

3D-Printed Facsimiles as Classroom Primary Sources: A Comparative Review

3D printing brings ancient artefacts into the hands of your students.

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Introduction

There are many reasons to teach from primary sources: to learn about the nature of historical evidence; to learn the processes of interpreting evidence; to develop awareness of language or other skills needed for specialist work; to inspire or even impassion; to focus learners on particular perspectives or events; to create a problem-focus for group inquiry; to complicate or challenge an understanding too simplistic.¹ Historical objects may be especially engaging for their richness and the evocative power that we feel ourselves, regardless of whether we were trained, as most of us indeed were, in predominantly textual methods.²

Rarely, however, do we teach with originals. Usually, we work through a mediated representation, by reading edited texts or facsimile reprints, or examining objects or artworks through photographs. For actual originals, most of us would have to make a field trip to a library or museum or borrow an object kit.³ Recent advances in 3D printing and scanning technologies now promise

another option. It is becoming easy and cheap to manufacture facsimiles for classroom use, and also to make 3D models of accessible local objects as a learning activity or as a contribution to the discipline's source corpora.⁴

Facsimiles can offer possibilities that museum originals usually do not – opportunities to handle objects, feeling how they fit into the hand or other parts of the body, and their tactile properties, and the possibility of turning them over to see what is on the other side. Produced at full size, facsimiles offer an immediate understanding of how big an object is, without the need to interpret a scale bar. Facsimiles can be incorporated into models and experiments to explore handling, interaction and architectural circulation. Given multiple object facsimiles, learners can regroup, resequence and reorient them to construct or communicate an interpretation – operations that are familiar to art historians, anthropologists and archaeologists, albeit often done in the imagination or using computer models to minimise wear on the originals.

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‘The tablet inspires sympathy and the writer is often imagined to have been a child, perhaps as young as six years old, and who perhaps left a fingerprint.’

Facsimile-based teaching is, however, fraught. Facsimiles adequately represent some aspects of the original while downplaying, omitting or misrepresenting others. They may present further information that is not part of the original. As 3D print quality increases, the realism increases, so how are learners to distinguish historical source representation from impression? Let us explore such challenges by considering a primary source that overlaps the textual and material realms, and for which it is possible to produce a deceptively realistic 3D print: an ancient Babylonian tablet.

Collectors, Curators and Accidents of History

It sometimes seems miraculous that certain historical sources survive at all. The source has to persist through disasters both natural and man-made, to escape both deliberate and incidental efforts at disposal, to endure mechanical rigours of weather and handling, and the chemical degradation of its own matter. Someone needs to recover, collect and preserve it. Even then, historians might not encounter and engage with it without further work by archivists, palaeographers, epigraphers, archaeologists, librarians and scientists.

Tablet YBC 7289 is especially interesting because it carries a kind of content that curators and archivists commonly discard: a school mathematics exercise. Formal education generates vast quantities of such texts in many cultures, and they seem always to have been ephemeral. Nor did the ancient Mesopotamians commit such learning artefacts to their immense archives and libraries. But being made of clay and discarded back into the soil, numerous discarded tablets survived intact. Mesopotamia’s learning artefacts survive in the thousands.

Mesopotamian tablets are found in various conditions. Official records are often excavated in large, organised collections, hardened by sun-baking before storage. When tablets are found fired to vitrification, this is understood as an incidental consequence of war. More often, tablets are still soft, and hence often scarred by the shovels, trowels and dental picks used during excavation and cleaning. Modern institutions have fired, desalinated and cleaned many tablets for preservation, and whitened many with ammonium chloride to increase contrast for photography. Such modifications are motivated by interest in the form rather than the matter; fragments without text are widely deemed ‘of no academic value.’⁵

Only a very few scholars work at transcribing. Armed with callipers and a pencil, transcribers closely measure

and draw every salient detail. Their projection is orthographic and shows only front and back; there is neither perspective nor shading so the drawings look flat. If there is writing on the other sides (edges), it is transcribed outside the drawing rather than through documenting the sides in their own right. Dotted shading shows where parts have gone missing although the nature of the damage – a spall, scrape or fracture; whether rough or smooth – is not normally included. The standard transcription of YBC 7289 is shown in Figure 1 overleaf.⁶

How this particular tablet came to be collected is unknown. It was part of the donation that became the Yale Babylonian Collection in 1909. Apart from that, the tablet, like many collected that early, has no further provenance. A transcript, translation and commentary were published in 1945, in a study of mathematical tablets by Neugebauer and Sachs.⁷ Since then, it has become something of an icon among mathematicians and historians of mathematics, a tangible and content-accessible symbol of the discipline’s antiquity and heritage.⁸ The text comprises merely a few numbers, posing at most a minor linguistic challenge in an easily learnt notation. The diagram, though in an ancient visual language, is still easily understood today. The problem is simple and familiar: the square’s side length is multiplied by $\sqrt{2}$ to find the diagonal. This provides evidence that the Mesopotamians had a way to precisely approximate that irrational root.⁹ The textbook-style problem, coupled with the tablet’s size and lenticular shape, its crudely finished surface and the imprecise handwriting, all stand behind its classification as a learning artefact produced by a trainee scribe.¹⁰ The tablet hence inspires sympathy and the writer is often imagined to have been a child, perhaps as young as six years old, and who perhaps left a fingerprint.¹¹

Like many museums, the Yale Babylonian Collection is scanning its entire collection to increase accessibility. This particular tablet was addressed early in that process due to the high number of inquiries that it attracts. It was included in a pilot project in 2014 that sought to evaluate a wide range of digitisation methods, when object scanning was framed predominantly by research and pre-commercial development, so the scanners included research prototypes and bespoke apparatus. The main goal then was to formulate principles and a protocol for sufficiently faithful digitisation:

- What information could each process record?
- What did each process omit?
- What governs the quality of the data?
- How should scanning processes be operationalised?

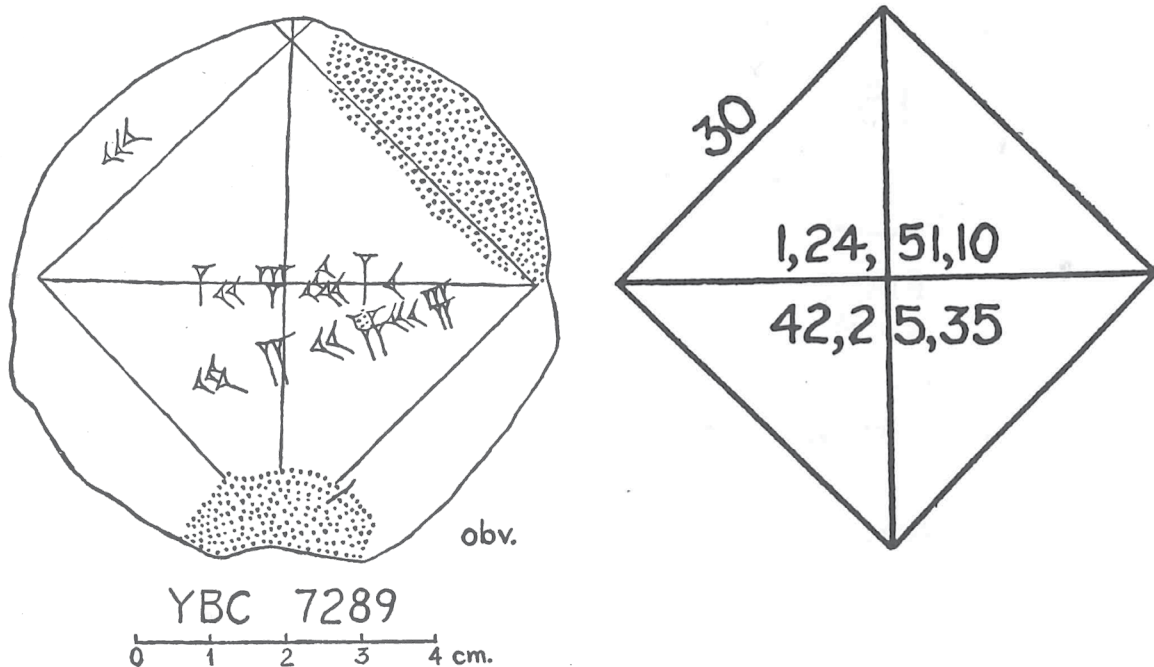


Figure 1 The 3D model rendered in Blender to show both obverse and reverse faces under an arrangement of three lights that helps to communicate depth and inscribed detail. Below the rendering: the transcription and translation from Neugebauer and Sachs, *Mathematical Cuneiform Texts*. The small wedges in ‘24’ and ‘25’, and the shakily written ‘35’ and ‘51’, are especially challenging to represent by 3D printing.

A further request for scanning came in 2017. By then, Artec’s handheld Spider scanner was in commercial production. This new scanner incidentally created an opportunity to compare the new scanning method against those trialled in 2014. The present study gave reason to scan it still again in the same year, using the same Spider scanner set to operate at a higher resolution.¹²

In spite of the tablet’s fame, its display vitrine in Yale’s Sterling Memorial Library is no crowded shrine. The

tablet is not under intense critique from Assyriologists, and few mathematicians make the pilgrimage. Nor have plaster casts – a well-established norm for replicating all manner of ancient *spolia* – made facsimiles widely available, as the labour-intensive process of moulding, casting and hand-painting has never achieved large-scale distribution. Digitisation and subsequent replication, in contrast, could broaden the accessibility of such texts immensely and immediately, at least for people with access to internet connections and 3D printing amenities.

Digitisation: The Technician as Transcriber

We played no part in scanning the tablet, just as most history educators play no part in transcribing, editing and translating the textual sources that they bring to classroom learning. Unlike textual sources, digital scans lack footnotes and translators' introductions to guide our reading, and 3D scanning methods are changing too quickly to permit a canonical reference along the lines of Gaskell's *New Introduction to Bibliography*.¹³ At its essence, scanning and model-processing are comparable to transcription in the sense that the scanning technician must identify the salient information and attend to its faithful representation in a three-dimensional mesh that closely approximates the object's surface.

Like transcription, scanning is complicated and subjective, and benefits from expertise. On the other hand, 3D digitisation differs from transcription in having wide hobbyist appeal. Smartphones are powerful enough to do the computational work of photogrammetry, which computes a 3D model from multiple photographs of an object or space. Institutions such as New York's Metropolitan Museum of Art actively encourage visitors to make and share photogrammetric models while perusing the galleries. While this increases accessibility and engagement, it can be hard for an historian downloading the model to find out what modelling process was used, how the working conditions affected the model and what decisions contributed to its production.¹⁴

Our key historical concern is, what types of question may a 3D model be good for answering? Does it represent the necessary information and, if not, would we be able to tell what is changed or missing? Would we be alerted to the importance of information that we had not thought to seek?

As mentioned above, our tablet was scanned using an Artec Spider. The technician holds the scanner 20 to 30 centimetres from the object while walking around it, or while the object rotates on a turntable. The Spider absorbs a million points per second to construct a model with a spatial resolution of 0.1 millimetres and a colour resolution of 24 bits per pixel. The original tablet is small, rigid and robust so it can be mounted on a rotating stand and turned over. We are interested only in its opaque, matte exterior so overall it is an easy target. The resulting digital model is a fine wireframe mesh comprising innumerable triangular facets that closely approximate the object's surface.

The technician makes many expert decisions. Some decisions are driven by foresight towards subsequent use. For instance, the triangle mesh for broad, flat areas can be simplified from numerous tiny triangles to a much smaller number of larger triangles, reducing

the computational overhead for file storage, onscreen rendering and printing.

Other decisions are driven by shortcomings of the software and scanner. There may be spurious points, for instance, that the technician identifies and corrects. If the object has to be scanned piecemeal, or the scanner is confused by a repeating pattern, the technician may need to manually re-align the partial scans or add markers to guide the next attempt. The mesh triangles may be right where they should be, but not joined to each other, which would lead to the printout falling apart. Well-placed triangles may be oriented the wrong way. Although this looks the same in the wireframe, the triangles have a front and back that distinguish between the inside and outside of the surface. If the direction is wrong, the mesh will be inside-out and subsequent printing will be enlarged and rounded.

Addressing such issues constitutes 'cleaning up' the mesh. Important information may be lost through clean-up, especially when simplifying regions of tiny triangles into a smaller number of large triangles, and possibly when removing spurious 'noise' that is actually not spurious at all. Such losses are generally chosen to be of overall benefit to the print's uses and hence depend on the technician understanding what that use is. Similar dilemmas are faced when preparing textual sources. Just as it helps historians to know about transcription protocols, editorial principles and experience-based connoisseurship of the genre or corpus, it similarly helps to know about the skills, principles and empirical experience that scanning technicians bring to their authorship of the mesh.

We received a finished digital model: an abstract description of a material object to which we have no direct access. The model has been freed from the limitations of materiality – nothing in it is fuzzy, frayed, friable or otherwise ill-defined. We examined the model using Blender, a free, open-source 3D-modelling suite.¹⁵ Blender let us magnify the model hundreds of times larger than the original, and to examine it using all three of a flat monitor, a 3D monitor, and 3D virtual-reality goggles. The wireframe mesh confronted us with an overwhelming volume of detail and demonstrated that resolution is not a straightforward measure.

Because the surface is approximated by triangular facets that lie approximately parallel with the actual surface, rounding affects some kinds of detail more than others. Depending on the lighting and viewpoint, the facets can produce unrealistically large glints. This happens especially where facets are large, and also along sharp edges. When we make a small shift to avoid the reflection from one facet, an adjacent facet often poses exactly the same problem. In other places, the resolution is astonishingly fine. We could see the thickness of the museum label (standard practice is to

write these labels in Indian ink on a broad brushstroke of removable lacquer) risen slightly above the surrounding surface, especially when we rendered the image without colour. We did not, however, find impressions from the fibres of the writing tool. Nor could we find a way to discern, from the model, whether that information is likely present on the original. Still, the model was good enough that Blender allowed us to render images better than any photograph we have seen in print (Figure 1), and it let us look at views that textbooks do not show. We could examine the tablet's edges, for example, and peer deeply into the inscriptions and cracks.

While 3D rendering software clearly offers prospects for worthwhile classroom explorations, we will turn our attention now to the *cause célèbre* – the prints themselves.

Printing and Finishing: Casting Shadows of a Platonist Ideal

Just as the digitisation process affects what information is recorded, removed or added, information is also added and removed by the processes and media of printing. 3D prints merely approximate the digital ideal – Plato would be proud! This point, we will see, is a key to interpreting them well.

Just as a traditional printer makes informed choices about ink and paper, and pays close attention to the alignments and movements of paper, type and press that

render word and image visible to the reader, 3D print technicians also have choices to make, and processes to monitor and correct.

For this review, we printed the tablet using four reasonably available technologies. Salient features of the technologies are summarised in Table 1.

Print resolution is tricky to interpret. The specifications describe the very precise positioning of the laser beam and extrusion nozzle, but print resolution is lower because beams and nozzles have non-zero diameters. Surface accuracy is achieved by tracing the nozzle or beam not along the edge, but just inside it so the accreted material is always within the model's boundaries. The associated offset has to be set by the technician, who allows for the radius of the beam or nozzle, and also for how much the material or the accretion zone spreads. Tracing just inside the edge can produce very sharp internal angles, while external angles are unavoidably rounded off. It is sometimes possible to improve the print resolution by orienting the print so that sharp edges are horizontal, and hence subject to the fine z -axis resolution rather than the coarser resolution in the x - y plane. Such settings may need adjustment when materials are changed, entailing different melting points, solidification rates, and spread. While manufacturers strive for predictability, expert print technicians employ their own experiential knowledge to match materials and individual printer quirks to the specific needs of any particular project.

Comparison of 3D Printer Technologies

	FUSED DEPOSITION	STEREO LITHOGRAPHY	LASER SINTERING	BINDER-JET
Printer	Makerbot Replicator	Formlabs Form 2	Eos Formiga P100	Z-Corp (model unknown)
Material	grey PLA	white gloss resin	white nylon	gypsum
x-y resolution	0.11 mm	0.14 mm	0.05 mm	0.08 mm
z resolution	0.1 mm	0.025 mm	0.1 mm	0.1 mm
Surface, visual	satin sleeks	smooth gloss	fine grit	coarse grit
Surface, tactile	finely ridged	hard, smooth	slightly rough	rough
Interior	hollow with mesh	solid	solid	solid
Mass	28 g	89 g	73 g	110 g
Approximate cost	\$3	\$10	\$100	\$80

Table 1 Note that the specified resolutions describe printer control rather than the resultant print. Print resolution is limited by factors such as laser spot size, extrusion nozzle diameter and plastic temperature, ink wicking outwards through the plaster bed, material deposition speed, and mechanical noise.

FUSED DEPOSITION

Our first print was made using the most common 3D print method, fused deposition modelling (FDM, also called fused-filament fabrication, FFF). This process entails extruding a melted plastic filament into cross-sectional laminae that accumulate into a model. Many public, school and university libraries have FDM printers for communal use. We set our printer's resolution to the higher end of its range, at the cost of a longer print time. Given historians' usual interest in the writing on Mesopotamian tablets, plus the irregularity of this particular tablet's writing, there seemed no point in trying a lower-resolution option.

FDM-printed models often require physical support during printing. Typically, that support is generated automatically by the printer software, which prints a scaffold that can be broken and cut away later. When printers use only a single material, information will be obscured wherever the scaffold joins the model. Using different materials to print the scaffold and the model preserves the distinction between them. Our printer prints the scaffolds in poly(vinyl acetate) (PVA), while printing the model itself using poly(lactic acid) (PLA). The PVA scaffold can be dissolved away in water, leaving no marks on the model surface. Print orientations and scaffold design can sometimes be customised to minimise interference with historically important information. We arranged for our main text faces to be vertical for this reason, so that the scaffolds would not touch the text surfaces.

PHOTOLITHOGRAPHY

Our second print was made by photolithography (PL, also called resin printing, photo-solidification or optical fabrication). A laser traces a cross-section onto the underside of a support plate immersed in a tank of resin, selectively solidifying the resin into a layer of the print. As the support plate rises, it pulls the print up with it while the laser continues to add further layers below. This method supports overhangs with scaffolds printed in the same material. We chose a print orientation that kept the scaffolding on the reverse so that the iconic text and diagram were as pristine as possible, while the back – widely regarded as too poorly preserved to be worth transcribing – can show us the extent to which scaffolds perturb the surface. The scaffold was generated automatically and designed to break off the print. Most of it readily came away, leaving behind a grid of bumps each about a millimetre wide. These would normally be cut off manually, and the blemishes hidden by blending into the surrounding surface, but we retained them to communicate the associated limitation of the reproduction (Figure 2).

When exterior surface representation is the primary goal of 3D printing, thick objects, such as this tablet, are commonly printed as hollow shells. Holes can be left to drain out unused resin for recycling in subsequent prints. Rather than compromise our surface, we chose to solidify the innards completely. We also hoped that the retained resin's weight would communicate the solidity of the clay original.



Figure 2 Reverse of the SL resin print with bumps left after breaking the scaffold away.



Figure 3 Left to right: fused-deposition PLA print; stereolithographic resin print; laser-sintered nylon print; gypsum print.

SELECTIVE LASER SINTERING

Our third printing method, selective laser sintering (SLS), entails spreading out thin layers of finely powdered polymer, metal, ceramic or glass that are traced over with a laser, heating the particles just enough to sinter together (i.e. to fuse without fully melting).

Tough materials such as nylon and metals can lend more classroom durability than brittle resin. Machine size, machine price and operating cost limit the availability of SLS printers. Our SLS print cost about three times as much as the SL resin print. The resolution is also lower. We surmise that this is due primarily to the larger laser beam diameter, which is in turn due to infrared laser beams being harder to narrow down than the ultraviolet lasers in SL resin printing.

Because the unused powder supports all overhangs, SLS printing does not entail the compromises associated with scaffolds. SLS printing is hence especially amenable to vessels and linked, nested or closely fitted objects, such as chain mail, wirework jewellery and gear trains.

We proceeded with an SLS print in white nylon primarily out of interest in the surface finish. Because the nylon particles are sintered rather than fully fused, microscopic gaps remain between them. The surface is hence porous, resulting in a satin or matte finish and a slightly rough touch. The finished print looks and feels much like unglazed porcelain.

SLS prints can absorb dyes so they can be coloured without burying surface details beneath the thickness of paint. On the other hand, the surface also absorbs skin oils and dirt during classroom handling. While nylon is reputed to wash up well with soap and water, dirt can be sealed out with a coat of paint, epoxy resin, cyanoacrylate or lacquer. Again, provision must be made for material inside the model. As with resin, it can be drained out through holes. We chose to seal it in.

The model is recovered by digging, brushing and vacuuming away the surrounding bed of unused powder. This process aptly recalls the recovery of *spolia* from desert sands. Remaining powder is typically dislodged using compressed air, bead-blasting, or brushes and prods.

BINDER-JET PRINTING

Binder-jet printing also involves a powder-bed but can operate in full colour, albeit at a much lower resolution. The print medium can be finely ground stone, plus a binder of coloured glue, or gypsum (plaster of Paris) activated and bound using water-based ink. The glue or ink is dispensed using an ink-jet printer head. Because the liquid wicks a short distance, it limits both spatial resolution and colour control. Dug from the powder-bed, fresh prints are fragile and the ink still soluble, though durability can be increased for classroom use by infiltrating with wax, epoxy resin, cyanoacrylate or shellac. Infiltrants may alter the colour intensity and change the surface finish. Ideally, we would have planned for this from the outset but the print bureau we dealt with does not provide a colour matching service, and colour control does not appear to be a major concern in the 3D printing industry.

We found a gypsum print satisfyingly rough to the touch, evocative of sandstone or coarse terracotta. The initial tactility and colour – fitting for a Babylonian tablet, even if not accurate – turned out to be largely unchanged by cyanoacrylate infiltration, but the colour was substantially darkened and intensified by an epoxy coating.

Interpreting the Prints

When the four prints are juxtaposed (Figure 3), the evident differences prompt questions about which is best for classroom use. Legibility differed conspicuously between them, and they differed also in other ways. Which one is better depends on what we are reading for.

For reading the text and diagram, the full-colour gypsum prints were most accessible owing to the writing being pale, and contrasting strongly against the darker surrounds. The SLS nylon print, being matte white, was also very legible. The FDM and SL prints were much more difficult to read. The FDM surface is confused by satin sleeks due to the print process, and the SL print is so glossy that the writing is obscured by reflections and cannot be thrown into shadow. It is worth noting that the SL print had the highest resolution of the four that we tested, yet its legibility was compromised by the surface finish.

The prints all enabled haptic examination. They made it possible to manipulate the objects, to perceive the actual shape and size in contrast to the flattened idealisations of photographs and transcriptions. We showed the prints to various small groups, who intuitively felt and manipulated in addition to looking, discovering what felt like natural ways to hold it (Figure 4). When the tablet was held in one hand, it was easy to imagine holding a stylus in the other, and to try out possible writing postures to evaluate their feasibility and implications. A next step could be to try recreating the tablet in modelling clay to further develop interpretation. We were surprised to find that the FDM-printed tablet proved very easy to drop. When asked why, people told us that its lightness made it difficult to control.

On the visual inspection front, historians of scribal practice require very fine details: the linear and angular dimensions of the wedges, and subtle texturing left by the fibres of the reeds from which styli were made. Such evidence has shown that cuneiform scripts were written left-to-right, top-to-bottom, and that styli were made from reeds cut to a particular cross-section.¹⁶ For social history and history of technology, such readings may be more interesting than the textual content. None of the prints shows detail so fine as reed-fibre impressions, nor indicates whether we might expect to find such information on the original. The prints do,

however, show enough detail to invite interpretation about the order in which the individual wedges were impressed to form the cuneiform characters, and the order in which the lines were made to diagram the square. Students might inquire whether the diagram lines were incised by dragging the stylus through the clay, or impressed by a long, thin edge. It is difficult to make clean impressions by dragging because clay can stretch, twist and crack alongside the tool. Curved lines are especially hard to execute, and other tablets show that the Mesopotamians struggled to produce even straight lines cleanly.¹⁷ This difficulty – especially if accessible by 3D-printed replicas – can be used to learn about cuneiform writing technique, and hence how tool, medium and technique contribute to the form of the script and the rate of writing. On the tablet prints, we could also discern the order in which many adjacent or overlapping marks were laid down. Even the crudest of our 3D prints was clear enough to support argument that the individual numerals were written left-to-right, top-to-bottom, and that the square's diagonals were drawn first, and then its sides.

There is information in the deep holes that transcription avoids (except by dots that indicate some kind of damage). A large crack looks to have formed along one of the square's sides. The sheer drop next to it – visibly undercut on the SL resin and SLS nylon prints, but



Figure 4 Discovering by touch and grasp that the tablet does not nestle into the palm without fingers getting in the way of writing, at least in this adult hand. Would it fit better into a child's hand, or are we holding it wrongly?



Figure 5 A technological mediation artefact: print layers visible as topographic contours at an ‘end’ of the FDM print.

partially filled-in on the FDM print – gives the impression that the clay broke where the stylus weakened it. Such a reading accords with interpretations of many other broken tablets, notably where the clay is understood to have been heavily stressed by erasure and rewriting.¹⁸

There is a danger that some prints might be mistaken for originals. The gypsum prints in particular have plausible colours, and are weighty and rough to touch, just as we would expect of ancient clay. We showed it to fifteen students and academics, at least half of whom were mistakenly impressed by our having somehow obtained the original. The SLS gypsum print (without epoxy) looks and feels like unglazed stoneware; the SLS-printed nylon like unglazed porcelain bisque. Though the truth is there on the surface, the clues are subtle, and it takes time and skill to perceive and interpret them. How is a novice to notice, let alone compensate for, such representational limitations?

Representational limitations are easier to assess through the FDM print, it being obviously cheap plastic due to its weight, colour and finish. An important cautionary feature is the contour lines along its edge. They look like the contour lines on topographic maps, and that is exactly what they are (Figure 5). These contour lines are not inherent in the scan, but are created by the print process. While the SLS and binder-jet prints also have topographic lines, they are much less obvious, perhaps disguised by the surface grittiness. Such production artefacts should be actively sought out and incorporated into the reading because they remind students that we are looking at a technology-mediated representation. They specifically highlight the quantised rounding inherent in all digitisation processes, and quantify what size details will have been lost. From there, it is reasonable to consider what other information has been lost or gained, and hence what historical questions the representation is good for answering.

All of the prints also offer an invitation to experience what historians really do when examining surface details: we turn the object back and forth, or move a light around, trying to catch glints and shadows to make salient details more visible by their contrast. This labour can take great care, for often different parts of a text are revealed by different lighting so that the whole cannot be viewed at once. Careful reading is a meticulous, time-consuming and often patience-testing task that is humbly downplayed by the crisp line drawings of published transcripts.

Conclusion: What Are 3D Prints Good For?

There are several reasons for wanting to see museum originals, such as the finer and denser information that they contain, true scale, authenticity and the object’s inherent value.¹⁹ The Mesopotamian tablet replicas show that 3D prints can help to contribute to providing at least the first three of these, if not also a strong hint towards the last. Moreover, these replicas are robust enough for classroom handling, and replaceable. They can be turned over to inspect the reverse, which most published transcriptions ignore. Even originals can usually not be examined on all sides because they are mounted against opaque surfaces and illuminated and oriented to emphasise the features most salient to the exhibition’s claims.

On the other hand, no facsimile can be comprehensively faithful, nor is it intended to be. The tablet prints illustrate the limits of resolution, the confusion due to reflectiveness, and the deceptiveness of colour and weight. We found the tablets suitable for teaching the script, and for investigating how Mesopotamian texts were held and written, but we also found that textual fidelity depends crucially on the text being clear enough on the original. This particular tablet, having been written by a relatively unskilled hand, shows that very

small details will not always be represented by current 3D printing techniques. When the writing is irregular, those fine details can matter a great deal. These particular concerns presume that the text is what we need. In primary, secondary and undergraduate history teaching, our focus is more likely to be less textual, more contextual – what the tablet’s form and execution suggests about the technology of writing, the scribal profession, the lives of children, or the status and role of mathematical knowledge.

This line of argument also plays on a misunderstanding of what facsimiles are intended to do. Their purposes differ from those of museum shop replicas, and of historical film props. They are often useful to evoke, but their primary purpose is to support the investigation of particular scholarly problems. Facsimiles hence perpetuate particular historiographical perspectives even at the same time as they offer a challenge.

Reading facsimiles (or replicas) from a material culture perspective, we can treat production artefacts as part of the text. We hence accept those limitations by construing the facsimiles as mediated representations: production artefacts apprise us of how the original source may have been transformed by intervening people, technologies and the fabrication medium. Adopting this perspective aligns with materialist approaches already established in textual scholarship, such as the use of physical and historical bibliography to establish a text, the wearing-down or cracking of type or woodcuts to demonstrate common equipment, printer or location, or the examination of unlined construction marks and witness marks to deduce conceptual processes behind a diagram, machine or building. Such an approach also offers possibilities of treating objects as primary sources, leading learners to the many consequences of privileging written language above other kinds of record.

Imperfection may hence be a very special advantage of 3D-printed facsimiles. Learners may examine the layer striations, scaffold scars, contour curves and other such

features to evaluate how detailed the representation is, and hence to deduce its inherent limitations. The production technology is still crude so those defects are relatively clear. In contrast, photography – a representation technology long refined and already well entrenched in our classrooms – makes editorial action invisible. Adjustments to lighting, exposure, contrast or colour balance all tend to be invisible through their own success. It is the same with translations and critical texts, though we may be lucky to have an introduction and footnotes apprising us of the extent and nature of editorial discretion. 3D prints hence offer a direct engagement with representation processes, in contrast to the process descriptions typical of prepared texts. Eyes, a magnifying glass and a perceptive touch offer opportunities to broaden our students’ ‘skills in the analysis and use of sources’ and to take a broader perspective on ‘using historical sources as evidence’ (quoting from the *The Victorian Curriculum F–10: History*), in tune with the recent growth of material culture and bibliographic methods in history, and in particular ‘to recognising the role of ICT in providing access to sources and the need to ask relevant questions of those sources.’²⁰

3D-printed facsimiles hence gesture towards the practicalities of historical research: for what reasons might a learner or researcher need to consult a museum original rather than a representation? For what kinds of question does it become justifiable for a library or museum to grant access to a fragile manuscript or a rare coin, rather than redirecting researchers to high-quality photographs or scans? Through such questions, our 3D-printed tablet replicas offer a reply to Leinhardt and Crowley’s challenge, ‘Why would anyone bother to visit a museum to see the actual artefact when virtual copies are so easy to come by?’²¹ Clearly, the evidence needs to suffice for the problem being tackled, and representations may or may not be up to the task. So, rather than replacing original sources, facsimiles can help students to learn why original sources still matter, why the age of the museum is not over yet.

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Image credit: Maurizio Pesce CC BY 2.0 (p.4)

Online Repositories of Heritage Object Models

SMITHSONIAN INSTITUTION

Colour and monochrome scans of diverse objects, almost all downloadable, some with interpretative context notes. Strengths in vertebrate fossils, classical sculpture, Americana.

Online viewer with controls for rotation, magnification, lighting, cross-sectioning, measurement. Supporting classroom resources.

<https://3D.si.edu/>

DIGITAL APPLICATIONS IN ARCHAEOLOGY AND CULTURAL HERITAGE

An online, peer-reviewed journal that publishes 3D digital cultural heritage models with related articles that describe both the site or object, and also the model-making process. Some articles describe applications in teaching. Some articles (and their models) are published for open access.

<https://www.journals.elsevier.com/digital-applications-in-archaeology-and-cultural-heritage>

THINGIVERSE

A MakerBot-associated repository whose users include the Metropolitan Museum of Art. The MET encourages the public to make their own models when visiting.

The MET

<https://www.thingiverse.com/met/about>

KMODDL

Manually constructed models of nineteenth-century kinematic instruction models, along with photographs of the original objects (from collections in the US, Russia and Italy) and scans of associated textual sources.

<http://kmoddl.library.cornell.edu/>

EUROPEANA COLLECTIONS

A database for European cultural institutions, whose 51 million records include over 3,500 for 3D models.

<https://www.europeana.eu/>

SKETCHFAB

A privately run, general-purpose model repository that disseminates 3D models uploaded by anyone. Uploaders include many heritage-custodial institutions. In addition to the examples listed below (all with at least 100 models), search for 'university' or 'museum' under 'users.' Many further high-quality heritage models can be found by browsing through the 'pro' user listing.

<https://sketchfab.com/models/categories/cultural-heritage-history>

British Museum

<https://sketchfab.com/britishmuseum>

Chung Kang Museum

https://sketchfab.com/ncku_museum

Mel Fisher Maritime Museum

<https://sketchfab.com/mfmaritimemuseum>

Santa Cruz Museum of Art and History

<https://sketchfab.com/santacruzmah>

Royal Museum for Central Africa

<https://sketchfab.com/africamuseum>

Archaeological 3D virtual museum

<https://sketchfab.com/laboratorinatura>

Virtual Museum Ingushetia

<https://sketchfab.com/virtualmuseuming>

University of South Florida

https://sketchfab.com/USF_digital

University of New England – archaeology

https://sketchfab.com/Melanie_Fillios-UNE

Endnotes

- David Hicks and Peter Doolittle, 'Social Studies Teachers' Use of Classroom-Based and Web-based Historical Primary Sources,' *Theory and Research in Social Education* 32 (2004), 213–247; Keith C. Barton, 'Primary Sources in History: Breaking Through the Myths,' *Phi Delta Kappan* 86 (2005), 745–753; Sam Wineburg and Daisy Martin, 'Tampering with History: Adapting Primary Sources for Struggling Readers,' *Social Education* 73 (2009), 212–216.
- John Staats, 'In Touch with the Past? Researching 'Haptic History': A Multi-Disciplinary Approach to Teaching History Through Objects and Artefacts,' *Teaching History* 48 (2014), 4–7.
- On some educational functions of objects and exhibits in museums, see Annelies Van de Ven, 'Education Between Artefact and Text,' *Agora* 50 (2015), 28–36; Angela Casey, 'Reading Objects: Using Museum Objects to Build Contexts for Literature and Language Studies,' *metAphor* (2012), 55–57. Artefact kits for modern Australian history are available for loan; see Brandi Bugh and Anne-Louise Muir, 'Holding History: Heritage Victoria's Artefact Education Kits,' *Agora* 52 (2017), 75–77.
- Scanning and printing technologies are changing too quickly for most views to stay current for long but, for a still-useful and brief appraisal of 3D printing's usefulness in history and heritage work, see Moritz Neumüller, Andreas Richinger, Florian Rist and Christian Kern, '3D Printing for Cultural Heritage: Preservation, Accessibility, Research and Education' in *3D Research Challenges in Cultural Heritage*, ed. Marinos Ioannides and Ewald Quak (New York: Heidelberg, 2014), 119–134.
- Quote from Marianne Odlyha, 'The Applications of Thermoanalytical Techniques to The Preservation of Art and Archaeological Objects,' in *Handbook of Thermal Analysis and Calorimetry*, ed. Michael E. Brown and Patrick K. Gallagher, vol. 2, 47–96 (Amsterdam: Elsevier, 2003): 68.
- For high-resolution images that demonstrate the fineness of detail in the scan, and which may be useful as classroom representations, see Alistair Kwan, 'Mesopotamian Tablet YBC 7289,' *Figshare*, <http://doi.org/10.17608/k6.auckland.6114425> (20 April 2018).
- Otto Neugebauer and A.J. Sachs, *Mathematical Cuneiform Texts* (New Haven, Connecticut: American Oriental Society and the American Schools of Oriental Research, 1945), 42–43.

- 8 The tablet was recently celebrated as the first of a series of ‘mathematical treasures’ on the cover of *MAA Focus* 32/6 (Dec 2012/Jan 2013), the news magazine of the Mathematical Association of America.
- 9 See e.g. David Fowler and Eleanor Robson, ‘Square Root Approximations in Old Babylonian Mathematics: YBC 7289 in context,’ *Historia mathematica* 25 (1998), 366–378, pp. 366, 368–369.
- 10 On Mesopotamian learners’ texts, their survival and their contextualised interpretation, see Christine Proust, ‘Masters’ Writings and Students’ Writings: School Material in Mesopotamia’ in *From Text to ‘Lived’ Resources*, ed. Ghislaine Gueudet, Birgit Pepin and Luc Trouche (Dordrecht: Springer, 2011), 161–179.
- 11 The fingerprint interpretation is widespread in oral lore and rare in print, but see e.g. Clemency Montelle, ‘Roots, Rocks, and Newton-Raphson Algorithms for Approximating 3000 years Apart’ in *Mathematical Time Capsules: Historical Modules for the Mathematics Classroom*, ed. Dick Jardine and Amy Shell-Gellasch (Washington, DC: Mathematical Association of America, 2011), 239, caption to figure 30.9.
- 12 Institute for the Preservation of Cultural Heritage, ‘A 3D-print of Ancient History: One of the Most Famous Mathematical Texts from Mesopotamia,’ *Institute for the Preservation of Cultural Heritage*, 16 January 2016, <https://ipch.yale.edu/news/3d-print-ancient-history-one-most-famous-mathematical-texts-mesopotamia>. Further information was provided by Chelsea Graham, email message to Alistair Kwan, 29 November 2017. On the scanning technologies and processes explored during the 2014 scanning project, see Yale Digital Collections Center, ‘Babylonian Collection Digital Imaging Demonstration Project,’ YDC2, 26 March 2014, <http://ydc2.yale.edu/babylonian-collection-digital-imaging-demonstration-project>.
- 13 Philip Gaskell, *New Introduction to Bibliography* (New Castle, Delaware: Oak Knoll, 1995).
- 14 In contrast, the KMODDL models of nineteenth-century kinematic teaching apparatus were drawn using CAD software rather than scanned from the objects. Comparing the CAD models with accompanying photographs of the originals quickly reveals that geometry has been approximated, more so in the support structures than in the gearing. This suggests that the digitisation process was focused on documenting mechanical operation (and ensuring that the printed models really do work), and not so much on manufacturing processes or design aesthetics.
- 15 Ton Roosendal et al., Blender, version 2.79 (Amsterdam: Stichting Blender Foundation, 2017-09-11); software available at www.blender.org.
- 16 No extant styli are known. Stylus reconstruction efforts began c. 1906, and have recently benefitted from the precise measurements obtainable by 3D imaging. See Michele Cammarosano, ‘The Cuneiform Stylus,’ *Mesopotamia: rivista di archeologia, epigrafia e storia orientale antica*, 49 (2014), 53–90.
- 17 See e.g. tablets with diagrams in Jöran Friberg, *A Remarkable Collection of Babylonian Mathematical Texts* (Springer: 2007). Tablet MS 4515 depicts a labyrinth that demonstrates, through its crudeness, the difficulty of drawing lines into clay.
- 18 Christine Proust, ‘Masters’ Writings and Students’ Writings,’ 168.
- 19 On these four reasons for studying original objects, see Gaea Leinhardt and Kevin Crowley, ‘Objects of Learning, Objects of Talk: Changing Minds in Museums’ in *Perspectives on Object-Centered Learning in Museums*, ed. Scott G. Paris (Mahwah, New Jersey: Lawrence Erlbaum Associates, 2002), 273–292.
- 20 Victorian Curriculum and Assessment Authority, ‘Rationale and Aims’ and item VCHHC123 in *The Victorian Curriculum F–10: History*, victoriancurriculum.vcaa.vic.edu.au.
- 21 Leinhardt and Crowley, ‘Objects of Learning,’ 273.