PREPARATION OF FOSSIL AND OSTEOLOGICAL 3D-PRINTABLE MODELS FROM FREELY AVAILABLE CT-SCAN MOVIES

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ABSTRACT

Changes in the online availability of 3D models of skeletal elements and 3D printer technology have made it feasible to develop a fossil or osteological collection from scratch. Many online sites have models that can be freely downloaded and 3D printed. Other sites have CT-scan movies online—which can be downloaded and turned into printable 3D models by using the free software suite SPIERS. Post-processing of the printed models (sanding, painting, etc.) can make them almost visually indistinguishable from real specimens.

Keywords: three-dimensional printing; CT-scan; teaching

RESUMO [in Portuguese]

Alterações na disponibilidade on-line de modelos 3D de elementos esqueléticos e a tecnologia de impressão 3D tornaram possível desenvolver uma colecção, a partir do zero, de osteologia ou fósseis. Muitos sítios on-line têm modelos que podem ser descarregados gratuitamente e impressos em 3D. Outros sítios disponibilizam filmes de tomografias computorizadas que podem ser descarregados e convertidos em modelos 3D para impressão usando programa informático livre SPIERS. O pós-processamento dos modelos impressos (lixamento, pintura, etc.) pode torná-los quase indistinguíveis dos espécimes reais.

INTRODUCTION

The most powerful way to teach students about evolution is through the use of fossil or biological specimens (Rahman et al., 2012). With specimens in hand, students can make their own observations and test the assertions of their instructors—but, more importantly, they can experience the evidence for evolution themselves. Ideally, to teach about evolution, comparative anatomy, or other similar topics, one would have a set of charismatic modern and fossil specimens at hand to demonstrate the course of evolution.

Many have been lured into paleontology or vertebrate evolution classes with the prospect of getting to see and touch some of these. However, more often than not in classes such as these, the skulls turn out to be merely drawings and the only real bones that students get to touch are those scavenged from recent roadkill. The fact is that it is difficult, and expensive, to build a vertebrate collection. Few institutions have the resources to go out and collect their own dinosaur skeletons. Likewise, procuring modern comparative skeletons is difficult.

Few institutions can afford or provide access to a comprehensive set of real specimens. Quality replicas provide a way for many institutions to build vertebrate collections. Physical models have been shown to be an effective way to educate students at a lower cost than real specimens (Yammine and Violato, 2016), superior to the performance of 3D computer models (Preece et al., 2013). From a replica, one can experience and interact with the object in 3D in a way that is not possible with drawings or computer animations. Purchasing quality replicas of modern species is more attainable than real skeletons, but is still expensive—for example, a fully mounted duck-billed platypus skeleton replica is nearly $600.

For all of the advantages of having a fully stocked vertebrate teaching collection (real or replica), one must acknowledge that there are some things you cannot do with a typical vertebrate teaching collection. The skull of an elephant will always be big, and shape comparisons between juveniles and adults will always be obscured by the difference in size. However, with 3D printing, you can easily scale down large objects, or scale up small objects, making them more useful for the teaching of the visually impaired (Horowitz and Schultz, 2014; Teshima et al., 2010). Doing so, you can have juveniles and adults printed at the same size to better compare the changes in shape that take place during growth, without confusing the changes with increasing size.

3D printers are becoming much more widespread and easier to access. There are a number of applications to geology alone (D'Urso et al., 2000; Teshima et al., 2010; Rahman et al., 2012; Hasiuk 2014; Horowitz and Schultz, 2014; Lautenschlager and Rücklin, 2014; Hasiuk and Harding, 2016), not to mention other fields (Niven et al., 2009; Preece et al., 2013; McMenamin et al., 2014; Scalfani and Vaid, 2014; Thomas et al., 2016). While anyone can download ready-made models from places like thingiverse.com, it is relatively easy to prepare your own model from freely available CT-scan movies.

A WORD ON OWNERSHIP, COPYRIGHT AND FAIR USE

Very little has been written or said in the paleontological sphere about the ownership and copyright of 3D data (but see Mallison and Wings, 2014: 8). However, this is of critical importance for users of online 3D data, lest you create legal problems for yourself or your institution. Anyone who has worked with museum specimens knows that they often have a web of ownership and permissions that extends from the collection manager to the board of trustees. This can lead to a situation where someone who may have collected and prepared the specimen does not ultimately own the rights to the images of the specimen that they may have taken. 3D would logically follow this same web of ownership, with the result that any 3D models of specimens would still be owned by the museum or repository. However, the museums or repositories are often bound by the requirements of granting agencies or university requirements that stipulate open access to data generated. The United States National Science Foundation has been helping to lead this charge with the expectation that data generated with its funds be made publically available to other researchers when reasonable (https://www.nsf.gov/bfa/dias/policy/dmp.jsp).

The first step in this process is to check what the website housing the data says about copyright, terms of use, and data ownership. There is no universal code regarding 3D data in

academia. Each website has its own take on it (some do not even mention copyright at all). AfricanFossils.org, Morphosource, and Phenome10k all put their data under Creative Commons Licensing (https://creativecommons .org/licenses/by-nc/4.0/). This means that as long as you properly attribute the source of the data, you can use it for any non-commercial purpose, like education or research. Other websites have their own, unique statements. The Digital Morphology Museum (KUPRI) simply states on its homepage: "The goal of this site is to enable you to view the scans of non-human primates and mammals and to download scan data from our database for your original research. It is our great pleasure if you can make use of these data and we hope that they will provide new insights into primate and mammalian evolution." Aves3D endorses usage for 'personal education of website visitors and non-commercial scientific research and education' as long as the source is acknowledged. Digimorph's statement endorses use of their data for 'personal education', but is silent on the subject of classroom usage. We recommend that when there is doubt about how you can use the data, contact the site administrator for guidance / permission. You may need to pursue further permission from the person who scanned the item.

THE PROCEDURE

What you need to begin

To start with, you need a decent graphics computer with lots of free memory. SPIERSedit recommends a 64-bit system with at least 2Gb of RAM, a fast/large hard-disk. SPIERSview recommends a fast graphics card. On that computer, we recommend the following software packages (freeware): ImageJ (http://imagej.nih.gov/), SPIERSedit and SPIERSview (http://spiers-software.org/; Sutton et al., 2012), MeshLab (http://meshlab.sourceforge.net/), netfabb Basic (http://www.netfabb.com/basic.php), and software supplied by your 3D printer (i.e. Makerbot Desktop for the Makerbot printers, http://www.makerbot.com/desktop). This final portion of the protocol was written specifically for an extrusion-type 3D printer—it can easily be modified for other types of printers.

Where do you find scans?

The online repositories for 3D data are just developing now. Several have emerged in the past few years, and there is no centralized search mechanism for them yet. There are still scientists who post CT-scan datasets on their

Table 1 - Web resources for 3D skeletal models. 3D indicates that 3D filetypes (.stl, .ply, etc) are available. Dollar signs ($) mean that the models are not free.

Name	Website	File types
African Fossils	http://africanfossils.org/	3D
Artec 3D	https://www.artec3d.com/3d-models	3D
Aves3D	http://aves3d.org/	3D
CG trader	https://www.cgtrader.com/	$, 3D
DigiMorph	http://digimorph.org/	CT-scan movies, 3D
Digital Morphology Museum, KUPRI	http://dmm.pri.kyoto-u.ac.jp/dmm/WebGallery/index.html	CT-scan movies
GB3D	http://www.3d-fossils.ac.uk/home.html	3D
Idaho Virtualization Laboratory	http://imnh.isu.edu/home/idaho-virtualization-laboratory/	Must request for models
MorphoSource	http://morphosource.org/	3D
Phenome10k	http://phenome10k.org/	3D
Shapeways	http://www.shapeways.com/	$, 3D
Sketchfab	https://sketchfab.com/	Some free 3D
Smithsonian Human Origins	http://humanorigins.si.edu/evidence/3d-collection	Must request for models
Smithsonian X 3D	http://3d.si.edu/browser	3D
Thingiverse	http://www.thingiverse.com/	3D
U-M Online 3D Repository	http://umorf.ummp.lsa.umich.edu/wp/	No downloads

lab websites (e.g. Dr. Larry Witmer, http://www.ohio.edu/people/witmerl/lab.htm), or places that have them available for viewing, like Digimorph (http://digimorph.org/). Datadryad.org, a site for the storage of scientific data, hosts some CT-scans, and we expect that number to grow in the coming years. There are a host of sites specific to 3D models themselves—where you do not have to worry about converting CT-scan movies into models—places like Morphosource, Phenome10K and others (Table 1).

Downloading movies or 3D files is fairly straightforward on most sites. On DigiMorph, it is a little more complicated, as many of the CT-scan datasets there do not have download links. The way to download them is to click on the slice movie name, in order to bring up the pop-up movie window. What you do next depends on what internet browser you are using. It is easiest to download the movie files (.mp4) using Mozilla Firefox as your browser. Using Firefox, you right-click on the movie and choose *Save video as*.

Movie to slices

After you have downloaded your movie, you need to do some initial processing in ImageJ. To load the movie in ImageJ, you need to go to *File > Open*, then choose your movie. A popup window will appear, in which you will need to select Convert to 8-bit grayscale and Use virtual stack. The first thing you should do is to remove any text in the movie. Some movie files have slice numbers or text (file name, scale bar, etc.) in them, and you need to remove them from the files to make a printable file. You can remove them later using the SPIERS software, but it is easier to remove them in ImageJ. Just use the rectangular selection tool and erase the text from all frames.

The most important thing that you need to do is to convert the file from a movie to a folder that contains all of the 'slices' of the model. Essentially, what you are doing is creating a digital 'flipbook', with all of the digital 'pages' of the 'flipbook' in one folder in the proper order. To do this, you need to go to *File > Save As > Image Sequence*. This will cause a popup window to appear; in the window you need to choose the format .bmp and change the name / numbering as appropriate. After you finish with that window, it will bring up the Save window, where you will choose where to save the files. We strongly recommend creating a new folder in which to save all of the new images.

Slices to model

To create the model you need to load all of the images into SPIERSedit, and tell the program how to recognize which pixels in each image are to be a part of the resulting model. SPIERS has been discussed in publications (e.g. Sutton et al., 2012, 2014) and interested readers are urged to consult them and the manuals for both SPIERSedit and SPIERSview.

First, you open SPIERSedit. You load your images by going to *File > New*—and then select all bmp files in your folder. Next, you will use the Generation window to set a grayscale value that captures the bone or fossil to the degree you want (basically, you are now telling the program which values of gray will become a part of your model). This approach works best for isolated specimens; it is a bit trickier when the specimen is surrounded by matrix (a fossil) or tissue (a preserved modern animal cadaver). Usually, if there is matrix or tissue surrounding the item of interest, it will usually be a darker shade of grey. Thus, by refining the greyscale level, you can digitally 'prepare' a fossil from the matrix or 'dissect' a bone from an animal. First, select a slice of the animal that encompasses a lot of variation. Then, use the sliding bar to select the grayscale value—click 'generate' to see if the value works well. If not, change the grayscale value, and hit generate again. Each model is different, and a guess and test approach must be used. Once you are satisfied with the grayscale, select all the slices in the slice selector window, and click generate again. This will apply your grayscale threshold to all slices. At this point, you can go ahead and make a model that can be 3D printed.

To make a model, you go to *output > export SPIERS view and launch*. At this point you may notice some problems with the model—for example, the model being compressed or extended unusually in the axis that each slice was produced. This is because the thickness of each slice of the model is not set correctly. To fix that, go to the Output window, click on the settings tab, and change the value of slices/mm—usually to 0.5, 1.5, or 2 slices/mm as these are typical values for the number of slices/mm. The correctness of the values used can be crosschecked against the dimensions of the specimen. You may also notice that the model is 'holey' or unusually thick—these are signs that you need to re-adjust the contrast in the model.

SPIERS exports its models as a .spv file which can only be read by the program SPIERSview. Within SPIERSview, you can apply some smoothing to the model, as well as export it as a .stl file, which is the file type that will be used in all succeeding pieces of software.

Dissecting the model

Certain types of models will require additional preparation. For example, if you have a scan of a cranium and jaw together, you may want to digitally dissect the jaw from the cranium so that they can be articulated with a movable joint as in life. Having a fully articulated jaw and skull with mobile jaw joint is obviously more realistic. However, dissecting the jaw from the model you have produced is difficult. It can be done during the post-processing phase (i.e. after the model is printed), but this runs the risk of breaking your model beyond easy repair (especially for those who are not gifted sculptors). To dissect the jaw off the model you need to go into curves mode in SPIERSedit—the use of which is covered in detail in the SPIERSedit manual. The curves option is a way to essentially lasso an area that you want to include in a separate model. Simply put, you lasso the lower jaw in each slice and combine them together to make a model of the lower jaw. You can use the same approach to remove extraneous text / scale bars—basically, you select everything *but* extraneous text on the frames, and then copy that curve to each frame.

For the lower jaw, create a separate curve for the jaw, and use that curve to create a boundary between the skull and jaw. Difficulties will include interlocking teeth and the jaw joints. Add extra points to the curve to make a more complex polygon that will enable you to weave the curve around the interlocking teeth, or the jaw joint. Once you have created a curve that includes all of the points you want, you need to move all of those points to a mask. You must be in mask mode, click the toggle button to ensure that your curve is filled in rather than just an outline, create a mask, select both your new mask and your curve (and select all slices), and the go to *Mask > Mask from curve*. Then click on your new mask, and open the output window, and create a new output object from your mask.

Post-processing of the digital model

Despite having the finished model, you are not quite ready to print. Open the model in Meshlab, and you will notice that the model appears very dark. Due to an idiosyncracy of SPIERSedit, the models are essentially created inside out. To fix this, you need to go to *Filters > Normals, Curvatures, and Orientation > Invert Faces Orientation*. Other useful tools under the Filters tab include tools for simplification (i.e. making the model smaller, e.g. Quadriatic edge collapse decimation), and for smoothing (e.g. Laplacian smooth, which for each vertex a new position is calculated based on the neighboring vertices). See http://www.3d-coform.eu/index.php/tools/meshlab for more information, as well as tutorials on youtube.com. See Sutton et al., (2014) for more details. These techniques are essentially removing data from your model; when used to too great of a degree, they can easily reduce the resolution and make the model appear blocky (there are no hard and fast rules for how much smoothing or simplification you can do to a model). Use them with caution in an iterative fashion and make sure you save your model before you use them.

Netfabb Basic is a good program to do some basic repairs on the model. Go to *Extras > Repair* part to fix minor errors in the model. You can also use Netfabb Basic to slice up models that are too big for the print area of your printer (be sure to check the dimensions of the printable area of your 3D printer). The pieces can then be joined together after printing to create a larger model than could be printing a scaled down version of the model by itself. To do this, you must use the *Cuts* panel in the lower right hand corner of the Netfabb Basic window. We recommend trying to cut the object along a plane of symmetry. One advantage of this is that you can have the cut surface placed downward on the 3D printer and avoid printing many of the extraneous supports that would normally print under a more irregular surface (extrusion based printers have to build thin supports in order to support overhanging bits of morphology while the plastic is still molten). After digitally cutting the model, you must export each part individually as an .stl file.

Printing and finishing

There are several different ways of printing out 3D models (Tschopp and Dzemski, 2012). One

of the most commercially accessible methods is extrusion-based additive printers (like the Makerbot printer which was used by the authors). In this mode of printing, molten plastic filaments are extruded onto a surface, layer-by-layer. The model is built of these successive layers—which can be printed solid, hollow, or with a honeycomb-like internal framework for strength. Externally, the printer will print a network of supports to support overhanging parts of the model (Figure 1A). Once the printing is finished, these external supports will need to be removed. The supports will, in most cases, break away easily, leaving little trace of their presence on the model. Others will need to be delicately removed by sanding, or with a hand-held Dremel tool. We
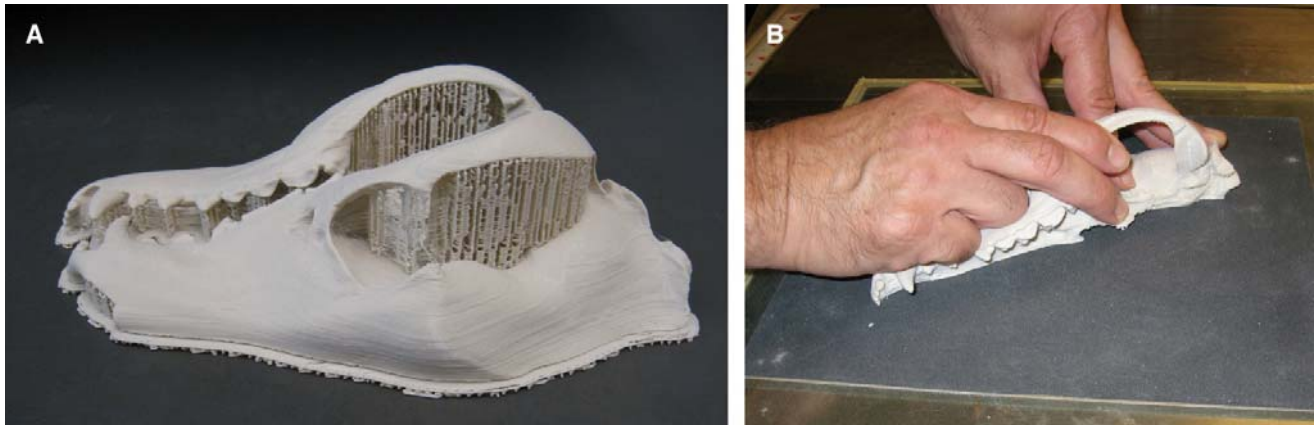

Figure 1 - Tasmanian Wolf (*Thylacinus cynocephalus*) cranium from the Idaho Virtualization Lab (https://sketchfab.com/models/67f1975ef2e940929b4eeef3de769f6e#). The skull took about 12 hours to print total. A) Freshly printed skull halves showing the extraneous supports that were printed along with the skull. B) Sanding half of the skull to aid in fitting it together with the other half.
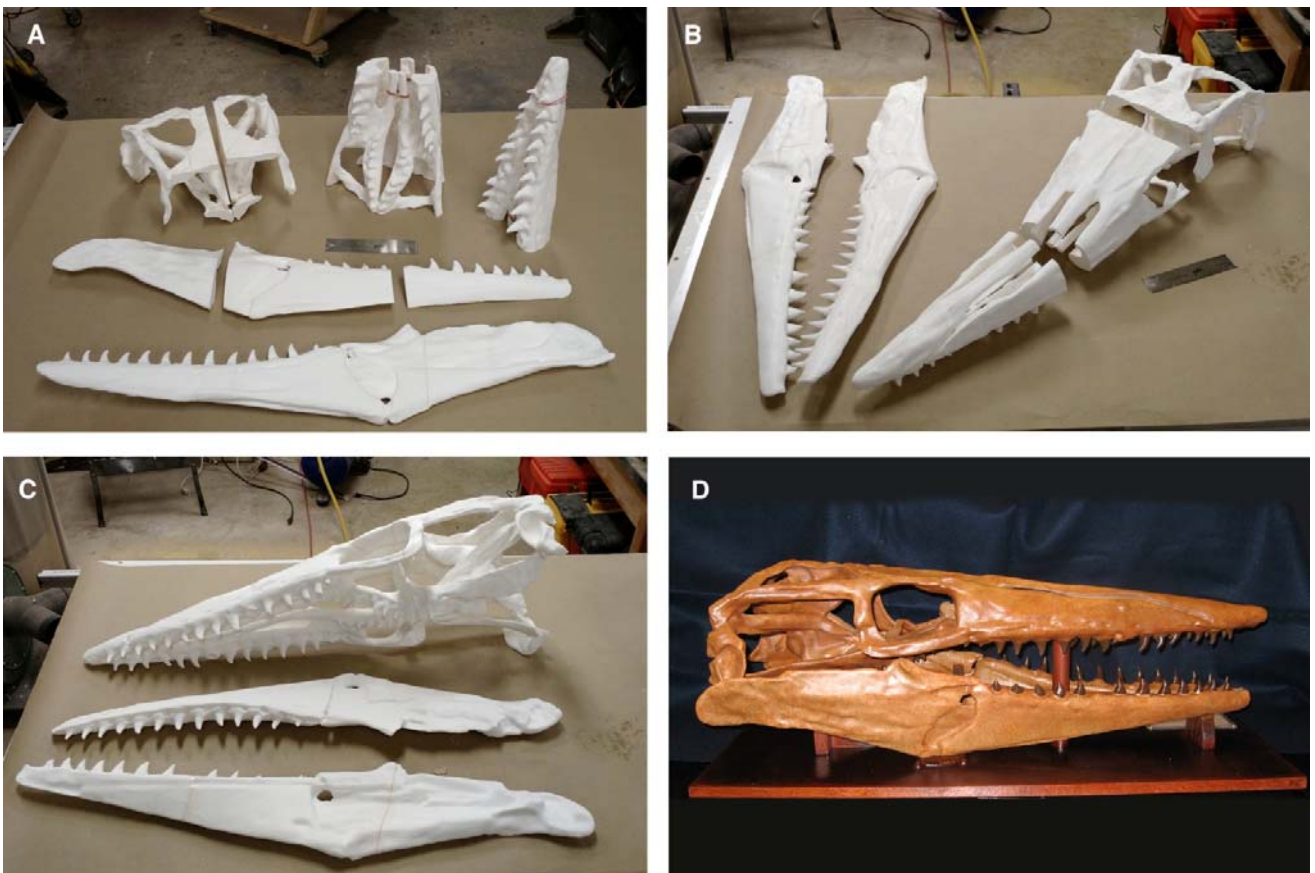

Figure 2 - Progression of assembly for a mosasaur skull and jaws (*Tylosaurus proriger* [https://sketchfab.com/models/5b8ef5d8a2ce4ee986b645bb672fcc20], no longer available for download). The model was constructed out of 12 parts, and each part took between 12-24 hours to print. A) The cleaned and sanded pieces, ready for gluing. B) First step of gluing together completed. C) Final gluing completed. D) Skull after covering with epoxy and painting.

recommend lightly sanding the entire model with a Dremel tool (with an abrasive wheel attachment) to help minimize the layered appearance.

Once you have the parts cleaned of support material, the assembly and finishing process can begin (Figure 2A). First, you should dry fit all parts for best fit and alignment. Get rid of any expectation of a perfect fit—commercial grade 3D printers will typically introduce some amount of minor warping or distortion. All flat surfaces that are to be mated should be sanded smooth to ensure closest contact (Figure 3A). A sheet of 150 and 320 grit emery (sanding) paper spray mounted to a glass plate makes an even sanding surface. This will accommodate most printed pieces. The flat side of the piece is rubbed in light circular or figure eight pattern against the abrasive surface, 150 grit first then 320 grit (Figure 1B).

When the surfaces are satisfactorily smooth and fit cleanly they may be glued together (Figures 2A-C, 3B). Start by drilling several holes in each surface being glued (Figure 3C). 1/16 to 1/8 in holes are preferred depending on the surface area. The holes need not match up from side to side as their function is to afford an additional anchor spot for the glue. Check that no burs from drilling the holes have altered the fit of the pieces. The glue of choice is 5 minuet epoxy, it is strong, permanent, and sets quickly. We prefer Devcon brand but any good quality brand should suffice. Mix the epoxy according to directions and apply evenly to one surface. Quickly mate to the other surface and rub them together to squeeze out as much excess epoxy as possible. This will also force the glue into the holes where it will form a "rivet like" connection (Figure 3C). Wipe away all excess epoxy from the joint, a cloth dampened with denatured alcohol may make this easier. Hold the pieces in position until the epoxy is set (approx. 10 minutes). Repeat this process until all the pieces are assembled to complete the skull and /or jaw (Figures 2B-C).

Now that the skull is assembled you will want to fill all joint lines and imperfections (Figure 3D). Several materials will work for this process. Selection of which is best to use is left to your budget and preference.

We recommend the following: PC-11 Marine white epoxy paste. This is nice for small imperfections and joint lines. It has a good working time, is reasonably inexpensive, and smooths easily with a finger dipped in alcohol.

Aves Studio's Apoxie sculpt and Apoxie paste. The sculpt material is a two part plastic clay that's great for major fills and additions. The paste is more fluid and can fill and smooth large rough areas. Both have a long work time and smooth easily with Aves safety solvent or alcohol. Devcon 5 minute epoxy Gel is nice for small quick imperfections and joining pieces that have a troublesome or gapped fit.

All of the above mentioned materials can be cleaned up with denatured alcohol or lacquer thinner and can be sanded when cured.

After addressing the imperfections and joint lines you will want to smooth the skull surface to at least partially hide the isomorphic lines left by the printing process. Smooth-On Inc. makes a product called XTC-3D that is specifically designed to do this job. It is a two-part epoxy with good self-leveling properties and a short work time. We have found it best to mix small batches of around 20 grams by weight or ¾ of a plastic shot glass full. Follow the directions and pour the mixture into a shallow tray from which to work. This will slow the cure process and maximize your work time. Clean your brush with lacquer thinner or acetone before the product sets and cures. Two or more coats may be needed or desired to eliminate the isomorphic lines. XTC-3D can be colored with SO Strong, another Smooth-On product. This can be useful to see where you have been and provide a base color. XTC-3D cures to a high gloss finish. Though we have not tried it, we believe any good quality epoxy finishing resin might work as well.

The final stage will be painting the skull model. We recommend several light coats of a flat white primer such as Krylon to provide a uniform base color. This also makes it easier to spot any drips or other imperfections you may have missed. When all corrections are made and you're happy with the surface apply whatever color treatment you prefer. We tend to use acrylic paints as they generally come in a wider range of colors from which to work. No matter what treatment you choose; if the skulls are going to be handled, you may want to protect them with several clear topcoats (Figure 2D).

DISCUSSION

We estimate that our department has spent about $500 for these models (now numbering over 40)—plastic filament for the printer, paint, epoxy, etc.—versus the over $10,000 it would
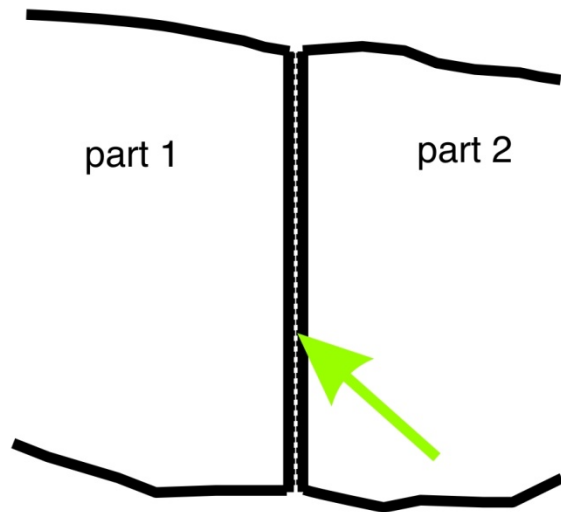
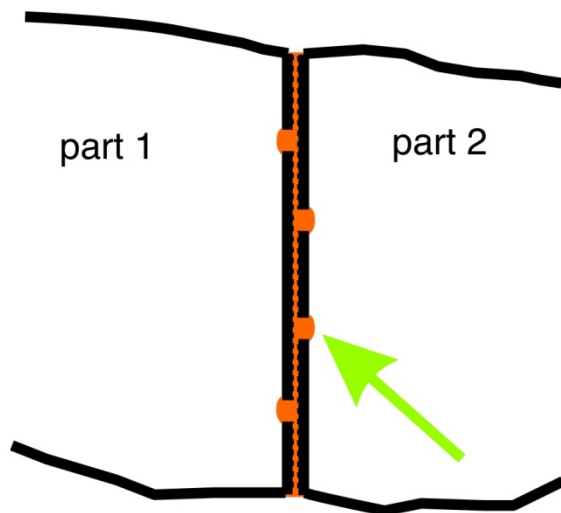# Cross section view of parts being joined

A

part 1   part 2
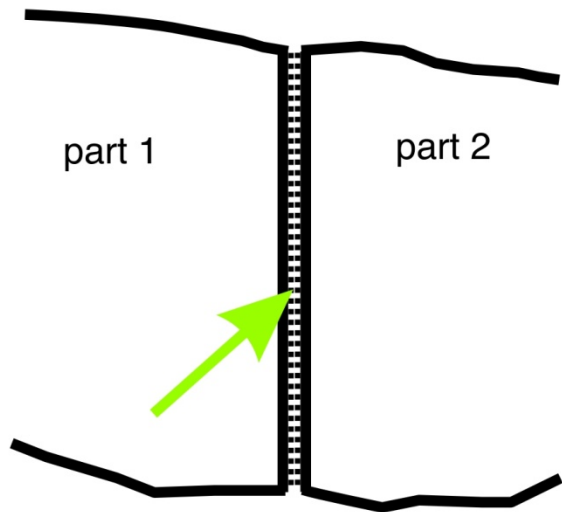
As printed, flat surfaces are rough
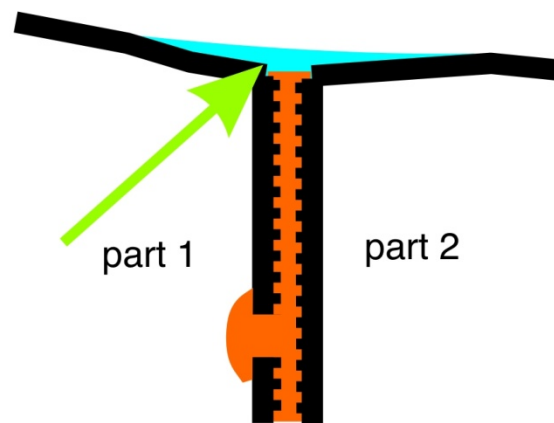and make poor contact with wider gaps.

B

part 1   part 2

After sanding, the gap is smaller
affording better fit and alignment.

C

part 1   part 2

In addition to the surface contact the
epoxy glue will ooze into the drilled holes
to better grip and bond the parts together.

D

part 1   part 2

Epoxy type paste is applied to the joint
seam and smoothed into the surrounding
contour effectively hiding the joint.

Figure 3 - A detailed schematic drawing showing how to glue together pieces of a multipart model shown as a progression of four steps, A-D. A) Step 1, showing the poor fit of the two parts prior to sanding. B) Step 2, sanding the surface of contact improves the fit of the two pieces. C) Step 3, by drilling holes into surface of contact, one can improve the grip of the epoxy glue. D) Step 4, by filling the external joint with epoxy type paste, one can make the joint essentially invisible.

have cost to purchase casts and replicas. This is almost certainly a poor estimate because many of the specimens we have printed are not commercially available, or not commercially available at the sizes we have printed them. Printing large models can take up to a week for a large, complex piece—multipiece print jobs will take even longer. The finishing of the models can take several days, including time for sanding, gluing (if necessary for multipiece models), applying epoxy, and painting. As an example, the Tasmanian wolf skull (Figure 1) cost less $10 in materials and could have been finished (print-to-paint) in a week. In contrast, the *Tylosaurus* model (Figure 2) was printed over the course of a month and cost about $100 in filament alone.

The discussion here has thus far been focused on vertebrate fossils and skeletal elements. One can just as easily print invertebrate fossils using the same methods above. A word of caution:

any specimen with delicate bones (many types of fish) or thin, spindly legs (arthropods) will be very difficult to make. They are difficult not because of printing but because removing the supports that print as a consequence of extrusion printing is difficult to do without also inadvertently breaking the fragile model.

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