Using network thinking to understand transmission and innovation in ancient societies

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I begin not with an ancient innovation, but with a modern one with which we are all familiar: the car. And I want to imagine how an archaeological perspective on this innovation might proceed. First, it would be a key form of evidence for archaeologists to understand 20th century society. Ubiquitous, with a complex and resilient materiality, it induced new forms of mobility that transformed nearly every social arena. Second, the archaeologist would seek to place it in its long-term context, as an innovation that was made possible not only by the invention of the combustion engine, but by wheel technology stretching back millennia, not to mention road technology of almost as great an antiquity.

But this 'archaeological' perspective on the car seems very far removed from how both scholars and laypeople view this innovation. For example, sociologists John Urry and Mimi Sheller, in their paper 'the new mobilities paradigm', argue that scholarship has largely failed to examine the significance of the car. This they attribute to a 'sedentarist' viewpoint in much sociology, geography and anthropology (Sheller and Urry 2006; though see Lemonnier 2012). The same could also be said of archaeology, which has not grasped mobility very successfully, but the point here is rather that archaeologists would certainly have latched onto the car because they are obliged to think of social change through the proxy of technological and material culture change, because that is all there is to work with. Sociologists have many other options, so why bother with the materiality of the car? And concerning the second aspect, the long-term, you will not find many accounts that take the story of the car back to the 4th millennium BC. Rather they begin in the 1880s, or at best the industrial revolution. However, one archaeologist *does* take the story much further back—as we can partially see in figure 1, which shows the earliest uses of the wheel in European prehistory—and I think that is very instructive (Hodder 2012). My point is to hereby underline two fundamental features of archaeological thinking on societies: they are focussed both on materiality, and the long-term. This would be true of the car and the 20th century were we archaeologists of the future, but is also pertinent to many significant ancient innovations, such as how the origins of farming and pottery are bound up with the first sedentary communities, and bronze metallurgy is tied up with the origins of complex society. In other words, we tend to think of long-term 'entanglements' of things, technologies, ideas and people when we think of communities and societies.

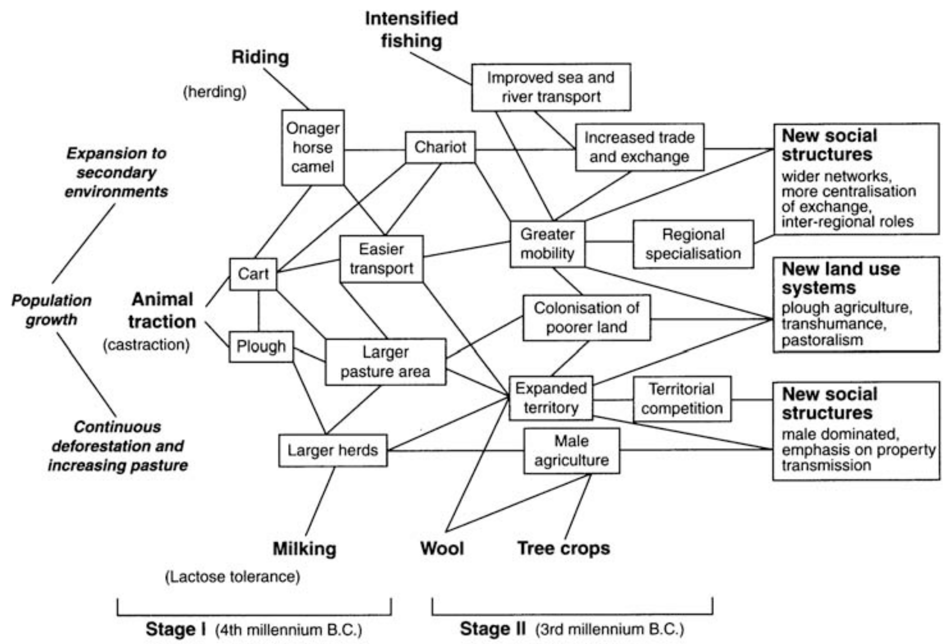

Figure 1: 'the introduction of the wheel in European prehistory' (Hodder 2012, in turn from Sherratt 1981)

This is a very general starting point. But it is important because it goes some way towards accounting for the rise in archaeology of 'evolutionary' approaches for explaining change. On the one hand, evolutionary theory obviously takes the long-term seriously. And on the other, "Darwinian evolutionary theory when applied to cultural change very clearly de-centers the human" (Hodder 2012, 139). So, for example, it is possible to identify a series of artefacts alone as a kind of cultural 'population'. If we use the example of stone projectile points, then small, random changes at the micro-scale of individual projectile point types, as they are 'reproduced' over space and time can, through selection, lead to changes at the (macro) population level, including 'speciation' (O'Brien & Shennan 2010, 9-10; see also Pitt-Rivers, figure 2). Evolutionary approaches fill a hole in terms of actually providing mechanisms linking micro- and macro-scales for *explaining* change.

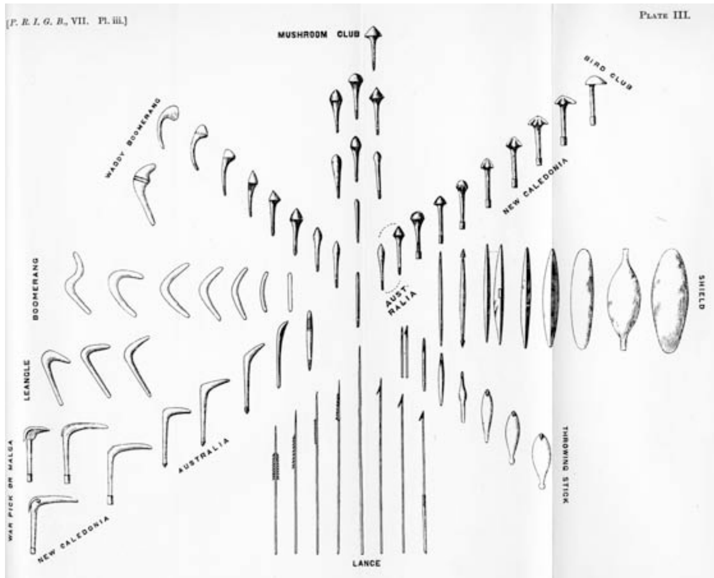

Figure 2. Pitt-Rivers’ artefact typologies.

However, the advantages they offer are offset by some serious disadvantages too. First is the question as to how a ‘new’ technology or form occurs. An evolutionary, phylogenetic approach maintains that technologies evolve incrementally through the ‘descent of form’ (and moreover that those incremental modifications conferring benefit are selected for). This model cannot account, however, for those very common instances of technologies or types that are not just versions of earlier processes or objects.[1] Archaeologists do not have very good models at all for these ‘revolutions’ in technology – but we can find a very helpful approach in the work of economist W. Brian Arthur, who takes examples of innovations like the jet engine, radar, or the laser, and describes them as ‘combinatorial’ (Arthur 2009). How *do* radically different technologies emerge? They are usually not completely novel, but combinations of already existing entities. Combinations do not occur randomly, but as a function of the structure of the system. One might think of the first pottery as combinatorial – it was not totally new, but piggybacked on preexisting ‘container’ technologies (gourds, baskets, wood, etc – see Knappett et al. 2010). Similarly, the first metals—in all their alchemy—probably piggybacked on

[1] Is technological change the same as typological change? It is conceivable that we should distinguish between process innovation and product innovation respectively In the Aegean Bronze Age, we see examples of both, and in many cases a new technology is bound up with a new type: so rotative kinetic energy in pottery production is used to make finer-walled vessels imitating metals, like carinated cups; and new seal types in hard stones are made possible by new lathe techniques. Other innovations to consider would be figurative frescoes and lime plaster, and new drinking forms like Ephyraean goblets and kylikes.

pyrotechnological expertise gained through pottery firing, and some of the earliest metal forms are actually skeuomorphs of stone axes. What is interesting here, especially in the context of work by scholars like Tal Dagan, is that Arthur has likened such combinatorial innovations to lateral gene transfer: though he says if it is rare in biology, it's the norm in technology (Arthur 2009). I am also intrigued by the use of network modeling in lateral gene transfer work since, as will become apparent, I am quite convinced of the validity of network ideas for exploring processes of technological change. Anyway, one could argue that such modifications in recent evolutionary approaches can accommodate 'lateral' technological shifts.

Second is the important distinction between invention and innovation, which is commonly made in practice-based approaches to technological change, but which seems to feature much less in evolutionary approaches (e.g. Shennan and O'Brien 2010). Individual technological inventions occur constantly. Many will never see the light of day beyond their localized context, perhaps remaining in the hands of a single individual. So how do some *inventions* come to be *innovations*, i.e. *transmitted* and hence more widely adopted? This process not only requires social relations, but also some kind of cognitive sharing. How this works remains pretty mysterious, and is an interesting lacuna in research, whether in economics, sociology, or archaeology. One explanation is that innovation is often studied 'a posteriori', after the fact, a perspective that cannot take proper account of the forward-facing moment of creativity (see van der Leeuw 2008).

And we can then combine these two points—technological invention is combinatorial, and needs to be brokered to become innovation—into a *third*, which goes something like this: technological inventions that combine existing ones in a 'fitting' way within the existing social/cognitive structure are more likely to be adopted and find themselves transmitted as innovations. This takes on board a very important critique by archaeologist Ian Hodder: communities generally don't decide on one technology over another because of the reproductive fitness it will confer, but because of its 'fittingness' within the existing technological framework (Hodder 2012).

So, those inventions that spread must have a good fit within existing technological practices and structures (see also Arthur 2009, chapter 2, on 'combination and structure'). An important observation that Hodder makes is that 'fittingness' operates across multiple scales, from micro-scale affordances to macro-scale coherences, in what he calls 'nested fittingness'. We can extend this into the domain of *learning*. At the micro-scale, some innovations require depth of learning for adoption, so we need to acknowledge the difficulty of individual learning in many cases – indeed what can be a matter of converting know-that into know-how. At a broader, 'meso' scale, we should acknowledge that such learning processes often require social support networks, or what have been called 'communities of practice' (Wenger 1998). And at a still broader 'macro' scale, inter-community connections may be significant for the 'brokerage' of disembodied information into embodied knowledge, and hence widespread dissemination.

These multi-scale demands on learning, and the need for nested fittingness, do not imply, though, that only small, incremental changes are feasible. The combination of two known but unrelated things into a third quite different thing can also have fittingness in some cases. It has even been argued that this is a fundamental cognitive process, as exemplified in the notion of 'conceptual blending' (Fauconnier and Turner 2002). One rather nice example, admittedly from science fiction, is the light sabre, a conceptual blend of a sword and a laser emitter (Li et al. 2012). A rather more mundane example is that of the queue, which Hutchins argues blends material and conceptual structure: "conceptually blending the physical structure of the line with an imagined directional trajector turns the line into a queue" (Hutchins 2005, 1559).

So, to briefly review, our approach is contextual, practice-based, and distributed. The agency for change (ie invention and then innovation, as contextualized practices) is distributed across people and things, and across multiple scales – which requires an acknowledgement of their complex entanglements. This being the case, we should expect in one setting (or entanglement; or network) a given technology may thrive, while the exact same technology will not catch on at all in a different setting (indeed, one might wonder then if one can even really call two technologies in such different contexts 'the same'). What I want to do now is try to illustrate this with an archaeological case study that shows how 'one' technology catches on in some areas in some periods, but not in others. Actually, archaeology is full of such examples (e.g. early farming, early iron technology). The case study I use here in the potter's wheel in the east Mediterranean, c. 4000 years ago.

Here we're dealing with a process innovation, and one that is not just incremental. It really requires a quite different conceptualization of the construction of a pot, through the use of rotative kinetic energy to draw up the vessel walls. We do not have many workshops excavated, and have just a few wheel devices recovered, so the actual technical set-up is not very clear. We mostly have to work from the forming traces on the vessels themselves.

The default assumptions for this innovation are that a) it first occurred in the Near East, and spread from there, and b) it is much more efficient than coil-building, so as soon as it becomes known to potters, and they need to increase production (because of growth of demand through urbanization), it will be adopted. Yet recent work has shown the spread of this innovation to be rather less predictable than these assumptions would suggest.

First, even in the 'Near East' it is not a simple question of an unfolding of the technique over time. Work by Valentine Roux in the southern Levant shows that it comes and goes, and is actually quite fragile. Here the innovation of wheel-fashioning is first seen in the Chalcolithic period (c. 4000-3500 BC),[2] used principally for making ceremonial bowls. With the start of Early Bronze (EB) I, c. 3500 BC, the wheel technique disappears amid significant settlement contraction and other cultural changes. It then reappears centuries later in EB II, c. 3000 BC, and continues into EB III. However, wheel-fashioning was only responsible for about 3% of the pottery in use, at least as represented at one of the

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[2] Note the early date, probably earlier than the first use of the wheel for vehicles (c. 3400 BC). What is the relationship between the two? The potter's wheel is not included in figure 1 above, and neither does it feature in other discussions of the invention of the wheel for transport, such as Bulliet (1990) or Anthony (2007).

principal sites of the southern Levant, Tel Yarmouth (Roux 2010, 227). Roux suggests that this points to only a very limited number of artisans using the wheel, a situation that persists for the next 500 years or so, throughout EB III. Another period of collapse ensues in EB IV, towards the end of the 3rd millennium BC, and again wheel-fashioning disappears, only to resurface some time later in the early 2nd millennium, “becoming predominant in the middle of the period (Middle Bronze Age II)” (Roux 2010, 227).

Roux has some interesting explanations for this pattern. Wheel-fashioning is a discontinuous invention that is organizationally demanding, and is only likely to succeed if supported by an elite – because it is costly to learn in terms of time investment and so it is highly probable that only a small number of artisans will acquire the skills, and produce pottery serving elite needs. This accounts for both the small percentages of wheel-fashioned pottery in most contexts, and what Roux calls the ‘fragility’ of the technological system, vulnerable to any turbulence in elite politics due to the very restricted size of the artisanal network. Roux also notes that some artisanal groups of this kind can be very ‘closed’ with highly circumscribed interactions with other artisans. Thus a closed and fragile system is very prone to this kind of boom and bust cycle. Her interpretation is actually quite compatible with the idea of fittingness.

And secondly, Roux makes the very important observation that it is not wheel-throwing as such, but wheel-fashioning, and so is more compatible in fact with pre-existing technologies of coil-building. This is because wheel-fashioning actually involves the application of rotative kinetic energy to coil-built rough-outs. The point at which the wheel is used to apply this energy can vary, such that it is used quite actively to draw each coil up, or only in the final shaping of a fully coiled vessel (Roux and Courty 1998). Such a technique is the kind of invention one might envisage emerging out of a long tradition of coil-building, though this is not to say that many archaeologists still imagine a process of wheel-throwing, i.e. the centring of a lump of clay on the wheel-head, from which a form is ‘thrown’. In most prehistoric contexts it is now apparent that this latter technique is hardly ever present.

Third, when one then looks at the possible 'spread' of this technology into the east Mediterranean, the picture is extremely varied – there is something of a mosaic of innovation over both time and space.

Figure 3. Map showing Cyprus and Anatolia (Oriental Institute).

Cyprus (figure 3), despite being closest to the Levant, does not see the potter's wheel for some time, and when it does, its use is quite spotty, with hand-building techniques continuing strongly (Crewe 2007; Crewe and Knappett 2012). In Anatolia (figure 3), the potter's wheel does see use quite early, from EB III (at sites like Kilise Tepe, Tarsus, and Troy). From there it then seems to spread to the Greek mainland (figure 4), but very unpredictably: at the site of Lefkandi in Euboea it does see some concerted uptake (Spencer 2010), while at Lerna in the Peloponnese it is only ever a small part of the assemblage, 2.5% at most (Choleva 2012), much like the situation described by Roux for Tel Yarmouth. And at the same time in the Cyclades, which sees some similar Anatolian influences at the end of EB II in the form of the 'Kastri group', we nonetheless see next to no uptake of the potter's wheel (see Nikolakopoulou forthcoming).

Figure 4 – the Aegean (after Interactive Ancient Mediterranean Web site).

Actually, the one big exception to this patchy picture is Crete (figure 4). Here the potter's wheel starts to be used for generating rotative kinetic energy c. 1950 BC – and there is no turning back. There is an extremely regular, uniform, gradual uptake and expansion of the technique, such that over the course of a couple of centuries, practically every single potter across the island is using the wheel for all his/her output. They begin just with small vessels like cups, then progress to taller and taller vessels with greater levels of difficulty, until eventually even the very large storage jars called 'pithoi' are being wheelmade. And the technique for all of these vessels, from the smallest cups to the largest jars, is not wheel-throwing, but wheel-fashioning, i.e. a combination technique of coils and RKE (see above; in Cretan context, Knappett 2004; Jeffra 2011). The wheel technique must have a 'fittingness' on Crete from 1900–1500 BC that it simply lacks anywhere else in the Aegean at this time. We need to understand this fittingness across a range of scales. At the micro-scale, it means that individual learning issues must have been overcome – for indeed, the wheel technique is not something that can be mastered at all easily, especially with what would probably have been rather unstable wheel devices, on a simple pivot. In turn, for the meso-scale, this implies that there must also have been communities of practice organized in such a way as to enable learning of new techniques, albeit within the framework of what we might imagine were quite structured apprenticeships. Furthermore, turning to the macro-scale, there must also at the inter-community level have existed effective brokerage of information into knowledge, for the initial invention to spread, and then indeed for the innovation to take hold so solidly for so many decades and centuries.

We might be a little more adventurous, and specific, in our interpretations. For example, the decision to invest in the skill needed for the wheel technique presumably took place in the context of the intensification of production, responding to increased consumer demand. Ethnographically, this is sometimes seen to entail a shift from part-time household to full-time workshop production. Moreover, this shift can also mean a change in the division of labour, such that pottery production changes from a mostly female to a predominantly male task. If one considers these and other related factors, then one might well think that there are a lot of things acting against such an innovation. So for the transition to occur so smoothly and so thoroughly as it does on Crete, suggests that production organization was already quite intense, full-time and specialized, so that the wheel was coherent within existing structures. Moreover, if we return to Roux's point about the fragility of an innovation when used by a 'closed' group with 'highly circumscribed interactions with other artisans', it is as if the complete opposite is the case for Crete – the way in which the innovation spreads across the island suggests instead a very open system, probably with much interaction among artisans, even between artisans engaged in different crafts such as stone, metal, basketry and textiles. As an innovation, its timing and nature invites us to think about the nature of Minoan society at the time, a subject attracting renewed attention, especially in terms of 'heterarchical' and 'House society' ideas. In short, scholars are now attracted to the idea that Cretan society was not the hierarchical entity that we imagine from the Near East. What would this mean for Roux's idea that innovation needs powerful elite brokers to take hold?

Anyway, there appear to be many factors working against innovation, suggesting that non-adoption is almost more normal than adoption. Certainly, this is the feeling one gets when considering the Cyclades. As we already mentioned, this island group does not see much take-up of the wheel when it comes from Anatolia and sees some success on the

Greek mainland. And now, a few centuries later, the islands again appear resistant. Crete is certainly in contact with these islands throughout the Middle Bronze Age – there are plenty of Cretan imports found on islands like Thera, Melos and Kea. And yet, there is absolutely no sign of any interest whatsoever in the wheel technique. That is, until around 1700 BC, towards the end of the MBA, which is when mere Cretan contact transforms itself into pretty deep Cretan influence – what has been called 'Minoanisation'. This describes a set of processes whereby Minoan culture from Crete is transmitted across much of the southern Aegean. Minoan architecture, weaving, pottery, stone vases, wall paintings – all appear outside of Crete as 'innovations' for the first time. Why does this happen, and why now? What does Crete gain from this, and what does the rest of the southern Aegean gain? Why is the transmission regionally diverse, such that the picture varies even from one island to another? And what role does Knossos play in all of this, seemingly not only the largest town on Crete at this stage, but also by far the largest site in the Aegean? Evidently there are new patterns of interaction, new socio-political configurations; on the one hand, choices are being made site by site on a local basis, but at the same time there is a wider logic behind it all. The Cycladic communities find themselves in new entanglements, new material networks, at a new scale, apparently driven by Knossos. 'The wheel' becomes a totally different kind of proposition to what it was two centuries previously.

If we try to explain this again in terms of the different scales of 'fittingness', then one would have to say now there must exist micro-scale opportunities for learning, meso-scale community changes, and macro-scale coherences. This probably means not only Minoan potters on hand to provide some kind of scaffolded learning, but also a sense that the technique is coherent with community values. And yet, there is a definite sense of resistance too: the wheel never fully replaces hand-building techniques, which remain in place, particularly for certain local wares. Which is interesting because it suggests that 'coherence' need not be total, but can be contested: some segments of the community resisted the wheel and what it meant – perhaps a matter of gender roles, or of a continued significance attributed to household production?

Regardless of the specifics of our interpretations, and however hypothetical, we do need to acknowledge the people-thing entanglements within which innovations have to cohere and fit. Hodder depicts such entanglements somewhat diagrammatically (see figure 5), though he resists calling these networks. He is explicitly concerned about what he perceives as the inability of networks to capture temporality – indeed he phrases it as their inability to get at the 'stickiness' of entanglements (Hodder 2012, 94). I would suggest that this is a matter of perception rather than of fact, as various recent studies in network science have shown ways to dynamicise networks for temporal evolution.

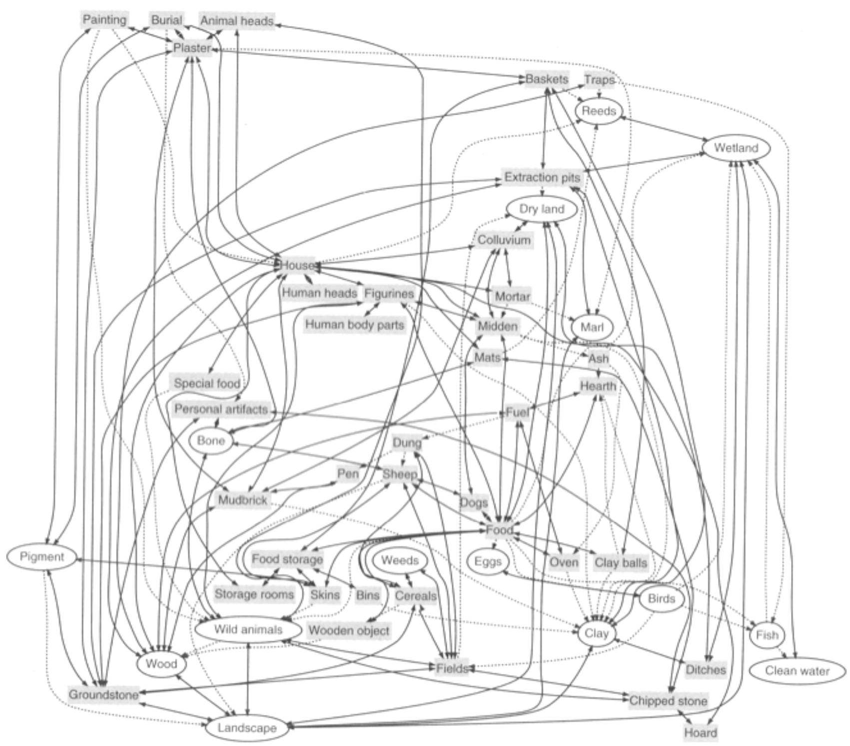

Figure 5 – entanglements at Catalhöyük (after Hodder 2012)

Personally, I am more optimistic than Hodder about the potential of network ideas, and have sought to develop network thinking in archaeological settings (Knappett 2011; Knappett 2013). However, doing so for artefact networks, or entanglements, is quite challenging, and up to now the 'network' component of this thinking is hardly formal at all, and more metaphorical (see *slides*). The justification for this is that it is more important to think clearly about the status of nodes and links than to apply prematurely some modelling techniques in which such choices can quickly become obscured by impressive visualisations. What *are* the nodes? What *are* the connections in assemblages? How does one thing lead onto another? If you start using the wheel to make some pots with thinner walls, and look like metal, thereby excluding others, and then those pots are used in some activities and not others, ceremonies from which some groups are excluded, what does that mean?

Network thinking, even in this rather loose sense, can certainly help us deal with heterogeneity of connections (people and things), with geometric and social space, and with time. Networks can also help us think across scales. Networks are both structured and dynamic. They can allow us to think about cognition and practice. Can we push the envelope though to think of more formal applications? I think we can. Indeed, networks *are* being used in archaeology more formally, principally to model interactions between sites at the regional and inter-regional scales. Typically in archaeology the practice has been to put the dots on the map, i.e. the locations of sites, and then somehow infer the kinds of interactions that occurred. Often a 'radial' or 'blob' model has been used, such that influence is imagined to radiate out from a site (Jennings 2006), the kind of thinking behind the use of Thiessen polygons, for example. This is problematic because it homogenizes space, and remains vague as to how sites would actually have interacted in the past. Network models have proven to be a useful solution to this problem, as they force us to think more explicitly about links: their directionality, strength, and frequency. So instead of just putting the dots on the map, a network model obliges us to then also draw links between them. There are different ways of doing this. One can draw real physical links that might be known in terms of road systems or itineraries. Another option is to use material culture proxies, such as the degree of similarity in pottery wares from site to site. Or one can be rather more hypothetical, and construct a model wherein all sites are potentially connected, but one wants to discover what benefit /cost there is to a site connecting with one site rather than another. This third option is basically what I have tried to do with colleagues from physics, in an attempt to understand some of the dynamics of Minoanisation.

What we have done is to create a very simple network of 39 nodes, representing what we think are the most important sites in the Aegean c. 1700 BC (figure 6; also Knappett et al. 2008). This is our basic input. We do not specify which sites are larger than others, nor which sites must connect. From there we wish to generate a set of outputs that will consist of a range of site sizes, and a range of connections, of differing strengths. How do we get such outputs from these simple inputs? We use a 'Hamiltonian' cost-benefit optimization model, which involves four parameters. Essentially, we try to balance the cost vs benefit of connecting with other sites, and the cost vs benefit of utilizing only local resources. So, for example, if we set our parameters such that there is high cost and low benefit from connecting to others, and high benefit and low cost from using local resources, our output will consist of a series of large sites that are completely unconnected to one another. There is simply no benefit in connecting. And one of our main assumptions, to be clear, is that the resulting 'network' or 'system' should, like many physical systems, find a low energy solution. At the other extreme, if we set our parameters in our model such that high benefit accrues from trade at little cost, we find outputs that are massively hyperconnected networks. Neither of these scenarios is particularly realistic, and it is the wide range of intermediate scenarios that interest us. When we make trade somewhat beneficial with some moderate costs, we are able to produce more 'realistic' networks that show strong local clustering, together with some weaker, long-distance links that hold the network together as a whole (see figure 7). What becomes interesting with these kinds of outputs is then to test how robust they are to small changes, to see which sites display consistently high connectivity or centrality, and which sites appear to act as gateways or hubs (Rivers et al. 2013). This has certainly been an invaluable exercise for us in grappling with Minoanisation, and trying to find new perspectives on why Knossos consistently seems central in these networks, the gateway role of Akrotiri on Thera, and the shifting dynamics of the network as one models increased costs in the wake of the Theran eruption (Knappett et al. 2011).

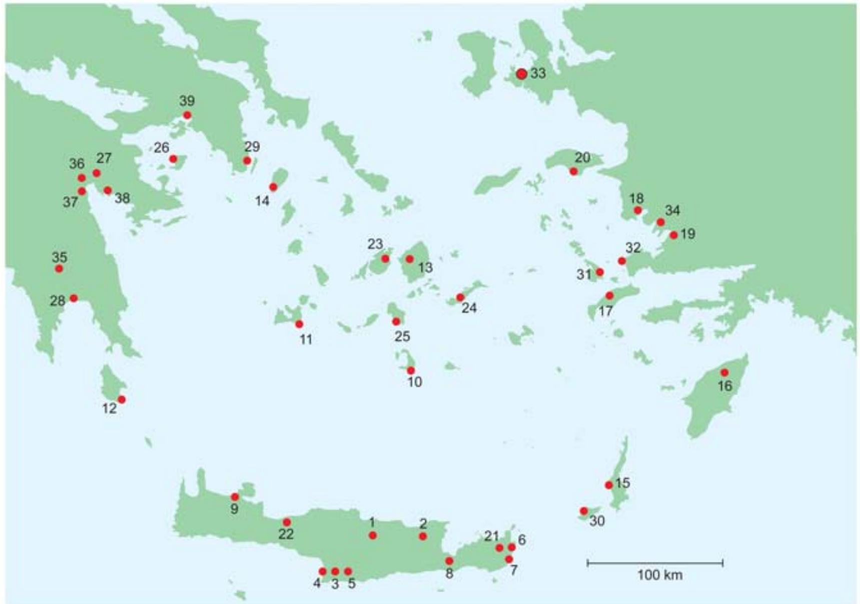

Figure 6 – key sites of Middle Bronze Age Aegean

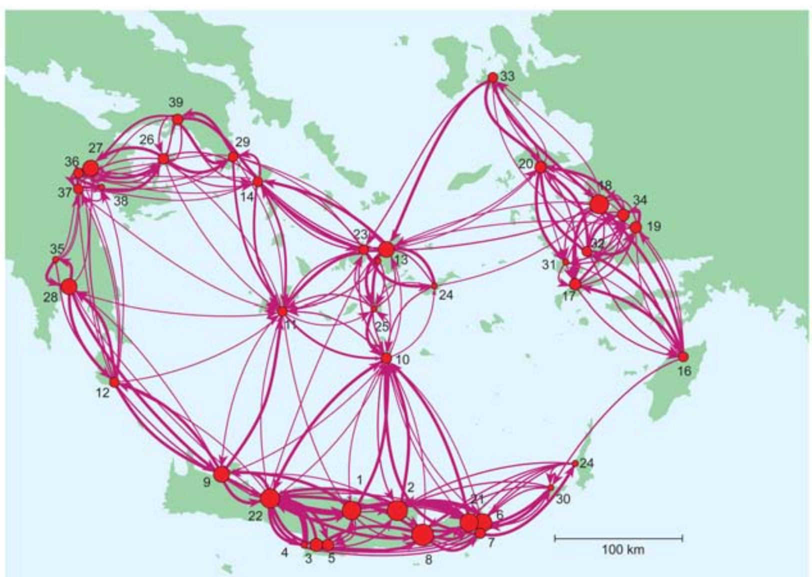

Figure 7 – network model output showing both local and regional connections

This is just one example of archaeological network modeling from my own research. Impressive work has appeared recently by Barbara Mills and her team on the US Southwest (Mills et al. 2013), as well as by Søren Sindbaek on Viking networks (Sindbaek 2013), and John Terrell in Oceania (Terrell 2010; 2013), to name just a few. All of these studies represent an important advance in our understanding of regional interactions, and indeed how systems of exchange and mobility evolve over time. However, archaeologists have as yet not quite made the same level of progress in using networks to throw light on people-thing entanglements, or what Lane and colleagues have very usefully dubbed 'agent-artefact space' (Lane et al. 2009). We basically need to dynamicise an agent-artefact network with costs and benefits to find where there is stability and where there is vulnerability. Why do some artefacts come and go, but some stick around? Dynamics of path dependence seem to have a lot to do with why some types and technologies persist while others are more vulnerable. It becomes a matter of trying to model entanglements, discovering something about their structure, and how the structure is related to the dynamics of the system. If we can do that, then we might be able to make progress with explaining innovations in a framework that is not reliant solely on 'phylogenetic' changes.[3]

By way of conclusion, we might note that 'network' approaches here highlight the interdisciplinary status of archaeology between the sciences and humanities. On the one hand, we have those network approaches in archaeology that are somewhat formal, and which adhere in some broad sense to a 'scientific' approach; and on the other hand we have those that are much more rooted in the humanities, and which use network as a loose metaphor for connectivity and interaction. The most satisfying archaeological interpretations, though, I would argue, are those that show sensitivity to, and engagement with, both of these poles. This is particularly relevant for this meeting, I feel, as the successful development of evolutionary models across the biological and sociocultural worlds can ill afford to gravitate towards one pole at the expense of the other.

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[3] Indeed, this was one of the principal objectives of the ISCOM project (ISCOM = Information Society as a Complex System), that is published in Lane et al. 2009, and which is an inspiration for the general outlook of this paper. The focus of ISCOM was modern innovations, such as those emerging from Silicon Valley, but with the hope that ideas like 'agent-artefact space' would also have traction for the social sciences more widely, archaeology included. Some archaeological case studies featured in the project, and although ancient datasets are inevitably more fragmentary than modern ones, this incompleteness served to provide worthwhile challenges from a modeling perspective.

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