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Additive Archaeology: An Alternative Framework for Recontextualising Archaeological Entities

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Abstract: Additive manufacturing poses a number of challenges to conventional understandings of materiality, including the so-called archaeological record. In particular, concepts such as real, virtual, and authentic are becoming increasingly unstable, as archaeological artefacts and assemblages can be digitalised, reiterated, extended and distributed through time and space as 3D printable entities. This paper argues that additive manufacturing represents a 'grand disciplinary challenge' to archaeological practice by offering a radical new generative framework within which to recontextualise and reconsider the nature of archaeological entities specifically within the domain of digital archaeology.

Keywords: 3D printing, additive manufacturing, archaeological record, digital archaeology, extended assemblages, ontology.

Introduction

Recent reports of wholesale destruction of precious cultural patrimony in the conflict zones of the Middle East serve to remind us once again of the contingent nature of the archaeological record, both in the form of its own physical testimony but also the testimony created by archaeologists. This status of patent vulnerability has imbued generations of archaeologists with a melancholic yearning to hang on to something, to archive everything, ideally in forensic detail [1] and create archaeological records of the material entities they encounter, particularly through fieldwork, and especially through excavation.

Recently, we have witnessed a fundamental shift in archaeological thinking from essentially epistemological questions about the nature of archaeological knowledge and how we secure it to ontological deliberations concerning the nature of archaeological entities [2]. For example, Gavin Lucas' very sophisticated exploration of the nature of the archaeological record elaborates on one central question: "What is the ontological relationship between 'methodological' concepts like stratigraphy and typology on the one hand and current 'theoretical' notions like materiality and agency on the other" [3, p.3]. Many concepts embedded in this text are rematerialisations of his sustained analysis. The unique aspect of this paper is that it attempts to expand on Lucas' seminal work in the domain of archaeological computing: that is, the *digital* archaeological record.

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I begin by offering a brief review of Gavin Lucas' characterisation of the archaeological record as a product of contending processes of materialisation and dematerialisation. Against this backdrop I then show how digitalisation and additive manufacturing technologies, known commonly as 3D printing, have the potential to redefine the nature of archaeological entities in the digital. This discussion leads me, finally, to propose a grand disciplinary challenge to build a new framework for recontectualising archaeological entities encountered in the field.

Materialising the Archaeological Record

The term 'archaeological record' has many possible meanings, but as Lucas shows they may usefully be condensed down to just three: the first connotation is that of material culture, materiality or artefacts understood in their broadest sense; the next meaning is expressed in terms of how deposits and assemblages come to be, something he labels as "formation theory"; finally there is the archaeological record as constructed in the present, also known as the archive. Lucas contends that all three aspects of the archaeological record need to be considered as an imbricated whole, because viewing any one facet in isolation can lead to fundamental disconnects or an "interpretive dilemma, in which explanations often hover between vacuity and incommensurability" [3, p.169].

Lucas seeks an alternative to this fragmentation of approaches by offering a new agenda of mutually constituting archaeological 'interventions' and 'entities'. In this account, the practices of the field archaeologist are not so much data collection but interventions, or material interactions, in which tools and procedures are mobilised locally to materialise new entities or artefacts (e.g. drawings, samples, photographs, context sheets, field diaries, finds and reports); it is these new, mobile, dynamic assemblages of autonomous objects that become archives. Lucas builds on Manuel DeLanda's assemblage theory [4], (which draws on the philosophy of Giles Deleuze and Felix Guattari), to rethink and deepen the concept of the 'archaeological assemblage', whilst still successfully encapsulating the interplay of its two traditional affinities of depositional and typological groups. In this reworking, assemblages are articulated in terms of external relationships, such as their relations to their environment and other assemblages, as opposed to the internal configurations of their component parts, which are recognised as having a certain amount of autonomy, insofar as they can move between assemblages and recombine elsewhere in other spatiotemporal contexts. Indeed, "Almost all, if not all, objects are strictly speaking residues of prior assemblages" [3, p. 204].

Central to Lucas' account of how an archaeological site is translated into an archive as the result of archaeological interventions are processes of materialisation and dematerialisation (see Figure 1), "in which objects and people are made and unmade, in which they have no stable essences but are contextually and historically contingent" [3, p.166]. Materialisation, or inscription, is characterised as a stabilizing force of assembly, one that pulls things together and organises them. Here, depositional processes (called containment or territorialisation) cohere to assemble, or gather, things in specific places. Complimentary processes (called enchainment or coding) cohere to generate recurring associations such as typological similarities or repeated find combinations. The symmetrical opposite of materialisation, is dematerialisation, a destabilizing, disassembling, or erasing, force characterised by the dual processes of exposure (or deterritorialisation) and dispersal. This entropic force pulls apart, separates, and displaces materials and artefacts from their original setting. These two forces are always in tension, one side fostering aggregation, persistence and continuity, the other producing gaps, absences and discontinuities. It is this conception of materialisation that enables Lucas "to conjoin what was previously separate: the ontology of things (i.e. materiality) and their biographies (formation theory)" and to argue that "the material world is, at any given time, an archive of this process of (de)materialization" [3, p.205].

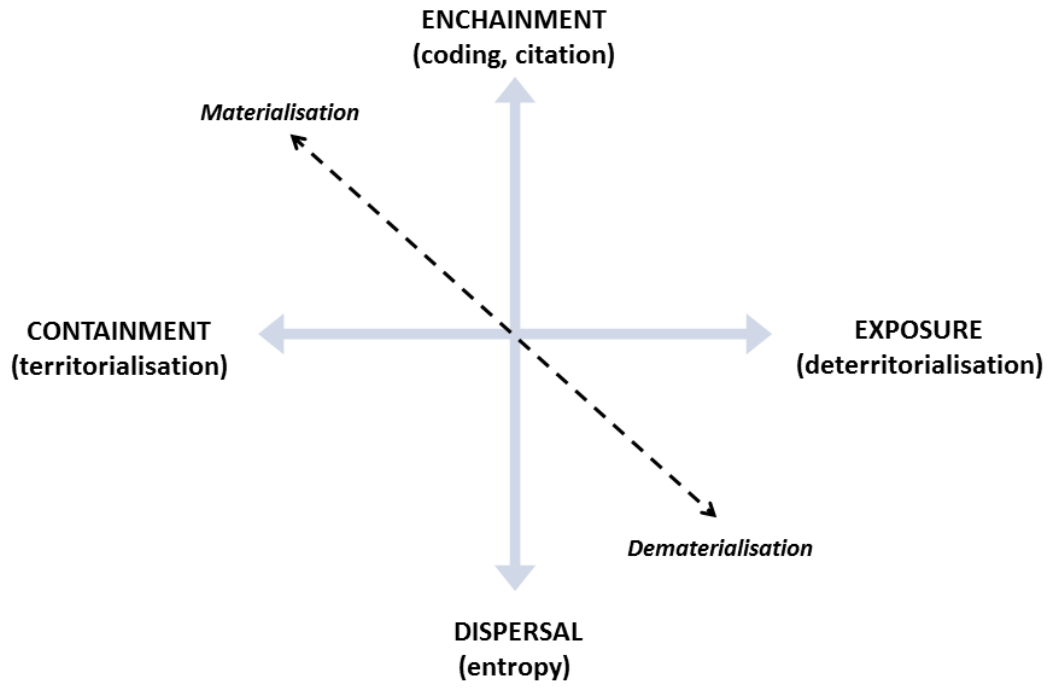

Figure 1. Materialisation versus Dematerialisation grid of forces (After Lucas [3, p.213])

Disrupting Material Discourse

Archaeology is material discourse *par excellence* and, as such, when an effective new technology is introduced into the archaeological mix, changes in practice and outlook are likely, and new insights are to be hoped for, as a new discursive iterability comes in to being. Until recently, archaeological objects materialised in the field (*i.e.*, artefacts, specimens, samples, photographs, drawings, plans, sections, descriptions, conversations, reports, etc.) were moved through archaeological laboratories, departments, museums, conference halls and publishing houses, following well known ways and observing tried and tested conventions. Such familiar choreography helped to solidify and stabilise the sites, the artefacts and the assemblages thus exposed within the world of archaeology [3, p.245, 5]. By contrast, a discontinuity, such as a new set of apparatus, or the introduction of new actants[1], may cause previously invisible tacit and stabilised knowledge, characterised by Bruno Latour [6] as 'black boxed', to re-emerge, explicitly, and briefly be exposed again for critical reconsideration, and perhaps reappraisal, thereby unsettling the quotidian symbiosis that is being constantly re-enacted in the self-replicating topology of the archaeological archive. For example, Lucas observes how the archaeological section is cut as a vertical face because we are predisposed to read it as a drawing, and more generally "the way we sculpt a site, the way we intervene with it, is set up precisely for the manner in which we read it in translation [3, p.239]. However, occasional windows of disruptive practice offer us another chance to reassess those entangled apparatus, techniques, methods, tools, truths and theoretical assumptions [7], those 'circulating references' [8], before they are again reified within the instruments, technology and praxis of contemporary archaeology. We are also presented with an opportunity to reflect on the ontological multiplicity of the 'new' multifaceted, 'extended assemblages', which emerge when things intra-act with one another in new ways, and thereby make a new translation, a new instantiation [9].

One potentially radically disruptive technology for archaeologists called, generically, *additive manufacturing*, but popularised and hyped now as *3D printing* and *rapid-prototyping*, has been emerging for decades, and encompasses a set of mature technologies which have long since passed over the peak of inflated expectations, through the trough of disillusionment, and are steadily advancing up the slope

of enlightenment to the stable plateau of productivity [10]. Additive manufacturing is disruptive for archaeologists because it poses a number of problems for conventional understandings of materiality [11-12], and especially the so-called archaeological record. In particular, concepts such as *real*, *virtual*, and *authentic* are becoming increasingly unstable as archaeological artefacts and assemblages are digitalised, reiterated, extended and distributed through time and space as 3D printable entities [11, 13-14].

Evolving Additive Manufacturing

At a very high level, the huge array of available additive manufacturing technologies can be loosely classified into three groupings. (For a full treatment see [15]). Selective extrusive printers in essence squirt, squeeze or spray pastes or powders through nozzles, syringes and funnels of all sizes to build up objects by depositing materials in layers. Selective binding printers by contrast, fuse, bind or glue materials together, again in a layers. The aforementioned technologies can, in one sense, be seen as producing analogue printing or additive manufacturing outputs using digital controllers. Currently at the cutting edge is true digital assembly using pre-manufactured physical objects. We can think of them as LEGO blocks. However, precise assembly of billions of small physical voxels made in different and multiple materials remains a huge computational and fabrication challenge. Of course, hybrids, deploying multiple print heads, deploying various different fabrication methods, could also be configured.

Hod Lipson and Melba Kurmar [15, p.265] summarise the evolution of additive manufacturing as three 'episodes' of gaining control over physical matter: control over geometry, composition, and behaviour. First is an unprecedented control over the geometry, or shape, of objects. 3D printers can already fabricate objects of almost any material in any shape. Next is control over the composition of matter. We have already entered into this episode where we go beyond just shaping external geometries to shaping the internal structure of materials with unprecedented fidelity, with the possibility of printing multiple materials including 'entangled components' which can be co-fabricated simultaneously. The final stage is control over the behaviour of materials, where they envisage programmable digital materials – made of discrete, discontinuous units – which are designed to function in a desired way, such as spongey, transparent, specular, shaded from grey at the top to brown at the bottom, maybe even embedded with nano-devices or other specifiable types of inclusions (see also [16, 17]). Voxel-based printing affords the notion of different types of voxels [18]. Consider the possibilities of a library of voxel types with archaeologically-defined materials and properties (e.g., compact, light brown, silty clay, with sparse white, coarse, sub-angular, components, etc.).

Archaeological Simulacra, Distributed Artefacts and Extended Assemblages

Control over *shape* provides a bridge between existing 3D modelling formats and the ability to repurpose them as 3D printed physical objects. Existing point clouds, terrain and solid models, indeed any system that can output STL format files can be 3D printed. Consequently, geometrically accurate 3D printing of artefacts [19], stratigraphy [20], monuments [21] and landscapes [22] is already established technologically. What is more interesting here is the range and depth of impacts additive manufacturing technology might have on archaeological practice and theory.

3D printing fundamentally changes our embodied intra-actions with the finds record and other archaeological assemblages [23-24]. Paola Di Giuseppantonio Di Franco *et al*, for example, demonstrate that 3D prints offer museum visitors an effective way to "increase perception, understanding and engagement through a tactile embodied experience" with printed artefacts [24]. The Smithsonian Museum is expanding its 'contact zone' by embarking on the ambitious X3D project, which aims to digitalise all 137 million iconic items in its collection, and make libraries of them available for 3D printing anywhere in the world [25, pp.5&32]. What is the ontological status of these new printed objects and the code describing them? Recent

applications in the study of cuneiform tablets and archaic bullae may cast some illuminating sidelights onto this question.

Cuneiform tablets are the world's oldest known writing system. Older still are bullae, a form of Mesopotamian record-keeping technology in which accounting tokens were sealed inside hollow clay envelopes. Intact bullae are extremely rare. Export of these fragile and priceless artefacts from their modern countries of discovery, or between major collections, is unsurprisingly restricted. Nevertheless, specialists all over the world want to examine every minute detail of the characters, but photographs and drawings are generally regarded as inadequate transcription [26, p.151, 27, p.176). Accessing the interiors of the bullae is only conceivable using non-invasive methods [28]. One promising approach currently being developed combines CT scanning and 3D printing capabilities to enable detailed visual and tactile examinations with minimal handling so that originals can be safe guarded [29].

Categorisations such as *replicas*, *copies* or *imitations* do not sit comfortably with these newly printed objects which burst free of such procrustean registers to be (re)printed, endlessly, in different materials, at different scales, with enhanced morphological features, with different material properties, in multiple spatio-temporal locales. Another way to think of them is as simulacra, that is having superficially similar skins to the prototype tablets and bullae, but made differently and intended for a different purpose, and embodying more potential for innovation and the creation of new identities [30, pp.56-57]. Each separate identity and purpose becomes an instantiation, a tangible, materially vibrant, reiteration, of a "distributed object" [27]. Simulacra are not restricted to impersonating artefacts. Nor are they confined to archaeological archives. In fact, they abound in the discipline's circulating references; appearing in the guise of photographed features (e.g., pre-excavation and post-excavated trowelled surfaces and sections). They crop up frequently as computer generated surface models draped with texture maps. Indeed, they figure in almost every topographic or building survey, photogrammetry, and the multitude of other techniques that record some aspect of the *surfaces* of archaeological entities. The point is, however, they are just husks bearing a superficial resemblance. Underneath, their true nature and substance is misplaced.

Returning to the 3D printed archaic bullae, these new originals can, for example, be broken open to reveal the accounting tokens previously locked within the belly of the prototype to instantiate further assemblages for study. But what have we instantiated; a virtual or an actual entity? The answer is both and, as such, as Victor Buchli [11, pp.281-282] highlights, conventional modern understandings of materiality now pose a problem since "the digital representation and the physical thing are difficult to meaningfully differentiate". However, although material things "remain and last as long as the material of which they are made of lasts" [32, p.206], these physical objects are subject to decay, damage and mishandling. Ultimately, and perhaps ironically, it is the 'immaterial digital code' that emerges as the most *stable entity* between and betwixt virtual and physical worlds [11, pp.281-283]. Although buried under a deep stratigraphic sequence of software layers, in fact the code actually exists on a physical inorganic substrate. The code can be conceptualised as "a second-order form of materiality" [33, p.122]. Nevertheless, the act of inscription using this multi-sensorial mnemotechnology is indeed *orthothetic* in nature [34] as it captures the 'exact' spatial pose of some material entity or assemblage - from one unique fleeting moment of time - and makes it available, in code, exactly as sampled, theoretically for all time.

According to David Berry, the ontological rift between software and material is perhaps beginning to be bridged: "While many objects remain firmly material and within our grasp, it is easy to see how softwarized forms of simulacra lie just beyond the horizon" [33, p.95]. Simulacra afford surfaces, and their appearance, or aesthetic, a special place in the archaeological record [35]. The bullae, however, are more complex and draw attention to the concept of *boundedness*; inside and outside. They raise questions about the nature of the archaeological record when the excavated 'material' is composed of interior 'spaces'. Sometimes a bounded space denotes the inside of a place, such as a painted cave, or of an object, such as the manipulated inside walls of the bullae. Juxtaposed to these are negative spaces, or voids, delimiting exterior boundaries, often indicative of dematerialisation. Immaterial, yet, at times, they remain profoundly intransigent, absence-presences. For example, the poignant, entombed hollows at Pompeii; those fossilised echoes of the final

moments of the people who succumbed to a pyroclastic surge and were then immured within the ashes of Vesuvius [14]. Empty moulds or reservoirs full of mortal terror, neither structure, nor artefact, nor deposit, they sit on the cusp of being either (or neither) positive or negative stratigraphic features. Ontologically ambiguous, stratigraphically a collection of sealed contexts, this immaterial assemblage is simultaneously earlier, co-terminus, and later than the layer of volcanic spew.

Boundaries can also be ambiguous in virtual archaeology. Paradoxically, although the additive manufacturing digital code is orthothetic, the encoded entities are actually extremely permeable and extensible. Whereas the limits of the physical objects may be clearly defined surfaces, the boundaries of the digital object are drawn by the same file format in which they are encoded, that is the same digital code that marks the content and the voids. Such digital artefacts and assemblages besides being porous are easily networked, replicated, aggregated, augmented, processed or transcoded into other formats [33], and thereby extended. They are also susceptible to new kinds of exploration and analysis. Indeed, they can be reconceptualised and recontextualised.

If the immaterial orthothetic digital code for the mere *husk* of an object can give rise to such rich material and discursive intra-actions, imagine the transcendental potency that might be obtained by encoding the substance, including the interstitial structures, compositions and relationships buried beneath the skin of these material *things*. Hidden within are hitherto unknown caches of material and immaterial possibility. It should also be acknowledged that these artefacts do not exist naturally in splendid isolation. Instead they are entangled with other *things* and constrained by the contexts from which they emerge. Conventionally, archaeologists describe these associated things as an 'assemblage', a loosely defined concept which commonly refers to either a collection of things attributed to a common find-context or a collection of things grouped together on the basis of typological similarities [3, pp.193-198]. In either case, however, different configurations are discernible depending on where in the matrix of relationships between these things, their context, us, all our apparatus, and theoretical assumptions, the phenomenon is studied. As Chris Fowler puts it: "Each time we instantiate a network, assemblage, or phenomenon, it is different: a unique configuration. Yet ... many of the components, actants, intra-actions, and so on do endure in similar ways from one instantiation to the next. One assemblage bleeds into others. These 'new' assemblages are not exactly the same as the previous instantiations, but some of their properties seem to endure from one set of relations to another." Thus extended and distributed these entities are in turn available for extensive reiteration [9, p.242].

By locating our investigations within these contexts and looking out and around as well as inside the assemblage - using whatever apparatus is available, and constraints notwithstanding - we still find ourselves surrounded by other assemblages of entities being extended through countless constellations and topologies, themselves subsumed within, and once again constrained by, both overlapping and nested assemblages [4]. Perhaps then this enduring code, associated with a Digital Object Identifier (DOI) might be both a fertile, as well as persistent, place to situate, locate and recontextualise archaeological entities; to develop new virtual archaeological archives, and by so doing engender novel reiterations of the archaeological record.

How high dare we reset our aspirations? The bar is seemingly set too low with simple reiterations of artefact geometries and their superficial properties. This is, however, not to decry the possibility and value of preserving the forms, and other aesthetic elements of artefacts, buildings and landscapes as a safeguard against the possibility of the physical originals being damaged, disfigured, stolen or destroyed. Several iconic sites, such as the Lascaux Caves and the Tomb of Tutankhamun, famously demonstrate that large numbers of people are ready to negotiate with convincing cultural patrimony substitutes when the original is unavailable. Nevertheless, I would argue that archaeologists should aspire to produce even more complex, weightier, solid, materially vibrant, and empirically engorged instantiations. In other words, to 3D print archaeological contexts and their associated assemblages. At once we are confronted by fundamental questions concerning the nature and characterisation of archaeological entities, contexts or assemblages. Therein is the paramount challenge.

Towards an Additive Archaeology

As additive manufacturing evolved from producing primarily single-material, homogenous shapes to producing multi-material geometries in full colour with functionally graded materials and microstructures, it created the need for a standard interchange file format that could support these powerful new features.

The response was the Additive Manufacturing File format (AMF), an open standard for describing objects for additive manufacturing processes such as 3D printing [36]. What is striking about the AMF format is that it encapsulates many of the key descriptive elements found on the typical context and object recording sheets used on a modern archaeological excavation (e.g. Figure 2), but does so in much finer *spatio-compositional*, that is in both macro-morphological and micro-morphological, detail.

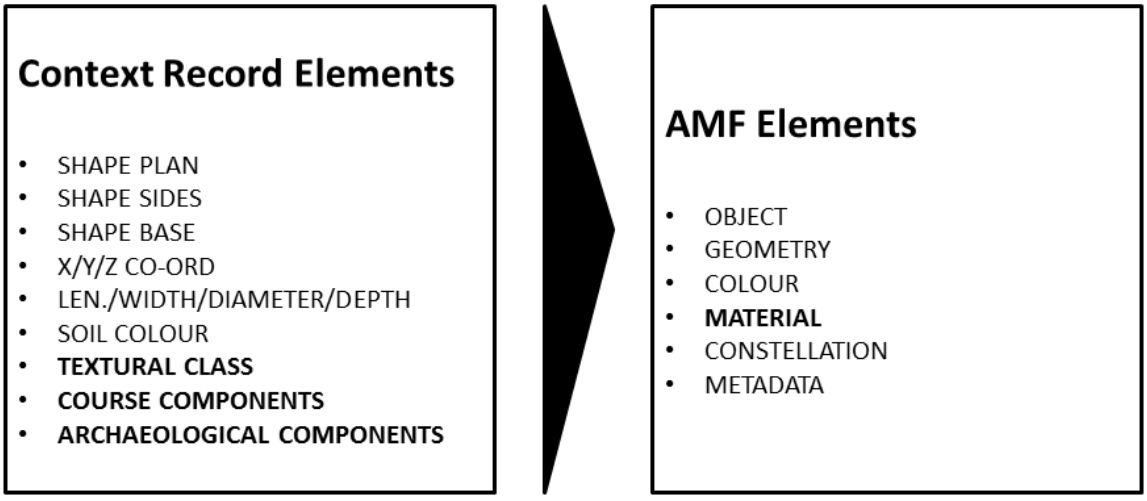

Figure 2. The AMF Format encapsulates many of the key elements of a standard archaeological field context recording template.

This technology challenges archaeologists to rethink how the archaeological record is materialised. By incorporating AMF-like concepts into archaeological recording practice perhaps we can better foster and promote a renewed multi-modal sensorial prominence and increased cognitive depth. Some will argue that existing procedures are adequate for current (epistemological) needs. However, in a uniquely destructive discipline, are we not ethically obliged to strive constantly for superior recording practices and access to the archaeological record that we simultaneously destroy and create? Christopher Witmore has articulated the value of *anticipation*, and it is very difficult to disagree with his assertion that "there is absolutely no excuse for not considering how archaeologists, or myriad other interested groups, will engage the material past 10, 50, 100 or more years from now" [37].

Contemporary archaeological discourse undoubtedly privileges the scopic, but this need not be the case [3, pp.237-244, 23, 24). What is to stop archaeologists from recording their excavations so that they could be refabricated in ways, for instance, that are not just synthetically haptic but authentically tactile, or perhaps made with the same material properties and characteristics and therefore also affording acoustic responses and auralisations? From a digital archaeology resource point of view, it would require prodigious amounts of computer processing power and storage, orders of magnitude greater than currently available (depending on the resolution we choose) not to mention the availability of versatile, multi-graded, multi-material fabrication units. The greatest obstacle, of course, will be the development of new techniques to collect the required data and the orthothetic code necessary to enable novel instantiations to be fabricated. This is not to suggest that all excavations *should* be 3D printed. The long-term value of this proposal will emerge from the experiences researchers will gain during the mission to refine, or re-engineer, the processes of archaeological field recording so that excavations, contexts and assemblages *could be* refabricated in

extremely fine and detailed three-dimensional definition. To be able to print a site for multi-sensual reiteration archaeologists will have to improve their methods substantively in order to achieve the kind of hyper-engorged empiricism implied by this new *additive archaeology*. In the shorter term, physically refabricated excavations could provide exemplary environments for highlighting ontological multiplicity, to articulate the epistemic virtues, or otherwise, of different exploration strategies, for developing archaeological skills, critical thinking and creativity. Besides their inherent capacity for near infinite reiterability, such material engagement offers a way to re-establish the *enactive context* needed to reproduce the cognitive processes that archaeologist enjoy in the field [23]. Such a physically, and intellectually, stimulating material interface to the archaeological record would provide, in essence, a multi-sensorial platform to explore the entangled apparatus, techniques, methods, tools, and theoretical assumptions of archaeological praxis. As David Kirch puts it "When we engage these material things, we do not just harness them, we actually think with them. They serve as material vehicles for thought" [38, p.121].

Glimpses of additive archaeology can be discerned already in the work of soil scientists and archaeologists conducting virtual excavations involving both scientific visualisations and 3D printing. For example, soil scientists using a combination of Computed Tomography (CT) and 3D printing now have the ability to explore the intricate and detailed structures of soils, and set up multiple experimental investigations [39]. Archaeologists are also producing ultra-high definition archaeological records. For instance, a coin hoard found in one of two pots near Selby in the north of England, can be non-intrusively disaggregated, separated, translated, re-aggregated and rematerialised. CT data, which can be resolved down to two microns, were processed to produce an animation [40] and 3D prints of some of the coins which remained *in situ* within the pot [41].

Challenges and Discussion

Additive manufacturing technology therefore offers the basis for a radical new generative framework within which to relocate and reconsider the nature of archaeological artefacts, assemblages and contexts. Additive archaeologies are already starting to destabilise our circulating references and disrupt both transcultural and disciplinary discourses and narratives. Direct access to these extended entities by almost anyone, almost anywhere, means that they may be (re)materialised in any transcultural space, and thereby effectively disintermediating the views, opinions, interpretations and 'authority' of archaeologists and cultural resource managers. A richer multivalent and ontologically fecund archaeology is emerging.

In this multi-vocal world, some actants could be marginalised and others brought to centre stage. The testimony of artefacts, assemblages and contexts, in particular, could be either disrupted or enhanced depending on the material qualities or properties around which archaeologists, curators or conservators decide to shape their interpretations. At this point, a hypothetical example might be useful. Take, for instance, the issue of preserving a desiccated codex. One curatorial intervention might be to conserve the artefact in its brittle condition of discovery. Alternatively, the curator might deem it more appropriate to request some kind of restitution to enhance the text or make the codex more robust for presentation. Formerly, the curator had to decide on the 'ideal state' or best option [42, Ch.7]. In the digitally defined record, however, a curator could pursue any or all of these options in tandem or in parallel. The encoded codex could be fabricated as a colourful, legible, document printed on a supple, yet hard wearing, material for the perusal of any visitor. Alongside it, the encoded codex could also be rendered in the precise form, with the exact same material properties, of the original artefact, as recovered, thereby creating an extended assemblage of contrasting material properties to facilitate comparison and engender critical discussion.

Archaeologists can and must make even greater efforts than they do today to improve the ways in which they intra-act and demonstrate the value we and our apparatus bring to this new multi-vocal environment. With this in mind, I would like to respond to Jeremy Huggett's [43-44] call for disciplinary grand challenges for the next generation of archaeologists. In my view, such challenges should be catalysts for renewed innovation, strength of purpose, more focused direction and increased momentum to research. I submit that *the 3D fabrication of an archaeological excavation* represents such a challenge for digital archaeology.

By which I mean that the refabricated excavation will be both a geometrically and compositionally accurate reiteration. A heuristic rematerialisation through which the curious can explore iteratively, reflexively and extensively the disaggregation and recomposition of archaeological entities encountered through archaeological intervention in such a way as to engender a virtuous, multivalent cycle of recontextualisation, analysis and synthesis. In striving to meet this challenge one can envisage the discipline establishing elements of an exemplary platform for strategic innovation affording the development, and structured introduction, of novel and distinctly archaeological approaches to understanding archaeological entities.

Where then to start? Of course, it would be premature to be prescriptive at this early stage. The issue needs to be discussed broadly, across multidisciplinary boundaries. We can, however, at least make a few high-level suggestions to help ignite the debate called for here. Not wishing to throw the baby out with the bath water, we could begin pragmatically and limit our scope initially to reiterating entities described by conventional archaeological practice. In other words those entities which stabalise existing circulating references (e.g., structures, artefacts, features, deposits, cuts, fills, etc., including *inter alia* texture classes, inclusions, compactness, colour and shape details). The difference being that now the *entire* entity, both macro-morphology (geometry) and micro-morphology (composition), will be described and reiterated in much finer, richer, three-dimensional detail, retaining the physical relationships of the artefacts, assemblages and contexts rather than abstracting them into specialist collections and reports. From this point we might attempt to define a new trajectory along which to characterise more sophisticated and amorphous entities (e.g., the graded changes often noted in a deposit's make-up, which are typically diffuse with no clearly defined boundaries or surfaces). Some constituents of the archaeological community might strike out in other directions looking for ways of characterising and 3D manufacturing even more intangible entities such as invisible, remotely-sensed *anomalies*. Moving further afield still, in this electronically connected universe of loosely bounded digital archaeological entities, one can envisage that previously unrecognised implicit patterns, (i.e., new entities and assemblages), will emerge as unguided, automatic, statistical or machine learning mechanisms crawl and sift through this exploding cloud of immaterial 'big data' [35, p.91].

One first step might be to secure a clearly delineated block of archaeology, say, a 1m cube of archaeological material and subject it to detailed tomographic and other scans and surveys. This will require a multi-disciplinary team of archaeologists, computer scientists, soil scientists, etc., to reverse engineer the archaeological entities thus created. Another approach might be to create multi-material printing definitions, specific immaterial code, enabling the context descriptions typically found in modern field archaeology units' field manuals to be (re)materialised by adapting approaches such as those being developed in the *Variable Property Rapid Prototyping* [16] and *Spec2Fab* [17] initiatives.

In the end, however, the lack of definition about what it means to *refabricate* an archaeological excavation is the essence of the challenge: *how do we characterise archaeological entities?*

Releasing the spirit of a new kind of virtual archaeology thus adds another technological nuance to the debate on the ontology of archaeology. Additive manufacturing provides a credible stimulus to current archaeological thought and practice, if we persist.

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Notes

Rather than using the terms "actor" and "interactions" I have adopted the neologisms of 'actant' (after Latour [6]) and 'intra-action' (after Barad [7]). Here an actant is any entity (archaeologist, material, object, apparatus, technique, theoretical assumption, method, or force) capable of affecting another entity. Intra-action refers to the mutually constituting, entangled effects of actants connecting, intersecting or otherwise affecting one another

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