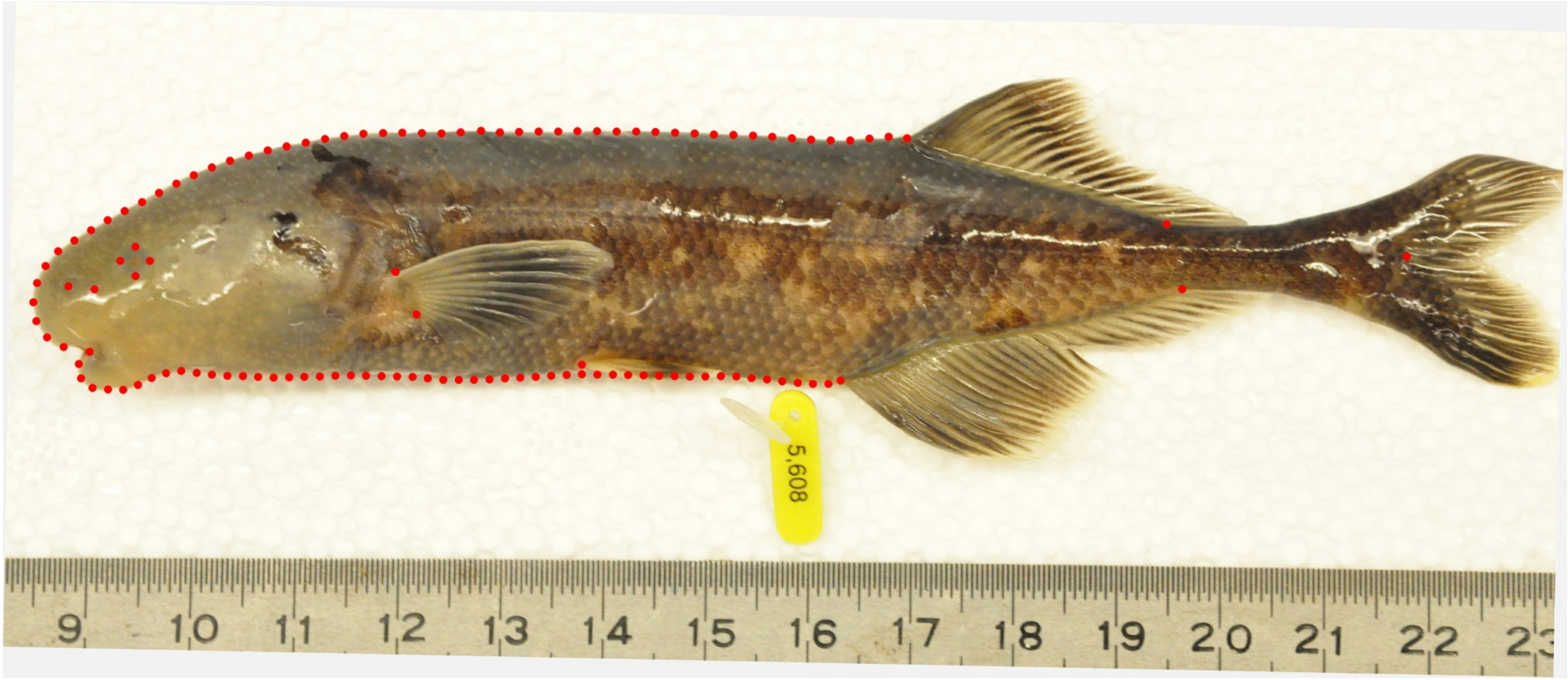
A researcher’s perspective

MIRIAM ZELDITCH
DONALD SWIDERSKI
UNIVERSITY OF MICHIGAN

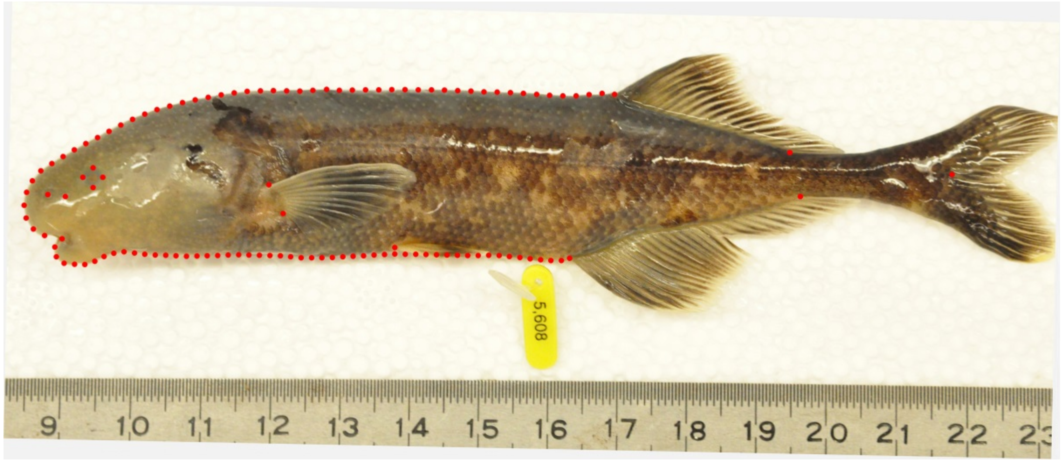
Image analysis:

Getting quantitative morphological data from images



You have a lot of issues to work out.
We want to give our perspective on what matters to researchers who will use the images to collect morphological data

- What we will do with the images
- How we collect data from them
- What makes images scientifically useful (or useless)



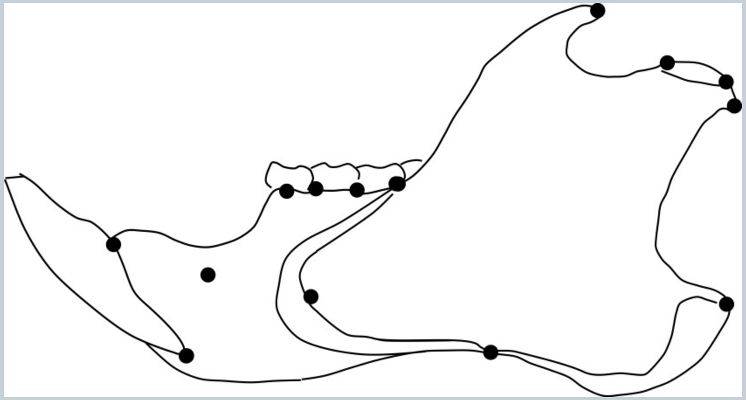
Outline

- A general overview (2D data collection)
  - How we collect the data
  - What makes the data useful (or not)
- Special issues raised by 3D imaging
  - Don will talk about these
    - He sees in 3D and works on 3D data…

We are mammalogists

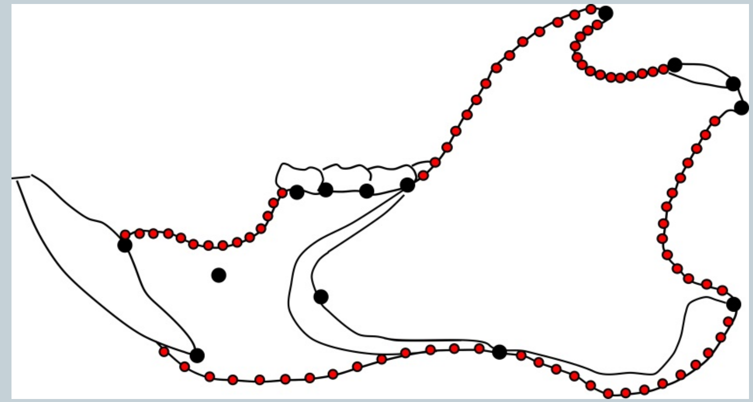
- Most examples will come from our studies of mammalian skeletal material
- For reasons important to this talk, we can't use examples from older work on fishes
- But we will get to one issue specific to fluid-preserved specimens
  - Bending

Landmark data



Discrete anatomical loci that correspond from specimen to specimen (and species to species).

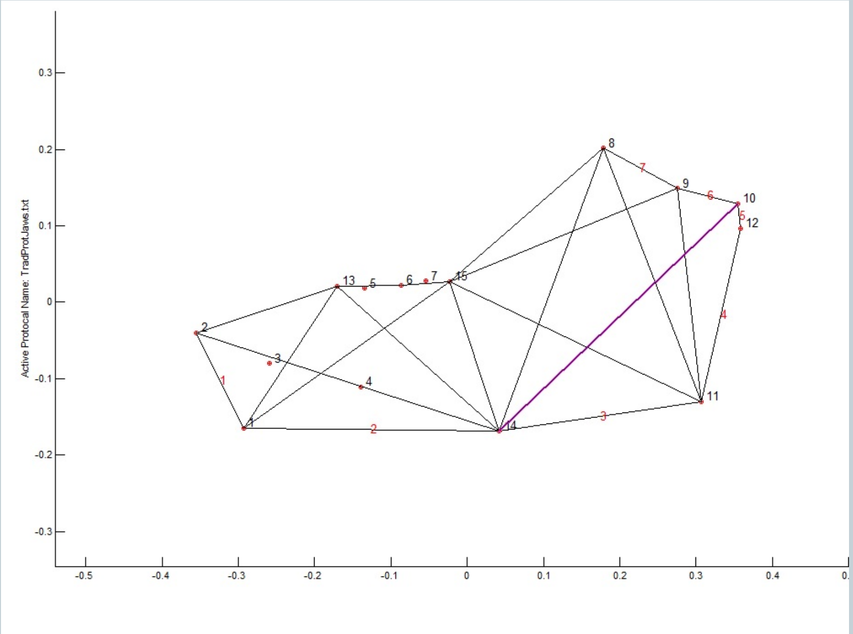
Semilandmarks



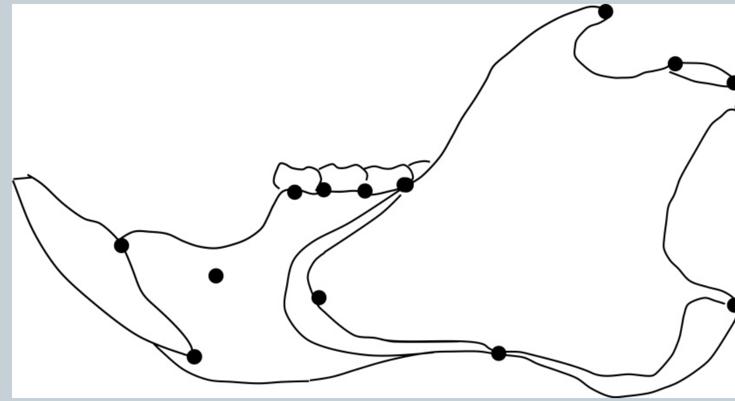
When landmarks are not enough we sample curves (and surfaces) with semilandmarks

“Traditional morphometric data”

- In the 1990’s, it was common to use landmarks as the endpoints of length measurements
- So after digitizing the landmarks and a ruler, the data were used to measure lengths



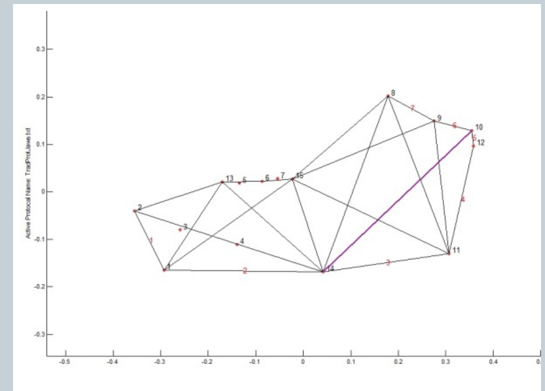
Current view of "traditional"



Young researchers now seem to use "traditional" for data limited to landmarks

Semilandmarks are "non-traditional"

Current view of “traditional”



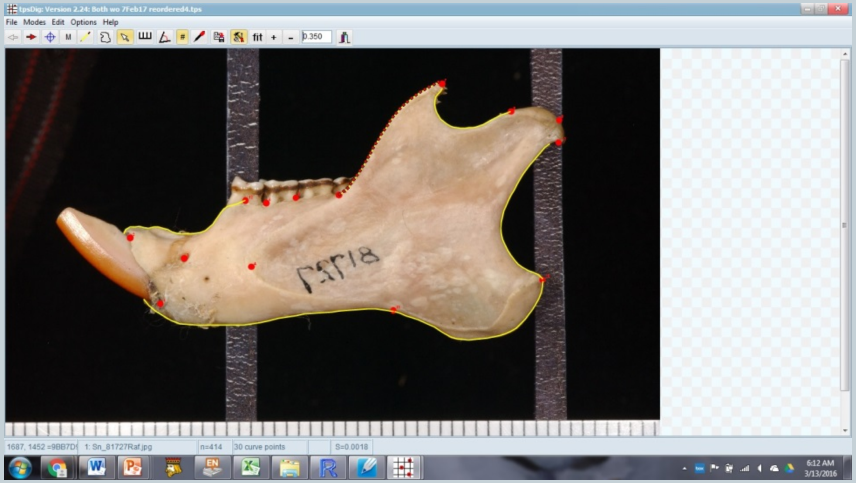
This matters because what we need from the photographs are accurate estimates of the full set of coordinates landmarks and semilandmarks
(plus a ruler)

First Steps

- Process images
  - Crop
  - Enhance (brightness, contrast)
  - Reflect (if some have noses pointing left, others right)
  - Label the photos: the names of the photos will be the names of the specimens in the data file

How do we collect the data?

- We read in the photos to a digitizing program
  - tpsDig

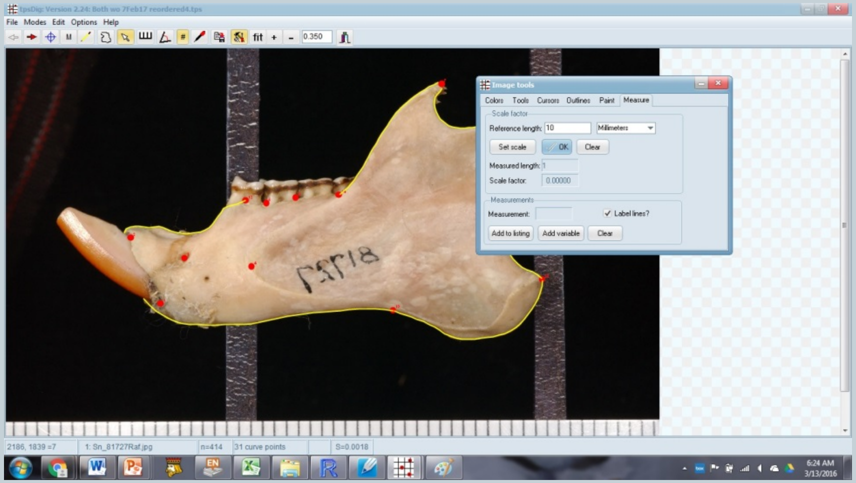


Some of the file types that tpsDig can open

- TIFF, JPG, GIF, PCX, BMP, PNG, WMF, EMF, AVI

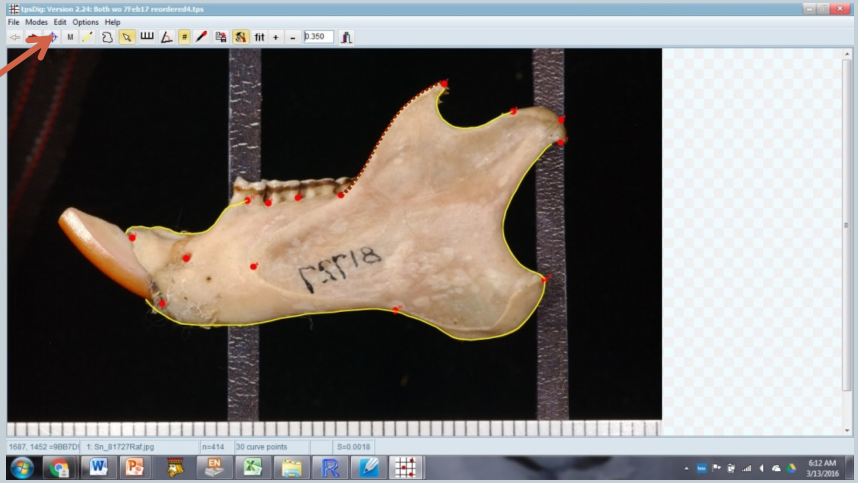
How do we collect the data?

- We want to record information about the scale of the image
  - These were photographed at different magnifications



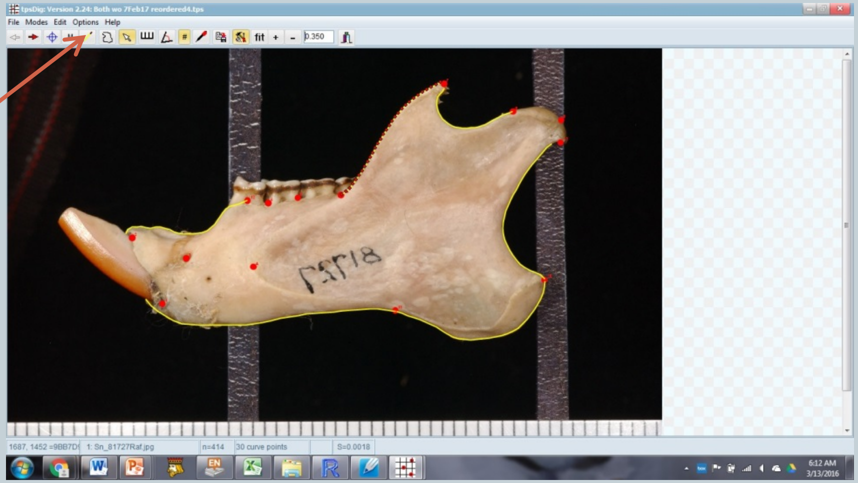
How do we collect the data?

- Using one tool, we select the landmarks



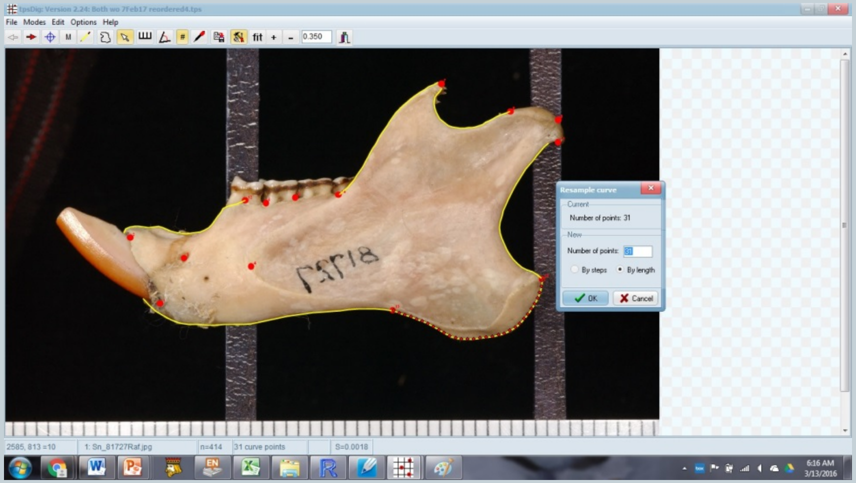
How do we collect the data?

- Using another tool, we select draw a curve between the landmarks



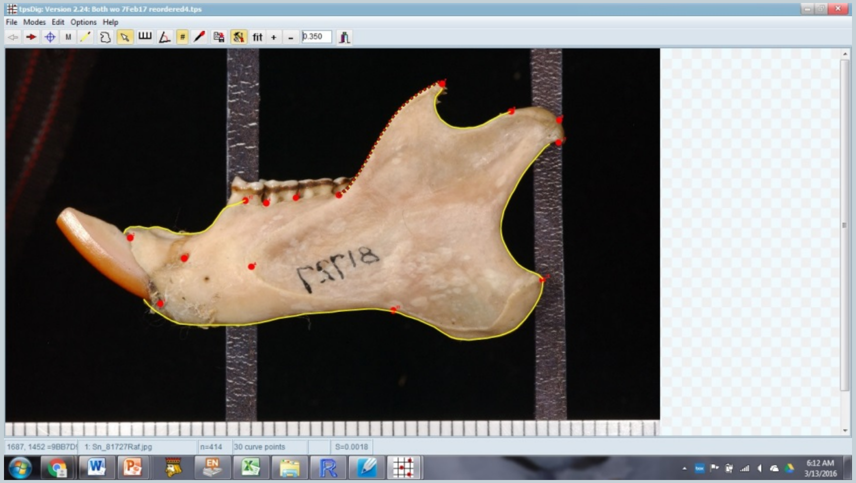
How do we collect the data?

- Right click on a curve
  - Say how many points you want
  - You get that many (evenly spaced)



How do we collect the data?

- Go to the next specimen and repeat
  - In this case, ca 1600 times



What the data file looks like

```
LM=15
298.00000 233.00000
223.00000 348.00000
330.00000 306.00000T
430.00000 305.00000
427.00000 413.00000
479.00000 413.00000
507.00000 415.00000
746.00000 571.00000
837.00000 523.00000
925.00000 506.00000
859.00000 243.00000
932.00000 481.00000
393.00000 411.00000
582.00000 237.00000
534.00000 416.00000
IMAGE=Cn_FMNH_34134La.tif
ID=0
SCALE=0.004033
```

The LM=15 means that there are 15 landmarks
The coordinates are in two columns, *x* then *y*
The name of the image is the name of the photograph file
The ID is the order of the specimen in the file (starts at zero because C begins numbering at zero)
The scale factor is the last line
This is all there is to the file

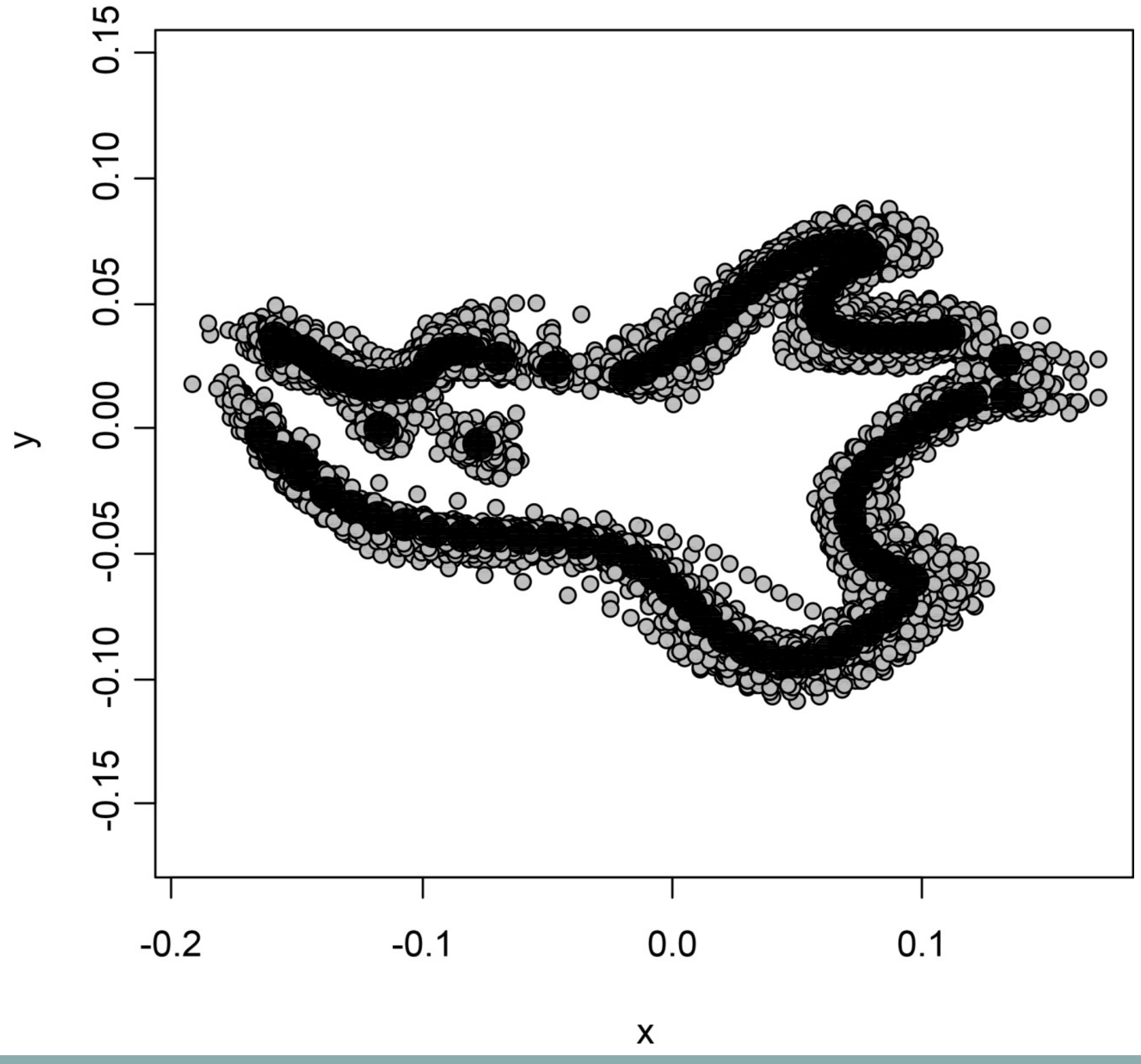
What do we do with the coordinates?

- While digitizing, we did not worry about magnification, position or orientation of specimens within the picture plane
- Variation in all of those will produce variation in the coordinates
- We need to remove that nuisance (non-shape) variation
- "Size" (scale) is part of that nuisance variation but we want to keep it because size is also important

Superimposition

- “Superimposition” is the process of removing non-shape information from the coordinate data.
- The method comes directly from the mathematical definition of shape
- As of 1993, morphometricians stopped arguing about how to do this correctly.
- Presently, there are two methods for superimposing semilandmarks but not much argument about it.

Superimposition



Assumption

- All the variation is due either to shape or to those three nuisance parameters
- Any variation that is not in those nuisance parameters will remain after superimposition
- Variation due to inconsistent orientation within the picture plane is a nuisance (and a real pain for the digitizer)
- The real pain is that variation of the picture plane will be treated as real variation in shape

Variation within the picture plane

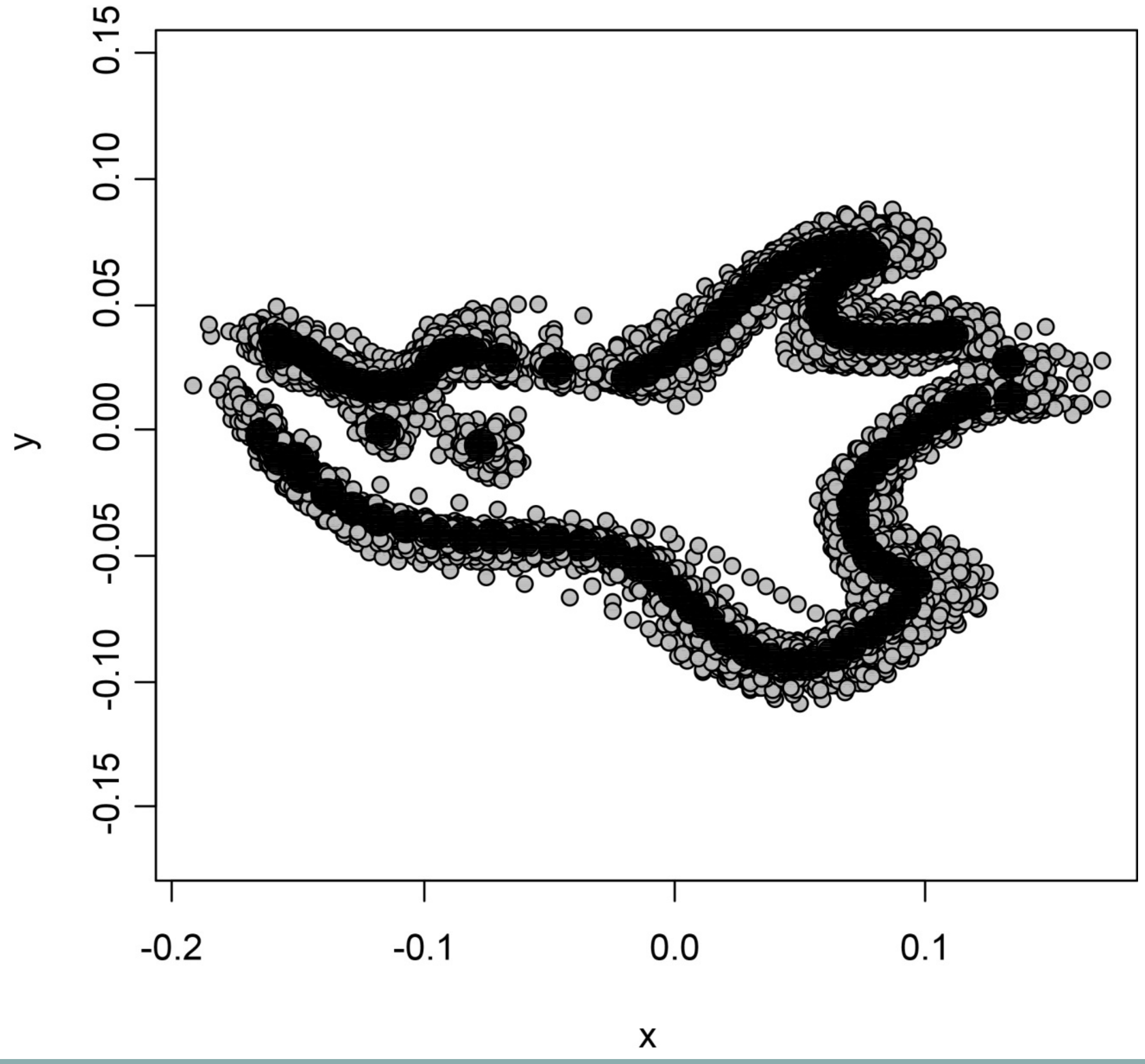
But we can fix that

- We can open the images in a photo editor and rotate them to a common orientation

What we *cannot* fix

- Variation of the picture plane
- Landmarks or curves obscured by tags…

Data: Configurations



Data: Configurations

- From each specimen we get one datum: its configuration of points
- Landmarks and semilandmarks
- If landmarks are missing, that specimen's data are not within the same mathematical space as the others
- We can estimate missing landmarks, but many researchers may be unwilling to do that

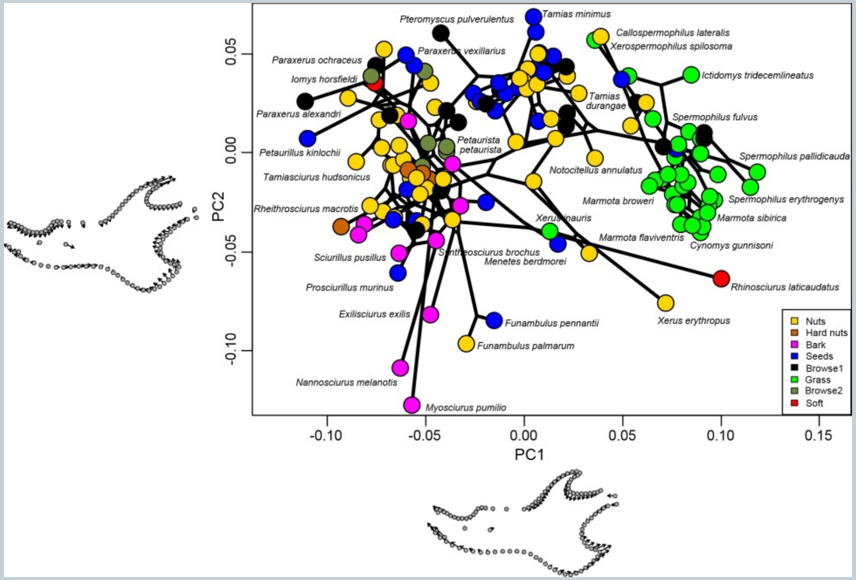
What can we do with superimposed configurations?

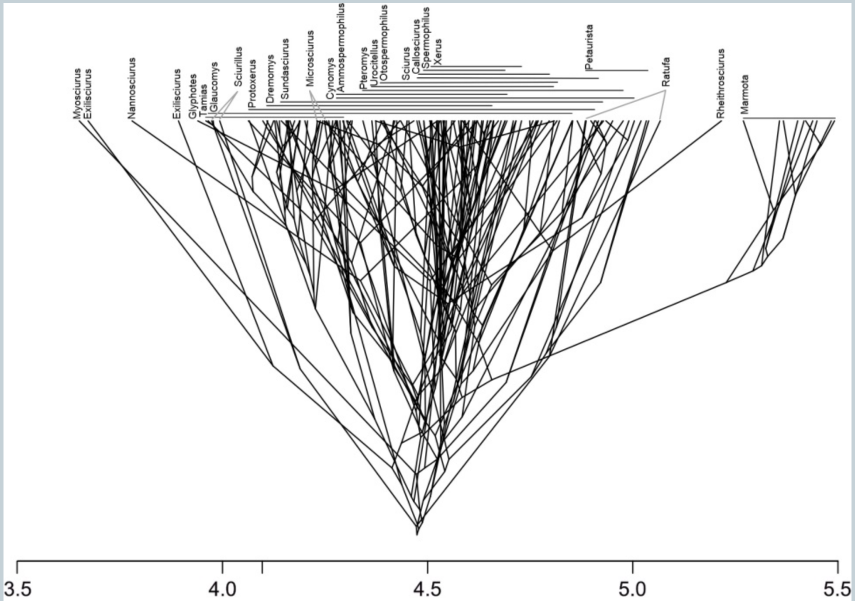
- Test hypotheses about shape
  - Example: Does the evolution of dietary niches explain the evolution of jaw shape?

Effects of size and diet on jaw shape

Effect	Df	SS	MS	R^2	F	P
Size	1	0.029	0.029	0.080	18.716	0.001
Diet	7	0.090	0.016	0.256	8.582	0.001
Size x Diet	7	0.045	0.007	0.115	3.850	0.001
Residuals	129	0.243	0.002	0.450		
Total	144	0.441				

Graphics: Phylomorphospace and traitgram





A fish example…

- I wish I could have drawn all my examples from fluid preserved specimens…

They do present some special problems

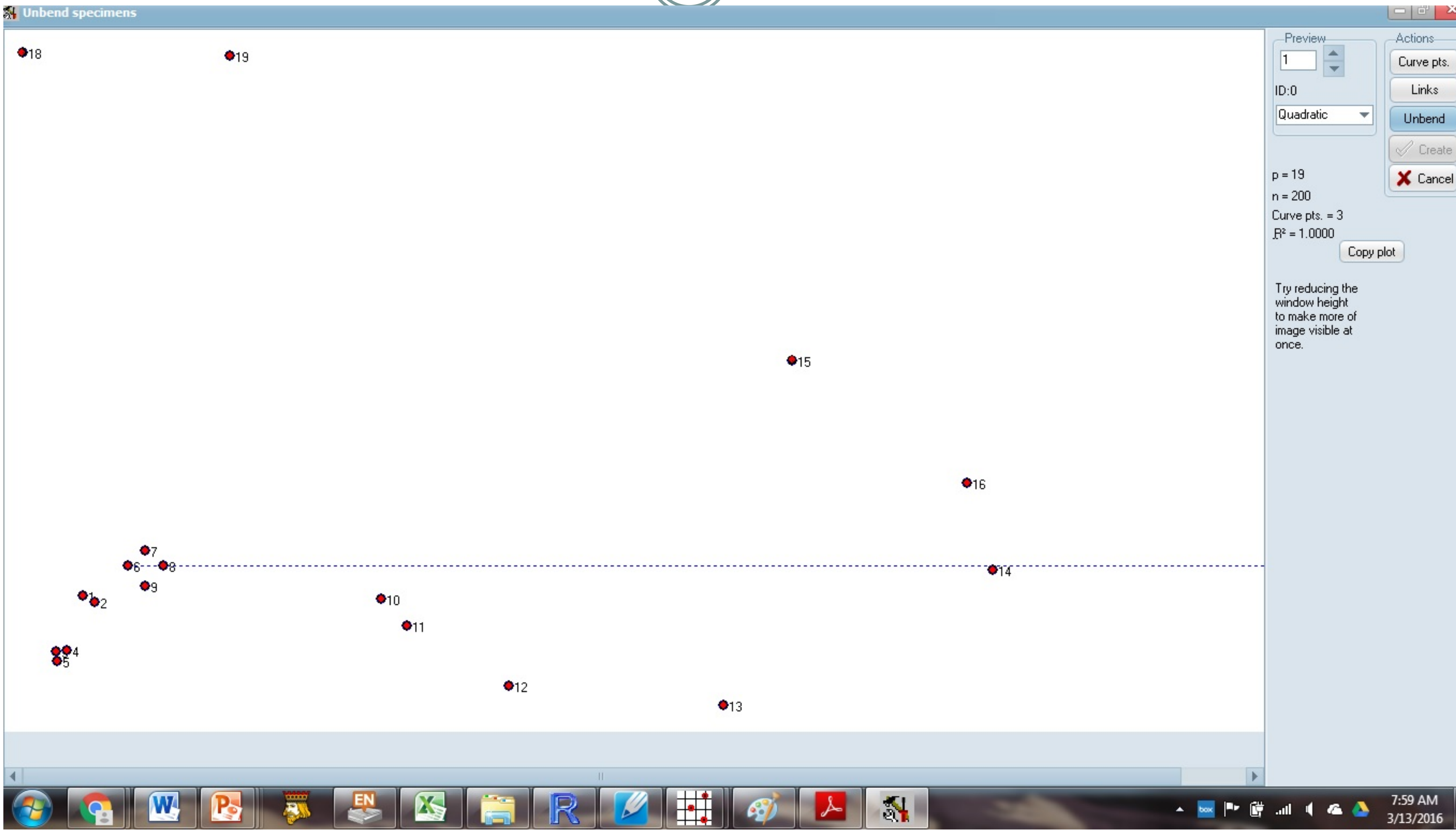
Preservational artifacts

Bending along the body axis is the main source of variation in most of the samples

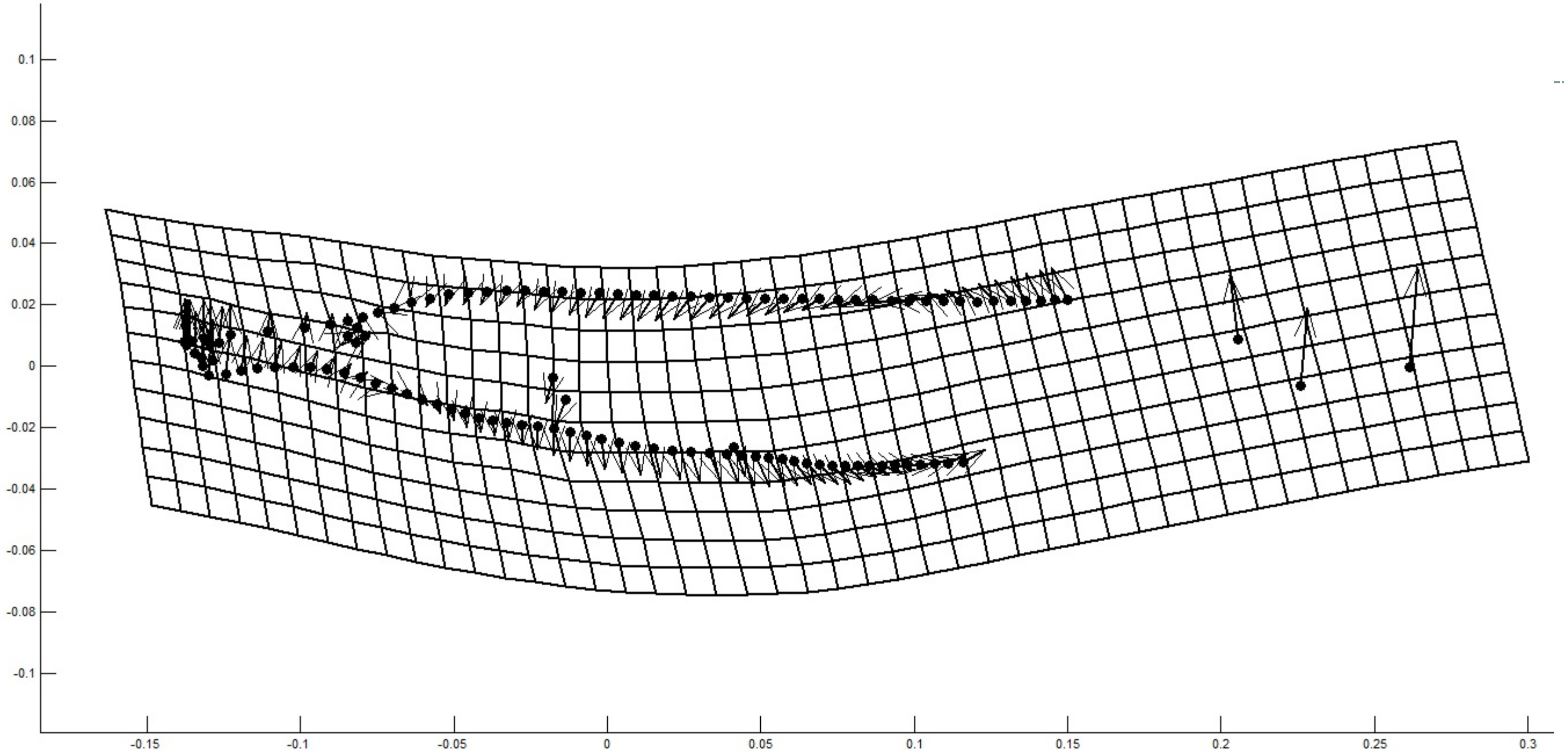
That is actually convenient because it gives us a simple way to remove that artifact

It works better than the alternative...

Removing bending: Align



Removing bending: Regression

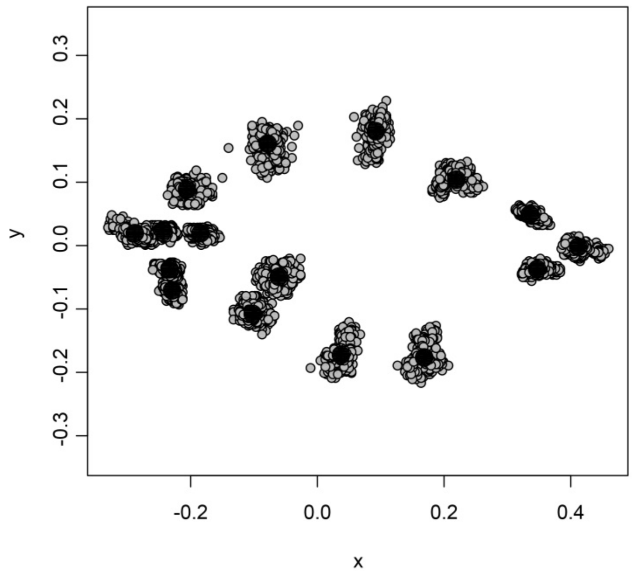


Principal Component 1: Bending

Removing bending

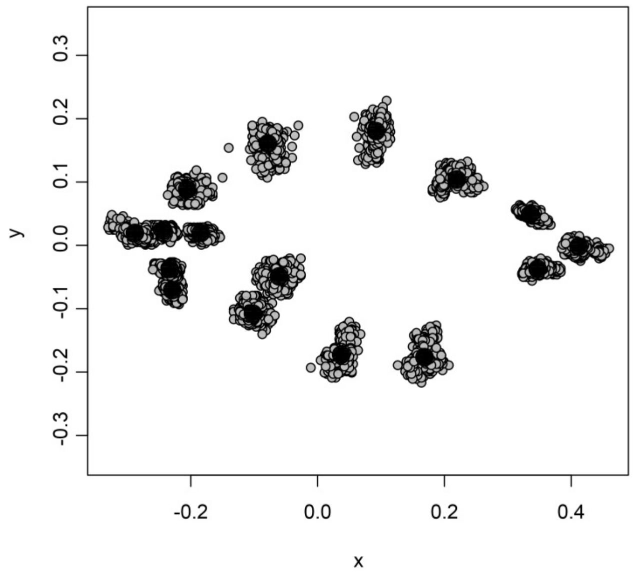
- We can either remove PC1 from the data (but that leaves us PCs rather than coordinates
- We can statistically remove the variation along PC1 from the coordinates
  - Regress on PC1 scores, add residuals from the regression to the mean

Ending with a fish example



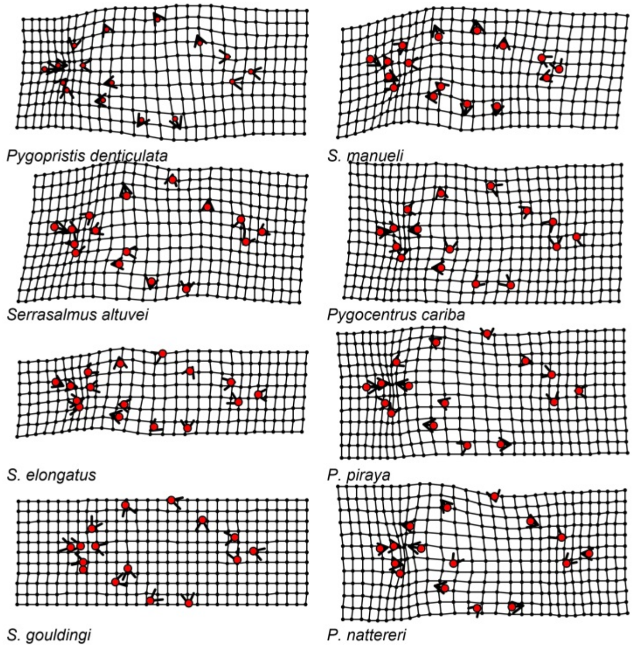
Part of an example

- Ontogenetic series from nine species
  - Compare ontogenies
  - Remove variation within species due to ontogeny
  - Look at variation at youngest and oldest ages

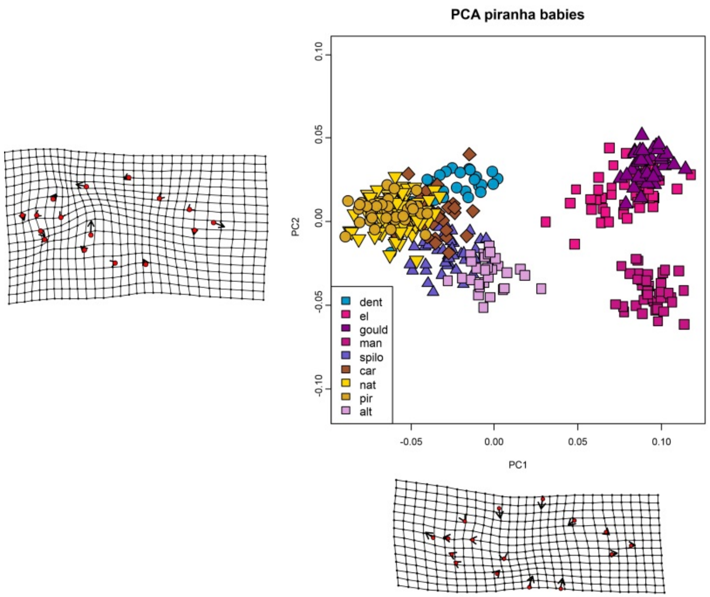


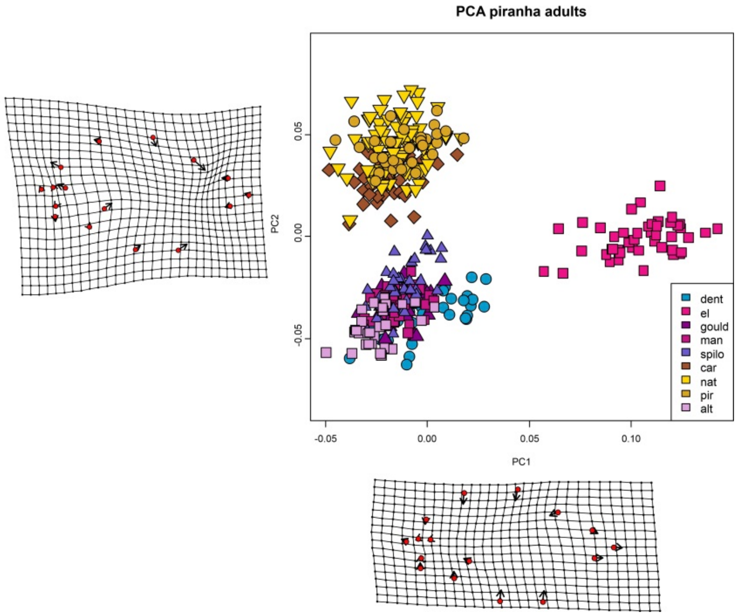
Comparing ontogenies

- All species differ (statistically significantly) in their ontogenies

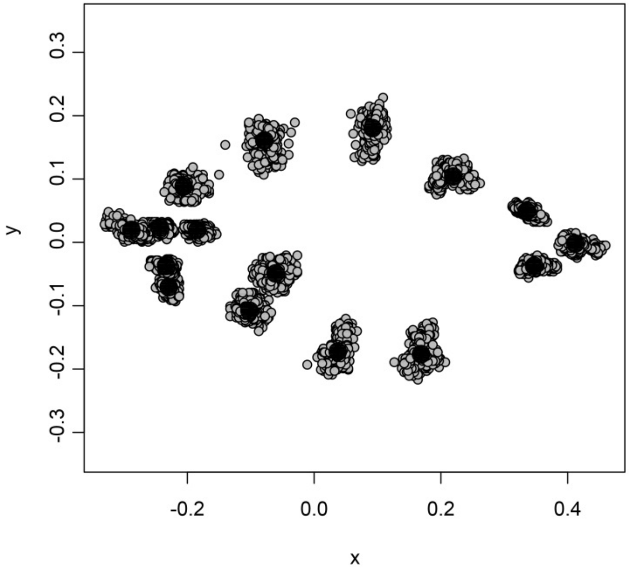


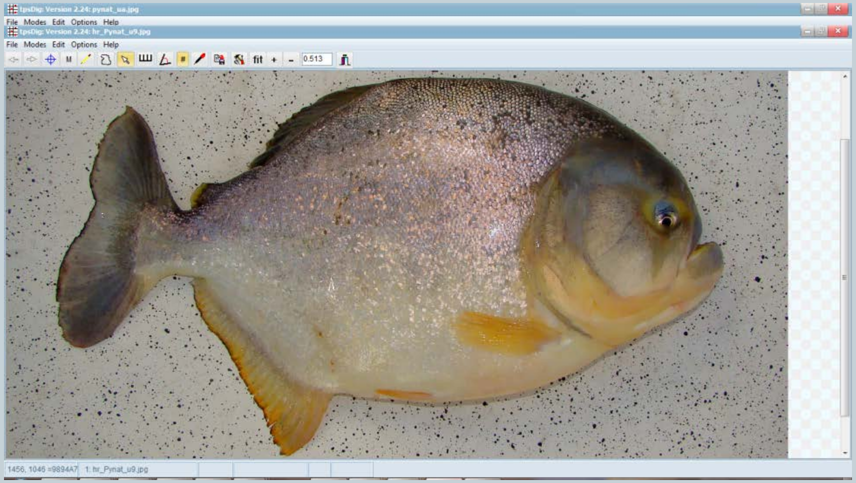
Principal components of the estimated juvenile and adult shapes of these nine species





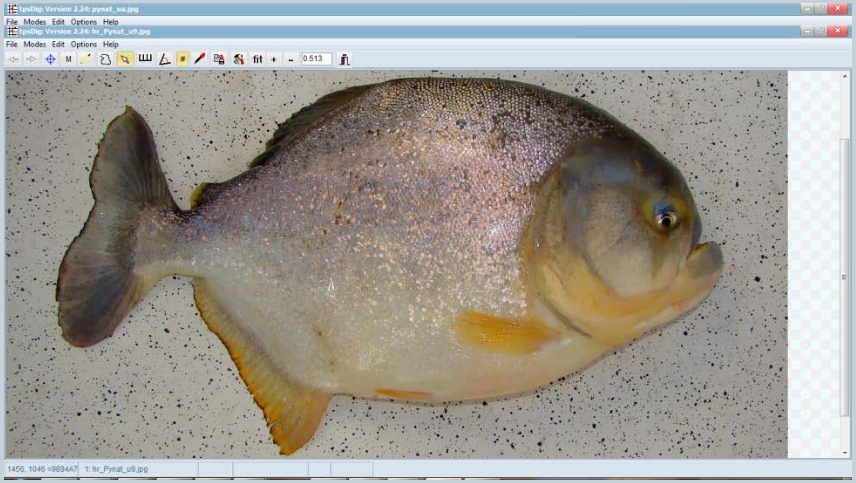
There is a lot going on with head profiles…





There is a lot going on with head profiles…

- We can't go back to the images and add the missing information



We don't have the images

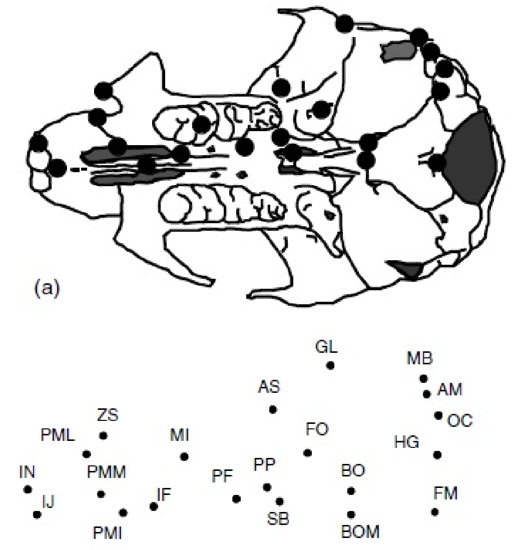
- These fish were imaged in the 1990's
- Digital cameras could not yet take research-quality photographs
- The images were obtained by an obsolete technology
  - A frame-grabber
    - I don't have images, just data files

The data files are *not* obsolete

- The first version of this digitizing program was written in 1997
  - But the present version backwardly compatible to an even older program (one that predates videodigitizing)
- The piranha data were collected in 1995
  - And I can analyze them in any program written then or this year

Even older data files

- These data were first used in a study published in 1992
- The skulls were photographed
- The photographs were printed
- The landmarks were digitized on a tablet using the program that predated tpsDig, on a computer running DOS



Old images from digital cameras...

(Mus musculus)
Photographed: 2000

(Peromyscus maniculatus bairdii)
Photographed: 2007

We can still use photos from decades ago

- This is good enough for what we intended
- If I had wanted to measure the teeth, I'd have needed higher resolution
  - And to focus on the tooth row

Photography and obsolescence

- Digital cameras will no doubt continue to improve
- But as long as they produce JPGs, image files will be backwardly compatible with older ones
- A real technological revolution might make digital photography obsolete
- That revolution could raise scientific standards too high for today’s digital cameras
- I won’t guess if or when that might happen…

Until the revolution comes, what we *can* deal with

- Inconsistencies in data file formats
  - There are several digitizing programs (not just tpsDig)
  - Some morphometric software can read multiple formats
  - Using any of these (freely available) programs, one file format can be converted to another
  - They can easily be converted into a standard spreadsheet format and, from that, into whatever the program needs

What else we can deal with

- Any image file type that you provide will work
- We can do some adjustments (crop, enhance, save to another file type
  - PhotoShop or freeware photo editors

What else we can deal with

- Storing images
  - I have our dataset (>1600 tiff files, 2020 files, 4.5GB) in my back pocket
  - All the data that I have ever collected from all photographs taken over my entire career are on this computer…

What we need from images…

Good images for digitizing
(from Olivier Larouche)

What we *can't* deal with

Gaping mouth, tilted

The string is in the way of landmarks

What we *can't* deal with

Fins damaged

Fins deformed by preservation

Problems with Fishbase pictures

The most common problems

1. Low resolution (dpi)
2. Lacked a ruler or a length measurement for the specimen
3. Nonstandard orientation and parallax problems
   (especially when pictures are taken in the field)

What else we *can't* deal with

- Small sample sizes
- The minimum useful sample size depends on the objectives of a study
  - Many macroevolutionary studies use just 10 specimens per species
  - Studies of geographic variation need more than that per locality
  - Taxonomic studies need large samples to sort out sexual dimorphism, ontogenetic variation, geographic variation, etc.
    - Many taxonomic studies rely on molecular data
    - But since about 2005, there are efforts towards an integrative taxonomy using molecular, morphological and ecological data

Getting adequate samples

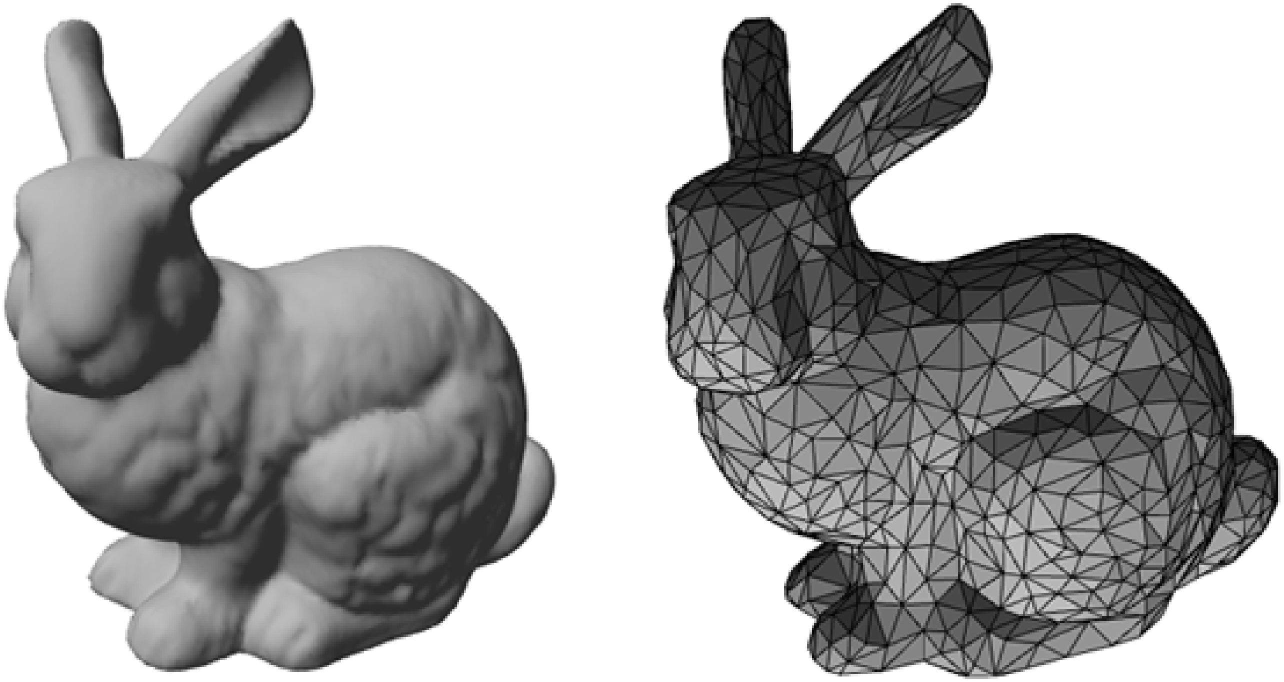
- We will likely need specimens from multiple museums so we need a standard orientation for all images
- For 2D data, orientation of the photographic plane is the main issue

Summary: What we need (2D images)

- Consistently oriented specimens
  - A fundamental limitation of 2D images is their restriction to a plane
    - All specimens must be oriented within the same photographic plane
- “Adequate” photography (digital SLR cameras)
  - Not badly over-exposed or with other obvious problems
- A ruler in every photograph
- This won’t be enough for all researchers
  - An image that is useful for analyses of body shape might not be useful for a study of teeth…

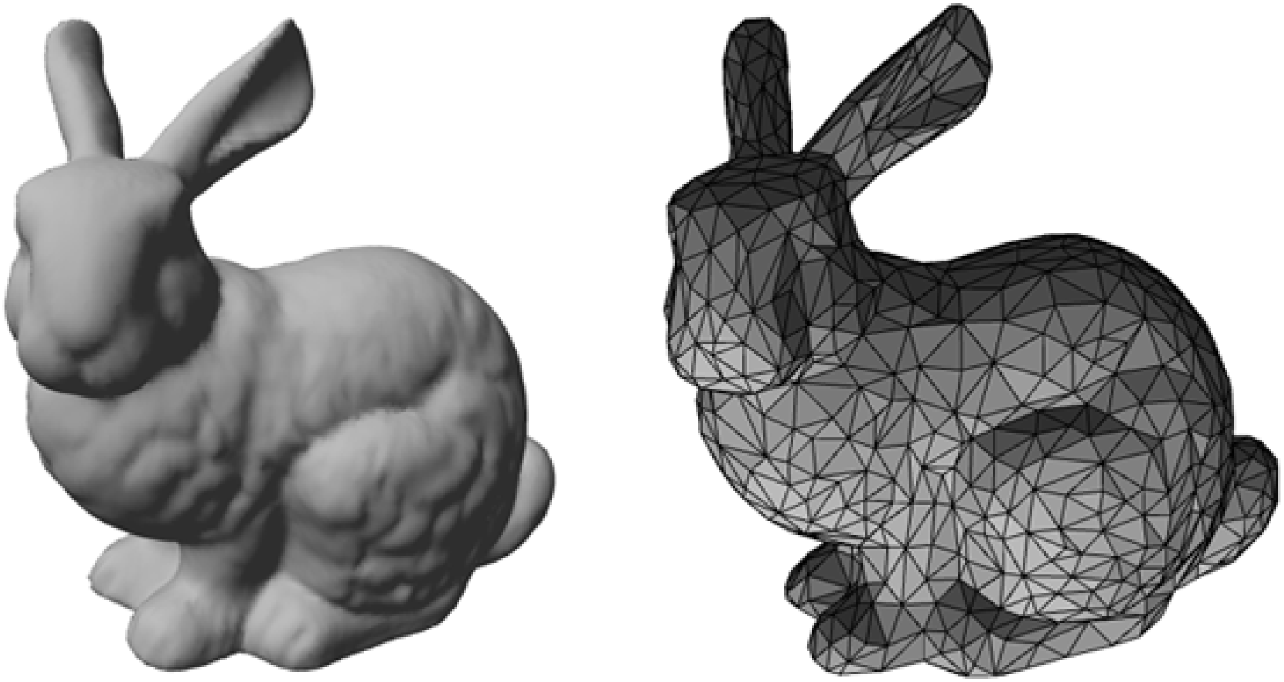
What Makes 3D Different from 2D?

Most systems produce 3D models



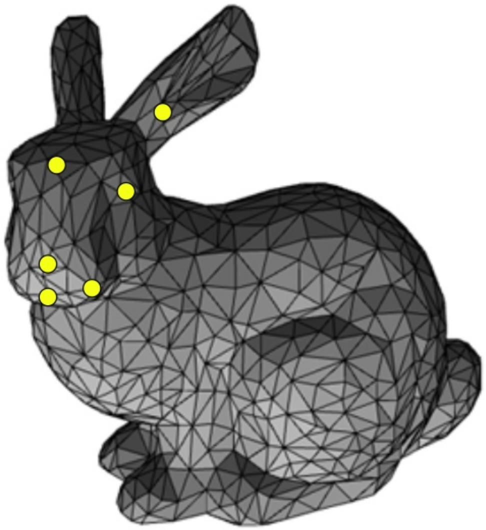
The Stanford Bunny

For the purpose of analysis, these models are equivalent to photographs – they represent the morphology that is the subject of analysis

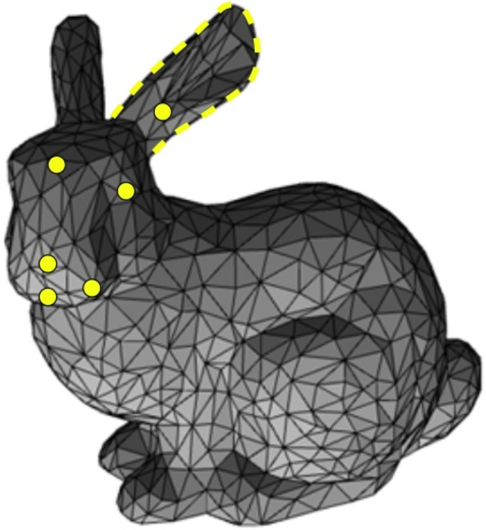


The Stanford Bunny

In the context of geometric morphometrics, that means:

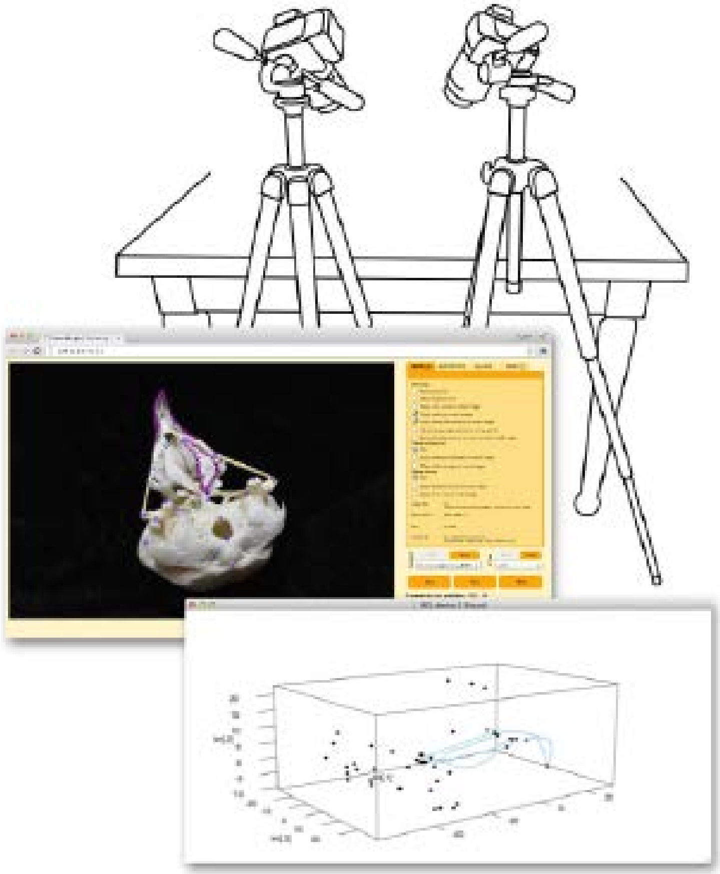


identify/select landmarks,



trace curves and interpolate semilandmarks

Most image capture systems produce 3D models
- the main exception is StereoMorph



http://home.uchicago.edu/~aolsen/software/stereomorph.shtml

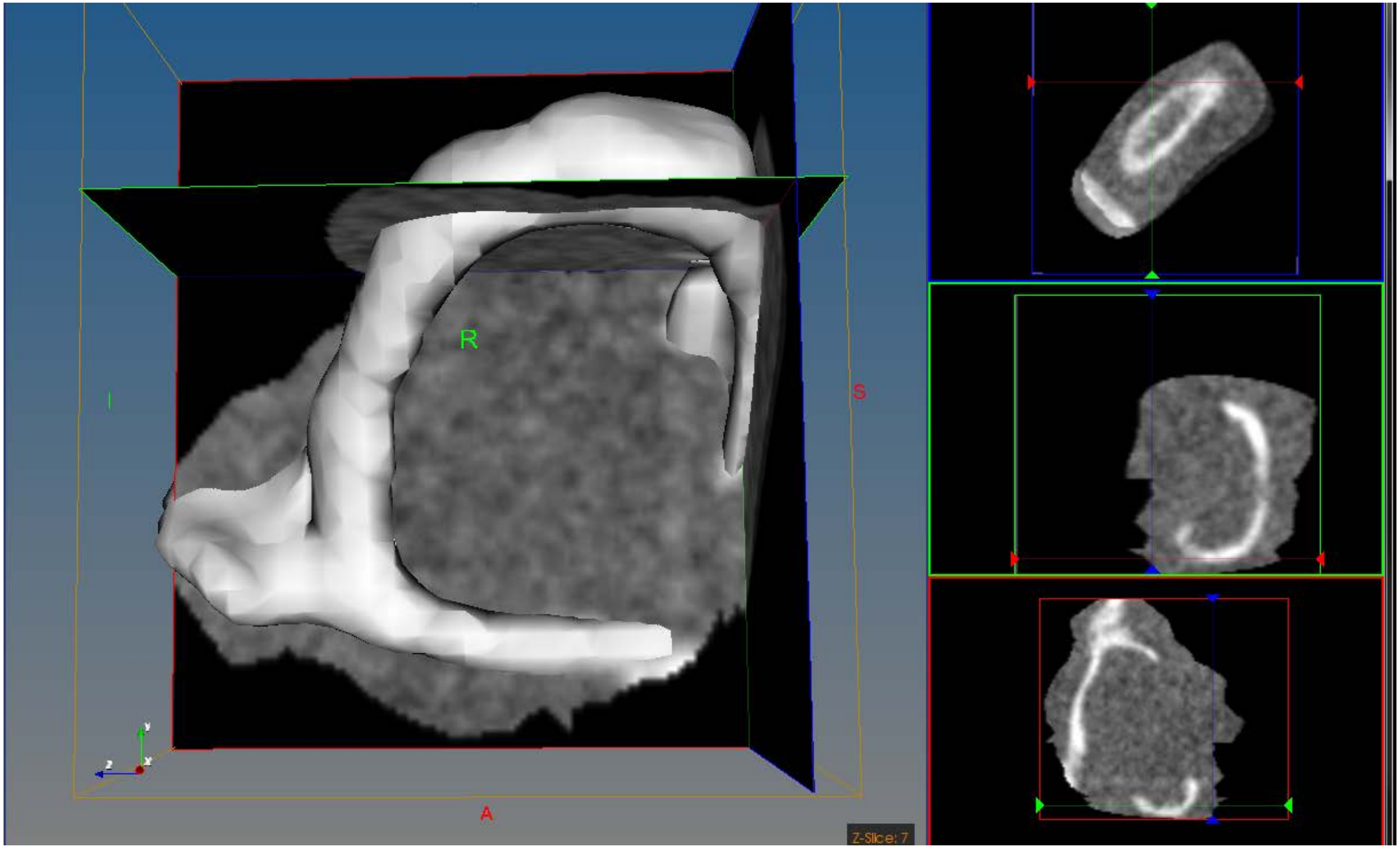
Olsen, A. M. and M. W. Westneat. 2015. StereoMorph: an R package for the collection of 3D landmarks and curves using a stereo camera set-up. *Methods in Ecology and Evolution*. 6:341-356. DOI: 10.1111/2041-210X.12326.

We will not be discussing arm-digitizers –
because they do not capture an image of the object,
from which you want to extract data

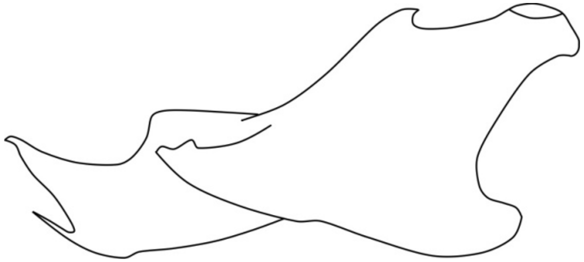
Where do models come from?

A photograph is a map of the intensity of reflected light
(1 or 3 channels for gray-scale or color)

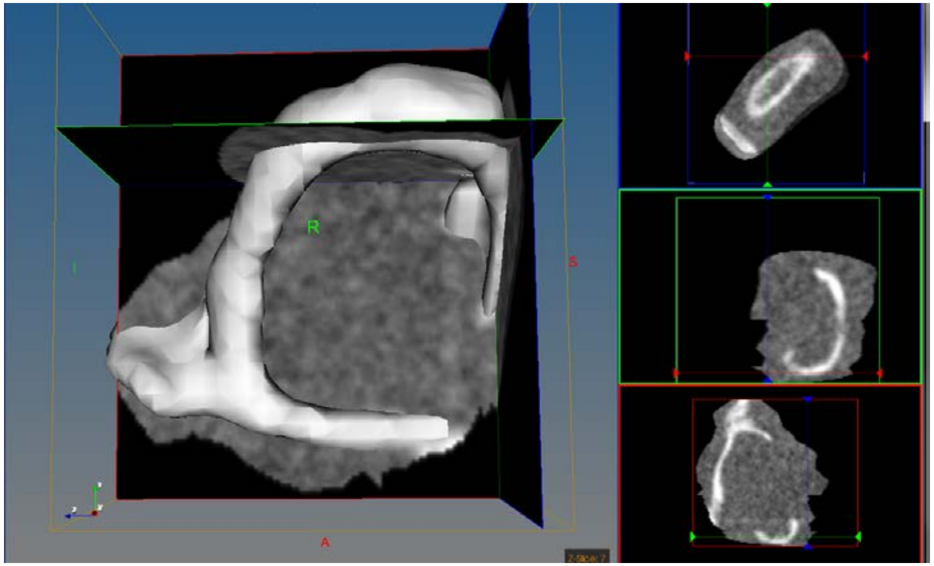
3D scanners produce volumes that are analogous

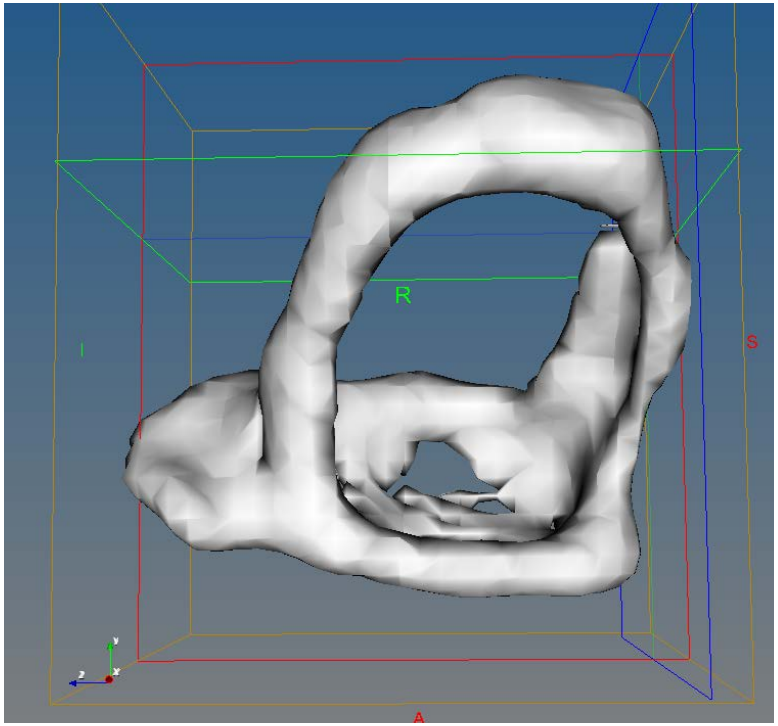


An outline (or silhouette) made from the photograph is a subset of the image data that marks edges of the object

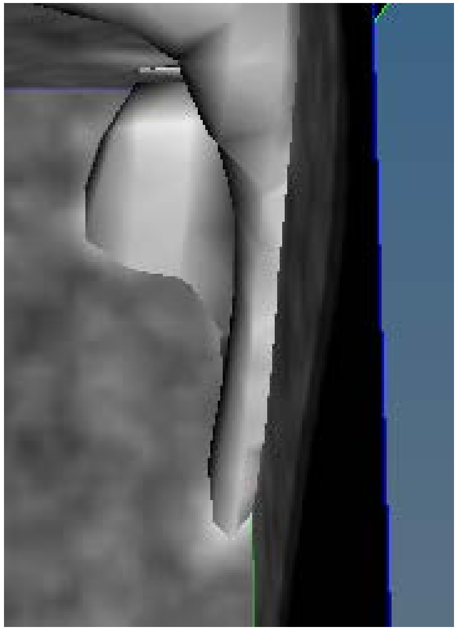


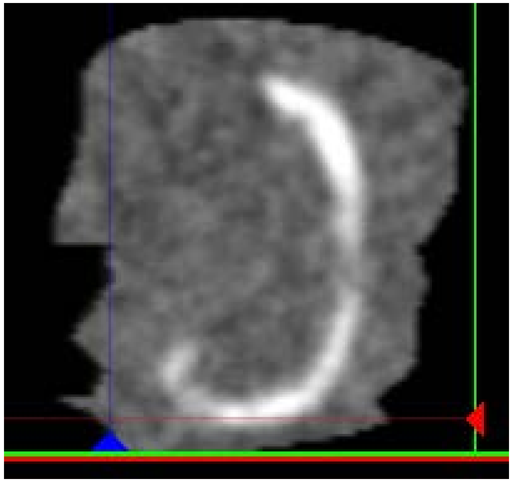
The 3D surface model is analogous to the 2D outline



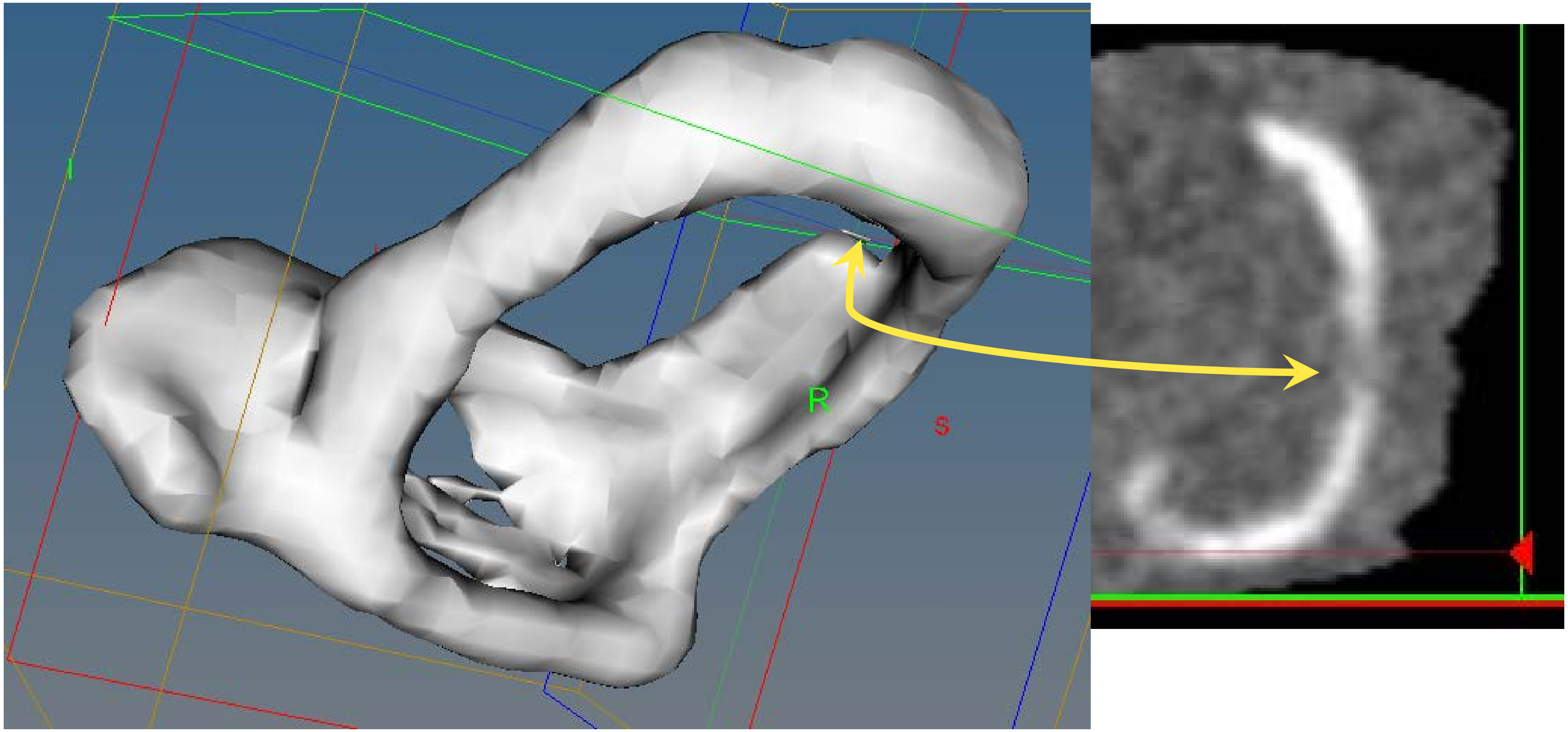


In photographs and scans, the location of the edge is inferred from the gradient across the edge





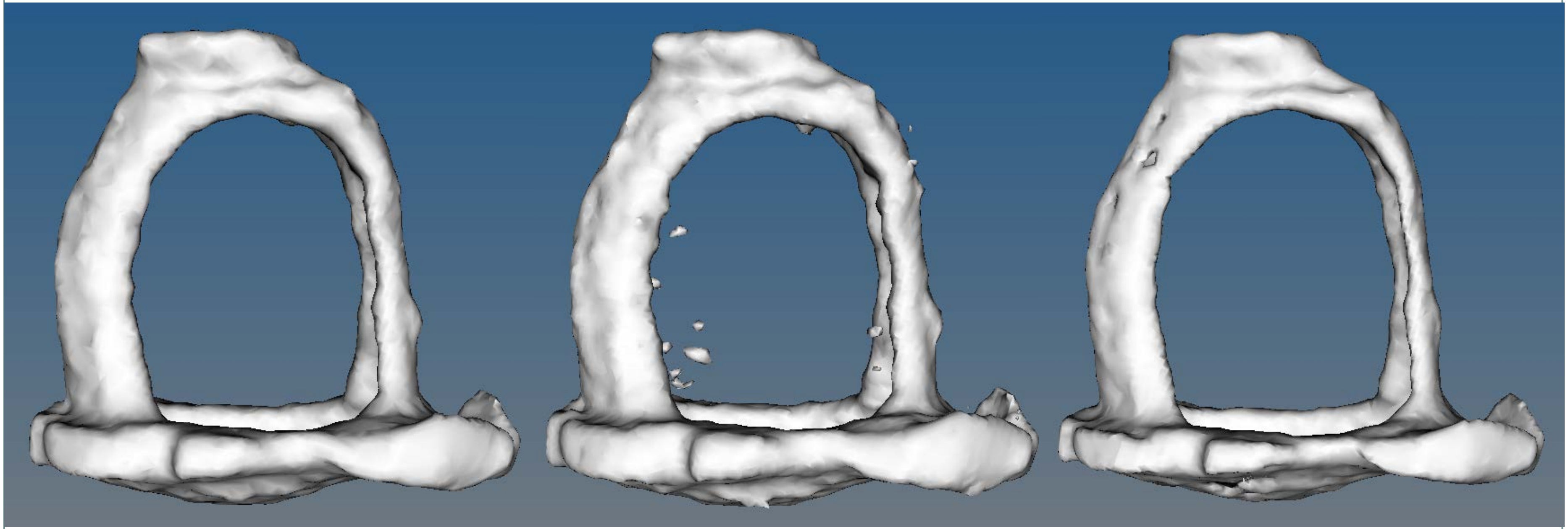
If the structure is thin relative to voxel dimensions, small variations in thickness or density can create artifacts – holes or surface bumps



500 µm

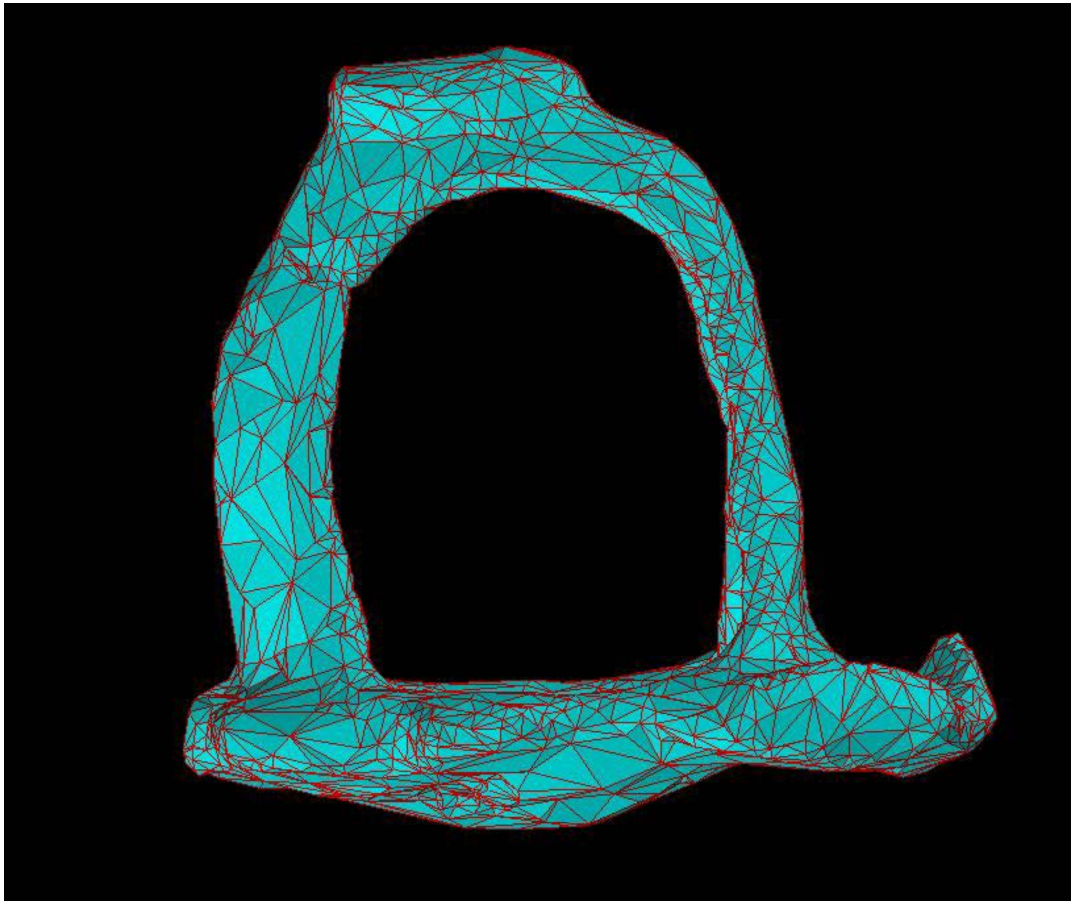
20 µm

If the structure is thin relative to voxel dimensions, small changes in thresholds and smoothing can alter the apparent dimensions of object.



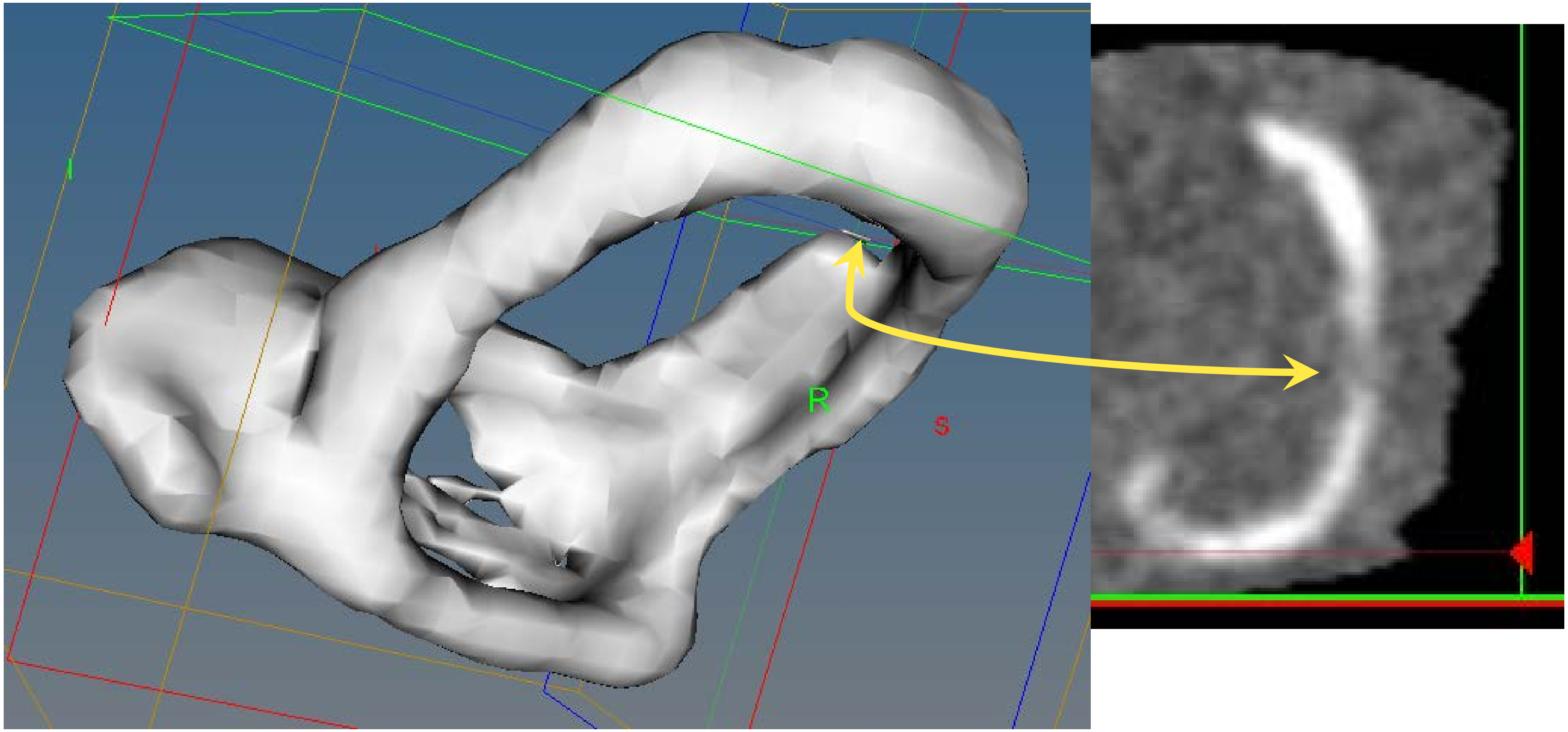
Area (mm^2)	0.851	0.882	0.803
Volume (mm^3)	0.017	0.019	0.011
Triangle Number	19,000	37,000	28,000

Low triangle number represents loss of data



Other Differences

When scanning hollow objects (skulls, tetrapod bones);
optimal scan resolution depends on the thickness of the walls,
not the thickness of the whole structure



500 µm

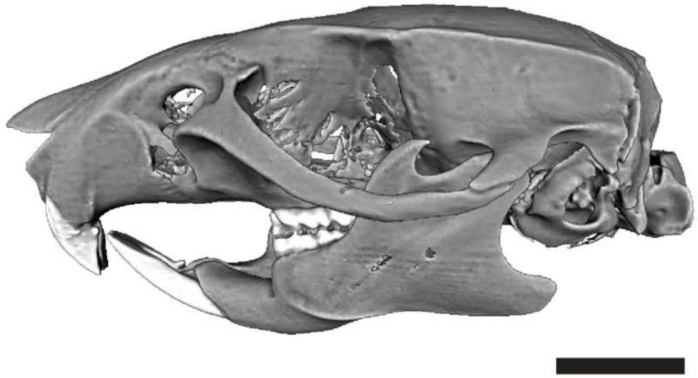
20 µm

Large file sizes

Typical digital photograph with dSLR – 2-10 MB

3D scans of stapes: 0.08 mm^3, 3-4 MB, *.vff -> 1 MB ascii *.ply
For entire ear at same resolution : 45 times the volume, 150-200 MB
Entire skull is about 100x the volume of the ear...

Scanning the skull at lower resultion than the ear may not be a good idea



Format Issues

There are many possible formats for encoding mesh data

File formats [edit]

There exist many different file formats for storing polygon mesh data. Each format is most effective when used for the purpose intended by its creator. Some of these formats are presented below:

File suffix	Format name	Organization(s)	Program(s)	Description
.raw	Raw mesh	Unknown	Various	Open, ASCII-only format. Each line contains 3 vertices, separated by spaces, to form a triangle, like so: X1 Y1 Z1 X2 Y2 Z2 X3 Y3 Z3
.blend	Blender File Format	Blender Foundation	Blender 3D	Open source, binary-only format
.fbx	Autodesk FBX Format	Autodesk	Various	Proprietary. Binary and ASCII specifications exist.
.3ds	3ds Max File	Autodesk	3ds Max	
.dae	Digital Asset Exchange (COLLADA)	Sony Computer Entertainment, Khronos Group	N/A	Stands for "**COLLA**borative **D**esign **A**ctivity". A universal format designed to prevent incompatibility.
.dgn	MicroStation File	Bentley Systems	MicroStation	
.3dm	Rhino File	Robert McNeel & Associates	Rhinoceros 3D	
.dxf	Drawing Exchange Format	Autodesk	AutoCAD	
.obj	Wavefront OBJ	Wavefront Technologies	Various	ASCII format describing 3D geometry alone. All faces' vertices are ordered counter-clockwise, thus removing the need to specify normals.
.ply	Polygon File Format	Stanford University	Unknown	Binary and ASCII
.pmd	Polygon Movie Maker data	Yu Higuchi	MikuMikuDance	Proprietary binary file format for storing humanoid model geometry with rigging, material, and physics information.
.stl	Stereolithography Format	3D Systems	Many	Binary and ASCII format originally designed to aid in "3D printing".
.amf	Additive Manufacturing File Format	ASTM International	N/A	Like the STL format, but with added native color, material, and constellation support.
.wrl	Virtual Reality Modeling Language	Web3D Consortium	Web Browsers	ISO Standard 14772-1:1997
.wrz	VRML Compressed	Web3D Consortium	Web Browsers	
.x3d, .x3db, .x3dv	Extensible 3D	Web3D Consortium	Web Browsers	ISO Standard 19775/19776/19777
.x3dz, .x3dbz, .x3dvz	X3D Compressed Binary	Web3D Consortium	Web Browsers	
.c4d	Cinema 4D File	MAXON	CINEMA 4D	
.lwo	LightWave 3D object File	NewTek	LightWave 3D	
.smb	SCOREC apf	RPI SCOREC	PUMI	Open source parallel adaptive unstructured 3D meshes for PDE based simulation workflows.
.msh	Gmsh Mesh	GMsh Developers	GMsh Project	Open source, providing an ASCII mesh description for linear and polynomially interpolated elements in 1 to 3 dimensions.
.mesh	OGRE XML	OGRE Development Team	OGRE, purebasic	Open Source. Binary (.mesh) and ASCII (.mesh.xml) format available. Includes data for vertex animation and Morph target animation (blendshape). Skeletal animation data in separate file (.skeleton).
.veg	Vega FEM tetrahedral mesh	Jernej Barbič	Vega FEM	Open Source. Stores a tetrahedral mesh and its material properties for FEM simulation. ASCII (.veg) and binary (.vegb) formats available.
.z3d	Z3d	Oleg Melashenko	Zanoza Modeler	-
.vtk	VTK mesh	VTK, Kitware	VTK, Paraview	Open, ASCII or binary format that contains many different data fields, including point data, cell data, and field data.

The ‘same’ format (same extension) can be binary or ascii

Inbox - dlswider@umich.e × | 3d mesh formats - Google × | Polygon mesh - Wikipedia ×

https://en.wikipedia.org/wiki/Polygon_mesh

Apps | Bookmarks | bookmarks

File formats [edit]

There exist many different file formats for storing polygon mesh data. Each format is most effective when used for the purpose intended by its creator. Some of these formats are presented below:

File suffix	Format name	Organization(s)	Program(s)	Description
.raw	Raw mesh	Unknown	Various	Open, ASCII-only format. Each line contains 3 vertices, separated by spaces, to form a triangle, like so: X1 Y1 Z1 X2 Y2 Z2 X3 Y3 Z3
.blend	Blender File Format	Blender Foundation	Blender 3D	Open source, binary-only format
.fbx	Autodesk FBX Format	Autodesk	Various	Proprietary. Binary and ASCII specifications exist.
.3ds	3ds Max File	Autodesk	3ds Max	
.dae	Digital Asset Exchange (COLLADA)	Sony Computer Entertainment, Khronos Group	N/A	Stands for "**COLLA**borative **D**esign **A**ctivity". A universal format designed to prevent incompatibility.
.dgn	MicroStation File	Bentley Systems	MicroStation	
.3dm	Rhino File	Robert McNeel & Associates	Rhinoceros 3D	
.dxf	Drawing Exchange Format	Autodesk	AutoCAD	
.obj	Wavefront OBJ	Wavefront Technologies	Various	ASCII format describing 3D geometry alone. All faces' vertices are ordered counter-clockwise, thus removing the need to specify normals.
.ply	Polygon File Format	Stanford University	Unknown	Binary and ASCII
.pmd	Polygon Movie Maker data	Yu Higuchi	MikuMikuDance	Proprietary binary file format for storing humanoid model geometry with rigging, material, and physics information.
.stl	Stereolithography Format	3D Systems	Many	Binary and ASCII format originally designed to aid in 3D printing".
.amf	Additive Manufacturing File Format	ASTM International	N/A	Like the STL format, but with added native color, material, and constellation support.
.wrl	Virtual Reality Modeling Language	Web3D Consortium	Web Browsers	ISO Standard 14772-1:1997
.wrz	VRML Compressed	Web3D Consortium	Web Browsers	
.x3d, .x3db, .x3dv	Extensible 3D	Web3D Consortium	Web Browsers	ISO Standard 19775/19776/19777
.x3dz, .x3dbz, .x3dvz	X3D Compressed Binary	Web3D Consortium	Web Browsers	
.c4d	Cinema 4D File	MAXON	CINEMA 4D	
.lwo	LightWave 3D object File	NewTek	LightWave 3D	
.smb	SCOREC apf	RPI SCOREC	PUMI	Open source parallel adaptive unstructured 3D meshes for PDE based simulation workflows.
.msh	Gmsh Mesh	GMsh Developers	GMsh Project	Open source, providing an ASCII mesh description for linear and polynomially interpolated elements in 1 to 3 dimensions.
.mesh	OGRE XML	OGRE Development Team	OGRE, purebasic	Open Source. Binary (.mesh) and ASCII (.mesh.xml) format available. Includes data for vertex animation and Morph target animation (blendshape). Skeletal animation data in separate file (.skeleton).
.veg	Vega FEM tetrahedral mesh	Jernej Barbič	Vega FEM	Open Source. Stores a tetrahedral mesh and its material properties for FEM simulation. ASCII (.veg) and binary (.vegb) formats available.
.z3d	Z3d	Oleg Melashenko	Zanoza Modeler	-
.vtk	VTK mesh	VTK, Kitware	VTK, Paraview	Open, ASCII or binary format that contains many different data fields, including point data, cell data, and field data.

Fields and codes may vary for the 'same' format; may use command lines from different languages

File formats [edit]

There exist many different file formats for storing polygon mesh data. Each format is most effective when used for the purpose intended by its creator. Some of these formats are presented below:

File suffix	Format name	Organization(s)	Program(s)	Description
.raw	Raw mesh	Unknown	Various	Open, ASCII-only format. Each line contains 3 vertices, separated by spaces, to form a triangle, like so: X1 Y1 Z1 X2 Y2 Z2 X3 Y3 Z3
.blend	Blender File Format	Blender Foundation	Blender 3D	Open source, binary-only format
.fbx	Autodesk FBX Format	Autodesk	Various	Proprietary. Binary and ASCII specifications exist.
.3ds	3ds Max File	Autodesk	3ds Max	
.dae	Digital Asset Exchange (COLLADA)	Sony Computer Entertainment, Khronos Group	N/A	Stands for "**COLLA**borative **D**esign **A**ctivity". A universal format designed to prevent incompatibility.
.dgn	MicroStation File	Bentley Systems	MicroStation	
.3dm	Rhino File	Robert McNeel & Associates	Rhinoceros 3D	
.dxf	Drawing Exchange Format	Autodesk	AutoCAD	
.obj	Wavefront OBJ	Wavefront Technologies	Various	ASCII format describing 3D geometry alone. All faces' vertices are ordered counter-clockwise, thus removing the need to specify normals.
.ply	Polygon File Format	Stanford University	Unknown	Binary and ASCII
.pmd	Polygon Movie Maker data	Yu Higuchi	MikuMikuDance	Proprietary binary file format for storing humanoid model geometry with rigging, material, and physics information.
.stl	Stereolithography Format	3D Systems	Many	Binary and ASCII format originally designed to aid in "3D printing".
.amf	Additive Manufacturing File Format	ASTM International	N/A	Like the STL format, but with added native color, material, and constellation support.
.wrl	Virtual Reality Modeling Language	Web3D Consortium	Web Browsers	ISO Standard 14772-1:1997
.wrz	VRML Compressed	Web3D Consortium	Web Browsers	
.x3d, .x3db, .x3dv	Extensible 3D	Web3D Consortium	Web Browsers	ISO Standard 19775/19776/19777
.x3dz, .x3dbz, .x3dvz	X3D Compressed Binary	Web3D Consortium	Web Browsers	
.c4d	Cinema 4D File	MAXON	CINEMA 4D	
.lwo	LightWave 3D object File	NewTek	LightWave 3D	
.smb	SCOREC apf	RPI SCOREC	PUMI	Open source parallel adaptive unstructured 3D meshes for PDE based simulation workflows.
.msh	Gmsh Mesh	GMsh Developers	GMsh Project	Open source, providing an ASCII mesh description for linear and polynomially interpolated elements in 1 to 3 dimensions.
.mesh	OGRE XML	OGRE Development Team	OGRE, purebasic	Open Source. Binary (.mesh) and ASCII (.mesh.xml) format available. Includes data for vertex animation and Morph target animation (blendshape). Skeletal animation data in separate file (.skeleton).
.veg	Vega FEM tetrahedral mesh	Jernej Barbič	Vega FEM	Open Source. Stores a tetrahedral mesh and its material properties for FEM simulation. ASCII (.veg) and binary (.vegb) formats available.
.z3d	Z3d	Oleg Melashenko	Zanoza Modeler	
.vtk	VTK mesh	VTK, Kitware	VTK, Paraview	Open, ASCII or binary format that contains many different data fields, including point data, cell data, and field data.

Compression may be good for the Web, but it is bad for data

Inbox - dlswider@umich.e | 3d mesh formats - Google | Polygon mesh - Wikipedia

https://en.wikipedia.org/wiki/Polygon_mesh

Apps | Bookmarks | bookmarks

File formats [edit]

There exist many different file formats for storing polygon mesh data. Each format is most effective when used for the purpose intended by its creator. Some of these formats are presented below:

File suffix	Format name	Organization(s)	Program(s)	Description
.raw	Raw mesh	Unknown	Various	Open, ASCII-only format. Each line contains 3 vertices, separated by spaces, to form a triangle, like so: X1 Y1 Z1 X2 Y2 Z2 X3 Y3 Z3
.blend	Blender File Format	Blender Foundation	Blender 3D	Open source, binary-only format
.fbx	Autodesk FBX Format	Autodesk	Various	Proprietary. Binary and ASCII specifications exist.
.3ds	3ds Max File	Autodesk	3ds Max	
.dae	Digital Asset Exchange (COLLADA)	Sony Computer Entertainment, Khronos Group	N/A	Stands for "**COLLA**borative Design **A**ctivity". A universal format designed to prevent incompatibility.
.dgn	MicroStation File	Bentley Systems	MicroStation	
.3dm	Rhino File	Robert McNeel & Associates	Rhinoceros 3D	
.dxf	Drawing Exchange Format	Autodesk	AutoCAD	
.obj	Wavefront OBJ	Wavefront Technologies	Various	ASCII format describing 3D geometry alone. All faces' vertices are ordered counter-clockwise, thus removing the need to specify normals.
.ply	Polygon File Format	Stanford University	Unknown	Binary and ASCII
.pmd	Polygon Movie Maker data	Yu Higuchi	MikuMikuDance	Proprietary binary file format for storing humanoid model geometry with rigging, material, and physics information.
.stl	Stereolithography Format	3D Systems	Many	Binary and ASCII format originally designed to aid in "3D printing".
.amf	Additive Manufacturing File Format	ASTM International	N/A	Like the STL format, but with added native color, material, and constellation support.
.wrl	Virtual Reality Modeling Language	Web3D Consortium	Web Browsers	ISO Standard 14772-1:1997
.wrz	VRML Compressed	Web3D Consortium	Web Browsers	
.x3d, .x3db, .x3dv	Extensible 3D	Web3D Consortium	Web Browsers	ISO Standard 19775/19776/19777
.x3dz, .x3dbz, .x3dvz	X3D Compressed Binary	Web3D Consortium	Web Browsers	
.c4d	Cinema 4D File	MAXON	CINEMA 4D	
.lwo	LightWave 3D object File	NewTek	LightWave 3D	
.smb	SCOREC apf	RPI SCOREC	PUMI	Open source parallel adaptive unstructured 3D meshes for PDE based simulation workflows.
.msh	Gmsh Mesh	GMsh Developers	GMsh Project	Open source, providing an ASCII mesh description for linear and polynomially interpolated elements in 1 to 3 dimensions.
.mesh	OGRE XML	OGRE Development Team	OGRE, purebasic	Open Source. Binary (.mesh) and ASCII (.mesh.xml) format available. Includes data for vertex animation and Morph target animation (blendshape). Skeletal animation data in separate file (.skeleton).
.veg	Vega FEM tetrahedral mesh	Jernej Barbič	Vega FEM	Open Source. Stores a tetrahedral mesh and its material properties for FEM simulation. ASCII (.veg) and binary (.vegb) formats available.
.z3d	Z3d	Oleg Melashenko	Zanoza Modeler	-
.vtk	VTK mesh	VTK, Kitware	VTK, Paraview	Open, ASCII or binary format that contains many different data fields, including point data, cell data, and field data.

What Geomorph can read (therefore, what I need):

File formats [edit]

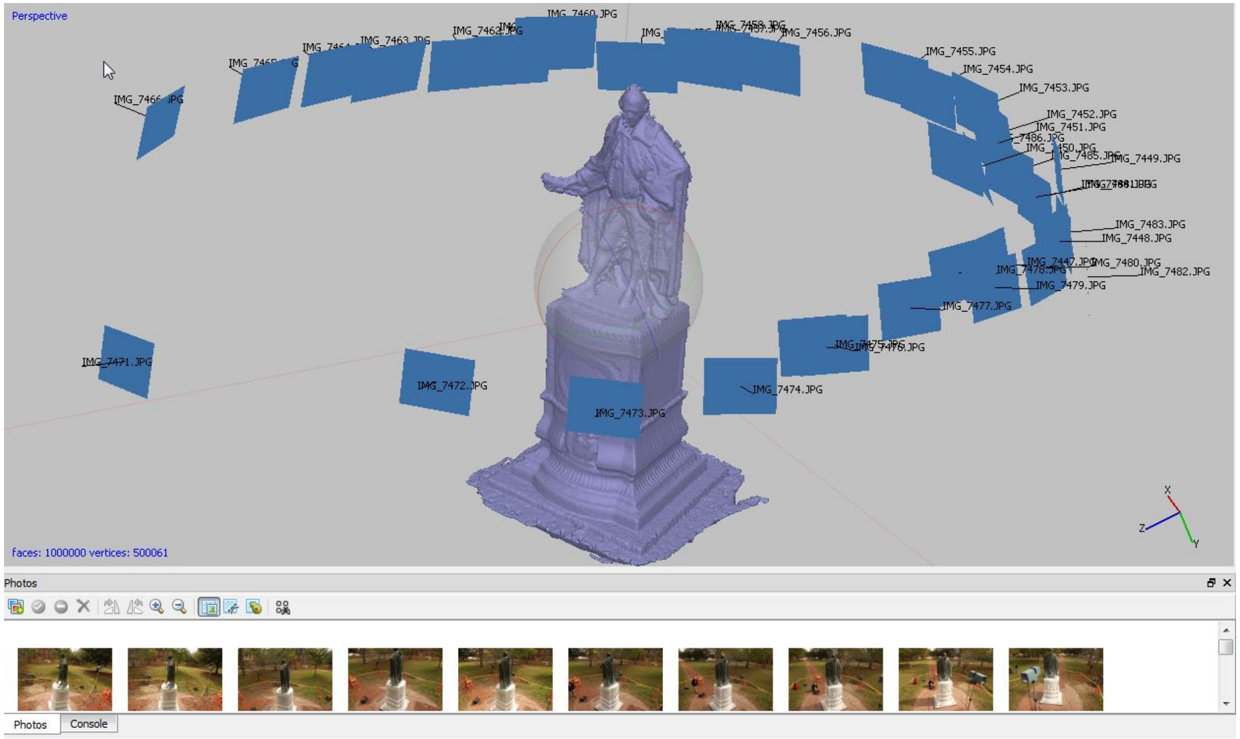
There exist many different file formats for storing polygon mesh data. Each format is most effective when used for the purpose intended by its creator. Some of these formats are presented below:

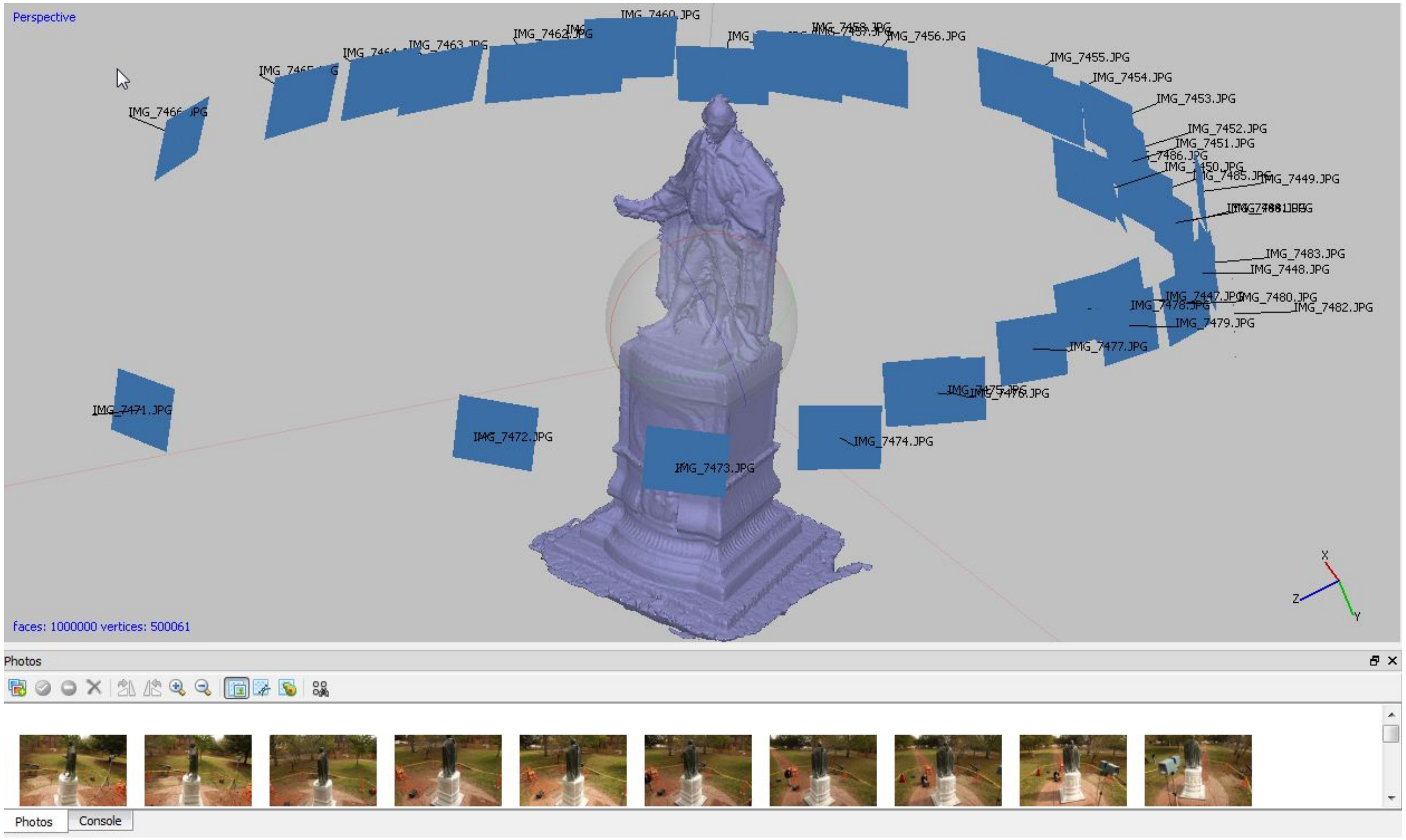
File suffix	Format name	Organization(s)	Program(s)	Description
.raw	Raw mesh	Unknown	Various	Open, ASCII-only format. Each line contains 3 vertices, separated by spaces, to form a triangle, like so: X1 Y1 Z1 X2 Y2 Z2 X3 Y3 Z3
.blend	Blender File Format	Blender Foundation	Blender 3D	Open source, binary-only format
.fbx	Autodesk FBX Format	Autodesk	Various	Proprietary. Binary and ASCII specifications exist.
.3ds	3ds Max File	Autodesk	3ds Max	
.dae	Digital Asset Exchange (COLLADA)	Sony Computer Entertainment, Khronos Group	N/A	Stands for "**COLLA**borative Design **A**ctivity". A universal format designed to prevent incompatibility.
.dgn	MicroStation File	Bentley Systems	MicroStation	
.3dm	Rhino File	Robert McNeel & Associates	Rhinoceros 3D	
.dxf	Drawing Exchange Format	Autodesk	AutoCAD	
.obj	Wavefront OBJ	Wavefront Technologies	Various	ASCII format describing 3D geometry alone. All faces' vertices are ordered counter-clockwise, thus removing the need to specify normals.
.ply	Polygon File Format	Stanford University	Unknown	Binary and ASCII
.pmd	Polygon Movie Maker data	Yu Higuchi	MikuMikuDance	Proprietary binary file format for storing humanoid model geometry with rigging, material, and physics information.
.stl	Stereolithography Format	3D Systems	Many	Binary and ASCII format originally designed to aid in "3D printing".
.amf	Additive Manufacturing File Format	ASTM International	N/A	Like the STL format, but with added native color, material, and constellation support.
.wrl	Virtual Reality Modeling Language	Web3D Consortium	Web Browsers	ISO Standard 14772-1:1997
.wrz	VRML Compressed	Web3D Consortium	Web Browsers	
.x3d, .x3db, .x3dv	Extensible 3D	Web3D Consortium	Web Browsers	ISO Standard 19775/19776/19777
.x3dz, .x3dbz, .x3dvz	X3D Compressed Binary	Web3D Consortium	Web Browsers	
.c4d	Cinema 4D File	MAXON	CINEMA 4D	
.lwo	LightWave 3D object File	NewTek	LightWave 3D	
.smb	SCOREC apf	RPI SCOREC	PUMI	Open source parallel adaptive unstructured 3D meshes for PDE based simulation workflows.
.msh	Gmsh Mesh	GMsh Developers	GMsh Project	Open source, providing an ASCII mesh description for linear and polynomially interpolated elements in 1 to 3 dimensions.
.mesh	OGRE XML	OGRE Development Team	OGRE, purebasic	Open Source. Binary (.mesh) and ASCII (.mesh.xml) format available. Includes data for vertex animation and Morph target animation (blendshape). Skeletal animation data in separate file (.skeleton).
.veg	Vega FEM tetrahedral mesh	Jernej Barbič	Vega FEM	Open Source. Stores a tetrahedral mesh and its material properties for FEM simulation. ASCII (.veg) and binary (.vegb) formats available.
.z3d	Z3d	Oleg Melashenko	Zanoza Modeler	-
.vtk	VTK mesh	VTK, Kitware	VTK, Paraview	Open, ASCII or binary format that contains many different data fields, including point data, cell data, and field data.

What does not differ between 2D and 3D

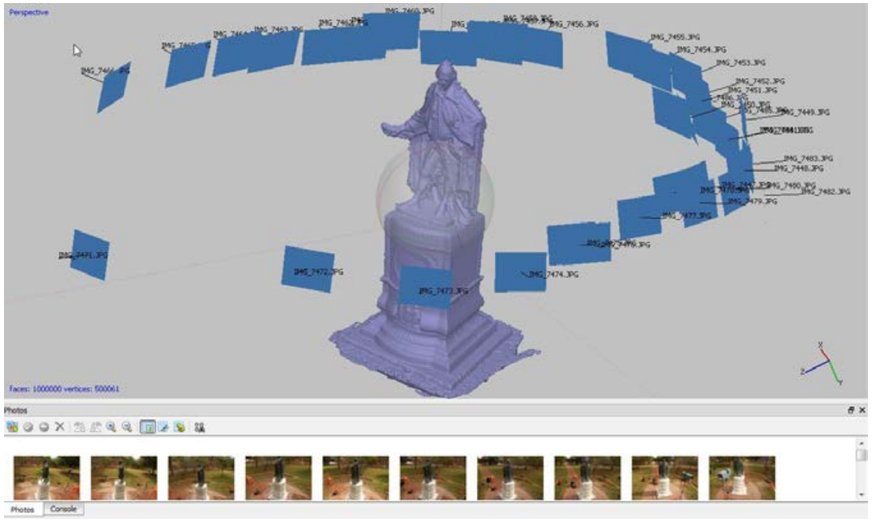
- We cannot fix low resolution
- We cannot fix broken or deformed specimens
- One size / resolution does not fit all
- We need coordinates of landmarks and semilandmarks with a degree of accuracy;
- Once we have the coordinates, all analyses are the same

Photogrammetry



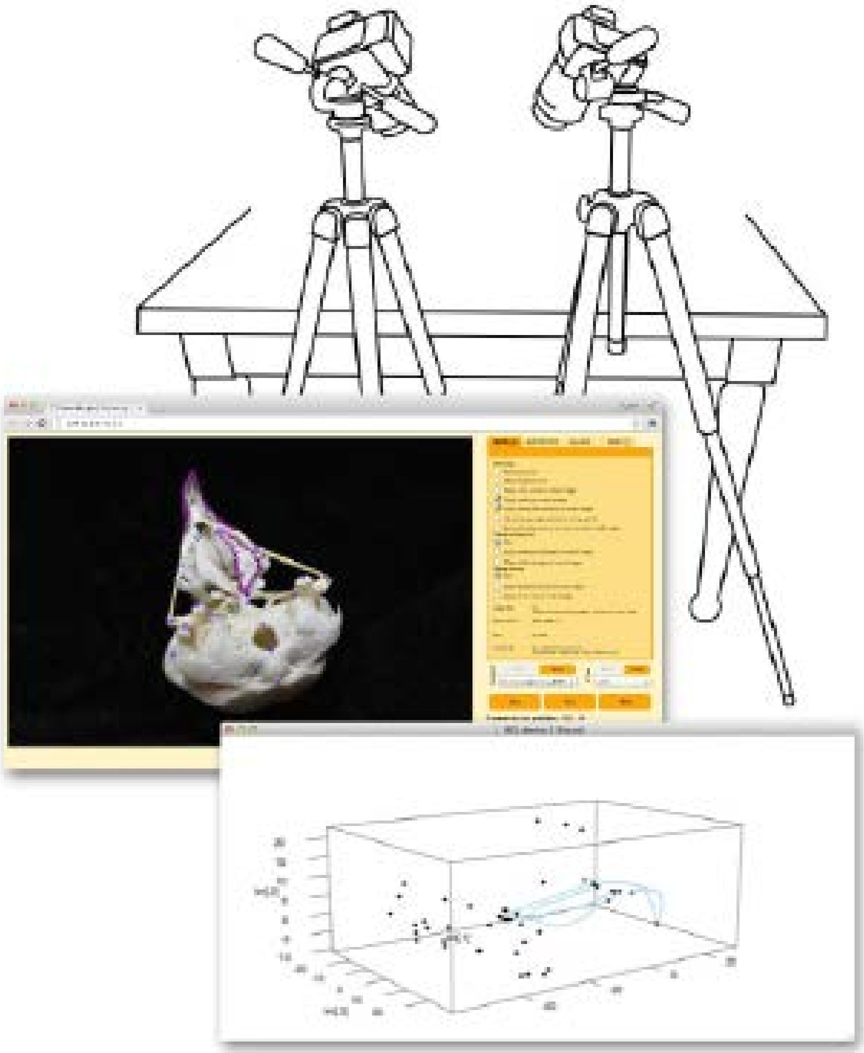


Conventional photogrammetry uses a series of overlapping images to build the model (by triangulating a large number of corresponding features)



The equipment is cheaper than CT or most high quality laser scanners
Building models is computationally intensive and requires high feature density
Thin ‘shells’ of bone or other translucent material make computations difficult.

StereoMorph take a simplified approach to photogrammetry



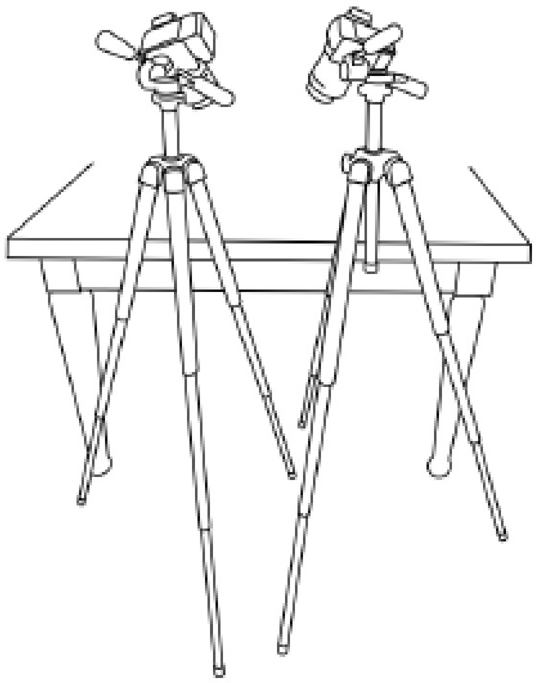
http://home.uchicago.edu/~aolsen/software/stereomorph.shtml

Olsen, A. M. and M. W. Westneat. 2015. StereoMorph: an R package for the collection of 3D landmarks and curves using a stereo camera set-up. *Methods in Ecology and Evolution*. 6:341-356. DOI: 10.1111/2041-210X.12326.

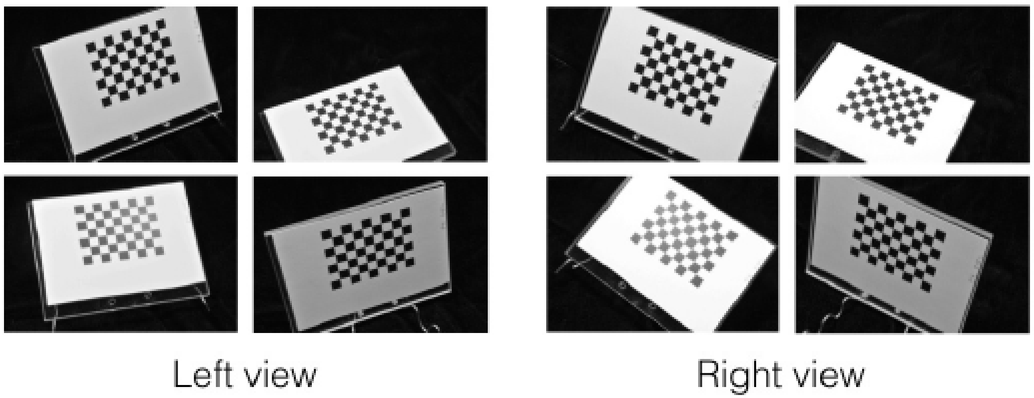
Paired cameras are used to take overlapping images

Camera positions are fixed for the entire session

Differences between view points are calibrated



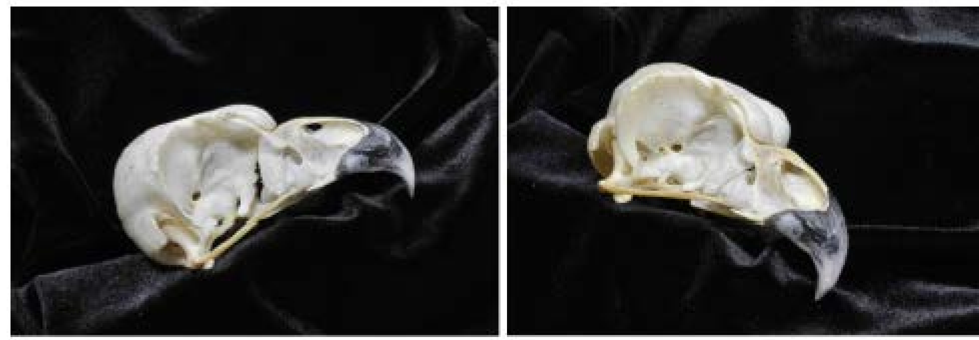
One possible camera arrangement.



Several pairs of images are taken

Left Right

Multiple view points increase the number of features that can be analyzed



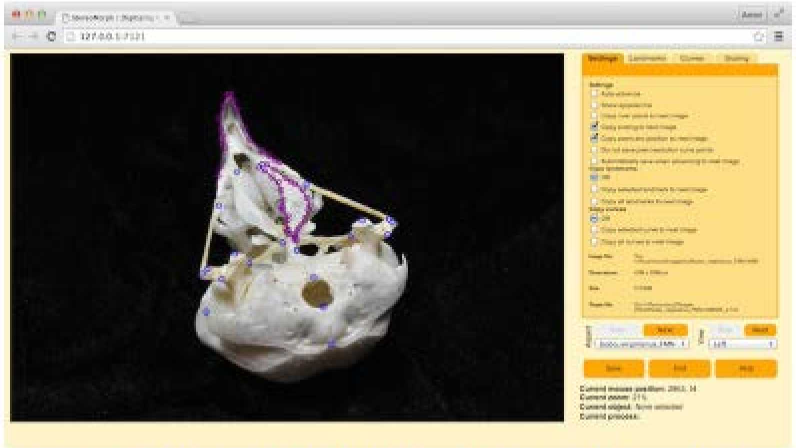
Left Right

An knowledgable user can easily design a small set of pairs to cover the subject (~9 for this skull)

Left Right

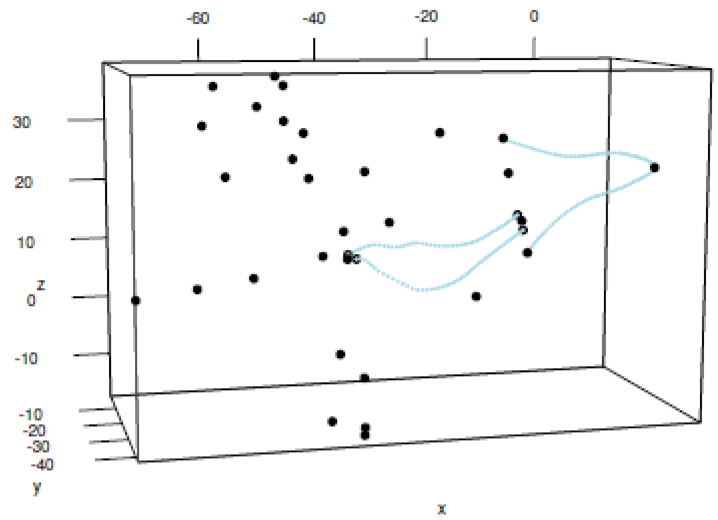
The landmarks visible in both images of a pair are digitized *in both images*; same for semi-landmarks

The landmarks visible in two pairs of images should be digitized in all four images – more is better. These points are used to compute the difference in the specimen's position between the pairs



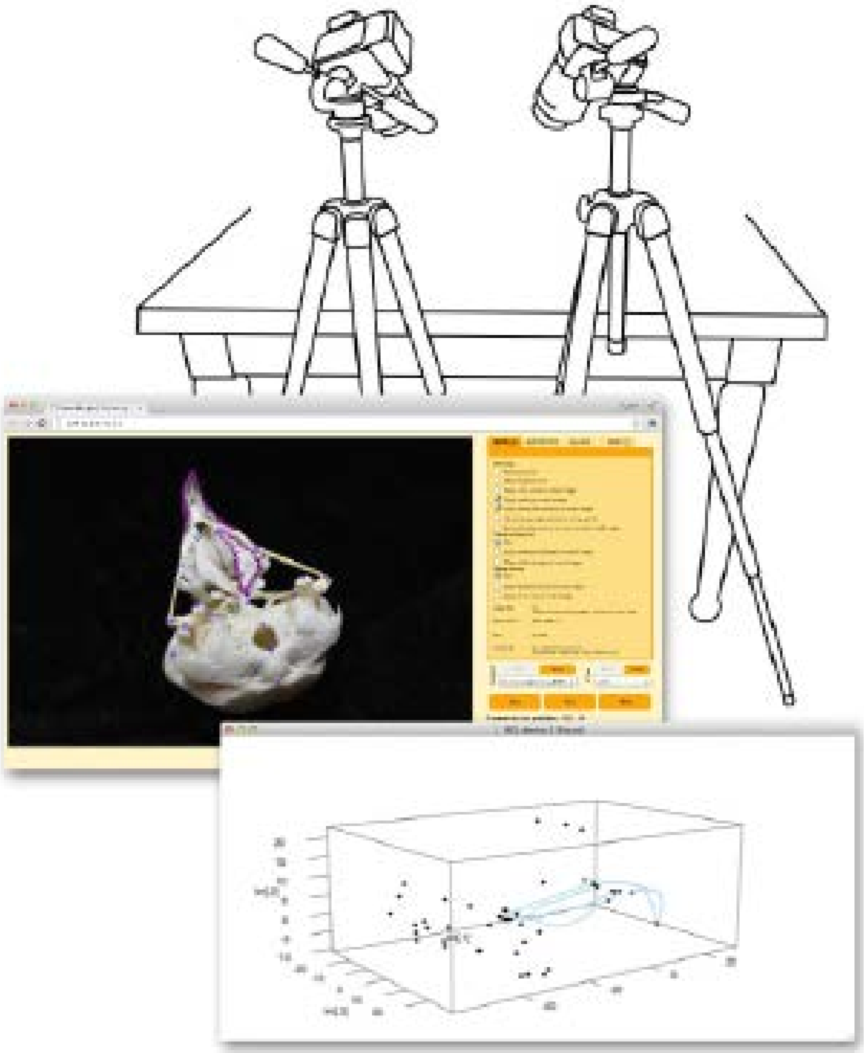
The StereoMorph digitizing app launched with a stereo image set.

Output is the set of coordinates for the landmarks and semilandmarks. No model is computed.



Plot of reconstructed and unified landmarks and curve points using plot3d() in the rgl package.

Caveat: we have not yet vetted this approach, but plan to do so soon



http://home.uchicago.edu/~aolsen/software/stereomorph.shtml

Olsen, A. M. and M. W. Westneat. 2015. StereoMorph: an R package for the collection of 3D landmarks and curves using a stereo camera set-up. *Methods in Ecology and Evolution*. 6:341-356. DOI: 10.1111/2041-210X.12326.