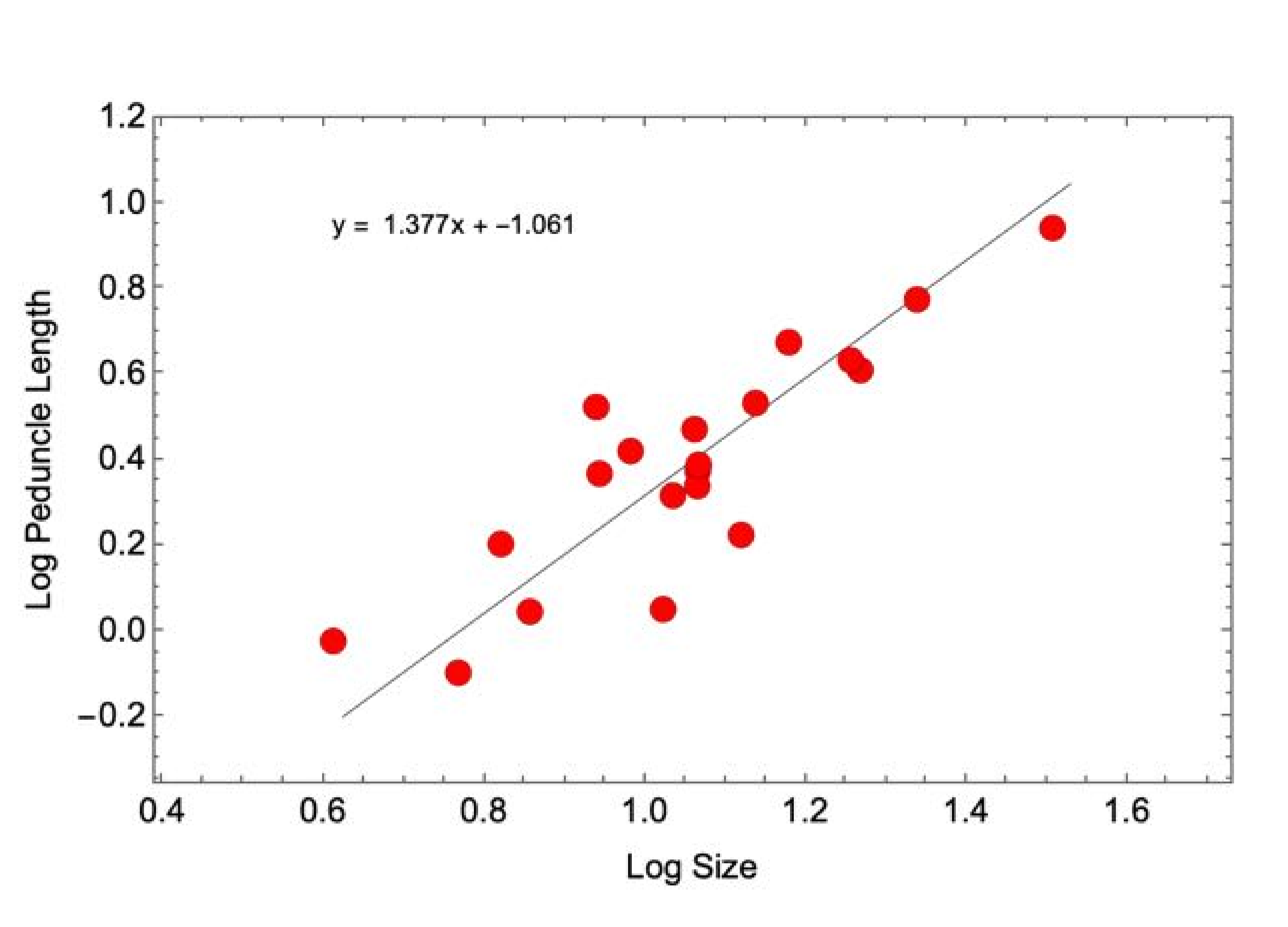
Morphometric Data: Fish Dataset

Species	Pre-Orbit Length	Head Length	Pre-Dorsal Length	Pre-Pectoral Length	Pre-Pelvic Length	Pre-Anal Length	Std. Length	Fork Length	Total Length	Snout Length	Eye Diam.	Pectoral Fin Length	Dorsal Fin Length	Peduncle Length	Body Depth
Anisotremus virginicus	2.835	7.769	7.572	8.505	8.702	16.213	25.000	27.848	29.320	3.533	1.669	7.453	14.875	2.356	10.800
Anthias anthias	2.439	11.057	9.350	11.220	10.244	25.772	40.000	44.553	57.073	2.989	1.707	12.709	32.276	4.065	12.439
Anthias argus	1.207	4.135	4.803	4.315	4.007	9.786	15.000	17.491	17.491	1.383	0.745	3.288	8.964	1.592	4.983
Archosargus rhomboidalis	1.662	4.864	5.982	5.831	4.683	12.689	20.000	21.813	23.082	2.473	1.027	4.108	12.266	2.326	8.822
Chelmon rostratus	3.320	5.547	4.984	6.279	5.585	8.848	15.000	16.969	16.613	3.381	0.938	2.782	9.415	1.106	7.052
Conodon nobilis	2.106	6.853	7.236	7.198	6.815	16.539	25.000	27.335	29.479	2.528	1.110	4.238	16.233	2.067	7.695
Epinephelus merra	2.545	6.655	9.491	8.582	8.618	21.055	30.000	36.182	34.582	3.055	1.127	5.966	19.781	1.672	8.182
Gerres erythrourus	3.063	7.047	8.578	7.108	6.893	16.636	25.000	27.206	32.629	3.574	1.317	8.477	14.308	2.176	10.172
Holacanthus ciliaris	3.066	8.748	3.358	8.310	7.775	20.819	27.000	36.783	35.323	3.184	1.655	5.851	41.663	4.721	18.155
Holocentrus adscensionis	2.058	8.232	8.155	8.918	8.841	16.615	25.000	28.925	29.420	2.943	1.601	8.052	15.206	2.439	8.460
Johnius carutta	0.928	3.301	3.817	3.390	3.242	9.402	14.000	15.945	15.945	1.093	0.472	2.698	9.491	0.796	3.301
Lonchurus lanceolatus	1.560	6.120	6.920	6.600	6.640	14.040	22.000	30.000	30.000	1.826	0.600	9.890	15.320	1.120	5.280
Oligoplites saliens	2.541	7.719	11.507	8.055	7.527	13.712	35.000	36.055	39.986	2.833	1.151	5.323	20.760	3.404	10.212
Ophiocara macrolepidota	1.383	5.390	6.667	5.284	5.142	10.461	20.000	24.362	24.362	1.636	1.028	5.032	10.284	3.333	6.028
Perca fluviatilis	3.594	16.212	12.247	12.330	14.808	34.470	50.000	55.700	59.253	4.405	2.395	9.902	29.409	5.948	16.274
Pomacentrus pavo	0.667	2.272	2.541	2.353	2.609	5.197	8.500	9.956	12.531	0.791	0.458	2.105	6.714	0.944	3.734
Pomadasys furcatus	6.762	22.779	21.428	24.130	26.211	46.494	70.000	73.954	88.516	9.049	5.096	13.028	42.125	8.737	23.818
Sparisoma chrysopterum	3.303	7.988	8.257	7.873	7.565	16.667	25.000	28.226	30.338	4.382	1.190	5.806	14.324	2.957	8.909
Trachichthys australis	1.602	6.817	10.144	6.283	5.339	13.306	20.000	22.587	25.791	2.945	3.450	5.252	6.858	2.628	10.883
Umbrina cirrosa	3.311	12.157	11.886	11.886	11.886	26.594	40.000	44.125	46.459	4.145	1.682	12.144	25.834	4.288	13.894

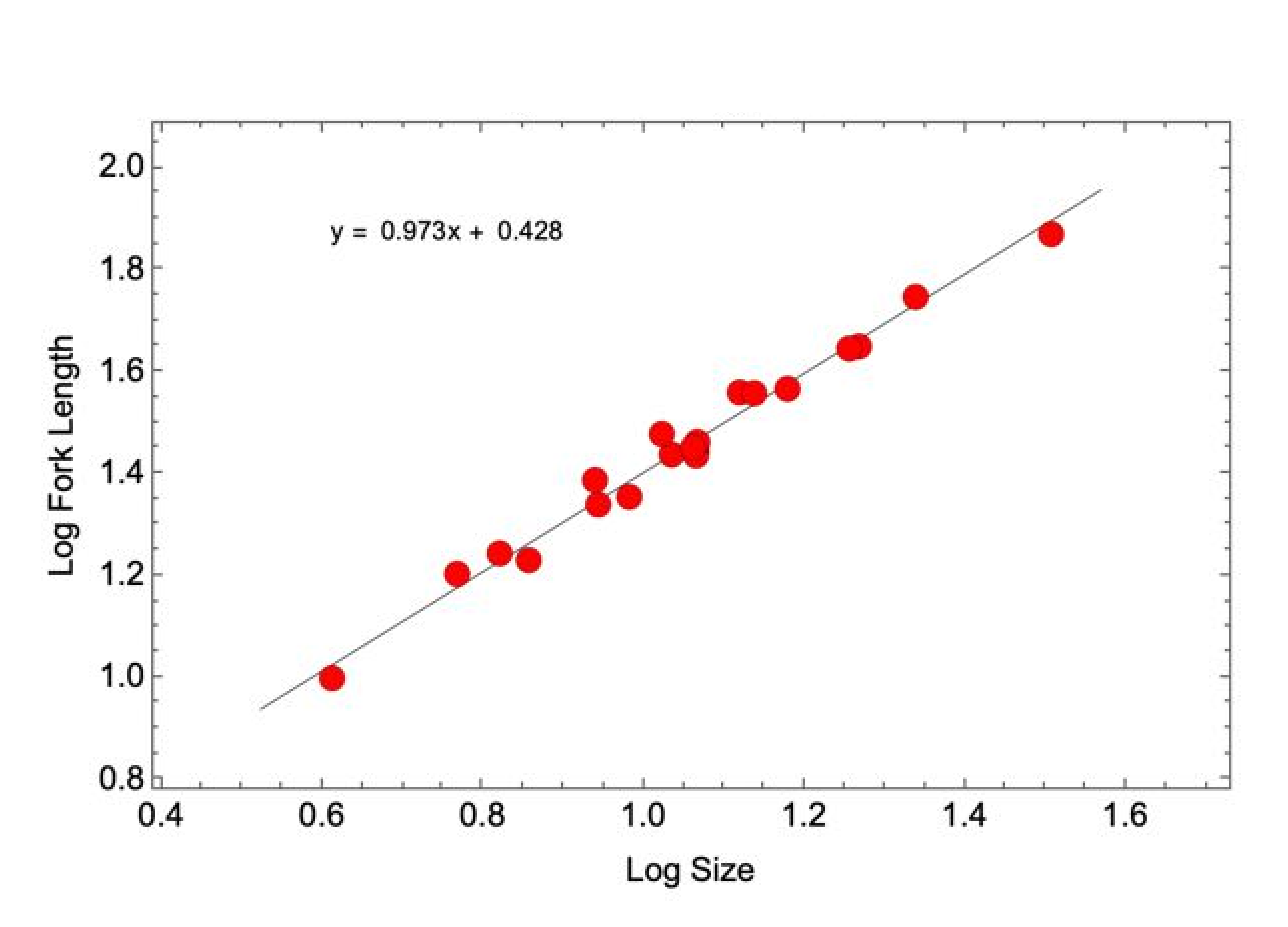
Description & Analysis of Morphology

Morphometric Data: Fish Dataset

- Positive Allometry - local rate of size increase > global size increase.
- Negative Allometry - local rate of size increase < global size increase.



Positive Allometry



Negative Allometry

Description & Analysis of Morphology

Morphometric Data: Fish Dataset

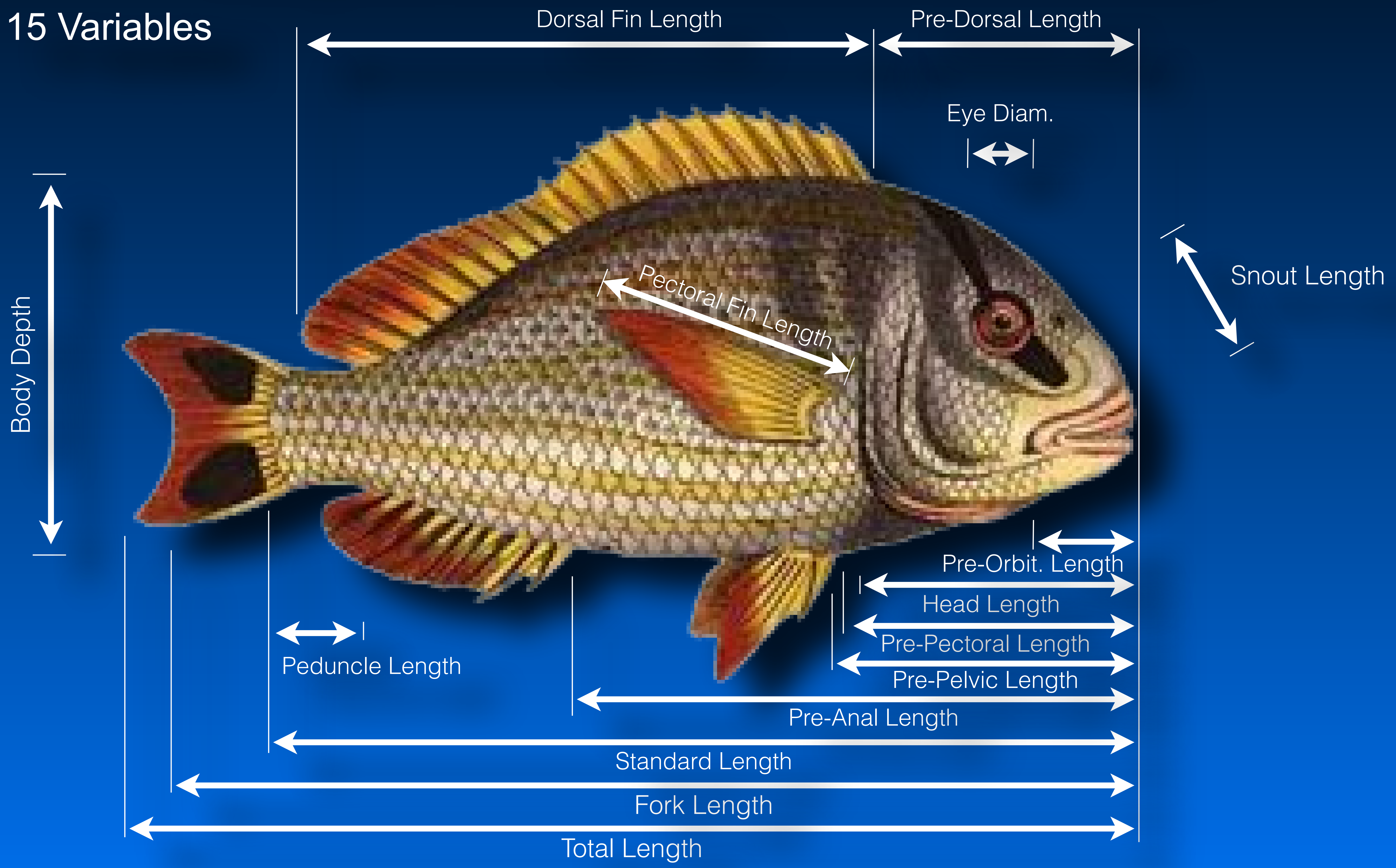
Analysis of Allometry using Linear Regression

Character	Equation	y-Intercept	Slope	Allometry
Pre-Orbit Length	y = 0.877x - 0.860	-0.860	0.877	Negative Allometry
Head Length	y = 1.036x - 0.721	-0.721	1.036	Positive Allometry
Pre-Dorsal Length	y = 0.869x - 0.289	-0.289	0.869	Negative Allometry
Pre-Pectoral Length	y = 0.974x - 0.552	-0.553	0.974	Negative Allometry
Pre-Pelvic Length	y = 1.035x - 0.718	-0.718	1.035	Positive Allometry
Pre-Anal Length	y = 1.011x - 0.313	-0.313	1.011	Positive Allometry
Std. Length	y = 0.987x - 0.057	-0.057	0.987	Negative Allometry
Fork Length	y = 0.951x + 0.092	0.092	0.951	Negative Allometry
Total Length	-	-	-	Isometry
Snout Length	y = 0.918x - 0.844	-0.844	0.918	Negative Allometry
Eye Diam.	y = 0.968x - 1,298	-1.298	0.968	Negative Allometry
Pectoral Fin Length	y = 1.001x - 0.731	-0.731	1.001	Positive Allometry
Dorsal Fin Length	y = 1.016x - 0.324	-0.324	1.016	Positive Allometry
Peduncle Length	y = 1.132x - 1.421	-1.421	1.132	Positive Allometry
Body Depth	y = 0.912x - 0.316	-0.316	0.912	Negative Allometry

Description & Analysis of Morphology

Morphometric Data: Linear Distances

15 Variables

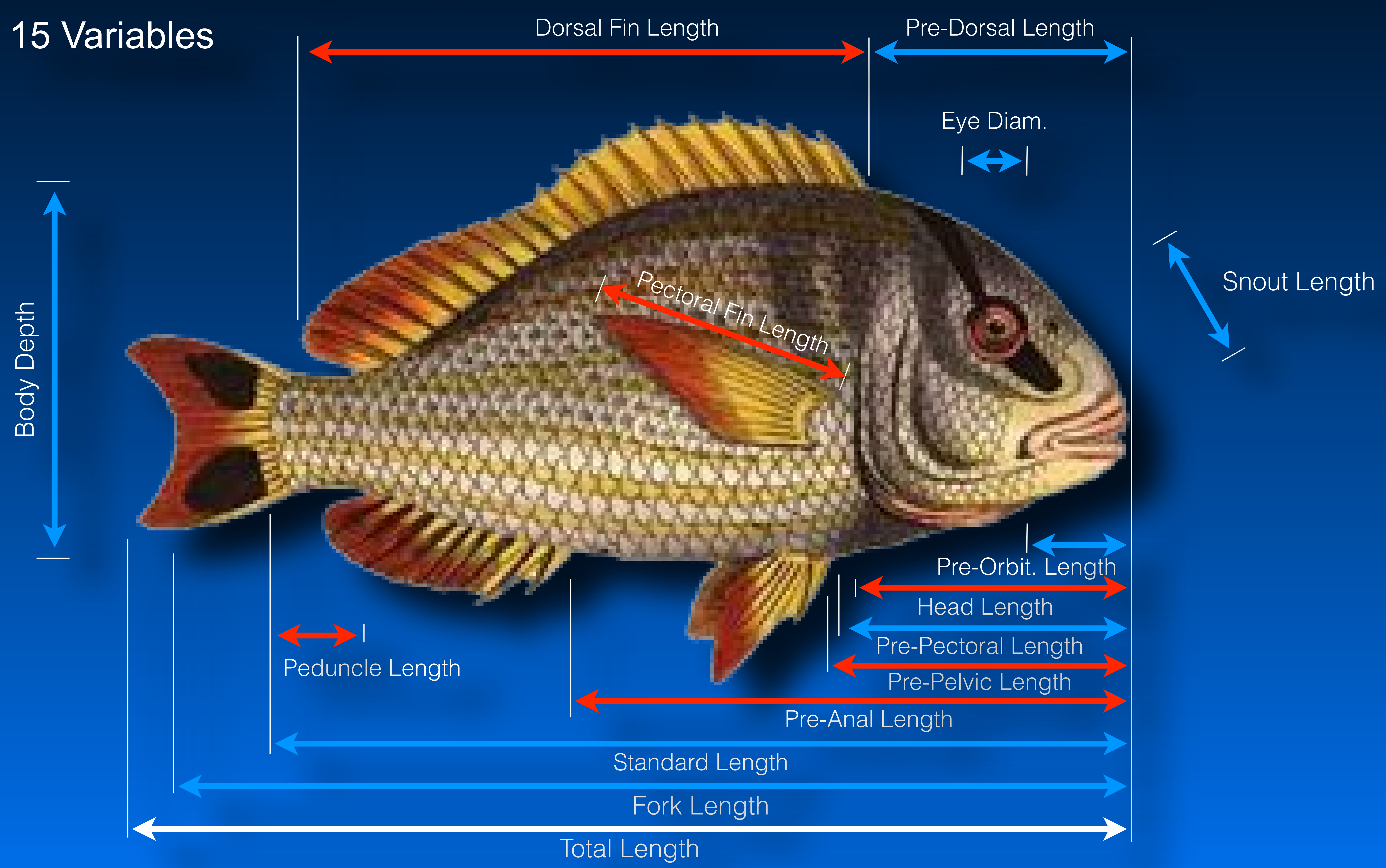


Anisotremus virginicus

Description & Analysis of Morphology

Morphometric Data: Linear Distances

15 Variables



Anisotremus virginicus

Description & Analysis of Morphology

Morphometric Data: Fish Dataset

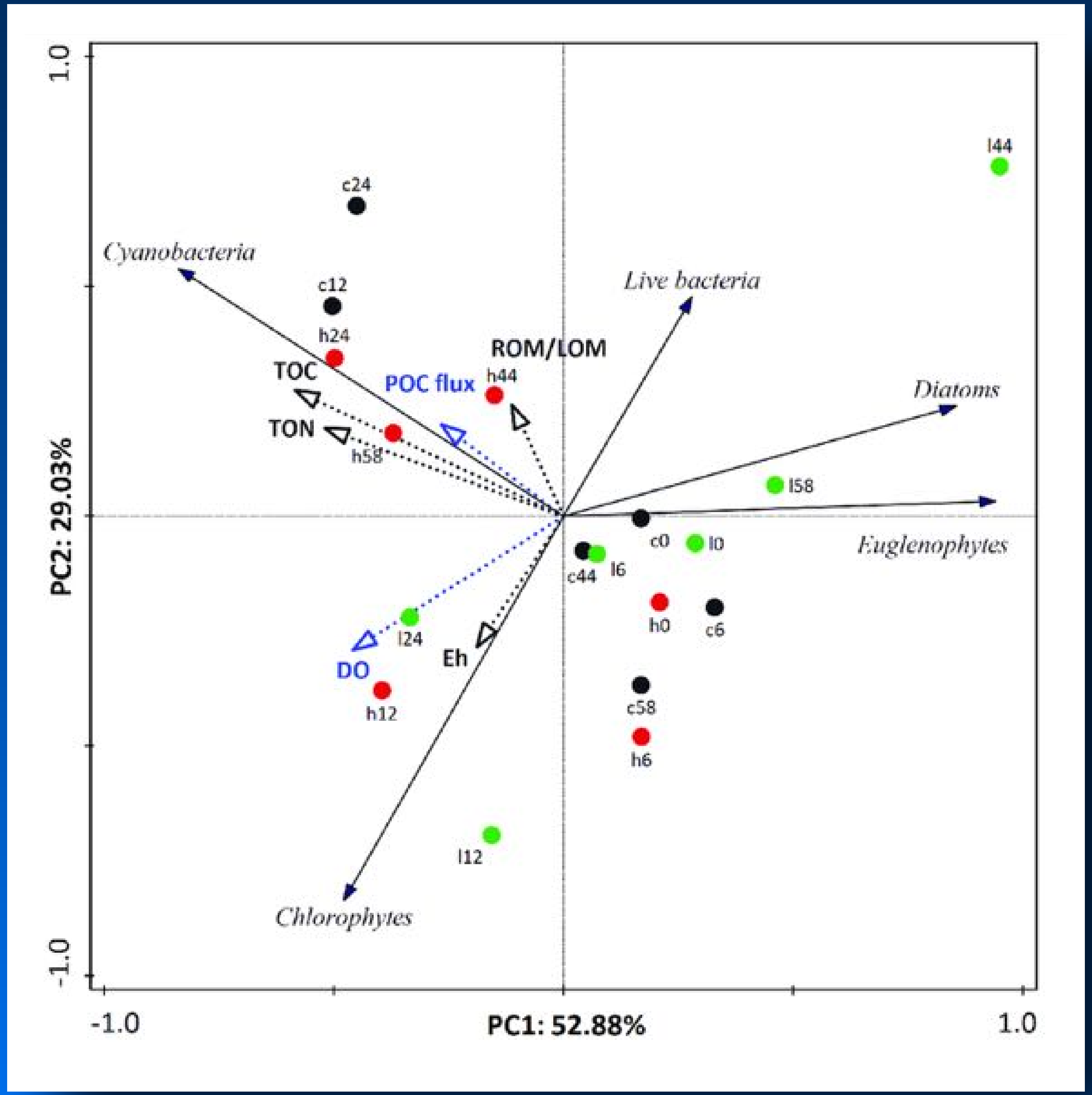
Analysis of Allometry using Linear Regression

Character	Equation	y-Intercept	Slope	Conf. Interval (95%)	Allometry
Pre-Orbit Length	y = 0.877x - 0.860	-0.860	0.877	0.609 - 1.165	Isometry
Head Length	y = 1.036x - 0.721	-0.721	1.036	0.900 - 1.172	Isometry
Pre-Dorsal Length	y = 0.869x - 0.289	-0.289	0.869	0.634 - 1.103	Isometry
Pre-Pectoral Length	y = 0.974x - 0.552	-0.553	0.974	0.832 - 1.115	Isometry
Pre-Pelvic Length	y = 1.035x - 0.718	-0.718	1.035	0.891 - 1.179	Isometry
Pre-Anal Length	y = 1.011x - 0.313	-0.313	1.011	0.887 - 1.135	Isometry
Std. Length	y = 0.987x - 0.057	-0.057	0.987	0.919 - 1.055	Isometry
Fork Length	y = 0.951x + 0.092	0.092	0.951	0.879 - 1.023	Isometry
Total Length	-	-	-	-	-
Snout Length	y = 0.918x - 0.844	-0.844	0.918	0.644 - 1.193	Isometry
Eye Diam.	y = 0.968x - 1,298	-1.298	0.968	0.641 - 1.294	Isometry
Pectoral Fin Length	y = 1.001x - 0.731	-0.731	1.001	0.793 - 1.208	Isometry
Dorsal Fin Length	y = 1.016x - 0.324	-0.324	1.016	0.795 - 1.238	Isometry
Peduncle Length	y = 1.132x - 1.421	-1.421	1.132	0.895 - 1.405	Isometry
Body Depth	y = 0.912x - 0.316	-0.316	0.912	0.690 - 1.133	Isometry

Description & Analysis of Morphology

Morphometric Data Analysis: Shape Variation

Ordination - the spatial representation of a set of data collected from a set of objects such that objects with similar data values are located close together and those with different data values are located further apart.



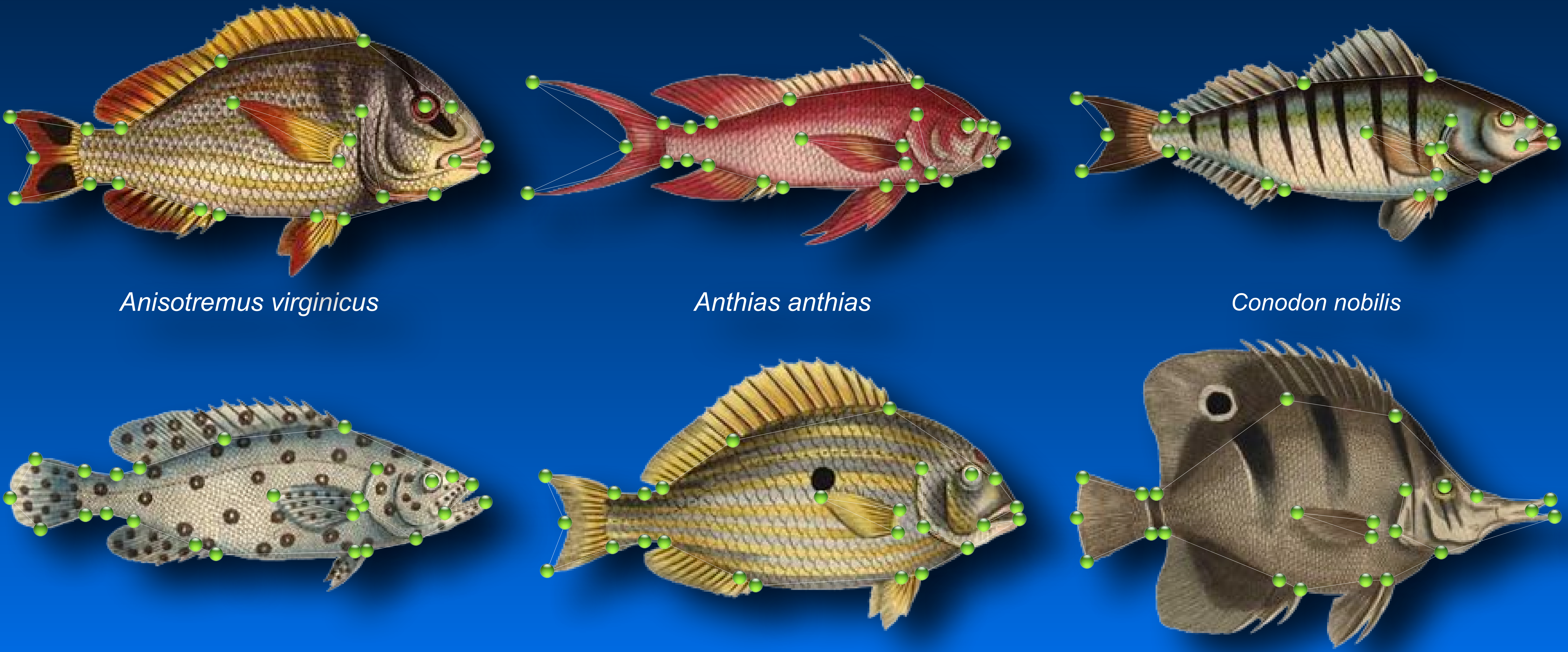
Methods

- Principal Components Analysis (PCA)
- Principal Coordinates Analysis (PCoord)
- Multidimensional Scaling (MDS)
- Correspondence Analysis (CA)
- Cluster Analysis
- Network Analysis
- Factor Analysis (FA)
- Canonical Correlation Analysis (CCA)
- Discriminant Function Analysis (DFA)
- Machine Learning (ML)

Description & Analysis of Morphology

Geometric Morphometrics

The analysis of configurations of point locations (landmarks, semilandmarks) collected from sample of objects for the purpose of representing aspects of the sample's variation in form.

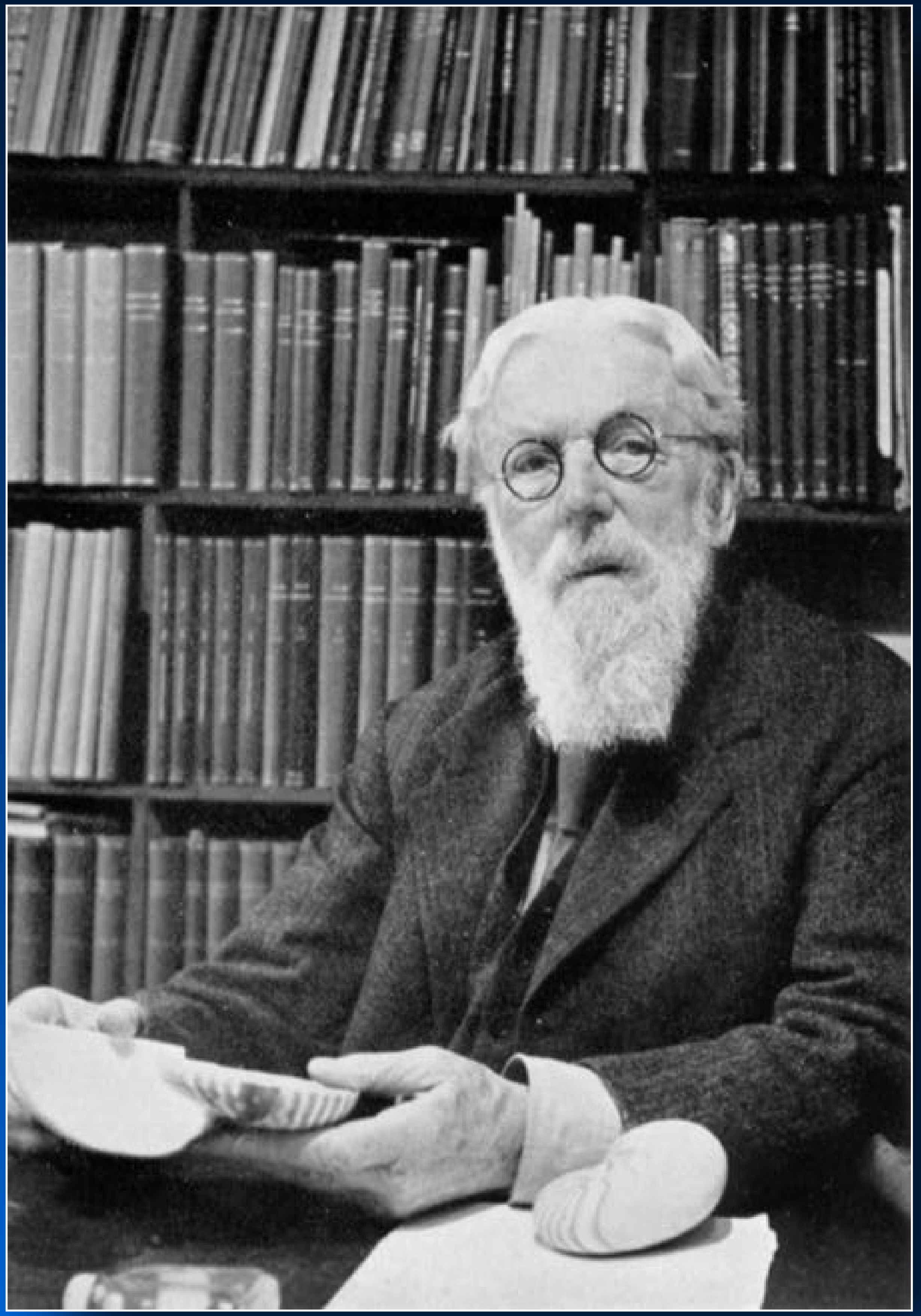


Anisotremus virginicus — *Anthias anthias* — *Conodon nobilis*

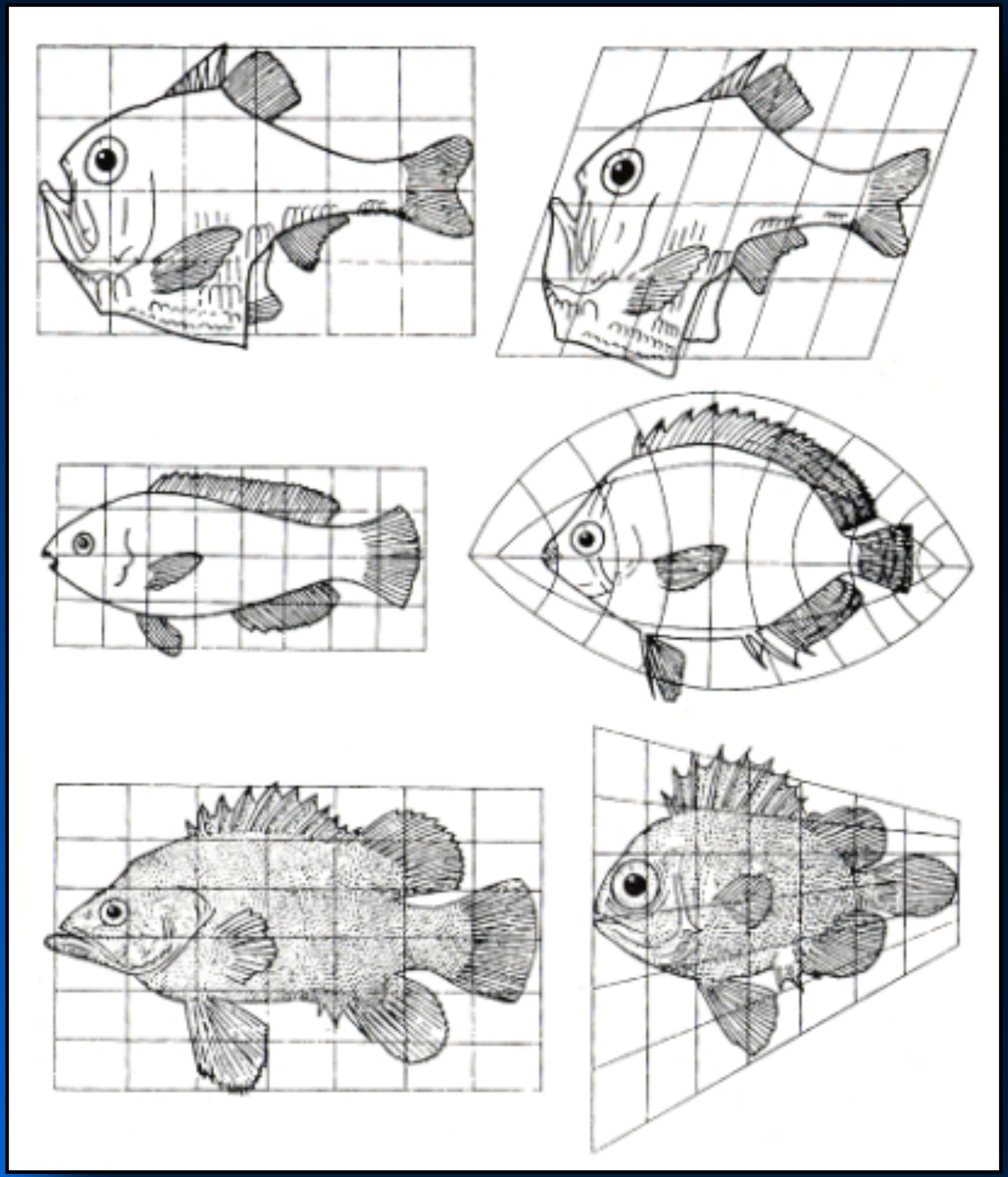
Anthias argus — *Archosargus rhomboidalis* — *Chelmon rostratus*

Description & Analysis of Morphology

Form Change as a Geometric Defomation



D’Arcy Wentworth Thompson
(1860 – 1948)

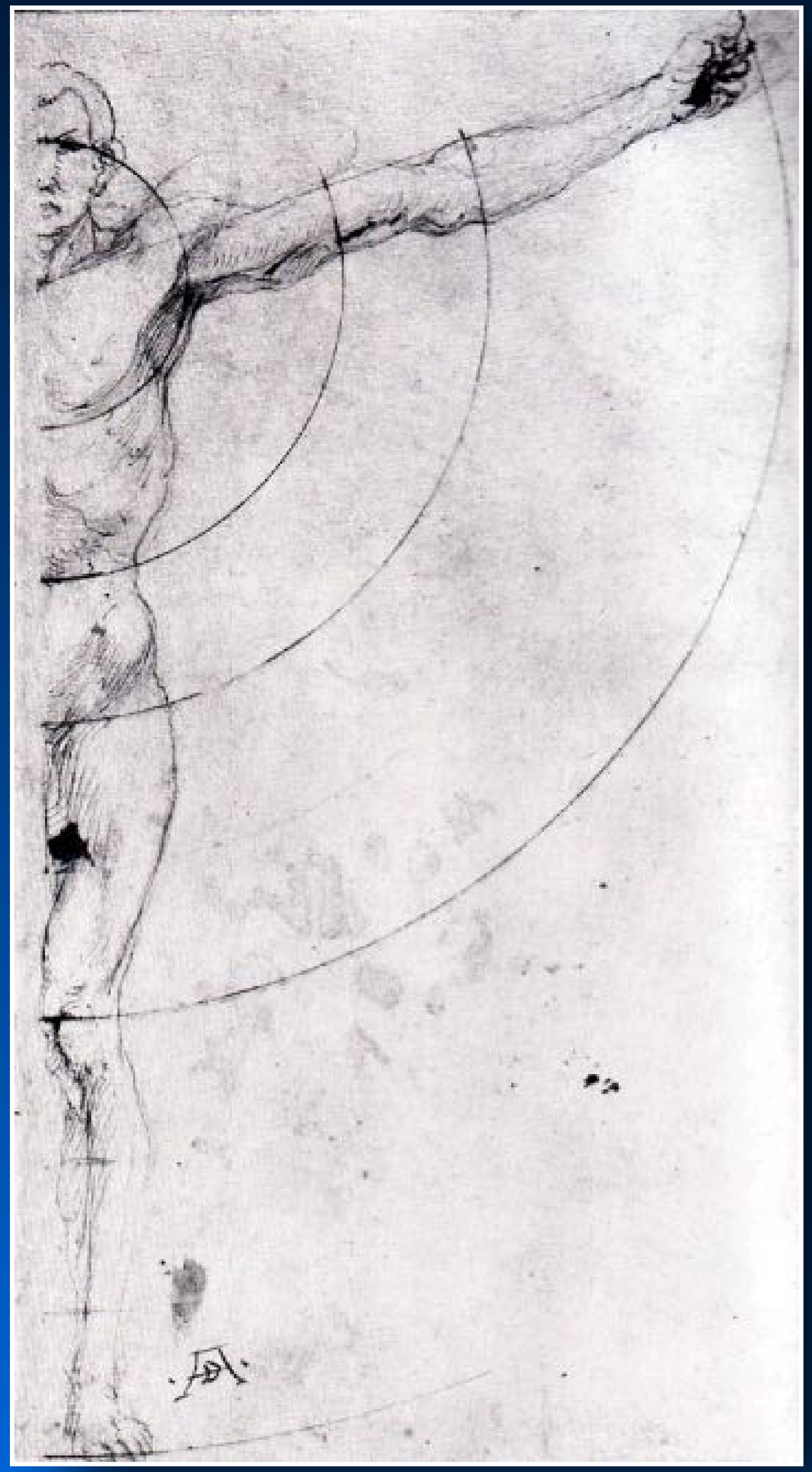


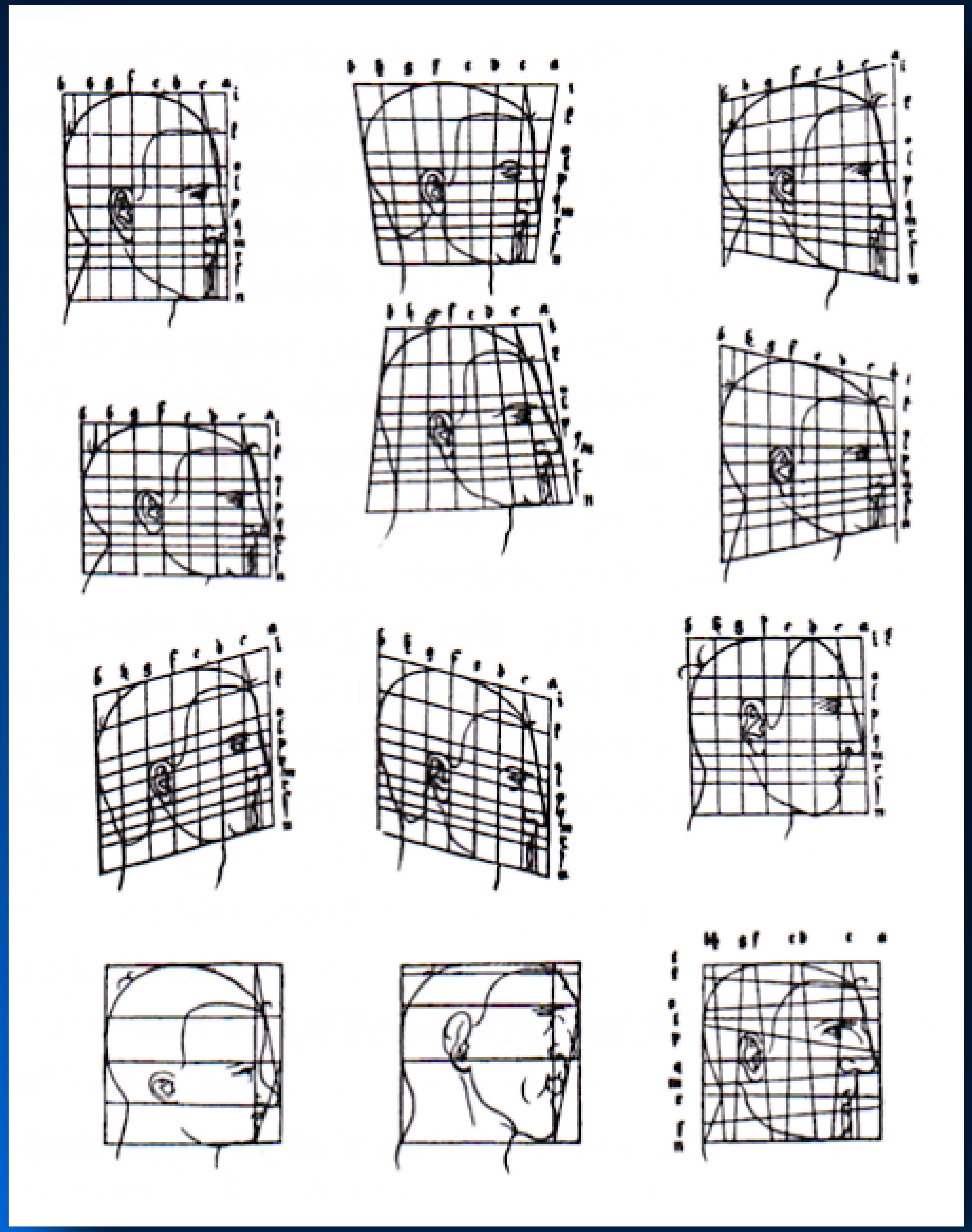
Shape Change as a Geometric
Deformation

Description & Analysis of Morphology

Artistic & Architectural Origins

Albrecht Dürer
(1471 - 1528)





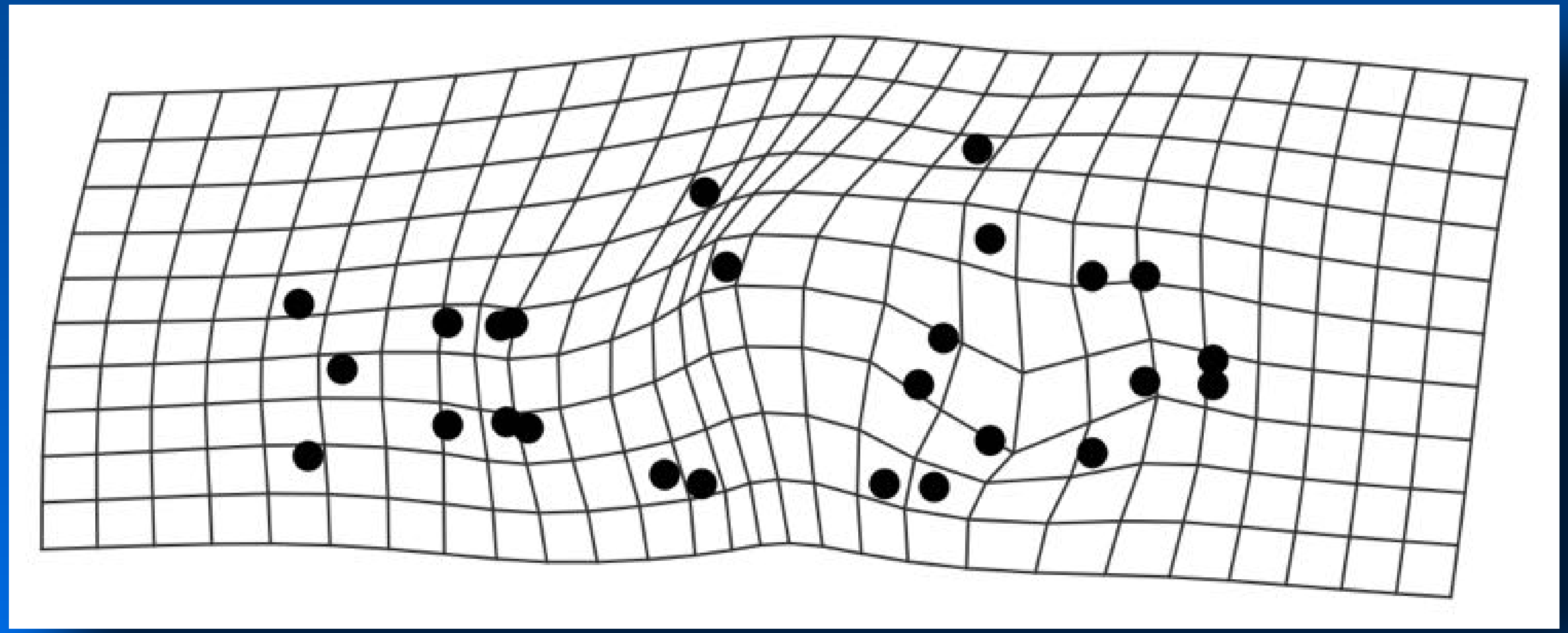
Vire Bücher von Menchlicher
Proportion (1524)

Description & Analysis of Morphology

Geometric Morphometrics

The Thin Plate Spline

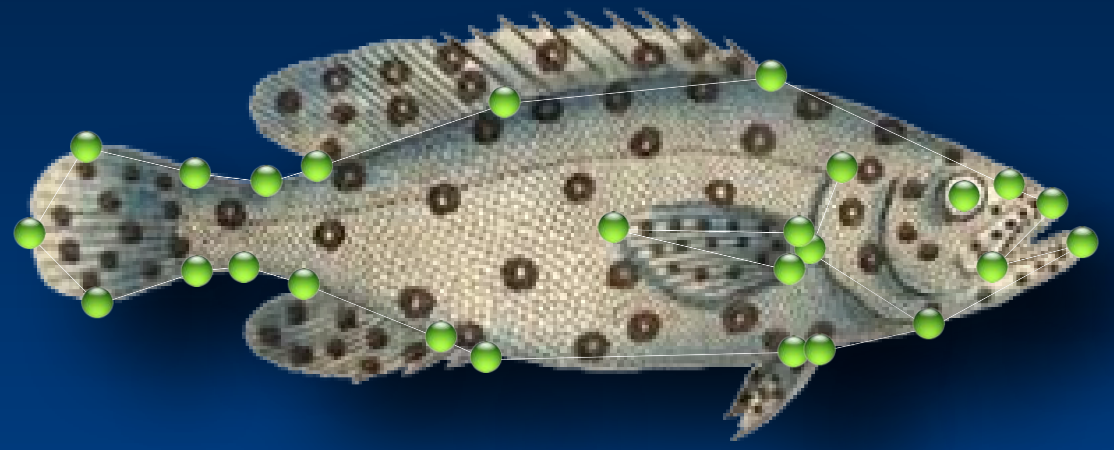
Archosargus rhomboidalis *Anisotremus virginicus*



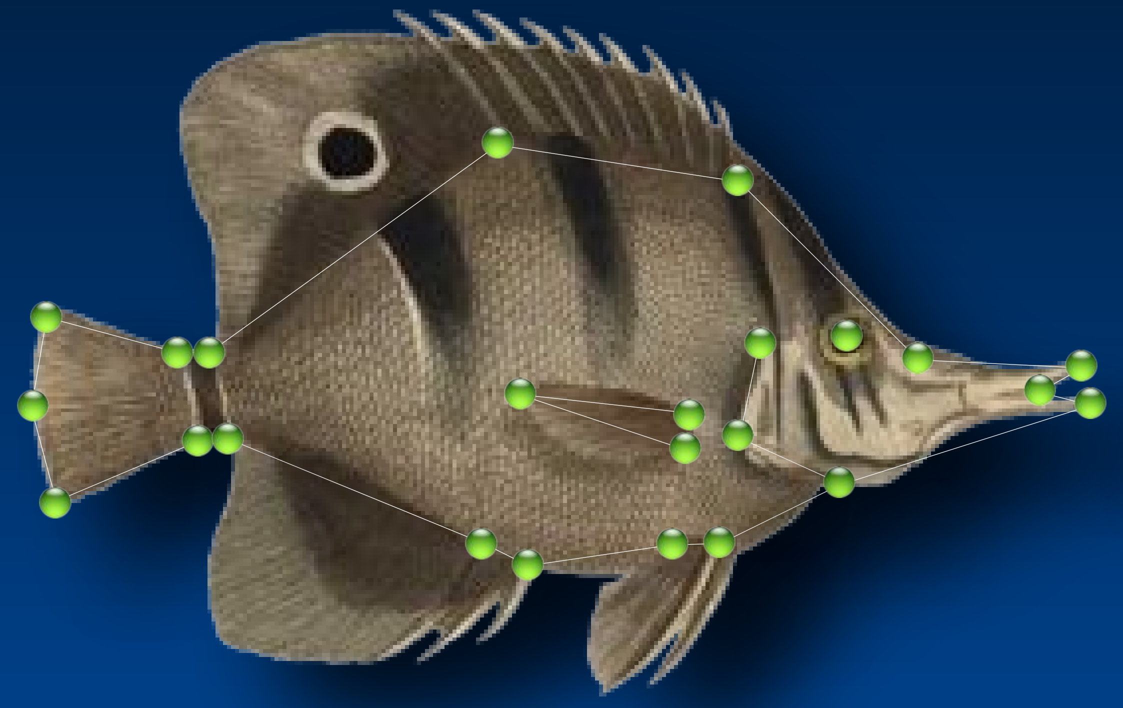
Description & Analysis of Morphology

Geometric Morphometrics

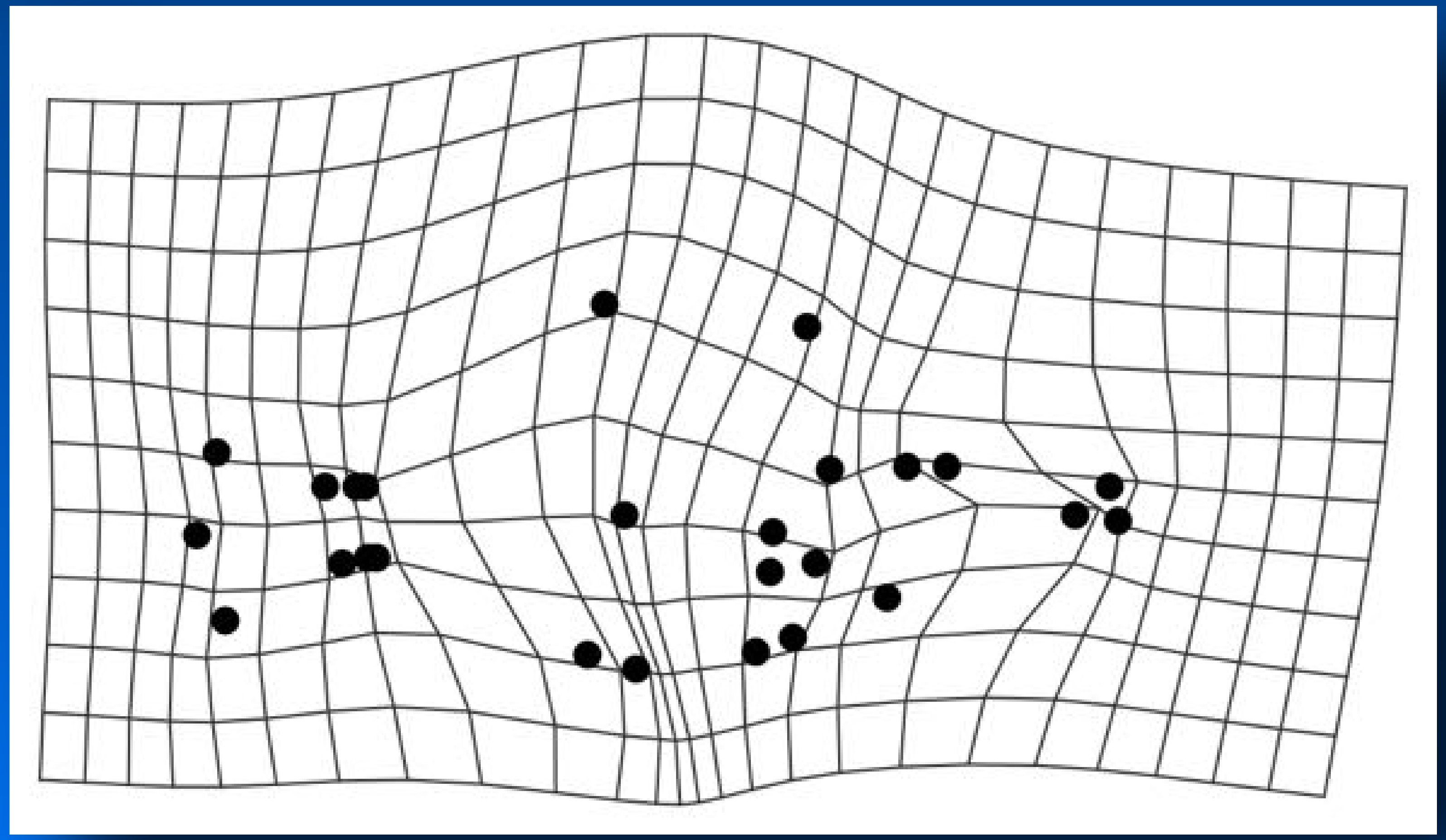
The Thin Plate Spline



Anthias argus

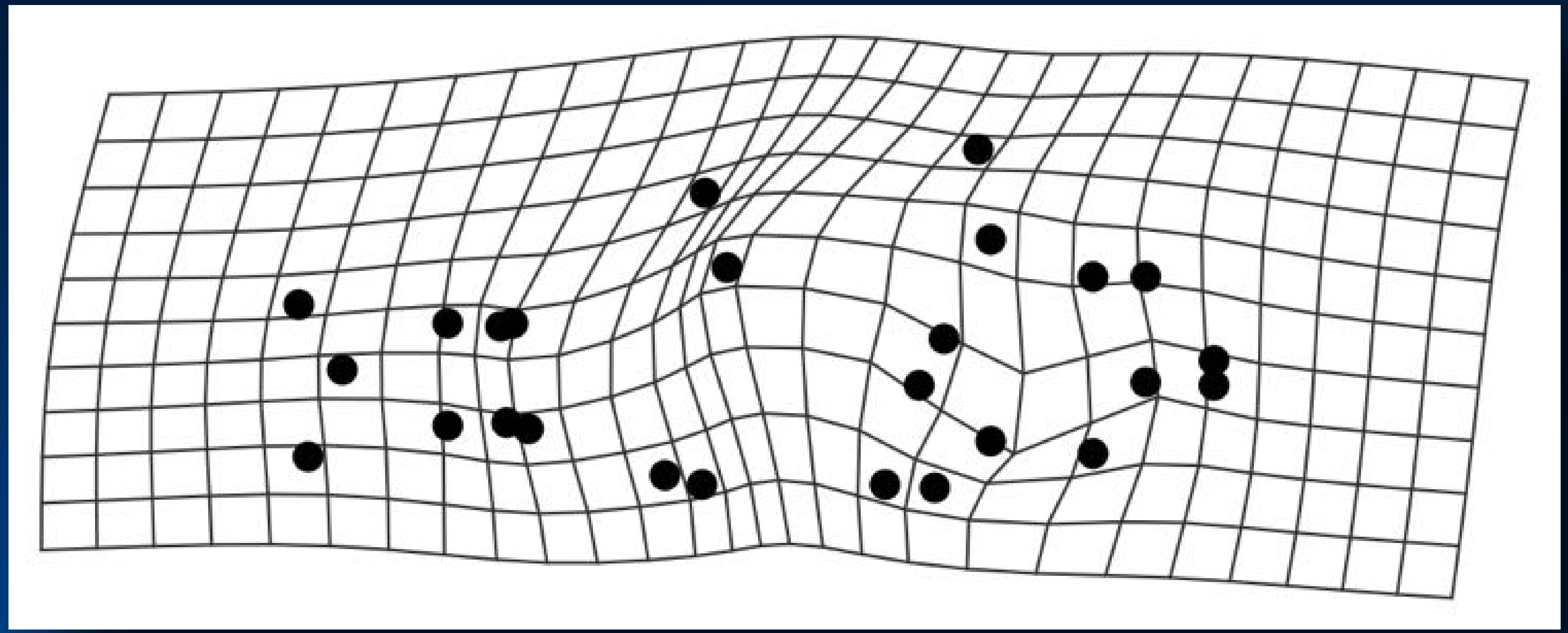


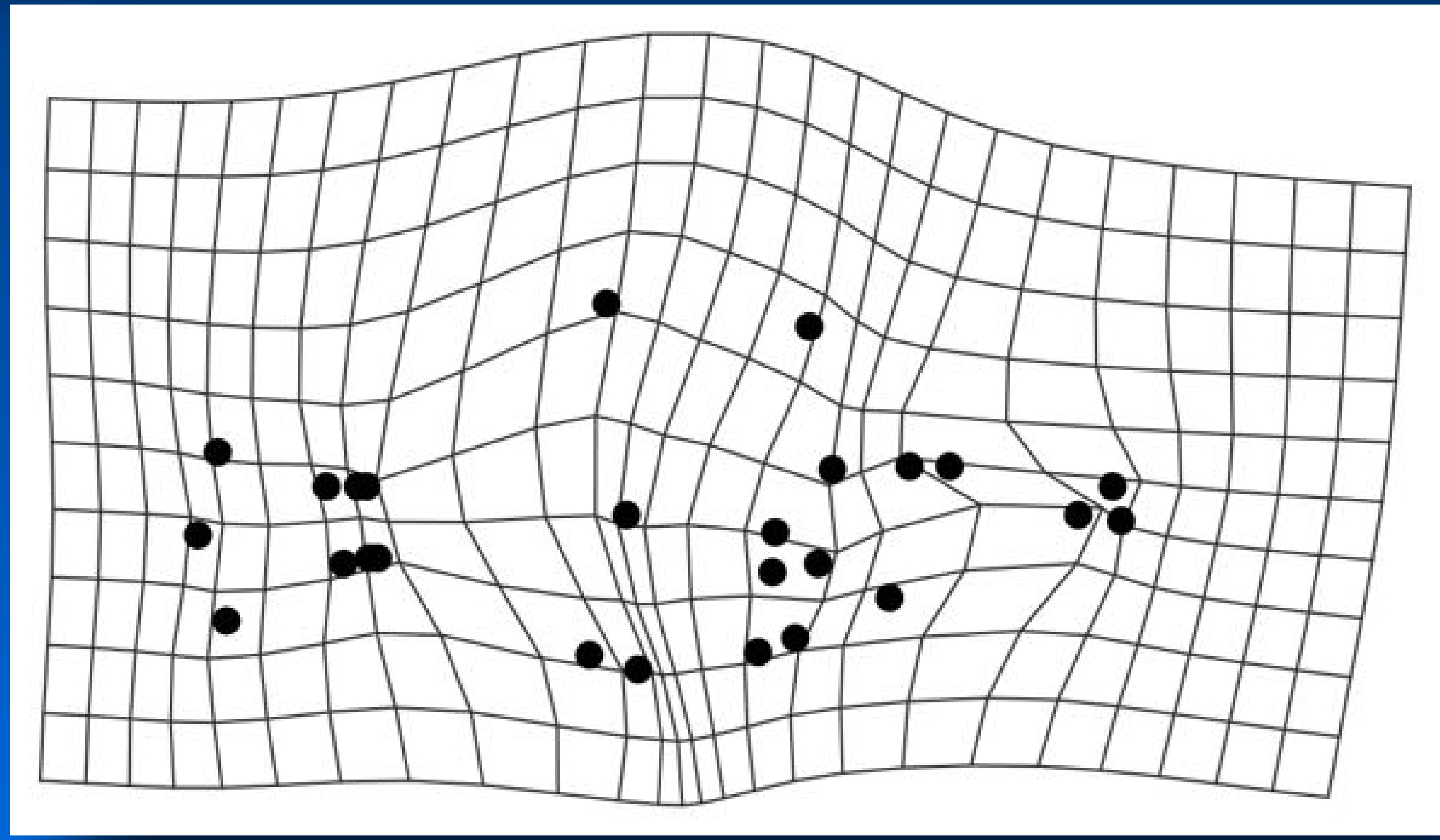
Chelmon rostratus



Description & Analysis of Morphology

Issues with Thin Plate Spines (TPS)





Advantages

- Inherently objective.
- Technology can be used to extend researcher's level of perception.
- Produces Thompsonesque deformation-based summaries of form/shape change.
- Fairly good results can be obtained with a minimum of training.
- Looks abstract, complex and "scientific".
- Can be used to calculate a "distance" between configurations.

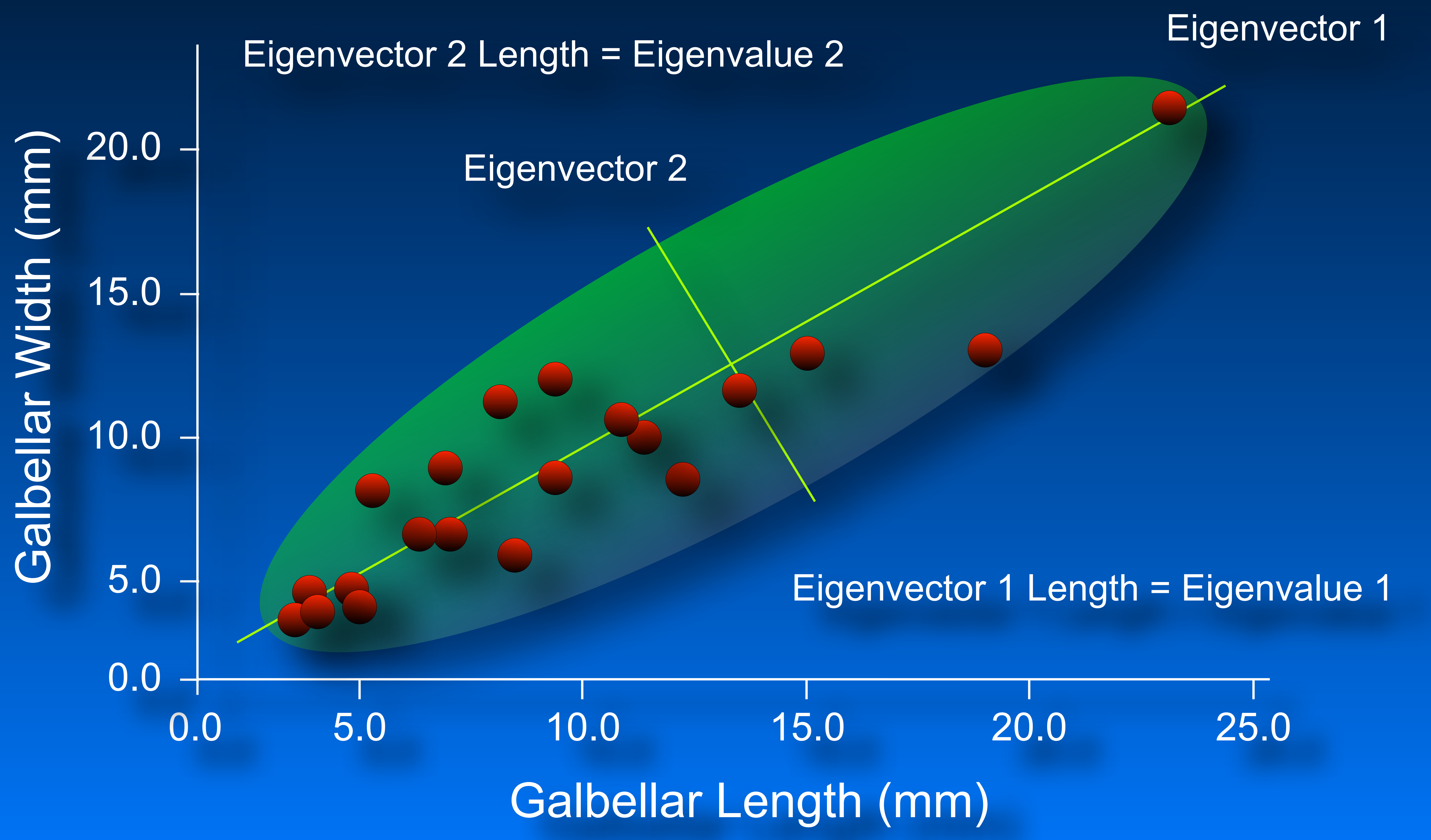
Disadvantages

- Cumbersome to calculate.
- Difficult to interpret.
  - Interpolations between landmark points can be inaccurate.
  - The underlying model is mathematical, not biological.
  - Can easily result in interpolations that make no biological sense.

Species: Definitions & Concepts

Principal Components Analysis

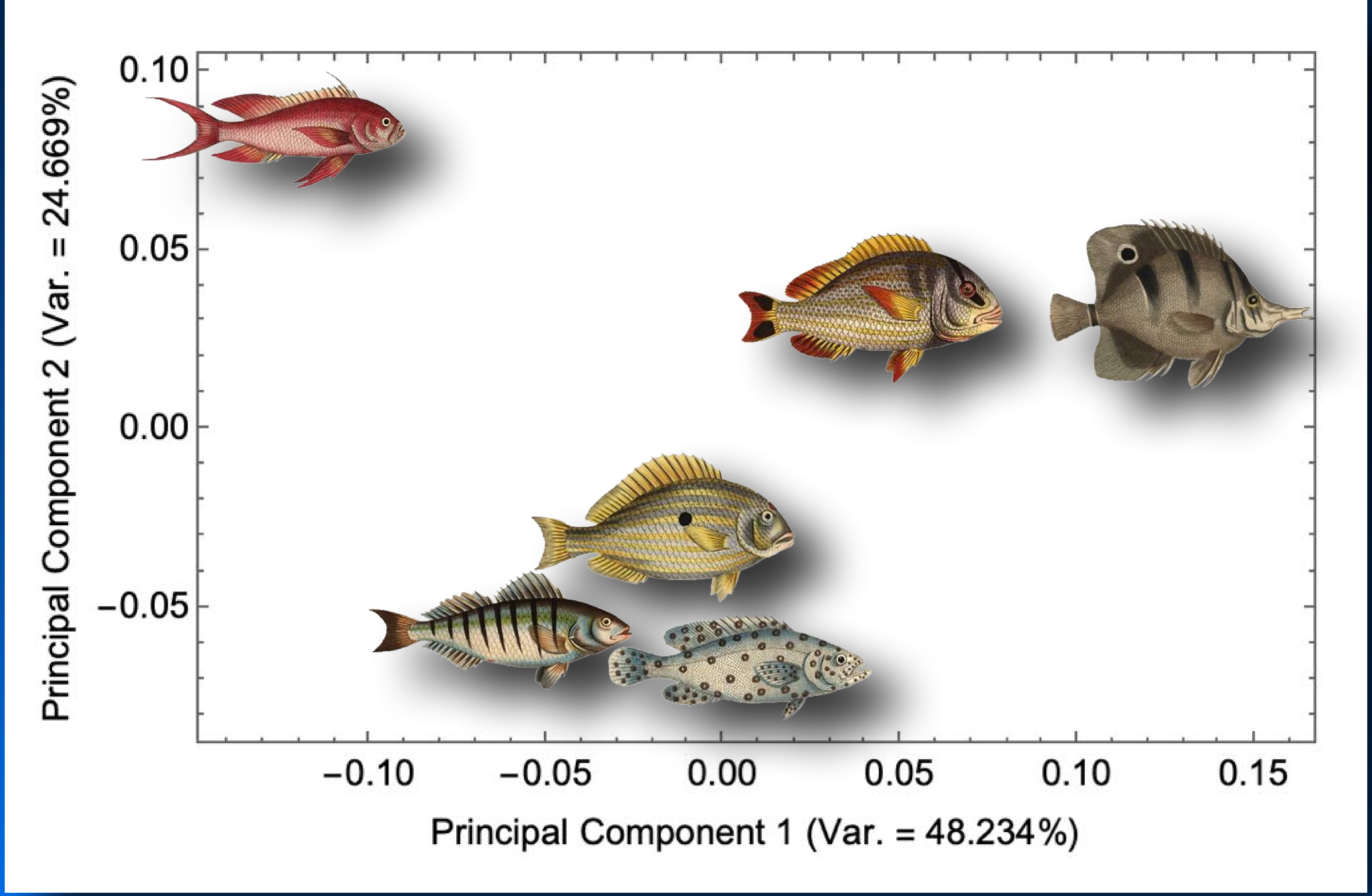
Vector sets used to characterize a data set in multiple dimensions.



Description & Analysis of Morphology

Geometric Morphometrics: Landmarks

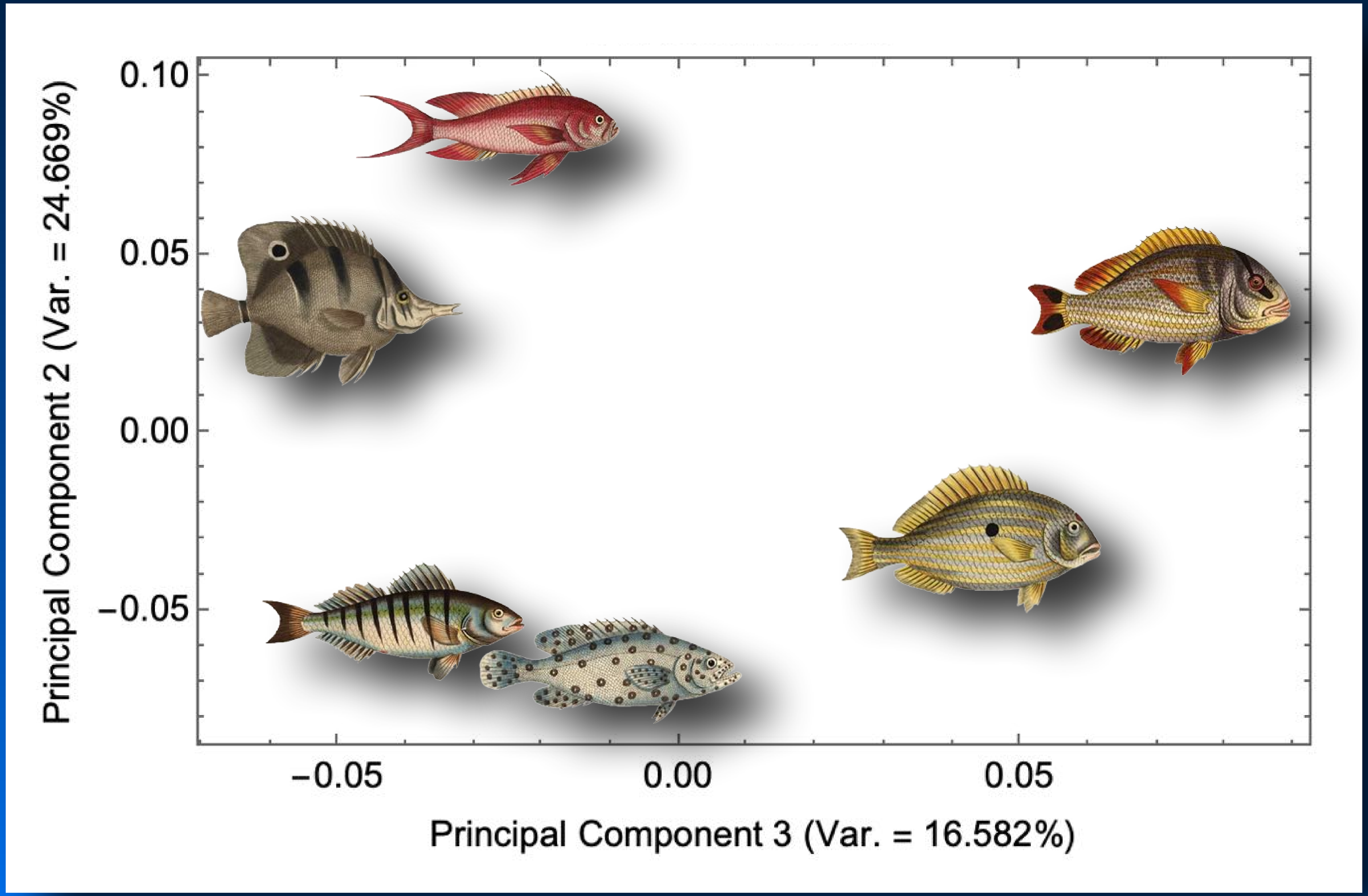
Procrustes Covariance-Based PCA



Description & Analysis of Morphology

Geometric Morphometrics: Landmarks

Procrustes Covariance-Based PCA

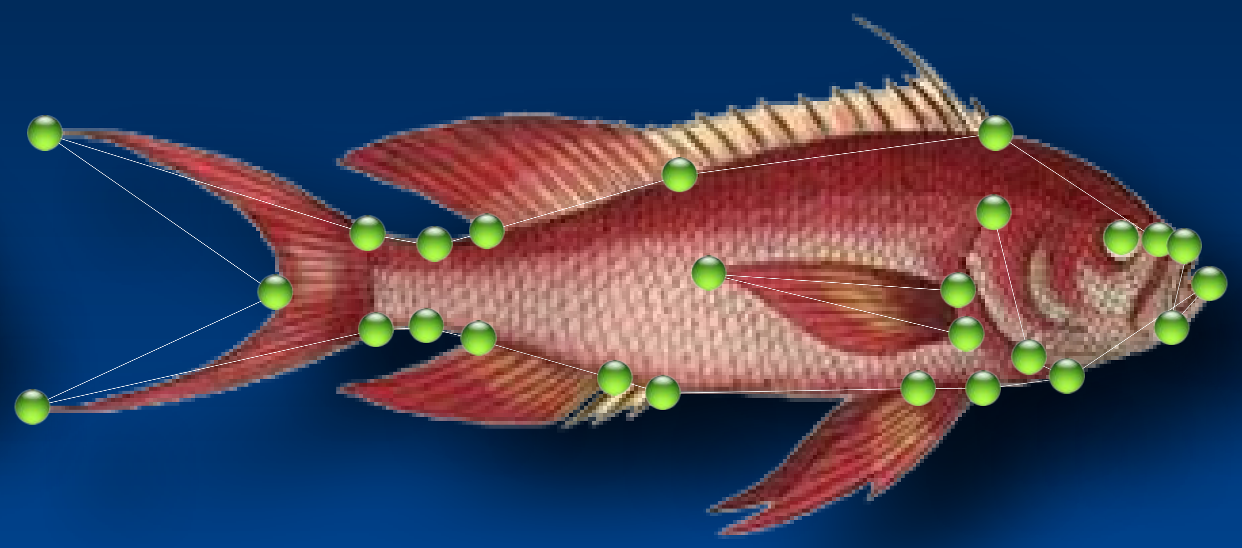


Description & Analysis of Morphology

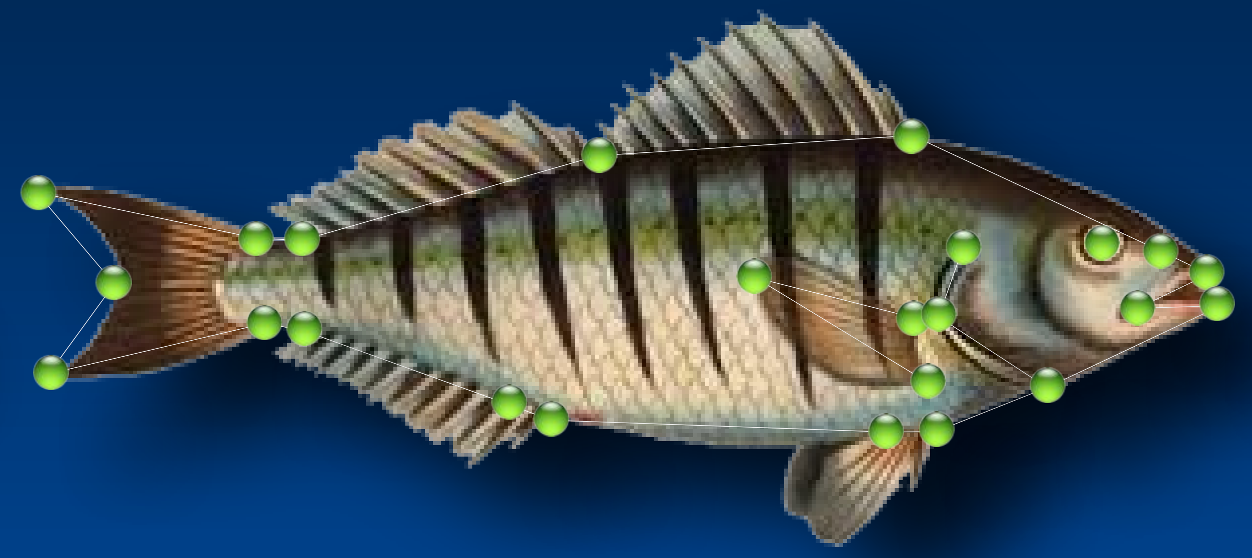
Geometric Morphometrics: Outline Semilandmarks

Semilandmarks are used (typically) when the forms under consideration contain an insufficient number of landmark points to enable their shapes to be represented accurately.

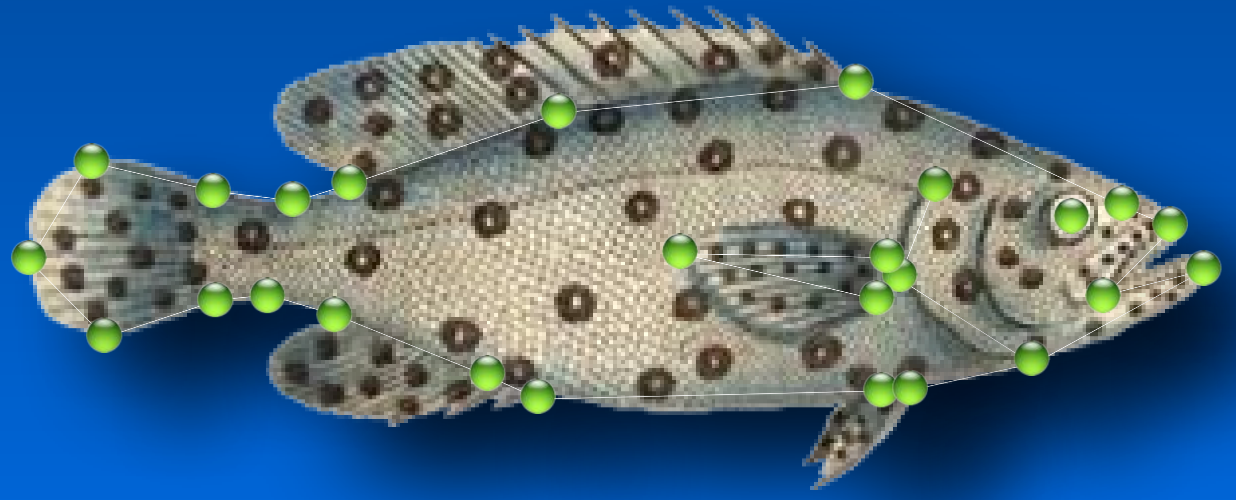
Anisotremus virginicus



Anthias anthias

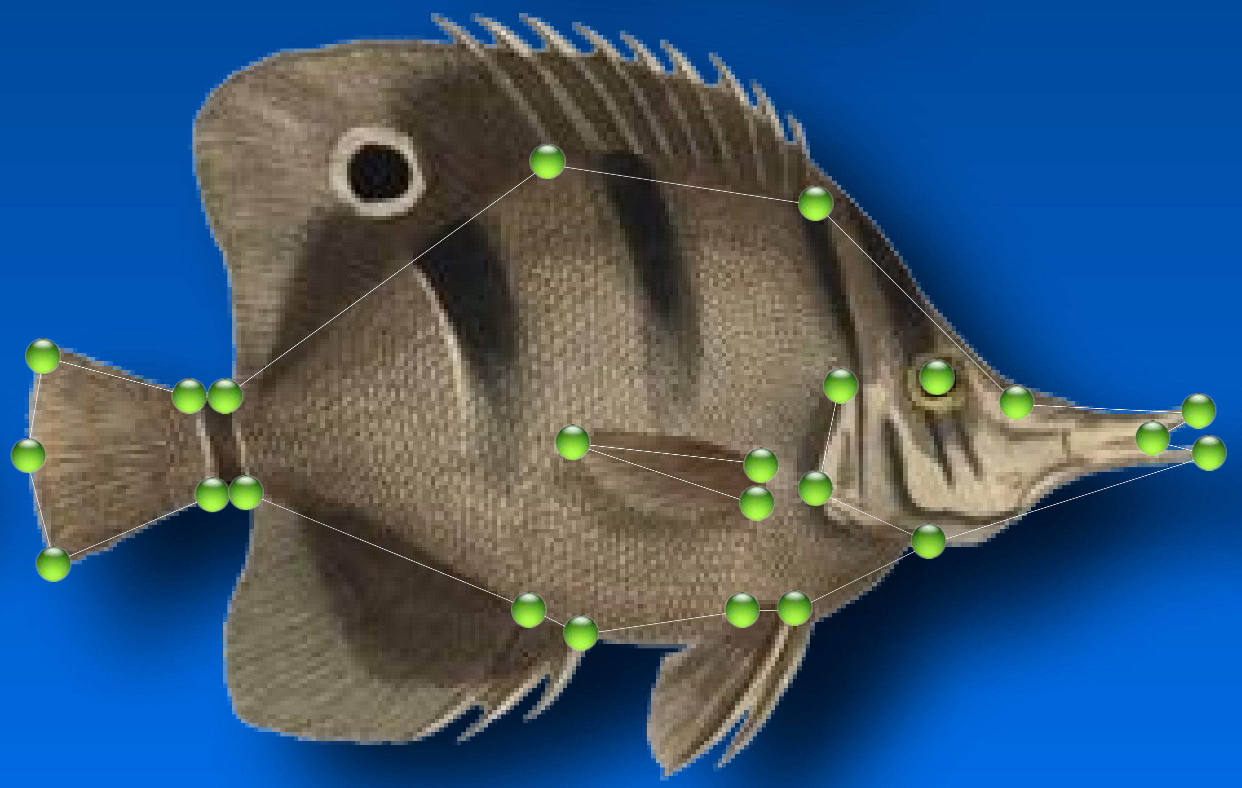


Conodon nobilis



Anthias argus

Archosargus rhomboidalis



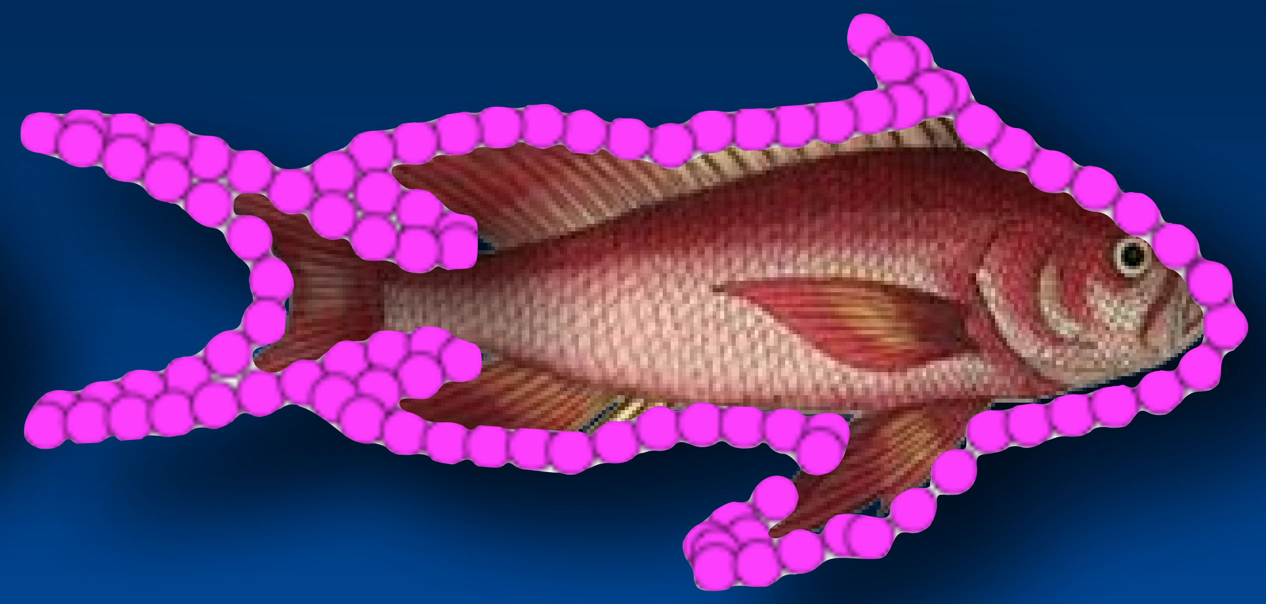
Chelmon rostratus

Description & Analysis of Morphology

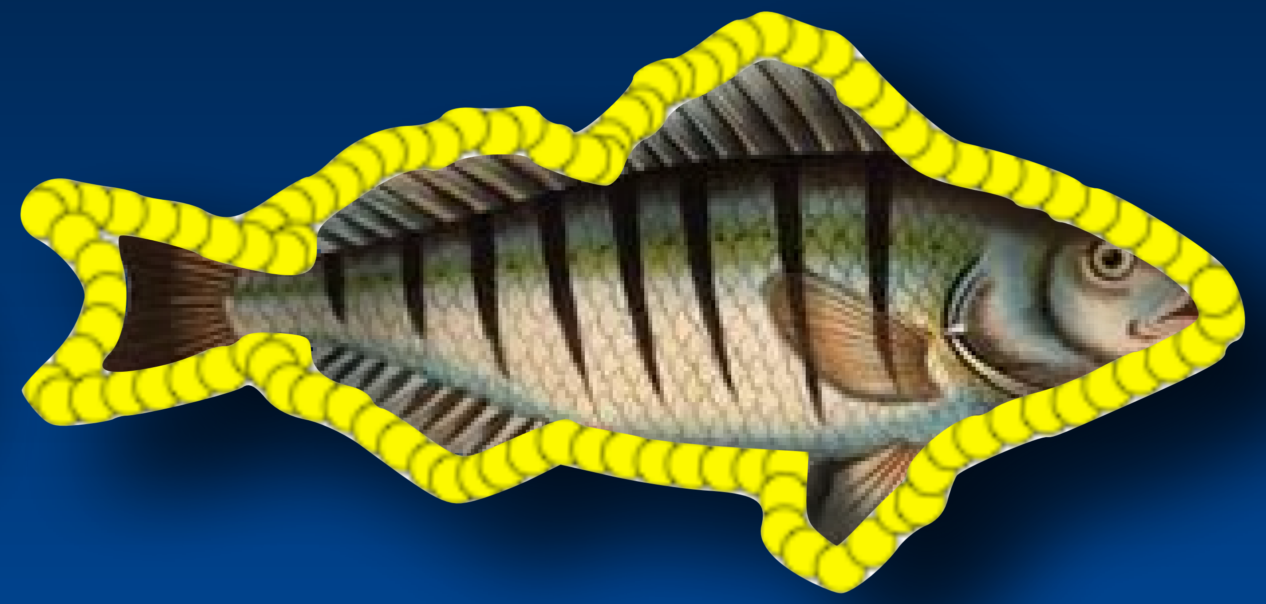
Geometric Morphometrics: Outline Semilandmarks

Semilandmarks are used (typically) when the forms under consideration contain an insufficient number of landmark points to enable their shapes to be represented accurately.

Anisotremus virginicus

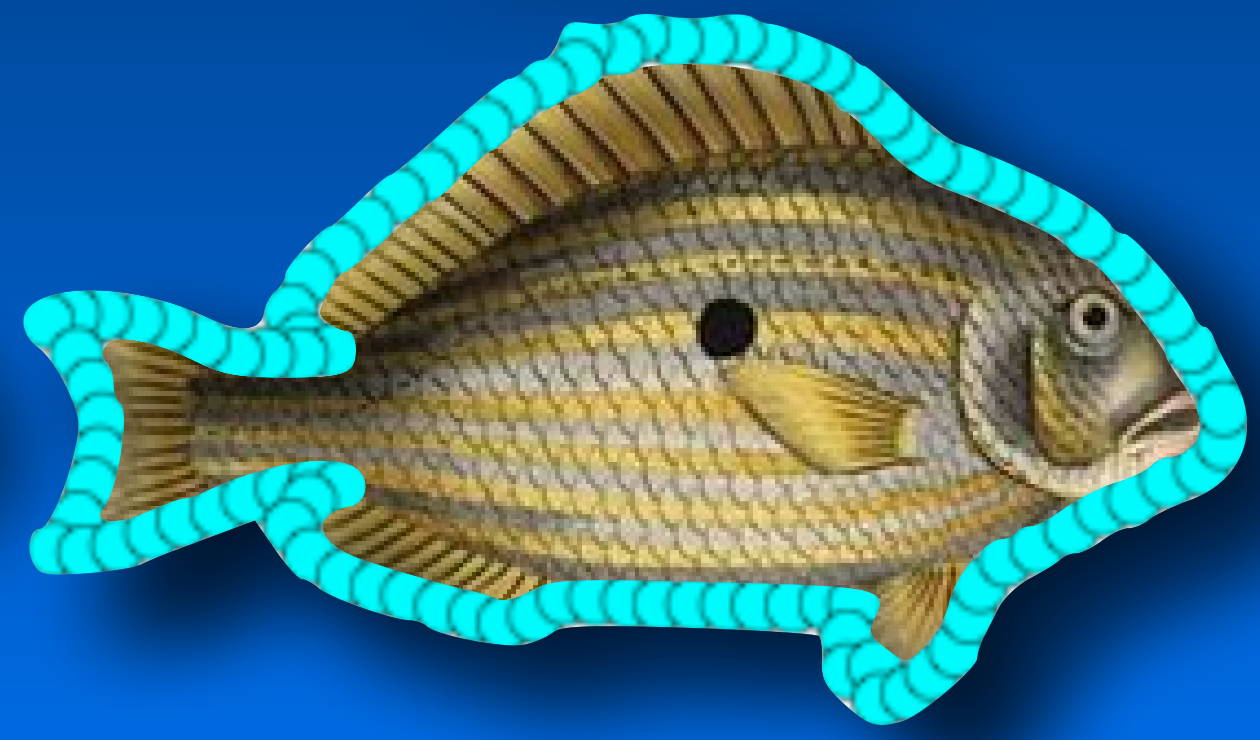


Anthias anthias

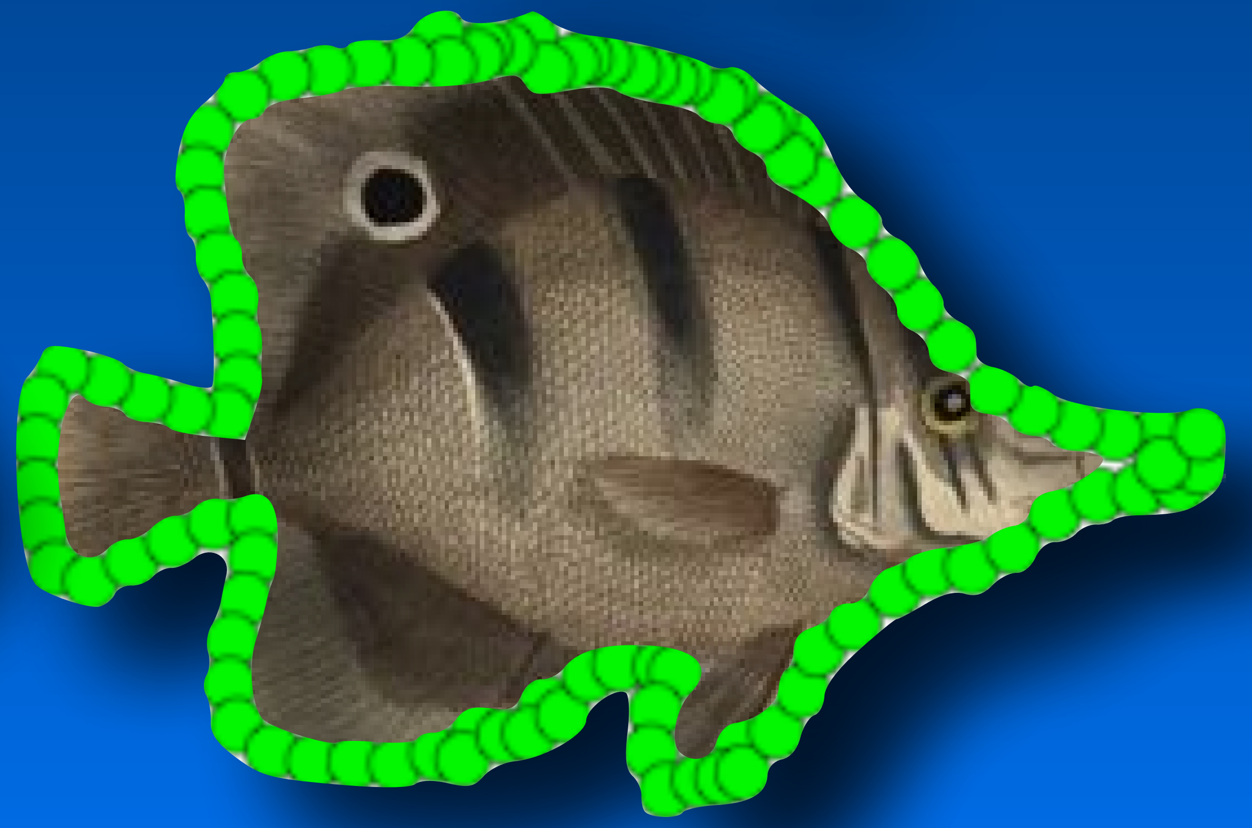


Conodon nobilis

Anthias argus



Archosargus rhomboidalis



Chelmon rostratus

Description & Analysis of Morphology

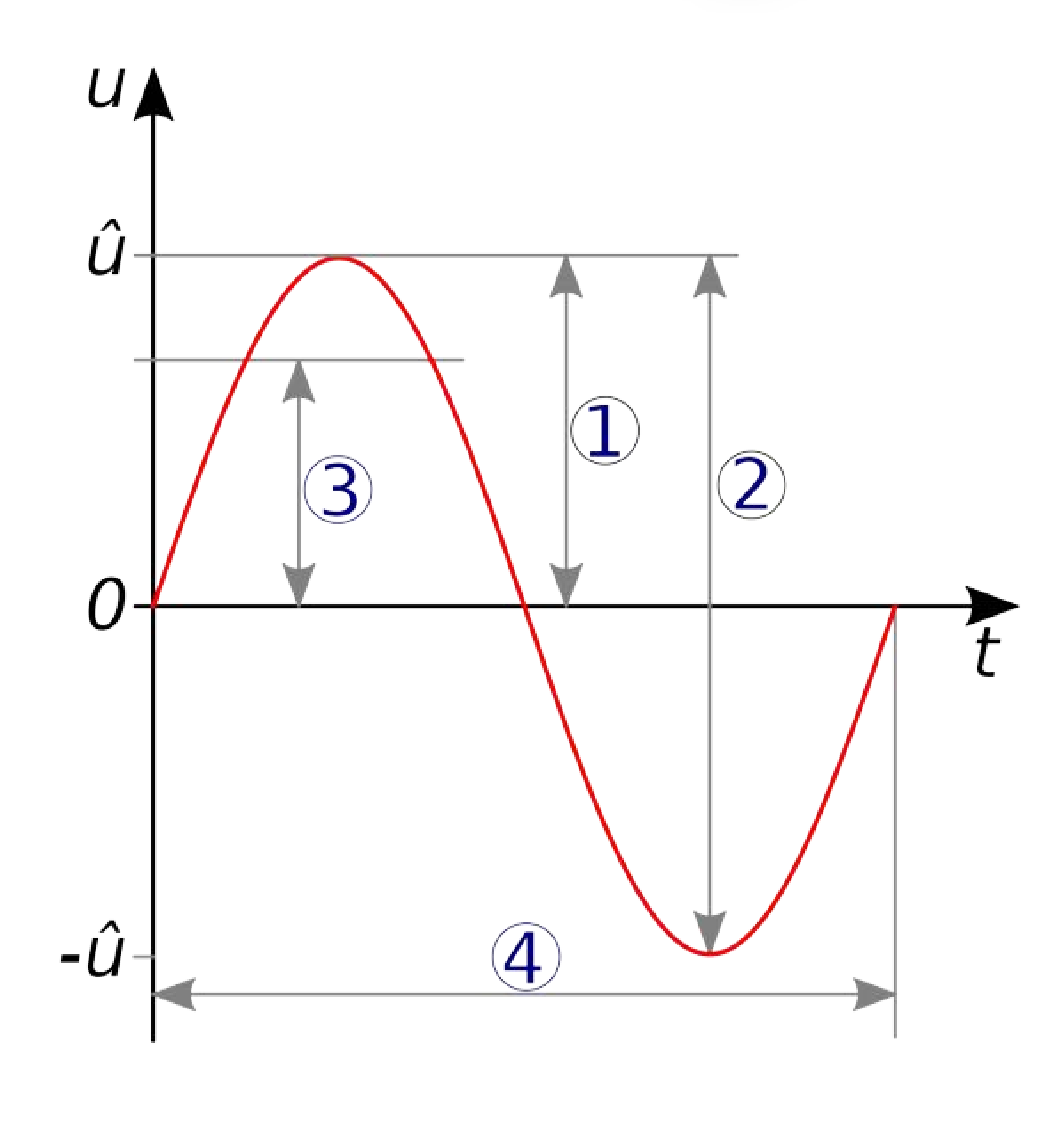
When to use Outlines

- When an object is not composed of multiple parts the relative locations of which can be represented adequately by a single point.
- When the object is rigid (*e.g.*, bone, shell) such that its outline doesn't change.
- When the set out outline semilandmarks exhibit reasonable levels of topological correspondence across all objects in the sample.
- When the hypothesis of interest pertains to, or can be reasonably supposed to involve, the object's outline.

Description & Analysis of Morphology

Analysis of Outline Data: Fourier Analysis

Jean-Baptiste Joseph Fourier
(1768–1830)

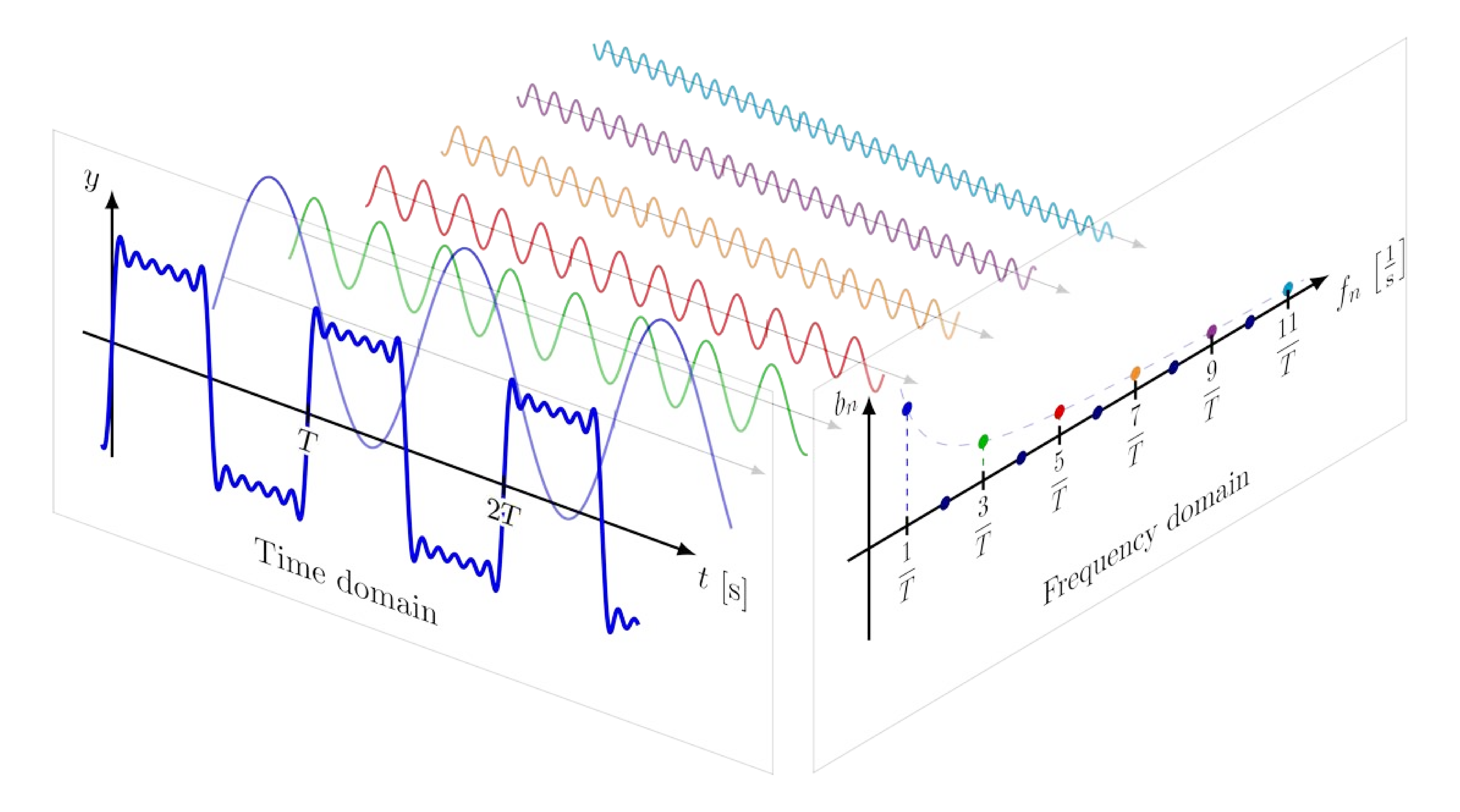


Periodic Mathematical
Function

Description & Analysis of Morphology

Analysis of Outline Data: Fourier Analysis

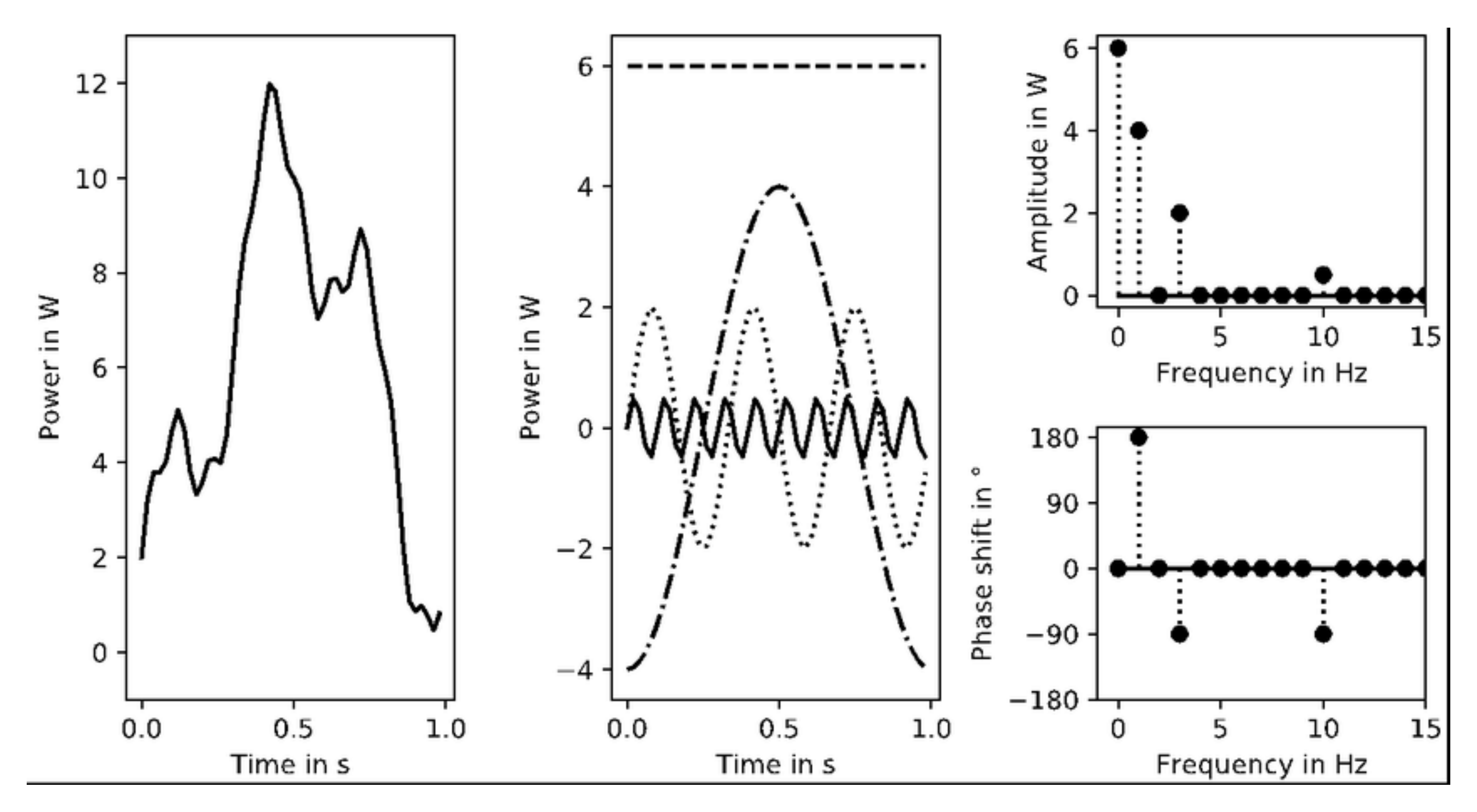
Fourier Decomposition of a Complex Periodic Function



Description & Analysis of Morphology

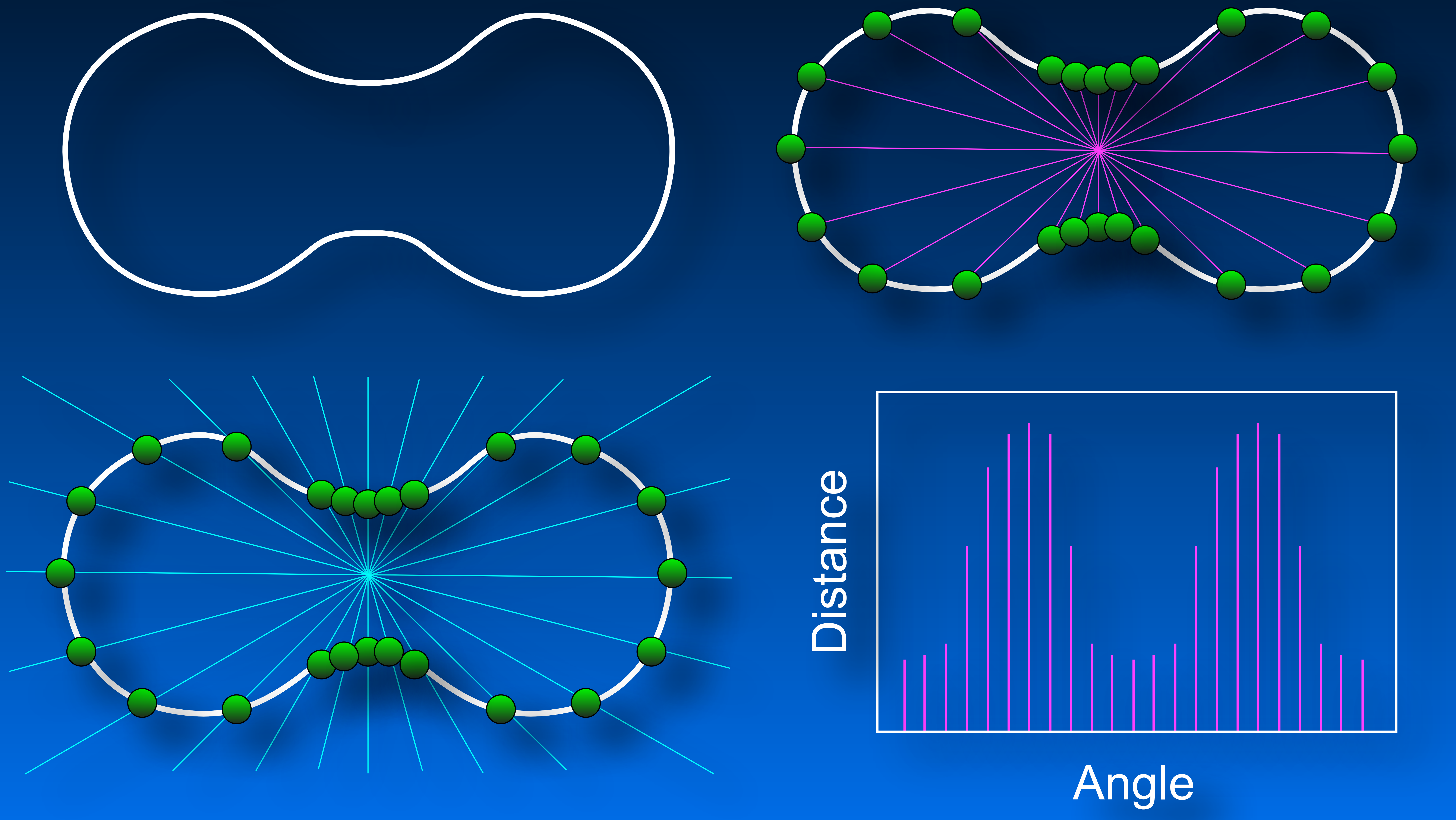
Analysis of Outline Data: Radial Fourier Analysis

Fourier Harmonic Decomposition



Description & Analysis of Morphology

Analysis of Outline Data: Radial Fourier Analysis



Description & Analysis of Morphology

Analysis of Outline Data: Radial Fourier Analysis

Radial Fourier Harmonic Series

6.2.1 *Closed-form Fourier equation*

The equation describing the decomposition of a closed shape is:

$$r(\theta) = r_0 + \sum_{n=1}^{N} r_n \cos(n\theta - \phi_n), \tag{6.1}$$

where:

- $r(\theta)$ represents the mathematical function of the radius r at an angle θ in the space defined by polar coordinates
- r_0 is the average radius of the outline defined in the polar coordinate system
- n is the individual shape component number ($n = 1, \ldots, N$) (commonly referred to as a harmonic number)
- N is the total number of shape components
- r_n is the magnitude of the contribution of the nth shape term (commonly referred to as the harmonic amplitude)
- θ represents the polar angle of the individual radius represented by $r(\theta)$, and
- ϕ_n represents the phase angle associated with harmonic n.

Description & Analysis of Morphology

Analysis of Outline Data: Radial Fourier Analysis

Radial Fourier Harmonic Coefficients

$$a_j = \frac{2}{m}\sum_{i=1}^{m} F(i)\cos\left(\frac{2\pi j}{m}\right),$$

and

$$b_j = \frac{2}{m}\sum_{i=1} F(i)\sin\left(\frac{2\pi j}{m}\right),$$

where:

- a_j represents the real jth component of the Fourier transform
- b_j represents the complex jth component of the Fourier transform
- m is the number of polar vectors defining the shape being analyzed, and
- $F(i)$ is the length of the radius at θ_i (the raw data consists of a series of angles (θ) and radii (F)).

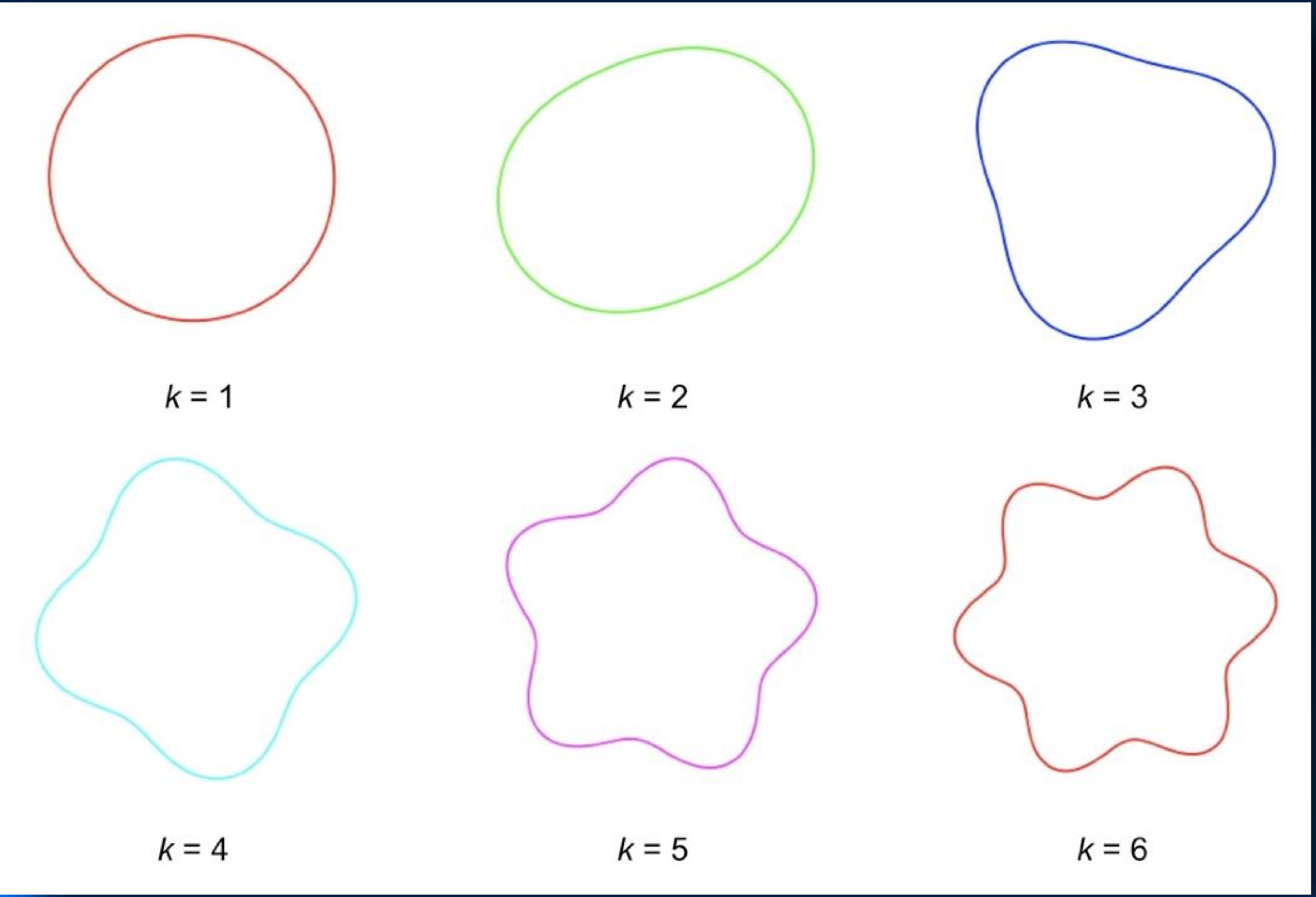
$$r_j = \sqrt{a_j^2 + b_j^2},$$

$$\phi_j = \tan^{-1}\left(\frac{b_j}{a_j}\right),$$

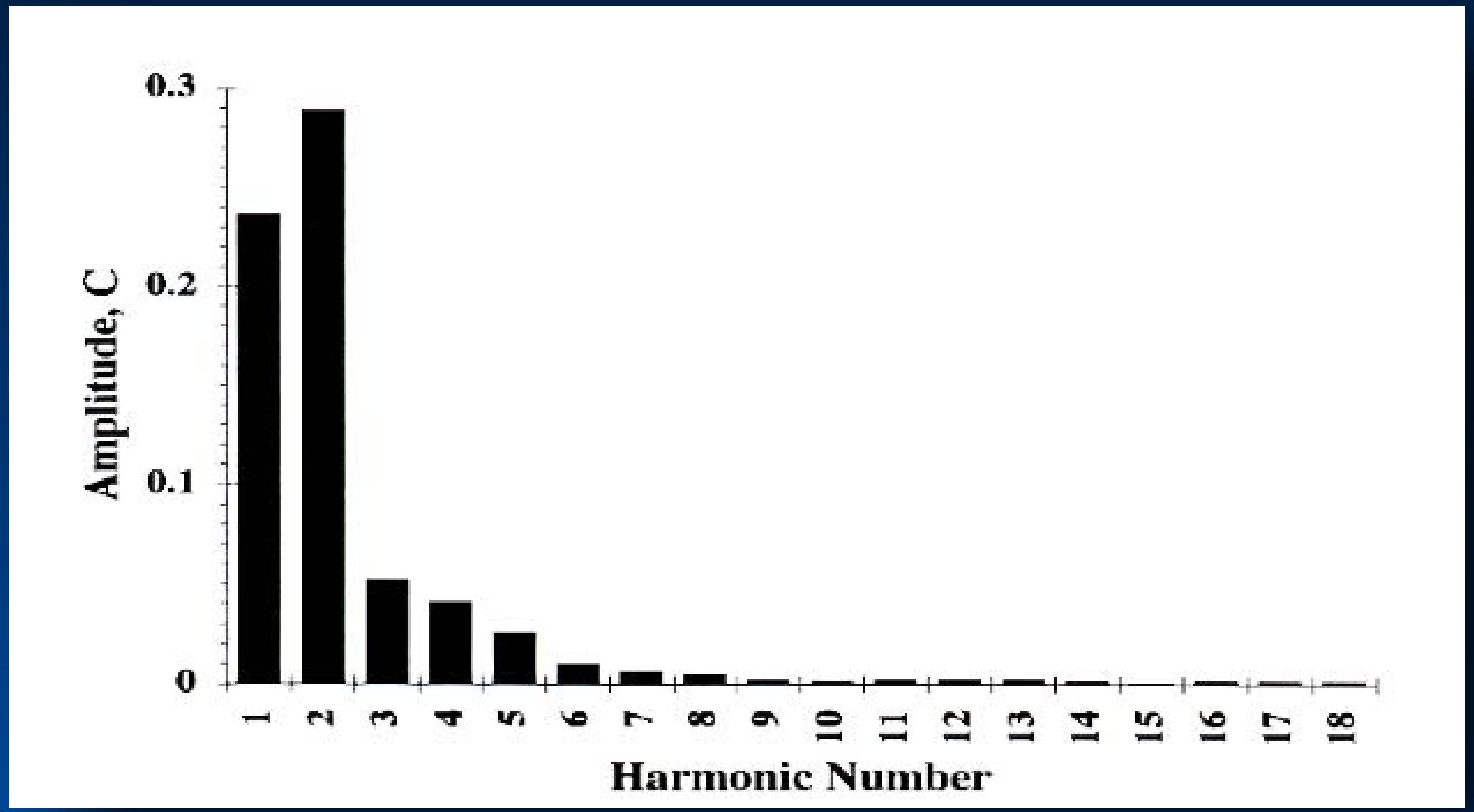
Description & Analysis of Morphology

Analysis of Outline Data: Radial Fourier Analysis

Fourier Harmonic Series



Fourier Harmonic Spectrum



Fourier Harmonic Distance Coefficient

$$DH_{jk} = \sqrt{\left(\frac{1}{n}\right)\sum_{i=1}^{n}\left(\left[r_{ij}\cos\phi_{ij} - r_{ik}\cos\phi_{ik}\right]^2 + \left[r_{ij}\sin\phi_{ij} - r_{ik}\sin\phi_{ik}\right]^2\right)}$$

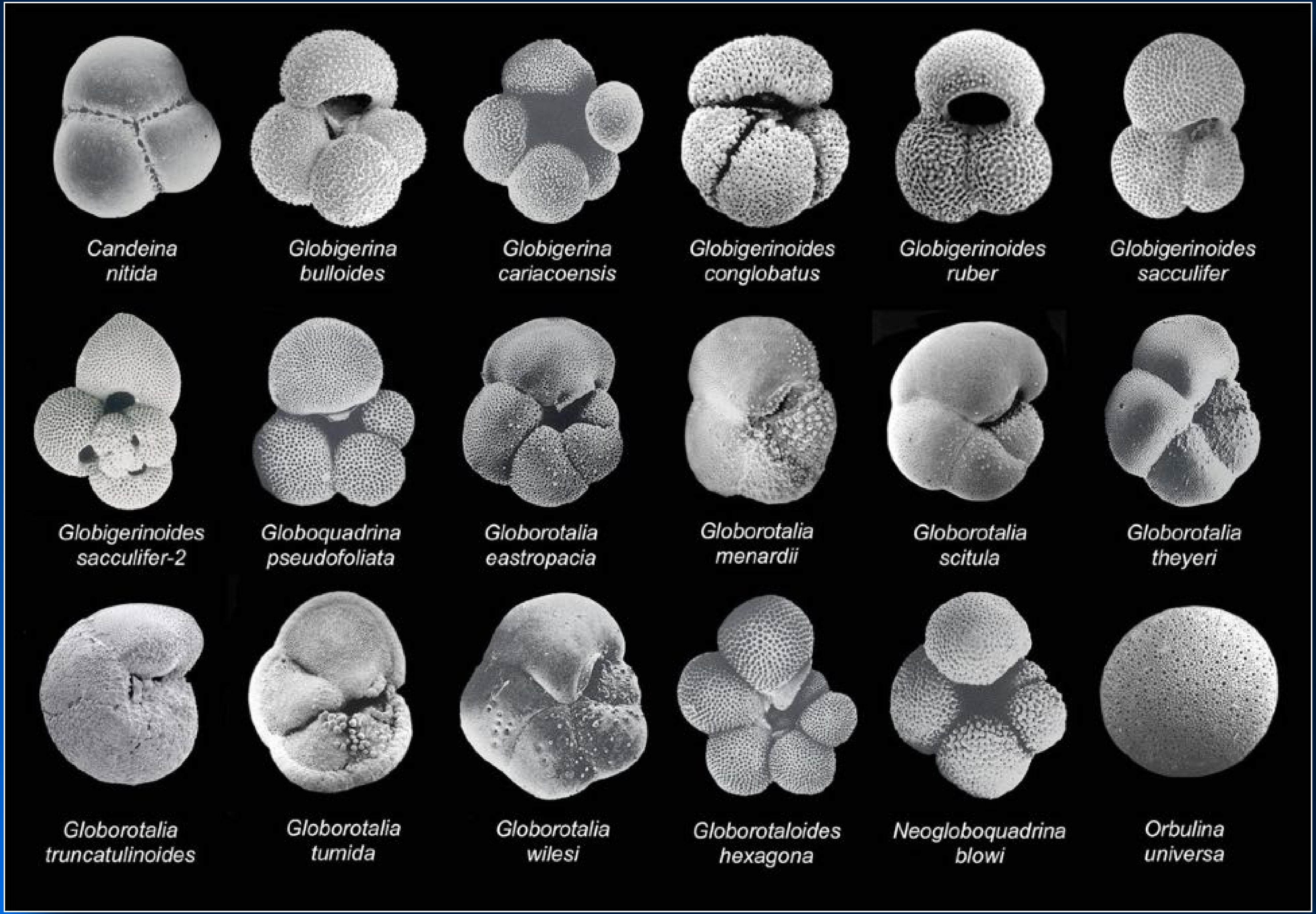
Where: r = amplitude

ϕ = phase angle

Description & Analysis of Morphology

Analysis of Outline Data: Radial Fourier Analysis

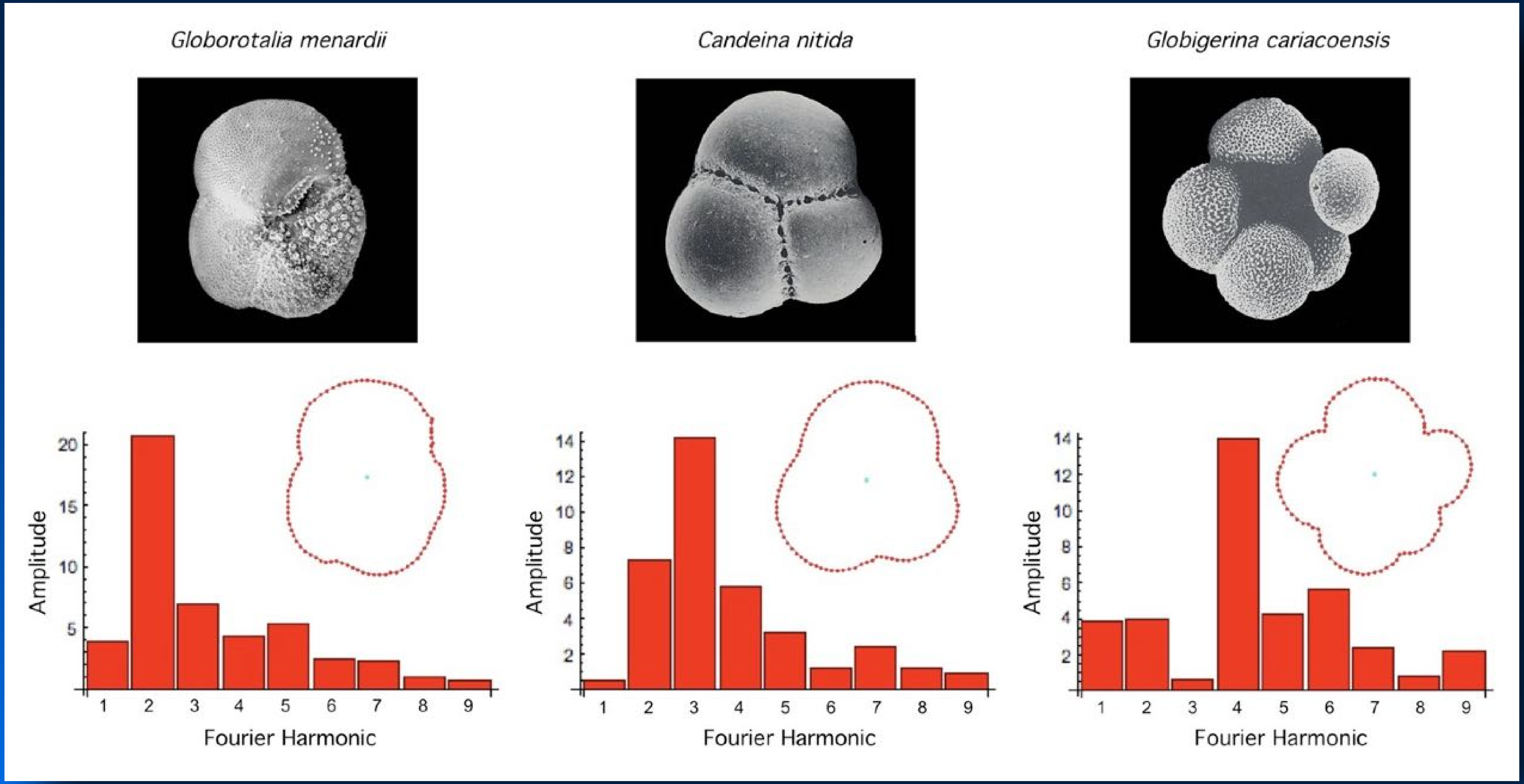
Example: Planktonic Foraminifera



Description & Analysis of Morphology

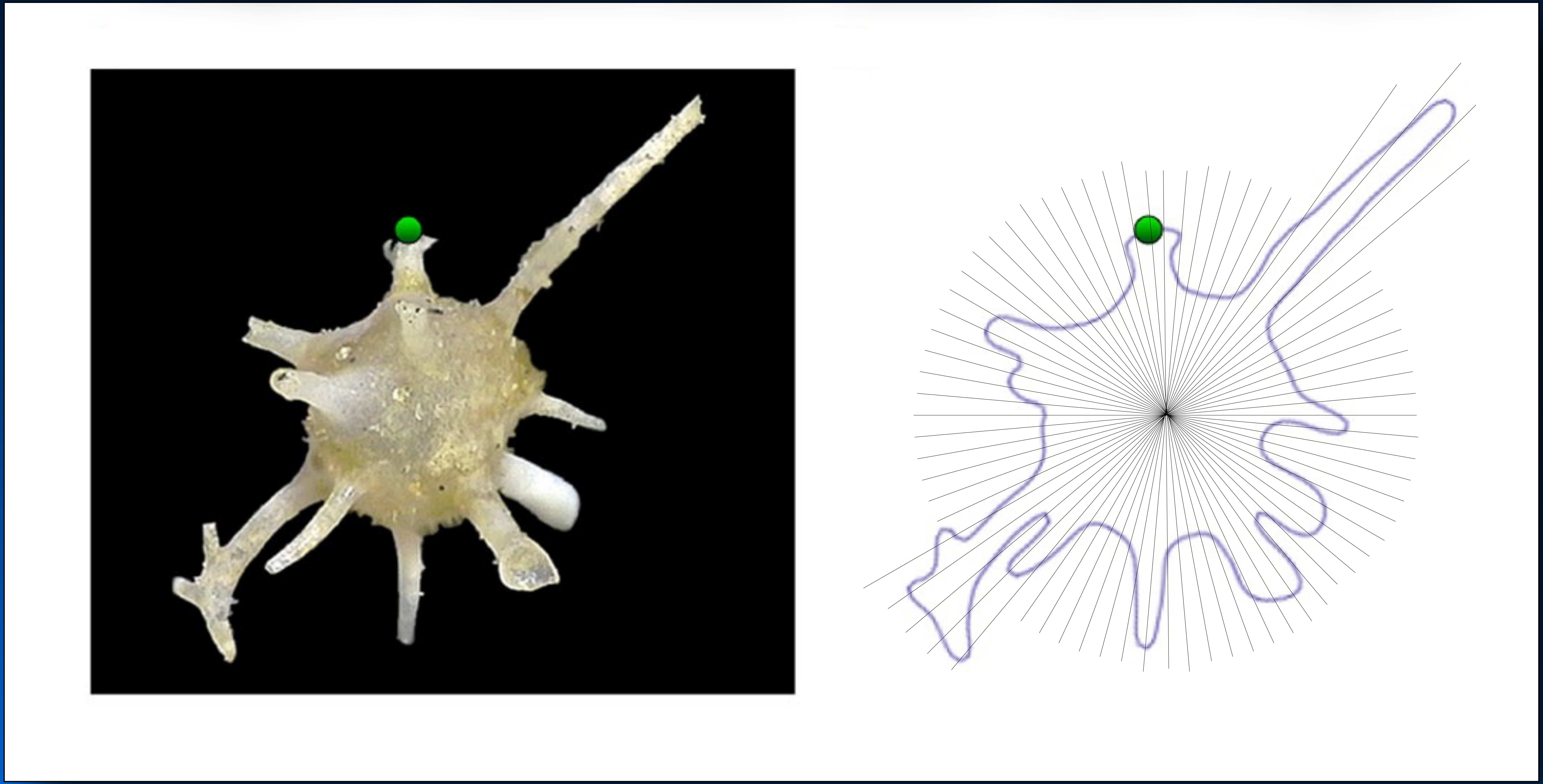
Analysis of Outline Data: Radial Fourier Analysis

Example: Planktonic Foraminifera



Description & Analysis of Morphology

Analysis of Outline Data: Radial Fourier Analysis?



Radial Fourier analysis requires the outlines to be closed and single-valued. However, many outlines of interest to biologists are multi-valued.

Description & Analysis of Morphology

Analysis of Outline Data: Elliptical Fourier Analysis

Elliptical Fourier Harmonic Series

$$x(t) = \sum_{n=1}^{N} \left[A_n \cos\left(\frac{2\pi nt}{T}\right) + B_n \sin\left(\frac{2\pi nt}{T}\right) \right]$$

$$y(t) = \sum_{n=1}^{N} \left[C_n \cos\left(\frac{2\pi nt}{T}\right) + D_n \sin\left(\frac{2\pi nt}{T}\right) \right]$$

Where: n = the harmonic number
N = the maximum harmonic number
t = displacement along outline
T = total displacement

Description & Analysis of Morphology

Analysis of Outline Data: Elliptical Fourier Analysis

Elliptical Fourier Harmonic Coefficients

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

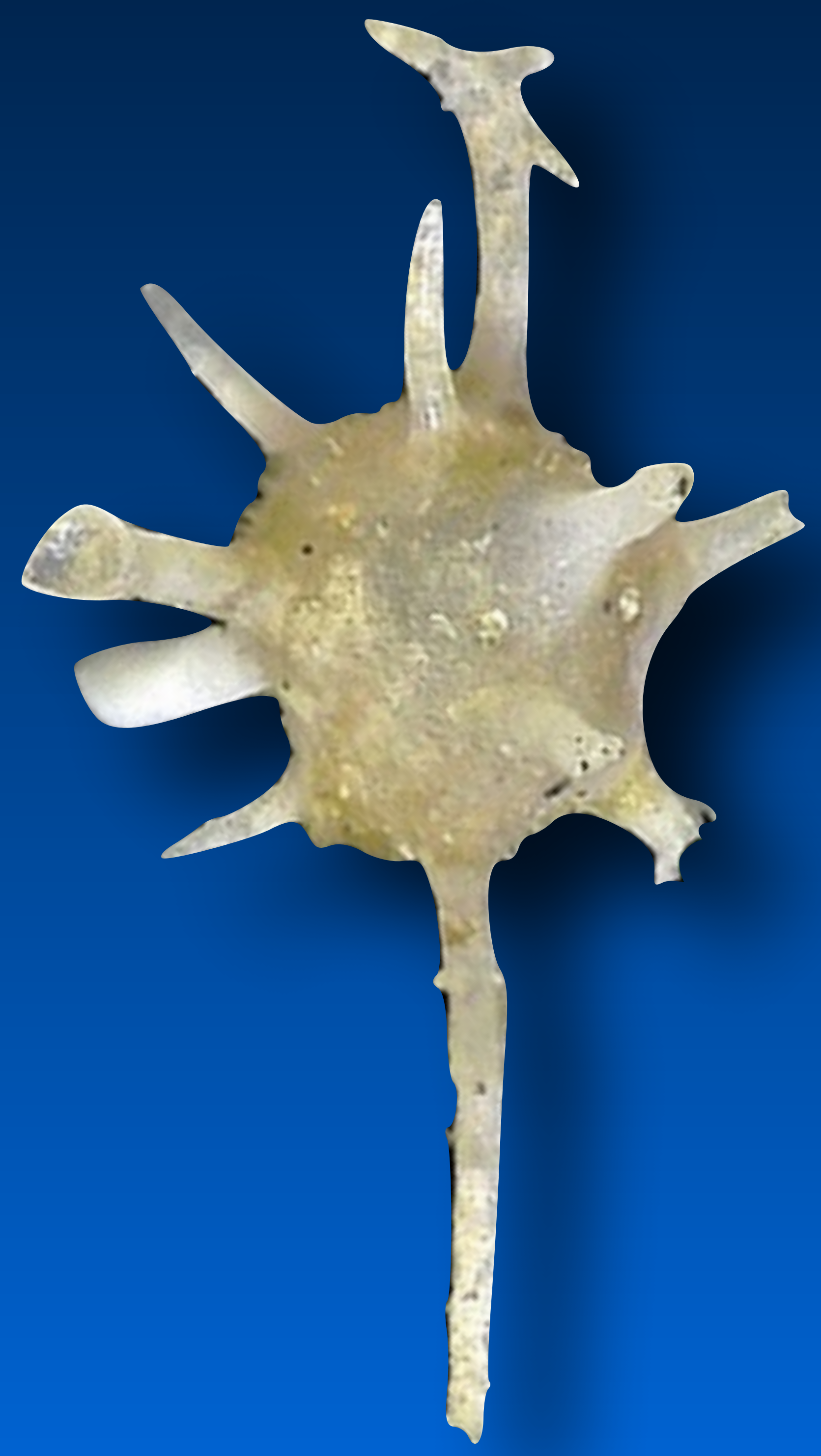
$$B_n = \frac{T}{2n^2\pi^2}\sum_{p=1}^{k}\frac{\Delta x_p}{\Delta t_p}\left[\sin\left(\frac{2\pi n t_p}{T}\right)-\sin\left(\frac{2\pi n t_{p-1}}{T}\right)\right] \qquad D_n = \frac{T}{2n^2\pi^2}\sum_{p=1}^{k}\frac{\Delta y_p}{\Delta t_p}\left[\sin\left(\frac{2\pi n t_p}{T}\right)-\sin\left(\frac{2\pi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

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

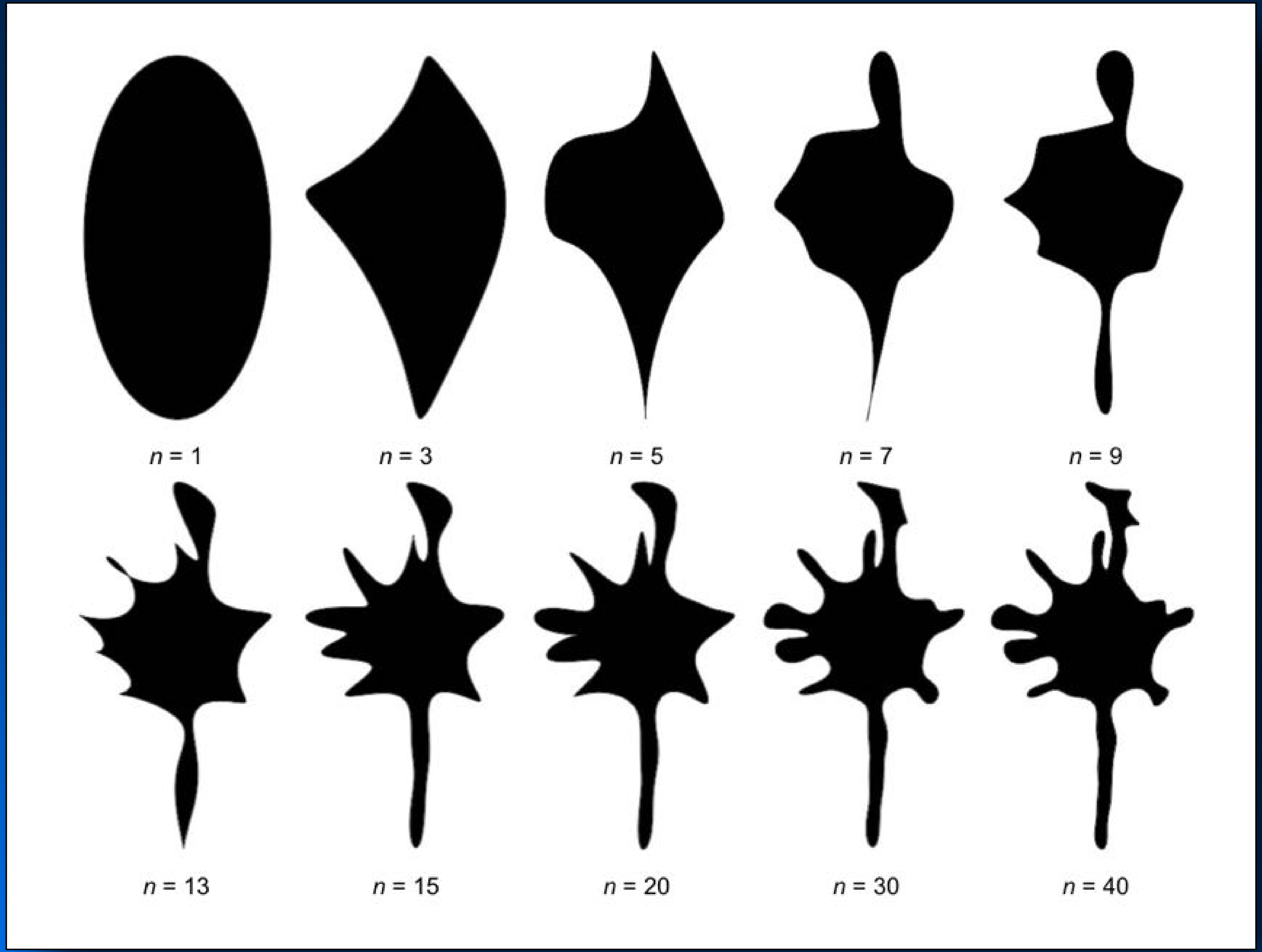
Description & Analysis of Morphology

Analysis of Outline Data: Elliptical Fourier Analysis

Elliptical Fourier Harmonic Reconstruction



Ramulina globulifera

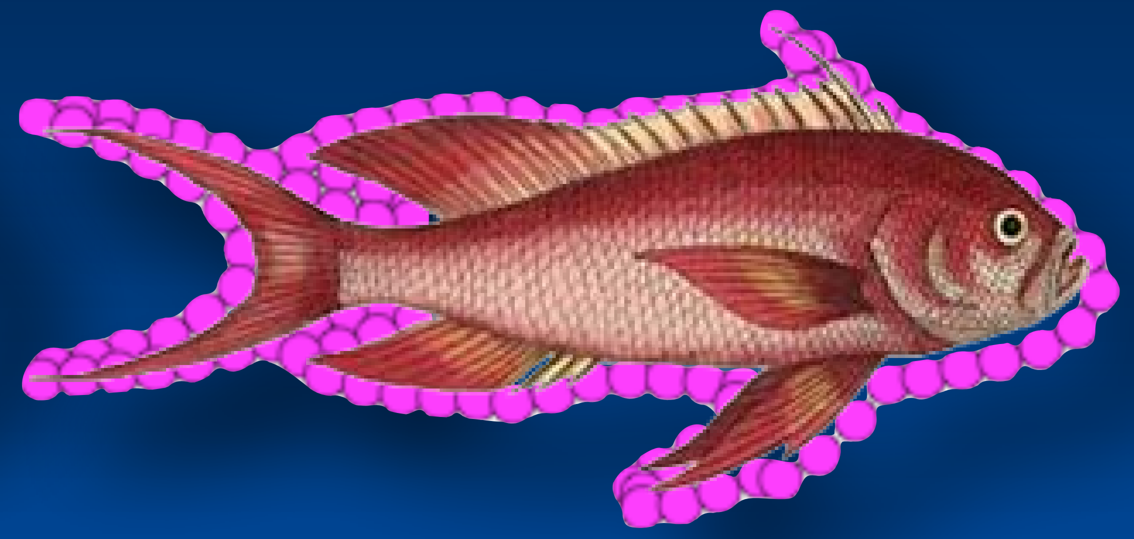


Description & Analysis of Morphology

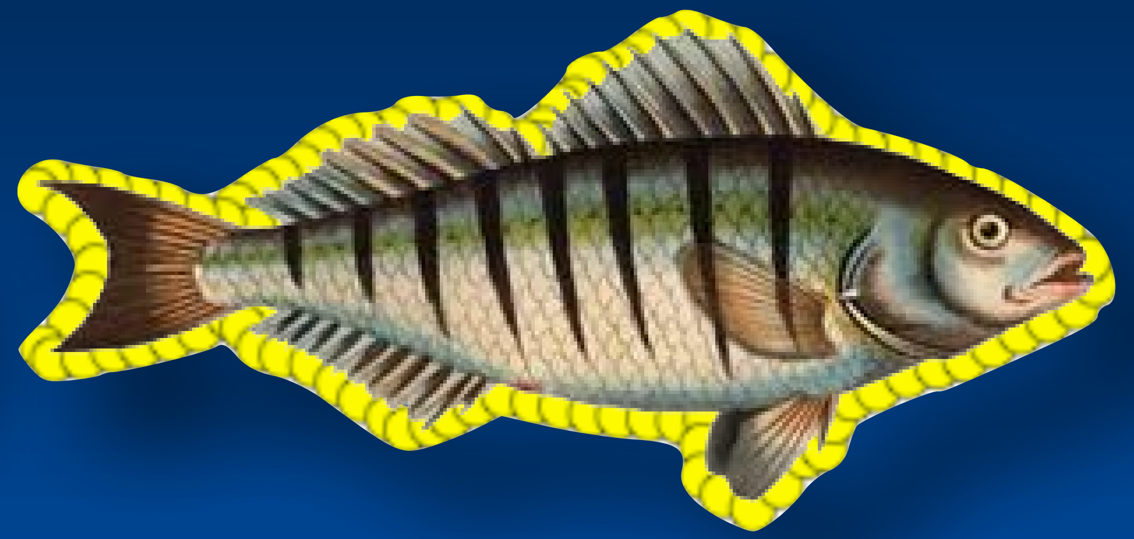
Geometric Morphometrics: Outline Semilandmarks

Semilandmarks are used (typically) when the forms under consideration contain an insufficient number of landmark points to enable their shapes to be represented accurately

Anisotremus virginicus



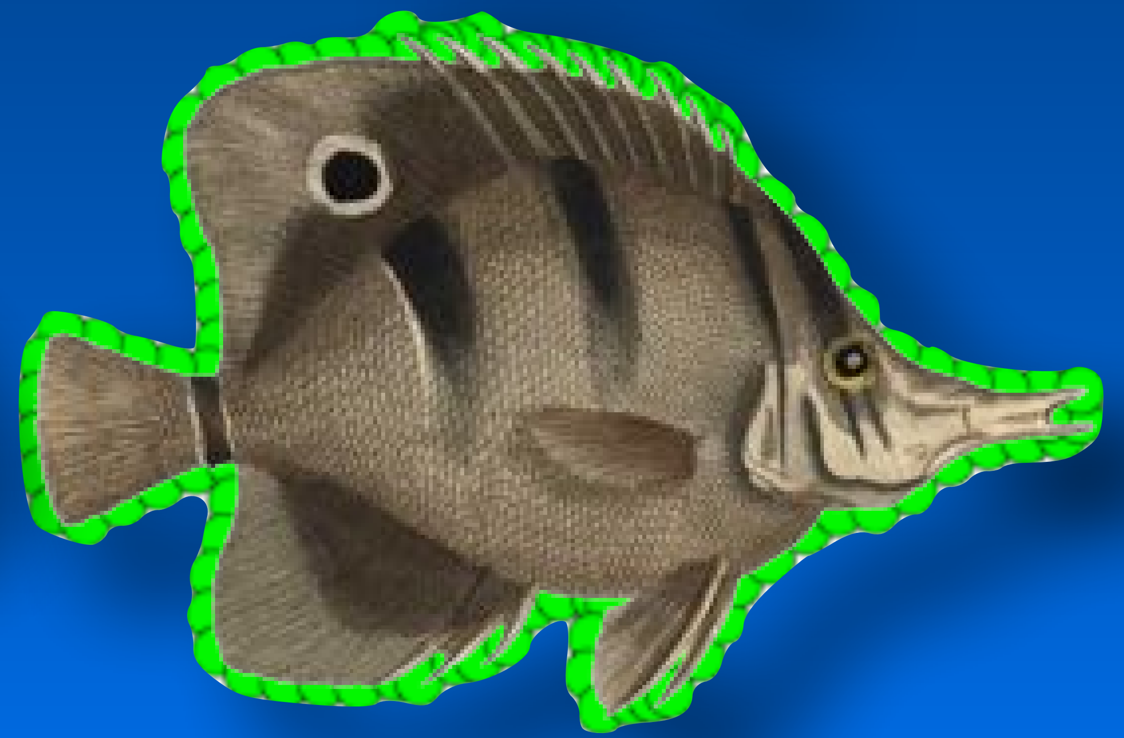
Anthias anthias



Conodon nobilis

Anthias argus

Archosargus rhomboidalis

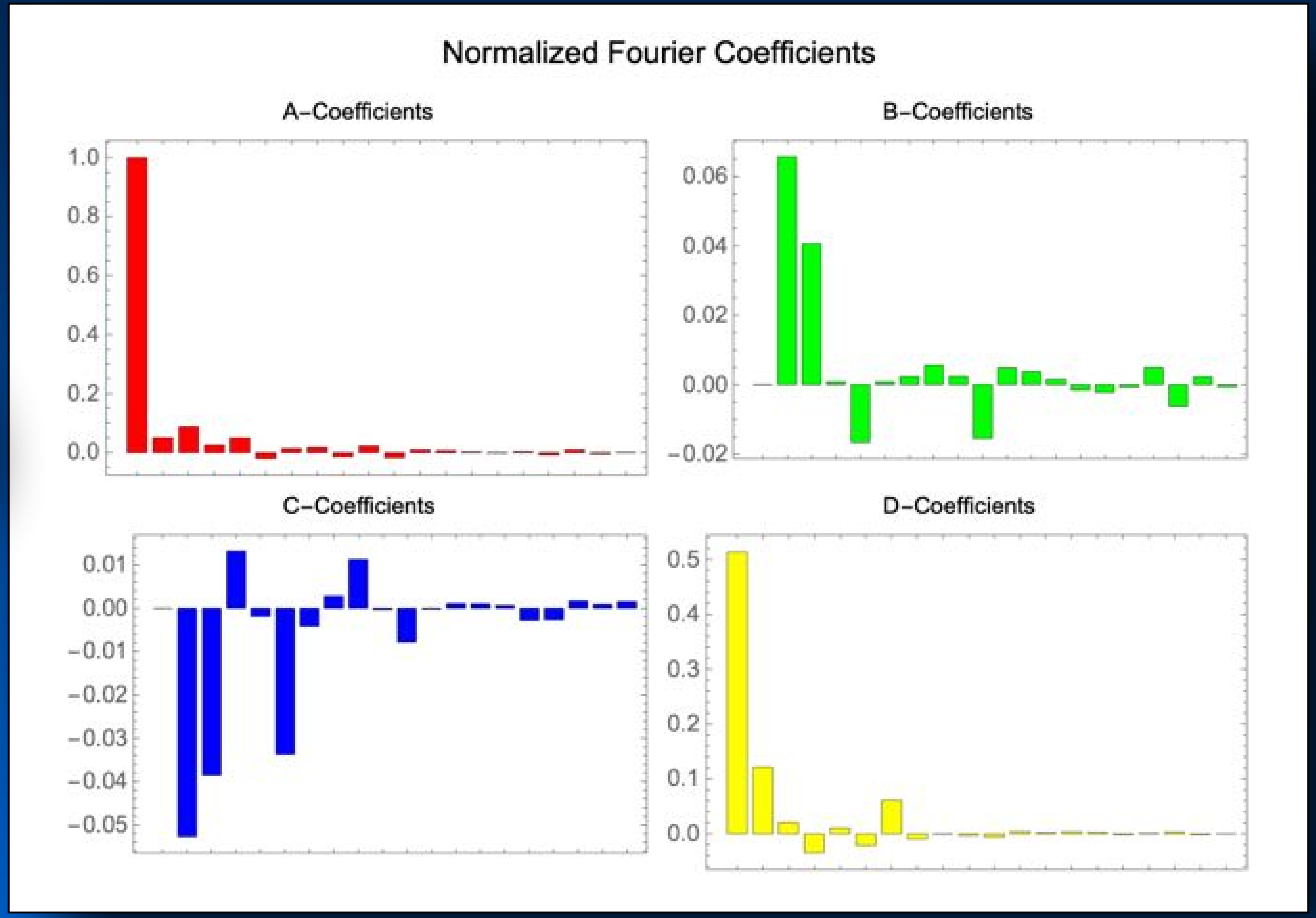


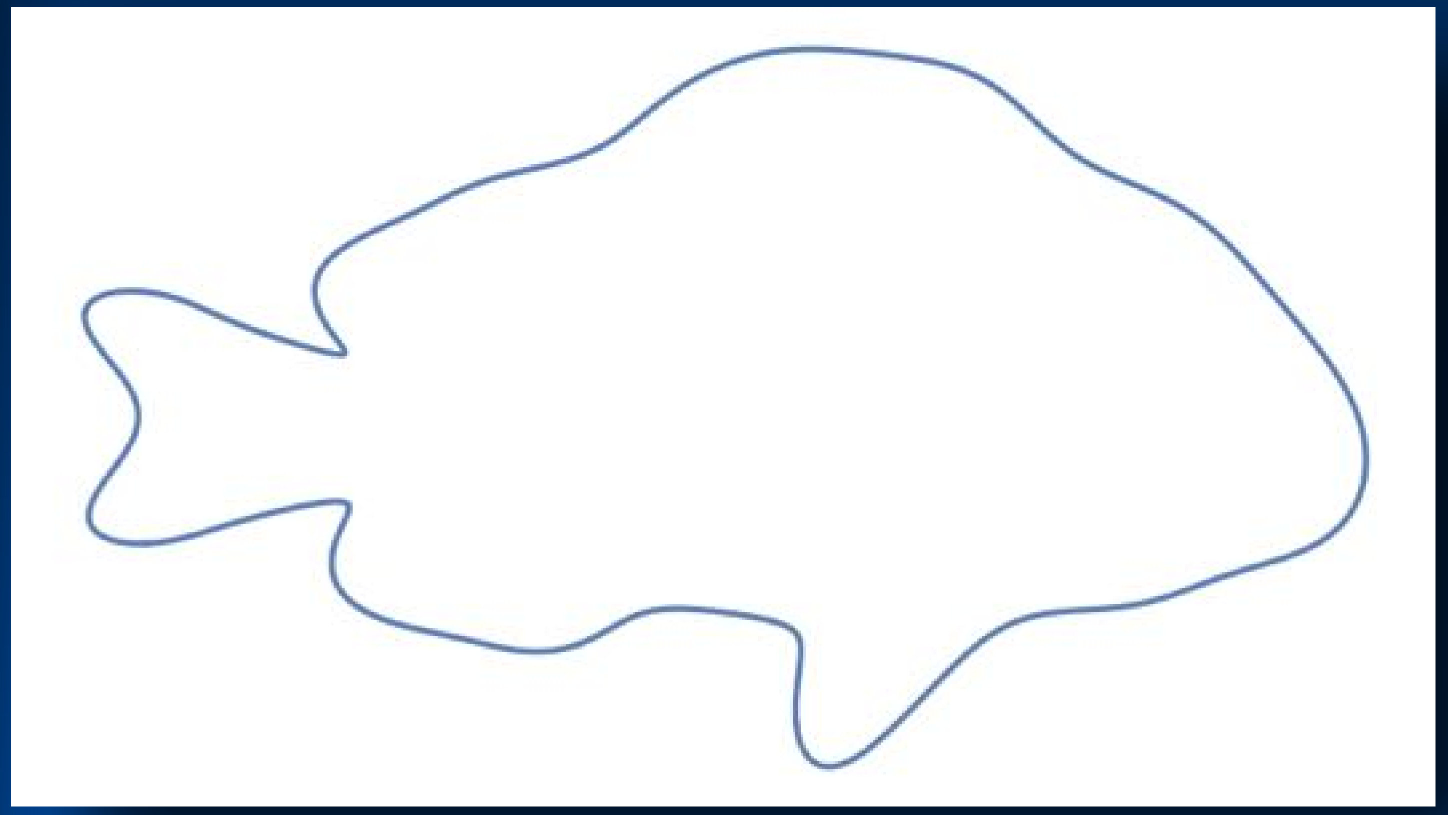
Chelmon rostratus

Description & Analysis of Morphology

Geometric Morphometrics: Elliptical Fourier Analysis

Anisotremus virginicus



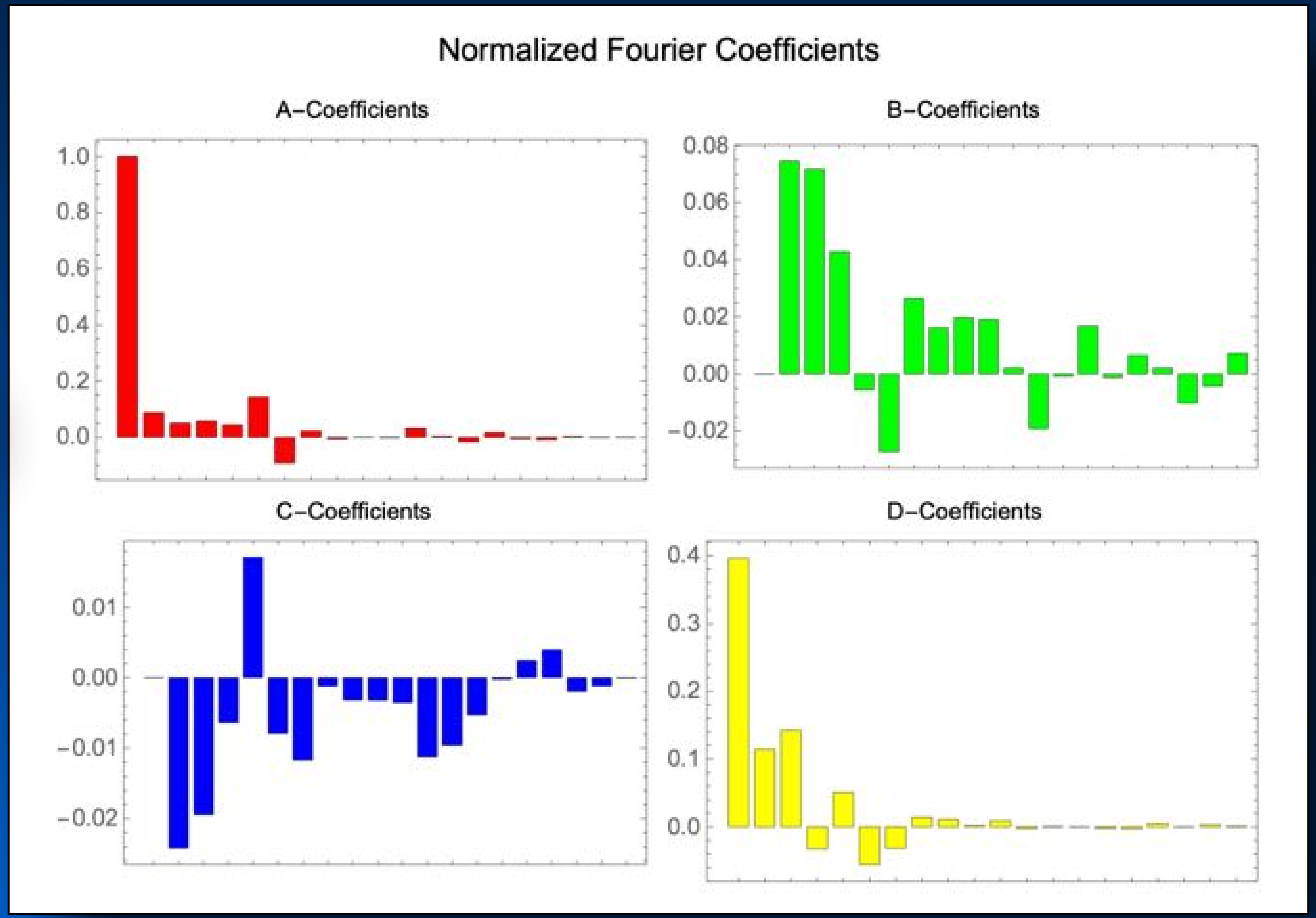


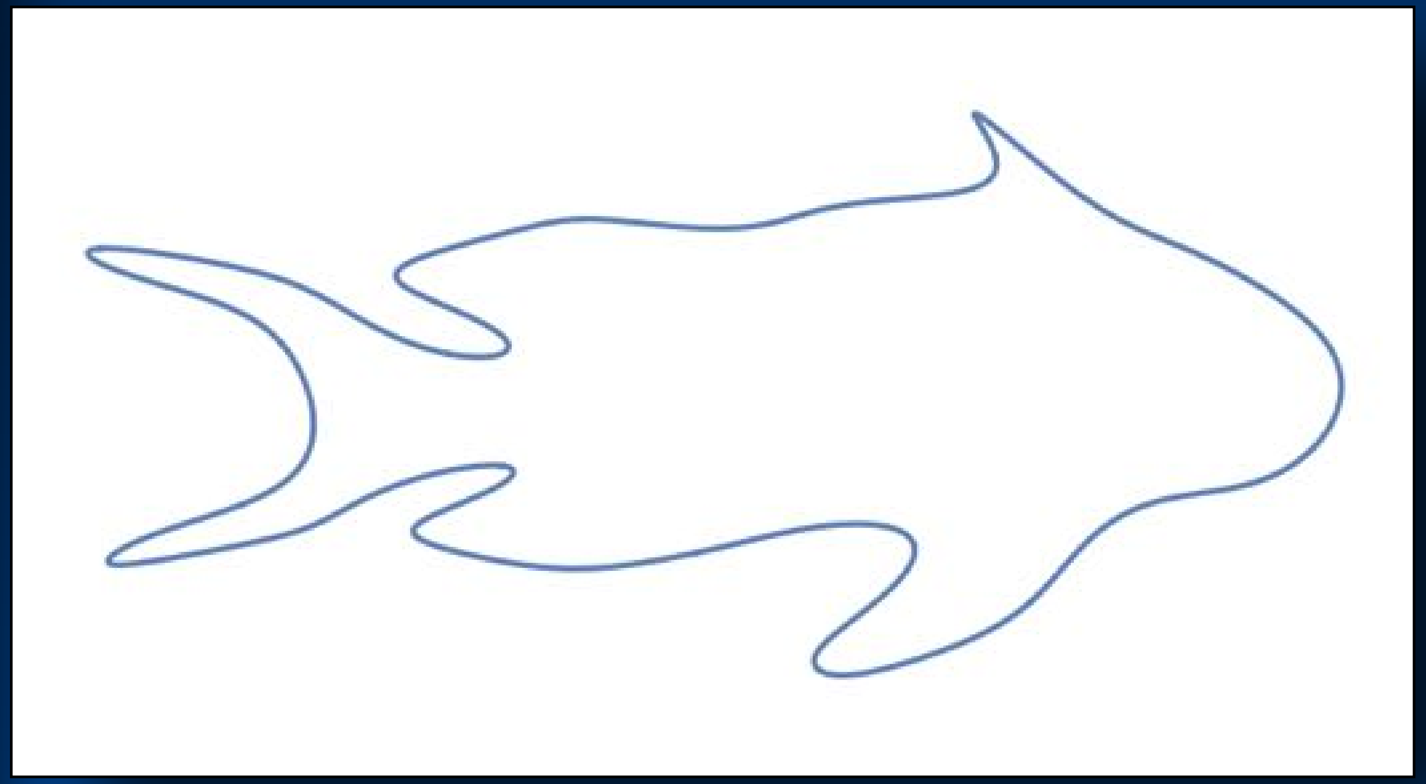
20 Harmonic Reconstruction

Description & Analysis of Morphology

Geometric Morphometrics: Elliptical Fourier Analysis

Anthias anthias



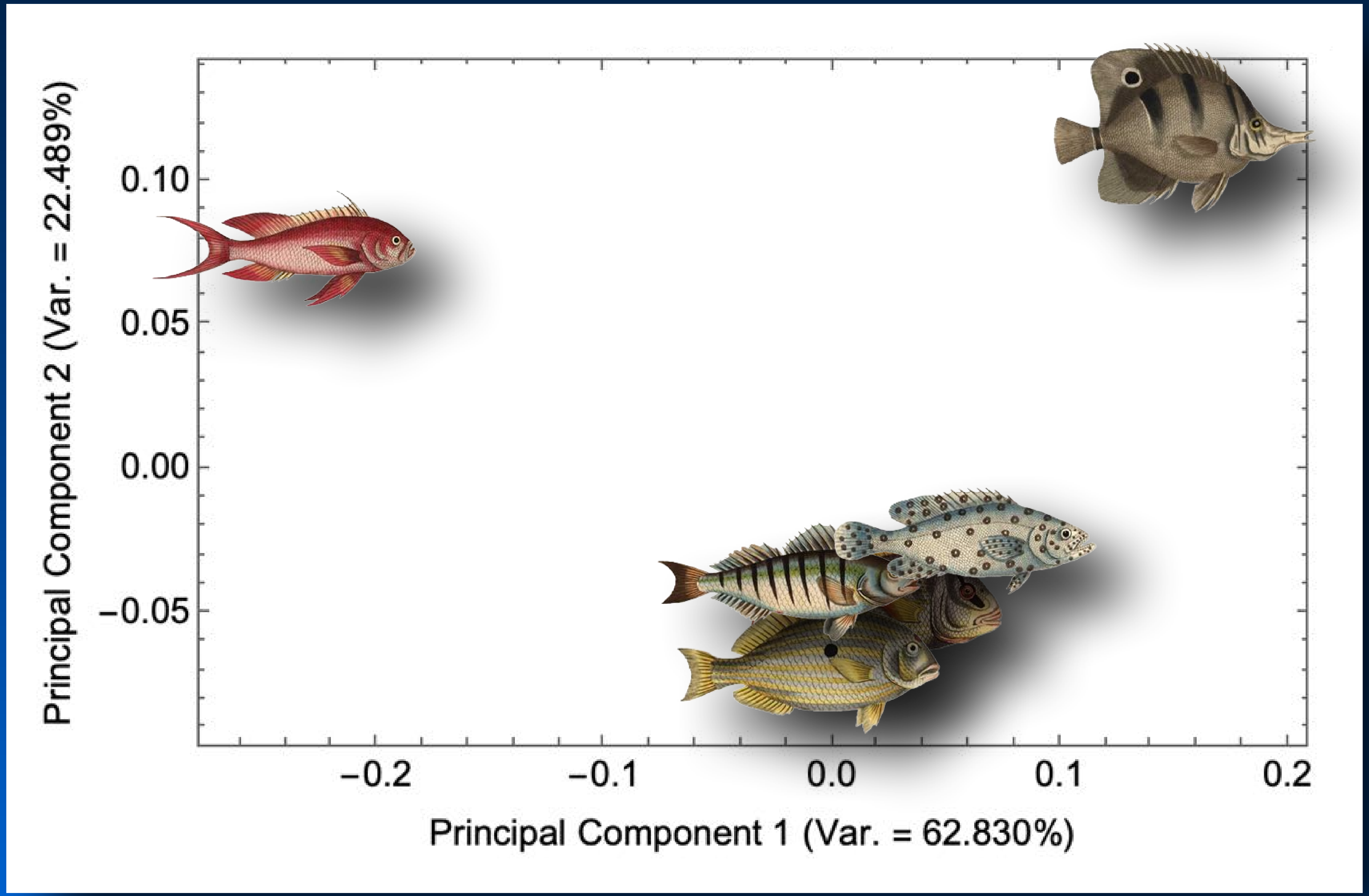


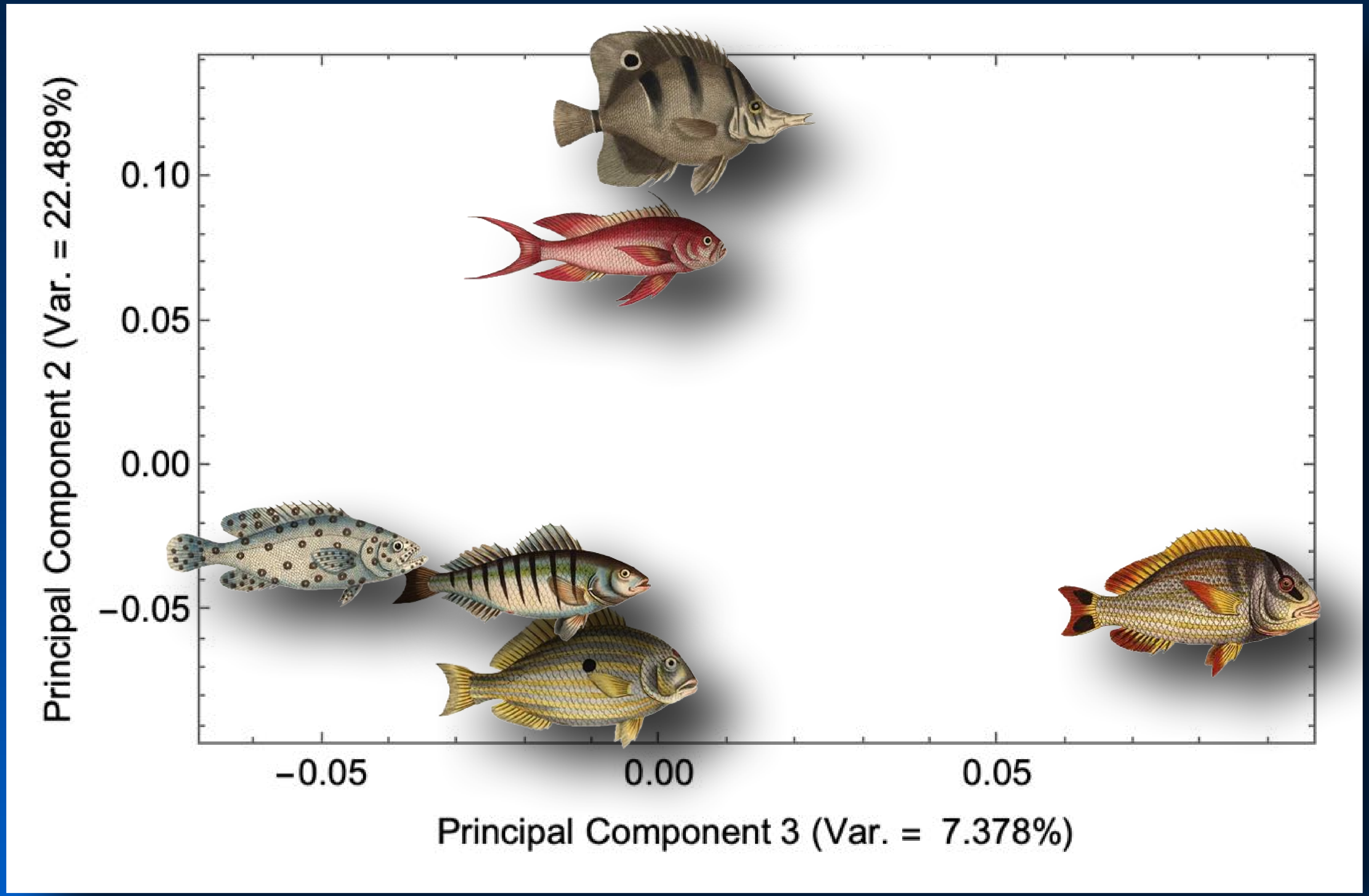
20 Harmonic Reconstruction

Description & Analysis of Morphology

Geometric Morphometrics

Elliptical Fourier PCA





Description & Analysis of Morphology

Geometric Morphometrics: Outline Semilandmarks

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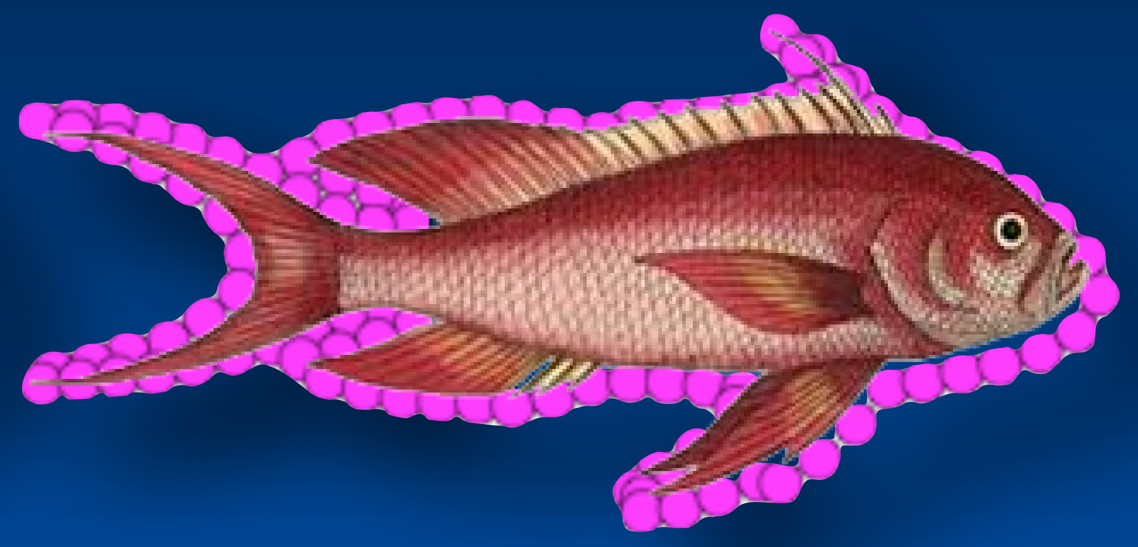
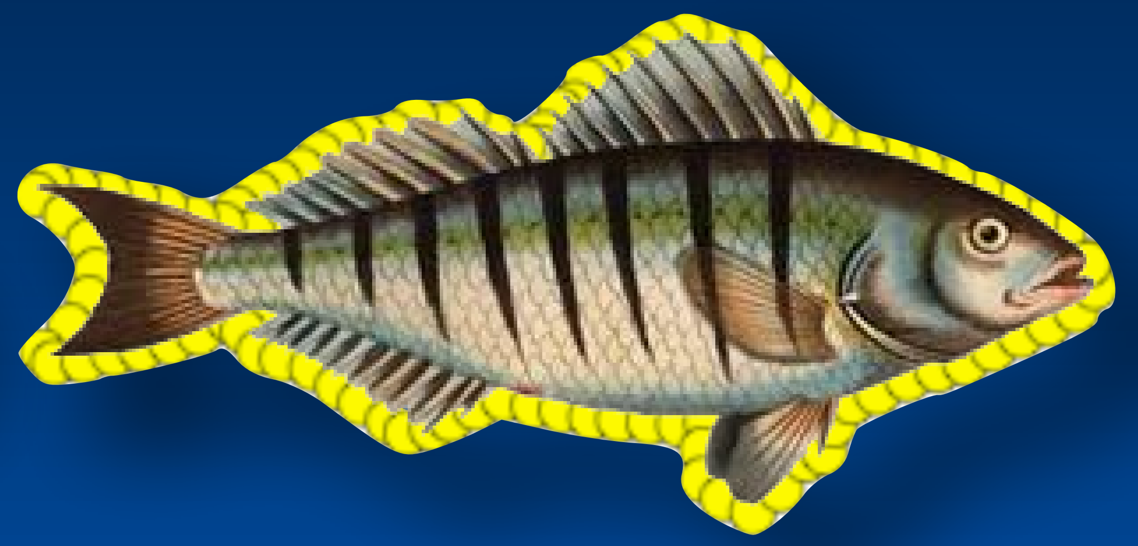
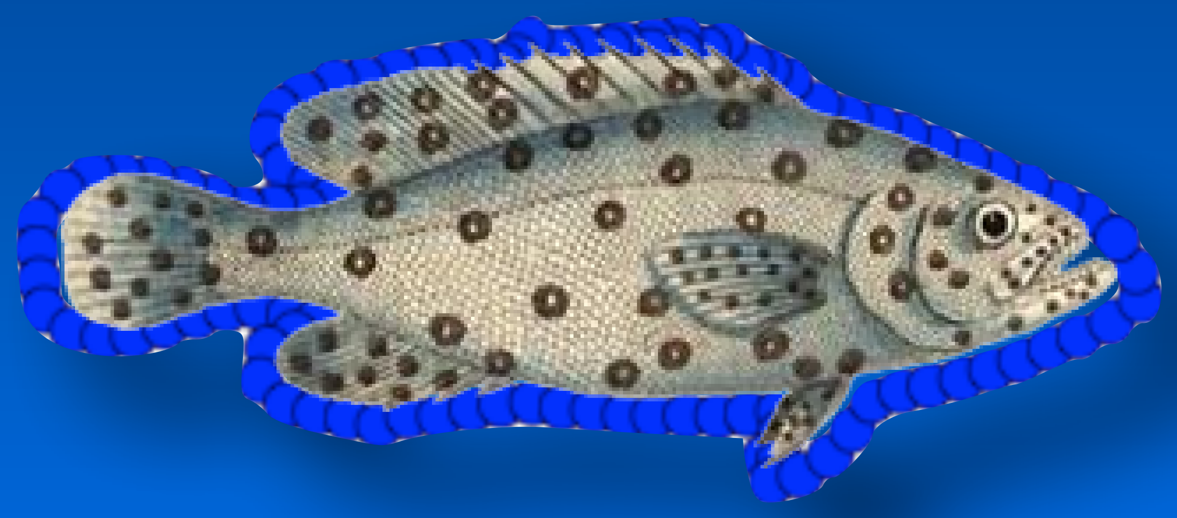
Anisotremus virginicus



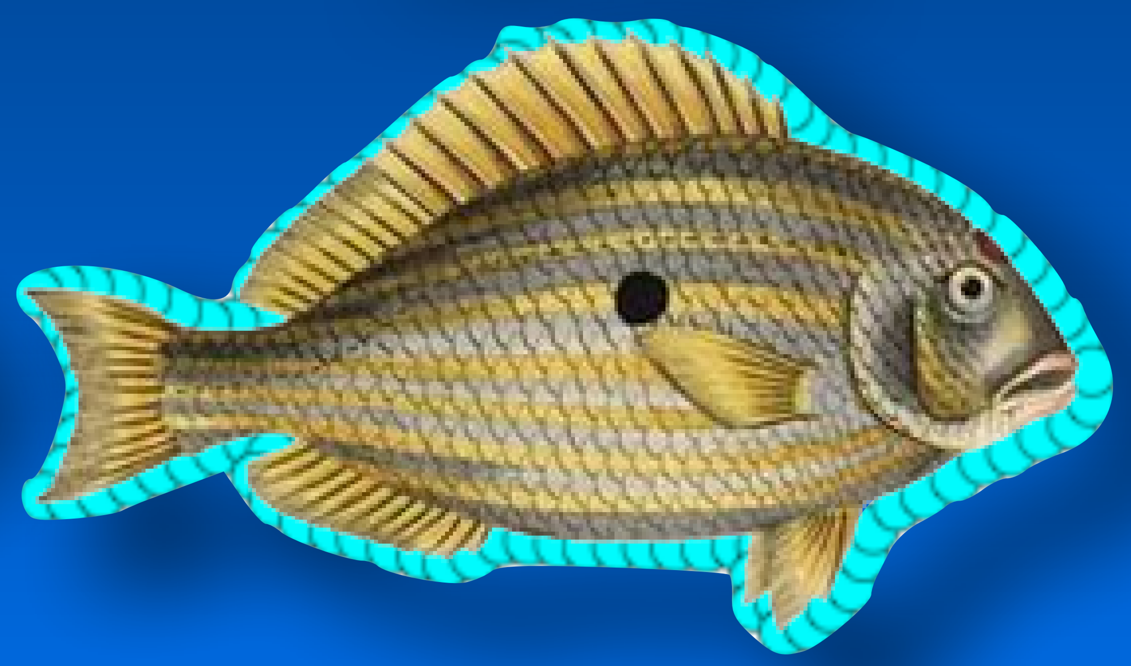
Anthias anthias



Conodon nobilis



Anthias argus

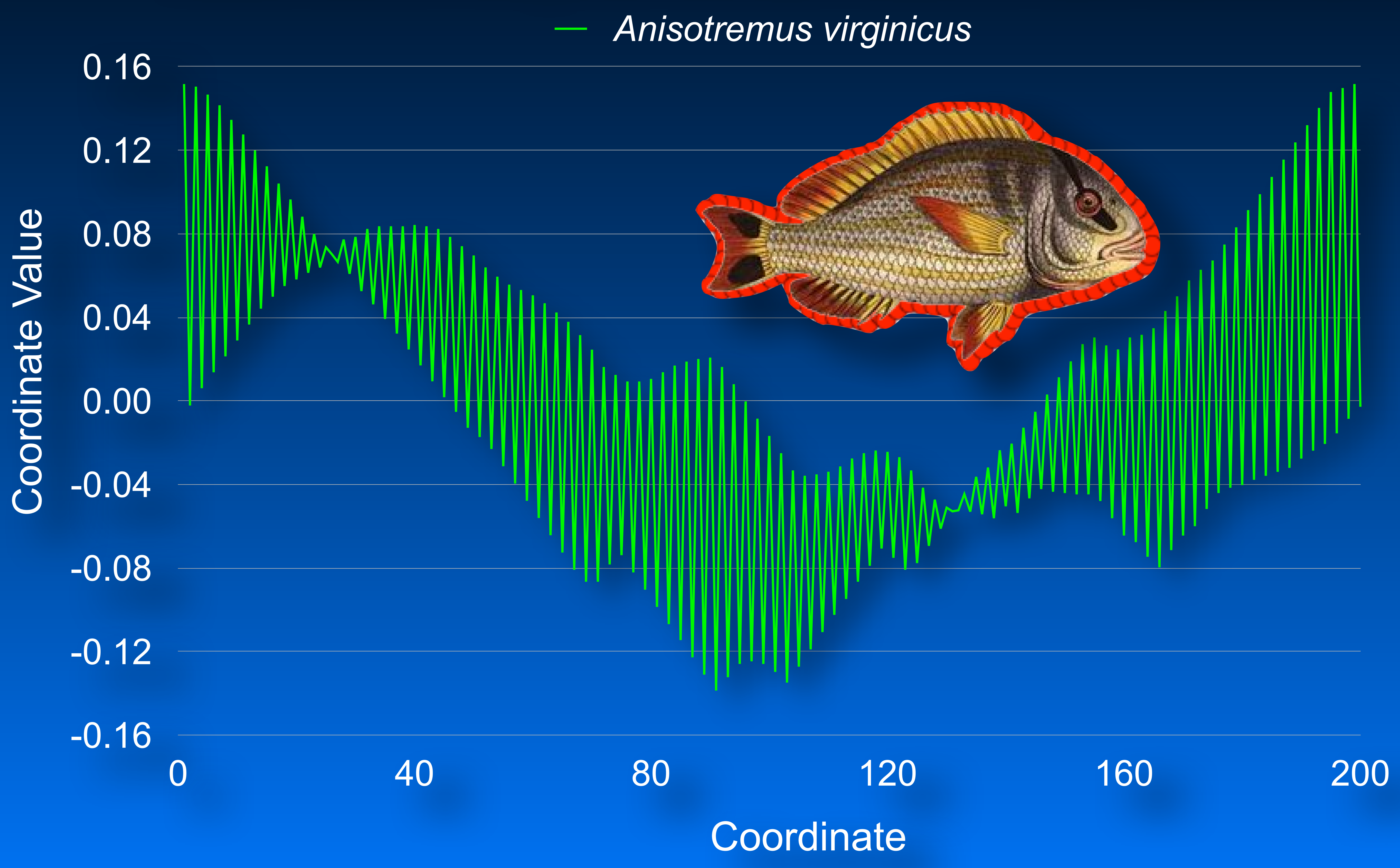


Archosargus rhomboidalis

Chelmon rostratus

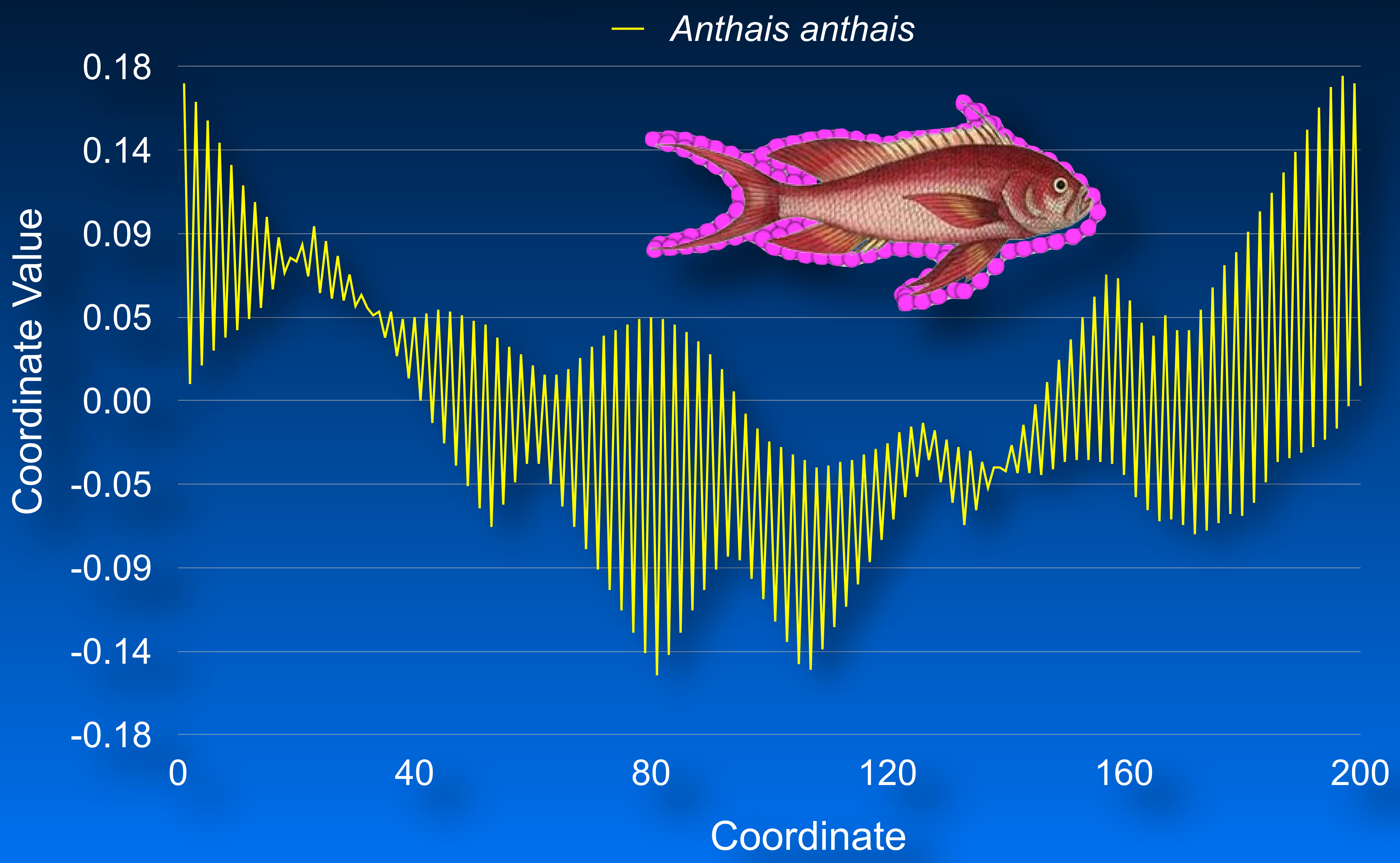
Description & Analysis of Morphology

Geometric Morphometrics: Outline Semilandmarks



Description & Analysis of Morphology

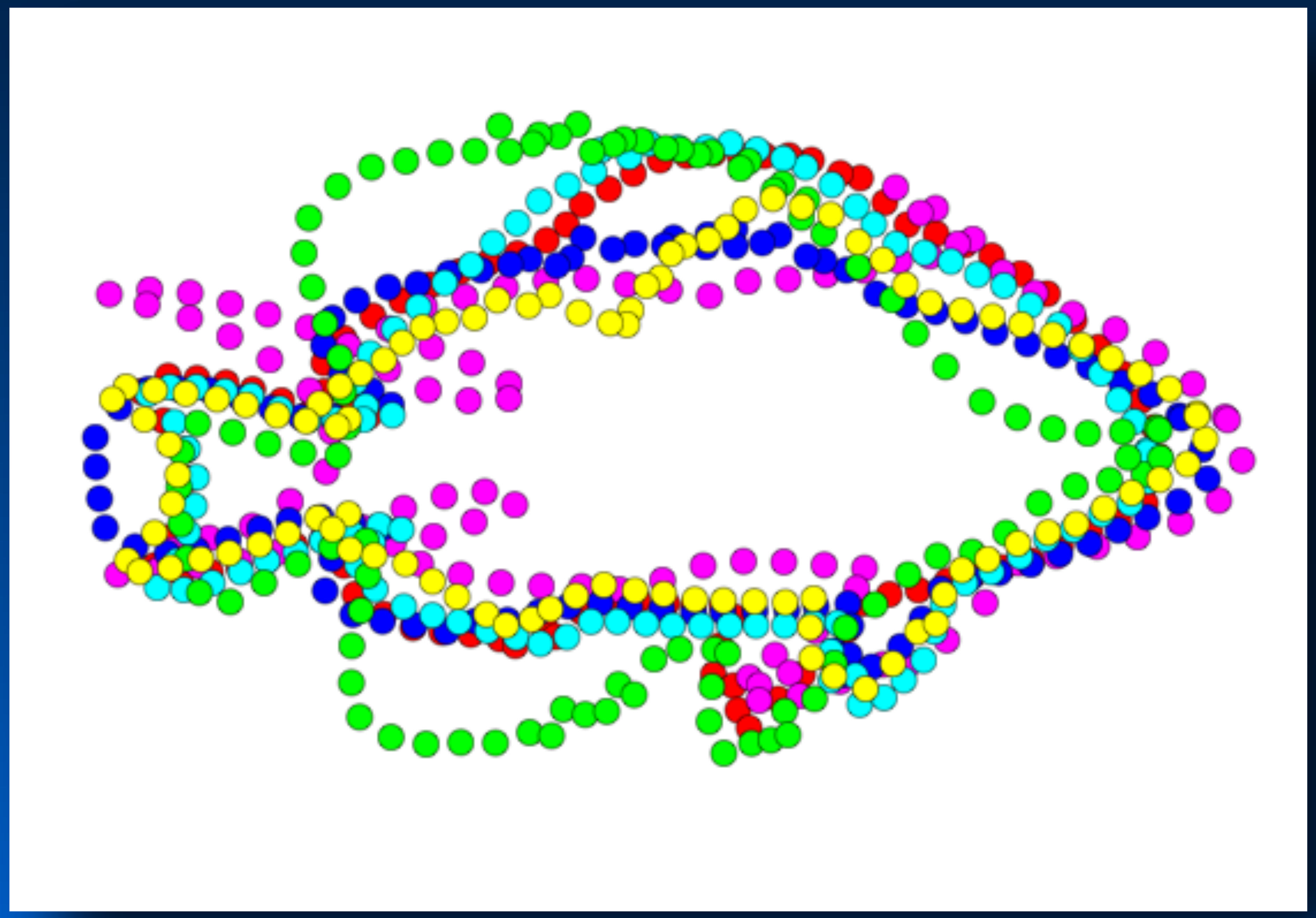
Geometric Morphometrics: Outline Semilandmarks



Description & Analysis of Morphology

Geometric Morphometrics: Outline Semilandmarks

Direct Comparison of Outline Shape Functions

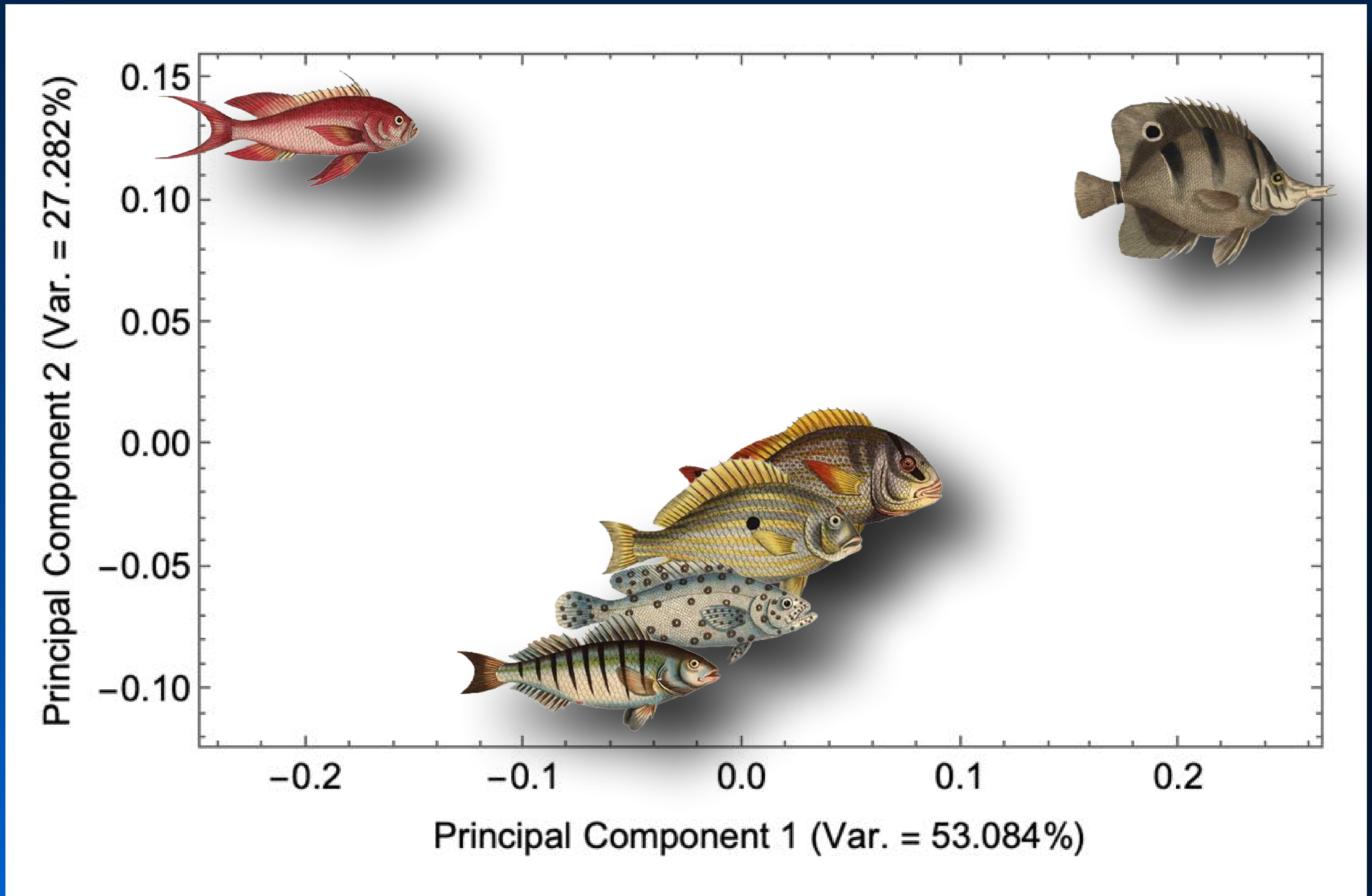


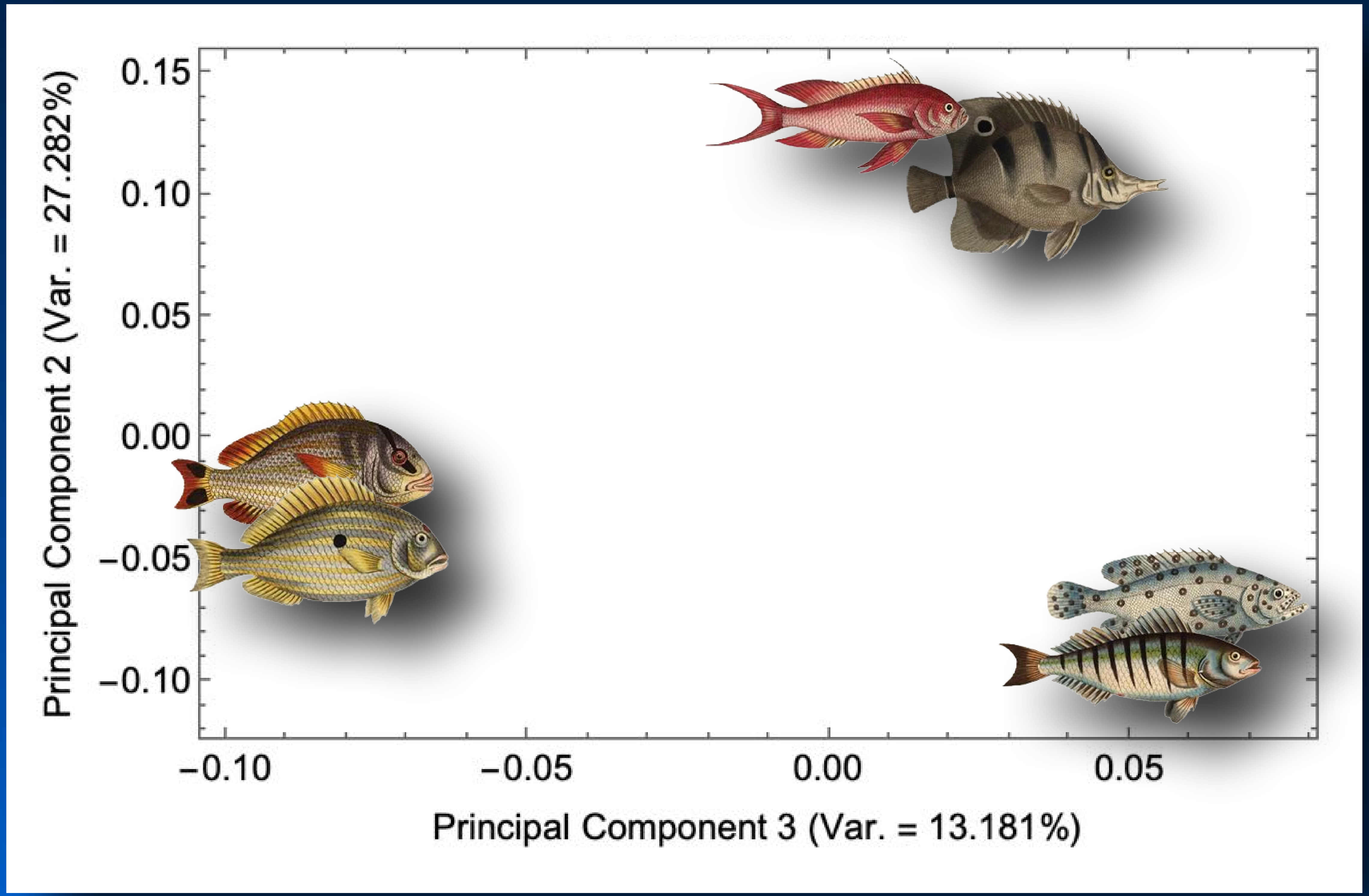
$$cov_{jk} = \frac{\sum_{i=1}^{n} x_{ij} \cdot x_{ik} - \left(\frac{\sum_{i=1}^{n} x_{ij} \cdot \sum_{i=1}^{n} x_{ik}}{n}\right)}{n-1}$$

Description & Analysis of Morphology

Geometric Morphometrics: Outline Semilandmarks

Procrustes PCA = Eigenshape Analysis





Description & Analysis of Morphology

Geometric Morphometrics: Outline Semilandmarks

Fourier versus Eigenshape Analysis

Fourier Analysis - Eigenvectors of the covariance matrix calculated from all radial or elliptical Fourier amplitude and phase angle coefficients.

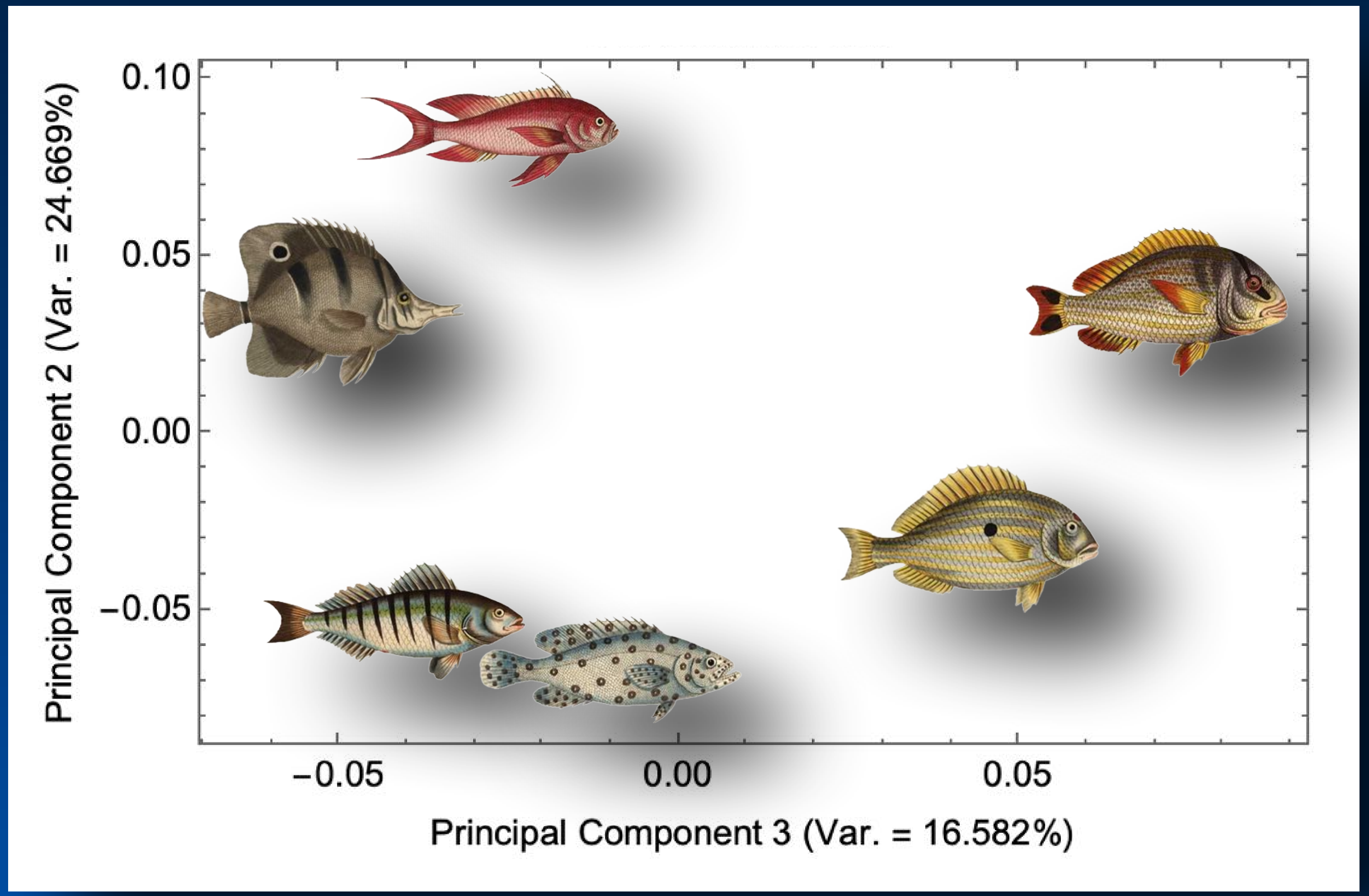
But the all radial or elliptical Fourier amplitude and phase angle coefficients are just harmonic re-descriptions of the outline coordinates.

Eigenshape Analysis - Eigenvectors of the covariance matrix calculation between (i.) Zahn & Roskies outline shape functions or (ii.) the Procrustes shape coordinates of outline semilandmark coordinate values.

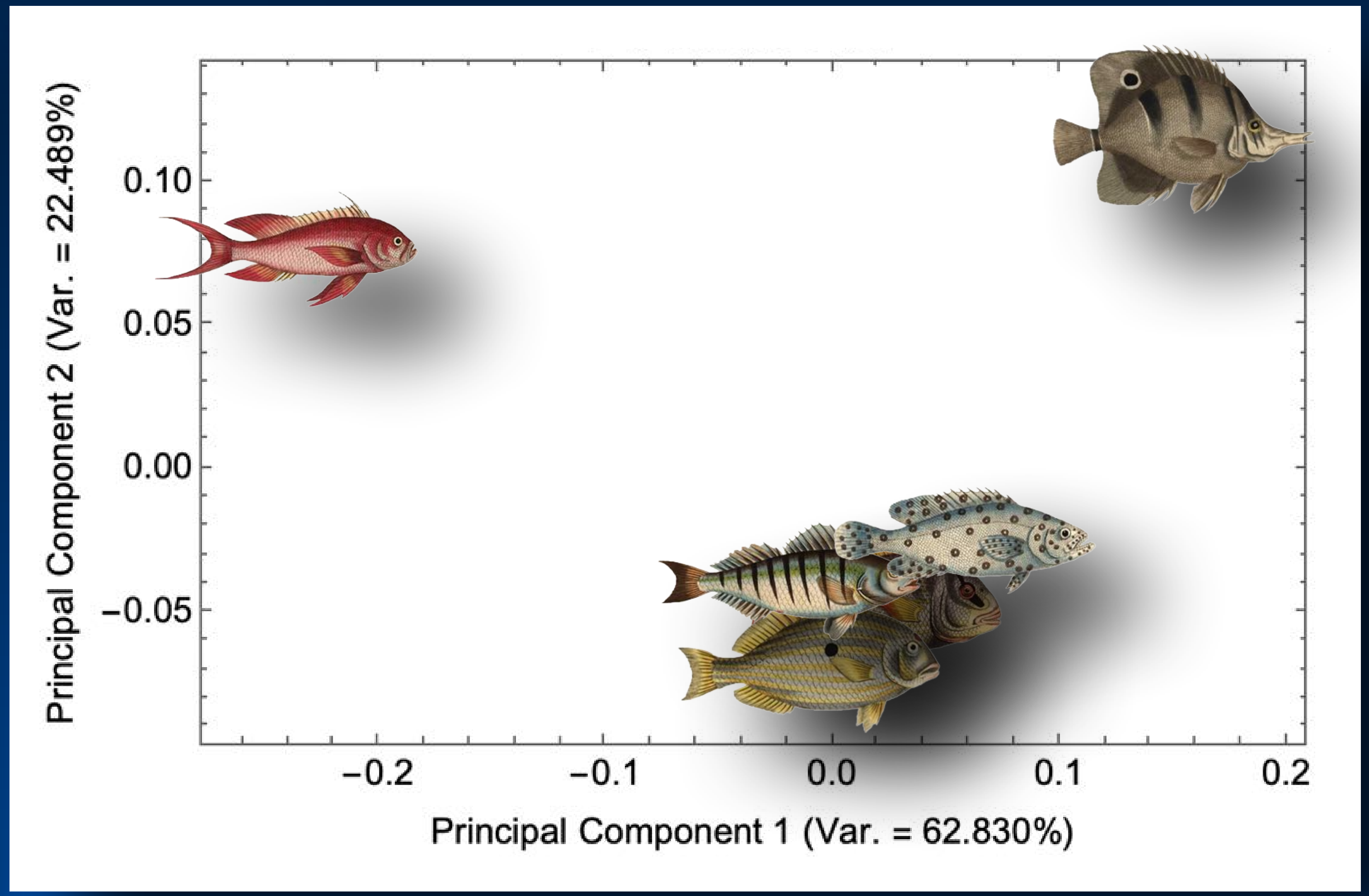
Description & Analysis of Morphology

Geometric Morphometrics: Ordination Summary

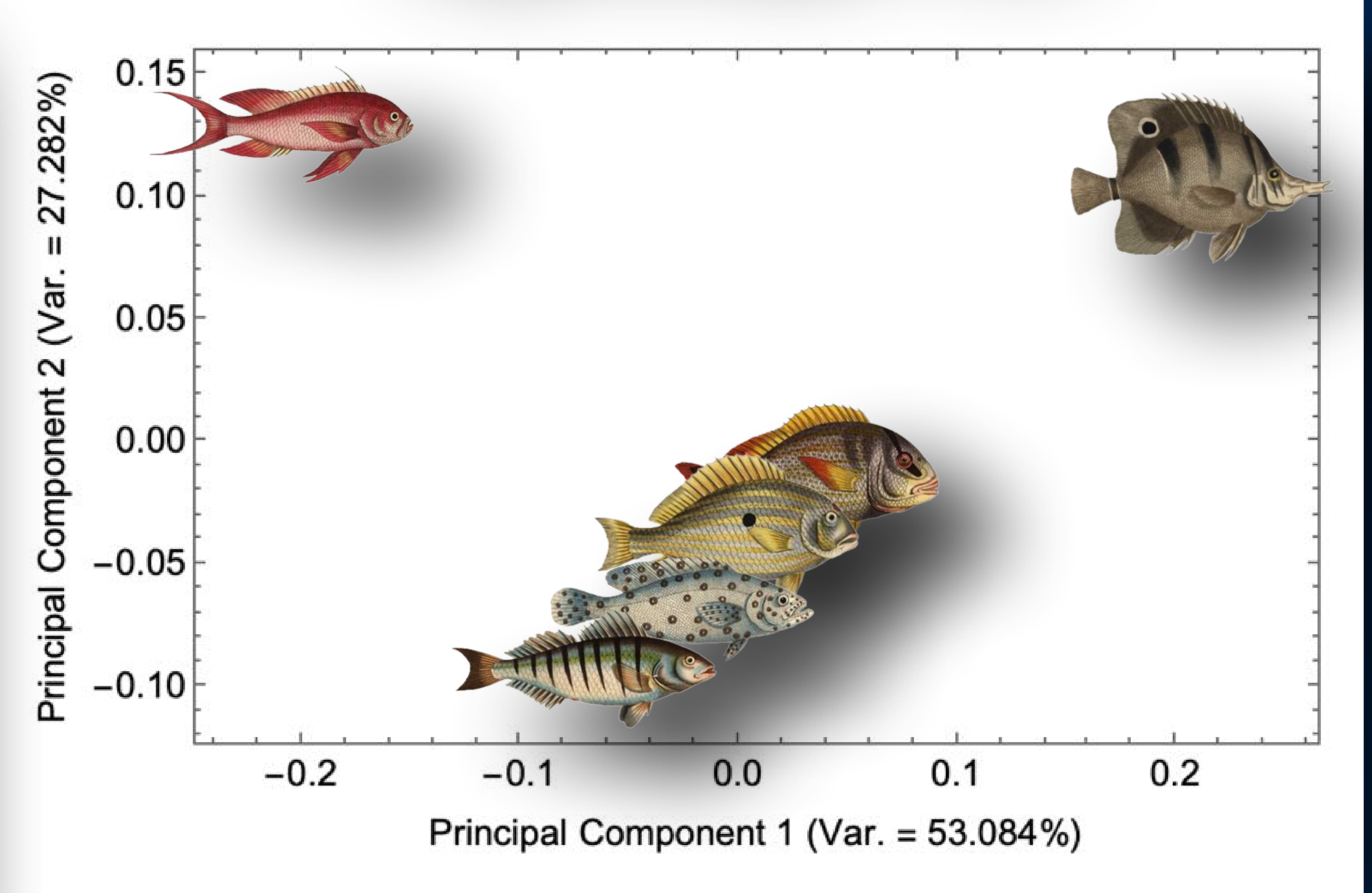
Procrustes PCA: Landmarks



Elliptical Fourier PCA



Eigenshape PCA



Note how the ordination answer obtained is conditioned on the data being compared. Landmark can have the advantage of forcing comparisons between truly comparable point locations, but usually there are only a few such strictly comparable across a set of forms. Semilandmark points sacrifice strict point-by-point comparability, but yields a more detailed representation of the overall form geometries.

Description & Analysis of Morphology

Geometric Morphometrics: Ordination Summary

- Use of ordination methods extends the visual capabilities of the researcher by revealing patterns in morphological data that cannot be perceived by classic visual inspection.
- In order to use these methods effectively it is necessary to understand …
  - … the type of pattern(s) each ordination method is designed t o sense;
  - the relation between the data collected and the morphological hypotheses under consideration;
  - the appropriateness of augmenting ordination-based data analysis procedures with formal statistical tests before making interpretations in order to avoid confirmation bias.
- As public-domain and low-cost software exists to implement all standard ordination procedures there is no excuse for not employing them routinely in paleobiological research.

NJU Course

Principles of Paleobiology

Description & Analysis of Morphology