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ARTICLE

A New Method for Classifying Dart and Arrow Projectile Points

Briggs Buchanan[1], Marcus J. Hamilton[2], and Robert S. Walker[3]

[1]Deparment of Anthropology and Sociology, University of Tulsa, Tulsa, OK, USA; [2]Department of Anthropology and School of Data Science, University of Texas, San Antonio, TX, USA and [3]Department of Anthropology, University of Missouri, Columbia, MO, USA
Corresponding author: Briggs Buchanan; Email: briggs-buchanan@utulsa.edu

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Abstract
A long-standing classification problem in archaeology is determining the type of weapon delivery system used by people in the past. This is usually done by comparing archaeological points to known dart and arrow points from the ethnographic and archaeological record. There are no simple criteria to discriminate between these two states and the challenge is to identify a subset of traits and their interactions to solve this problem. Here we introduce a Bayesian technique of classifying dart and arrow. Using machine-learning feature selection, we first find the optimal set of variables for classification. We then use a Generalized Additive Model to model the interaction of these variables in a Bayesian logistic framework to capture the nonlinear decision boundary between darts and arrows and assign probabilities of a point belonging to either state. To counteract the imbalance of having more arrows than darts, we adjust the typical decision cutoff using an iterative approach that balances sensitivity and specificity. We increase the sample of known arrow and dart points with 102 previously published specimens from the West. The code for our model is available and easily accessible through an online application. We apply our model to published dart-versus-arrow classifications to demonstrate its utility.

Resumen
Un problema de clasificación de larga data en arqueología es determinar el tipo de sistema de lanzamiento de armas utilizado por las personas en el pasado. Esto generalmente se hace comparando puntas arqueológicas con puntas de dardos y flechas conocidas del registro etnográfico y arqueológico. No existen criterios simples para discriminar entre estos dos tipos, y el desafío consiste en identificar un subconjunto de rasgos y sus interacciones para resolver este problema. Aquí presentamos una técnica bayesiana para clasificar entre dardos y flechas. Utilizando una selección de características basada en aprendizaje automático, primero identificamos el conjunto óptimo de variables para la clasificación. Luego usamos un Modelo Aditivo Generalizado para modelar la interacción de estas variables en un marco logístico bayesiano, con el fin de capturar el límite de decisión no lineal entre dardos y flechas y asignar probabilidades a que una punta pertenezca a uno u otro tipo. Para contrarrestar el desequilibrio de tener más flechas que dardos, ajustamos el punto de corte típico de decisión utilizando un enfoque iterativo que equilibra la sensibilidad y la especificidad. Ampliamos la muestra de puntas de flechas y dardos conocidas con 102 especímenes previamente publicados del Oeste. El código de nuestro modelo está disponible y es fácilmente accesible a través de una aplicación en línea. Aplicamos nuestro modelo a clasificaciones publicadas de dardos versus flechas para demostrar su utilidad.

Keywords: Bayesian logistic regression; bow and arrow; dart and atlatl; Shiny application; statistical classification; stone projectile points

Palabras clave: regresión logística bayesiana; arco y fleche; dardo y atlatl; aplicación Shiny; clasificación estadística; puntos de proyectil de Piedra

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The archaeological record of North America is characterized by stone projectile points spanning at least the last 13,000 years, which have been classified into numerous types (e.g., Justice 1987, 2002a, 2002b; Justice and Kudlaty 1999; Turner and Hester 1999). Archaeologists assume, based on historical and ethnographic accounts, that projectile points were used with one of two weapon delivery systems: attached to the end of a dart and launched with an atlatl (or spear thrower) or with the bow and arrow. Otherwise, they would have been attached to a spear and thrust or thrown. A long-standing problem in archaeology has been how to distinguish between the weapon delivery mechanisms using only the stone projectile tip, given that the organic components of weapon systems rarely endure in the archaeological record. A number of methods have been developed to make this distinction based solely on the stone tip (e.g., Bradbury 1998; Browne 1938, 1940; Corliss 1972; Fenenga 1953; Hildebrandt and King 2012; Kidder 1938; Thomas 1978). Here, we present several methodological advances that provide a novel and better means of distinguishing stone dart and arrow projectile points.

Determining the weapon delivery system used by people in the past is important not only because it involves innovations in technology that harness different mechanical forces but also because there are additional consequences that this change in technology entails. The atlatl and dart and the bow and arrow are associated with a different suite of performance characteristics. Some of the differences highlighted in the literature include range, accuracy, aerodynamics, shots per unit time, killing power, and area and position needed for delivery (Bergman et al. 1988; Bettinger 2013; Browne 1940; Butler 1975; Christenson 1986; Cotterell and Kamminga 1990; Howard 1974; Hughes 1998; Hutchings and Brüchert 1997; Lepers and Rots 2020; Raymond 1986; Tomka 2013; Whittaker 2013), as well as the ability to learn the different technologies (Grund 2017; Whittaker and Kamp 2006; although see Breslawski et al. 2018). Although the specific types, dimensions, and materials of the weapons are important when making comparisons, generally it is thought that the atlatl and dart confers more killing power and higher kinetic energy than traditional bows used with arrows. On the other hand, the bow allows hunters to fire arrows with more accuracy and allows hunters to increase the rate of reloading and firing. The bow also permits hunters to fire arrows with less movement—presumably decreasing the probability of alerting prey to the hunter—and can be used from a greater variety of positions (e.g., from horseback or a tree). These trade-offs are highly dependent on the specific designs of weapons and materials available, as well as the environmental and social settings in which they are used. Despite these trade-offs, the historical records of different parts of North America indicate that the bow and arrow was the predominate weapon delivery system in use at European contact, except among some northern coastal groups and in parts of Mexico (Maschner and Mason 2013; Raymond 1986).

The transition from the atlatl and dart to the bow and arrow has additional implications for archaeologists. The innovation of the bow and arrow (not necessarily with the concurrent disuse of the dart and atlatl, see Bradbury 1998; Grund and Huzurbazar 2018; Lyman et al. 2008; Maschner and Mason 2013; Odell 1988; Smith et al. 2013; VanPool 2006; Walde 2014) provides a cultural historical marker (Ames et al. 2010; Blitz 1988; Bradbury 1998; Erlandson et al. 2014; Hildebrandt and King 2012; Knight and Keyser 1983; Nassaney and Pyle 1999; Odell 1988; Schroedl 2024; Shott 1993; Smith 2015; Smith et al. 2013) and is indicative of changes in not only the type of prey being hunted but also the efficiency of the hunt (Bettinger 2013; Mika et al. 2020; Tomka 2013). This technological change has also been linked to increases in social complexity and warfare (Blitz and Porth 2013; Lambert 2002; Maschner and Mason 2013; Mika et al. 2020; Milner et al. 2013; Reed and Geib 2013; VanPool and O'Brien 2013; Walde 2013).

Given the importance of the technological shift from atlatl and dart to bow and arrow, it is not surprising that many studies have attempted to resolve the timing of this transition in different regions (e.g., Ames et al. 2010; Bettinger and Eerkens 1999; Blitz 1988; Bradbury 1998; Corliss 1972; Erlandson et al. 2014; Erwin et al. 2005; Fenenga 1953; Hildebrandt and King 2012; Mika et al. 2020; Nassaney and Pyle 1999; Odell 1988; Patterson 1985; Rafferty 2018; Rorabaugh and Fulkerson 2015; Roth et al. 2011; Schroedl 2024; Shott 1993; Smith 2015; Smith et al. 2013; Stevens and Codding 2009; VanPool 2006; Walde 2014; Yohe 1998). These studies, as well as others, attempt to distinguish stone dart from arrow point tips using methods of morphometric discrimination. Early studies used the distributional pattern of a morphometric attribute such as weight or neck width (e.g., Corliss 1972; Fenenga 1953) to define two groups that could represent darts and arrows, with the assumption that the group with

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the larger dimensions represented darts. However, without being linked to known darts or arrows, it is uncertain if the two (or more) modes represented points used with different delivery systems or if the morphometric differences related to some other factor. Similarly, although experiments can shed light on the constraints of replicated weapon delivery systems (e.g., Christenson 1986; Eren et al. 2020; Hughes 1998; Lepers and Rots 2020; Mika et al. 2020; Raymond 1986), it has been known for some time (Browne 1940; Fenenga 1953) that small points can be used effectively with darts and atlatls and, conversely, that large points can be used to tip arrows. David Hurst Thomas drew attention to these issues in his landmark 1978 study. He suggested that the best way forward would be to document ethnohistorical and prehistoric stone points that were still hafted to the organic components of the original weapon system. Consequently, the attached stone point tips could be definitively classified as either darts or arrows. Thomas (1978) then used the stone points from known darts and arrows to build a classification model using linear discriminant analysis (LDA) with two primary assumptions: (1) the sample of stone dart and arrow points available characterize the statistical population of stone dart and arrow points and (2) these populations reflect similar distinctions in the past.

Most studies published after Thomas's work in 1978 use his discriminant analysis or a modified version of it (e.g., Bradbury 1998; Shott 1997). In the current study, we briefly review these methods and then introduce our model. To build our model, we begin by using machine-learning methods to find the optimal set of variables with the highest predictive accuracy for the classification. Using a dataset supplemented by the inclusion of additional known darts and arrows we construct a Bayesian nonlinear logistic regression model with smoothed splines to classify the points. We developed an open-access online application (Shiny app) for researchers so that they can use our model to classify points as darts or arrows easily. Finally, we apply our model to several datasets to demonstrate its utility. The model we develop here assigns probabilities to projectile points of being in one state or the other and should then be combined with additional lines of evidence.

Models Used to Differentiate Dart from Arrow Points

The Linear Discriminant Analysis Approach of Thomas (1978) and Shott (1997)

Several studies predate Thomas's 1978 publication (e.g., Corliss 1972; Fenenga 1953). However, we start with this study because many subsequent studies use his approach. In Thomas's original study, he measured a sample of 132 arrow points and 10 dart points. Critically, these specimens were either from ethnographic collections or archaeological assemblages that were exceptionally well preserved, so the specimens retained the organic components of the weapon systems as well as the attached, or hafted, stone points. Thomas used X-rays to obtain images of the hafted stone points, which definitively indicated that they were used with atlatls or bows. He then used LDA on the stone points' dimensions (length, width, thickness, and neck width) to discriminate between the functional types. The LDA found that width is the most important discriminatory variable, followed by thickness, neck width, and length. The resulting equation misclassified three of the 10 dart points (30%) as arrows and 17 of 132 arrow points (13%) as dart points.

Thomas recognized the shortcomings of his study. The classification procedure could misclassify both arrows and darts. The high rate of misclassification for darts was partially attributed to the small sample size. Subsequently, Shott (1997) added 30 additional measurements on hafted dart artifacts to bring the total to 39 darts (one specimen in Thomas's dataset was necessarily removed by Shott because two specimens with the same catalog number could be attributed to the artifact measured by Thomas. Shott removed this one from Thomas's sample and included measures of both points in his dataset). Using the larger dart sample, Shott (1997) carried out similar LDA analyses. He reported that nine of 39 darts points (23%) had been misclassified as arrows and that 14 of 132 arrows (10%) had been misclassified as darts. The augmentation of the dart sample improved the classification results. Shott then reduced the number of variables in LDA sequentially from three to one. The three-variable LDA produced the lowest rates of misclassification. The misclassification rates dropped to six out of 39 (15%) for darts and 12 out of 132 for arrows (9%). This LDA included width, thickness, and neck width, and it excluded length. Shott rationalized that point length was likely the most problematic variable of the four because it would have been subject to resharpening and reworking by hunters in the past.

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Although we think that Thomas's approach to distinguish archaeological dart and arrow points using known ethnographic and archaeological dart and arrow specimens is valid, improved statistical methods are now available to produce a better model. A few of the problems with the Thomas and Shott statistical method were pointed out by the authors themselves—that is, LDA relies on linear relationships among the variables and requires normality; Shott (1997) evaluated the normality assumption and showed that it had been violated for some of the data. Moreover, none of the classification analyses performed by Thomas and Shott use cross-validation, which is important for variable and model selection because it helps ensure model robustness and can be used to prevent overfitting and improve model evaluation (Kovarovic et al. 2011). Crucially, it is used to assess generalizability to new data—that is, it evaluates the model in terms of how well it performs using out-of-sample classifications. Finally, both Thomas and Shott use prior probabilities set at 0.5 for both dart and arrow. Given that the arrow sample is more than three times larger than the dart sample, this procedure can also produce spurious results. This is because classification procedures trained on this imbalanced data will classify out-of-sample points as arrows more often.

Our model, presented below, is a Bayesian logistic model with smoothed splines. Thomas and Shott use a frequentist LDA model without cross-validation. Consequently, our results are not directly comparable. However, we conducted an experiment using 10-fold cross-validation repeated five times each for 12 different classification models (see Supplementary Material 1). Given that this is a relatively simple classification problem, all of the algorithms did well in terms of accuracy of classification (>90%), but LDA ranked eleventh out of the 12 models. Another useful metric, particularly with imbalanced datasets, is Cohen's Kappa coefficient (Landis and Koch 1977). Kappa evaluates classification performance while considering agreement that could happen by chance. In terms of Kappa, LDA again does poorly, ranking eleventh out of 12 models. The top-performing algorithms allow for nonlinear relationships with predictor variables such as the Generalized Additive Models. Consequently, we use this approach in our Bayesian logistic model presented below, and we balance sensitivity and specificity of the classifier.

Developing a New Model: The Bayesian Logistic Model with Smoothed Splines

We use the dataset compiled by Thomas (1978) and augmented by Shott (1997), comprising 132 arrow points and 39 dart points, to build our classification model. Because two of the 171 specimens are not from North America (SA-3758 is from Peru, and D2429 is from Australia), we removed them from the dataset (see Supplementary Material 2). Both specimens were darts, and this reduces the number of darts in the sample to 37. Future studies that document a larger sample of well-preserved hafted darts and arrows in archaeological or ethnographic collections from outside of North America can be used to expand this dataset or to develop continent-specific classifications.

The expanded Thomas (1978) dataset uses four variables measured on the hafted dart and arrow specimens, including length, width, thickness, and neck width. In many cases, X-rays were needed to take these measurements, and additional measures such as weight could not be taken. Figure 1 shows the distributions of these variables for darts and arrows in our sample. Each of the variables shows overlap of dart and arrow measures, but width and length appear to show the least amount of overlap. Our first goal was to find the optimal set of variables with the highest predictive accuracy using machine-learning techniques. In addition to the above four variables, we considered all two-way (area measurements) and three-way (volume) interactions for a total of 14 potential variables to include or exclude in the final model. For variable selection, we used the elastic net algorithm (Zou and Hastie 2005) in the *glmnet* package of R with a logistic regression. Other model selection methods we considered were Lasso and Ridge regression. Lasso (Tibshirani 1996) is a popular algorithm for variable selection and is effective with high-dimensional data, but it tends toward overregularization. Ridge regression (Hoerl and Kennard 1988), on the other hand, tends toward underregularization. Elastic net has the advantage of balancing between the two by finding the optimal reduction of penalties that give the best regularization as evaluated by cross-validated metrics (leave-one-out). Elastic net tunes a hyperparameter, alpha, that ranges from 0 (Ridge) to 1 (Lasso). For our case, after scaling our variables, an alpha of 0.9 gives the highest predictive model. The variables with the highest predictive accuracy are length, width, and the

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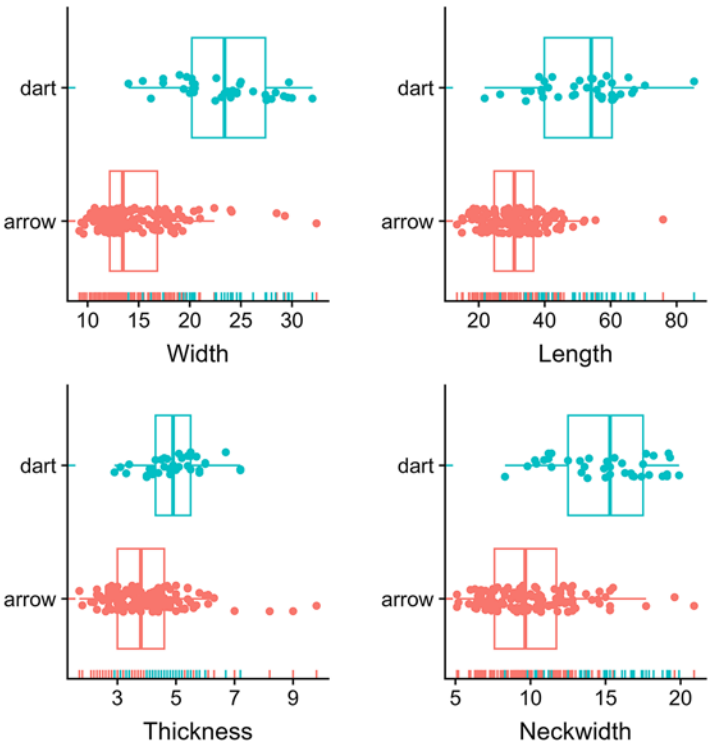


Figure 1. Box plots of the four variables—width, length, thickness, and neck width—measured on the sample of known darts and arrows compiled by Thomas (1978) and Shott (1997). (Color online)

interaction between length and width; the other 11 variables (neck width and thickness, and the other two-way and three-way interactions) are removed from the final model.

We should note here that several studies advocate using tip cross-sectional area (TCSA) and tip cross-sectional perimeter (TCSP) to distinguish between darts and arrows (Hughes 1998; Lombard et al. 2024; Shea 2006). TCSA and TCSP are derived measurements using width and thickness, whereas our model shows that thickness is not a useful discriminator of darts and arrows. It follows that tip cross-sectional measures incorporating point thickness will not perform as well as length, width, and length–width interaction in distinguishing darts from arrows. Although not optimal for distinguishing between darts and arrows, tip cross-sectional measures are useful for revealing the relative penetration-depth capacities of points (see Sitton et al. 2020). Consequently, they may be effective in assessing the relative performance of certain dart and arrow types but not necessarily in distinguishing between them.

We included group identifiers that indicated cultural group and region in our model to determine if group had a strong effect on the model. The group sample sizes range widely: some of the larger groupings of darts and arrows include the points from the Southwest, California, undifferentiated North America, and the Plains. The Southwest is the best represented region in the sample, and inclusion of a Southwest variable improved the model fit (positively predicting dart). The other groups had negligible effects on the model and were excluded from the final model.

Because our final model requires measurements for only length and width (and their interaction), we were able to expand our initial dataset of darts and arrows with samples that could not be used in the original variable selection model because not all of the four variables measured by Thomas (1978) were reported. Length and width measurements were published for additional hafted arrows and darts. The additional specimens include 14 hafted dart artifacts and 88 hafted arrow points. All the additional

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artifacts come from western North America. The additional dart points are derived primarily from Zeanah and Elston's (2001) publication and include six artifacts from Nevada, three from New Mexico, two from Utah, and one each from Arizona, Texas, and the Yukon (Thomas et al. 2023; Tuohy 1982; Zeanah and Elston 2001 [and references within]). The additional arrow-point sample includes one arrow from British Columbia (Keddie and Nelson 2005) and 87 hafted arrow points from the Great Basin and Colorado Plateau reported by Fowler and Matley (1979). The arrow collection reported by Fowler and Matley (1979) is part of the John Wesley Powell ethnographic collection amassed between 1867 and 1880. Among the material culture items collected by Powell were 12 arrows made by the Kaibab Southern Paiute, 31 arrows made by the Moapa Southern Paiute, 31 arrows made by the Southern Paiute of Utah, and 13 arrows made by the Deep Creek Gosiute. This brings the total dataset to 271, comprising 51 darts and 220 arrows.

The final Bayesian model is a logistic regression of dart versus arrow with smoothed splines. A logistic regression is used to model binary outcomes (dart vs. arrow). In our model, we fit smoothed splines to capture the complex, nonlinear relationship between the predictors and the log odds of the outcome. The splines are smoothed by penalizing overfitting to the data. This model was implemented in R 4.4.0 with the *brms* package (Bürkner 2017, 2018). We found that the significant interaction term between length and width identified by the elastic net algorithm as described above captures a slight nonlinear decision boundary between darts and arrows (see Figure 2). The spline that smooths for length and width is subtle, so we used low basis dimensions ($k = 3$). An additional advantage of our model is that it does not require neck width to make a classification. Shott (1997) pointed out that a number of point types do not possess necks. Therefore, this variable cannot be measured on many points. This model also includes an indicator variable for points from the Southwest, the single group that had a significant effect on the model outcome. Dart points from the Southwest tend to be shorter and narrower than darts from other regions (Figure 2). Weak prior probability distributions ($\mu = 0$, $\sigma = 2$) were assigned to all estimates. Sampling was carried out using the No-U-Turn Sampler (Hoffman and Gelman 2014). Final models were run with four chains for 10,000 iterations, each with a warm-up of 5,000 iterations. For all parameters, R-hat values (a model diagnostic with expected value equal to one) were exactly one and hence signify model convergence. Chains were inspected visually for sufficient mixing to ensure that model results were appropriate. The model passes a posterior predictive check, and the residuals are well behaved.

The dataset we used is imbalanced with more than four times the number of arrows ($n = 220$) than darts ($n = 51$). A consequence of this imbalance is the risk of misclassification biased against darts. To deal with this issue, we iteratively reduced the cutoff of the model from the normal 0.5 cutoff down to 0.15, where the model reaches a balance between sensitivity and specificity in the confusion matrix. This makes the model more sensitive to dart classification. The 0.15 nonlinear decision boundaries for points from the Southwest and for points from other regions are shown in Figure 2.

The code for the steps described above and for our new model is available as an R script at https://github.com/RobertSWalker/arrow_vs_dart (see Supplementary Material 3).

Using the Classification Model Online with the Shiny App

We also make the model available to use through an online application (https://robert-walker.shinyapps.io/arrows_darts/). The app was made using the Shiny package in R 4.4.0, and it allows users to input stone-point data through the web interface and obtain a probabilistic prediction for their artifact. To use the app to make a classification prediction, users input length and width of the stone point, decide if the point was found in the Southwest or not, and opt to set a different cutoff probability (default is 0.15). If the stone point has an incomplete length measurement, a length estimate is input if width is entered. After entering these data, the user can click the "Get prediction" button, which generates the results of the classification using the Bayesian logistic model with smoothed splines. The output includes the prediction (dart or arrow), the standard deviation of the prediction from the posterior distribution, and the odds of the prediction. The specimen also is displayed in the length-by-width plot with the nonlinear interaction space represented with gradient colors, similar to Figure 2. This app should be

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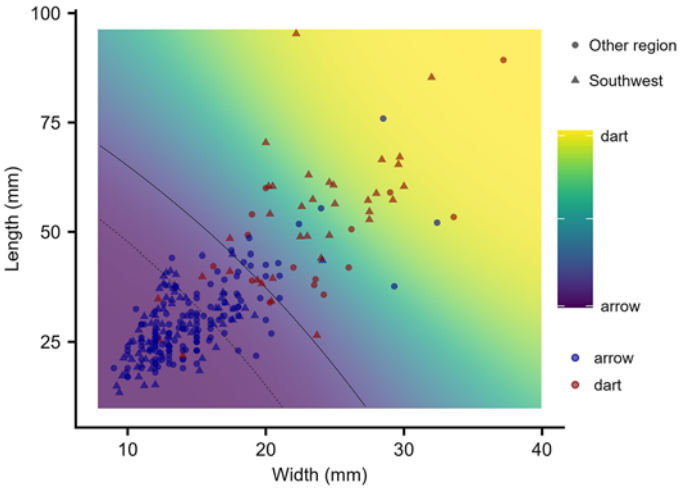


Figure 2. The best variables for classifying darts versus arrows are length, width, and Southwest. Our model with smoothed splines generates nonlinear decision boundaries (curved lines). The dotted line is the decision boundary with a cutoff of 0.15 for points from the Southwest, and the solid line is the decision boundary with a cutoff of 0.15 for points from other regions. This graph uses the expanded dataset of 51 darts and 220 arrows. (Color online)

useful for researchers who want to confirm or make classifications of individual points, and it can be used on mobile devices in the field. If larger datasets of points need to be classified, use of the model in the R platform is more efficient.

Applying the Model

Although the classification rates from our new model and previous models are not directly comparable given the lack of cross-validation on previously reported classification rates, applying our statistical model to well-known examples shows that our model produces different results. The goal of this section is to highlight (1) how our model can be used and (2) that it produces different results than previous techniques, thereby demonstrating that it does not replicate previous findings.

Classification Examples Using Thomas's (1978) and Shott's (1997) Method

The LDA classification of Thomas (1978) has been used widely in the archaeological literature; however, relatively few examples of these classifications include data in the publication. This is not unusual, given that publishing full datasets in archaeology has only recently become the accepted practice. Therefore, our examples are limited.

Knight and Keyser (1983) used Thomas's (1978) LDA to classify projectile points from dated contexts in Montana and Wyoming. Their goal was to use the LDA to classify projectiles points from the Archaic and Late Prehistoric periods that are believed to coincide with the dart-to-arrow transition in the region. They report that Thomas's LDA method classified 68% of the Archaic-aged points ($n = 88$) as darts, which they assume a priori were darts, and 98% of the Late Prehistoric points they assumed were arrows as arrows ($n = 134$). Knight and Keyser (1983) considered the results of Thomas's classification adequate, but they sought to improve it for the Northwestern Plains by using their archaeological point data to redefine the discriminant functions. They assumed that the transition from the Archaic to Late Prehistoric represented a concurrent and abrupt transition between the atlatl and dart and the bow and arrow. Based on this assumption, they carried out an LDA after assigning Archaic period points as darts and Late Prehistoric period points as arrows. Using our model, we can determine if this decision was justified. We find that our classification supports arrow use during the Late Prehistoric period. We classified 99% of the Late Prehistoric points as arrows (one Late Prehistoric point was classified as a dart; see Supplementary Material 4).

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On the other hand, our model disputes Knight and Keyser's (1983) suggestion that only darts were used in the Archaic period. Our model indicates that 36% of Archaic points (31 of 86) are classified as arrows, and 64% can be classified as darts (55 of 86). This finding suggests that the Archaic period assemblages in Knight and Keyser's (1983) study more likely represent a time when both weapon delivery systems were in use (for other examples, see Bradbury 1998; Grund and Huzurbazar 2018; Lyman et al. 2008; Maschner and Mason 2013; Odell 1988; Smith et al. 2013; VanPool 2006; Walde 2014).

In a second example, Smith and colleagues (2013) use the expanded Thomas (1978) and Shott (1997) dataset to classify points from the Great Basin. Smith and colleagues (2013) date organic materials attached to various Great Basin point types. The new dates redefine the time ranges for some types and have implications for the use of cross-dating based on typological and functional (dart versus arrow) assumptions. Smith and colleagues (2013) highlight these problems with an example of the Nicholarsen cache, which contained 21 Elko and 36 Rosegate typed points. The cache was dated to 1235 cal BP (calibrated years before present), a date at the young end of the Elko temporal span and the beginning of the Rosegate time period. Elko points are traditionally thought to have been used with the atlatl and dart and Rosegate points with the bow and arrow. Using Thomas's expanded comparative dataset, Smith and colleagues (2013) found that the Elko points all classified as darts and that nearly all the Rosegate points (92%) classified as arrows. This finding has confounded researchers, because the expectation has been that the two functional and stylistic types were in use during different time periods. Two explanations were offered to explain this co-occurrence: (1) the dart and arrow technologies were used simultaneously during this period (around 1235 cal BP), or (2) the functional and stylistic classifications do not work. Our reanalysis of the points found in the Nicholarsen cache supports the first explanation. Classifying the Nicholarsen cache points using our model shows that both types consist of dart and arrow points. We classified 18 (86%) of the Elko points as darts and three (14%) as arrows, and 30 (83%) of the Rosegate points as darts and six (17%) as arrows. For both Elko and Rosegate points, dart points are in the majority, and arrows are in the minority. No statistical difference in the proportions of darts or arrows in both types suggests that the cache does not represent two functionally different point types; instead, it suggests both point types (if they are two different types) could have been used with both atlatl and dart and bow and arrow. For a contrasting result, see Hockett et alia's (2014) use of Hildebrandt and King's (2012) dart-arrow index (discussed below), which characterizes all the points in the Nicholarsen cache as arrow points.

Testing the Hildebrandt and King (2012) Dart-Arrow Index

Another popular method for distinguishing darts from arrows is Hildebrandt and King's (2012) dart-arrow index (Amick 2024; Erlandson et al. 2014; Hornbaker and Jones 2024; Losey and Hull 2019; Rafferty 2018; Rorabaugh and Fulkerson 2015; Schroedl 2024; Walde 2014). Rather than using LDA, their formula adds neck width and thickness to create the dart-arrow index. Setting 11.8 mm as the cutoff, they assigned larger values as darts. Values less than 11.8 mm are classified as arrows. This index does not create dimensionless values, which is commonly done with indices to make them easier to use in comparative analyses. However, our primary issue with Hildebrandt and King (2012) is that they develop their index using well-known archaeological projectile point types in the Great Basin rather than using Thomas's method of starting with known dart and arrow points. The Great Basin typology relies on neck width and thickness among other variables to classify points (see Thomas 1981). Hildebrandt and King (2012) show that their dart-arrow index separates Great Basin types, some of which are assumed to have been used with atlatl and dart, and others with bow and arrow. They subsequently evaluate their index by comparing their cutoff value to mean values associated with the darts and arrows in the Thomas and Shott dataset as well as to additional arrows from Fowler and Matley (1979). They find that the darts have average dart-arrow index values above the cutoff as expected, but the arrows (except for the sample of 14 arrows from Pueblo Bonito [see Thomas 1978]) have high average index values, classifying them as dart points. Hildebrandt and King (2012) argue that the mismatch between their dart-arrow index and the ethnographic collections of arrows is due not to the inability of their index to separate darts and arrows reliably but to the unrepresentativeness of the ethnographic arrows. They suggest that the large samples

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Table 1. Comparison of Hildebrandt and King's (2012) Dart-Arrow Index Classifications of Select Great Basin Types with our Predictions from the Bayesian Logistic Regression Model with Smoothed Splines.

Type	H&K (2012) Prediction	Length	Width	Bayesian Probability[a]	Standard Deviation	Bayesian Logistic Model Prediction
Desert Side-Notched	Arrow	21.4	12.4	0.005	0.079	Arrow
Gunther	Arrow	26.0	15.0	0.016	0.130	Arrow
Rose Spring	Arrow	24.3	13.8	0.010	0.095	Arrow
Elko	Dart	32.4	20.2	0.109	0.312	Arrow
Gatecliff Split Stem	Dart	33.4	19.4	0.096	0.293	Arrow
Northern Side-Notched	Dart	29.8	21.3	0.119	0.328	Arrow
Great Basin Stemmed	Dart	54.7	24.1	0.697	0.459	Dart
Elko Experimental Before	Dart	47.5	26.4	0.695	0.462	Dart
Elko Experimental After	Arrow	38.2	23.6	0.337	0.472	Dart

[a]The Bayesian probabilities are interpretable relative to the decision cutoff of 0.15. Points with probabilities lower than 0.15 are more likely to be arrows, and those with probabilities higher than 0.15 are more likely darts. Probabilities closer to 0.15 and with large standard deviations have less certain predictions (see Figure 2).

of ethnographic arrows from across western North America are not representative of prehistoric arrows because of cultural disruptions after European contact or because arrows were being made specifically for ethnographers and therefore not made to be functional.

Hildebrandt and King (2012) assume that the alignment between their index and the archaeological types supports the validity of their index, but it is more likely that the alignment is a consequence of both the Great Basin typology and their dart-arrow index using neck width and thickness. We reevaluate the classifications made using Hildebrandt and King's (2012) dart-arrow index. Hildebrandt and King (2012:Table 1) provide average values for seven Great Basin projectile point types. Three of these are classified as arrow points, and four are classified as darts using their dart-arrowindex. Because only average values are available in Hildebrandt and King's (2012) article, we use these values to reclassify the types with our model. Our predictions differ substantially from Hildebrandt and King's predictions. We classified six of the projectile point types as arrow points and only one as a dart point (Table 1).

We also assess Hildebrandt and King's (2012) claim that their index is superior to Thomas's (1978) LDA classification because it does not use point length. They argue that point length is subject to alteration by resharpening after damage from use. In contrast, they state that their index includes only variables (neck width and thickness) that are minimally altered during resharpening events. To demonstrate this, Hildebrandt and King (2012) measured the experimental replicas of Elko points that were hafted onto darts and launched with atlatls by Flenniken and Raymond (1986). After those hafted points were damaged, Flenniken and Raymond resharpened the edges and reused the points. Hildebrandt and King (2012) use their index to show that Flenniken and Raymond's replica Elko dart points are classified as dart points, but after resharpening, they are classified as arrows. They contend that this is evidence that resharpening can change the functional designations of points when length is included in the classification algorithm. Although we have reservations about the subjectivity of the experiment carried out by Flenniken and Raymond, we reanalyzed the data on the replica points and show that resharpening does not change the functional designation when our model is used. Our model classifies the resharpened experimental Elko points as darts (Table 1). Furthermore, the results of our classifications question the validity of Flenniken and Raymond's (1986) decision to use replicated Elko-style points with atlatl and darts, because we classify the average archaeological Elko point reported by Hildebrandt and King as an arrow point (Table 1).

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On Including Point Length in Functional Classifications and the Misperceived Significant Impact of Resharpening

Several researchers do not use point length in their classification functions (e.g., Bradbury 1998; Hildebrandt and King 2012; Shott 1997). These researchers remove this variable on the grounds that point length complicates functional classification because it can be impacted by resharpening. The argument is that point length is the dimension most likely to be significantly altered by resharpening, whereas width, neck width, and thickness are less likely to be modified by resharpening. This is because the tip of the point does the cutting and penetrating work and can incur damage from use. Consequently, a damaged tip would need to be made sharp again to be effective. It is the modification to length made by resharpening that has the potential to change the functional designation of a point if length is used in the classification algorithm.

However, we suggest caution about assumptions concerning resharpening. First, it is impossible to know how much resharpening was carried out on individual points within different types because identifying evidence for resharpening is subjective (usually it is identified based on the presence of overlapping flake scars and differences in point shape and size, but neither of those lines of evidence are definitive, given that other processes can produce these signatures). Second, it usually assumed a priori that resharpening was ubiquitous. However, this is unclear. Third, assuming that the process of resharpening significantly alters the form of points across all types is an unsupported claim. Indeed, several studies now support the hypothesis that resharpening for some types was done in such a way as to maintain the shape of the point (see Buchanan et al. 2015; Smith et al. 2021). Although it is possible that some point types were designed to receive more resharpening than other types (e.g., Folsom; see Bement 2002), the process was still culturally constrained (and therefore as archaeologists, we can identify point types), and it likely maintained the overall form of the type as closely as possible (see Smith et al. 2021). This last argument is reinforced by the fact that point designs must incorporate functional demands, and those are manifest in the size and shape of a point. Allometric analyses of Paleoindian point types show that these designs are maintained over a range of sizes (which could be the result of resharpening but also differences in starting core size and the size of the available materials used to make the points; e.g., from a biface or flake) to maintain tradeoffs between performance characteristics such as penetration and durability (Buchanan and Hamilton 2021; also see Buchanan et al. 2022; Eren et al. 2020; Maguire et al. 2021).

In addition to these arguments, our analyses presented above conflict with the results of classification methods that exclude point length. Our model shows that length and width and the interaction of length and width are the best variables for classification of darts and arrows. Interestingly, our classification of Hildebrandt and King's (2012) example of resharpening—the Flenniken and Raymond (1986) experimental Elko dart point before and after being resharpened—showed that the classification of dart does not change after resharpening. This finding contrasts to Hildebrandt and King's (2012) classification. Although only a single example, it suggests that potential alteration of point length via resharpening does not automatically change the dart or arrow assignment.

Conclusions

We presented a new model for classifying stone dart and arrow points from North America and show that this model significantly improves upon previous methods. Our workflow began by using machine learning to find the optimal set of variables for classification. Because we identified length and width and their interaction as the best set of discriminatory variables (in addition to whether a point was from the Southwest region), we increased the sample size of darts and arrows in our model with additional published specimens. We then developed a Bayesian logistic regression model using smoothed splines to capture the nonlinear decision boundary between darts and arrows. We adjusted for the imbalance in the sample of darts and arrows by reducing the cutoff value to 0.15 to balance sensitivity and specificity in the confusion matrix. We made this model easy to use with an app that allows users to input stone point length and width (or only width) data and receive aJ classification.

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We applied our new model to examples demonstrating that we find different classifications from those that used Thomas's (1978) model and the expanded versions of his model. In the two cases—the Archaic and Late Prehistoric in Wyoming and Montana and the Great Basin—our model revealed more of a mix of darts and arrows when the transition was thought to have been more abrupt. We do not take the differing results as evidence that our model is more accurate than previous models; the examples simply show that our model does not repeat the classifications of older models. Here, we should emphasize that our model is a probabilistic one. Assigning individual points to either dart or arrow comes with a likelihood, and the classification based on our model is ideally used with other lines of evidence. Other lines of evidence for assigning weapon type could include diagnostic impact fractures, microscopic linear traces and other wear traces, residues, and ideally (but unrealistically) large samples of preserved darts and arrows to test the dart-versus-arrow hypothesis further. Caution also is needed when evaluating these other lines' evidence (see Helwig et al. 2014; Mukusha et al. 2024). However, we contend that statistical models based on point form, such as ours, remain a useful line of evidence. Others might disagree, citing experiments that small points can be used with darts and that large points can function when hafted to arrows (Browne 1938, 1940; Fenenga 1953). These findings imply that the size of points cannot be used to differentiate points used with the two weapon delivery systems. But we also know, based on the scaling of points (Buchanan and Hamilton 2021) and experiments on performance characteristics (e.g., Eren et al. 2020), that a large point used on an arrow does not perform optimally, nor does a small point on a dart. Furthermore, the known dart and arrow dataset shows us that, although there is some overlap, most arrow points are differentiated from most dart points. The North American archaeological record also demonstrates an overall trend from larger points to smaller points over time. The ethnographic record demonstrates that peoples in most regions of North America were using the bow and arrow at European contact. Together with the dating of well-preserved dart and atlatl artifacts, this indicates that the transition from atlatl and dart to bow and arrow occurred at some time in the deep past (e.g., see Grund and Huzurbazar 2018), and this timing undoubtedly varies across regions and cultures. Consequently, our model should be useful as a line of evidence to help classify stone points and define periods of transition in weapon delivery systems across the continent.

Our sample of known dart and arrow points comes exclusively from North America. The original samples of dart and arrow points used by Thomas (1978) and Shott (1997) included two specimens from outside of North America (Peru and Australia), which we removed. Until a larger sample of dart and arrow points from other continents is generated (although see Marsh et al. 2024), we considered it better to keep our model specific to North America. We do not know if the transition of dart to arrow in other parts of the world followed a similar morphological trajectory as it did in North America, so we would be cautious to apply our model beyond North America. We hope that future research focused on other continents will generate similar datasets of known darts and arrows (and spears; see Lombard et al. 2024) and will build comparable statistical models for distinguishing darts from arrows. With such studies, comparison of the evolution of weapon technology across continents might reveal patterns of morphological changes driven by physical constraints and perhaps interesting divergences resulting from historically contingent processes. Moreover, within the diverse environmental regions of North America, it might be the case that new models are needed to identify the regionally specific change from dart to arrow. We were able to do this for the Southwest region in our model; however, until larger datasets of known darts and arrows in other regions are available, we cannot know if different models will be required.

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Supplementary Material. For supplementary material accompanying this article, visit https://doi.org/10.1017/aaq.2025.10109.

Supplementary Material 1. Word document with the results of additional analyses of 10-fold cross-validation repeated five times each for 12 commonly used classification methods (text).

Supplementary Material 2. Excel file with data on known ethnographic and archaeological dart and arrow points (table).

Supplementary Material 3. R script with all the code necessary to run the models described in the manuscript (code).

Supplementary Material 4. Excel file with data on archaeological point specimens classified using previous models and reanalyzed in this study (table).

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