ARTICLES

A UNIFIED EVOLUTIONARY MODEL OF ARCHAEOLOGICAL STYLE AND FUNCTION BASED ON THE PRICE EQUATION

P. Jeffrey Brantingham

The style-function dichotomy lies at the heart of the evolutionary archaeology research program. It also is the source of much disagreement about how we should conceive of the processes of culture change. Evolutionary archaeologists tend to view archaeological attributes as either functional, if they respond to selection, or stylistic, if they do not. Others tend to see style and function as operating simultaneously. A resolution to this problem is proposed through development of a formal mathematical model of style- and function-based evolution using a hypothetical example of temporal patterns of ceramic decoration within a community of household-based potters. Simple replicator equations are proposed to describe the household-scale dynamics of change in the relative frequency of ceramic decoration. These low-level dynamics can be distinguished on the basis of whether or not change is correlated with some measure of performance, utility, or payoff. The replicator equations are then used to derive several versions of the Price Equation (Price 1970), a very general and powerful statement about total evolutionary change in any system. At this scale of analysis, total change is similarly partitioned into payoff-correlated (functional) and payoff-independent (stylistic) contributions and it is shown that these processes are likely to operate simultaneously. Tests of the model against simulated data show that it is possible to estimate with considerable accuracy the strength of functional and stylistic contributions to culture change under ideal conditions of site preservation. Further theoretical work is needed, however, to understand how diverse site formation and disturbance processes might impact application of the model in real archaeological settings.

La dicotomía entre estilo y función está en la base del programa de investigación de la arqueología evolucionista. También es el origen de mucho desacuerdo sobre cómo debemos imaginar los procesos de cambio cultural. Los arqueólogos evolucionistas clasifican los atributos arqueológicos como funcionales, si responden a selección, o estilísticos, si no lo hacen. Otros piensan que estilo y función opera al mismo tiempo. Se propone una resolución para este problema mediante el desarrollo de un modelo matemático de evolución basado en estilo y función, usando un ejemplo hipotético de patrones temporales de la decoración en la cerámica en una comunidad de ceramistas organizadas en unidades domésticas. Se proponen ecuaciones sencillas replicadoras para describir, en la escala de las unidades domésticas, las dinámicas de cambio en la frecuencia relativa de decoración de la cerámica. Puede distinguir entre estas dinámicas de bajo nivel si los cambios tienen correlación con realización, utilidad, o recompensa, o no. Se usa las ecuaciones replicador para obtener diferentes versiones de la Ecuación Price (Price 1970), una declaración general y fuerte sobre cambio evolutivo en un sistema. En esta escala de análisis, el cambio total está dividido en contribuciones funcionales (que tienen una correlación con recompensa) y contribuciones estilísticos (que no tienen correlación con recompensa), y se demuestra que estos procesos funcionan al mismo tiempo. Pruebas de este modelo usando datos simulados demuestran que es posible, con mucha precisión, estimar la importancia de contribuciones funciónales y contribuciónes estilísticas bajo de coediciones ideales de conservación de sitios arqueológicos. Sin embargo, necesitamos más investigaciones teóricas para comprender cómo los procesos diversos de la formación y alteración de sitios arqueológicos afectan la aplicación de este modelo en situaciones arqueológicas reales.

Evolutionary archaeology has long maintained a strict distinction between archaeological style and function—holding that evolution of the latter is under the control of selection, while evolution of the former is under the control of stochastic processes (Dunnell 1978; see also Sackett 1977):

Traits that have discrete selective values over measurable amounts of time should be accountable by natural selection and a set of external conditions. Traits identified as adaptively neutral will display a very different kind of behavior because their frequencies in a population are not directly accountable in terms

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> of selection and external contingencies. Their behavior should be more adequately accommodated by stochastic processes. . . . The dichotomy [between function and style] is mutually exclusive and exhaustive in principle [Dunnell 1978: 199].

Those seeking theoretical development and/or practical application of the above definitions, not surprisingly, have tended to treat individual archaeological attributes as responding to either selective pressures or stochastic forces but not some combination of both (e.g., Braun 1987; but see O'Brien and Holland 1992; O'Brien et al. 1994). Others have taken the position that a strict, mutually exclusive boundary between style and function likely only obtains in very rare and restricted cases and indeed that both may be operating simultaneously most of the time (Bettinger et al. 1996; Boone and Smith 1998; Franklin 1989). The implication is that the style-function dichotomy, at least as presented by evolutionary archaeology, is of limited utility for understanding cultural change.

This paper develops a series of formal mathematical models based on the core premise of the evolutionary archaeological position on style and function and then follows through to evaluate whether it is necessary to treat style and function as mutually exclusive phenomena. To be more consistent with current thinking about cultural evolution (Boyd and Richerson 1985; Henrich and McElreath 2003), it is suggested that more precise (and less contentious) definitions of function and style should focus on whether or not change in an archaeological attribute of interest is correlated with some measurable payoff; dropping any necessary reference to reproductive success, biological fitness, or natural selection. Change that is payoff-correlated may be termed "functional," whereas change that is payoff-independent may be termed "stylistic." Here "payoff" is a general term used to describe the differential performance or utility of socially or individually learned behaviors, including the items of material culture that are integral to these behaviors. Payoffs may be measured in any currency including power or prestige as well as more mundane economic ones such as time or energy. It is assumed that people have the ability to evaluate the expected performance or utility of alternative behaviors and to learn those that they deem, correctly or incorrectly, to yield higher payoffs. We are thus free to talk about selection as a more general process that operates on learned behaviors in the context of interactions between individuals or groups of individuals.

Stylistic, payoff-independent change also may originate at a low level, possibly as a result of individual choices (Hegmon 1995; Sackett 1977; Wiessner 1983). It might also simply be the result of errors associated with trial-and-error learning or the social transmission of learned behaviors (Boyd and Richerson 1985; Eerkens and Lipo 2005; Henrich 2004). The important observation here is that these particular choices, interactions, or transmission errors operate without regard for the differential performance or utility of those behaviors. In the core evolutionary archaeology literature payoff-independent change is frequently described as "undirected" or neutral, and the pattern of change is said to be stochastic. The point made by Dunnell (1978) and others is that if selection is to be the only source of directional change in the archaeological record, then variation must arise in all directions (i.e., it must be isotropic), creating the possibility that substantive change could occur in any direction. Selection is then the process that steps in to direct which variants or innovations persist, and which do not. Darwin himself was critically concerned with this issue having recognized that if an organism or population could anticipate what adaptations or innovations would yield higher fitness, then natural selection might cease to be *the* creative force in evolution, leaving a Lamarkian one in its stead (see Gould 2002). Most anthropologists would take issue, however, with the idea that innovations must only be isotropic (Boone and Smith 1998). Rather, it seems that many cultural innovations are decidedly anisotropic, biasing some directions of change over others.

Section one of this paper develops a hypothetical archaeological scenario involving a community of household-based potting groups. Our interest is in studying change within the community in the relative frequency at which ceramics are decorated with a specific design element. The target of this scenario—ceramic decoration—is chosen specifically because of its ambiguous position in the style-function dichotomy. On the one hand, decoration of ceramics with designs such as geometric, abstract, or naturalistic forms might be seen as stylistic in that such decorations have no obvious utilitarian function that is easily translated into an economic currency for measuring performance (Braun 1987; O'Brien et al. 1994). On the other, such decorations might play key roles in structuring communication and cooperation between members of a group with a range of possible consequences (Conkey and Hastorf 1990; Hegmon 1992; McElreath et al. 2003; Wiessner 1983; Wobst 1977). The focus on change in the relative frequency of ceramic decoration is congruent with the methodological approaches used by Kohler et al. (2004), Lyman and O'Brien (2000), Neiman (1995) and Shennan and Wilkinson (2001). Table 1 lists all of the variables, parameter ranges, and variable interpretations used throughout the paper.

Sections two and three of this paper cast the general model as two separate replicator equations giving, respectively, (1) payoff-correlated (i.e., functional) and (2) payoff-independent (i.e., stylistic) change in the relative frequency of ceramic decoration. Underlying payoff-correlated change is a so-called payoff function (Gintis 2000; Maynard Smith 1982; Weibull 1995), here illustrated as a simple linear function of decoration frequency. Appendix A shows how to derive this payoff function from a standard coordination game where a ceramic decoration serves as a *passive* marker of the mixed strategies deployed by households (see also McElreath et al. 2003). Payoff-independent change, by contrast, is underlain by stochastic fluctuations in the frequency at which individual households decide to decorate their ceramics. Whereas most studies have assumed that the stochastic processes underlying stylistic change must be neutral, or isotropic (see Neiman 1995), it is shown here that payoff-independent change may also lead to directional change while still being stochastic. Two independent, reduced forms of the Price Equation (Frank 1997; Price 1970) are derived to characterize the mechanisms driving functional and stylistic change in the mean frequency of ceramic decoration over time.

Section four shows how the independent payoff-correlated and payoff-independent replicator equations may be combined into a single master equation. It is then a relatively short step to the full Price Equation (Frank 1997; Gintis 2000; Price 1970), an elegant partitioning of total evolutionary change into components describing payoff-correlated and payoff-independent contributions. The Price Equation is a very general and flexible description of change in any system and has been used to bring formality to the study of evolutionary problems ranging from kin and group selection (Bowles et al. 2003; Grafen 2000; Hamilton 1970), to evolutionary economics (Gintis 2000) and processes of cultural evolution (Henrich 2001, 2004). Here I intend to show that the Price Equation also may be used to partition total evolutionary change in the mean frequency of ceramic decoration into components of function and style. Section five examines the dynamics of the full Price Equation and highlights the ways in which payoff-correlated and payoff-independent processes might combine to generate directional change in an archaeological assemblage.

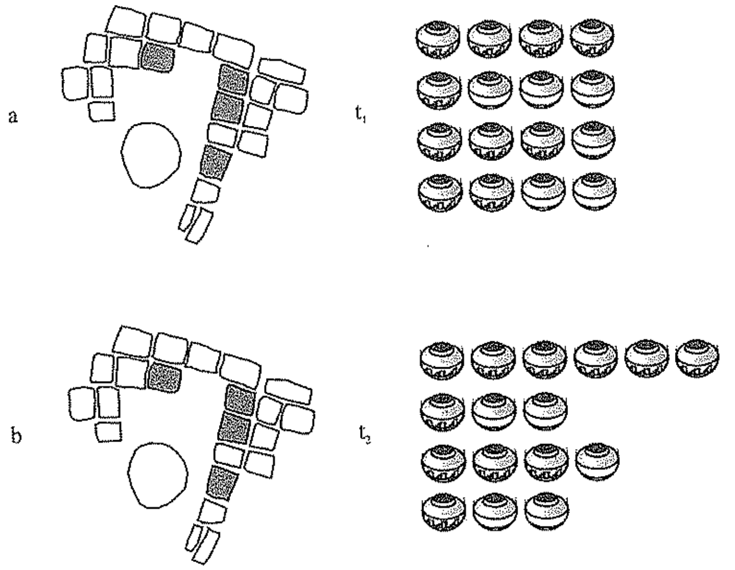
The final section of this paper outlines how the full Price Equation may be used to estimate the strength of functional and stylistic contributions to the evolution of an attribute of interest—here the frequency of ceramic decoration—in archaeological contexts. To avoid a lengthy discussion of taphonomic issues necessary for application of the model to a real archaeological case, the accuracy of the approach is tested against simulated data. This section thus identifies the minimum data requirements necessary to seek application of the model.

Household Ceramic Production

Assume there is a community of individuals organized into one or more households each identified by a unique index $i = 1, 2, \dots, I$ (Figure 1). At any given time interval each household produces n_i ceramic vessels and household i's share of all the pots produced is $p_i = n_i/N$, where N is the total number of pots produced by the community. Because p_i is a proportion $\sum p_i = 1$. In addition, each household has the option to decorate one or more of the pots it produces. Let z_i be the relative frequency of pots produced by household i decorated with some design element. Then $1 - z_i$ of the pots are undecorated. Note that $z = \sum p_i z_i$ is the mean frequency of ceramic decoration in the community and the product $p_i z_i$ is household i's contribution to the mean. Figure 1 illustrates the relationship between these variables in archaeological context at two different time periods (t_1 and t_2). It is assumed for simplicity that households are tied to specific domestic

Table 1. Description of Model Variables.

Variable	Value Range	Units	Description
i	> 1	count	household identifier
I	> 1	count	total number of households in community
n_i	≥ 0	count	number of ceramic vessels made by household *i* in one generation
N	≥ 0	count	total number of ceramic vessels made by the community in one generation
p_i	0–1	proportion	proportion of all ceramic vessels made by household *i* in one generation
z_i	0–1	relative frequency	relative frequency of ceramic decoration by household *i*
z	0–1	relative frequency	mean relative frequency of decorated ceramic vessels made by all households
w_0	1	payoff in arbitrary currency	baseline payoff to households expected in interactions
w_i	≥ 1	payoff in arbitrary currency	payoff to household *i* given ceramic decoration at proportional frequency z_i
w	≥ 1	payoff in arbitrary currency	mean payoff to all households given a mean proportion of ceramic decoration
w_i/w	≥ 0	scale free	relative payoff to household *i* ceramic decoration at proportional frequency z_i
δ_i	$-1 \leq \delta_i \leq 1$	relative frequency	stochastic fluctuation in the frequency of ceramic decoration within household *i*
p'_i	0–1	proportion	the proportion of ceramic vessels made by household *i* in the next generation
z'_i	0–1	relative frequency	relative frequency of decorated ceramic vessels made by household *i* in the next generation
z'	0–1	relative frequency	mean relative frequency of decorated ceramic vessels made by all households in the next generation
$\mathrm{COV}[w_i/w, z_i]$	-	relative payoff * relative frequency	covariance between relative payoffs and relative frequency of decorated ceramics
β_1	-	relative payoff / relative frequency	regression coefficient (slope) of reltive payoffs on relative frequency of decorated ceramics
$\mathrm{VAR}[z_i]$	-	squared relative frequency	variance in the relative frequency of decorated ceramics
$\mathrm{E}[\delta_i]$	$-1 \leq \mathrm{E}[\delta_i] \leq 1$	relative frequency	expected value (mean) of stochastic fluctuations in the relative frequency ceramic decoration
Δz	-	relative frequency / time	rate of change in the mean relative frequency of decorated ceramics
$\hat{\beta}_1$	-	relative payoff / relative frequency	estimate of regression coefficient of reltive payoffs on relative frequency of decorated ceramics
$\hat{\mathrm{E}}[\delta_i]$	$-1 \leq \mathrm{E}[\delta_i] \leq 1$	relative frequency	estimate of the expected value of stochastic fluctuations in the relative frequency ceramic decoration



i	p_i	z_i	$p_i z_i$	z
1	.25	1	.25	
2	.25	.25	.0625	.625
3	.25	.75	.1875	
4	.25	.5	.125	

i	p'_i	z'_i	$p'_i z'_i$	z'
1	.375	1	.375	
2	.1875	.333	.0625	.6875
3	.25	.75	.1875	
4	.1875	.333	.0625	

Figure 1. Relationship between archaeological assemblage formation and the primary variables of the frequency-based model. (a) A community at time t_1 is represented by a sample of four domestic structures each assumed to correspond to a unique household $i = 1, 2 \ldots, 4$. Each household produces a proportion p_i of the total jars made by the sampled community and each decorates their jars at a frequency z_i. The mean frequency of ceramic decoration z is the sum of the contributions made by each household $p_i z_i$. (b) At the next point in time t_2 changes (indicated by primes) are observed in both the proportion of jars made by individual households p'_i and the frequency of ceramic decoration within households z'_i. These evolutionary changes at the household level also shift the mean frequency of ceramic decoration z within the sampled community.

structures and produce pots in fixed, discrete generations. That is, pots are manufactured, used, and then discarded before any new pots are manufactured. The amount of time represented by a generation might vary from days to months to, perhaps, years. The important point is that the time scale is fundamentally ethnographic. At the beginning of t_1 each of four sampled households produces four pots and the total sampled community produces 16 pots (Figure 1a). Thus each household contributes a share $p_i = .25$ to the total ceramic assemblage, decorated or undecorated. Each household also decorates their pots at a different frequency. Household $i = 1$, for instance, decorates all of its pots (i.e., $z_1 = 1$), whereas household $i = 2$ decorates only one of its pots (i.e., $z_2 = .25$). These two groups contribute $p_1 z_1 = .25$ and $p_2 z_2 = .0625$, respectively, to the mean frequency of ceramic decoration in the community-wide assemblage. Adding up the contributions of each household gives the mean relative frequency of ceramic decoration in the community as $z = \sum p_i z_i, = .625$. These pots are used and discarded at the end of t_1, ideally within domestic structures corresponding to each household, and sixteen new pots are produced at the beginning of t_2 with noticeable changes in the proportion of pots made by each household and the frequencies at which each household decorates those pots (Figure 1b). These changes impact both the individual household frequency and the mean frequency of ceramic decoration at the community assemblage level.

Payoff-Correlated Change

The basic model outlined above leaves unspecified the mechanisms driving changes in the frequency of ceramic decoration from one time period to the next. As a first case, we may start with an assumption that the specific design element used in decorating pots plays some role, either active or passive, in social interactions between households. For example, the design element might serve as a marker of a households' probability of engaging in certain behaviors or activities. Households looking to coordinate their activities might use such markers to condition their behavior and thus increase their expected payoffs in interactions (Gintis et al. 2001; see also McElreath et al. 2003).

We can write a relatively simple replicator equation (Schuster and Sigmund 1983; Weibull 1995) to capture the essential dynamics of ceramic decoration at the scale of individual households

$$p_i' z_i = p_i \frac{w_i}{w} z_i. \qquad (1)$$

Equation (1) describes the payoff-proportional change in the share of pots made by household i. The term w_i is the expected payoff to household i when decorating their pots at frequency z_i and w is the mean payoff to all households in this generation of ceramic manufacturing. The term w_i/w is the relative payoff to household i with respect to all other households and has a mean value of one. Notice in Equation (1) that all of the change in decoration frequency is carried by the term $p_i \rightarrow p'_i$, the prime indicating a changed value in the next generation. If the relative payoff to household i is greater than one, then i's share of all the pots produced increases. If the relative payoff is less than one, then i's share decreases. In other words, decoration of ceramics at a given frequency confers some advantage (disadvantage), which is translated into a greater (lesser) proportion of the ceramic assemblage being manufactured by household i. Selection does not operate to increase or decrease the value of z_i, at least at a household-scale of analysis (see Gintis 2000).

A wide array of payoff functions could be used to model w_i. Here I assume that w_i is a simple linear function of z_i

$$w_i = uz_i + w_0 \qquad (2)$$

The payoff function includes a baseline payoff level w_0 and some constant benefit u—or cost if u is negative—assigned to each value of z_i (Appendix A). If u is positive, then higher payoffs come from decorating pots at higher frequencies. If u is negative, by contrast, then payoffs decline with increasing frequency of ceramic decoration.

That this process is also payoff-correlated over longer time scales may be demonstrated by deriving a general equation tracking change in the mean frequency of ceramic decoration over time. Remembering that the mean frequency of ceramic decoration in the community is given by $z = \sum p_i z_i$, we may write

$$\Delta z = z' - z = \sum_{i=1}^{I} p_i \frac{w_i}{w} z_i - \sum_{i=1}^{I} p_i z_i, \qquad (3)$$

where z is the mean relative frequency of decoration in the older and z' the mean in the younger of two sequential ceramic assemblages. Equation (3) is equivalent to the standard formula for the covariance between two random variables and thus may be rewritten as (Appendix B)

$$\Delta z = \mathrm{COV}\left[\frac{w_i}{w}, z_i\right]. \qquad (4)$$

Equation (4) is a reduced form of the Price Equation (Price 1970), an exact statement of payoff-correlated evolutionary change in any system (Frank 1997). The reduced Price Equation is deceptively straightforward. Here it links the rate of change in the mean relative frequency of ceramic decoration to the covariance between relative payoffs to individual households and the frequency at which those households decorate their ceramics. If relative payoffs and decoration frequencies both tend to be above their respective means, then the covariance is positive and the mean decoration frequency will increase. Conversely, if relative payoffs to individual households tend to be above the mean relative payoff when the household decoration frequencies are below the mean decoration frequency, then the covariance is negative and the mean frequency of ceramic decoration will decline. When there is no pattern to paired values of relative payoffs and decoration frequency, then the covariance is zero and the mean decoration frequency will remain unchanged.

The properties of Equation (4) may become more intuitive if it is rewritten as $\Delta z = \beta_1 \mathrm{VAR}[z_i]$, where β_1 is the slope (regression coefficient) of the linear least squares regression line of relative payoffs on the frequency of ceramic decoration, and $\mathrm{VAR}[z_i]$ is the variance in z_i (Frank 1997). As long as $\beta_1 \neq 0$, we can state that the change in the mean relative frequency of ceramic decoration over time is payoff-correlated (Appendix B). In other words, if decorating ceramics at different frequencies entails different outcomes in terms of performance, utility, or, more generally, payoffs, then there will be evolutionary changes in the mean frequency of ceramic decoration and we can attribute such change to a payoff-correlated process.

Figure 2 illustrates a process of payoff-correlated change. Shown is a payoff function with baseline payoff $w_0 = 1$ and an arbitrary positive

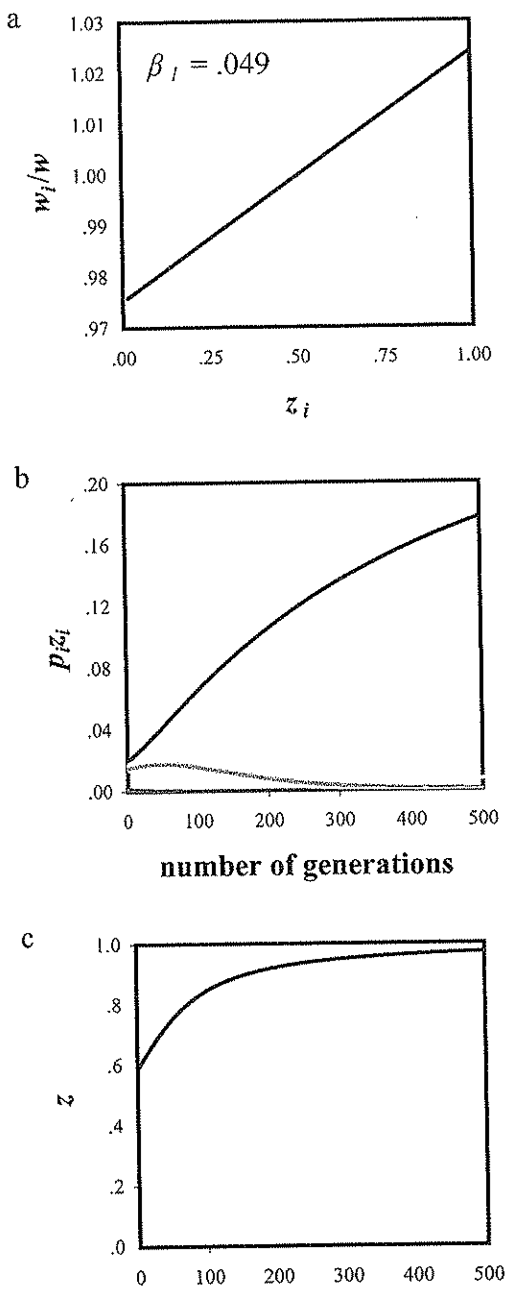


Figure 2. The relationship between (a) a positive payoff function ($\beta_1 = .049$) and changes in (b) the within-household and (c) mean ceramic decoration frequencies. Simulations in (b) and (c) are based on iteration of Equation (1) and show 500 assemblage formation events (generations) for fifty households. For clarity, panel (b) shows the paths followed by only five of the fifty households. At the outset, each household contributes an equal number of pots to the total assemblage (i.e., $p_i = .02$) and each begins with a randomly chosen frequency $z_i = [0, 1]$ at which they decorate their ceramics. The initial archaeological assemblage has a mean decoration frequency of $z = \sum p_i z_i = .5$.

slope of $\beta_1 = .049$ (Figure 2a). The positive slope of the payoff function implies that decoration of ceramics at higher frequencies reflects or confers an advantage, perhaps playing a role in the coordination of social activities. Those households initially decorating pots at high frequencies receive higher relative payoffs and see their share of the community assemblage of pots increase (Figure 2b). Those initially decorating at low frequencies receive lower relative payoffs and see their share fall. Eventually all pots are decorated at the same frequency and the mean frequency of ceramic decoration in an assemblage increases toward a maximum defined by the maximum value of z_i initially present in the community (Figure 2c). Equation (4), and its equivalent $\Delta z = \beta_1 \mathrm{VAR}[z_i]$, predict the evolutionary trajectory followed by mean decoration frequency, since initially $\mathrm{COV}[w_i/w, z_i] > 0$.

Figure 3 illustrates what happens if we change assumptions about the shape of the underlying payoff function. Figure 3a shows a case with baseline payoff $w_0 = 1$ and a negative slope of $\beta_1 = -.0513$. The implication here is that ceramic decoration at higher frequencies confers or reflects a disadvantage; perhaps it deters—for whatever reason—successful coordination of social activities. Given this negative payoff-correlated process, the pattern of change seen at the household and community-wide scales are reversed compared with the previous case (see Figure 2). Households initially decorating their ceramics at low frequency see their share of the community assemblage increase (Figure 3a) and the mean frequency of decoration declines toward the minimum value of z_i initially present in the community (Figure 3c). When there is no correlation between relative payoffs and decoration frequency (i.e., $\beta_1 = 0$) (Figure 3d), then there is no change in decoration frequencies at either the household (Figure 3e) or community scales (Figure 3f). The outcomes in both Figure 3c and f are also predicted by Equation (4), which gives $\mathrm{COV}[w_i/w, z_i] < 0$ and $\mathrm{COV}[w_i/w, z_i] = 0$, respectively.

Importantly, the trajectories of change both at the household and community assemblage scales are continuous. In other words, there are no abrupt, instantaneous changes in decoration frequencies from one time period to the next. Thus, a pure process of selection sometimes may be characterized by the *absence* of stochasticity (as suggested

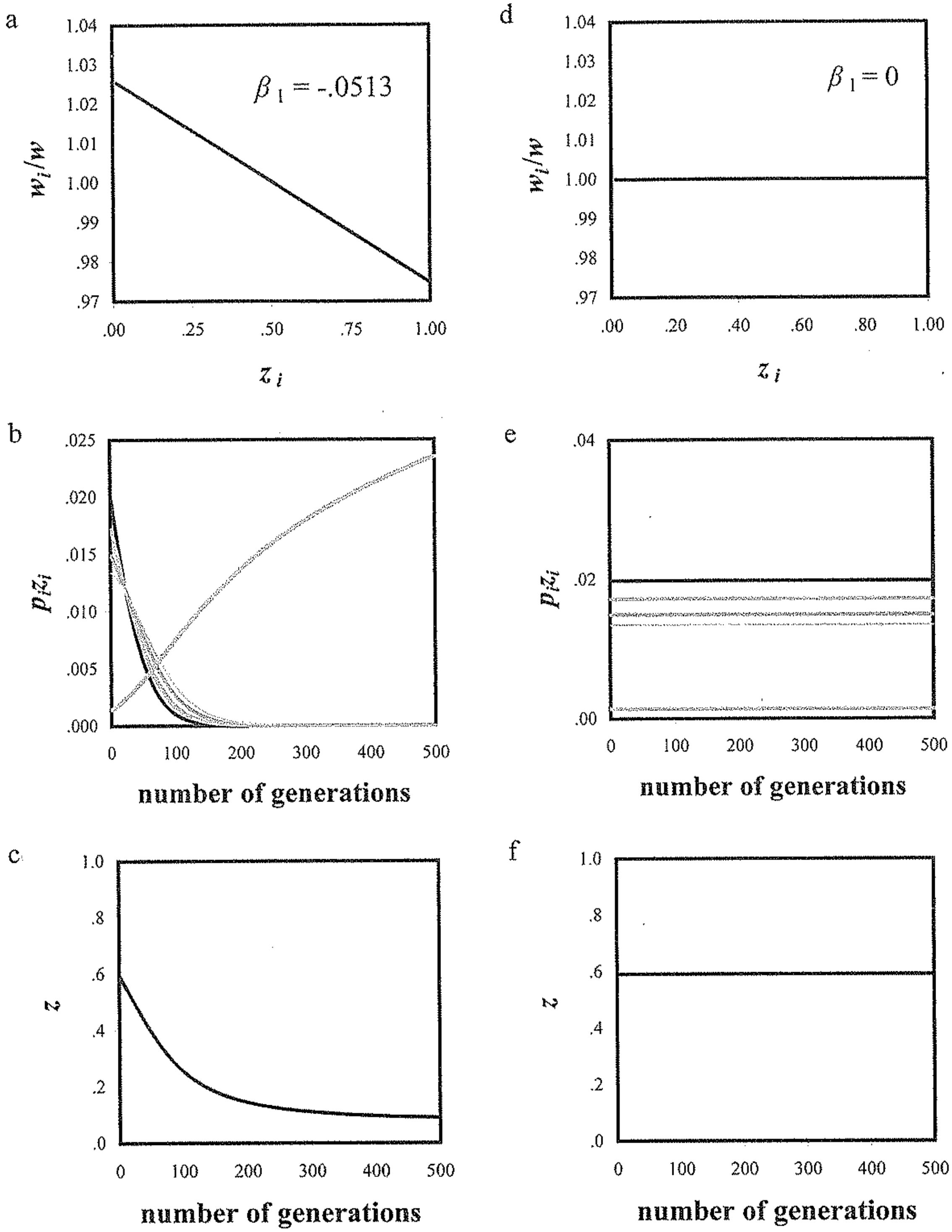


Figure 3. The relationships between (a and d) alternative payoff functions and changes in (b and e) the within-household and (c and f) mean ceramic decoration frequencies. Initial conditions are the same as shown in Figure 2 except that panels (a-c) show a negative payoff-correlated process of change (i.e., $\beta_1 = -.0513$), whereas (d-f) show the outcome when all decoration frequencies yield the same payoff (i.e., $\beta_1 = 0$).

by Dunnell [1978]). However, this pattern will hold only for relatively simple, monotonic payoff functions. If the payoff function underlying change is highly nonlinear—displaying peaks and valleys with many local optima—then the resulting evolutionary trajectories may *appear* stochastic. The appearance of stochasticity might also be exacerbated by biased site formation processes.

Payoff-Independent Change

It is also possible to envision a process whereby the frequency of ceramic decoration changes for reasons unrelated to any calculated payoffs. For example, the frequency of decoration among the jars made by household i may change because of inferential errors made during cultural transmission of potting traditions, or through conscious trial-and-error learning (Boyd and Richerson 1985; Eerkens and Lipo 2005; Henrich 2004). In either case, we can write a replicator equation for this process using the terms p_i and z_i from above with the addition of a variable δ_i describing stochastic fluctuations:

$$p_i z_i' = p_i\left(z_i + \delta_i\right). \tag{5}$$

In contrast with the payoff-correlated process of Equation (1), this new replicator equation assigns all of the change in the frequency of decoration to the variable $z_i \rightarrow z_i'$. Thus, Equation (5) implies that the share of the total assemblage of ceramic vessels made by i does not change (i.e., $p_i \rightarrow p_i$).

Equation (5) is fundamentally a Markov process, but there are many ways in which the random variable δ_i might be determined (see also Eerkens and Lipo 2005). Most illustrative in the present case is to assume that δ_i is a random variable drawn from a continuous unimodal probability density function such as a normal distribution with a mean μ and standard deviation σ.

$$p(\delta_i) = \frac{1}{\sigma\sqrt{2\pi}} e^{\left(\frac{(\delta_i - \mu)^2}{2\sigma^2}\right)} \tag{6}$$

The probability that the frequency of ceramic decoration in household i will change by an amount δ_i at any given discrete time interval is distributed as a symmetric, bell-shaped curve. Recalling the rules of sampling theory, the most common fluctuations will be μ in size, while more extreme fluctuations above and below the mean will be increasingly rare. Importantly, as long as neither the mean μ, nor the standard deviation σ of the distribution describing δ_i is itself a function of payoffs w_i, then Equation (5) is strictly payoff- independent.[1] This conclusion is emphasized below in derivation of the full Price Equation. For now, we can examine how Equation (5) may be used to describe long-term, evolutionary change in the mean frequency of ceramic decoration within the community.

By analogy with Equation 3, we may write:

$$\begin{aligned}\Delta z = z' - z &= \sum_{i=1}^{I} p_i\left(z_i + \delta_i\right) - \sum_{i=1}^{I} p_i z_i \\ &= \mathrm{E}[\delta_i]\end{aligned} \tag{7}$$

showing that the change in the mean frequency of decoration is determined by the mean, or expected value of δ_i. If the value of δ_i is drawn from a normal distribution, for example, then the expected value of δ_i is simply the mean μ of the probability distribution.

It is clear that specifying the *location* of the probability distribution used to model individual choices or transmission errors is critically important for determining the nature of payoff-independent change. Any probability distribution for δ_i where the mean $\mu = 0$ may be considered isotropic; fluctuations in frequency decoration tend to be both negative and positive and cancel one another out over the course of time. Thus, for a normal distribution with $\mu = 0$ and $\sigma = .01$, the expected value for any fluctuation $\mathrm{E}[\delta_i] = 0$ and most fluctuations will be contained with 95% probability in the range $2\sigma = \pm .02$. Calculated for a household manufacturing 100 ceramic vessels of which 50 are decorated, there is a 95 percent chance that the number of decorated vessels after one generation will be between 48 and 52, but most likely there will be no change in number at all. Played out over time, $\Delta z = 0$ and we should expect that the mean frequency of community ceramic decoration will not change. Figure 4a illustrates just such a case where δ_i is drawn from a normal distribution with mean $\mu = 0$ and a standard deviation $\sigma = .01$. The contributions of individual households to the mean frequency of ceramic decoration jumps from one assemblage formation event to the next, and, in some cases, there is strong directionality in the

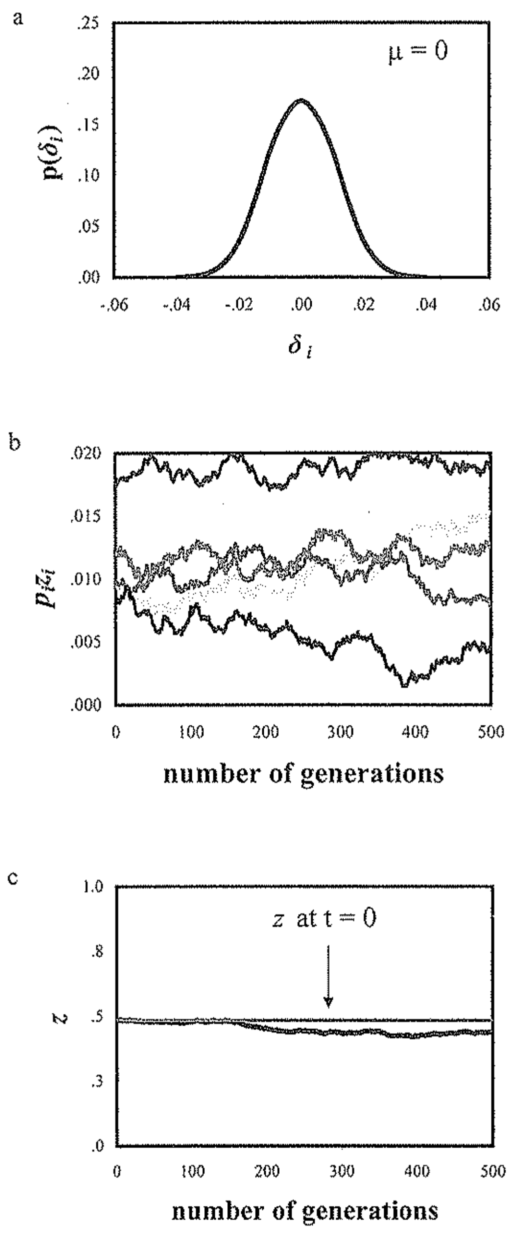


Figure 4. The relationship between (a) the probability distribution for δ_i and change in (b) the within-household and (c) mean frequency of ceramic decoration. Because the probability distribution in a is symmetrical with a mean of zero it qualifies as an isotropic processes. Initial conditions are the same as in Figure 2 except that the simulation is based on iterating Equation (5), with independent values of δ_i drawn from the probability distribution shown in (a).

trends followed by individual households (Figure 4b) (see also Neiman 1995). Overall, however, these fluctuations tend to cancel one another out and there is no long term change in the mean frequency ceramic decoration in the community. This is exactly what is predicted by Equation (7), which gives $\Delta z = E[\delta_i] = 0$. As noted by Eerkens and Lipo (2005), however, the variance in the frequency of ceramic decoration will tend to increase as a result of the modeled process.

Importantly, Equation (7) indicates that an isotropic process of change is not dependent upon δ_i being drawn from a symmetric probability distribution. It is only necessary that the mean of the distribution be zero. Conversely, Equation (7) also indicates that any probability distribution for δ_i where $\mu \neq 0$ will lead to directional change in the mean frequency of ceramic decoration, despite the fact that the process of change is payoff-independent. Changing assumptions about the nature of fluctuations δ_i has a significant impact on what we might expect to see archaeologically (Figure 5). In contrast to the symmetrical case shown in Figure 4a, that in Figure 5a is skewed with most of the probability mass falling below zero and a long tail extending over values greater than zero. Despite the difference in shape, the process modeled in Figure 5a is isotropic because the mean of the distribution is zero. The skewed isotropic distribution for δ_i produces much higher magnitude fluctuations in ceramic decoration frequency at the household level (compare Figure 4b and Figure 5b). Yet there is little difference in the mean frequency of decoration over the long term (compare Figure 4c and 5c). In other words, within-household fluctuations in z_i tend to cancel one another out leaving the mean frequency of decoration unchanged. As was the case above, the result shown in Figure 5c is predicted by Equation (7) since $\Delta z = E[\delta_i] = 0$.

In contrast, Figure 5d–f illustrates the dynamics of a non-isotropic process. Here we have a symmetrical normal probability distribution for δ_i with standard deviation $\sigma = .01$, but a positive mean $\mu = .01$. Positive fluctuations in within-household ceramic decoration tend to occur more frequently and are not cancelled out by matching negative fluctuations. This non-isotropic process, not surprisingly, translates into a strong directional trend in evolution both at the household (Figure 5e) and

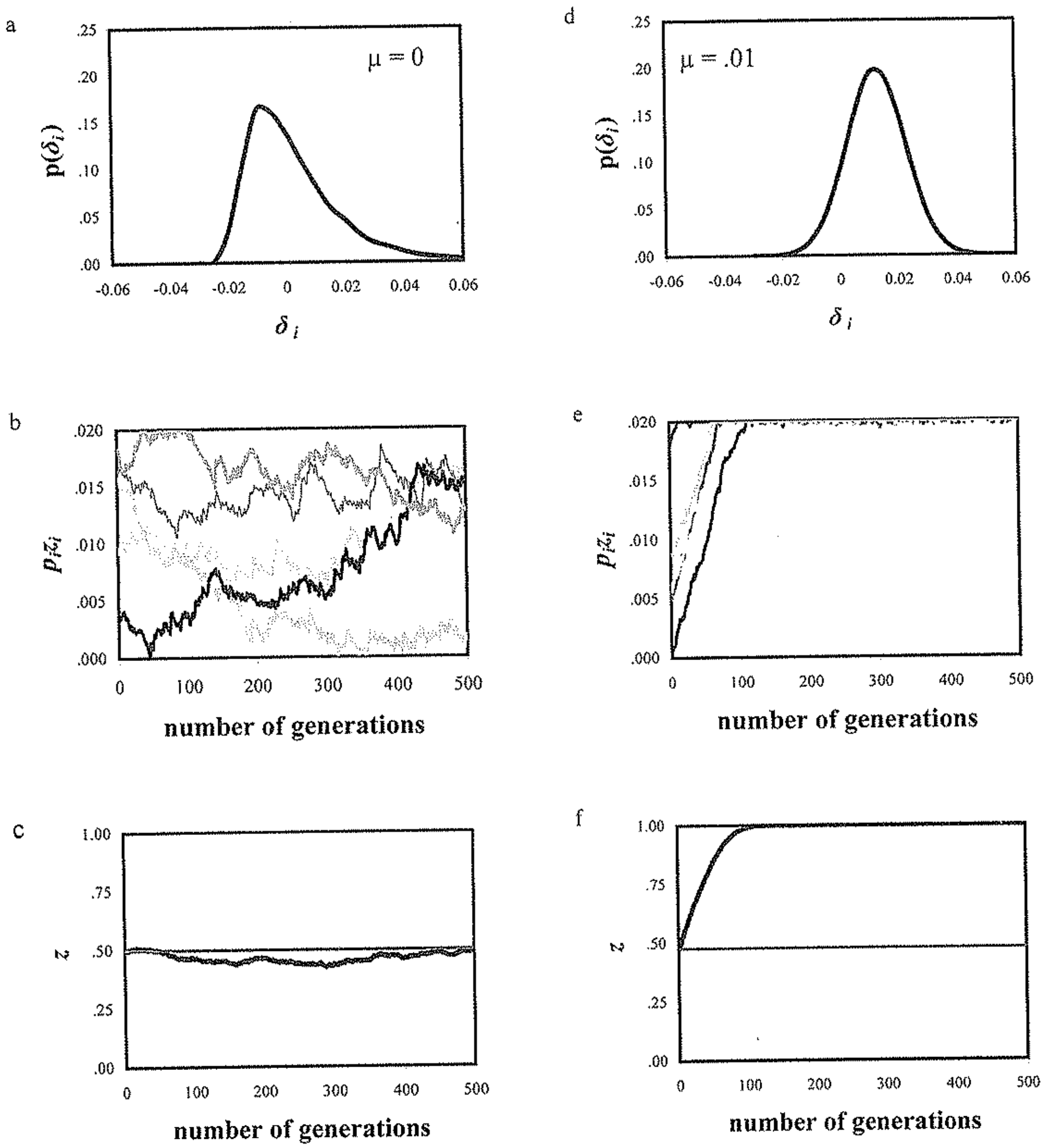


Figure 5. The relationship between (a and d) alternative probability distributions for δ_i and change in (b and e) within-household and (c and f) mean ceramic decoration frequencies. Initial conditions are the same as in Figure 4 except that panels (a-c) illustrate an asymmetric isotropic processes of change, while panels (d-f) illustrate a symmetric non-isotropic process.

community scales (Figure 5f). This result is also expected from Equation 7 given that $E[\delta_i] > 0$.

In sum, if stylistic change is modeled as a payoff-independent process, where the mechanism underlying change is random fluctuations arising from individual choices, errors during cultural transmission and/or trial-and-error learning; then it is reasonable to characterize this process as stochastic (Dunnell 1978). However, it is important to emphasize that certain stochastic processes may also lead to substantial directional change. The absence of directional change only obtains if the stochastic process is isotropic, and then only at the aggregate scale. Thus, while stochasticity may sometimes serve as a diagnostic criterion for payoff-independent processes of cultural change, the presence of directional change does not necessarily indicate that a payoff-correlated process is operating.

The Style-Function Partition

The two previous sections assumed that payoff-correlated and payoff-independent changes in the relative frequency of ceramic decoration are fundamentally separate processes. Much of the continuing debate over the nature of style and function centers, however, on the idea that both processes may be operating simultaneously or, at a minimum, that stylistic and functional contributions to change cannot readily be separated. If we assume that payoff-correlated and payoff-independent change are facets of a single process, we can write a unified replicator equation based on Equations (1) and (5).

$$p'_i z'_i = p_i \frac{w_i}{w}\left(z_i + \delta_i\right) \tag{8}$$

Equation (8) states that household i may contribute to a new frequency of ceramic decoration through change both in its share of the total assemblage of vessels p'_i and in the frequency at which it decides to decorate those vessels z'_i. The impact this complete process has on long-term change in the mean frequency of ceramic decoration is given by (Appendix B)

$$\begin{aligned}\Delta z = z' - z &= \sum_{i=1}^{I} p_i \frac{w_i}{w}\left(z_i + \delta_i\right) - \sum_{i=1}^{I} p_i z_i \\ &= \mathrm{COV}\left[\frac{w_i}{w}, z_i\right] + \mathrm{E}\left[\frac{w_i}{w}\delta_i\right]\end{aligned} \tag{9}$$

Equation (9) is the full Price Equation (Price 1970), which is read as a partition of *total* evolutionary change into a covariance component (describing the influence of selection), and an expectation component (describing the effect of introducing new variability[2] to the system [Frank 1997]). The initial term on the right side of Equation (9) is identical to Equation (4) and we may therefore rewrite it as $\mathrm{COV}[w_i/w, z_i] = \beta_1 \mathrm{VAR}[z_i]$, where β_1 is again the slope of the regression of w_i/w on z_i. For any value of $\beta_1 \neq 0$, the covariance term of Equation (9) produces payoff-correlated change in the mean frequency of ceramic decoration. However, a similar comparison of the second term Equation (9) with Equation (7), developed above to describe independent stylistic change, reveals the addition of a term representing relative payoffs. It is possible to show, however, that the second term in Equation (9) may also be payoff independent, which reduces the full Price Equation to that described in Appendix B:

$$\Delta z = \underbrace{\mathrm{COV}\left[w_i/w, z_i\right]}_{\text{function}} + \underbrace{\mathrm{E}\left[\delta_i\right]}_{\text{style}} \tag{10}$$

Equation (10) states that the total evolutionary change in the mean frequency of ceramic decoration is the *sum* of the payoff-correlated process given in Equation (4) and the payoff-independent process given in Equation (7). If we accept the definition of function as traits that change in ways associated with payoffs (or utility, or performance) and style as traits that change in ways unassociated with payoffs, then the full Price Equation gives an exact and complete statement of how these two components contribute to total evolutionary change.

Two things are immediately apparent about this formal specification of style and function. First, for an archaeological trait to be considered functional, and for selection to a contributing factor to change in that attribute over time, there must be at least two distinct variants of that trait. Using the alternative specification of the covariance term $\beta_1 \mathrm{VAR}[z_i]$, it is clear that if a trait does not vary (i.e., $\mathrm{VAR}[z_i] = 0$) then there can be no selection. If, for example, all households in a community decorate at the same frequency, then there is no basis for distinguishing between those households and no raw material upon which selection might be able to operate. The converse is also true: The magnitude of the contribution of selection to total evolutionary change in an attribute may increase as variance increases. This, of course, is a restatement of Fisher's fundamental theorem of natural selection (Frank 1997). Emphasis is placed on the word *may* because it is also necessary that payoffs and the attribute under study be correlated in some way (i.e., $\beta_1 \neq 0$). It is possible that there might be sufficient variance in a trait within a population to suspect selection (i.e., $\mathrm{VAR}[z_i] > 0$), but that different trait values entail no payoff differences (i.e., $\beta_1 = 0$). There is likewise no scope for selection under this condition. From a practical standpoint, therefore, the classification of an archaeological attribute as functional requires not only measurable variability, but also the specification of a model for how that variability translates into differential payoffs. General statements about more advanced technologies contributing to increased adaptation are insufficient as a model of selection. Rather, it is necessary to relate quantifiable variability in technology to some currency (Brantingham and Kuhn 2001; Braun 1987; Hayden 1998; Kuhn 1994; McElreath et al. 2003; Mills 2004; O'Brien et al. 1994; Stanish and Haley 2005; Surovell 2003; Ugan et al. 2003), and to show that these differences are sufficient for discriminating between attribute states (see Eerkens and Bettinger 2001). The one exception to the above statements concerns any situation where we believe that selection is strong enough to eliminate all variability and maintain the system in this state. That selection methodically destroys variation is obvious. In the absence of a process that introduces new variation, selection will very quickly produce a system where there is no variance in the trait under investigation. Or, even if there is a process that generates new variability, it may be eliminated so quickly that its presence is difficult to observe. In these cases, it may be possible to claim that an archaeological attribute is functional precisely because it shows no variance at all. However, I contend that this places an extra burden on the researcher to specify the model (i.e., payoff function) of how and why variability is eliminated. I emphasize, moreover, that one can not study function and payoff-correlated change in action in such situations, only the putative effects of a "ghost of selection past" (cf. Connell 1980).

Second, and more important as regards the style-function dichotomy, the full replicator equation, and full Price Equation derived from it, imply that payoff-correlated and payoff-independent change may operate simultaneously on the same attribute. That contributions from payoff-correlated and payoff-independent processes are summed to describe total evolutionary change seems to support Dunnell's (1978) claim that these two processes are indeed exhaustive, but it also seems to violate the mutual exclusivity clause of the style-function dichotomy. If the style-function dichotomy is taken to mean that change in some attribute of interest is either stylistic or functional, but not some combination of both, then the full Price Equation seems to open the door to many conditions where this might not hold.

The Dynamics of Style and Function

A simple dynamic analysis of the Price Equation emphasizes the myriad ways in which an archaeological attribute of interest may evolve (Figure 6). Solving Equation (10) for the condition $\Delta z = 0$ shows that functional and stylistic components of change must exactly balance one another out at equilibrium (i.e., $\text{COV}[w_i/w, z_i] = -\text{E}[\delta_i]$). The combination of terms giving equilibrium conditions are shown as a line sloping from upper-left to lower-right in Figure 6. In the present scenario, for example, selection against increases in the frequency of ceramic decoration (i.e., $\text{COV}[w_i/w, z_i] < 0$) would need to be balanced exactly by an opposite source of stochastic variation (i.e., $\text{E}[\delta_i] > 0$), for the system to remain in equilibrium. The pro-novelty bias in ceramic decoration identified by Shennan and Wilkinson (2001) in the Neolithic of Central Europe could conceivably provide just such a balance if selection for some reason started to work against novel forms of ceramic decoration. Henrich (2004) provides another good example where a model linking more advanced technologies to higher foraging returns leads to an expectation of cumulative directional change toward more complex technologies $\text{COV}[w_i/w, z_i] > 0$). However, population size-dependent errors in the learning of complex technological skills create an evolutionary counterweight against cumulative cultural change (i.e., $\text{E}[\delta_i] < 0$).

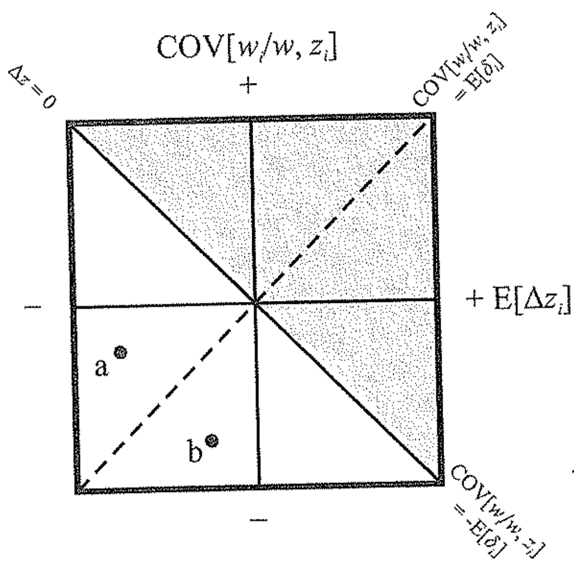


Figure 6. A phase diagram for payoff-correlated and payoff-independent contributions to total change in the mean frequency of ceramic decoration within a community of household based potters. See text for detailed description.

More difficult to analyze are situations where there is directional change in the mean frequency of decoration (Figure 6). There are three distinct sets of conditions in which directional change may obtain: (1) one of the two terms of the Price Equation is non-zero, while the other is zero; (2) both terms are non-zero and of the same sign; or (3) the two terms are of opposite signs, but one is sufficiently large to swamp the counteractive force of the other. Condition 1 states that directional change is driven only by payoff-correlated functional processes, or payoff-independent stylistic processes. In Figure 6, this condition holds for any point falling along one of the axes, excluding the origin. Condition 2, by contrast, states that payoff-correlated and payoff-independent processes are mutually reinforcing in driving directional change. Any points in the upper-right or lower-left quadrants describe such systems. Points falling along the line sloping from the lower-left to upper-right represent systems where payoff-correlated and payoff-independent processes contribute equally to directional change. Finally, Condition 3 states that either payoff-correlated or payoff-independent processes are sufficiently strong to outweigh any counteractive contributions from the other. In Figure 6, any points falling in the upper-left and lower-right quadrants represent such systems.

Two general implications of this dynamic analysis should be emphasized. First, the state space where either payoff-correlated or payoff-independent processes are exclusively responsible for change (Condition 1) is small relative to that where the two terms of the Price Equation are both non-zero (Conditions 2 and 3). Systems combining payoff-correlated and payoff-independent processes, therefore, might be expected to be far more likely to occur than those based solely on one or the other process. This general observation seems consistent with intuition about how change occurs in actual archaeological systems (see Bettinger et al. 1996).

Second, sustained, directional change in an attribute of interest alone is insufficient to determine whether change is driven by a payoff-correlated or payoff-independent process. For example, the two points labeled *a* and *b* in Figure 6 describe two separate systems where the mean frequency of ceramic decoration is declining at exactly the same rate. However, in the case system *a*, change is driven primarily by the covariance term, whereas with system *b* change is driven primarily by the expectation term. Making the traditional assumption that directional change is indicative of a dominant role of selection would be wrong in the case of system *b*.

Figure 7 further underscores the potential complexities involved when payoff-correlated and payoff-independent processes operate simultaneously. The first column illustrates a situation where a positive payoff function (Figure 7a) is combined with a skewed but isotropic distribution of changes in the frequency of ceramic decoration used by individual households (Figure 7b). Changes at the household scale are erratic (Figure 7c), but the mean frequency of ceramic decoration within the community increases over time (Figure 7d). Because the process of within-household change is isotropic, we know that the long-term positive trend in mean design element frequency is driven exclusively by selection (i.e., $\mathrm{COV}[w_i/w, z_i] > 0$, while $\mathrm{E}[\Delta z_i] = 0$).

The second column in Figure 7 illustrate the consequences of combining a positive payoff function with a positive-biased probability distribution for within-household change in ceramic decoration (i.e., $\mathrm{COV}[w_i/w, z_i] > 0$ and $\mathrm{E}[\Delta z_i] > 0$). This combination of processes generates a very similar pattern of change at the community scale (compare Figures 7d and h), but dramatic differences at the household scale (compare Figures 7c and g). The added contribution of a positive-biased fluctuation in the within-household frequency of ceramic decoration enhances selection; the two households starting with higher frequencies of decoration see their contributions $p_i z_i$ to the mean relative frequency z immediately amplified (Figure 7g). The mean frequency of the design element in the assemblages produced by the community increases monotonically over time (Figure 7h). Despite the broad similarity between Figures 7d and 7h, the latter pattern is driven by a combination of both payoff-correlated and payoff-independent processes.

Introducing counteractive evolutionary forces may complicate the picture even further. The final column in Figure 7 shows a negative payoff function (Figure 7i) combined with positive-biased fluctuations in the frequencies at which individual households decorate their pots (Figure 7j) (i.e., $\mathrm{COV}[w_i/w, z_i] < 0$, while $\mathrm{E}[\Delta z_i] > 0$). Selection ini-

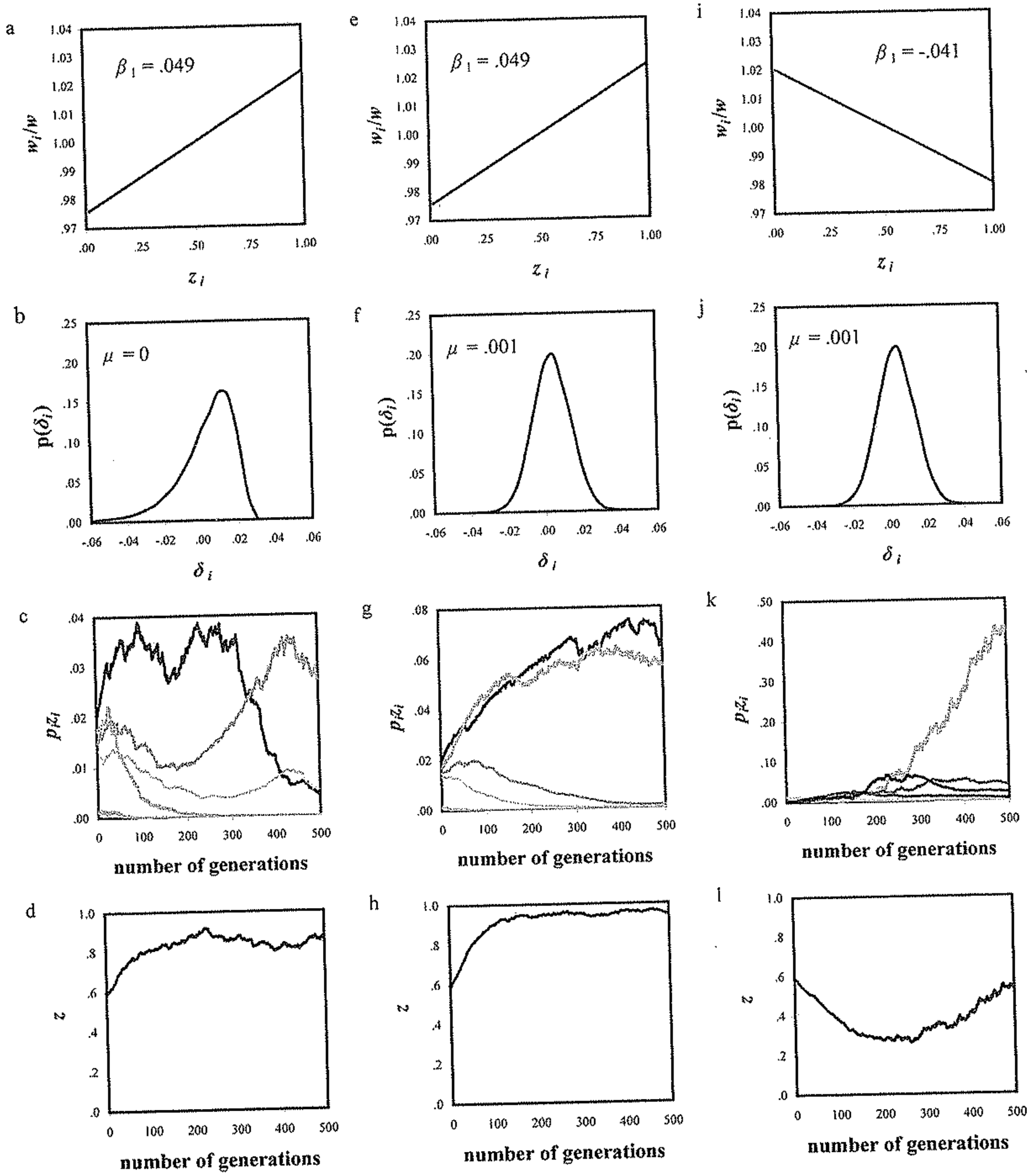


Figure 7. Change in the frequency of ceramic decoration driven by a combination of payoff-correlated and payoff-independent processes. (a-d) A positive payoff function is combined with an asymmetric isotropic source of stochastic fluctuations. (e-h) A positive payoff function is combined with a symmetric non-isotropic source of stochastic fluctuations. (i-l) A negative payoff function is combined with a symmetric non-isotropic source of stochastic fluctuations. (c, g, k) Change in the within-household frequency of ceramic decoration. (d, h, l) Change in the mean frequency of ceramic decoration. Initial conditions are the same as in Figure 2 except that the simulation is based on iterating Equation (8).

tially drives a decrease in the mean frequency of ceramic decoration, but the positive bias favoring an increased decoration within households eventually reverses this trend (Figure 7l). This reversal begins when the between-household variance in decoration frequency falls low enough to make $\beta_1 \text{VAR}[z_i] = \text{E}[\delta_i]$ (Figure 7k).

Archaeological Application of the Price Equation

Under the right conditions, it is possible to estimate values for the terms of the full Price Equation directly from archaeological data. A number of sites might ultimately prove to be appropriate for initial examination of the above models including, for example, the pueblos at Awatovi (Smith 1971) and Pecos (Kidder 1917, 1931; Kidder and Shepard 1936), both of which have particularly rich, stratified ceramic assemblages. However, application of the model to these or other archaeological cases would first require a careful consideration of site formation processes, disturbance, and chronology. Since these tasks are clearly beyond the scope of the current paper, I focus here on demonstrating the accuracy of a model fitting approach against simulated data where we know exactly what the results should be. This is an important step in model verification (see Brantingham 2006).

In the present scenario, if one is able to measure, over multiple time periods, the proportion of ceramic vessels made by individual households p_i and the frequency at which each of those households decorate their ceramics z_i, then one can calculate empirically both the rate of change in the mean frequency of decoration within the community Δz and the variance in the frequency of ceramic decoration between households $\text{VAR}[z_i]$. The linear regression of Δz on $\text{VAR}[z_i]$ will adhere to the equation

$$\Delta z = \underbrace{\hat{\beta}_1}_{\text{slope}} \text{VAR}[z_i] + \underbrace{\hat{E}[\delta_i]}_{\text{intercept}} \qquad (11)$$

which, as discussed above, is an alternative specification of the full Price Equation. The slope of the resulting regression line $\hat{\beta}_1$ is an estimate for the true value β_1 (Figure 8). Then $\hat{\beta}_1 \text{VAR}[z_i] = \text{COV}[w_i/w, z_i]$ is the estimated contribution of payoff-correlated processes to change in the mean ceramic decoration frequency. Similarly, the intercept of the regression line $\hat{\text{E}}[\delta_i]$ is an estimate of the true value of

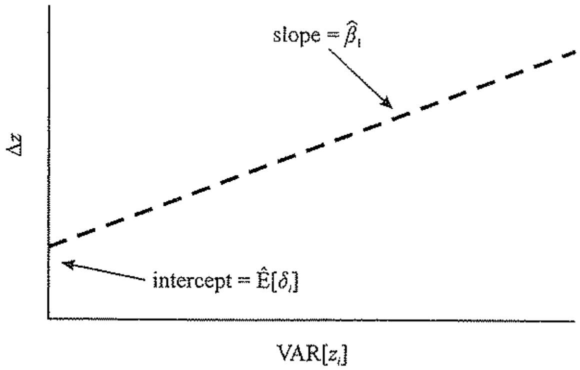


Figure 8. Schematic diagram showing how to estimate the terms of the Price Equation from a linear regression of the rate of change in mean ceramic decoration frequency Δz on the variance in the frequency of ceramic decoration between households $\text{VAR}[z_i]$.

$\text{E}[\delta_i]$, which is the contribution of payoff-independent processes to change in the mean decoration frequency.

Figures 9 and 10 illustrate how this approach may be implemented. Figure 9 simulates the evolution of ceramic decoration in a community of 50 households over the course of 2,000 ceramic manufacturing generations. The model may be taken to represent an ideal archeological setting where (1) each household can be readily identified with a domestic structure and (2) each generation of ceramics manufactured by a household is discarded within its corresponding domestic structure as a discrete depositional unit (see Figure 1). Here I combine a positive payoff function (β_1 = .005) and a small positive-biased source of fluctuations ($\text{E}[\delta_i]$ = .0001) in the frequency of ceramic decoration within individual households. In this case, ceramic decoration is initially rare in the community; only five of the fifty households deploy decorations in the first generation of manufacturing. As expected, the mean frequency of decoration increases toward unity over the course of time. The between-household variance in decoration frequency initially increases as decoration becomes more common in the community, but then begins to decline toward zero as households in the community converge on decorating their pots at the same frequency.[3]

Figure 10 plots empirically calculated values of Δz against $\text{VAR}[z_i]$ for the first 794 ceramic manufacturing generations of the simulated sequence shown in Figure 9. This is the portion of the

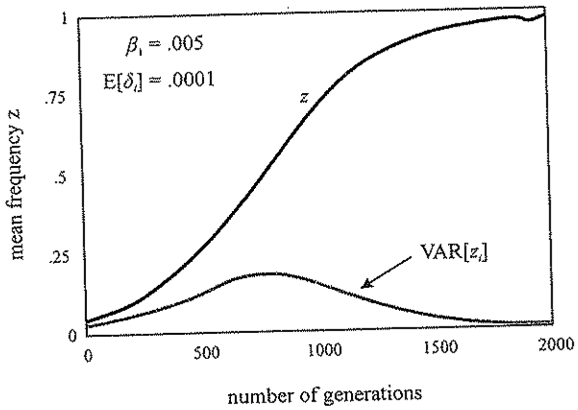


Figure 9. Simulated evolution of the mean frequency ceramic decoration within a community of 50 households. The simulation combines a positive payoff function (β_1 = .005) and a positive-biased source of stochastic fluctuations in within-household decoration frequency (μ = .0001). The between-household variance in decoration frequency is also shown.

sequence where the variance in ceramic decoration is still increasing and both payoff-correlated and payoff-independent processes are expected to be operating unconstrained. The variance in decoration frequency is calculated for each of the 794 stratigraphically distinct time periods following the standard formula VAR[z_i] = $\sum p_i(z_i - z)^2$. For example, in the oldest of four stratigraphic units, we might have two households who manufacture proportions p_1 = .5 and p_2 = .5 of the ceramics produced by the entire community and each decorates their ceramics at frequencies z_1 = .4 and z_2 = .6. The variance in decoration frequency between households for this oldest stratigraphic unit would be VAR[z_i] = .01. The rate of change in the mean frequency of decoration within the community is calculated empirically for each stratigraphically distinct time period as $z = z' - z$, where $z = \sum p_i z_i$ is the mean decoration frequency in the focal time period and $z' = \sum p'_i z'_i$ is the mean decoration frequency in the next immediate (younger) time period. For example, if the mean frequencies of ceramic decoration in four sequential strata (from oldest to youngest) are z = .5, z' = .55, z'' = .57 and z''' = .54, then the change in the mean frequency from the oldest stratum to the next youngest is $\Delta z = z' - z$ = .05, from the second oldest to the next youngest $\Delta z' = z'' - z'$ = .02, and from the third oldest to the youngest $\Delta z'' = z''' - z''$ = –.03. Plotting the calculated values of VAR[z_i] and Δz for the oldest stratum gives a point {VAR[z_i], Δz} = {.01, .05}.

The linear regression of Δz on VAR[z_i] for all 794 discrete time periods in the simulation gives a strong positive relationship (r = .77) (Figure 10). In general, the rate of change in the mean frequency of ceramic decoration is highest when the variance in the frequency of decoration between households is highest. More importantly, the slope and intercept of the regression are estimated, respectively, as $\hat{\beta}_1$ = .0048 (95 percent CI .0045–.0051) and $\hat{E}[\delta_i]$ = .0001 (95 percent CI .00009–.00015). These estimates are highly significant (F = 1152.38; p << .000001) and are practically indistinguishable from the known values β_1 = .005 and E[δ_i] = .0001 used in the simulation. The inset in Figure 10 shows that similar results may be obtained with much smaller samples, provided that Δz is calculated from known sequential stratigraphic units. The linear regression of Δz on VAR[z_i] for a random sample of 15 paired stratigraphic units[4] gives estimates $\hat{\beta}_1$= .0045 (95 percent CI .0028–.0062) and $\hat{E}[\delta_i]$ = .0001 (95 percent CI .00009–.00015). These results are also highly significant (F = 34.18; p < .00006) and indistinguishable from the known values.

Overall, the results presented above suggest that it is feasible to generate reliable estimates of the strength of payoff-correlated (functional) and payoff-independent (stylistic) contributions to the evolution of an archaeological attribute such as ceramic decoration frequencies within a community. Whether it is possible to obtain similarly accurate estimates for the full range of payoff-correlated and payoff-independent evolutionary systems illustrated in Figure 6 is presently unclear. For example, the estimates $\hat{\beta}_1$ and $\hat{E}[\delta_i]$ may diverge strongly from expectations when selection is very stringent and/or there are heavily biased random fluctuations (i.e., COV[w_i/w, z_i] and/or E[δ_i] is very large). The estimates may also be inaccurate when values of z_i are clustered near one (or both) of the boundaries (i.e., $z_i \rightarrow$ 1 or 0), since the possible directions of change are limited there. For example, even if random fluctuations in the frequency of ceramic decoration within households is biased toward positive values (i.e., E[δ_i] > 0), a household already decorating all of its pots (i.e., z_i = 1.0) can only respond to negative fluctuations. Both of these issues deserve further investigation.

More significantly, perhaps, the extent to which site formation and disturbance processes impact the accuracy and precision of estimates like those pre-

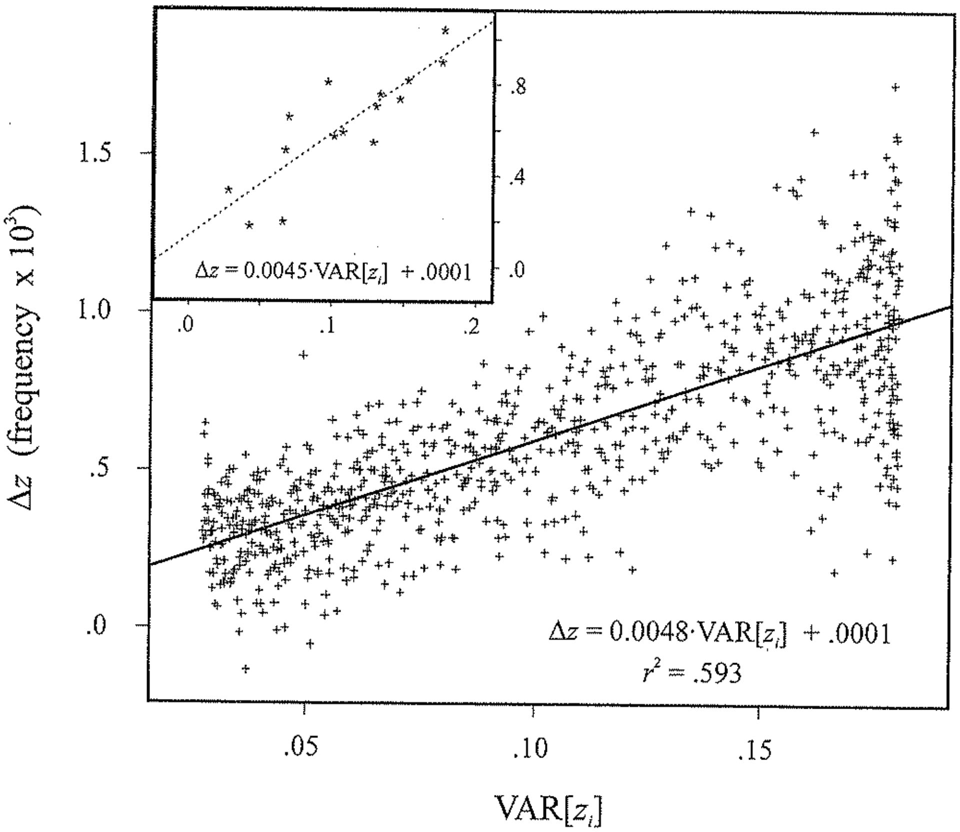


Figure 10. Linear regression of Δz on VAR[z_i] for the first 794 assemblage formation events (generations) of the simulated archaeological sequence shown in Figure 9. Inset shows a regression analysis for a random sample of 15 paired (sequential) assemblages drawn from the original 794 assemblages. The regression estimates $\hat{\beta}_1$(slope) and $\hat{E}[\delta_i]$ (intercept) in both cases are very close to the expected values.

sented above is unclear. The Price Equation (and Fisher's fundamental theorem) indicate that the rate of change in the mean value of an attribute is often proportional to the variance represented in that attribute. Any site formation or disturbance processes that distort the relationship between Δz and VAR[z_i] will surely also distort empirical estimates of the strengths of payoff-correlated and payoff-independent processes. For example, if occupation at a particular site is continuous over three consecutive time periods t_1, t_2 and t_3, then the variance in between-household ceramic decoration frequency during period t_1 should provide accurate information about the rate of change in mean decoration frequency observed between periods t_1 and t_2, assuming of course that selection is operating. Similarly, the variance in between-household ceramic decoration frequency during period t_2 should provide accurate information about the rate of change in mean decoration frequency between periods t_2 and t_3. If, however, there was a depositional hiatus in period t_2, then the variance in observed during t_1 might not provide accurate information about the rate of change in mean decoration frequency between periods t_1 and t_3; the observed change between t_1 and t_3 is likely to be greater than that expected given the observed variance in t_1. While this is a simplistic scenario, it does suggest that more theoretical work is warranted before seeking archaeological applications of the Price Equation model of style and function.

Conclusions

The style-function dichotomy is central to the evolutionary archaeological perspective on culture change. Not only does it form the basis for defining and then recognizing when selection is operating within the archaeological record, but it also proves to be a key assumption for successful cultural historical reconstruction (O'Brien and Lyman 1999). This paper started by adopting the primary supposition that function and style can be distinguished, respectively, on the basis of whether change in an attribute is correlated with some measurable payoff and is therefore subject to selection, or is not and is therefore more likely subject to stochastic forces. "Payoff" is used here as a term to describe the performance or utility of socially learned behaviors. It is in no way dependent upon assuming that all behavior can be ultimately reasoned down to reproductive success.

These assumptions were used to model the process of culture change at a low level based on simple replicator equations treating payoff-correlated and payoff-independent processes first as mutually exclusive and then as simultaneous forces. It was shown that these replicator equations can be used to derive a very general evolutionary model referred to as the Price Equation (Frank 1997; Price 1970), which allows one to make predictions about the direction and rate of evolutionary change in a system. The Price Equation states that the rate of change in the mean value of an archaeological trait of interest—here ceramic decoration frequencies—is the sum of payoff-correlated and payoff-independent processes. One of the primary conclusions is therefore that style and function are not mutually exclusive, though they may be exhaustive descriptions of all sources of change as originally suggested by Dunnell (1978). However, this is little comfort given the range of ways in which function and style might combine to generate directional culture change.

Simulations were used to demonstrate that the two terms of the Price Equation giving, respectively, the strength of payoff-correlated and payoff-independent processes may be estimated with considerable accuracy in well-preserved archaeological contexts with information that is commonly collected in the field. However, the simulation test of the empirical approach presented here is meant only to show the potential for future applications. Additional work is needed to explore how the model is effected by variable site formation processes and poor site preservation.

Acknowledgments. Special thanks to Luke Barton, Liane Brantingham, Briggs Buchanan, Mark Collard, R.G. Matson, Karthik Panchanathan and three anonymous reviewers for their comments on earlier versions of this paper.

Appendix A: Payoff Functions

The following derivation of a payoff function for mixed strategy, symmetric games follows Weibull (1995). First, assume two individual households engage in a two-strategy game where the payoff matrix **A** for any household is given by:

$$\mathbf{A} = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix}. \quad (12)$$

The matrix entries a_{mn} are the payoffs to household i for pitting strategy m against a strategy n deployed by household j. For example, a_{11} is the payoff to household i when playing strategy 1 against household j's strategy 1.

I assume that within-household ceramic decoration frequencies z_i and z_j in some way correspond to the probabilities that households i and j play strategy 1, respectively. Then $1 - z_i$ and $1 - z_j$ are the complimentary probabilities that i and j play strategy 2. The payoff matrix A may be translated into a linear equation giving the payoff w_i to household i in any one round of play.

$$\begin{aligned} w_i = z_i\left[a_{11}z_j + a_{12}(1-z_j)\right] \\ +\left(1-z_i\right)\left[a_{21}z_j + a_{22}(1-z_j)\right] \end{aligned} \quad (13)$$

Equation (13) states that the payoff to household i is determined by the probability that i plays strategy 1 *and* household j plays strategy 1 *or* strategy 2, *or* household i plays strategy 2 *and* household j plays strategy 1 *or* 2. Each of these outcomes is assigned the appropriate payoff a_{mn} from matrix A. As Weibull (1995) demonstrates, Equation (13) is sufficiently general to model an array of game forms including classic Prisoner's Dilemma and Hawk-Dove games simply by choosing different values for the terms a_{mn}. A pure coordination game obtains if $a_{11} > a_{22} > a_{21} \geq a_{12}$.

When considering games involving random pairing of households, Equation (13) must be modified to give the expected payoff to household i across all possible dyadic interactions.

$$\begin{aligned} w_i = z_i\left[a_{11}z + a_{12}(1-z)\right] \\ +\left(1-z_i\right)\left[a_{21}z + a_{22}(1-z)\right] \end{aligned} \quad (14)$$

Here, z_j has been replaced by the mean ceramic decoration frequency z within the community z, which assumed to reflect the probability that any randomly chosen household will play strategy 1. The mean payoff w in the community then may be calculated as:

$$w = \sum_{i=1}^{I} p_i w_i = a_{11} z^2 + z(1-z)(a_{12} + a_{21}) + a_{22}(1-z)^2 \quad (15)$$

The first term on the right hand side of Equation (15) is the share of the mean payoff that would come from two households chosen at random both playing strategy 1. Similarly, the last term is the share of the expected payoff coming from the two households both playing strategy 2. The middle term is the share of the expected payoff coming from the two households playing alternative strategies.

The linear relationship between w_i and z_i modeled in Equation (14) is general for all 2x2 matrices. It is therefore possible to greatly simplify payoff calculations by substituting a linear function in the form $w_i = uz_i + w_0$ (Equation [2]). Here w_0 is the minimum absolute payoff assigned to any value of z_i and the slope of the payoff relationship u is the first derivative of Equation (14).

Appendix B: Derivation of the Price Equation

The reduced Price Equation for independent payoff-correlated change (Equation [4]) is derived as follows. Let z' be the mean frequency of ceramic decoration the assemblage after replication (see Equation [1]). The change in the mean frequency of decoration is:

$$\Delta z = z' - z = \sum_{i=1}^{I} p_i \frac{w_i}{w} z_i - \sum_{i=1}^{I} p_i z_i \quad (16)$$

Price (1970) recognized that the right side of Equation (16) is equivalent in form to the formula describing the covariance between two random variables (Frank 1997; Grafen 2000), namely

$$\mathrm{COV}\left[\frac{w_i}{w}, z_i\right] = \mathrm{E}\left[\frac{w_i}{w} z_i\right] - \mathrm{E}\left[\frac{w_i}{w}\right]\mathrm{E}\left[z_i\right] = \sum_{i=1}^{I} p_i \frac{w_i}{w} z_i - \sum_{i=1}^{I} p_i \frac{w_i}{w} \cdot \sum_{i=1}^{I} p_i z_i \quad (17)$$

Equations (16), (17), and (4) are thus equivalent because the mean relative payoff $\mathrm{E}[w_i/w] = \sum p_i(w_i/w) = 1$ and may be freely introduced.

We can determine that the reduced Price Equation represents a payoff-correlated process by rewriting the covariance term as:

$$\Delta z = \mathrm{COV}\left[\frac{w_i}{w}, z_i\right] = \beta_1 \mathrm{VAR}\left[z_i\right] \quad (18)$$

The term β_1 is the total regression coefficient (slope) for the linear least squares regressions of w_i/w on z_i (Frank 1997). Relative payoffs are correlated with the frequency ceramic decoration for any $\beta_1 \neq 0$. Therefore, for any nontrivial case of $\mathrm{VAR}[z_i] > 0$, the change in the mean frequency of the ceramic decoration is payoff-correlated for any $\beta_1 \neq 0$. Because β_1 is the slope of the least squares regression line of w_i/w on z_i, we can infer from Equation 18 that $\beta_1 = u/w$. Therefore, Δz is necessarily a payoff-correlated process for any $u \neq 0$.

The derivation of the full Price Equation and the determination that it includes both payoff-correlated and payoff-independent components follows a very similar logic. As above, the key operation is the introduction of the term $\mathrm{E}[w_i/w] = \sum p_i(w_i/w) = 1$

$$\begin{aligned}
\Delta z &= z' - z \\
&= \sum_{i=1}^{I} p_i \frac{w_i}{w}(z_i + \delta_i) - \sum_{i=1}^{I} p_i z_i \\
&= \sum_{i=1}^{I} p_i \frac{w_i}{w} z_i + \sum_{i=1}^{I} p_i \frac{w_i}{w} \delta_i - \sum_{i=1}^{I} p_i z_i \\
&= \sum_{i=1}^{I} p_i \frac{w_i}{w} z_i - \sum_{i=1}^{I} p_i \frac{w_i}{w} \sum_{i=1}^{I} p_i z_i + \sum_{i=1}^{I} p_i \frac{w_i}{w} \delta_i \\
&= \mathrm{E}\left[\frac{w_i}{w} z_i\right] - \mathrm{E}\left[\frac{w_i}{w}\right]\mathrm{E}\left[z_i\right] + \mathrm{E}\left[\frac{w_i}{w}\delta_i\right]
\end{aligned}$$

which is equivalent to Equation (9).

To show that the full Price Equation is also payoff-independent note that $\mathrm{E}[w_i/w \infty \delta_i] = \mathrm{COV}[w_i/w, \delta_i] + \mathrm{E}[w_i/w]\mathrm{E}[\delta_i]$ (Stirzaker 2003). Using the alternative specification of the covariance formula Equation (9) is restated as:

$$\Delta z = \beta_1 \mathrm{VAR}\left[z_i\right] + \beta_2 \mathrm{VAR}\left[\delta_i\right] + \mathrm{E}\left[\frac{w_i}{w}\right]\mathrm{E}\left[\delta_i\right] \quad (19)$$

where β_2 is the slope of the line (regression coefficient) obtained in the linear least squares regression of w_i/w on δ_i. As long as the stochastic process generating within-household changes in the frequency of ceramic decoration δ_i contains no terms related to payoffs, the regression coefficient $\beta_2 = 0$. Dropping the term $\beta_2\mathrm{VAR}[\delta_i]$ and noting that $E[w_i/w] = 1$ we arrive at Equation (10).

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Notes

1. It is possible to imagine a process whereby groups receiving lower payoffs tend to be more risk prone and therefore bias larger random fluctuations. Groups with higher payoffs similarly might tend to be risk averse and therefore bias smaller random fluctuations. This type of a stochastic process would be payoff-correlated.

2. By noting that $\Delta z_i = z'_i - z_i = z_i + \delta_i - z_i = \delta_i$ we could replace δ_i with Δz_i in Equation 9 to yield the standard notation of Frank (1997) and others.

3. At the start of the simulation $\beta_1 \text{VAR}[z_i] = .000113$ and $E[\delta_i] = .0001$ meaning that stylistic pressures are approximately equal to functional pressures in driving increases in the mean decoration frequency. At the point of maximum variance $\beta_1 \text{VAR}[z_i] = .0009$ meaning that functional pressures are nine times stronger than stylistic ones, which remain constant.

4. A total of 15 stratigraphic pairs was sampled at random from the complete sequence of 794 time intervals such that the strata in each pair were immediately adjacent to one another in time. The observed mean decoration frequencies in the two sequential strata of each pair were used to calculate Δz, while $\text{VAR}[z_i]$ was calculated for the lower (older) of the two strata.

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