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A simple model of technological intensification

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Abstract

Ugan, Bright and Rogers [When is technology worth the trouble? Journal of Archaeological Science 30 (10) (2003) 1315–1329] develop procurement and processing versions of an optimization model, termed the tech investment model, to formalize the conditions that favor investing time in the manufacture of more productive but more costly technologies. Their approach captures the tradeoffs that occur as less costly versions are supplanted by more costly versions of the same category of technology (e.g., fishhooks), but not the tradeoffs that occur when more costly categories of technology supplant different but less costly categories used for the same purpose (e.g., hook and line vs. spear). We (i) propose an alternative model in which different categories of technology are characterized by separate cost–benefit curves, (ii) develop point-estimate and curve-estimate versions on this model, and (iii) show how they might be applied using the development of weaponry in aboriginal California as an example.

Keywords: Technology; Technological investment; Bow; Atlatl; Human behavioral ecology; Foraging theory; Marginal analysis

1. Introduction

Ugan, Bright and Rogers [9] develop procurement and processing versions of an optimization model, termed the tech investment model, showing that as increased time is devoted to these subsistence activities it pays to invest more in technologies that increase their rate of return. Theirs is an important conceptual contribution, formalizing intuitive insights found in archaeological and ethnographic discussions of technological change. We see analytical problems, however, in the way Ugan, Bright and Rogers (hereafter, UBR) operationalize the model, specifically in their illustration of how technological functions are derived, which is said to be their primary goal [9, pp. 1318, 1323]. Granting theirs was a mainly heuristic exercise and that, as they note [9, pp. 1317, 1318] they were forced to take liberties with their empirical data, we worry that others will follow their methodology when exploring problems of this kind. We argue that while the UBR technological investment model represents intensification within a given technological category, it misrepresents what happens when one category (e.g., hooks) replaces another (e.g., spears). We recommend the use of alternative approaches we believe are more generalized as well as easy to implement. In the interest of space, we attend here only to the procurement version of the UBR model.

2. Conceptual problems with the UBR model

The key relationship in the UBR procurement model is both simple and familiar: increasing investment in technology improves procurement returns at a decreasing marginal rate, as where harvesting a resource requires a tool that when crudely made in 1 h produces a net gain of 1 kg/h, and when more finely made in 2 h produces a net gain of 1.5 kg/h. Here, the first hour of technological investment increases the rate of procurement by 1.0 kg/h, the second hour by only 0.5 kg/h. Since the crude tool generates a higher rate of procurement per unit of technological investment, the more costly form will make

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sense only in the presence of other factors, the most salient being the amount of time the tool is used for procuring resources. We call this variable its use time, designated by *u*. If return rates for a particular technology are imagined as being maximized relative to use time in addition to the time spent in manufacture, more costly technologies can outperform less costly ones.

In the example above, if exactly 1 h is spent in resource procurement, the crude and finely finished tools will produce exactly the same overall rate of return: made in 1 h and used for 1 h, the crude tool yields 1 kg, or 1 kg/2 h = 0.5 kg/h; made in 2 h and used for 1 h, the finely finished tool yields 1.5 kg, or 1.5 kg/3 h = 0.5 kg/h. The critical use time, υ, for the finely finished tool – the amount of time that must be devoted to procurement to make it viable in the presence of its cruder counterpart – is thus 1 h. If any more than 1 h is spent in procurement, the more costly technology generates the higher rate of return; if any less than 1 h is spent in procurement, the cheaper technology is preferable. In our terminology, $\upsilon_{a\leftrightarrow b}$ represents the critical use time for switching from technological alternative *a* to *b* or back.

UBR [9, pp. 1317–1320] illustrate this principle using Great Basin fishing data [5,8] that document the return rates associated with different categories of technology used for Lahontan cutthroat trout (*Oncorhynchus clarki henshawi*) and cui-ui (*Chasmistes cujus*): hook and line, spear, multiple hook, A-frame dip net, and 100′ gill net, from least to most costly (see our Table 1). They envision the general form of the relationship between return rate and alternative forms of technological investment in Great Basin fishing gear as a continuous function that increases at decreasing rate, the tangent to which at any given point defines the critical use time (υ), i.e., procurement time required to justify the corresponding amount of technological investment [9, their Fig. 1]. Of several possible candidates for the specific form of this function, they prefer the negative exponential:

$$f(m)=a\left(1-e^{-km}\right)$$

where

$f(m)$ is the rate of return,
a is the maximal possible rate of return,
k is the rapidity with which the function reaches its maximum value, and
m is the time invested in the technology.

They plot the manufacturing times and return rates of each technological alternative for Great Basin fishing and compute a best fit for the negative exponential to the set of points. From this curve they determine the critical procurement times required to make each technology viable relative to the next least costly alternative.

The results are intuitively plausible: large procurement use time is required to justify costly technologies (Table 1). By their calculations, while it takes only about 0.04 h of fishing time to justify the 2.25 h needed to fashion a simple hook and line, it takes more than 9155 h to justify the 350 h needed to make a 100′ gill net [9, Table 2].

We believe, however, that the UBR approach is inappropriate in this context because the technological improvements that increase Great Basin fishing returns are not appropriately represented by a single, continuous function, the alternative technologies (hook, spear, net) not being continuous developments of each other. A spear is not a modified hook, any more than a net is a modified spear. Because they are discretely different kinds of things, hook, spear, and net are more properly characterized by separate functions. When so conceived, marginal analysis of intensification over alternative categories of technology and the calculation of critical use time times required to justify a particular investment are easy to compute and, importantly, often different than that found by UBR [9].

As they note [9, p. 1317], UBR conceive their model as analogous to Charnov's [1] marginal value theorem and to Metcalfe and Barlow's [6] model of field processing and transport. However, in both these models, a single, continuous function is used to represent only one patch- or resource-type; in fact, having a unique, continuous curve defines the type. Alternative patches or resources require a multi-curve version of the model [cf. 7], not the alignment of multiple patch- or resource-types along a single curve. At several points during their discussion UBR [9] invoke broadly similar cases: $5000 professional stoves and $300 chef's knives vs. a monetary continuum of cheaper models [9, p. 1316], sharpening a knife for 1 h vs. 30 h [9, p. 1321], and unwieldy large nets vs. shorter ones [9, p. 1321]. In these cases, the changes in return rate relative to technological investment can be thought of as a unique, continuous function because the base technological unit remains more or less the same: the same knife can be sharpened for 1 h, 2 h, or 30 h. Gill nets can be made 10′, 100′, or 1000′ long. But these singular trajectories are

Table 1
Critical use times, $\upsilon_{x\leftrightarrow y}$, for fishing technologies under the point-estimate and UBR [9] models

Technology	Return rate[a] $f_i(m_i)$ (kg/h)	Manufacturing time[a] m_i (h)	$f_i(m_i)/m_i$	Critical procurement time[b] $\upsilon_{x\leftrightarrow y}$	
				Point-estimate (h)	UBR [9] (h)
Hook and line	3.413	2.25	1.52	0.00[c]	0.04
Spear	34.483	4.00	8.62	−2.06[d]	0.11
Multiple hook	103.093	30.50	3.38	9.32	7.54
A-frame dip net	200.000	99.00	2.02	42.37	115.13
100′ gill net	250.000	350.00	0.71	905.00	9155.45

[a] Data from Ugan et al. [9, Table 1].
[b] Computed for each technology relative to its next least costly alternative, e.g., spear vs. hook and line, multiple hook vs. spear, etc.
[c] We derive this value by assuming that no technological investment produces a return rate of zero, which is unlikely since fish are frequently caught bare-hand (e.g., [4, Map 49]), the return rate of which is unknown to us.
[d] This value is negative because $f_i(m_i)/m_i$ for hook and line is less than that for the spear, making the spear superior for any use time. For the same reason, hook and line is inferior to the multiple hook rig ($\upsilon_{\text{hook and line}\leftrightarrow\text{multiple hook rig}} = -1.28$ h) and A-frame dip net ($\upsilon_{\text{hook and line}\leftrightarrow\text{A-frame dip net}} = -0.57$ h). Hook and line is viable, however, at very low use times when the only other available technology is the 100′ gill net ($\upsilon_{\text{hook and line}\leftrightarrow 100' \text{ gill net}} = 2.56$ h).

very different from the technological shifting of gears that occurs as spears replace hook-and-line, and are in turn replaced by multiple hook-and-line, A-frame dip nets, and finally gill nets, whatever their length.

The root problem of the UBR procurement model is a version of the ecological fallacy, the assumption that one can infer individual properties, such as a particular person's height, from an aggregate property of a larger group (the average height of three individuals). The UBR approach assumes that the function obtaining *within* any single category of Great Basin fishing technology (as one moves, say, from less costly to more costly A-frame dip nets) is the same as the function fit to point representations *among* these technologies (i.e., as one moves from the least costly hook and line to the most costly 100′ gill net). This is the upshot of the curve-fitting procedure employed by UBR [9]: to generate a gain function which then is taken to characterize the gain function of individual categories of fishing technology. But, it is one thing to argue that marginal gains on technological investment always decline – both across technologies and within them – and quite another to argue that all technological alternatives in a class align to exactly the same function. There is simply no reason to think that the shape of the function that governs dip nets is conterminous with that which governs spears, or that either is the same as the function that governs Great Basin fishing technology as a whole.

For our purposes then, we define a *category* of technology as a structurally related set of forms which can be envisioned as modifications of one another occupying a single, continuous gain function or discontinuous segments of a single gain function. A *class* of technology is all of those known or potential categories applied to a particular subsistence pursuit. Thus, a technology that added barbs or other elaborations to a basic hook would constitute a single category, and all hooks in addition to spears, nets, etc., used for fishing would constitute a class of technology made up of alternative categories.

3. How the conceptual problems matter

The UBR approach is narrowly restrictive or misleading in several respects. For instance, it requires that marginal gains always be steeper with cheap technologies than more costly ones. That is, if one assumes a universal function, cheaper technologies always capture the relatively large marginal returns on the left side of the curve. This of course need not be true. Further, it prohibits us from envisioning a novel technology which has a higher or lower return rate for a given investment (m), that is, one which is displaced so that its return curve rests wholly or partially above or below that of another technology. It likewise requires that each of the technologies to be examined is such that its most expensive version has a return rate virtually identical to – continuous with – the least expensive version of another technology, up to the right-most entry. For each of these various reasons, we have characterized the UBR approach as highly restrictive relative to the set of possibilities we presumably want to examine.

There are as well operational difficulties with the UBR approach, in that any gap in our empirical knowledge, or any technological innovation that alters the function describing the relationship among technologies, will necessarily change the function describing each *individual* technology. For example, removing any one of the Great Basin fishing technologies that Ugan et al. [9] use to derive their general fishing technology function will change the function for each of the remaining individual technologies. This interdependence is not a desirable model attribute; the procurement gains associated with different levels of investment in gill nets are surely independent of the presence or absence of, say, spears. Cost–benefit functions for each technological alternative must be determined individually.

As a consequence of these problems, the UBR approach does not necessarily find a correct solution to the question of interest: what is the critical level of use time (υ) predicting that one technology will replace another? In the UBR approach, alternative technologies are presumed to occupy, without overlap or gaps, continuous segments of the same cost–benefit function. Critical use time times are determined by the tangent to this function. However, if segments overlap they are effectively equivalent for purposes of analysis, and replacement is indeterminate within the range of overlap. If gaps are present, as where the most costly version of a cheap technology is much cheaper than the least costly version of the next most costly one, the tangent will overestimate critical procurement time, perhaps by a large amount (Fig. 1; tangents ii and iii). The correct solution to the critical use time here is not a tangent at all, but rather the slope of the chord, the line that connects the cheapest version of the costly technology and the most costly version of the cheaper technology (Fig. 1; line i).

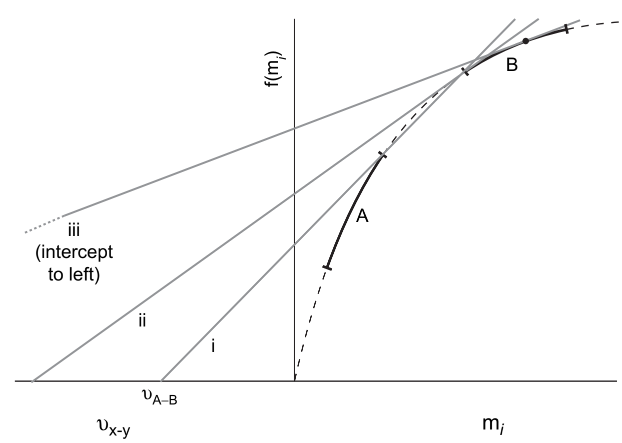

Fig. 1. Critical use times for technologies discontinuously distributed on a single gain function like that proposed by Ugan et al. [9]. $f(m_i)$ is the gain function, m_i the manufacturing time, and υ_{x-y} is the critical use threshold for switching to more intensive technologies. (i) Shows the correct estimate of υ_{A-B}, based on the line linking the endpoints of segments *A* and *B*; (ii) shows the higher υ_{A-B} estimate that follows from selecting the tangent to the lower endpoint of segment *B*; (iii) (intercept not shown) depicts the very high υ_{A-B} that would follow from a tangent to a point within the technology *B* segment.

Thus, for the UBR approach to work, all technologies must occupy non-overlapping segments of the gain function, without gaps. Neither condition is likely, nor should they be assumed. Even where both conditions are true, the tangent approach would require that we know the endpoints of all alternative technology segments. It is the leftmost endpoint of a segment, not a point value somewhere within the segment, which determines the critical use time. This is to say that υ is given by the tangent at the point defined by least costly version. Tangents to the segment anywhere to the right of this show the use times warranting investment in a more costly version *of the same technology*. This is a second reason why the UBR approach is predisposed to overestimate υ for Great Basin fishing technologies. In their analysis, UBR [9] determine υ using tangents at the points on the gain function defined by levels of technological investment for which they have empirical data (e.g., 2.25 h for hook and line; [9, Fig. 2]). The correct procedure would be based on the tangent at the endpoints joining the alternative technology segments. Any other point represents some amount of intensification of a particular technology, not a switch to it, and will over-estimate υ for that technology (Fig. 1), again, perhaps by a large amount.

4. An alternative approach

The single-function, marginalist approach is best suited to understanding why options within a category of technology are present in more or less intensified, more costly and less costly, versions, e.g., why finely finished fishhooks might replace cruder ones or vice versa. It is, for reasons given above, ill-suited to explicate the conditions that cause one technological category to replace another used for the same purpose, e.g., why spears replace fishhooks.

Most of these problems are cured if we apply the marginal approach assuming that each functional category of technologies has a unique cost–benefit curve. Where one is able to describe these curves precisely for two categories of technology that differed in cost, say *a* and *b*, the line simultaneously tangent to both would define $\upsilon_{a\leftrightarrow b}$ (see Section 4.2). The problem, of course, is that we cannot always muster the data or otherwise justify the assumptions necessary to derive curves at this level of detail. The more usual case is represented in the data used by UBR [9] for Great Basin fishing technology: five technological categories each represented by a single data point. Such data may warrant a straightforward approach that minimizes assumptions, produces useful insights and does not exaggerate what we know. This is especially important for empirically-driven models attempting to make quantitative predictions; heuristic models designed for making structural predictions (e.g., increase in the independent variable causes an increase or a decrease in the dependent variable) have more latitude.

4.1. A simple, point-estimate model

Our simple, point-estimate model isolates data points rather than the functions assumed to contain them. We compare two alternative categories of technology – one less costly with lower returns, the other more costly with higher returns. The two point comparison can easily be extended to more line segments. A technology that that yields a higher rate of return, $f_2(m_2)>f_1(m_1)$, but at greater relative cost in technological investment, $m_2>m_1$, will be favored when:

$$\frac{f_2(m_2)}{m_2+v}>\frac{f_1(m_1)}{m_1+v}$$

where

v is the use time, the time expended in procurement,
m_i is the manufacturing time, amount of time expended producing a particular kind of procurement implement or facility,
$f_i(m_i)$ is the amount of a resource (in, say, kcal) that can be procured using a particular technology i; a function of the time required to manufacture it, m_i.

From the above we can define the critical use time, as

$$v_{1\leftrightarrow 2}=\frac{f_1(m_1)m_2-f_2(m_2)m_1}{f_2(m_2)-f_1(m_1)}$$

This is the time expended in procurement at which the less costly and more costly technologies produce equivalent returns.

This comparison is required only when, as in the original UBR model, one technology produces a higher rate of procurement, i.e., $f_2(m_2)>f_1(m_1)$, in the presence of a cheaper technology, i.e., $m_1<m_2$, that improves procurement at a higher rate of per unit of technological investment, $f_1(m_1)/m_1>f_2(m_2)/m_2$. If these three conditions are not all met, one technology will never be viable in the presence of the other. It will never pay to invest in a more costly technology that yields a lower rate of procurement, i.e., $m_2>m_1$ and $f_2(m_2)<f_1(m_1)$. Neither can it ever pay to invest in a cheaper, less productive technology if technological investment in the more costly and productive technology improves procurement at a higher rate, i.e., $m_1<m_2$ and $f_1(m_1)<f_2(m_2)$, but $f_2(m_2)/m_2>f_1(m_1)/m_1$. Such cases, if seen empirically, require explanation but cannot be rendered meaningful by a model meant to depict rational economic behavior under the assumptions in play here.

Because we wish to examine only incremental costs and benefits associated with different levels of technological investment, we assume that the base energy costs (e.g., kcal/h) of searching, pursuing and processing resources, and the energy devoted manufacture, are constant across the technological types being compared, and that there are no external constraints on energy or time. An additional assumption of our model (and that of UBR [9, p. 1316]) is that refinement of a given tool through intensified manufacture does not affect use life. This may not be true. Refinement may increase or decrease durability and thus tool lifespan, a problem for separate analysis. We note, however, that a technology with a critical use time (υ) greater than its use life will never be optimal.

Fig. 2 illustrates a basic case, for three point-estimate technologies, *A* through *C*. If only *A* and *B* are present, then, reading use times (u) from right to left from the origin, line ii gives $\upsilon_{a\leftrightarrow b}$. Any use time less than this value favors technology *A*; greater than this value favors technology *B*. If the technology represented by point-estimate *C* joins the picture, it will displace *B* and shift the critical use threshold for *a*, $\upsilon_{a\leftrightarrow c}$, to the right (line i).

Our point-estimate approach gives quantitative results that differ markedly from the UBR model in several important respects (Table 1). In the UBR solution, the cheapest technology – hook and line – is viable at very low use times (0.04–0.11 h); in our model hook and line technology is *never* viable in the presence of spears, multiple hooks, or A-frame dip nets, and viable in the presence of the 100′ gill net only when use time is less than 2.6 h, a finding in accord with ethnographic evidence suggesting very limited use of hook and line relative to other fishing technologies in aboriginal North America. Hook and line fishing is prominent only in Alaska and the Northwest Coast, where the importance of fishing simply magnifies their absolute frequency of use [2, p. 206]. The reason for our result is easy to see: the gain in procurement for time invested in manufacture $f_1(m_1)/m_1$ for hook and line is lower than for all the more costly technologies except the 100′ gill net (Table 1). As UBR note [9, p. 1318], it is only their curve-fitting approach that allows hook and line to outperform other technologies when use times are low, their gain function assigning hook and line a return rate of 8.52 kg/h, which is more than twice the rate actually observed (3.41 kg/h). This underscores that the UBR curve-fitting approach cannot derive critical switching values unless the data are forced (by curve fitting) to meet the assumption that all technologies align to the same gain function, making each of them viable (i.e., superior to all others for certain use times). This has the undesirable consequence of giving greater weight to gain functions than the data they are meant to fit. Estimation of ethnographic return rates and manufacturing times is prone to many sources of error, but none of them is lessened by fitting these estimates to a single gain function, for reasons noted above. The point-estimate approach does not suffer this assumption and its attendant problems.

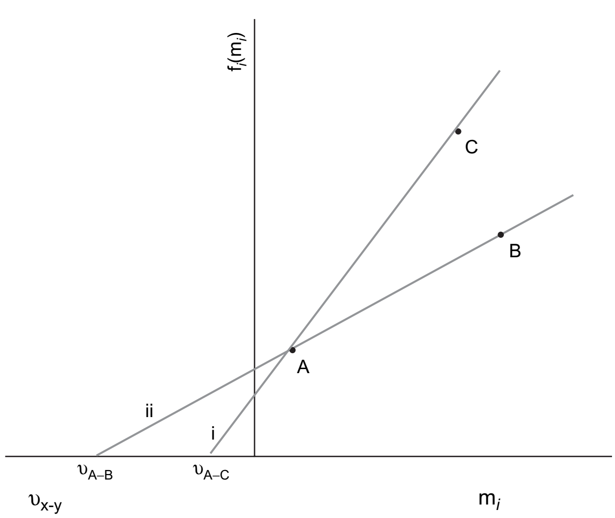

Fig. 2. Simple, point-estimate model for estimating use time thresholds at which an optimal forager will switch to a different technological alternative. $f_i(m_i)$ is the gain function, m_i the manufacturing time, and υ_{x-y} is the critical use threshold for switching between different technologies. Three technologies, *A*–*C*, are shown. If only technologies *A* and *B* are available, the intercept of (ii) and the *X*-axis gives υ_{A-B} for switching between *A* and *B*. If technology *C* enters the picture, it will displace *B* under all circumstances, and lower the υ_{A-C} threshold at which technology *A* is displaced or adopted (see (i)).

According to UBR, the A-frame dip net becomes more practical than a multiple hook rig only when one expects to spend more than about 115 h using it for fishing. Our estimate of 42 h is a nearly threefold reduction in the υ for this technology. Again, this difference arises because the UBR model sees the relationship between A-frame dip nets and multiple hook rigs in terms of a single, curvilinear function the shape of which is collectively determined by all the different fishing technologies considered (hook, spear, multiple hook, dip net, gill net). The A-frame dip net is not compared to the next least costly known technology – the multiple hook rig – but rather to an imagined technology immediately to its left on the function, most likely a marginally less costly version of itself. This, and the assumption that technological investment increases procurement at a decreasing rate across a sequence of alternative technologies, make the conditions needed to justify the A-frame dip net, or any high investment and thus low slope technology, unrealistically large. For the most costly Great Basin fishing technology – the 100′ gill net – the UBR approach over-estimates υ 10-fold (Table 1).

The differences between our estimates of υ and those of UBR boil down to the trajectory of their gain function and the position and proximity of observed data points. The closer the data points are to the fitted function, the more consistent the differences will be. Where all the data points fit the gain function exactly, our estimates will always be less than those obtained using the UBR function, in amounts varying directly with the distance between adjacent points and their distance from the origin on the *X*-axis, the measure of manufacturing time.

Perhaps the greatest advantage of the point-estimate approach is that, whether or not technologies align to a single function, it will always be as precise as the data actually in hand allow. As such, it eliminates the thorny problem of having to decide whether two tool forms represent different categories of technology or different versions (more, less costly) of the same category. In theory, individual categories of technology are defined by a continuous trajectory of modification yielding a succession of forms that align to a single, continuous gain function. In practice, this can seldom be demonstrated, especially with ethnographic data. Even where that assumption seems eminently plausible – where known points representing obviously related forms can be fitted to a single function – there may be gaps in the trajectory of modification reflecting structural differences inherent in the technology or its manufacture, such that the gain function is discontinuous;

in that case each segment must be treated separately. Where there is uncertainty about gaps, endpoints or the form the gain function should take (e.g., continuous or not) the point-estimate model may be the best approach.

4.2. A less simple, curve-estimate model

For structural predictions or heuristic purposes we may require a more complex, curve-estimate model. We may even have the empirical data to make such a model appropriate for quantitative predictions. The function that characterizes a particular technological alternative is likely to be shaped like a shepherd's crook, staff to the left, or something between an ''r'' and an ''n'' shape (Fig. 3). The ascending portion of this form could be displaced to an X-intercept to the right of the origin if there is a significant period of investment prior to any functionality (e.g., in locating, cutting and curing the wood for a bow staff). Subsequent to that, return rates increase at a decreasing rate, either to an asymptote (r-shaped) or a peak followed by decreasing returns (n-shaped) as functionality is achieved, refined, and perhaps refined past the point of positive net returns. Asymptotic, r-shaped functions imply that intensification always enhances function at a rate greater than its cost (which would never be the case for a true asymptote and constant cost). It is more likely that benefits will eventually be overweighted by investment costs, as in UBR's 30 h of knife sharpening, decoration being

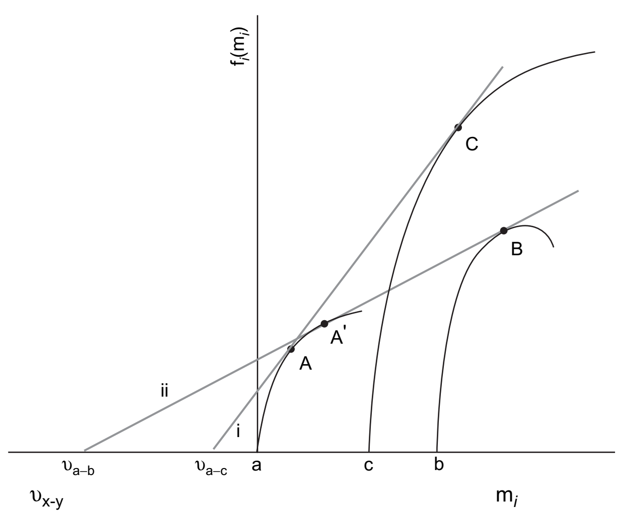

Fig. 3. Less simple, curve-estimate model for finding use time thresholds at which an optimal forager will switch to a different technological alternative. $f_i(m_i)$ is the gain function, m_i is the manufacturing time, and υ_{x-y} is the critical use threshold for switching between different technologies. Three technologies are shown ($a-c$); the points $A-C$ are in the same positions as for Fig. 2. If only technologies a and b are available, the intercept of (ii) and the X-axis gives υ_{a-b} for switching between a and b. If technology c enters the picture, it will displace b under all circumstances, and lower the threshold at which technology a is displaced (see υ_{a-c}). Note as well that compared to the point threshold model, we now expect that technology a will be more refined (point A') when it is abandoned for b. In this form of the model, changing use life (υ_{x-y}) and the slope of the associated tangent will alter investment within alternative technologies as well as determine the switch points between them. If technology a is used in the presence of c, it will occur in a less refined form than it would occur in the presence of b.

another example. In the case of fishhooks adding a small, shallow barb may increase catch rate relative to a cheaper barb-less version, but two barbs or a very large, steep barb may make setting the hook difficult and in this way decrease effectiveness. While conceptually important, the distinction between these n-shaped and r-shaped cases is moot for purposes of deriving υ, given that manufacturing investment that decreases the rate of procurement (the right hand side of n-shaped functions) will never enter the optimal solution. Where observed empirically, n-shaped expressions imply economically non-rational behavior under the rules in play in the model, and require explanation in other terms. Heavily decorated fish hooks that function no better than undecorated ones, for example, may be satisfying ritual or magical requirements, producing benefits not reflected in return rates. The UBR approach requires that there always be positive gains to manufacturing investment, thus it precludes observing this kind of non-optimal investment.

Fig. 3 depicts three technological alternatives, a through c. If only a and b are present, then, reading right to left, a will be the preferred technology for use times up to the X-axis intersection of tangent (ii), $\upsilon_{a\leftrightarrow b}$. Technology a will be intensified to A' before it is superseded by b at manufacturing intensity B. In effect, technology b will be the option of choice for use times beyond $\upsilon_{a\leftrightarrow b}$. If technology c enters the picture it will displace b for any use time. Note that $\upsilon_{a\leftrightarrow c}$ is now set by tangent i; it is shorter in duration. We also can observe that technology a will be superseded by c at a lower level of refinement, A. Through experimentation with the shape and placement of gain functions relative to one another, this model allows the analyst a quite flexible representation of the intensification trajectory of alternative technologies, with a corresponding increase in analytical generality.

The UBR model allows for only one alternative technology devoted to a particular task at any time, assuming that all individuals in the population have the same use times. In our alternative, it is possible for two forms to co-exist, although only at the point they share a critical use time. Under the assumption of optimality, it is unlikely that more than two variants of a technology co-exist for a particular use, for the same reason that three points randomly located in a plane are unlikely to lie on the same line. In both the UBR and our model, different forms of a technology also may co-exist if the behavior of subgroups in the population leads to different use lives. An adult provisioning a family may fish sufficiently to justify the manufacture of a net; an elderly individual or youth who engages only occasionally in short fishing trips for personal consumption may find it more expedient to use a spear.

Relationships evident in Fig. 3 potentially give us a conceptual means of distinguishing between alternative technological innovations that are endogenous developments of a society and those that are adopted by diffusion from surrounding societies, a long-standing problem in archaeology. The most common *local* sequence will entail a pattern in which the technology being replaced is progressively refined to a point that its marginal return is equivalent to that of its successor. A develops to A' before B will be adopted. By contrast, we would expect a more discontinuous pattern from imported technologies, which are more likely to truncate or reverse refinement of the technological alternative being replaced. Odds are the replacement will be superior to a greater than marginal degree. *C* replaces *B* abruptly, with the added implication that *A*, if it continues to be produced, now will be in a *less* refined form (A' shifting to *A*). The history of weaponry in aboriginal California furnishes a potential example.

The use of the earliest really effective hunting weapon in California, the atlatl, is attested only archaeologically, the bow having replaced the atlatl sometime after A.D. 600. Groups at contact thus possessed only the bow, nearly always in two versions, the less costly self bow, usually reserved for rough use, small game, and play, and more effective sinew backed bow, whose production required the more costly extra steps of preparing, attaching, and finishing the layer of sinew that added both strength and use life. The maintenance of both forms suggests technological differentiation corresponding to different regions of a single cost–benefit technological function, the sinew backed bow serving for the most time-consuming, high payoff uses (large game, warfare, and the like), the self bow for incidental, low payoff uses (small game). Support for this is found in the record post-contact, when, with the advent of much more costly and effective firearms, bow use declined dramatically and bow production shifted almost entirely to the cheaper self bow form, its sinew backed counterpart virtually disappearing [3]. The effect of firearms on bow technology in California, then, is exactly as the effect of technology *c* on technology *a*, in Fig. 3. Without firearms (= technology *c*), bows assumes both cheap ($A =$ self bow) and costly ($A' =$ sinew back bow) versions; the introduction of firearms displaces the sinew back bow, leaving only the self bow, A' to *A*. This, in turn, helps clarify the sequence of technological shifts resulting in the demise of the atlatl. The ethnographic record from California suggests that the atlatl was not viable as weapon when the self and sinew backed bow were both present, but not whether it was viable when just one of them was present, specifically whether the atlatl and self bow coexisted until the advent of the more costly sinew backed bow, and if so, the nature of that technological differentiation. Our approach makes it possible to explore some of the possibilities.

It is simplest to pursue this problem via our simpler point-estimate model, using two points to represent the left (cheap, low return) and right (costly, high return) regions of the function describing bow technology as a whole, as shown in Fig. 4i. The open triangle on the lower left represents the self bow, which in comparison to the sinew backed bow (open circle, upper right), is cheaper to make, $m_{\text{self}} < m_{\text{backed}}$, yields lower returns, $f_{\text{self}}(m_{\text{self}}) < f_{\text{backed}}(m_{\text{backed}})$, but produces a greater gain in return per unit of technological investment, $f_{\text{self}}(m_{\text{self}})/m_{\text{self}} > f_{\text{backed}}(m_{\text{backed}})/m_{\text{backed}}$, as required for the two to coexist. We can use these plotted relationships and our knowledge of culture history to clarify how the bow replaced the atlatl. The point representing the atlatl is not shown in Fig. 4i; its position is what we are trying to establish. If our model applies, it must fall *below* the line connecting the open triangle and open circle (the points representing the self and sinew backed bow) and also *below* the line from the open triangle (self bow) to the origin. If it fell anywhere on or above these lines the atlatl alone, the atlatl and sinew backed bow, the atlatl and self bow, or all three, would be viable, none of these being in accord with the facts. If it fell in the shaded areas, for instance, all three would all be viable simultaneously. Given the historical constraint that the atlatl did not co-exist ethnographically with both the self and sinew backed bow – that is, it does not lie anywhere above the lines connecting the origin, self, and sinew backed bow – we can ask if it would co-occur with just the self bow. To be viable in this situation, the atlatl would have to both generate higher returns and be more costly to make (region s + a, Fig. 4ii). While the former (higher returns) is possible, the latter (more costly to make) seems less likely, suggesting that it was the advent of bow technology in the form of the simple self bow, not the later addition of the sinew backed bow, which made the atlatl wholly obsolete. This, of course, is in accord with the ethnographic record from eastern North American, where only the self bow is present and the atlatl entirely absent [2, pp. 349–356].

It is plausible, on the other hand, that the atlatl would remain viable where only the sinew backed bow is available, serving much the same function than as the self bow when the sinew backed bow is also present, i.e., for low use time activities. This situation may hold in the central and eastern Arctic, where the atlatl and sinew backed (or reinforced) bow are both present but the self bow is absent owing to the lack of suitable wood. The persistence of the Arctic atlatl is generally (and quite correctly) attributed to its use from watercraft (kayak), which allowed only one free hand (the other holding the paddle) and exposed the sinew reinforced and sinew strung Arctic bow to moisture. However, the Arctic atlatl was also used on land for some low return activities that were carried out with the bow elsewhere in North America (e.g., bird hunting; [10, Fig. 11]). Continuing use of the atlatl for such purposes in the Arctic may help explain the delay in the diffusion of the bow technology from the Old to New World, the cost and complication of producing the obligate sinew backed Arctic form discouraging atlatl using groups further south from experimenting with it as a start up technology. Many such patterns are potentially observable in the archaeological record.

The exercise in which we try to imagine the cost and return rate of the atlatl relative to bows (Fig. 4) highlights one last aspect of technological change not generally appreciated. Technological intensification is most usually envisioned as occurring through the incremental addition of innovations that are marginally more costly and productive, i.e., by adding to the right end of a concave technological function, at the edge of the technological envelope. There is no reason to think, however, that technological innovation will proceed this way. There is often greater potential for what might be called ''in-filling innovation'', developing viable technologies that fit in cost between existing technological forms. Commonly, modern-day inventions are of this sort. There is, thus, no reason to think that, in a given instance, the array of technologies in play within a class will approximate

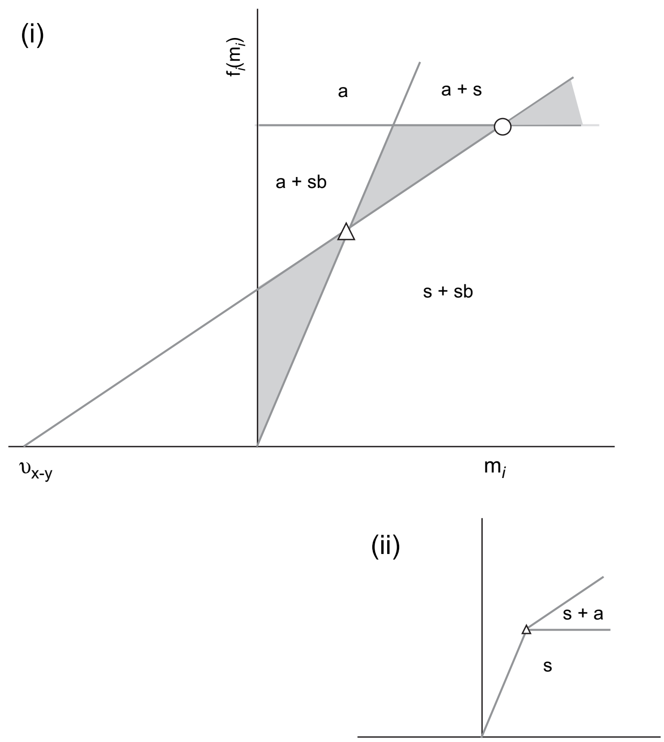

Fig. 4. (i) The technology comparison for point-estimate returns to the self bow (open triangle, *s*), sinew backed bow (open circle, sb) and atlatl (various positions, *a*). The diagram shows the optimal technological combination for all possible positions of the atlatl, given the point-estimates for the self and sinew backed bows. For instance, if the cost–benefit attributes of the atlatl cause it to fall in the shaded regions, it will co-exist with both the self and sinew backed bows (s + sb + a) over a range of use times from zero to infinity. Stable combinations of technology (e.g., a + sb = atlatl plus sinew back bow) for other atlatl positions are shown, again given a range of use times. This type of diagram allows us to generate hypotheses about the cultural history of technological development, given cost–benefit attributes of the implements available. Thus, the smaller pull-out figure (ii) shows the necessary conditions for the atlatl to be viable in the presence of the self bow, given that it is not found in combination with the self and sinew backed bow (see text for discussion).

anything like a neat concave function, indeed, there is no reason to think there are enough technologies of the right kind to permit this. All that can be assumed is that the return rate–production cost relationship of coexisting technological alternatives will be monotonically non-decreasing.

5. Conclusion

We want to reiterate our view that the model of technological investment developed by Ugan, Bright, and Rogers [9] is an important contribution to our understanding of technology and technological change. It is only with the application that we have problems, and then only because others may use it as a methodological blueprint. The procurement version of the UBR [9] model of technological intensification applies to an unrealistic and restricted set of conditions; it may generate misleading estimates of the use times required to make more or less costly technologies the option of choice. We propose point- and curve-estimate variants of a similar model that avoid these shortcomings, mainly by treating alternative technological categories as separate points or functions. We likewise note that $\upsilon_{x\leftrightarrow y}$ may in some cases be found not by tangents, but by a straight line that connects points or the end points of curve segments. The approach advocated here avoids the aggregation problems of fitting a single curve across disparate categories of technology; it does not force the positioning of curves with high and low marginal gains; it provides for flexibility in the positioning, shape and ordering of the gain functions for alternative forms of technological investment; and, it recognizes the independence of these functions and the potential for gaps among them. Notably, using a point-estimate model and the same data set from the Great Basin, we generate critical use threshold estimates that are sometimes higher ($\upsilon_{\text{spear}\leftrightarrow\text{multiple hook rig}}$) but more often much lower than those of UBR, the largest divergences associated with the most costly technologies ($\upsilon_{\text{multiple hook rig}\leftrightarrow\text{A-frame dip net}}$ and $\upsilon_{\text{A-frame dip net}\leftrightarrow 100'\text{ gill net}}$). To exemplify its potential, we describe how our model predicts divergences between local technological development and diffusion of innovations. It may also help us sort out more general issues surrounding the development of technology and its impact on subsistence economics.

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