

# VIRTUAL PALEONTOLOGY – AN OVERVIEW

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**ABSTRACT.**—Virtual paleontology is the study of fossils through three-dimensional digital visualizations; it represents a powerful and well-established set of tools for the analysis and dissemination of fossil-data. Techniques are divisible into tomographic (i.e. slice-based) and surface-based types. Tomography has a long pre-digital history, but the recent explosion of virtual paleontology has resulted primarily from developments in X-ray computed tomography (CT), and of surface-based technologies such as laser scanning. Destructive tomographic methods include forms of physical-optical tomography (e.g. serial grinding); these are powerful but problematic techniques. Focused Ion Beam (FIB) tomography is a modern alternative for microfossils, also destructive but capable of extremely high resolutions. Non-destructive tomographic methods include the many forms of CT; these are the most widely used data-capture techniques at present, but are not universally applicable. Where CT is inappropriate, other non-destructive technologies (neutron tomography, magnetic resonance imaging, optical tomography) may prove suitable. Surface-based methods provide portable and convenient data capture for surface topography and texture, and may be appropriate when internal morphology is not of interest; technologies include

laser scanning, photogrammetry, and mechanical digitization. Reconstruction methods that produce visualizations from raw data are many and various; selection of an appropriate workflow will depend on many factors, but is an important consideration that should be addressed prior to any study. The vast majority of three-dimensional fossils can now be studied using some form of virtual paleontology, and barriers to broader uptake are being eroded. Technical issues regarding data-sharing, however, remain problematic. Technological developments continue; those promising tomographic recovery of compositional data are of particular relevance to paleontology.

## INTRODUCTION

### **What is Virtual Paleontology, and why is it needed?**

The term ‘virtual paleontology’ is used here in the sense of Sutton et al. (2014) – the study of fossils through three-dimensional digital visualizations (‘virtual fossils’), such as that shown in Fig. 1. Two-dimensional techniques that might be considered to be virtual paleontology tools also exist (e.g. Hammer et al., 2002), but in line with common usage we do not consider them here. For the sake of simplicity, our concept of virtual paleontology also excludes the manual construction of idealized virtual models of fossil taxa (e.g. Haug et al., 2012, fig. 11). Virtual paleontology, in our sense, therefore requires three-dimensionally preserved fossils. Whilst the compression of fossils onto a genuinely two-dimensional plane does occur, it is the exception; in most preservational scenarios at least an element of the original three-dimensionality is retained. These techniques are thus applicable (to some degree) to most paleontological material. Three-dimensional preservation retains more morphological information than true two-dimensional modes, but typically this information is problematic to extract. Many physical or chemical isolation/preparation methods exist (see e.g. Sutton, 2008), but these are variously prone to specimen damage, loss of association between

disarticulated or weakly connected parts of fossils, issues with scaling to large or small specimen sizes, and inability to recover data from inside a fossil. Virtual paleontology can be thought of as a set of tools for more complete data-extraction from this sort of material.

The virtual paleontology approach, in addition to simple utility in data-extraction, also brings many novel advantages. Virtual specimens are typically more convenient to work with, requiring only a computer rather than expensive and lab-bound microscopes. They can be used for outreach and education (Rahman et al., 2012), and allow for virtual dissection and sectioning, where parts of the specimen can be isolated for clarity without risk of damage. They allow for mark-up, typically in the form of color applied to discrete anatomical elements, which can greatly increase the ease of interpretation. They can be used as the basis for quantitative studies of functional morphology, such as finite-element analysis of stress and strain (e.g. Rayfield, 2007), or hydrodynamic flow modeling (e.g. Rahman et al., 2015). Finally, as virtual specimens are simply computer files, they can be easily copied and disseminated, facilitating collaborative analysis and publication.

### **Tomography and surface-based virtual paleontology.**

A detailed taxonomy of virtual paleontology techniques is presented below, but the fundamental division of virtual paleontological data-capture techniques must be introduced at this stage. This is between (a) *tomography* and (b) *surface-based* techniques. Tomography is the study of three-dimensional structures through a series of two-dimensional parallel ‘slices’ through a specimen (Fig. 2). In tomography, an individual slice-image is termed a *tomogram*, and a complete set of tomograms a *tomographic dataset*. Any device capable of producing tomograms is a *tomograph*; tomographs range from serial-grinding devices to sophisticated X-ray-based scanners. Surface-based techniques are those where the geometry of an external

surface is digitized in some fashion (e.g. laser scanning, photogrammetry); these do not involve slices, and do not capture data from the interior of a fossil.

## **HISTORY OF VIRTUAL PALEONTOLOGY**

The history of virtual paleontology is relatively short when considered narrowly, but the use of its precursors and related methods is deep-rooted in the subject. The paleontological community has long appreciated the value of three-dimensional data and models, despite the difficulties in actually obtaining them using older methods, and the current explosion in virtual paleontology represents the satisfaction of a long-present hunger.

Virtual Paleontology, in the sense used here, originated in the early 1980s with X-ray computed tomography of vertebrate fossils. Tomography prior to digital visualization, however, has a long history. It was introduced to paleontology in the early 20th Century by the eccentric Oxford polymath William Sollas, who noted the utility of serial sectioning in biology and realized that serial grinding could provide similar datasets for paleontologists. His method (Sollas, 1903) utilized a custom-made serial-grinding tomograph capable of operating at 25  $\mu\text{m}$  intervals, photography of exposed surfaces, and manual tracing from glass photographic plates. Sollas applied his approach to a wide range of fossils; in the process he demonstrated the utility of tomography to a broad audience. He also described (Sollas, 1903) a physical-model visualization technique in which tomograms were traced onto thin layers of beeswax which were then cut out, stacked, and weakly heated to fuse them into a model. A similar though less aesthetically pleasing approach, using glued cardboard slices rather than fused wax, was also in early use and was probably also his invention. Sollas was primarily a vertebrate paleontologist, and it was in this field that his methods first became widely accepted, for instance in the seminal studies of Stensiö (1927) on the cranial anatomy of

Devonian fish. By the mid-20th Century, however, serial grinding had become a well-established technique, and was applied to many fossil vertebrates, invertebrates, and plants. Brachiopods provide an example of a group whose study was revolutionized by the technique; these invertebrates are often preserved three-dimensionally and articulated with valves firmly closed, concealing informative internal structures such as lophophore supports. Following the pioneering work of Muir-Wood (1934), the use of manually traced serial sections to document these structures has become almost ubiquitous.

A variety of serial-grinding tomographs have been used since Sollas's work (e.g. Croft, 1950; Ager, 1965; Sutton et al., 2001b), varying in terms of their complexity, degree of automation, maximum specimen size, and minimum grind-interval. Two variants on the technique that can mitigate its destructive nature have also been important. Firstly, acetate peels (see Galtier & Phillips, 1999) have been widely used as a means of data capture, especially but not exclusively in paleobotany. Peels, in some ways, are superior to photography of surfaces – they provide a permanent record of mineralogy and when stained can increase contrast between certain types of material. 'Peeling' is however ill-suited to modern visualization techniques (see below), and historical peel-datasets are thus often of limited utility. Secondly, serial sawing using fine saws (Kermack, 1970) became popular for larger (vertebrate) fossils in the late 20<sup>th</sup> Century; this approach retains original material, although at the cost of a reduction in inter-tomogram spacing.

All forms of tomography involving physical exposure of a surface and eventual optical imaging of that surface, whether with the intermediate of a peel and whether through photography or tracing, are grouped here as *physical-optical tomography* (sensu Sutton, 2008).

While tomography was commonplace in the 20th Century, physical model-making (in wax, cardboard or any other material) became increasingly rare. Workers on particular groups (e.g. brachiopods) became sufficiently familiar with tomograms to be able to mentally visualize the data, and the benefits of being able to directly communicate these visualizations were perhaps overlooked. Reconstructions from tomographic data, where published, typically took the form of idealized pictorial or diagrammatic representations from such mentally-assembled models (e.g. the cupule reconstructions of Long, 1960); while aesthetically pleasing, this form of reconstruction lacked objectivity. However, as physical models were undoubtedly difficult to assemble, fragile, difficult to transport, and hard to work with, effective direct visualization had to await digital technology; this was not achieved for physical-optical data until the start of the 21st Century.

Tomography in paleontology has seen an enormous rise in uptake in recent years – Fig. 3 provides a crude estimate of this, measured by the use of the term “tomography” in the paleontological literature; it shows a slow and steady rise, followed by a large upswing in the second half of the first decade of the 21<sup>st</sup> Century. This upswing primarily reflects the “CT revolution” (*sensu* Sutton et al., 2014); the increasing availability and popularity of X-ray CT. X-ray computed axial tomography (CT or CAT scanning) arose from medical radiography in the early 1970s. Early machines were limited in availability and resolution, so it was not until 1982 that CT was first applied to vertebrate fossils (Tate and Cann, 1982). The first high-profile paleontological application was to *Archaeopteryx* (Haubitz et al., 1988). The growth of medical CT was accompanied by the development of three-dimensional digital visualization tools, of which early paleontological studies took advantage. Subsequently, the technology has become increasingly commonplace for the study of vertebrate fossils, which are often suitably-scaled for medical scanners. Serious CT study of smaller fossils began with

the advent of widely available X-ray microtomography (XMT /  $\mu$ CT) scanners, which can resolve features down to a few microns in size. The paleontological pioneers of micro-scale CT used high-resolution spiral CT (see Rowe et al., 2001; [www.digimorph.org](http://www.digimorph.org)), but in the last 15 years XMT studies have proliferated, reflecting the increasing availability of relatively low-cost scanners. More recently, the advent of X-ray tomography beamlines at third-generation synchrotrons (see e.g. Donoghue et al., 2006; Tafforeau et al., 2006) has provided facilities for extremely high-resolution and high-fidelity CT study of fossils, including many intractable to lab-based XMT.

The CT revolution has hugely increased the uptake of tomography, but alongside it traditional physical-optical methods have enjoyed a limited renaissance, as for some material they remain the only practical means of data recovery. When married to modern digital photography, these methods can produce very high-fidelity data. Watters and Grotzinger (2001) provides an early example, applying these techniques to the Precambrian *Namacalathus*, but the most important example is the study of the invertebrate fossils of the Silurian Herefordshire Lagerstätte (see Briggs et al., 2008 for a summary), where an entire invertebrate fauna has been reconstructed via physical-optical tomography.

Pre-existing physical-optical datasets often consist of low-density (i.e. sparsely-spaced) tomograms. This drove early experimentation with vector surfacing (e.g. Chapman, 1989; Herbert, 1999) in which traced structures were connected and surfaced to produce relatively crude reconstructions; other idiosyncratic approaches to visualization were also trialled (e.g. Hammer, 1999). It was, however, the application of the ‘mainstream’ medical technique of isosurface-based rendering (see below) to high-density Herefordshire data by Sutton et al. (2001a, b) that first produced genuinely high-fidelity virtual models from physical-optical

data. This approach to visualization has been dominant since that study, although volume rendering (e.g. Hagadorn et al., 2006) and vector surfacing (e.g. Kamenz et al., 2008) have found occasional applications.

Other ‘niche’ approaches to paleontological tomography explored in recent years include magnetic resonance imaging (MRI), neutron tomography, optical tomography, and focussed ion beam (FIB) tomography. MRI is a routine medical scanning technology, but often performs poorly on solid materials. Applications have hence been rare (Mietchen et al., 2008, Clark et al., 2004). Neutron tomography utilizes neutron beams to perform tomography in a manner analogous to CT. Some studies have demonstrated limited utility, particularly in fossils preserving organic compounds or where the relatively weak absorption of neutrons by metal-rich rocks allows large and dense specimens to be imaged where X-rays fail (Schwarz et al., 2005; Winkler, 2006, Laaß & Schillinger, 2015). A relatively low resolution and limited availability have, however, militated against a broad uptake. Optical tomography (serial focusing – typically using confocal microscopy) is a very high-resolution non-destructive technique for data-capture from small translucent specimens. Confocal microscopy was first applied to fossils in the 1990s (e.g. Scott and Hemsley, 1991), but applications of optical tomography to fossils since have been sporadic (e.g. Ascaso et al., 2003; Kamenz et al., 2008). Finally, focussed ion beam (FIB) microscopes (see e.g. Phaneuf, 1999) can use their beam to mill material at regular intervals, and can hence (laboriously) perform nano-scale tomography on fossils (e.g. Schiffbauer and Xiao, 2009; Wacey et al., 2012); this approach has seen rare but persistent application in recent years.

Surface-based techniques do not use tomography, but digitize the topography of the surface of a specimen, typically also capturing surface color. They provide a powerful approach



201 where the surface morphology represents the primary information of interest. Their history of  
202 usage is short. Mechanical digitization uses a ‘robotic’ arm equipped with sensors to record  
203 the position of a tip in 3-D space, and can hence collect surface points over an object. This  
204 approach was sporadically applied to vertebrate fossils in paleontology in the early 21st  
205 Century (Wilhite, 2003; Mallison et al., 2009), but has been superseded by non-contact  
206 approaches, i.e. laser scanning and photogrammetry. Laser scanning is a general term for a  
207 set of techniques where the reflection of a scanned laser-beam from a surface is used to  
208 record surface topography. The first portable scanners capable of rapid and precise scanning  
209 became available in the late 1990s, and have continued to improve since. Paleontological  
210 applications commenced with a study of part of a dinosaur skull (Lyons et al., 2000), and  
211 subsequently a flurry of work has used the approach on a broad range of fossils including  
212 vertebrates (Bates et al., 2009a), footprints (Bates et al., 2008, 2009b), and Ediacaran  
213 problematica (see e.g. Antcliff and Brasier, 2011). The technique is also in curatorial use for  
214 major museum-based digitization initiatives (e.g. GB3D, [www.3d-fossils.ac.uk](http://www.3d-fossils.ac.uk); the  
215 Smithsonian X 3D project, [www.3d.si.edu](http://www.3d.si.edu)). Photogrammetry is an alternative approach  
216 which assembles three-dimensional models from a set of two-dimensional photographs of an  
217 object. Analogue photogrammetry has a history, in cartography in particular (see e.g. Kraus,  
218 2007), and the widespread use of stereo-pairs to provide a form of three-dimensional model  
219 can also be seen as a forerunner of true photogrammetry-based virtual paleontology. Digital  
220 photogrammetry, which reconstructs models direct from digitally captured images, is now  
221 widely used in (for example) forensics and archaeology; and it has been shown to be at least  
222 as effective as laser scanning for some fossil materials (Falkingham, 2012). Paleontological  
223 applications began with reconstruction of dinosaur tracks (e.g. Breithaupt and Matthews,  
224 2001); while publications using it are still relatively scarce, it can be expected to become  
225 increasingly important in the near future.

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## DATA CAPTURE METHODS

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### **Destructive Tomography**

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There are a great many approaches to 3-D data-capture available to paleontologists, and the vast majority of fossils will be amenable to at least one of these methods. Figure 4 provides a classification scheme for these (following Sutton et al., 2014). The most fundamental division is between surface-based and tomographic techniques (see above). Tomographic techniques are divided into destructive and non-destructive approaches, the former including traditional approaches such as serial grinding, and the latter encompassing scanning technologies such as CT. Surface techniques are divided into contact and non-contact categories. See Fig. 4 for further subdivisions.

This includes all forms of tomography which at least partially destroy the specimen in the production of the tomographic dataset. Tomograms are produced by physical exposure of a surface, which is then imaged in some way. The destructive nature of these methods is obviously undesirable; it can be seen as the conversion of a specimen from physical into digital form (rather than simple destruction), but this conversion process is never perfect. Data will be lost between tomograms, and no imaging technique can capture all information contained in an exposed surface; errors and mishaps are also unavoidable even where great care is taken. Destructive tomography always precludes the application of some future and potentially better data-extraction technique, and should thus be viewed as a last resort. Most destructive techniques are also time-consuming and labor-intensive; while equipment costs can be low, labor requirements can result in great expense. Additionally, destructively-gathered tomographic datasets typically require registration (alignment) of images prior to visualization (see below), which can also be time-consuming.

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252 Despite these caveats, destructive techniques remain the best option for some fossils that are  
253 not easily amenable to non-destructive tomographic techniques. The fossils of the  
254 Herefordshire Lagerstätte (Briggs et al., 2008) provide just such an example; these show  
255 insufficient X-ray attenuation contrast for CT study, are too opaque for optical tomography,  
256 and are too small-scale for other techniques. Image capture of surfaces also facilitates data-  
257 rich imaging modes; color photography can capture subtleties of composition not evident in  
258 X-ray CT, and FIB techniques (see below) are capable of compositional, chemical, and  
259 crystallographic mapping of surfaces. Finally, some historical specimens have already been  
260 subjected to destructive physical-optical tomography; reconstruction using the existing data is  
261 here the only choice.

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263 *Physical-optical tomography.*—

264 This term was introduced by Sutton (2008) to encompass a range of well-established  
265 destructive tomographic techniques; it is roughly equivalent to ‘serial sectioning’. It  
266 encompasses three approaches to serial exposure of tomographic surfaces.

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268 Serial grinding (or lapping) is the most widely used approach. Specimens are positioned  
269 against an abrasive surface, motion is employed to physically grind away a small thickness of  
270 material (typically 10 µm–1 mm). Details of methodology are many and various – see Sutton  
271 et al. (2001b, 2014) for one example. Equipment requirements can be as simple as a glass  
272 plate with abrasive powder, although more constrained grinding (and hence better  
273 reconstructions) require grinding-tomographs capable of removal of known thicknesses, and  
274 which guarantee that tomographic planes are parallel. Typically, these involve mounting  
275 specimens in an apparatus attached to a grinding wheel (see e.g. Croft, 1950; Ager, 1965),

and modern implementations typically make use of lapping machines intended for thin-section production (e.g. Sutton et al., 2014). Grinding-based tomography is maximally destructive and can be slow, especially for larger specimens, but can provide very closely spaced tomograms, and hence high-resolution reconstructions; structures as small as 10  $\mu\text{m}$  are accessible. The grinding process also doubles as a polishing process, resulting in surfaces well suited for high-fidelity imaging.

Serial sawing exposes surfaces by cutting, preserving material in-between as wafers. Saws capable of fine cuts are preferable as they minimize the loss of material. Cheap fine-blade low-speed saws with a kerf under 0.4 mm are widely available and allow specimens to be clamped and precisely positioned; however, these can have high cut-times and are limited to specimens a few centimeters in size. Faster fine-blade saws (see e.g. Maisey, 1975) are expensive and also have size-restrictions. Wire saws (also expensive) have low kerfs and can cut large specimens, but single cuts can take hours. Reconstructions from serial-sawing data are complicated by the exposure of two (mirrored) surfaces by each cut, and the resulting inconsistent (alternating) inter-tomogram spacing. Sawing is fundamentally a lower-resolution technique than grinding methods, and does not produce surfaces that are as well polished. For these reasons, while occasionally used by vertebrate paleontologists, it has never been widely adopted. For large specimens not amenable to non-destructive tomography however, it may represent the only option.

Serial slicing involves serially removing and retaining fine slices of material with a microtome. The technique is widely used in biology and is capable of very high resolution, but is difficult with geological materials. Poplin and Ricqles (1970) described a variant applicable to fossils, but this is complex and laborious, and has only rarely been employed

(see e.g Kielan-Jaworowska et al., 1986). Modern high-precision ultramicrotomy can be carried out within a scanning electron microscope using dedicated equipment (see, e.g. Reingruber et al., 2011, Ma et al., 2016); this high-resolution technique might be appropriate for resin-mounted macerated fossils, but has yet to be trialled in paleontological research. All microtomy techniques, however, produce tomograms prone to image-distortions; these can degrade visualizations.

In physical-optical tomography, tomogram images are generated by photography or manual tracing. Direct digital photography of exposed surfaces is the preferred approach, using photographic techniques applicable to the specimen type and scale. See Sutton et al. (2014) for a full discussion. Cellulose acetate peels (or just ‘peels’) have been widely used as a means of producing a permanent record of fossil surfaces, for both physical-optical tomography and other purposes (see e.g. Galtier and Phillips, 1999). Serially-prepared peels can be scanned, photographed, or traced, and theoretically used for 3-D visualization.

However, even the best-prepared peels are prone to wrinkles, bubbles, tears stretches, and inconsistency of contrast, which render them very difficult to use for this purpose.

Interpretative tracings of structures, either direct from the surface or from photographs, can be used as an alternative input into visualization. These provide an effective means of cleaning difficult data, but may introduce ‘worker bias’, as well as complicating workflows. While historically important, this approach is now rarely used.

There are many pitfalls to be avoided when generating a physical-optical dataset for reconstruction. Importantly, reconstruction requires that all information within a tomographic image comes from a single plane; care must be taken that photography of translucent specimens or specimens with topography does not violate this requirement. Equally important

is the emplacement of fiduciary markings (e.g. vertical drilled holes) that can be used to guide registration (see below). See Sutton et al. (2014) for full discussion.

#### *Focused Ion Beam tomography (FIB).*—

FIB is a lab-based tool for the imaging, milling, and deposition of material at the sub-micrometer scale, widely used in materials science and the semiconductor industry (Phaneuf, 1999; Volkert and Minor, 2007). FIB machines can be used to sequentially mill and image specimens, and thus act as destructive tomographs for the study of structures as small as 5 nm (Uchic et al., 2007). Recent studies (Schiffbauer and Xiao, 2009, 2011; Wacey et al., 2012; Brasier et al., 2015) have demonstrated the paleontological utility of the technique, which can also theoretically provide data on the chemical/crystallographic structure of each tomogram if EDS (Energy-Dispersive X-ray Spectroscopy), EBSD (Electron Backscatter Diffraction) or SIMS (Secondary Ion Mass Spectrometry) detection is carried out. FIB is fully destructive and extremely time-consuming, with milling times per tomogram of up to an hour. Despite this, however, its extremely high resolution and potential to record compositional data render it a powerful tool.

#### **Non-destructive tomography**

A number of technologies exist which can create tomographic datasets, through interactions between electromagnetic radiation or subatomic particles and matter, without damaging the sample. This is desirable as it allows the sample to be subjected to future analyses, although note that there are rare situations in which non-destructive tomography can impact on future studies (Sutton et al., 2014), and that, for very high resolution work, sample preparation may be partially destructive. Non-destructive tomography is typically quick: most technologies acquire data in minutes to hours, and datasets are pre-registered (see below). There *are* fossils

which are not amenable to non-destructive approaches, but for many specimens they are effective tools; even where only partially effective, they represent a valuable initial approach. Numerous forms exist: X-ray computed tomography is the most widespread – in particular the high resolution form X-ray microtomography (XMT /  $\mu$ CT) – and is hence treated here in the greatest detail. Other approaches (including MRI, neutron tomography, confocal laser scanning microscopy, and optical tomography) have found more limited, but nevertheless important applications.

#### *Principles of CT.—*

All CT scans share the same principles: A large number of X-radiographs (=projections) of an object, collected at different angles, are used to compute a tomographic dataset (Abel et al., 2012). Approaches differ in detail between different forms of CT. In microtomography, where voxels (3D pixels) typically range between  $\sim 1\ \mu\text{m}$  and  $\sim 100\ \mu\text{m}$  in size, a sample is placed on a rotating manipulator between an X-ray source and a 2-D flat-panel detector (Fig. 6). In contrast, medical, many industrial, and some high-resolution scanners rotate an X-ray source and detector around the object being scanned (Ketcham and Carlson, 2001).

Laboratory X-ray sources accelerate electrons (produced by heating a tungsten filament) into a target metal, where their deceleration creates a multi-wavelength ('polychromatic') X-ray beam, typically cone-shaped (Fig. 6A). Many samples are better imaged using a single wavelength ('monochromatic') beam of parallel X-rays, such as that created by a synchrotron (a form of particle accelerator; see Donoghue et al., 2006). Numerous algorithms for computing tomograms from projections exist; 'filtered back projection' is the most commonly encountered. The majority of tomographic datasets reconstructed in this manner are 3-D maps of X-ray attenuation within an object. X-ray attenuation is linked to the atomic

number and mass density variations within a sample, and thus can, in many samples, differentiate fossil from host sediment. A range of artifacts exist; see Sutton et al. (2014) for full discussion and mitigation strategies.

#### *Medical CT.—*

The source and detector in a medical CT scanner are placed on a rotating ‘gantry’; detectors in modern systems allow multiple slices to be collected simultaneously, and are hence rapid. The sample is placed on a mount/table, which is translated horizontally within the rotating gantry; these scanners are termed ‘spiral/helical’, reflecting the relative path of detector and specimen. Spatial resolution will typically be in the region of millimeters (although better resolution is attainable on specialized spiral scanners), but decimeter-scale fossils can be scanned provided the X-ray source is strong enough to penetrate the sample.

#### *Micro- and nanotomography.—*

Lab-based microtomography scanners (and nanotomography scanners, which can achieve higher resolution, e.g. through the use of optics) are typically designed for versatility, so have a large number of scanning options. Because the specimen is rotated within a cone beam (Fig. 6A) and a flat-panel detector is used to collect projections (Fig. 6B), geometric magnification can be used – the closer a sample is to the source, the larger its radiograph appears on the detector panel. The current and voltage used to accelerate electrons, and hence the energy of the source’s X-rays, can also be modified. Attenuation of lower energies is more closely related to atomic number, providing greater contrast between materials. These X-rays can struggle to penetrate dense geological samples, and can thus produce ‘beam hardening’ artifacts in which the centre of a scanned object appears artificially darkened; these artifacts complicate visualization. Polychromatic lab-based sources always emit some lower energy



X-rays that can cause beam hardening, but this problem can be addressed with filters – thin pieces of metal placed between the source and the sample to absorb lower energy X-rays. Lab-based CT scanning hence involves modifying the source voltage/current, and beam filtration, balancing the need for strong attenuation contrast with the need to avoid beam hardening. For a full overview of these considerations see Sutton et al. (2014). The process of scanning is otherwise relatively simple, requiring that the sample is stably positioned at the centre of rotation of the stage (mounting in florists' foam is a common approach), and that the exposure for each projection allows enough X-rays to penetrate the sample without saturating the detector panel outside the specimen. All scanners collect 'calibration images' to reduce artifacts from variations in detector sensitivity, and some possess additional optics to increase resolution. The technique can theoretically provide resolutions from tens of microns down to 50 nm with additional optics. Without optics, resolution is limited by the 'spot size' size of the X-ray source, but resolution is also linked to the size of the object scanned: the sample should remain within the field of view throughout a 360° rotation. Thus for a 2000 x 2000 pixel detector, resolution will be 1/2000th the greatest dimension of the sample.

#### *Synchrotron CT.—*

A synchrotron is a particle accelerator capable of producing a very high photon flux; synchrotrons have been widely used as intense X-ray sources in recent years. Scans are conducted on beamlines, and all beamlines differ in their precise characteristics. Very high resolution scanning is often referred to as synchrotron radiation X-ray tomographic microscopy (SRXTM; Donoghue et al., 2006). The key difference between tomography in a synchrotron and lab setting is that synchrotrons produce an intense, monochromatic, and parallel beam (Fig. 6C). This allows powerful optics to be used which can create very high

resolution datasets, although these lack geometric magnification (voxel size is constant irrespective of the sample to detector distance). In addition to attenuation, synchrotrons can create tomograms based on the phase shift of the X-ray beam, which relies on refraction within a sample. In samples with low attenuation contrast, such approaches can provide usable data. Resolutions vary between beamlines: minimum feature sizes in the order of tens of nanometers can be achieved, albeit with a concomitantly small field of view, whilst some beamlines can scan specimens several centimeters in size.

*Alternative forms of non-destructive tomography.—*

For specimens preserved in translucent rocks such as cherts, optical serial-focusing can recover usable tomographic data. This involves shining visible, UV, or IR light through a sample, and then recording tomograms using digital microscopy at different focal depths, to recover an image stack. Optical tomography can be achieved with conventional light microscopy (Kamenz et al., 2008), but here the inclusion of details outside the focal plane can complicate analysis. Hence, a commonly employed variant uses confocal laser scanning microscopy, an approach which concurrently images single focal planes, with out-of-focus light eliminated through the addition of a pinhole in the light path. This works best when samples autofluoresce, and has been applied to many chert-hosted fossils (Schopf and Kudryavtsev, 2009, Shi et al., 2013, Hickman-Lewis et al., in press).

Magnetic resonance imaging (MRI) has also found limited applications in paleontology (e.g. Clark et al., 2004): this uses strong magnetic fields to map the nuclei of some elements (often hydrogen) within a sample, and is capable of achieving resolutions in the region of 100  $\mu\text{m}$ . Whilst well-suited to biological samples, it is of limited utility in paleontology, and generally works well only when mapping water within crystalline phases (Mietchen et al., 2008).

Neutron tomography is similar in principle to X-ray-based tomography, but differs in that the incident radiation comprises neutrons, which attenuate based on interactions with the nuclei of a material (Winkler 2006). Attenuation from light atoms such as hydrogen is stronger than those with higher atomic numbers. This, coupled with higher penetration capabilities, makes neutron tomography a useful alternative for very large and/or dense samples (e.g. Schwarz et al., 2005), at a resolution of tens of micrometers. There has, however, been limited uptake in paleontology to date.

### **Surface-based techniques**

Surface-based methods non-destructively capture the topography of an object in three dimensions; some also capture color data from that surface. Surface techniques tend to be inexpensive, accessible, non-destructive, and rapid; this combination renders them powerful weapons in the virtual paleontologist's armory. The collected datasets do not include details of the sample's interior, but the extent to which this is problematic will depend entirely on research goals. For many specimens already isolated from their matrix, surface capture may well be sufficient – vertebrate bones are an excellent example, and most applications of surface-based techniques have been in vertebrate paleontology.

#### *Laser scanning.—*

Laser scanning is the most common surface-based technique employed today, both in paleontology and other fields. It uses a reflected laser beam to characterize the exterior 3-D shape and appearance of an object at distance. Laser scanning does not normally require sample preparation. Scanners range from hand-held devices for imaging small samples at sub-millimeter resolutions, to long-range systems capable of scanning larger field sites. Sutton et al. (2014) provide a detailed summary. If multiple scans are carried out for a single

specimen (e.g. to capture all surfaces of the object), the resulting point-clouds will need to be registered using computer software to obtain a complete 3-D reconstruction (see below). As an aid, reference objects such as spheres may need to be incorporated into the scanned scenes.

Triangulation-based scanners possess an angled sensor offset from the laser source, and use position of reflection-impact on this sensor to determine target range through triangulation. Full object coverage is achieved by automatic scanning of the beam across the surface, and/or movement of the object, for example by rotation on a stage. A variety of instruments exist, capable of resolutions approaching 50  $\mu\text{m}$  and/or ranges of up to a few meters. Triangulation scanners often perform poorly in bright sunlight, but are suitable for laboratory use; they have been used to study many centimeter-scale fossils including Ediacaran organisms (e.g. Antcliffe and Brasier, 2011), insects (e.g. Béthoux et al., 2004), trace fossils (e.g. Platt et al., 2010), and vertebrates (e.g. Zhang et al., 2000).

Time-of-flight scanners use pulsed lasers and precise timing of received reflections to calculate distance-to-target from the traversal-time of light. The beam is scanned over a surface (typically using a system of rotating mirrors); data-point capture rates are typically tens of thousands per second. Scanners are ‘luggable’ and often tripod-mounted; they can operate at ranges of 1 km or more, and image at resolutions down to a few millimeters. They are tolerant of outdoor conditions, and are ideal for field applications such as dinosaur trackway studies (e.g. Bates et al., 2008), as well as reconstruction of large vertebrate skeletons (e.g. Bates et al., 2009a).

Phase-shift scanners are similar to time-of-flight scanners, but measure distance by modulating beam power and comparing the phase of the reflection. Their capabilities are similar to those of time-of-flight scanners, although their range is an order of magnitude lower and their capture-rate an order of magnitude higher. Paleontological applications have been limited to a few field studies of assemblages (e.g. Haring et al., 2009).

#### *Photogrammetry.—*

Photogrammetry determines surface topography from multiple two-dimensional photographs acquired from different viewpoints. It is widely used in cartography, medicine, forensics, and archaeology. It requires only basic and highly portable equipment: a digital camera for data capture, and a computer with appropriate software for reconstruction. High-quality reconstructions require consistent lighting conditions and a large number of images (typically over 100), but the quality of the camera is not critical. Reconstruction of a point-cloud from images is now generally automated, and can be achieved with open-source software. Recent studies have shown that photogrammetry is capable of producing reconstructions of paleontological material with similar or better resolutions (i.e. denser point clouds) than many laser scanners (Remondino et al., 2010; Falkingham, 2012). The method is scale-less, and so is theoretically applicable to surfaces of any size; very small specimens are amenable to SEM photogrammetry (e.g. Kearsley et al., 2007), although no paleontological work has yet been published using this variant. Applications to date have primarily documented dinosaur skeletons (e.g. Stoinski, 2011) and track-sites (e.g. Bates et al., 2009b), but the technique has great potential for broader uptake.

#### *Mechanical digitization.—*

Mechanical or contact digitization uses a mechanical arm with rotational/positional sensors at each joint, and a digitizing tip. The tip is moved manually over the surface of a specimen, and its position in three dimensions is recorded by the sensors. The technique has been used for the collection of landmark data for morphometric studies (e.g. Green and Alemseged, 2012), but also as a data-capture methodology for virtual paleontology; Mallison et al. (2009) provide full documentation and a workflow. Digitization accuracy under ideal conditions can reach 50  $\mu\text{m}$  (manufacturer's data, [www.3d-microscribe.com](http://www.3d-microscribe.com)), and Mallison et al. (2009) reported accuracy was close to 1 mm for a 200 mm specimen. The method is relatively cheap, and data-capture time is normally low. Resultant datasets and reconstructions are also small, facilitating their dissemination, storage, and visualization. However accuracy is lower than that of laser scanning and photogrammetry, and surface color is not captured. Additionally, there is a small risk of damage to specimens from contact with the digitizing tip and the need to emplace markings (see Mallison et al., 2009). The method is best suited to large and robust specimens with relatively simple morphology; for these reasons, paleontological applications to date have focused on isolated vertebrate bones.

#### **Summary of data-capture methods**

The methods detailed above differ in many ways, and selection of the most appropriate can be daunting. Figure 5 provides a summary of scales of operation and other key aspects of methods, and is provided as an aid to selection; a more complete guide is provided by Sutton et al. (2014). Method selection will in practice need to take into account factors such as the properties of the specimen to be studied (e.g. X-ray contrast, scale, translucency), availability of and familiarity with equipment, degree of concern over specimen-damage, and financial restrictions.

## RECONSTRUCTION AND VISUALIZATION METHODS

Raw captured data can sometimes be visualized directly and with minimum user-intervention by software bundled with the capture-device. This will, however, rarely provide an optimal model, and in many cases no such facility will be available. An understanding of the methods and workflows required for visualization is hence important. Figure 7 summarizes the stages through which data may pass from capture to an output model suitable for study. A typical methodology will generate a triangle-mesh model, as these provide maximal flexibility in terms of model-production and data-interchange. However there are many possible routes and workflows, and selection should be based on the type of input data, preparation requirements, software availability, and the use to which the final model will be put. Software will, in all cases, be required; detailed discussion of available packages is beyond the scope of this review, except to note that both commercial and free packages exist. SPIERS (Sutton et al., 2012) is an example of a free software-suite for tomographic reconstruction and visualization.

### **Reconstruction of tomographic data**

#### *Registration.—*

A registered tomographic dataset is one where the tomograms are correctly aligned (registered) with respect to one another, such that objects do not ‘jump around’ when the tomogram sequence is viewed in order. Reconstruction of un-registered datasets is not possible, and imperfect registration degrades models. Some data-capture techniques naturally provide registered data; these include optical tomography, CT, neutron tomography, and MRI (CT and neutron tomography require conversion of data from raw attenuation images to registered computed tomograms, but this is normally performed just after acquisition by the scanner software). Physical-optical and FIB datasets are typically un-registered.

Registration of datasets is a discrete reconstruction step that precedes all others. It comprises the digital translation, rotation, and sometimes rescaling of tomograms, to ensure that correct alignment is achieved. Registration is greatly facilitated by the presence of ‘fiduciary markings’ such as drilled holes or edges (see Sutton et al., 2014) in the tomograms; these allow the correct position of a tomogram to be deduced by ensuring that the markings are in the same position in each image. In their absence, the morphology of the specimen itself is the only guide to registration, and this is fraught with difficulties. Registration requires dedicated software, and can be manual, automatic, or semi-automatic (automatic followed by manual fine-tuning). Our experience is that automatic registration can only be relied upon for unusually ‘clean’ datasets; in most cases, manual or semi-automatic registration will be necessary, and this can be time-consuming.

#### *Isosurfacing.*—

The most commonly used reconstruction workflows treat a tomographic dataset as a ‘volume’, and involve the calculation of an ‘isosurface’ to represent the specimen. A volume is the 3-D equivalent of a pixel-based (raster) image, comprising a three-dimensional grid of equally sized 3-D volume elements (voxels) instead of a two-dimensional grid of pixels. Voxels, like pixels, each represent a single measurement of color, attenuation, or simply brightness. A registered tomographic dataset with regular tomogram spacing does not need ‘conversion’ into a volume; it is a conceptual shift. An isosurface is a three-dimensional surface connecting all points of a constant intensity within the volume. With a correctly determined ‘threshold’ level (i.e. color/brightness-based cut-off), the isosurface will follow the boundary of the specimen under study; the provision of visual-feedback tools to aid in this determination is a key function of reconstruction software. Isosurfaces are usually generated using the marching cubes algorithm (Lorensen and Cline, 1987), which produces a



triangle-mesh dataset (see below) defining the isosurface or isosurfaces – there is no requirement for all points to connect into a single surface. The marching cubes algorithm is robust and well understood, but for high-resolution datasets it can produce surfaces with a prohibitively high triangle-count, potentially hundreds of millions or more. Mesh-simplification algorithms can help mitigate this issue (see Sutton et al., 2014), but are not a panacea; simplification or noise-reduction prior to isosurface reconstruction is often necessary, either through virtual preparation (see below), or by reducing tomogram resolution.

#### *Vector surfacing.*—

Vector surfacing (*sensu* Sutton et al., 2014) involves the manual or semi-automatic tracing of structures of interest in each tomogram, normally in the form of closed loops defined as spline curves. Stacked two-dimensional splines from multiple tomograms are used to generate a mathematically defined three-dimensional surface, typically in the form of a triangle mesh. This historically important approach produces low triangle-count models, and can produce ‘smoother’ outputs than isosurface-based approaches where inter-tomogram spacing is high and/or inconsistent. It is also not sensitive to variations (e.g. in lighting or quality) between tomograms; requiring only that a tracing can be made. In general, it performs well for simple objects such as individual vertebrate bones, but not for complex objects that merge and split between tomograms. Vector surfacing remains viable, but has become an uncommon approach in recent years (though see e.g. Maloof et al., 2010), as appropriate software is rare and the method is time-consuming, requiring an extra interpretation stage. For datasets with a high tomogram frequency (e.g. from scanners), it has no particular advantages beyond reduction of triangle-count.

*Virtual preparation.—*

Volume data can be reconstructed ‘raw’, but in most cases isosurface-based reconstructions are greatly improved by preparation work, the virtual equivalent of the manual preparation work traditionally employed to physically expose specimens. Preparation involves either modifying voxel-values by brightening or darkening them (see e.g. Sutton et al., 2001), applying masks/labels to split the final model into discrete parts or regions-of-interest (see e.g. Abel et al., 2012; Sutton et al., 2012), or refining visualization rules in an attempt to improve discrimination. Depending on the capabilities of the software used, volume preparation can be carried out either in two dimensions, on a tomogram-by-tomogram basis, or in three dimensions; the latter approach is generally faster, but the former more precise. Virtual preparation is a time-consuming and skilled task, but can greatly increase the fidelity and scientific value of any resulting visualization. Note that preparation, particularly in terms of the application of masks/labels, is also applicable to direct volume rendering (see below).

**Reconstruction of surface-based data.**

Laser scanning and photogrammetry (see above) typically generate data in the form of ‘point clouds’, a series of points in three-dimensional space for which a position (and often a color) is recorded. Mechanical digitization may either generate point clouds or spline curves suitable for vector-surfacing (see above).

Point-cloud data for an object often comprises several point-cloud datasets, resulting from the need to scan objects from different angles, or to use multiple scan-stations to ensure full coverage. The process of fusing these datasets into one is normally termed registration (not to be confused with tomographic registration, see above). Registration is achieved via identification of correspondences between separate datasets, enabling their relative positions

to be determined; it is normally carried out automatically or semi-automatically by software associated with the acquisition device.

Point clouds can be directly visualized (see below), or can be surfaced through triangulation algorithms to produce a triangle mesh. The latter approach allows conversion of the model into a similar format to that produced by other virtual paleontological workflows and increases the range of visualization options. It is, however, not computationally straightforward; while effective algorithms exist (see e.g. Salman et al., 2010), they are still the subject of active research, and not always integrated into reconstruction software.

## **Visualization**

Visualization is the final stage of reconstruction, where data is converted into a model that can be studied directly, either through on-screen manipulation and viewing, or as a physical model. Triangle-mesh data, the most common form, is treated in the most detail.

### *Visualization of triangles meshes.—*

Modern graphics-hardware is heavily optimized for visualizing triangle-mesh objects, and hence even modest computers are capable of very fast rendering of datasets of this type. This fit of hardware to data provides a compelling reason to convert data to this format where possible; while hardware-accelerated rendering can produce static images, its real power lies in interactive visualization systems where fast rendering speeds allow the user to manipulate a virtual model, rotating, zooming, and altering visibility of discrete elements at will. Powerful workstation-class computers allow even very large datasets to be studied in this way, but the degree to which interactive viewing is practical depends on the efficiency of the software as well as the speed of the hardware.

Triangle-mesh datasets are often processed (‘filtered’) prior to visualization. Filters may for instance be used to decrease triangle count, to smooth out blockiness, or to remove disconnected ‘islands’. Such filters modify data, so should be used with care – see Sutton et al. (2014) for more detail.

Triangle-mesh models can also be visualized using slower but more photorealistic techniques such as ray-tracing; this approach is recommended for the production of high-quality static images or pre-rendered animations for publication. Triangle meshes are also amenable to 3-D printing, a term which encompasses a set of techniques for the production of a physical three-dimensional object from a digital model. 3-D printed models are typically inferior to virtual models for research purposes, but are well suited to the communication of results to non-specialist audiences (see e.g. Rahman et al., 2012).

#### *Direct volume rendering.—*

Methods exist for the direct visualization of volume data, obviating the need for isosurface calculation (see e.g. Lichtenbelt et al., 1998). These vary in detail and in computational efficiency, but all directly project a volume onto a 2-D image without producing a triangle-mesh, via a ‘transfer function’ that determines a color to be displayed from the density of (or gradient between) voxels. These approaches cope well with specimens in which gradations are present, as no arbitrary thresholding is required, automatically implement translucency of structures, and can visualize any color information in the original volume. Results can rival triangle-mesh visualizations aesthetically. However, rendering speeds are normally substantially slower than those for triangle-mesh datasets, and rendering requires the presence of the full volume dataset, which can hamper both visualization on less-powerful hardware and data-sharing. Software availability is a further limiting factor, although the *Drishti*

package ([sf.anu.edu.au/Vizlab/drishti/](http://sf.anu.edu.au/Vizlab/drishti/)) provides a free solution. Likely for these reasons, uptake in paleontology has been limited (though see e.g. Schiffbauer and Xiao, 2009; Albani et al., 2010).

#### *Direct point-cloud rendering.—*

The direct rendering of point-cloud data from surface-based capture techniques is straightforward; points are simply projected from three into two dimensions, and drawn as small colored squares or circles in the appropriate position. Direct point-cloud rendering is normally less visually appealing than triangle-mesh based rendering and often slower, as it is less amenable to hardware acceleration. However, it avoids the non-trivial triangulation step (see above) and is hence simpler to achieve. For dense point clouds, it may be an adequate means to visualize surface data, and where points are sparse it has the benefit of making this sparsity clear to the viewer.

## **CHALLENGES AND DEVELOPMENTS**

Virtual paleontology is now firmly established as an important tool, or more properly set of tools, for the study and dissemination of paleontological specimens. The vast majority of three-dimensionally preserved fossils can now be successfully studied using some form of virtual paleontology, and the advantages to the approach are now widely understood. Nonetheless, there are still barriers to the further and faster uptake of these methods. One such barrier is the ‘difficulty’ of these methods, both perceived and actual. The increasing availability of reconstruction software, the improved visibility of the techniques, and the increasing number of publications describing methods are actively combating this problem. Nonetheless, virtual paleontology can be an expensive and time-consuming undertaking, and like all techniques, should only be deployed where benefits outweigh costs.

Perhaps the greatest potential in virtual paleontology lies in improved data-availability for researchers. Fossil data underlying paleontological research has always been available via museum repositories of specimens, but the logistical difficulties hamper routine re-study of material. Virtual specimens are (in theory) far easier to access. The dissemination of three-dimensional morphological data underlying ‘virtual paleontology’ publications is clearly desirable in the interests of scientific clarity, as well as to facilitate further research on the specimens (see e.g. Callaway, 2011). Just as gene-sequence data is routinely made available to all interested parties via GenBank ([www.ncbi.nlm.nih.gov/genbank](http://www.ncbi.nlm.nih.gov/genbank)), with immeasurable benefits for genetic science (Strasser, 2008), the routine publication of virtual fossil data would be hugely beneficial for the science of paleontology. While such data releases are becoming increasingly common, they are still far from ubiquitous. This may partly reflect a reluctance amongst researchers to ‘give away’ data without guarantee of reciprocation (Sutton et al., 2012), but technical impediments are also an issue. Virtual paleontological data can take many different forms depending on the approach used (Fig. 7), can reach very large file-sizes, and there is no agreement as to exactly which data constitutes ‘the specimen’ (e.g. raw tomograms? prepared tomograms? triangle-mesh models?). There is also no agreement as to which file format should be used for any particular data type (though see Sutton et al., 2012), or indeed as to which of the many existing online repositories should be preferred. Sutton et al. (2014) provide a more in-depth discussion of these problems, which remain obstructive to the development of the science.

The techniques available for virtual paleontology have changed radically in the last 20 years. Most techniques, for instance, have seen improvements in resolution; these improvements are likely to continue. The importance of non-destructive (scanning) methods is likely to continue to increase, as the necessary equipment becomes increasingly available at a lower

cost. Nonetheless, destructive methods will continue to find niche applications, especially FIB tomography, which provides the highest resolution of any method discussed. Surface-based techniques have seen a rapid increase in paleontological usage in recent years, and the increasing availability of photogrammetry is likely to drive further uptake; attractions of this approach include its scale-agnostic nature, high portability, and very low equipment costs.

While other tomographic methods will continue to have some applications, X-ray computed tomography (CT) is likely to remain the mainstay of virtual paleontology; access costs should continue to fall, and resolution and availability continue to increase. Developments in phase-contrast methods (at synchrotrons and also with lab sources) are already greatly increasing the resolving power of CT for difficult (i.e. low attenuation-contrast) specimens. Additionally, the development of new methods capable of mapping elemental or mineralogical composition in three dimensions are of great potential significance; color CT is perhaps the most exciting of these. These methods are still experimental and/or prohibitively time consuming (Sutton et al., 2014), but should they become practical we predict a very significant paleontological uptake.

Virtual paleontology is no longer a niche undertaking; these techniques are now at the core of the discipline. Their ongoing development will only continue to increase their importance in the future.

## ACKNOWLEDGEMENTS

Imran Rahman was supported by an 1851 Royal Commission Research Fellowship. We also thank the Paleontological Society for support of this short course.

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989 FIGURES AND CAPTIONS

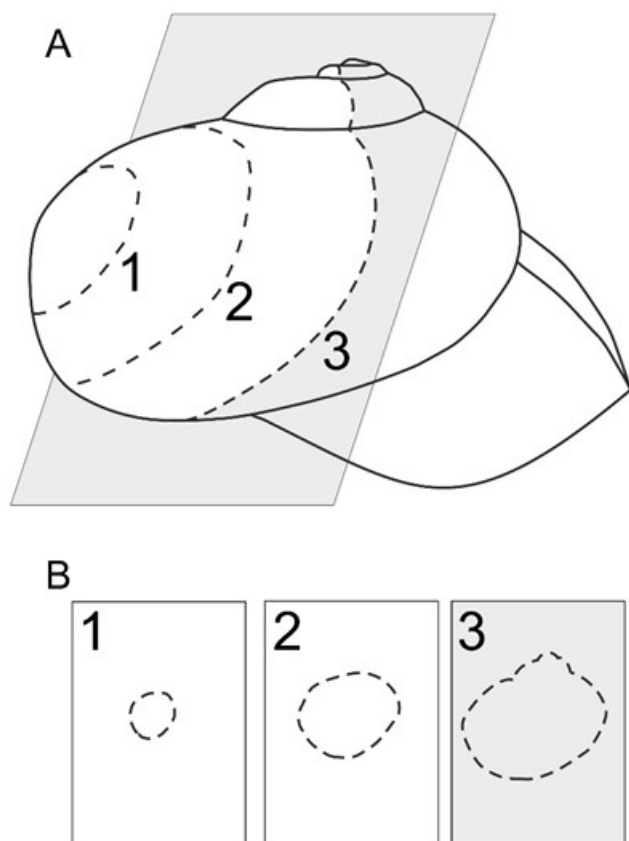


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991 FIGURE 1.— An example of a virtual fossil. *Offacolus kingi*, OUMNH C.29557, from the  
992 Silurian Herefordshire Lagerstätte, UK. Scale bar = 1 mm.

993





994

995 FIGURE 2.— Tomography – 3-D reconstruction using a series of two-dimensional slices.

996 Idealized example (after Sutton, 2008, fig. 1). (A) Three parallel and evenly spaced serial

997 tomograms (1–3) through an idealized gastropod fossil; (B) Resultant tomographic dataset.

998

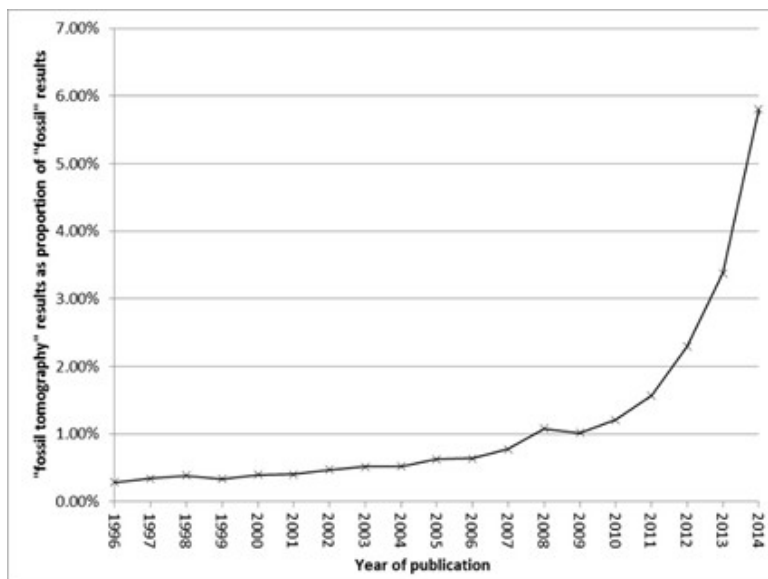


FIGURE 3.— Relative increase in the importance of tomography in paleontology from 1996–2014, as calculated by the ratio of publications including “fossil” and “tomography” to those only including the word “fossil”. Data from Google Scholar (scholar.google.co.uk), Jan 2015. While these data inevitably include biases, they give a clear indication of trends.

Tomography						Surface-based			
Destructive		Non-destructive				Non-contact			
Physical-optical		Optical		Rotational radiation transmission scanning		Active			
Serial sawing Serial grinding Serial slicing  Focused ion beam (FIB) tomography Confocal laser scanning microscopy (CLSM) Serial focusing with light microscopes Magnetic resonance imaging (MRI)				X-Ray (CT)		Triangulation-based laser scanning Time-of-flight laser scanning Phase shift laser scanning Photogrammetry Mechanical digitization			
				Neutron tomography	Attenuation-based			Phase-based	
					Nano-CT Micro-CT (XMT/ $\mu$ CT) Medical & industrial CT Synchrotron CT (SRXTM) Synchrotron phase-contrast CT Lab-source phase-contrast CT				

FIGURE 4.— A simple taxonomy of data-capture methodologies (modified from Sutton et al., 2014, fig. 7.1).

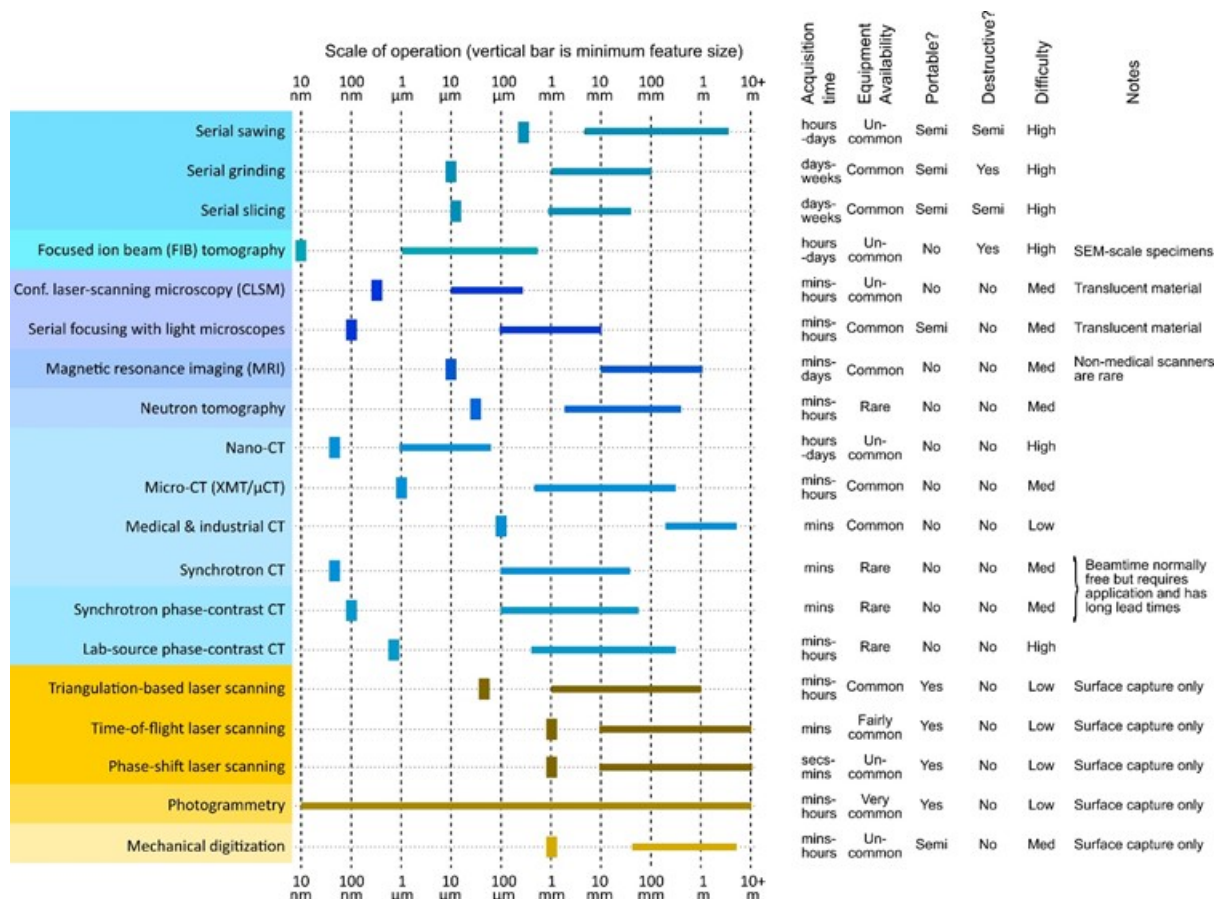


FIGURE 5.— Comparison of methodologies by scale and other important qualities (simplified from Sutton et al., 2014, fig. 7.3 and table 7.1). For scale, thick lines represent approximate range of feature-of-interest sizes, and vertical bars represent approximate minimum resolvable feature size. Note that photogrammetry is scale-agnostic; the minimum size given (for SEM photogrammetry) is notional. Other data are largely indicative guides. Note that semi-destructive approaches are those where some material is destroyed, but the majority is retained; portable equipment can be easily carried by a single person, potentially into the field, while semi-portable equipment is ‘luggable’ from one laboratory to another; difficulty is a qualitative estimate of how complex and challenging the entire procedure will be to a relative novice; complications with visualization are included in the estimate, as are likely degrees of technical support available.

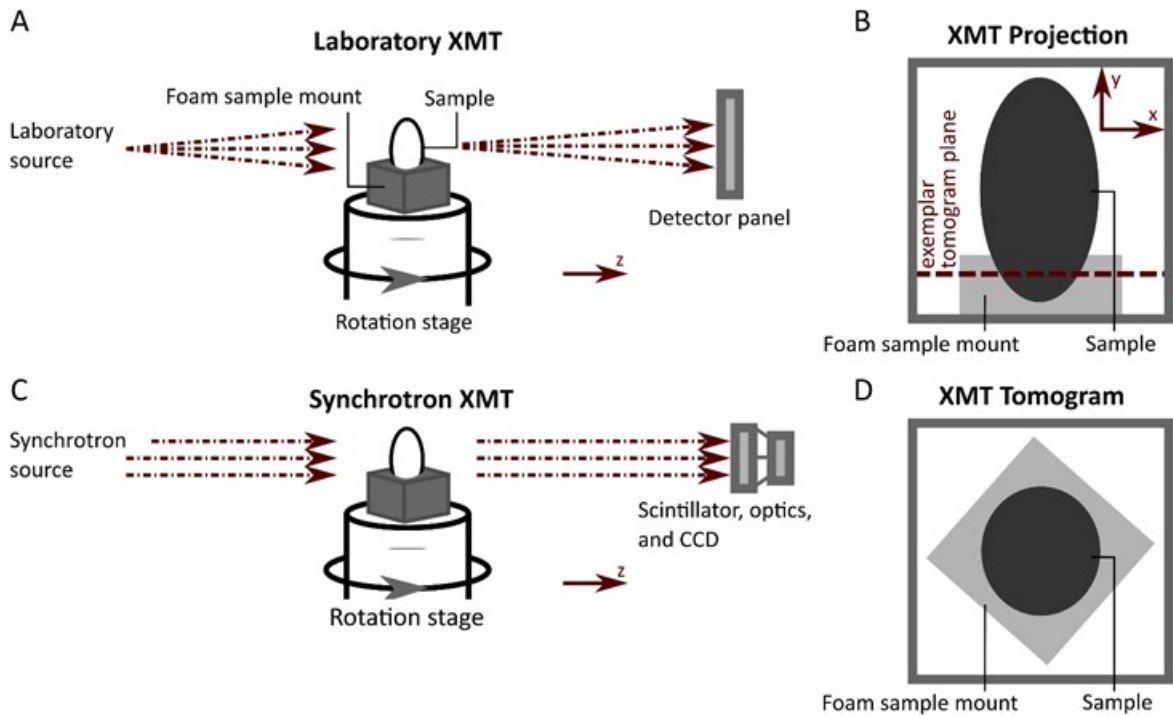


FIGURE 6.— Comparison of different forms of X-ray computed tomography. (A) A laboratory-based X-ray microtomography setup, showing a sample mounted in florists foam on a rotation stage. Of note is the cone beam configuration providing geometric magnification. (B) An X-ray projection of the sample from panel (A), with a plane marked on which will be reconstructed as a tomogram. (C) A possible synchrotron-based X-ray microtomography setup. The beam is parallel, and magnification is provide by optics behind a scintillator, which fluoresces on exposure to X-rays. (D) An exemplar tomogram, based on the exemplar tomogram plane in panel (B).

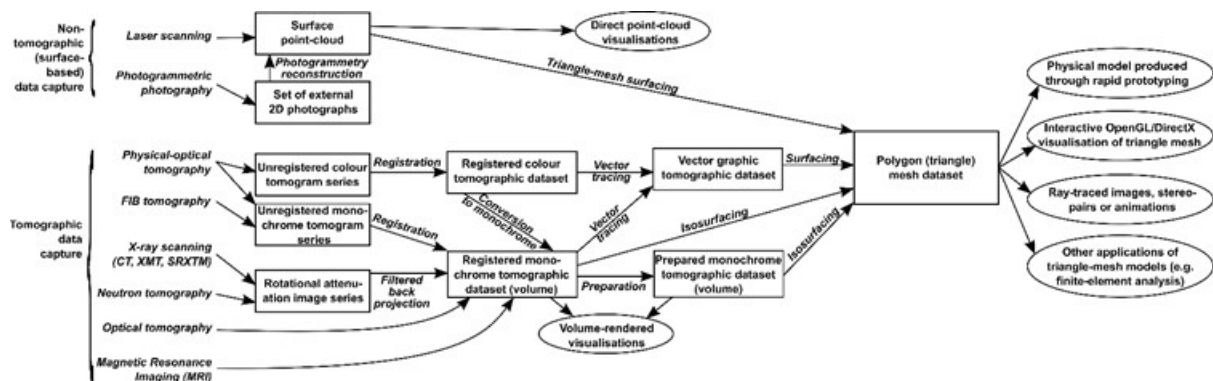


FIGURE 7.— Common reconstruction workflows. Rectangles; data-set types generated

during the reconstruction process. Ellipses; outputs (visualizations, models, etc.). Unbounded

text at top; inputs. Modified from Sutton et al. (2012, fig. 2). Reproduced with permission of

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