Design Space and Cultural Transmission: Case Studies from Paleoindian Eastern North America

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Abstract Tool design is a *cultural trait*—a term long used in anthropology as a unit of transmittable information that encodes particular behavioral characteristics of individuals or groups. After they are transmitted, cultural traits serve as units of replication in that they can be modified as part of a cultural repertoire through processes such as recombination, loss, or partial alteration. Artifacts and other components of the archaeological record serve as proxies for studying the transmission (and modification) of cultural traits, provided there is analytical clarity in defining and measuring whatever it is that is being transmitted. Our interest here is in tool design, and we illustrate how to create analytical units that allow us to map tool-design space and to begin to understand how that space was used at different points in time. We first introduce the concept of fitness landscape and impose a model of cultural learning over it, then turn to four methods that are useful for the analysis of design space: paradigmatic classification, phylogenetic analysis, distance graphs, and geometric morphometrics. Each method builds on the others in logical fashion, which allows creation of testable hypotheses concerning cultural transmission and the evolutionary processes that shape it, including invention (mutation), selection, and drift. For examples, we turn to several case studies

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that focus on Early Paleoindian–period projectile points from eastern North America, the earliest widespread and currently recognizable remains of hunter–gatherers in late Pleistocene North America.

Introduction

Tool design is a long-studied aspect of the archaeological record—a fact that should come as no surprise, given that the record is often described in terms of tools of various types, each of which includes specimens of diverse shapes and sizes. As Bleed (1986, p. 737) points out, all technological systems "result from a design process." Archaeologically, design is almost always studied with respect to how a particular tool was manufactured for a particular use, with the term "use," or "function," implying interaction between the object and the environment and encompassing an almost infinite number of possibilities. Design variability in objects potentially affects their performance in any such interaction. In the case of stone tools, design is one component that determines how well they serve as, say, a saw or knife, or in the case of pottery, design is directly related to a vessel's efficacy in cooking and/or storage.

Studying design requires relating formal attributes and manufacturing aspects to patterns of use. Such a relationship is not always immediately obvious because oftentimes the manufacturing process itself is unclear or the functional variability of a tool can encompass a range of interactions. To overcome these obstacles, archaeologists have devised clever methods such as reverse engineering, experimentation, use-wear analysis, and mathematical modeling (e.g., Schiffer and Skibo 1989; Skibo *et al.* 1989; Whittaker 1994; Lyman *et al.* 1998; Brantingham and Kuhn 2001; Patten 2005; Waguespack *et al.* 2009; Boulanger and Hudson 2012; Eren and Lycett 2012; Lipo *et al.* 2012; Eren *et al.* 2013, 2014; Key 2013; Lycett and Eren 2013; Miller 2014; Key and Lycett 2015; Smallwood 2015).

Design is a *cultural trait*—a term that has long been used in anthropology as a heritable unit of information that encodes behavioral characteristics of individuals or groups (Driver 1973; McNett 1979; Lyman and O'Brien 2003; O'Brien *et al.* 2010). Because they can exist at various scales of inclusiveness and can exhibit considerable flexibility, cultural traits have many of the characteristics of Hull's (1981) "replicators"—entities that pass on their structure directly through replication (Lyman and O'Brien 1998; O'Brien and Lyman 2000, 2002a; Williams 2002). Replicators are theoretical units, whereas the visible effects of replication, whether behavioral or genetic, are empirical units (Aunger 2002; Shennan 2002). Those effects are manifest in artifacts, features, and other components of the archaeological record, and they serve as evidence of inheritance (and modification) of cultural traits, provided there is analytical clarity over how the units used to measure the inheritance process are defined (O'Brien and Lyman 2000).

Stimulated in large part by an ever-growing interest in the evolutionary relationship between biology and culture, the cultural-inheritance process itself has come into much

sharper focus (e.g., Boyd and Richerson 1995; Bettinger and Eerkens 1999; Richerson and Boyd 2005; Lipo et al. 2006; Mace et al. 2005; Borgerhoff Mulder et al. 2006; Mesoudi et al. 2006; Stark et al. 2008; Shennan 2009; O'Brien and Shennan 2010; Mesoudi 2011a; Claidière and André 2012; Eerkens et al. 2014; Lycett 2015). Central to this interest is *cultural transmission*—the means by which units of information make their way across the social landscape (Henrich and Boyd 1998; Shennan 2002; Mesoudi 2011a; Tostevin 2012; Lycett 2014; Jordan 2015). With respect to our purposes here, cultural transmission is the process by which humans inherit, modify, and pass on information about tool-design space, which, as we discuss in more detail later, is an *n*-dimensional hyperspace defined by the intersection of all possible character states of mutually exclusive characters exhibited by a set of objects.

There are several tools that are useful for examining design space, including the four we discuss here: paradigmatic classification, phylogenetic analysis, distance graphs, and geometric morphometrics. Although all four methods are seeing increased usage in cultural studies (e.g., Tehrani and Collard 2002; Gray and Atkinson 2003; Holden and Mace 2003; Jordan and Shennan 2003; Rexová et al. 2003; Lipo 2006; Beck and Jones 2007; Slice 2007; Gray et al. 2009; Coward et al. 2008; Jordan et al. 2009; Lycett 2009a, b, 2010; Buchanan and Collard 2010; Cochrane and Lipo 2010; Currie et al. 2010; Heggarty et al. 2010; Tehrani et al. 2010; Bowern 2012; Buchanan et al. 2012, 2014; Thulman 2012; Cochrane 2013; Knappett 2013; Lycett and von Cramon-Taubadel 2013; Tehrani 2013; Jennings and Waters 2014; Östborn and Gerding 2014, 2015; Smith et al. 2015), the fact that they are derived not from anthropology or archaeology but from other disciplines perhaps has limited a wider acceptance. The methods build on each other in logical fashion and allow creation of testable hypotheses concerning cultural transmission and the evolutionary processes that shape it, including invention (mutation), selection, and drift. As examples, we turn to several case studies that focus on Early Paleoindian–period projectile points from North America, the earliest widespread and currently recognizable remains of hunter–gatherers on the continent.

Before turning to that discussion, we take a brief look at design space not from the archaeologist's viewpoint but from that of agents making decisions about what to design and how to design it. We can never hope to get inside the heads of Paleoindian flintknappers, but we *can* call on an extensive body of theory about how humans acquire and transmit cultural information and then link that theory to two heuristic devices in order to characterize the kinds of inputs that were potentially available to those knappers when they were designing and manufacturing their tools. One heuristic is the *fitness landscape* and the other is a two-dimensional map of *decision making* that plots kinds of learning that underlie decision making against the clarity of risks and benefits involved in making a decision. We emphasize that our treatment of these topics is necessarily brief. Much of our work has been and will continue to be dedicated to exploring the issues in considerable detail, both generally (Bentley et al. 2011a, b; O'Brien and Bentley 2011; Bentley et al. 2014; Brock et al. 2014) and specifically with respect to the design and manufacture of Clovis points across eastern North America (Buchanan et al. 2014, 2015; O'Brien et al. 2014; Boulanger et al. 2015; Eren et al. 2015a; O'Brien et al. 2015a, b).

Design Space and Fitness Landscapes

We earlier described design space as an *n*-dimensional hyperspace defined by the intersection of all possible character states of mutually exclusive characters. Here, we simplify things a bit and think of design space as a three-dimensional landscape that contains peaks of varying height, with height being a proxy for *fitness*. When we use the term "fitness," it is in terms of the success that one design or segment of design—a "character," or "trait"—exhibits relative to another, with success measured in terms of how often something is replicated. As we explore in more detail later, fitness in this sense is a property of classes (Madsen et al. 1999), which are created through the intersection of character states. Although the fitness of classes as measured through differential replication is not *necessarily* linked to the fitness of humans—defined as the propensity of individuals to live longer, have more offspring, and the like—there is considerable evidence that the relative fitness of one tool design over another can affect the relative fitness of the agents using the tools (Leonard and Jones 1987; Dunnell 1989; O'Brien and Holland 1992, 1995; O'Brien *et al.* 1994, 2003; Lyman and O'Brien 1998, 2001; Ramenofsky 1998; Leonard 2001; O'Brien and Lyman 2003).

The replacement of the atlatl by the bow and arrow over large segments of prehistoric North America, albeit at different times (Lyman *et al.* 2008, 2009), is an excellent case in point. There now can be no doubt that the new technology led to fundamental changes in human relationships, including different strategies of warfare (Bingham *et al.* 2013). Another example is the introduction of a particular ceramic technology in the midwestern United States ca. A.D. 400—the beginning of the early Late Woodland period—that allowed rapid processing of oily and starchy seeds into porridges and gruels (O'Brien *et al.* 1994). If early Late Woodland groups began substituting these carbohydrate-rich foods for human milk, children could have been weaned earlier (Buikstra *et al.* 1986). Any resulting decrease in the lactation period would have allowed the birth rate to rise slightly, if only by one additional offspring per child-bearing woman (O'Brien 1987). Buikstra *et al.* (1986) do, in fact, note increased fertility during the early Late Woodland period.

Sewell Wright (1932, 1988) introduced the metaphor of a fitness landscape to describe the possible mutational trajectories that lineages take (evolve) from genotypes that lie in regions of low fitness to regions of higher fitness (Kvitek and Sherlock 2011). We can borrow this metaphorical landscape and adapt its features so that the highest peak on the landscape corresponds to the optimal design of something, and lower peaks correspond to designs that, although not optimal, are good enough for the intended function *at particular points in time*. The landscape also contains valleys, which correspond to designs that yield negative fitness. An example of the latter would be a stone spear tip that is so thin that it consistently snaps on the slightest impact—not the best weapon to have when facing a charging animal.

There might be any number of pathways that agents can take as they move about the landscape—a process that Kauffman *et al.* (2000) refer to as an *adaptive walk*. For example, the agent shown in green in Fig. 1 finds a method of producing more-functional projectile points and thus jumps from one peak to another, slightly higher peak. Further experimentation leads to an even better design, and thus he jumps to a still-higher peak on the design landscape. The agent shown in blue takes more steps, climbing and jumping along the way, finally landing on the highest peak and making
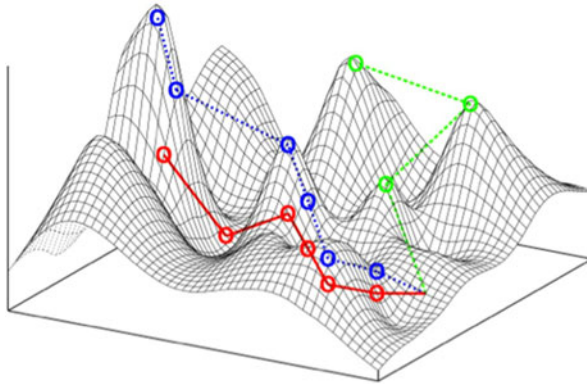
Fig. 1 Three agents taking adaptive walks on a fitness landscape (courtesy Randy Olson). This model is highly simplified in that it assumes a static landscape, which is rarely the case

his way to the top. The agent shown in red does well for a while but then takes a path that leads to lower fitness values before he rights himself and climbs halfway up the slope of the highest peak. This model is highly simplified in that it assumes a static landscape, which is rarely the case. As we will see below, the actions of other agents are constantly affecting the landscape as they adopt or do not adopt inventions. Those actions create "dynamic fitness landscapes" (Kauffman 1995).

Agents navigate across a fitness landscape using cultural knowledge acquired through learning—either individual learning or social learning, the latter defined as learning by observing or interacting with others (Heyes 1994). The behavioral sciences tend to emphasize social learning, which is not surprising given the extraordinary ability humans have for substantially accumulating socially learned information over generations (Tomasello *et al.* 1993), but this focus overlooks the fact that whereas social learning spreads behaviors, it depends on individual learning to generate them in the first place.

Humans use social learning for a variety of adaptive reasons (Richerson and Boyd 2000; Kameda and Nakanishi 2002; Laland 2004; Whiten 2005; Rendell *et al.* 2010; Bentley and O'Brien 2011; Henrich and Broesch 2011; Laland *et al.* 2011; Hoppitt and Laland 2013; Aoki and Feldman 2014; Aoki and Mesoudi 2015). Social learning is not only the basis for human culture, organizations, and technology (Whiten *et al.* 2011) but also a driver of cultural evolution, as humans continue to "learn things from others, improve those things, transmit them to the next generation, where they are improved again, and so on" (Richerson and Boyd 2005, p. 4). Lest we make it sound as if cultural evolution is "progressive," it is important to note that cultural transmission mechanisms and social learning "can exhibit runaway properties that lead to the rapid spread of nonadaptive or even maladaptive traits" (Jordan 2015, p. 29; see also Henrich (2004) and Enquist *et al.* (2007)). These are the valleys on a fitness landscape that we mentioned earlier.

In individual learning, agents modify existing behaviors through trial and error to suit their own needs. A learner might, for example, obtain the basic behavior from a parent or master and then begin to tinker with it absent any influence from other people. He or she might eventually pass on the behavior to another, less-skilled agent, perhaps a child. Boyd and Richerson (1985) refer to this as "guided variation." The guided-variation model shows that, in the absence of selection for a particular trait, a

population will move toward whichever trait is favored by people's individual-learning biases. This occurs even when the strength of guided variation is weak (Mesoudi 2011a). This form of learning is called "unbiased" (Boyd and Richerson 1985; Henrich 2001) because at the population level it approximately replicates the distribution of behaviors from the previous generation.

We can simplify the fitness landscape shown in Fig. 1 by removing the peaks, thus creating the flat, two-dimensional cultural landscape shown in Fig. 2. The new landscape is defined by *kind of learning* along the east–west axis and by *costs and benefits* along the north–south axis. Along the western edge, agents are purely individual learners—they use no information from others in making decisions. Along the eastern edge, agents are purely social learners—their decisions are based solely on copying, verbal instruction, imitation, or other similar social processes. In between the extremes is a balance between the two—a flexible measure of the agents represented. The midpoint could represent, for example, a population of half social learners and half individual learners, or each individual giving a 50 % weight to his or her own experience and a likewise amount to that of others. Location along the east–west axis may not always affect the equilibrium toward which each behavior evolves, but it will certainly affect the dynamics by which that equilibrium is approached.

We can compare the kinds of learning to the costs and benefits related to that knowledge. The farther north on the map we go, the more attuned agents' decisions will be to the potential costs and payoffs of their design decisions. A projectile-point manufacturer, for example, might quickly learn that a certain shape of a base makes a point susceptible to catastrophic failure and thus would likely change the design. Such a decision might be made individually, as shown in the northwest quadrant of Fig. 2, or there might be socially identified authoritative experts, as shown in the northeast
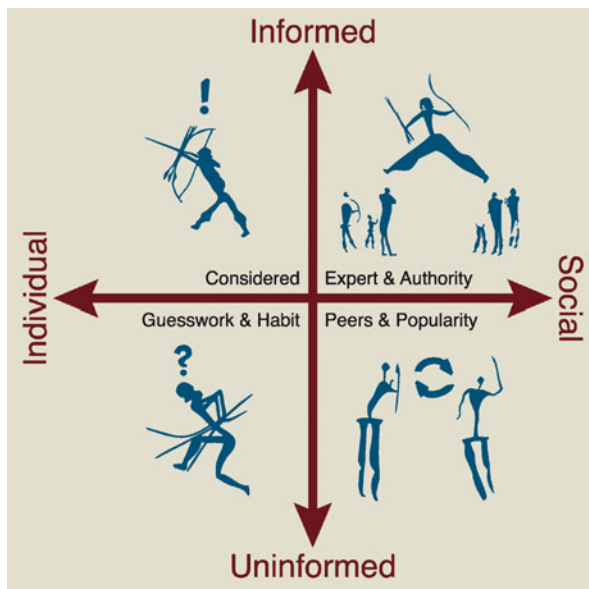

Fig. 2 A four-quadrant map for understanding different domains of human decision making, based on whether a decision is made individually or socially (east–west axis) and the transparency of options and payoffs that inform a decision (north–south axis) (after Bentley *et al.* 2014)

quadrant. As we move south, the relation between an action and its impact on performance becomes less clear. At the extreme southern edge of the map are cases that correspond to total indifference, where choice is based either on randomly guessing among all possible choices (lower left) or copying from a randomly chosen individual (lower right). This area of the cost/benefit spectrum represents cases in which agents perhaps are overwhelmed by decision fatigue—for example, when the number of choices becomes prohibitively large to be processed effectively.

We show this uncertainty in Fig. 3, which imposes our design-fitness landscape onto the map.[1] We represent degree of uncertainty by clouds, which, in the southern half of the map, begin to obscure the tops of some of the fitness peaks. Imagine that stone projectile points are variable in design such that some perform better than others for the purpose of, say, hunting bison. As the relationship between that variability and the performance for hunting bison becomes less clear to an agent, it also becomes less clear what changes might be made to increase the performance of a point. Thus, an individual learner is likely to produce variation in design that drifts from one form to the other. If an agent, however, learns socially, he or she may be able to use the actions of other agents as a guide, although they may be in no better shape to make informed decisions. As the connection between the variation produced and the outcome becomes clearer, agents can make more-informed choices, either singly or collectively.

One point worth noting is that as soon as an agent begins learning socially, he or she has moved from a simple fitness landscape—a static model of payoffs and costs—where technological invention is the result of a probabilistic search within a fixed population of possibilities—to a dynamic fitness landscape (e.g., Kauffman 1995; Kauffman et al. 2000), in which innovation, defined as adoptions by other agents (Schumpeter 1942), affects the landscape of invention, defined as the potential adaptiveness of current or new agent behavior. Agents who lack the information to relate variation with outcomes on a technological landscape are likely to get stuck on a local optimum or even in a technological dead end, often depending on exactly where an agent started the process of learning (Stuart and Podolny 1996; Lobo and Macready 1999; Kauffman et al. 2000; Mesoudi and O'Brien 2008a, b; Lake and Venti 2009; Mesoudi 2010). A technological optimum may not even exist on the design landscape (Kane 1996), and even when there are ephemeral, optimal solutions, it is never possible to completely map out a dynamic, complex design space, and optimal peaks can become suboptimal (O'Brien and Bentley 2011).

Humans use a mix of learning strategies, sometimes learning individually—we produce information—and other times learning socially—we scrounge information (Mesoudi 2008). When should we do one as opposed to the other, and how does the shift affect fitness? Based on our model of learning and outcomes, we expect that agents will learn individually when there is complete transparency in terms of cost and payoff and learn socially at all other times. But things are more complicated than that because rarely will there be 100 % transparency, and the rewards for some design solutions will vary. Mesoudi (2008, 2010), for example, demonstrated that individual learning was significantly more adaptive on a unimodal adaptive landscape, where

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[1] Our landscape here is strictly impressionistic and intended only as an example. Realistic three-dimensional maps of decision making that incorporate fitness peaks are extremely complicated to model (Brock et al. 2014).
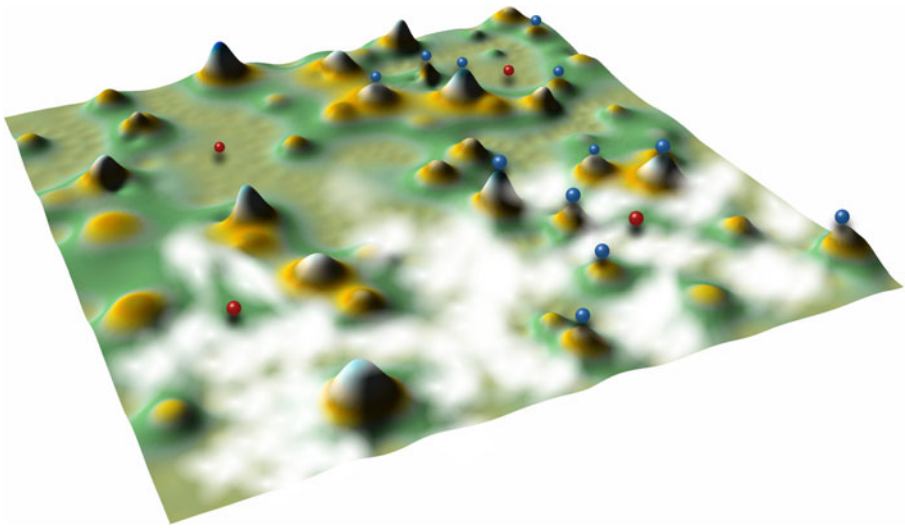
Fig. 3 The four-quadrant map shown in Fig. 2 with a fitness landscape superimposed (view is from the *southwest corner*, which is at the *lower left* of the figure). The presence or absence of clouds corresponds to the transparency of potential costs and payoffs of a decision. Agents are shown in *red*; potential sources of information from which agents can learn—other agents—are shown in *blue*

there is but a single optimal design or behavior, than on a multimodal adaptive landscape, where there are multiple locally optimal designs or behaviors of different fitness. In cases where there is but a single optimal solution, simple reinforcement learning will always lead to the best possible design or behavior, irrespective of starting point. In contrast, when there are multiple possible solutions, individual learners can become fixed on locally optimal but globally suboptimal design peaks, reducing the mean fitness of the population. Copying successful individuals allows agents to jump from locally optimal peaks found by means of individual learning to the globally optimal peak located by a more successful member of the population (Rendell *et al*. 2010, 2011).

Paleoindian Design Space

We use this brief introduction to learning and fitness landscapes to examine how design space was navigated by Paleoindian peoples who colonized North America during the late Pleistocene. The exact timing of colonization is open to question, but our interest here is in the period 13,300–11,900 calendar years before present (calBP), a time span commonly referred to as the Early Paleoindian period. We focus primarily on the first part of that time span—the Clovis period (see below)—which is marked by a distinctive stone and bone/ivory technology, prominent features of which are bifacially chipped, lanceolate projectile points used to tip spears that were thrust and/or thrown (Fig. 4). Clovis points were first documented in the American Southwest (Figgins 1933; Cotter 1937, 1938) and have since been found throughout North America, including Canada and northern Mexico (Anderson and Faught 1998, 2000; Waters and Stafford 2007; Goebel *et al*. 2008; Anderson *et al*. 2010; Prasciunas 2011;
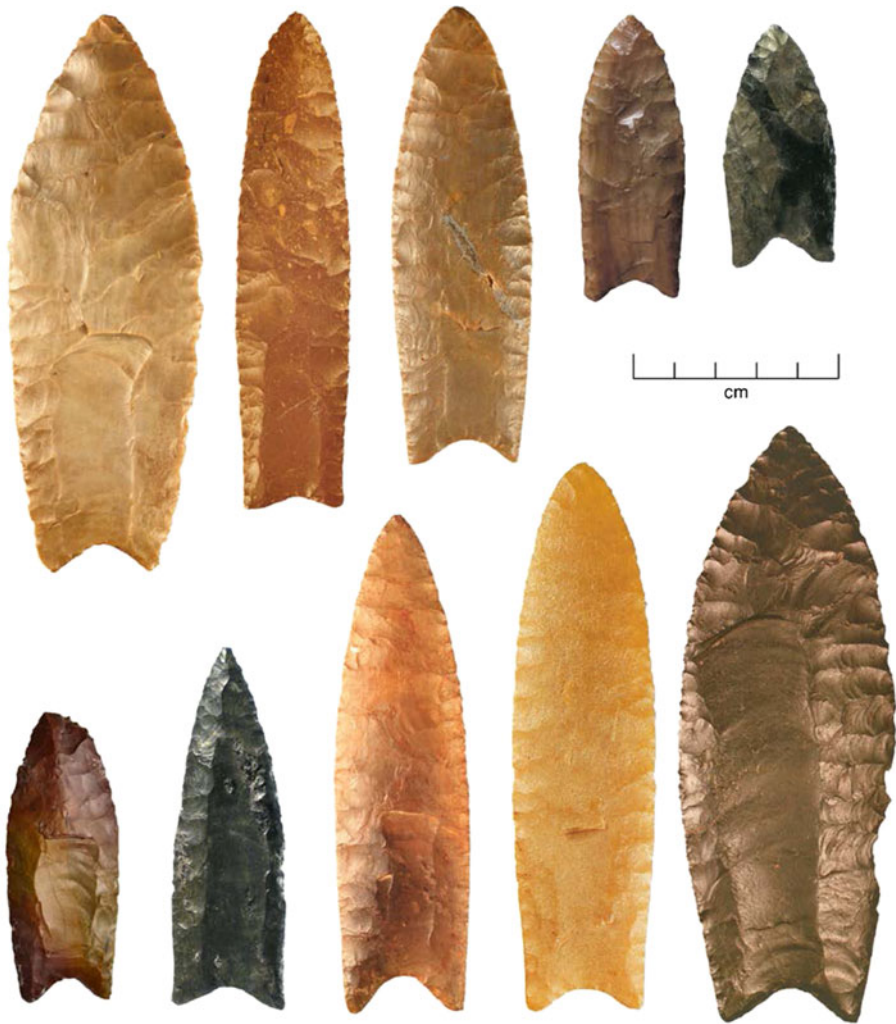
Fig. 4 Clovis points from various North American sites. *Top row* (*left to right*): Townsend Co., Kentucky; unknown county, North Carolina; Williamson Co., Tennessee; Lewis Co., Kentucky (courtesy D. Meltzer); Essex Co., Massachusetts (courtesy J. Boudreau). *Bottom row* (*left to right*): Barnstable Co., Massachusetts (courtesy E. L. Bell); Essex Co., Massachusetts (courtesy J. Boudreau); Humphreys Co., Tennessee; Green Co., Kentucky; Columbia Co., Arkansas. All images from Whitt (2010) unless noted

Buchanan *et al.* 2012; Smallwood 2012; Graf *et al.* 2014; Sanchez *et al.* 2014; Anderson *et al.* 2015; Smallwood and Jennings 2015).

Precise dating of the time span when Clovis points were made is anything but straightforward (e.g., Anderson *et al.* 2015; Fiedel 2015), but common practice is to place the Clovis period between ca. 13,300 and 12,800 calBP in the West and between ca. 12,800 and 12,500 calBP in the East, although more restrictive date and spatial ranges have been proposed (e.g., Waters and Stafford 2007). The difference in chronological ranges between the East and the West has been explained as the result of Clovis points originating in the West and then spreading eastward as the result of population movement (e.g., Hamilton and Buchanan 2009; Lothrop *et al.* 2011;

Morrow 2015; Smith *et al.* 2015). It seems highly unlikely, however, that the small sample of radiocarbon dates for the Clovis period has captured the earliest or latest use of Clovis points (Waguespack 2007; O'Brien *et al.* 2014; Prasciunas and Surovell 2015) in either half of the continent, so we use the ranges above as estimates.

Units and Design Space

One problem we immediately face when starting to examine Clovis design space is trying to figure out what exactly a Clovis point is. To many archaeologists, this will sound like a rather silly statement, given that knowledgeable researchers—not to mention artifact collectors—intuitively "know" what a Clovis point is. Perhaps, but consider Table 1, which lists seven descriptions of Clovis points, including one of the first general descriptions of the type (Wormington 1957) and a description of specimens from the Clovis type site, Blackwater Draw, New Mexico (Hester 1972). Although there are overlapping features among the descriptions, the only ones that are common to all seven—and which therefore might be taken as definitive—are that Clovis points have concave bases and fluted faces.

We are by no means the first to point out the lack of uniformity in the Clovis type (e.g., Haynes (1983), Howard (1990), Anderson *et al.* (2015) and various papers in Smallwood and Jennings (2015), especially Smith *et al.* (2015)). Faught (2006, p. 171), for example, in discussing the classification of Paleoindian points from Florida, noted that "fluted points are universally classified as Clovis, regardless of whether the base is straight or waisted, or what the basal shape is." Thulman (2012, p. 1599) makes a similar point, noting that types based on limited samples of isolated specimens "usually fail to capture the variation in point form due to manufacturing variability and resharpening. Appending suffixes such as '-oid' (ex., Folsomoid) or '-like' emphasize the variability but do not hone the definitions. Even though these problems are apparent and occasionally discussed…archaeology as a discipline has an inertia that keeps it dependent on 'type specimens' and traditional point descriptions." Finally, Anderson *et al.* (2010, pp. 69–70) note that Paleoindian projectile points are typically classified using a "plethora of stylistic and technological variants or type names, many of which are restricted to small areas or regions, or else are classified so generally (i.e., as 'Clovis' or 'fluted') or differently from region to region that potentially meaningful variability within these categories likely goes unrecognized."

Anderson and colleagues' point is difficult to overemphasize with respect to "meaningful," which for our purposes is defined in evolutionary terms. What accounts for variation in Clovis point shape? Is it the result of drift, by which we mean the stochastic accumulation of adaptively neutral changes (copy error) that are random at the population level (Morrow and Morrow 1999; Eerkens and Lipo 2005; Bentley *et al.* 2007; Buchanan and Hamilton 2009), or are there adaptive reasons that might have to do with environment and prey (Buchanan *et al.* 2014), especially the replacement of one kind of prey by another, such as occurred with mammoth and bison at the tail end of the Pleistocene (Buchanan *et al.* 2011; Bement and Carter 2015; Fiedel 2015)? What about a third possibility—that the differences reflect both processes, each operating at a similar or different scale (O'Brien *et al.* 2014; Eren *et al.* 2015a; Lycett and von Cramon-Taubadel 2015)? To answer these evolutionary questions requires that we

Table 1 Seven published descriptions of the Clovis point type. Note that the only commonality among all is that Clovis points are fluted and have concave bases

	Length	Width	Parallel sides	Convex sides	Concave base	Sides fluted	Basal constriction	Retouch	Basal grinding	Flute length
Wormington (1957)	1.5–5 in.		x	x	x	2			x	$\frac{1}{2}$–$\frac{2}{3}$
Ritchie (1961)	1–5 in.		x	x	x	1–2			x	
Prufer and Baby (1963)			x	x	x	1–2	Never			
Roosa (1965)		Max. at midline			x	1–2		Never		
Hester (1972)	2–6 in.	1–2 in.	x	x	x	2	Slight	x	x	$\frac{1}{3}$–$\frac{2}{3}$
Cox (1986)			x	x	x	2		Never	x	$<\frac{1}{2}$
Justice (1987)			x	x	x	1–2			x	$<\frac{1}{2}$

describe Clovis points in terms of a formal and technical design space as accurately as possible and map this design space across eastern North America.

The lack of uniformity in projectile-point types rests on a conflation of two kinds of units: *intensional* units and *extensional* units (Dunnell 1971, 1986; O'Brien and Lyman 2000, 2002b; Lyman and O'Brien 2002; Hart and Brumbach 2003; Nolan and Cook 2011). The former are defined, whereas the latter are described—a distinction that is anything but merely a matter of semantics. An intensional definition comprises the necessary and sufficient conditions that something must exhibit in order to be included in a particular unit. Importantly, the investigator creates the unit by imposing definitive conditions, or features, on it and does so for a specific analytical purpose. Conversely, an extensional unit is created by enumerating observed features of actual specimens that one a priori *thinks* should be members of the same unit. Think back to the descriptions in Table 1: They differ, and rather dramatically, because different analysts, using different sets of specimens, drew up the descriptions based on what they saw in front of them, which they a priori had decided were Clovis points. If the same person were consistently doing the typing and creating the descriptions, then any bias might be judged to be systematic, but that is rarely if ever the case in archaeology.

To be fair, we don't mean to imply that there is no analytical role for traditional units such as projectile-point types because some of them are useful for such purposes as tracking the passage of time (O'Brien and Lyman 1999; Lyman and O'Brien 2005), but even the most useful types are not multipurpose units, as Brew (1946) and Steward (1954) recognized decades ago. Neither are the kinds of intensional units—paradigmatic classes—that we discuss below. Rather, they are useful for *specific* analytical purposes, here the mapping of Clovis design space and determining which segments of that space were used at which times and in which places.

The procedure for constructing the intensional units we discuss here was spelled out independently by Shaw (1969) in paleontology and by Dunnell (1971) in archaeology and termed *paradigmatic classification* by the latter. A paradigmatic classification defines mutually exclusive characters that encompass the range of variation of a specific set of units, termed classes, each of which is defined by a set of character states. Any state of a character theoretically can combine with any state of another character; whether they actually do or not is a separate, empirical question. As a simple example of how paradigmatic classification works, Fig. 5 illustrates a three-character classification. Character X, *height*, has two states; character Y, *depth*, has three; and character Z, *width*, has two.[2] The classes formed by the intersections of various character states are the three-character boxes shown in the diagram. There are 12 of them ($2 \times 3 \times 2$)—1IA, 1IIA, 2IB, and so on. Each class defines a separate area of our design space, here a three-dimensional structure that maps intersections of height, depth, and width.

Paradigmatic classes exhibit several important characteristics. First, all selected characters are equally important in formulating all classes. Second, paradigmatic classes are unambiguous in terms both of internal structure and of their application to the creation of groups of objects. Because all states of a particular character are

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[2] Although the three characters are constructed from a continuous variable—length—we can divide it into any number of bins.
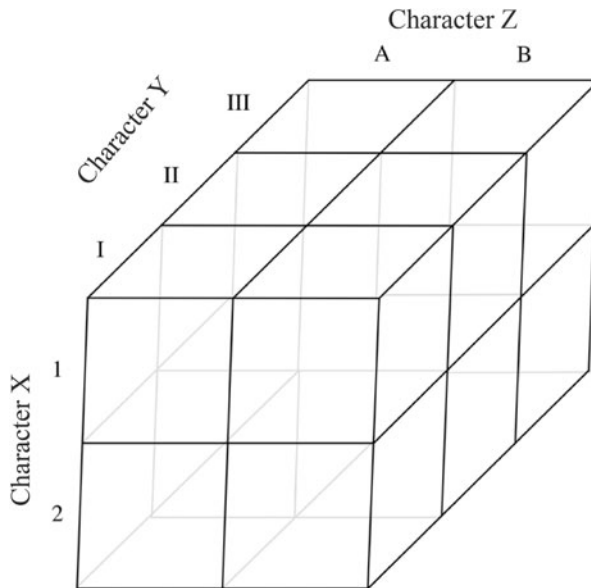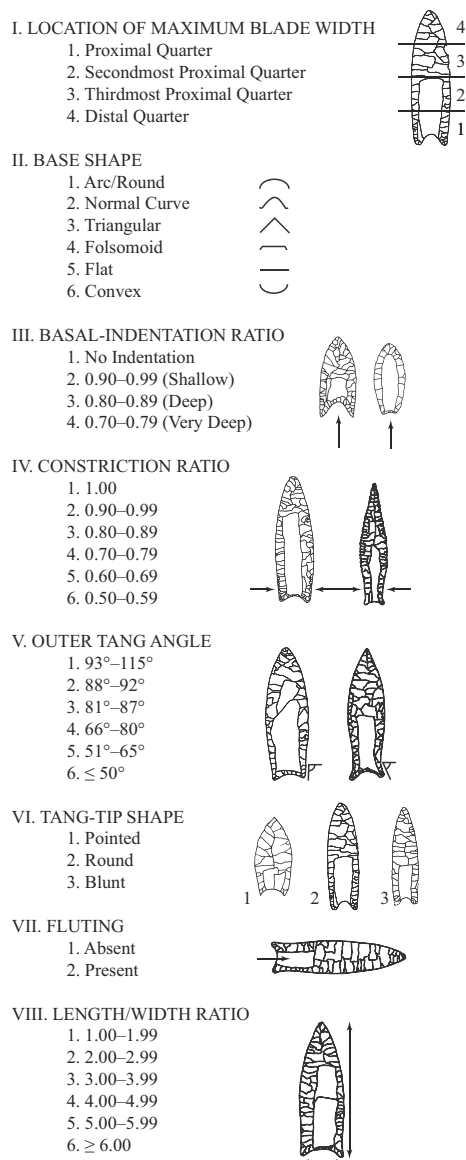
Fig. 5 A simple three-dimensional paradigmatic classification system showing the intersection of the character states of each character (from O'Brien *et al.* 2010). Twelve classes are represented (2×3×2), which collectively define the available design space

mutually exclusive, there can be no internal contradiction. In other words, things cannot be green and blue at the same time. If they are green, they are in one class; if they are blue, they are in another class. Third, individual classes are comparable to all other classes in the same classification because all classes are built using exactly the same characters. Fourth, any paradigmatic classification is infinitely expandable, meaning that character states can be added as needed. Similarly, deletion of a character found to be analytically useless or ambiguous does not require re-examining specimens (e.g., Beck and Jones 1989).

For comparability, we have used the same suite of characters in many of our analyses of Paleoindian projectile points from eastern North America (O'Brien *et al.* 2001, 2002, 2012, 2013, 2014, 2015; Darwent and O'Brien 2006; Eren *et al.* 2015a; O'Brien *et al.* 2015a, b). The eight characters are defined as follows, with individual character states shown in Fig. 6:

I.   Location of maximum blade width—the quarter section of a specimen in which the widest point of the blade occurs.
II. Base shape—qualitative assessment of the shape of the basal indentation.
III. Basal-indentation ratio—the ratio between the medial length of a specimen and its maximum length; the smaller the ratio, the deeper the indentation.
IV. Basal-constriction ratio—the ratio between the minimum blade width (proximal to the point of maximum blade width) and the maximum blade width; the smaller the ratio, the higher the amount of constriction.
V.   Outer tang angle—the degree of tang expansion from the short axis of a specimen; the lower the angle, the greater the expansion.
VI. Tang-tip shape—the shape of the tip ends of tangs.

Fig. 6 Characters and character states used in the analyses of projectile points from eastern North America

I. LOCATION OF MAXIMUM BLADE WIDTH
    1. Proximal Quarter
    2. Secondmost Proximal Quarter
    3. Thirdmost Proximal Quarter
    4. Distal Quarter

II. BASE SHAPE
    1. Arc/Round
    2. Normal Curve
    3. Triangular
    4. Folsomoid
    5. Flat
    6. Convex

III. BASAL-INDENTATION RATIO
    1. No Indentation
    2. 0.90–0.99 (Shallow)
    3. 0.80–0.89 (Deep)
    4. 0.70–0.79 (Very Deep)

IV. CONSTRICTION RATIO
    1. 1.00
    2. 0.90–0.99
    3. 0.80–0.89
    4. 0.70–0.79
    5. 0.60–0.69
    6. 0.50–0.59

V. OUTER TANG ANGLE
    1. 93°–115°
    2. 88°–92°
    3. 81°–87°
    4. 66°–80°
    5. 51°–65°
    6. ≤ 50°

VI. TANG-TIP SHAPE
    1. Pointed
    2. Round
    3. Blunt

VII. FLUTING
    1. Absent
    2. Present

VIII. LENGTH/WIDTH RATIO
    1. 1.00–1.99
    2. 2.00–2.99
    3. 3.00–3.99
    4. 4.00–4.99
    5. 5.00–5.99
    6. ≥ 6.00

VII.   Fluting—the removal of one or more large flakes (>1 cm long) from the base of a specimen and parallel to its long axis; subsequent flake removal may obliterate earlier flake scars.

VIII.   Length/width ratio—the maximum length of a specimen divided by its maximum width.

Our choice of which characters to use was based on expectations as to which parts of a projectile point would change most over time as a result of evolutionary processes such as selection and drift. Considerable variation exists in the overall size and shape of

Paleoindian points, as is evident in the group of Clovis points illustrated in Fig. 4, so we selected characters I, IV, and VIII to explore changes in size and shape. Figure 4 also indicates that the hafting element of Paleoindian projectile points is a likely region in which to find other good candidates. Five characters—II, III, V, VI, and VII—were selected to monitor changes in such features as base shape, the shape of tang tips, and the angle formed by a tang relative to the long axis of a specimen.

It bears repeating that there is a significant difference between the history of Paleoindian points and the *evolutionary* history of Paleoindian points. The former is found in the myriad proposed sequences for which types of point replaced which other types (e.g., Anderson *et al.* 1996, 2015 [see especially Fig. 1]). These sequences are usually built on inference, given the paucity of radiocarbon dates in the East (Waters and Stafford 2007; Prasciunas and Surovell 2015), especially in the Southeast (Anderson *et al.* 2015), but even with absolute dates all we know is what preceded or followed what. This is *historical continuity*—one form following another, perhaps changing ever so slightly—but it is not *heritable continuity*—one form producing another form (Lyman and O'Brien 1998, 2006). Recall our earlier distinction between replicators, which are theoretical units, and the effects of replication. Here, when we talk about one form "producing" another form, we are referring to theoretical units; we are not referring to actual projectile points, which are empirical units, producing little baby points.

Heritable continuity is the hallmark of evolution in that two things are similar because they share a homologous relation. As paleontologist George Gaylord Simpson (1961) pointed out, monozygotic twins are twins not because they are similar; rather, they are similar because they are twins. The same applies to projectile points: Two points are Clovis not because they are similar; rather, they are similar because they are Clovis points.

Paradigmatic classification presents us with the ability to examine heritable continuity and to monitor changes in characters through time at the scale of single characters or packages of linked characters (O'Brien *et al.* 2010). Importantly—for reasons that we hope will be made clear in the following section—paradigmatic classification produces units that are amenable to hierarchical arrangement. Take, for example, the arrangement of four hypothetical classes created from eight characters as shown in Fig. 7a. The ancestral class, *x*, undergoes one character-state change, in character IV (1→2), to produce class y (represented by 11222324). Class *y* undergoes two state changes, in characters VII (2→1) and VIII (4→3), to produce class *z* (11222313). Class *z* undergoes one state change in character I (1→2) to produce class 21222313. This arrangement is hierarchical in the sense of a nesting of less-inclusive, lower-level units within more-inclusive, higher-level units. To simplify, considering only characters that change states—I, IV, VII, and VIII—and ranking the characters in the order listed in Fig. 7a, the hierarchy of possible combinations of character states gives the 16 possible classes as shown in Fig. 7b. Only four of the classes are actually represented by empirical specimens in Fig. 7b, but we emphasize that empty design space can be analytically significant, especially with respect to adaptation. For example, Henrich and Boyd (1998) ask why the aboriginal peoples of New Guinea do not fletch their arrows, given the likelihood that people in coastal New Guinea have had considerable contact with and have observed others using fletching for centuries. The emptiness of design space raises the question "Why not?" in an analytically meaningful way (Gould 1991; McGhee 2011).
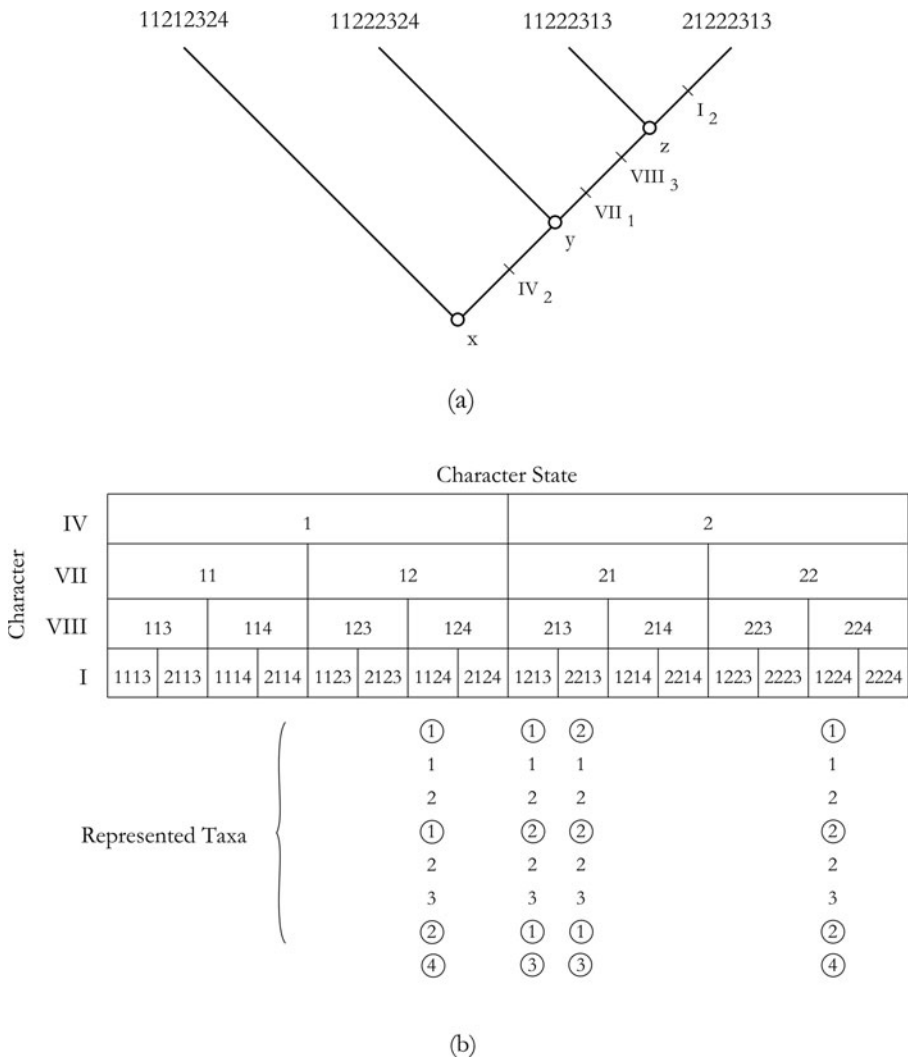
Fig. 7 Phylogenetic arrangement of four fictional taxa (the number strings) created from eight characters: **a** tree showing historical progression of character-state changes (*Roman numerals* identify the characters, and *Arabic numerals* identify the character states); **b** nested hierarchical arrangement of character states showing empirically filled design space (labeled "represented taxa") and empty design space; character states common to all classes are *not* circled (from O'Brien *et al.* 2002)

Undoubtedly, any number of constraints may come into play in terms of limiting the size of the realized portion of design space, including the fact that a particular character state cannot, for mechanical or physical reasons, combine with a character state of another character (Beck and Jones 1989). Importantly, constraints are internal to phenomena—projectile points, for example—whereas evolutionary sorting processes such as selection and drift are external to the phenomena. Constraint can serve as a possible cause of directional change toward one variant (and thus build adaptation) as opposed to another—what Gould (2002) referred to as "channeling."

Cladistics

The ability of paradigmatic classification to produce units that can be arranged hierarchically makes it highly suitable for use in *cladistics*, which is the method we have used to reconstruct ancestral, or *phylogenetic*, relationships among eastern North American Paleoindian points. Cladistics was developed in the 1940s (Hennig 1966) and today is a main method of phylogenetic reconstruction used in biology, although it is not without controversy even among adherents—controversy that is not only methodological (e.g., Goloboff 2003; Revell *et al.* 2008; Simmons 2012) but philosophical as well (e.g., Brower 2009; Brower and De Pinna 2012; Nixon and Carpenter 2012; Farris 2014).[3] The logical basis for applying cladistics to prehistoric stone tools is the same as it for applying it to any biological dataset: Stone tools were parts of complex systems that comprised any number of parts that acted in concert to produce a functional unit (O'Brien *et al.* 2013). The kinds of changes that occurred over generations of Clovis point manufacture, for example, were highly constrained in that new structures and functions usually arose through modification of existing structures and functions as opposed to suddenly rising anew. Thus, "the history of these changes is recorded in the similarities and differences in the complex characteristics of related [objects]—in the extent to which the characteristics of their common ancestors have been modified by subsequent additions, losses, and transformations" (Brown and Lomolino 1998, p. 328).

It is difficult to overemphasize that cladistics creates *hypothetical* statements of relatedness (Patterson 1988)—rendered as trees—based on the model and parameters used (Archibald *et al.* 2003), not irrefutable statements of precise phylogenetic relationships. Riede (2011, p. 799) emphasizes that point with respect to the output of cultural phylogenetics: "a given phylogeny constitutes a quantitative hypothesis of the…relatedness among the chosen units of analysis…Such hypotheses can then be evaluated statistically and in relation to external datasets, such as stratigraphic, geographical or radiocarbon dating information."

Often, there is a failure to make clear the distinction between methods of phylogenetic inference—"tree-building" methods—and phylogenetic comparative methods, which rely on the trees to understand patterns of descent in order to examine the distribution of adaptive (functional) features (O'Brien *et al*. 2013). Together, the methods are based on the "logical proposition that given data about the present distribution of traits across taxa and knowledge about the historical relationships between these taxa, it is possible to infer what the traits were like in the past and how they have changed to give rise to their present distribution" (Currie and Mace 2011, p. 1110; see also Pagel 1999). The modern comparative method is designed to escape what has become known as "Galton's problem": Comparative studies of adaptation are irrelevant if the possibility of a common origin of the supposedly adaptive features under examination cannot be ruled out (Naroll 1970; Mace and Pagel 1994). This requires a working knowledge of the phylogeny of units included

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[3] Technically, cladistics is a particular method for creating hypotheses of evolutionary relationships (Brinkman and Leipe 2001), but we follow what has become common practice and refer to several phylogenetic methods collectively as cladistics. These include maximum likelihood and Bayesian Markov Chain Monte Carlo, both of which calculate probabilities through reference to an explicit evolutionary model from which the data are assumed to be distributed identically (Kolaczckowski and Thornton 2004).

in an analysis. This applies as much to Paleoindian projectile points as it does to biological taxa. It makes little sense, for example, to talk about certain projectile-point shapes being "adapted" for particular kinds of environment/prey if we can't rule out homology as the cause of similarity.

The central tenet of cladistics is that not all similarities are equally useful for reconstructing phylogenetic relationships. Cladistics divides similarities into three kinds: *shared derived traits*, which are similarities between two or more taxa (classes) that are inherited (derived) from their most recent common ancestor, which is defined as a hypothetical collection of character states, some of which define descendant forms; *shared ancestral traits*, which are similarities between two or more taxa that are inherited from a more-distant common ancestor; and *homoplasies*, which are similarities resulting from processes other than descent from a common ancestor, such as convergence, parallelism, and horizontal transmission between and among lineages (Sanderson and Hufford 1996).

Of these three types of similarity, only shared derived traits are informative with respect to phylogenetic relationships. Put another way, a shared derived trait is an evolutionary novelty that two taxa possess because they inherited it from the immediate common ancestor in which the novelty first appeared. In Fig. 7a, for example, the character-state change $IV_1{\rightarrow}IV_2$ creates a shared ancestral trait that unites three taxa but is not helpful in understanding the precise evolutionary relationship of those taxa. Character states VII_1 and $VIII_3$ are shared derived traits relative to 11222313 and 21222313; it is those changes, and only those changes, that set them off on a separate evolutionary trajectory from their ancestral taxon, y (11222324). Character state I_2 is the derived trait that creates the final distinction shown, the evolutionary split between 21222313 and 11222313.

Cladistic analysis proceeds in four steps:

1. A character-state matrix is generated, which shows the states of the characters exhibited by each taxon.
2. The direction of evolutionary change among the states of each character is established. In Fig. 7, we set the direction, or polarity, of the changes strictly as an example, but in most cases we don't know the direction. Several methods have been developed to facilitate determination of polarity; the one we use below is outgroup analysis (Maddison *et al*. 1984), which entails examining a close relative of the study group. When a character occurs in two states among the study group, but only one of the states is found in the outgroup, the principle of parsimony is invoked (see point 4 below), and the state found only in the study group is deemed to be evolutionarily novel with respect to the outgroup state. In Fig. 7a, taxon x (11212324) is the outgroup. Later, we discuss one specific method of selecting an outgroup.
3. A branching diagram of relationships is constructed for each character. This is done by joining the two most derived taxa by two intersecting lines and then successively connecting each of the other taxa according to how derived they are. Each group of taxa defined by a set of intersecting lines corresponds to a clade—hence the "nestedness"—and the diagram is referred to as a tree. Ideally, the distribution of the character states among the taxa will be such that all the character distributions imply relationships among the taxa that are congruent with one another.

Normally, however, a number of the character distributions will suggest relationships that are incompatible. As we noted above, this phenomenon—homoplasy—is the result of processes other than descent from a common ancestor. The problems caused by homoplasy are dealt with through the fourth step.

4. An ensemble tree is generated—one that is consistent with the largest number of characters and therefore requires the smallest number of homoplasies to account for the distribution of character states among the taxa. This tree is referred to as the "most parsimonious" solution. Parsimony trees are evaluated on the basis of the minimum number of character-state changes required to create them, without assuming a priori a specific distribution of trait changes. With respect to cultural phylogenetics, this compensates for the process pathways, biases, and random variation that characterize cultural transmission (García Rivero and O'Brien 2014). We return to this important issue below.

There are numerous techniques for measuring the goodness of fit between a data set and an estimated tree, including the *consistency index* (Kluge and Farris 1969), *bootstrapping* (Felsenstein 1985; Efron *et al.* 1996), and the *retention index* (Farris 1989a, b). Here, for simplicity, we use the retention index (RI), which measures the number of similarities in a dataset that are retained as homologies in relation to a given tree. It is insensitive to both the presence of derived character states that are present in only a single taxon and the number of characters or taxa employed. Thus, it can be compared among studies (Sanderson and Donoghue 1989). The index ranges from zero, which indicates a lack of fit between the tree and the data set, to 1.0, which represents a perfect fit.

In our discussion below, we use the paradigmatic classification outlined earlier (Fig. 6) and the same database of 1113 Paleoindian points from eastern North America used in O'Brien *et al.* (2014).[4] Points in the sample come from 20 eastern US states and 3 Canadian provinces. Our classification resulted in a total of 763 classes, each representing a filled segment of design space, from which we selected a subset of classes that contained four or more specimens each. This created a subsample of 218 specimens spread over 41 classes. The number four has no significance; as in previous studies, we used it solely as a means of controlling for idiosyncrasies arising from such things as individual skill level and occasional mistakes. This yields a conservative number of taxa and allows us to examine the spatial distribution of specimens within a taxon. Following O'Brien *et al.* (2001, 2014), we labeled the classes using abbreviations of the projectile-point type names that appeared in the literature alongside the specimens we incorporated (e.g., K = Clovis, Q = Quad, S = Simpson, and Suw = Suwannee).[5]

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[4] O'Brien *et al.* (2014) note that the database consists of 1813 specimens. That number is a typographical error.

[5] Because it is much easier to use class abbreviations than it is to write out class definitions (the number strings)—not to mention easier to remember—we use the abbreviations. Note that the abbreviations are based on commonly used type names. In each case, the type names were taken directly from the literature in which the specimens were illustrated. For example, Class DAQS contains six specimens, at least one of which was originally referred to as a Dalton (D) point, at least one as an Arkabutla (A) point, at least one as a Quad (Q) point, and at least one as a Simpson (S) point. Echoing our discussion in the text, this ought to give us pause the next time we think about using traditional projectile-point types as analytical units.

We used the computer program PAUP* (v. 4) (Swofford 1998) to generate the phylogenetic trees. To provide a starting point—see point 2 above—we instructed PAUP* to root the trees with class KDR (our outgroup), which occurrence seriation had shown to be the oldest class (O'Brien *et al.* 2001, 2002). Within PAUP*, we used the heuristic search method in three separate runs of 100, 10,000, and 100,000 replicates (see details in O'Brien *et al.* 2015a). Although this method is not guaranteed to identify a single globally optimal tree, it is the most computationally efficient method when dealing with large numbers of taxa. Each run returned multiple equally parsimonious trees. Consequently, we calculated a 50 % majority-rule consensus tree, which places classes in their most common positions across the sample of trees (Swofford 1991), using the trees returned in the 100-replicate sample.

The tree (Fig. 8) contains 48 character-state changes, represented by boxes, each of which is labeled with a Roman numeral indicating the character that has changed; the subscript Arabic numeral indicates the evolved character state. The 24 black boxes indicate convergent changes in character states, the 17 half-shaded boxes indicate reversals to ancestral states, and the 7 white boxes indicate phylogenetically informative changes—those that result from descent with modification and not from adaptive convergence or character-state reversal. Although our primary interest here is in the character states, note that the tree contains several well-developed clades, represented by Roman numerals I–VI. The orange clade (I), at the top of the tree, contains four classes, all of which contain specimens originally identified in the literature as Clovis (represented by "K"). The blue clade (II) contains seven classes that contain specimens identified as Bull Brook (Bull), Gainey (Gain), Debert (Deb), Clovis, and Redstone (R). The first three types are traditionally recognized as extending from the Great Lakes (Gainey), through Massachusetts and adjoining states (Bull Brook), into the Canadian Maritime provinces (Debert) (Ellis and Deller 1997; Bradley *et al.* 2008; Morrow 2015; Smith *et al.* 2015). The red clade (III) comprises nine classes containing specimens from a large number of traditional types. One well-represented type is Quad (Q), and another is Dalton (D) (Anderson *et al.* 2015). Note the small three-class subclade that contains only Clovis, Debert, and Gainey. The small green clade (IV) comprises four classes made up of Clovis, Cumberland (C), and lesser-known types. The small light-blue clade (V) comprises three classes, all containing Clovis, and the purple clade (VI) comprises three classes, all containing Cumberland. In terms of position, the purple clade extends well back into the tree; it split off at the same time as the ancestor (Ke) that produced all other clades.

Cladistic methods are built around the premise that transmission (inheritance) is vertical, but we know this is not always the case, whether we're speaking of genetic transmission or cultural transmission (Jordan 2015). In short, transmission oftentimes is "messy," which means that instead of a tree with branches that are ever expanding, the branches can cross over and become parts of other branches, creating a reticulate tree. Biological evolution can involve not only reticulation (Arnold 1997; Endler 1998; Doolittle 1999), where between-species hybridization might be as high as 15–25 % in plants and as high as 10 % in animals (Rhymer and Simberloff 1996; Mallet 2005), but also cospeciation (Page 2003) and lateral (horizontal) gene transfer (Rosewich and Kistler 2000; Dagan and Martin 2007). With respect to cultural transmission, "cultures do not always behave like species" (Ross *et al.* 2013), by which we mean that with cultures we expect even higher rates of horizontal transmission than with biology
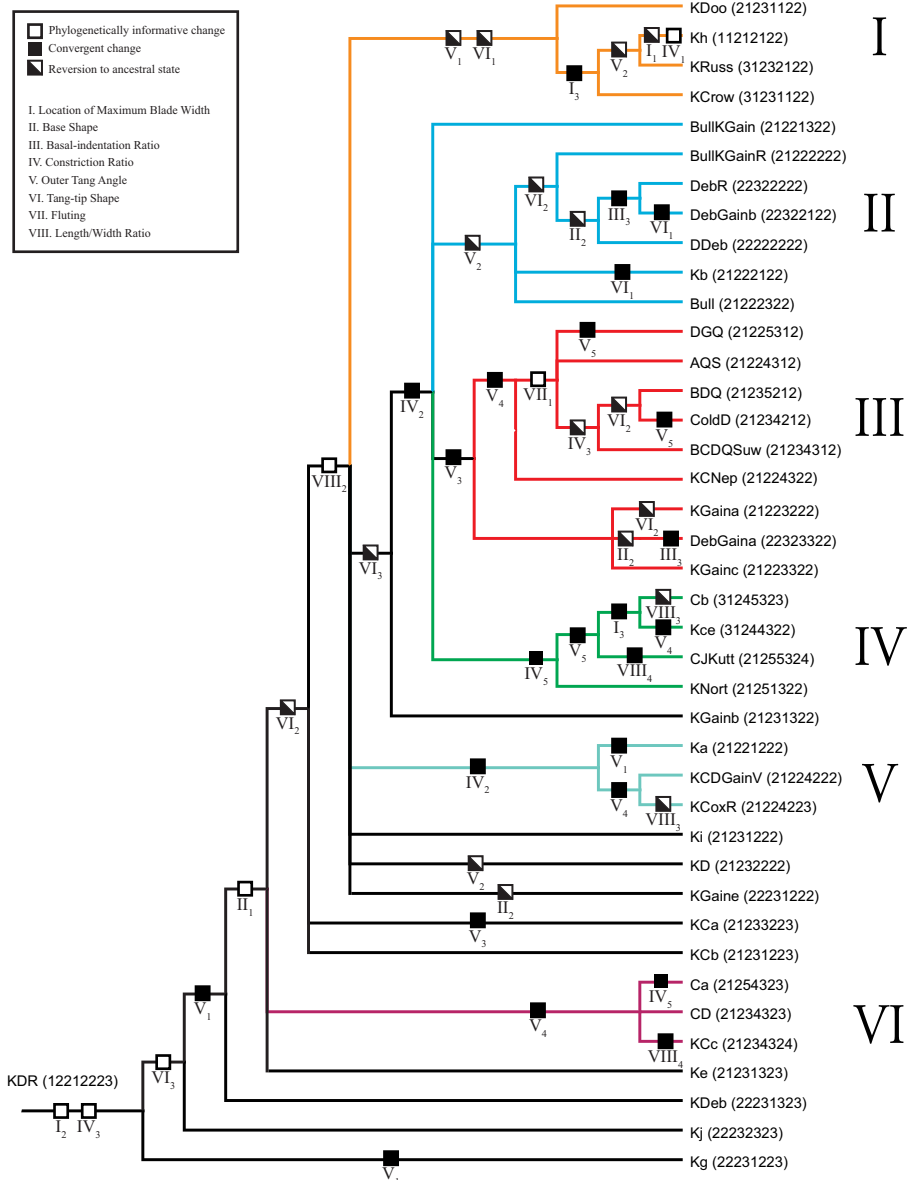
Fig. 8 Fifty-percent majority-rule consensus tree of 41 taxa based on 100 replicates. The *boxes* show the 48 changes in character states. *Roman numerals* denote characters, and *subscript numbers* denote character states. *Open boxes* indicate phylogenetically informative changes; *shaded boxes* indicate parallel or convergent changes (homoplasy); and *half-shaded boxes* indicate characters that reverted to an ancestral state. Clades I–VI are shown in *different colors*

(Boyd *et al.* 1997), which can, theoretically, further reduce the ability of cladistics to resolve an accurate population history (Nunn *et al.* 2006, 2010; Prentiss *et al.* 2013; Crema *et al.* 2014). Borgerhoff Mulder *et al.* (2006) examined this problem through simulations and determined that with increasing horizontal transmission relative to

vertical transmission, geographical distance can be a better predictor of cultural-trait variation than phylogenetic distance.

How do we measure the possible effects of horizontal transmission? Recall that one measure of goodness of fit between a data set and a given tree is the RI. The tree shown in Fig. 8, for example, has an RI of 0.72, which is considerably higher than some accepted trees for biological taxa (Collard *et al.* 2006). Thus, we might assume that it is a fairly faithful representation of the true phylogeny of projectile-point classes. Perhaps, but several simulations of cultural transmission (e.g., Nunn *et al.* 2010; Crema *et al.* 2014) have shown that the RI is not always a robust proxy for detecting branching versus blending signals. Crema *et al.* (2014), for example, noticed that even when cultural interaction is virtually absent, different rates of innovation and frequency of fission events can produce a variety of results that might be mistakenly attributed to a stronger or weaker signal of blending. Similarly, horizontal transmission is constrained by how spatial distance decreases the likelihood of interaction.

Minimum Design-Space Distance Graphs

Fortunately, there are several methods that can be used to investigate the effects of horizontal transmission, including network analysis, which often relies on algorithms such as NeighborNet (Bryant and Moulton 2002; Huson and Bryant 2006) to create planar phylogenetic networks that are useful for identifying complex transmission histories of cultural convergence and divergence (Ross *et al.* 2013; see also Bryant *et al.* (2005) and Gray *et al.* (2010)). Here, our focus is on the creation of graphs that map the minimal design-space distance between classes of projectile points. In contrast to cladistic representations of relatedness, which are based on the distribution of shared derived character states, minimum design-space graphs record the minimum number of character-state changes needed to generate the total similarity between assemblages, regardless of whether that similarity arises as a result of homology or convergence. This results in a different, and complementary, view of artifact variation in design space.

Given a paradigmatic structure to design space, we employ Hamming distance (Hamming 1980), where the distance metric is the least number of character-state substitutions needed to connect a set of classes. The full set of such distances yields a pairwise distance matrix between assemblages, which when represented as a graph is the complete graph over N assemblages. The distances form edge weights on the graph. Edges are then evaluated to find paths that represent the maximum number of shared character states between vertices, which is equivalent to finding the subgraph that yields the smallest total edge weight. Edges not belonging to this subgraph are removed. The result is the minimum total similarity within a design-space classification among the analyzed assemblages.

Because an outgroup comparison is not used, the minimum design-space distance graph includes cladistic relations concerning ancestor–descendant relationship but also incorporates other sources of similarity. Some relations will be homoplasies, which still require investigation of convergence using the usual tools of detailed structural and functional analysis. Other relations may arise as a result of sharing through cultural transmission, following patterns other than the dominant phylogenetic tree given by shared derived character states.
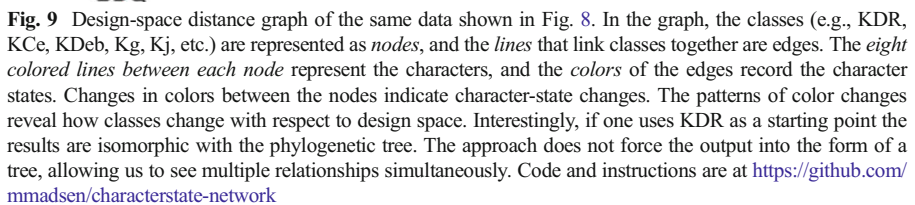
As an example of how a design-space distance graph works, take a paradigmatic classification that consists of three characters, each of which has three states. Let's say that 2 of the possible 27 classes ($3 \times 3 \times 3$) are defined as 321 and 322. Those two classes are isomorphic with respect to the first two characters but differ with respect to the third. We can then use the number of shared character states as a means of generating edges between classes as represented by vertices in a graph representation. If we limit the edges in the graph to those that have the greatest number of character states in common, we can create a parsimonious representation of patterns of sharing among a group of classes. This representation will necessarily share many similarities with the results of a cladistic analysis but would preserve all character-state continuity rather than emphasize hypothesized branching caused by sequences of trait adoption.

Using this approach on the 41 projectile-point classes used to construct the phylogenetic tree shown in Fig. 8 yields the graphical representation shown in Fig. 9. Vertices represent classes, and edges link classes in terms of the number of traits held in common across the eight characters. The graph has multiple edges for each pair of vertices, where edge color represents character-state values in each character. Thus, the figure reveals the degree to which classes reflect continuity as a result of inheritance and how the character states of classes change. Linear associations of classes represent sequences of sharing and innovation that likely took place over time. Branches or multiple edges reflect equivalent degrees of sharing and may indicate greater degree of simultaneous sharing between taxa where temporal patterns are not discernable.

When we compare the graph representation with the phylogenetic tree (Fig. 8), we see close congruence between the branches of the graph and the clades in the tree. Each clade represents hypothesized closely related classes, and the graph suggests that these relationships are sequential and thus may be chronological. We also can see from the patterns of colors in the edges that character states change from one state to another and often back again—the same pattern seen on the tree, with its 17 reversals to ancestral states. This character-state "flipping" points to states that are not strongly different in terms of fitness and thus are neutral with respect to one another. In other words, change is attributable to drift—a point that will take on increasing significance throughout the rest of the paper.

Character-State Changes

In terms of design space, the first characters to change on the tree shown in Fig. 8 were location of maximum blade width (character I) and constriction ratio (character IV). Maximum blade width changed from the first proximal quarter in the outgroup to the secondmost proximal quarter, and constriction ratio changed from state 1 (1.00 [no constriction]) to state 3 (0.80–0.89). The two characters that exhibit the most changes are outer tang angle (character V), with 16 changes, and tang-tip shape (character VI), with 9. Note in particular all the instances of reversal and convergence with respect to outer tang angle, with a trend toward more acute angles, creating "fishtail" points. The third highest number of changes (7) occurs in the constriction ratio (character IV). All three characters—constriction ratio, outer tang angle, and tang-tip shape—are related to the hafting element of a projectile point. Twenty-seven of the 48 changes involve the haft area; the numerous instances of reversal and convergence indicate that that portion of Paleoindian projectile points was anything but stable from a design perspective,

Fig. 9 Design-space distance graph of the same data shown in Fig. 8. In the graph, the classes (e.g., KDR, KCe, KDeb, Kg, Kj, etc.) are represented as *nodes*, and the *lines* that link classes together are edges. The *eight colored lines between each node* represent the characters, and the *colors* of the edges record the character states. Changes in colors between the nodes indicate character-state changes. The patterns of color changes reveal how classes change with respect to design space. Interestingly, if one uses KDR as a starting point the results are isomorphic with the phylogenetic tree. The approach does not force the output into the form of a tree, allowing us to see multiple relationships simultaneously. Code and instructions are at https://github.com/mmadsen/characterstate-network

although as we noted above, many of the changes may have been adaptively neutral, allowing character states to flip back and forth over time because one works just as well another. Other characters change either moderately or almost not at all. Base shape (character II) has four changes, consisting of one shift from normal curve to arc-shaped and three reversals to the ancestral, normal-curve state. Blade width (character I) exhibits a few reversals and a single phylogenetically informative change. Finally,

the length/width ratio (character VIII) exhibits a few instances of reversal and convergence and one phylogenetically informative change.

O'Brien *et al.* (2014) conducted a preliminary analysis of the geographic distribution (by US state) of classes and character states, with several interesting, though preliminary, results. For example, points from a large contiguous area comprising Missouri, Arkansas, Kentucky, Tennessee, Mississippi, and Alabama had their maximum blade width (character I) in the secondmost proximal quarter, whereas virtually all points from the Northeast and the Middle and Southern Atlantic had their maximum blade width in the secondmost distal quarter (Fig. 10). Also, almost all points south of Pennsylvania had shallow basal-indentation ratios (character III), whereas points with deep indentation ratios were confined to the extreme Northeast. This comes as no great surprise, given that the considerable depth of the basal indentation is a characteristic of Debert points (MacDonald 1968) and other northeastern types (Ellis 2004; Bradley *et al.* 2008; Smith *et al.* 2015). With respect to constriction ratio (character IV), several trends are evident. Specimens with ratios in the 0.80–0.89 range tend to cluster in the southern states, as opposed to those with ratios in the 0.90–0.99 range, which cluster in the Northeast. The pattern for length/width ratio (character VIII) shows that point manufacturers regardless of region preferred ratios in the 2.00–2.99 range, with a secondary preference for ratios in the 3.00–3.99 range.

The results of that preliminary analysis can be expanded in several significant ways. Figure 11 shows the frequency distribution of character states for the same four characters shown in Fig. 10, but here we have plotted the actual values in addition to showing (in dashed red lines) the character-state bins. Only fluted points are included
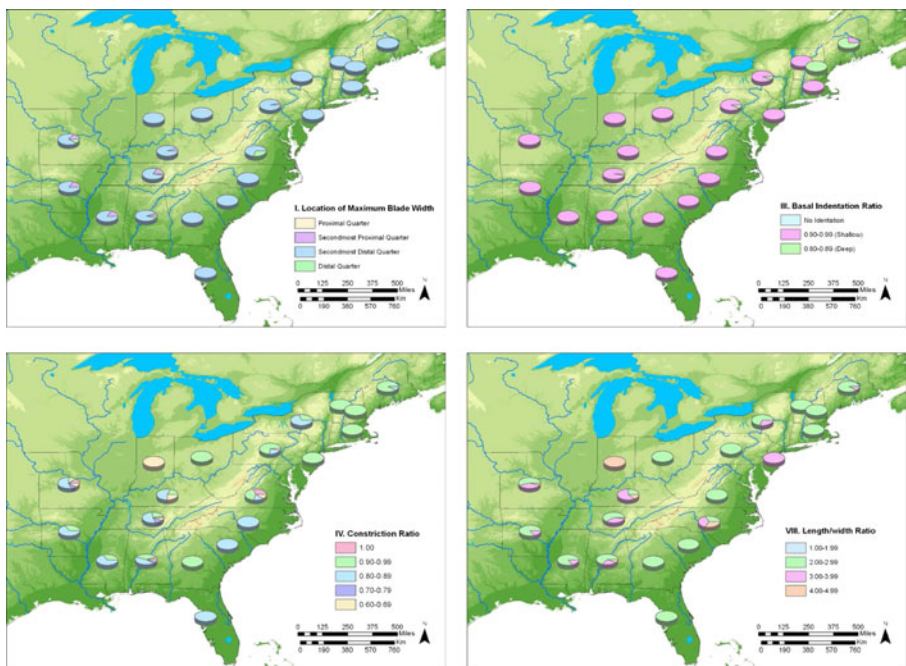

Fig. 10 Geographic distributions of states of characters I, III, IV, and VIII: location of maximum blade width, basal-indentation ratio, constriction ratio, and length/width ratio (after O'Brien *et al.* 2014)
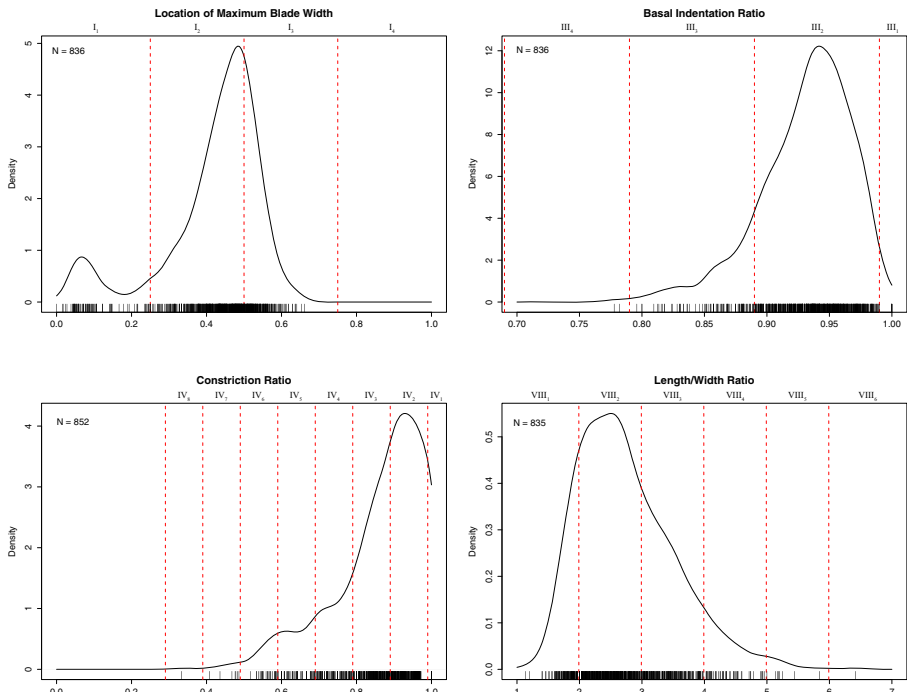
Fig. 11 Kernel-density estimates for four characters used in the paradigmatic classification: location of maximum blade width, basal-indentation ratio, basal-constriction ratio, and length/width ratio. Values on the X-axis are the uncoded ratio values used in the classification. *Dashed vertical lines* represent the arbitrary equal-interval character states used in the classification. The Y-axis shows the cumulative probability density (see Baxter and Cool (2010) for a discussion of the use of kernel density estimates in archaeological data)

here, which reduces the sample from 1113 specimens to 852. Several interesting features are apparent. With respect to character I, location of maximum blade width (836 specimens),[6] there is a heretofore-unrecognized peak at the midpoint between character states I_2 and I_3. Notice the dramatic decline at the midpoint of the character state I_3 bin. Also notice the peak at roughly the midrange value for character state I_1 and the dramatic decline to the right of that peak. At present, we have no explanation for the secondary mode, although our best guess is that it is adaptive as opposed to being the product of drift (see below). With respect to character III, basal-indentation ratio (836 specimens), the vast majority of specimens fall in character state III_2, with a steady monotonic decline into character state III_3. Character IV, constriction ratio (852 specimens), exhibits an even more striking distribution, with the greatest frequency in character state IV_2 and a steady decline in frequency through the other states, except for small blips in sections of IV_4 and IV_5. Character states IV_7 and IV_8 contain only seven specimens and one specimen, respectively, out of a total of 852 fluted points. Character VIII (835 specimens), length/width ratio, shows a heavy bias in favor of character state $VIII_2$, with very low representation in $VIII_5$ and $VIII_6$.

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[6] The number of specimens changes from character to character because we were conservative in which specimens to include. All 1113 points included in the overall sample were complete in terms of assigning particular character states to them, but they might have had small pieces missing that precluded exact measurements and thus were excluded from the analysis shown in Fig. 11.

These data, of course, are aggregates of all the projectile points included in the sample, regardless of origin. Although they tell us a lot about filled and unfilled sections of design space, they don't tell us anything about geographical patterns in terms of how Paleoindian design space was used. Using the gross patterns seen in Fig. 10 as a guide, and the data from Fig. 11, we can map frequency distributions for the same four characters by latitude (Fig. 12) to see what patterns might emerge. The boxes represent the middle 50 % of each sample, the black bars represent the median values, the whiskers represent three standard deviations on either side of the mean, and the black dots represent individual specimens that fall outside of three standard deviations. With respect to character I, location of maximum blade width, the secondary mode evident in Fig. 11 now takes on geographic significance, with the largest number of specimens located in the 35°–37° N latitude range. Those specimens are extreme outliers, having the widest part of their blades in the most-proximal quarter, whereas the majority of points have their widest parts farther up the blade. Even with those outliers, and they are fairly numerous, the overall pattern shows no definite trends by latitude: The median shifts back and forth between roughly the 0.4 and 0.5 marks on the map. With respect to character III, basal-indentation ratio, however, there does seem to be a clear trend: Overall, points have smaller ratios—signifying deeper basal concavities—with increasing latitude. As we pointed out earlier, this is not surprising, but here we have a more precise view of gradual latitudinal trends in basal-indentation ratio. The deepest bases do occur in the Northeast, but the trend toward deep bases starts well to the south.

With respect to character IV, basal-constriction ratio, there is a tendency for specimens above 38° N latitude to have progressively larger ratios, meaning the points are less fishtail-shaped. Again, this feature of northern points has long been recognized, but what was not clear was the progressive loss of the fishtail shape with increased latitude. The outliers seen at 40° N latitude and those between 34° N latitude and 38° N latitude, together with specimens represented by the long whiskers at those latitudes, include what are termed Cumberland points, which are long, narrow, and heavily fluted forms. Notice also the reduction in filled design space with increasing latitude, represented by a tightening of the distributions around the median. Mason (1962, p. 235) pointed out over a half-century ago that the Southeast appeared to contain "the greatest diversification in fluted point styles" (e.g., Simpson, Suwannee), and certainly the sizeable variation in basal-constriction ratio evident at 31°N is consistent with that view.[7] With respect to character VIII, length/width ratio, there is a trend for points to become slightly longer relative to width beginning at around 32°N (going north) and then a trend for them to become shorter relative to width beginning at around 36°N.

In summary, paradigmatic classification and phylogenetic analysis—the latter supported by design-space distance graphs—have allowed us not only to better understand the kinds of changes that Paleoindian points went through but to put those changes into an order that reflects not only history but heritability. Although preliminary, it appears

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[7] One of our recent studies (Eren et al. 2015b) focused on Paleoindian-point richness in eastern North America, with richness being the number of classes in our database per region. When the Southeast as a whole is compared statistically to the Northeast, Mason's (1962) prediction is upheld. Further, when we divide the Southeast into the Upper Southeast and the Lower Southeast, the former region exhibits greater class richness than either of the other two regions. The Upper Southeast contains portions of major waterways such as the Missouri, Mississippi, and Ohio rivers.
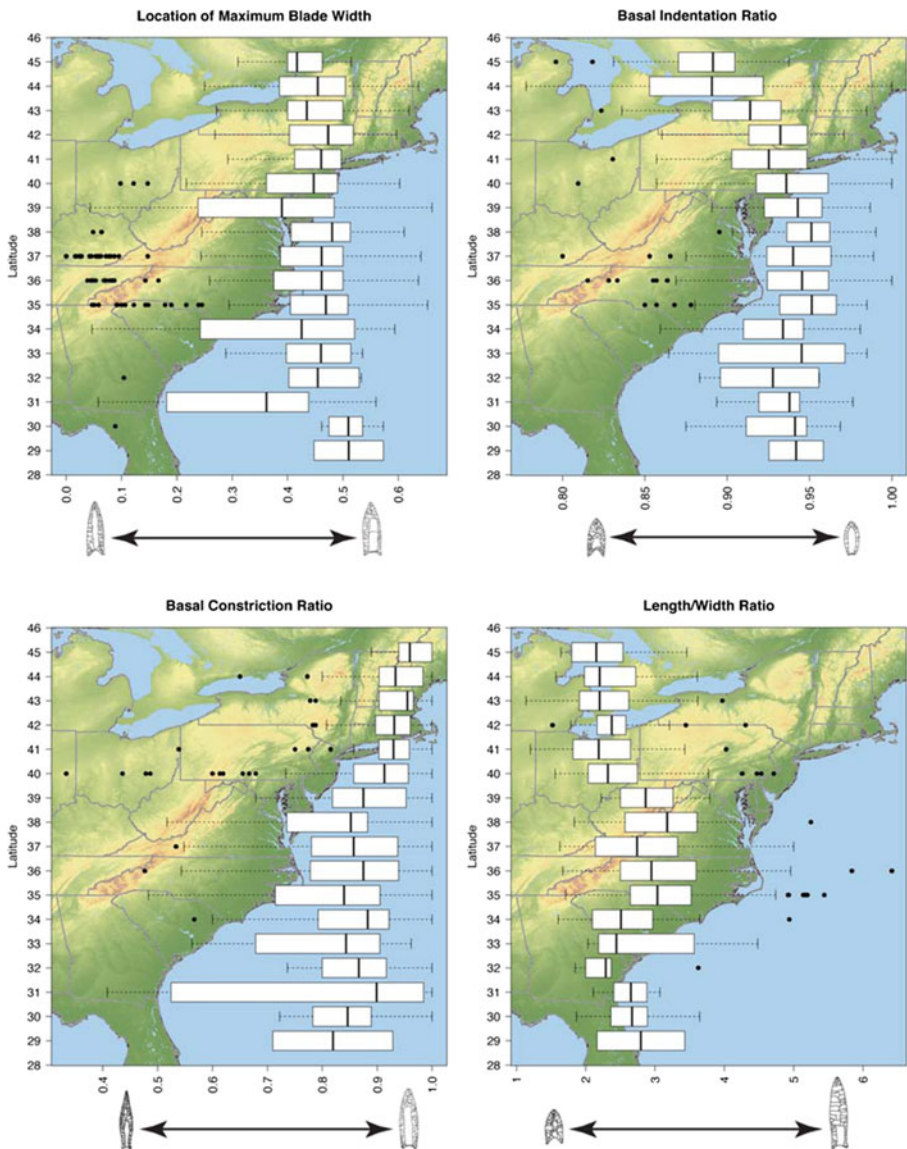
Fig. 12 Tukey boxplots, binned at each degree of latitude, showing north–south changes in the distributions of four characters used in the paradigmatic classification: location of maximum blade width, basal-indentation ratio, basal-constriction ratio, and length/width ratio. *Boxes* represent the interquartile range (the central 50 % of data). *Whiskers* are drawn at 1.5 times the upper and lower quartiles. *Central bar* is the median. Outliers—those points falling outside 1.5 times the upper and lower quartiles, equivalent to ±2.698-sigma—are shown as *solid dots*

as if that portion of design space with specimens was affected rather strongly by cultural drift, with drift in this case being the changes over time in neutral characters. Recall the latitudinal patterning in two of the characters—basal-indentation ratio (character III) and length/width ratio (character VIII)—and weak latitudinal differences in a third—basal-constriction ratio (character IV). This patterning is exactly what we

would expect with cultural transmission within and between finite, naturally fluctuating populations—a point that we discuss in more detail later.[8]

Geometric Morphometrics

So far, our discussion of design space has been in terms of standard morphometric interlandmark measurements—for example, basal-indentation ratio—but an important companion method for analyzing design space is geometric morphometrics (GM), which has recently seen increased usage in archaeology (e.g., Archer and Braun 2010; Buchanan and Collard 2010; Cardillo 2010; Costa 2010; Lycett *et al.* 2010; Shott and Trail 2010; Buchanan *et al.* 2011; Iovita and McPherron 2011; Charlin and González-José 2012; Eren and Lycett 2012; Thulman 2012; Wang *et al.* 2012; Lycett and von Cramon-Taubadel 2013; Boulanger *et al.* 2015; Smith *et al.* 2015). As we demonstrate with an example below, GM creates relative warps, or the principal components of shape variables, that reflect the major patterns of shape variation within a group of specimens.

In the briefest of terms, GM analysis begins by standardizing landmark configurations so that they are directly comparable. That is, comparisons are based on the shape of specimens rather than on their size. To accomplish this, a superimposition method—Generalized Procrustes Analysis—iteratively minimizes the sum of the squared distances among landmarks of each configuration by translating (shifting the configurations together in a fixed direction), rotating ("spinning" the configurations around a fixed point), and scaling the configurations by dividing the coordinates of each form by its centroid size, which is defined as the square root of the sum of the squared distances between the geometric center of the form and its landmarks (Bookstein 1991). The remaining differences in landmark position—the "Procrustes residuals"—represent the shape differences among the objects. Because GM deals with coordinate data as opposed to the interlandmark distances of standard morphometrics, it allows patterns of variation in shape to be easily visualized (Bookstein 1991; Zelditch *et al.* 2004; Slice 2007). Certain kinds of GM data can be used under a parsimony framework (Catalano *et al.* 2010; Goloboff and Catalano 2011; Catalano and Goloboff 2012), and we see this as a promising new avenue of research. However, as with any phylogenetic analysis, taxon construction remains a fundamental issue. That's why we referred to GM above as a "companion" method to the joint use of paradigmatic classification and cladistics in evolutionary studies.

GM has figured prominently in discussions of whether there are significant regional differences in the shape of Clovis points. Some archaeologists have identified regional differences (e.g., Anderson 1990; Smallwood 2012; Anderson *et al.* 2015) and suggested they could be products of either technological shifts associated with adaptive changes or the effects of cumulative variation in style through cultural drift/transmission. Others (e.g., Haynes 1964; Kelly and Todd 1988) have indicated that there are no significant regional differences. To test the models formally, Buchanan *et al.* (2014) used GM on 241 Clovis points from different regions of North America. They reasoned

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[8] Although not presented here, analysis of data generated by binning specimens by longitude showed no patterning. This parallels the findings of Smith *et al.* (2015), who note that in their study latitude was associated more strongly with shape than longitude was.

that if they found shape differences among regions that themselves were distinct enough in terms of environmental variables, they could attribute the shape differences to adaptation as a working hypothesis.

Figure 13 shows the consensus configuration of landmarks (top), which represents the average shape of all points in the sample, and the variation around each landmark (bottom). Note that the two basal landmarks (landmarks 2 and 3) are the most variable and that variation decreases toward the tip. Figure 14 plots the first two relative warps by region, with the first warp, representing 85 % of the overall variation, plotted on the X-axis and the second warp, representing 4 % of the variation, plotted on the Y-axis. Overlap among the regions is evident, but points from the East are more variable than those from the West, particularly along the second relative warp. The wireframes in Fig. 14 show deformation from the consensus configuration at the positive and negative ends of each axis to illustrate Clovis shape space. That space is defined along the first relative warp by elliptical blades with deeply concave bases to the left (negative end)—represented by a point from Shoop (Pennsylvania)—and by more linear blades with shallow, rounded concave bases to the right (positive end)—represented by a point
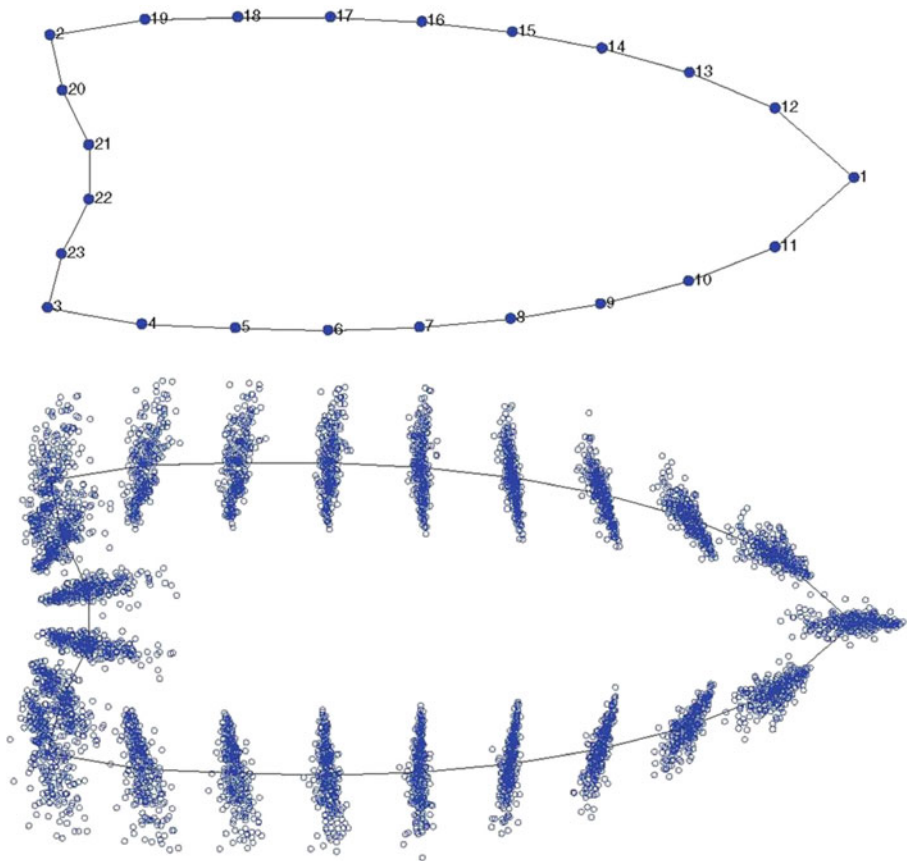

Fig. 13 Results of a geometric morphometric shape analysis of 241 Clovis points from different regions of North America: *top*, consensus configuration of all landmark configurations; *bottom*, variation in landmark configurations after being translated, scaled, and rotated (from Buchanan *et al.* 2014)
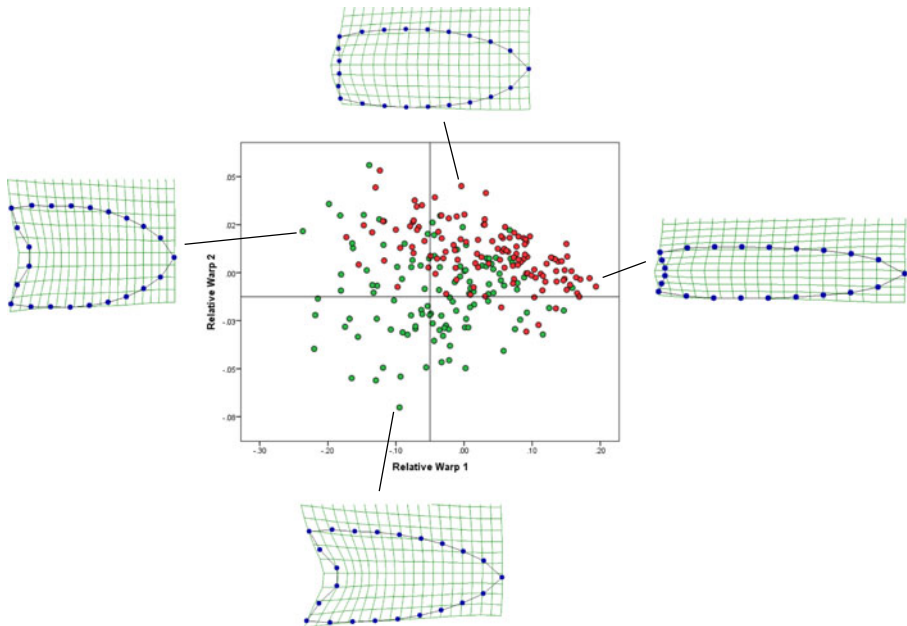
Fig. 14 Bivariate plot of relative warp 1 (85 %) against relative warp 2 (4.3 %) for 241 Clovis points (from Buchanan *et al.* 2014). *Red circles* indicate points from the West, and *green circles* indicate points from the East. The four images are deformations from the consensus configurations and display the shape space defined by the first two relative warps. The *upper point* is from Murray Springs (Arizona), the *point at the right* is from Simon (Idaho), the *lower point* is from Vail (Maine), and the *point at the left* is from Shoop (Pennsylvania)

from Simon (Idaho). Along the second relative warp, Clovis shape space is defined by lanceolate blades with straight bases at the upper (positive) end—represented by a point from Murray Springs (Arizona)—and more deltoid blades with deep, concave bases at the lower (negative) end—represented by a point from Vail (Maine). Significance tests showed that among the four subregions in the East, points from the Northeast were significantly different from those from the Middle Atlantic, Great Lakes, and Midcontinent.

In a similar study, Smith *et al.* (2015) used a sample of 144 Clovis points from 28 North American sites to determine if there were significant regional differences in shape. They, too, found that points from the Northeast, characterized by deep basal concavities and considerable variation in basal-concavity width, were distinct from points in three other regions—the Midcontinent, the Northwest, and the Southwest. In their words, "some early points from eastern North America…have the potential to represent point shapes that are beyond a limit, or a threshold, of point variability that is definitive of Clovis" (p. 161); the authors characterized Clovis as having "shallow basal concavities, greater length relative to width, and excurvate blades."

The two GM studies highlight two important issues: Even though both studies demonstrated that points from the Northeast differ significantly in shape from points from other regions, different conclusions were reached relative to (1) whether the points should be referred to as Clovis and (2) the factor(s) that contributed to the shape difference. With respect to the first point, if what we are measuring is variation in a tightly controlled manner, it probably doesn't matter where we make a division, as long

as it's clearly designated and results can be replicated (Eren and Desjardines 2015). With respect to the second point, Buchanan *et al.* (2014) provisionally explained shape differences in terms of adaptation—Clovis people modified their points to suit the characteristics of local prey and/or the habitats in which they hunted—whereas Smith *et al.* (2015) proposed that the differences between the Northeast and the rest of the continent "may be the result of variation caused by cultural drift…or founder effect…as people expanded into uninhabited territory at the end of the Pleistocene" (pp. 176–177).

Smith and colleagues' conclusion parallels that of Buchanan and Hamilton (2009), who, using interlandmark morphometrics in a study of 232 Clovis points from 26 North American assemblages, found no correlations between shape and regional environmental variables. They suggested that despite the wide variation in regional environmental conditions across North America during the late Pleistocene period, not enough time elapsed during the Clovis period for local selective gradients to have led to significant changes in point shape. The evidence they found of regional variation in point shape correlating significantly and positively with geographic distances between sites would be expected in situations where populations in proximity share either cultural phylogenetic histories or extensive horizontal transmission. This is compatible with a scenario of demic splits, which result in regional populations budding off from source populations while maintaining connections through social networks. In other words, as suggested by Smith *et al.* (2015), variation in shape is most likely a result of drift. As a consequence of sampling, drift is amplified in smaller populations, where the number of people from whom to copy, and the number of objects or traits to copy, are limited (Henrich 2004, 2006; Bentley and O'Brien 2011).

Lest we make it sound as if the factors affecting point shape are an either/or question—adaptation *or* drift—we should point out that the two sources of variation in point shape are not mutually exclusive and could simultaneously have contributed to interregional or intraregional differences (O'Brien *et al.* 2014; see also Kuhn (2012) and Lycett and von Cramon-Taubadel (2015)). In fact, we expect both drift and adaptation to be operating on point design. Colonizing populations do not necessarily stay in constant contact with one another, especially as geographic distance between them increases, and thus over time point shapes can begin to diverge. Similarly, a colonizing population may begin to adapt point shape to local environmental conditions, which might be different from those encountered by other populations. But even granting some variation in shape, it is apparent that variation occurred within fairly narrow bounds (Buchanan *et al.* 2014). However, in distinguishing between adaptation and drift, we generally agree with Lycett (2008, p. 2642) that "unless there is strong evidence for a departure from neutrality, it is unnecessary to evoke processes other than drift as an explanation for the factors producing given patterns of variability."

Discussion

As we have seen, the analysis of design space can provide key insights into macro- and microevolutionary evolutionary processes—adaptation and drift, for example—but as we pointed out earlier, our work on Paleoindian points has long had another goal, namely being able to tie our findings to models of cultural transmission, similar to what other studies have done using archaeological data (e.g., Bettinger and Eerkens 1997,

1999), mathematical simulation (Eerkens *et al.* 2006), or experimental simulations of cultural-transmission processes in laboratory settings (e.g., Mesoudi and O'Brien 2008a, b; Kempe *et al.* 2012, 2014; Schillinger *et al.* 2014a, b). Regardless of the precise amount of contact between Clovis groups, which undoubtedly was highly variable, can we determine, at either the regional or local level, what kinds of cultural transmission were involved in point manufacture? In other words, as Clovis (and later Paleoindian) point makers traversed design-fitness landscapes, such as the one in Fig. 3, what caused them to land on one part of the landscape as opposed to another? More precisely, what kind of learning was involved that led a point maker to select one part of the available design space as opposed to another?

Most studies have suggested that Clovis groups engaged in social learning of one kind or another, which for graphic purposes puts them in the eastern half of the map in Fig. 2. Hamilton and Buchanan's (2009) study, for example, found that (a) point size decreased through space and time, which follows predictions of the copy-error model, and (b) that variance in point size was statistically constant over time, which is consistent with biased-learning practices. Their reasoning for the standardization was that Clovis projectile-point technology is complex and would have required a significant amount of investment of time to learn effectively (Crabtree 1966; Whittaker 2004; Bradley *et al.* 2010). They proposed that under such conditions there likely was considerable variation in skill level (Henrich 2004, 2006; Bentley and O'Brien 2011)—one does not become a flintknapper, let alone an accomplished one, overnight (Pigeot 1990; Olausson 2008; Eren *et al.* 2011a, b)—such that recognized craftsmen could have held considerable prestige (Hamilton 2008).

Prestige bias—learning from (not simply copying) certain individuals to whom others freely show deference or respect in order to increase the amount and accuracy of information available to the learner (Henrich and Gil-White 2001; Reyes-Garcia *et al.* 2008)—allows a learner in a novel environment to quickly choose from whom to learn (provided the population is not so large as to "swallow up" highly skilled individuals (Bentley and O'Brien 2011)), thus maximizing his or her chances of acquiring adaptive behavioral solutions to a specific task or enterprise without having to assess directly the adaptiveness of every potential model's behavior (Atkisson *et al.* 2012). Prestige bias is represented in the northeast quadrant of the map shown in Fig. 2, where novices are learning from a master. In a fast-moving and fast-growing population subject to the widespread environmental changes of, say, the North American late Pleistocene landscape, which could create complex perturbations to the fitness landscape, prestige bias could have been a highly effective strategy for social learning (Hamilton 2008). Under circumstances where ecological conditions change, say, on a generational scale, the mean trait value is often optimal, leading to frequency-dependent bias or conformism (Henrich and Boyd 1998).

However, if ecological conditions change faster than that, individual trial and error or even a combination of individual and social learning may be the fitter strategy (Mesoudi 2008; Toelch *et al.* 2009). As Mesoudi (2014, p. 66) put it, models of cultural learning seem to indicate that "some mix of individual and social learning is adaptive in fluctuating environments that change too rapidly for innate, genetic responses to evolve, yet not so rapid that previous generations' solutions to problems are out-of-date." Increasing chronological resolution of the last several thousand years of the Pleistocene has shown that the transition to the Holocene at 11,700 calBP (Walker *et al.*

2009) was anything but gradual and uniform (e.g., Taylor *et al.* 1993; Roy *et al.* 1996; Hoek 2008; Steffensen *et al.* 2008; Denton *et al.* 2010), suggesting this would have been a time when individual learning might have conferred an advantage, especially if coupled with conformist bias (Hamilton and Buchanan 2009).

Conformist bias is represented in the southeast quadrant of the map (Fig. 2), where social forces are strong and the intensity of choice—the transparency of costs and benefits—across available options is small. The low intensity of choice may be the result of a large standard deviation of the random elements in the choice process, and that, in turn, may be a result of a lack of information about the choices relative to the differences in underlying values of the choices (Mesoudi and Lycett 2009). We represented this by the clouds obscuring fitness peaks in Fig. 3. In the extreme southeast, not only are the options themselves fairly equivalent (as in the southwest), but so too are the people who potentially serve as models. It is as if each person points to someone else and says, "I'll have what she's having" (Bentley *et al.* 2011a). This is the classic case of conformist bias.

Several other studies have shed light on the subject of learning and cultural transmission among Clovis groups. Sholts *et al.* (2012; see also Gingerich *et al.* 2014) used laser scanning and Fourier analysis to examine flake-scar patterns—relics of the tool-making process—on a sample of Clovis points from sites across North America. Their analysis suggested that flaking patterns were similar across the continent, "without evidence for diversification, regional adaptation, or independent innovation" (p. 3024). Sholts and colleagues also proposed that learning could have taken place at chert outcrops—quarry sites—where "Clovis knappers from different groups likely encountered each other…[which] would have allowed knappers to observe the tools and techniques used by other artisans, thereby facilitating the sharing of technological information." This sharing of technological information, Sholts and colleagues proposed, created the uniformity in production seen in their sample. If Sholts and colleagues are correct, then regardless of whether variation in shape is attributable to the vagaries of cultural transmission (drift) or adaptive change driven by environmental conditions (selection), patterns of flake removal appear to have been less sensitive.

Eren *et al.* (2015a) tested Sholts and colleagues' hypothesis using a sample of Clovis points from one environmentally homogeneous region of the Midcontinent. Statistical analysis of flake-scar patterning confirmed that the production technique was the same across the sample—similar to the findings of Sholts and colleagues—but GM analysis also showed differences in point shape associated with the stone outcrop from which particular Clovis points originated. Given that current archaeological evidence suggests stone outcrops were "hubs" of regional Clovis activity, the dichotomous, intraregional results of the study by Eren and colleagues confirms that Clovis foragers engaged in two tiers of social learning. The lower, ancestral, tier relates to point production and can be tied to conformist transmission of ancestral tool-making processes across the Clovis population. In other words, dispersing Clovis groups were still socially connected across large regions of North America and directly transmitting technological knowledge to each other, resulting in a low interregional variance in how points were being flaked. The upper, derived, tier relates to point shape, which shows more interregional variance. This can be tied to drift that resulted from individual groups spending more time at different stone-outcrop hubs (Fig. 15). As Eren *et al.* (2015a) point out, these results are predicted by both current understanding of cognition and memory systems
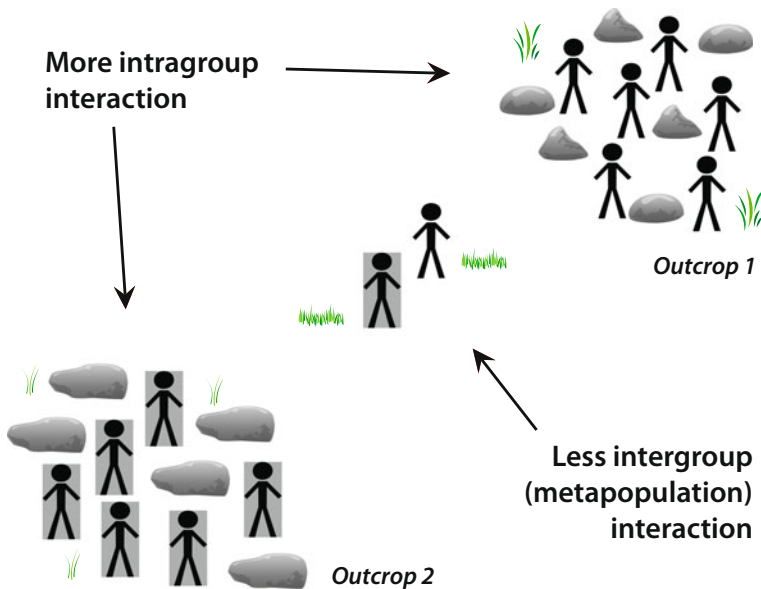
Fig. 15 A model of the evolution of two tiers of Clovis social learning. Through time, there was less intergroup (metapopulation) interaction and more localized interaction, which was tied to the differential use of chert outcrops by individual groups

(Thulman 2013) as well as by phylogenetic analyses of modern ethnographic material culture (e.g., Tehrani and Collard 2002), which suggest that technological design—for example, point shape—should have more potential for change than manufacturing techniques (see Tostevin 2012).

There is an important point here, and it concerns scale (Premo and Scholnick 2011). When we said in the above paragraph that point shape began to drift, we need to make clear that the drift is evident at the *megapopulation* level, as Clovis groups begin to "drift" apart, not at the *local-group* level. At the group level, the apparent pattern of increased experimentation in shape is what we would expect from the guided-variation model that we discussed earlier: In the absence of selection, a population will move toward whichever trait is favored by people's individual-learning biases (Mesoudi 2011b; Gingerich *et al.* 2014; O'Brien *et al.* 2014, 2015b). Again, this occurs even when the strength of guided variation is weak (Mesoudi 2011b). We propose that this "regionalization" parallels the findings of several studies that have noted increasing projectile-point diversification and shrinking "style zones" in the time period immediately following Clovis (post-ca. 11,900 calBP) (Tankersley 1989; Anderson 1995; Meltzer 2009; O'Brien *et al.* 2014, 2015b). Anderson *et al.* (2015, p. 32) put it this way:

> During the Younger Dryas this diversification continues, and indeed explodes, within the Southeast. Projectile point forms include morphologically distinctive fully fluted, basally thinned, and unfluted forms, with subregional variants evident, rather than a single more or less uniform style such as the Clovis form widespread previously. The following types or subtypes are assumed to occur at this time: Barnes, Beaver Lake, Clovis Variants, Cumberland, Dalton, Gainey,

Quad, Redstone, San Patrice, Suwannee, and Simpson, together with lanceolates resembling Plains Paleoindian forms.

Meltzer (2009, p. 286) suggests, and we agree, that this process can be read "as a relaxation in the pressure to maintain contact with distant kin, a reduction in the spatial scale and openness of the social systems, and a steady settling-in and filling of the landscape. Later Paleoindians no longer spanned the continent as their ancestors had, and their universe had become much smaller" (Fig. 16).

Conclusions

Our discussion of design space is meant to be anything but comprehensive. Rather, we attempt to touch on several specific theoretical and methodological issues—social and individual learning, fitness landscapes, paradigmatic classification, phylogenetic methods—that we view as useful in attempting to understand the design of prehistoric tools, here stone projectile points from eastern North America that date to the Early Paleoindian period. As we have seen, no one would argue that what typically are referred to as, say, Clovis points do not exhibit differences in shape. The question is, are there significant differences, and if so, why? From an evolutionary standpoint, what processes might have led to differences? To answer evolutionary questions requires the

Fig. 16 Late Paleoindian points from across North America showing increased diversity in shape and form. Compare the shapes and forms with those shown in Fig. 4, which most archaeologists would refer to as Clovis points. The increase in shapes and forms is attributed to shrinking "style zones" in the time period immediately following Clovis (post-ca. 11,900 calBP)

use of heuristic devices and analytical methods that can address them appropriately. That's why we view cladistics and paradigmatic classification as being so important: They help us identify which character-state changes are homologous—the result of inheritance—and which changes are analogous—the result of adaptation.

Beyond the examination of character states, the methods also allow us to examine the evolutionary ordering of *bundles* of character states—here projectile-point classes—and to plot those units spatially. The ability of GM to characterize artifact shape allows us to formulate evolutionary hypotheses, and design-space graphs using Hamming distance provide an important check on phylogenetic relationships. The two heuristic devices we introduced—fitness landscapes and a map of cultural learning—provide a simplified means of understanding the complexities of cultural transmission and the evolutionary implications of decision making in design space.

Lest we inadvertently make it sound as if these methods and heuristic devices are useful only on projectile points, we note that they are applicable to all stone tools and debitage. Given that these items often occur in far greater sample sizes than projectile points, analyses employing the above methods are likely to be robust. The few such analyses done to date have allowed inferences to be made about settlement patterns and hafting (e.g., Eren 2012), but there is much left to do from an evolutionary viewpoint. Phylogenetic analyses of tools and debitage, for example, could provide important complements to those of projectile points. Likewise, GM analyses of tools may complement those already published using size-adjusted interlandmark morphometrics (Andrews *et al.* 2015), either by supporting the earlier studies or by revealing new kinds of information.

Finally, although our primary objective here was to illustrate the relevance of various heuristic devices and methods to analyzing design space, it is significant that many of the studies we discuss underscore that cultural drift can play an important role in cultural evolution (e.g., Morrow and Morrow 1999; Hamilton and Buchanan 2009; Sholts *et al.* 2012; Eren *et al.* 2015a; Smith *et al.* 2015). When taken in aggregate, these studies have implications for the increasing North American projectile-point stylistic diversification and shrinking style zones throughout the Holocene we mentioned above. The studies suggest that the initial origins of this vast technological and cultural diversity can now be traced for the first time to cultural drift during the initial colonization process itself, as individual Clovis groups began to have less contact with each other. This important finding has parallels in the Old World (Lycett and von Cramon-Taubadel 2008). Boyd and Richerson (2010, p. 2010) perhaps said it best: "We know that social learning processes are very rapid, and that they can maintain behavioural differences among neighbouring human groups despite substantial flows of people and ideas between them. As a result, human groups are more like different species than populations of the same species, and this may be why phylogenetic methods work so well for cultural variation."

Compliance with Ethical Standards

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