

# Variable Importance Plots: An Introduction to the vip Package

by Brandon M. Greenwell and Bradley C. Boehmke

**Abstract** In the era of "big data", it is becoming more of a challenge to not only build state-of-the-art predictive models, but also gain an understanding of what's really going on in the data. For example, it is often of interest to know which, if any, of the predictors in a fitted model are relatively influential on the predicted outcome. Some modern algorithms—like random forests (RFs) and gradient boosted decision trees (GBMs)—have a natural way of quantifying the importance or relative influence of each feature. Other algorithms—like naive Bayes classifiers and support vector machines—are not capable of doing so and *model-agnostic approaches* are generally used to measure each predictor's importance. Enter **vip**, an R package for constructing variable importance scores/plots for many types of supervised learning algorithms using model-specific and novel model-agnostic approaches. We'll also discuss a novel way to display both feature importance and feature effects together using sparklines.

## Introduction

Too often machine learning (ML) models are summarized using a single metric (e.g., cross-validated accuracy) and then put into production. Although we often care about the predictions from these models, it is becoming routine to also understand the predictions! Understanding how an ML model makes its predictions helps build trust in the model and is the fundamental idea of the emerging field of *interpretable machine learning* (IML). For an in-depth discussion on IML, see [Molnar \(2019\)](#). In this paper, we focus on global methods for quantifying the importance of features in an ML model. Computing variable importance (VI) and communicating them through variable importance plots (VIPs) is a fundamental component of IML and is the main topic of this paper.

VI scores and VIPs can be constructed for general ML models using a number of packages. The **iml** package ([Molnar et al., 2018](#)) provides the `FeatureImp()` function which computes feature importance for general prediction models using the permutation approach (discussed later). It is written in **R6** ([Chang, 2019](#)) and allows the user to specify a generic loss function or select from a pre-defined list (e.g., `loss = "mse"` for mean squared error). It also allows the user to specify whether importance is measured as the difference or as the ratio of the original model error and the model error after permutation. The user can also specify the number of repetitions used when permuting each feature to help stabilize the variability in the procedure.

The **DALEX** package ([Biecek, 2018](#)) also provides permutation-based VI scores through the `variable_importance()` function. Similar to `iml::FeatureImp()`, this function allows the user to specify a loss function and how the importance scores are computed (e.g., using the difference or ratio). It also provides an option to sample the training data before shuffling the data to compute importance (the default is to use `n_sample = 1000`). This can help speed up computation.

The **caret** package ([Kuhn, 2017b](#)) includes a general `varImp()` function for computing model-specific and filter-based VI scores. Filter-based approaches, which are described in [Kuhn and Johnson \(2013\)](#), do not make use of the fitted model to measure VI. They also do not take into account the other predictors in the model. For regression problems, a popular approach to measuring the VI of a numeric predictor  $x$  is to first fit a flexible nonparametric model between  $x$  and the target  $Y$ ; for example, the locally-weighted polynomial regression (LOWESS) method developed by [Cleveland \(1979\)](#). From this fit, a pseudo- $R^2$  measure can be obtained from the resulting residuals and used as a measure of VI. For categorical predictors, a different method based on standard statistical tests (e.g.,  $t$ -tests and ANOVAs) can be employed; see [Kuhn and Johnson \(2013\)](#) for details. For classification problems, an area under the ROC curve (AUC) statistic can be used to quantify predictor importance. The AUC statistic is computed by using the predictor  $x$  as input to the ROC curve. If  $x$  can reasonably separate the classes of  $Y$ , that is a clear indicator that  $x$  is an important predictor (in terms of class separation) and this is captured in the corresponding AUC statistic. For problems with more than two classes, extensions of the ROC curve or a one-vs-all approach can be used.

If you use the **mlr** interface for fitting ML models ([Bischl et al., 2016](#)), then you can use the `getFeatureImportance()` function to extract model-specific VI scores from various tree-based models (e.g., RFs and GBMs). Unlike **caret**, the model needs to be fit via the **mlr** interface; for instance, you cannot use `getFeatureImportance()` on a **gbm** model ([Ridgeway, 2017](#)) unless it was fit using **mlr**.

While the **iml** and **DALEX** packages provide model-agnostic approaches to computing VI, **caret** provides model-specific approaches (e.g., using the absolute value of the  $t$ -statistic for linear models)

as well less accurate filter-based approaches. Furthermore, each package has a completely different interface (e.g., **iml** is written in R6). The **vip** package (Greenwell and Boehmke, 2018) strives to provide a consistent interface to both model-specific and model-agnostic approaches to feature importance that is simple to use. The three most important functions exported by **vip** are described below:

- `vi()` computes VI scores using model-specific or model-agnostic approaches (the results are always returned as a tibble (Müller and Wickham, 2019));
- `vip()` constructs VIPs using model-specific or model-agnostic approaches with **ggplot2**-style graphics (Wickham, 2016);
- `add_sparklines()` adds a novel sparkline representation of feature effects (e.g., *partial dependence plots*) to any VI table produced by `vi()`.

There's also a function called `vint()` (for variable interactions) but is experimental and will not be discussed here; the interested reader is pointed to Greenwell et al. (2018). Note that `vi()` is actually a wrapper around four workhorse functions: `vi_model()`, `vi_ice()`, `vi_pdp()`, and `vi_permute()`. These functions compute various types of VI scores. The first computes model-specific VI scores, while the latter three produce model-agnostic ones. The workhorse function that actually gets called is controlled by the `method` argument in `vi()`; the default is `method = "model"` which corresponds to model-specific VI (see ?vi for details and links to further documentation).

## Constructing VIPs in R

We'll illustrate major concepts using the Friedman 1 benchmark problem described in Friedman (1991) and Breiman (1996):

$$Y_i = 10 \sin(\pi X_{1i} X_{2i}) + 20(X_{3i} - 0.5)^2 + 10X_{4i} + 5X_{5i} + \epsilon_i, \quad i = 1, 2, \dots, n, \quad (1)$$

where  $\epsilon_i \stackrel{iid}{\sim} N(0, \sigma^2)$ . Data from this model can be generated using the `mlbench.friedman1()` function available in the **mlbench** package (Leisch and Dimitriadou, 2012). The inputs consist of 10 independent variables uniformly distributed on the interval  $[0, 1]$ ; however, only 5 out of these 10 are actually used in the true model. The code chunk below simulates 500 observations from the model in Equation (1) default with  $\sigma = 1$ .

```
# Simulate training data
set.seed(101) # for reproducibility
trn <- as.data.frame(mlbench::mlbench.friedman1(500)) # ?mlbench.friedman1
names(trn) <- gsub("^x\\.", "X", x = names(trn)) # to match notation

# Inspect data
tibble::as_tibble(trn)
#> Warning: `as.tibble()` is deprecated, use `as_tibble()` (but mind the new semantics).
#> This warning is displayed once per session.
#> # A tibble: 500 x 11
#>       X1    X2    X3    X4    X5    X6    X7    X8    X9   X10     y
#>   <dbl> <dbl> <dbl> <dbl> <dbl> <dbl> <dbl> <dbl> <dbl> <dbl> <dbl>
#> 1 0.372 0.406 0.102 0.322 0.693 0.758 0.518 0.530 0.878 0.763 14.9
#> 2 0.0438 0.602 0.602 0.999 0.776 0.533 0.509 0.487 0.118 0.176 15.3
#> 3 0.710 0.362 0.254 0.548 0.0180 0.765 0.715 0.844 0.334 0.118 15.1
#> 4 0.658 0.291 0.542 0.327 0.230 0.301 0.177 0.346 0.474 0.283 10.7
#> 5 0.250 0.794 0.383 0.947 0.462 0.00487 0.270 0.114 0.489 0.311 17.6
#> 6 0.300 0.701 0.992 0.386 0.666 0.198 0.924 0.775 0.736 0.974 18.3
#> 7 0.585 0.365 0.283 0.488 0.845 0.466 0.715 0.202 0.905 0.640 14.6
#> 8 0.333 0.552 0.858 0.509 0.697 0.388 0.260 0.355 0.517 0.165 17.0
#> 9 0.622 0.118 0.490 0.390 0.468 0.360 0.572 0.891 0.682 0.717 8.54
#> 10 0.546 0.150 0.476 0.706 0.829 0.373 0.192 0.873 0.456 0.694 15.0
#> # ... with 490 more rows
```

For these data, it should be clear that features  $X_1$ – $X_5$  are the most important! (The others don't influence  $Y$  at all.) Also, based on the form of the model, we'd expect  $X_4$  to be the most important feature, probably followed by  $X_1$  and  $X_2$ , both comparably important, with  $X_5$  probably less important. The influence of  $X_3$  is harder to determine due to its quadratic nature, but it seems likely that this nonlinearity will suppress this variable's influence since the total range of this term is from 0–1, the same as the  $X_5$  term.

## Model-specific VI

Some machine learning algorithms have their own way of quantifying the importance of each feature. We describe some of these in the subsections that follow. The issue with model-specific VI scores is that they are not necessarily comparable across different types of models. For example, directly computing the impurity-based VI scores from tree-based models to the  $t$ -statistic from linear models.

### Trees and tree ensembles

Decision trees probably offer the most natural model-specific approach to quantifying the importance of each feature. In a binary decision tree, at each node  $t$ , a single predictor is used to partition the data into two homogeneous groups. The chosen predictor is the one that maximizes some measure of improvement  $i^t$ . The relative importance of predictor  $X$  is the sum of the squared improvements over all internal nodes of the tree for which  $X$  was chosen as the partitioning variable; see [Breiman et al. \(1984\)](#) for details. This idea also extends to ensembles of decision trees, such as RFs and GBMs. In ensembles, the improvement score for each predictor is averaged across all the trees in the ensemble. Fortunately, due to the stabilizing effect of averaging, the improvement-based VI metric is often more reliable in large ensembles (see [Hastie et al. \(2009, p. 368\)](#)). RFs offer an additional method for computing VI scores. The idea is to use the leftover out-of-bag (OOB) data to construct validation-set errors for each tree. Then, each predictor is randomly shuffled in the OOB data and the error is computed again. The idea is that if variable  $X$  is important, then the validation error will go up when  $X$  is perturbed in the OOB data. The difference in the two errors is recorded for the OOB data then averaged across all trees in the forest. Later on, we'll discuss a more general permutation method that can be applied to any supervised learning model.

To illustrate, we fit a CART-like regression tree, RF, and GBM to the simulated training data. (Note: there are a number of different packages available for fitting these types of models, we just picked popular implementations for illustration.)

```
# Load required packages
library(rpart)          # for fitting CART-like decision trees
library(randomForest)   # for fitting RFs
library(xgboost)        # for fitting GBMs

# Fit a single regression tree
tree <- rpart(y ~ ., data = trn)

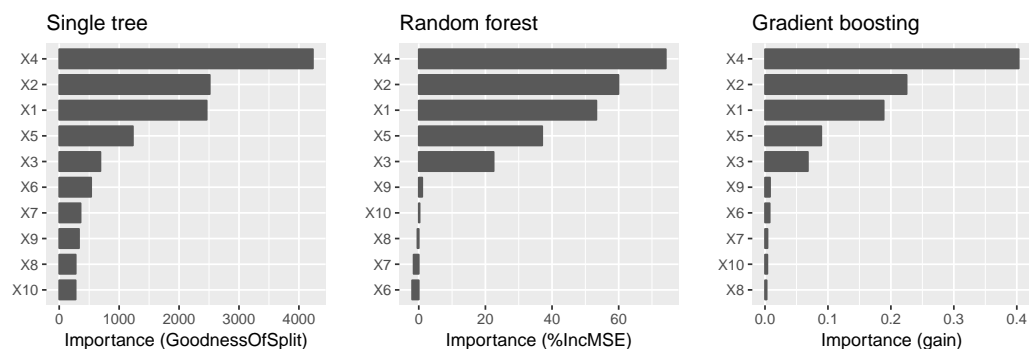
# Fit an RF
set.seed(101)
rfo <- randomForest(y ~ ., data = trn, importance = TRUE)

# Fit a GBM
set.seed(102)
bst <- xgboost(
  data = data.matrix(subset(trn, select = -y)),
  label = trn$y,
  objective = "reg:linear",
  nrounds = 100,
  max_depth = 5,
  eta = 0.3,
  verbose = 0 # suppress printing
)
```

Each of the above packages include the ability to compute VI scores for all the features in the model; however, the implementation is rather package specific, as shown in the code chunk below. The results are displayed in Figure 1 (code to reproduce these plots omitted).

```
# Extract VI scores from each model
vi_tree <- tree$variable.importance
vi_rfo <- rfo$variable.importance
vi_bst <- xgb.importance(model = bst)
```

As we would expect, all three methods rank the variables X1–X5 as more important than the others. While this is good news, it is unfortunate that we have to remember the different functions and ways of extracting and plotting VI scores from various model fitting functions. This is one place where **vip**



**Figure 1:** model-specific VIPs for the three different tree-based models fit to the simulated Friedman data.

can help...one function to rule them all! Once **vip** is loaded, we can use `vi()` to extract a tibble of VI scores.

```
# Load required packages
library(vip)
```

```
# Compute model-specific variable importance
vi(tree) # CART-like decision tree
#> # A tibble: 10 x 2
#>   Variable Importance
#>   <chr>           <dbl>
#> 1 X4             4234.
#> 2 X2             2513.
#> 3 X1             2461.
#> 4 X5             1230.
#> 5 X3              688.
#> 6 X6              533.
#> 7 X7              357.
#> 8 X9              331.
#> 9 X8              276.
#> 10 X10           275.
```

```
vi(rfo) # RF
#> # A tibble: 10 x 2
#>   Variable Importance
#>   <chr>           <dbl>
#> 1 X4              74.2
#> 2 X2              59.9
#> 3 X1              53.3
#> 4 X5              37.1
#> 5 X3              22.5
#> 6 X9               1.05
#> 7 X10             0.254
#> 8 X8             -0.408
#> 9 X7             -1.56
#> 10 X6            -2.00
```

```
vi(bst) # GBM
#> # A tibble: 10 x 2
#>   Variable Importance
#>   <chr>           <dbl>
#> 1 X4             0.403
#> 2 X2             0.225
#> 3 X1             0.189
#> 4 X5             0.0894
#> 5 X3             0.0682
#> 6 X9             0.00802
#> 7 X6             0.00746
```

```
#> 8 X7      0.00400
#> 9 X10     0.00377
#> 10 X8     0.00262
```

Notice how the `vi()` function always returns a tibble with two columns: Variable and Importance (the exception is coefficient-based models which also include a Sign column giving the sign of the corresponding coefficient). Also, by default, `vi()` always orders the VI scores from highest to lowest; this, among other options, can be controlled by the user (see `?vip::vi` for details). Plotting VI scores with `vip()` is just as straightforward. For example, the following code can be used to reproduce Figure 1.

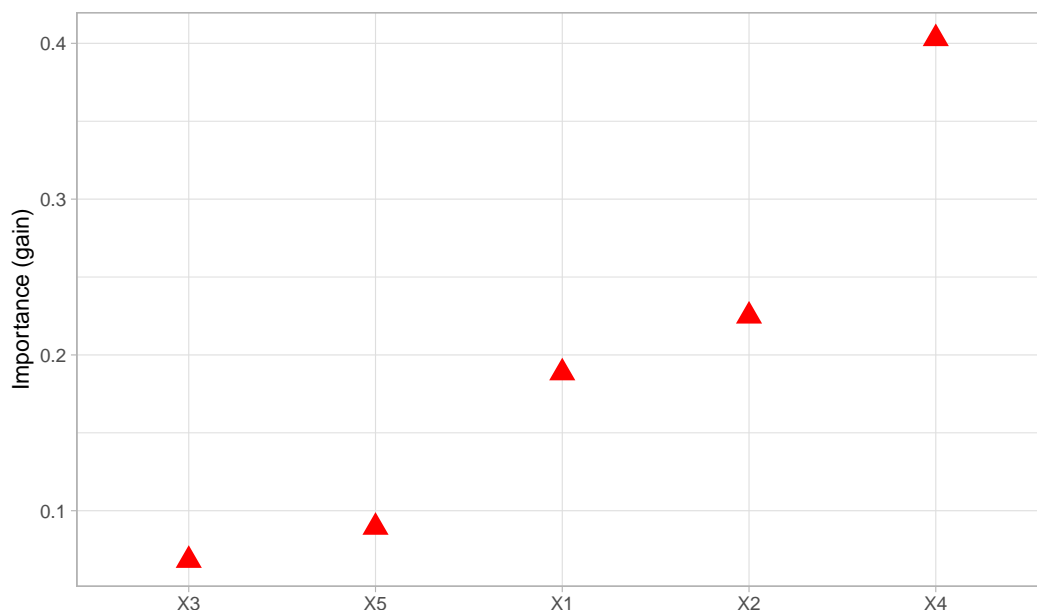
```
p1 <- vip(tree) + ggtitle("Single tree")
p2 <- vip(rfo) + ggtitle("Random forest")
p3 <- vip(bst) + ggtitle("Gradient boosting")
```

```
# Figure 1
grid.arrange(p1, p2, p3, nrow = 1)
```

Notice how the `vip()` function always returns a "ggplot" object (by default, this will be a bar plot). For large models with many features, a dot plot is more effective (in fact, a number of useful plotting options can be fiddled with). Below we call `vip()` and change a few useful options (the resulting plot is displayed in Figure 2).

```
# Load required packages
library(ggplot2) # for theme_light() function

vip(bst, num_features = 5, bar = FALSE, color, horizontal = FALSE,
    color = "red", shape = 17, size = 4) +
  theme_light()
```



**Figure 2:** Illustrating various options available in `vip()`.

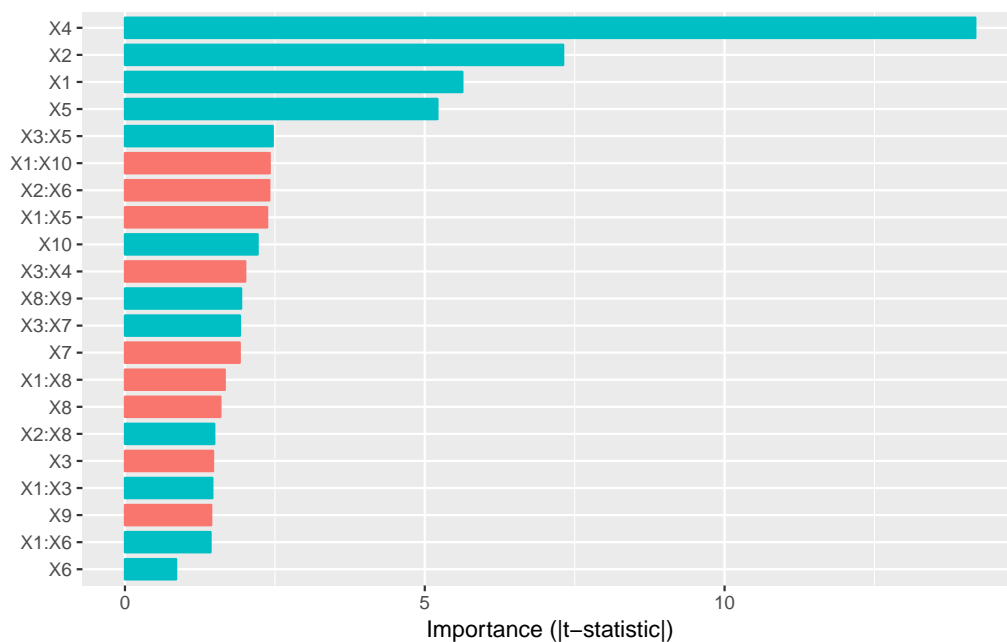
## Linear models

In multiple linear regression, or linear models (LMs), the absolute value of the *t*-statistic (or some other scaled variant of the estimated coefficients) is commonly used as a measure of VI. The same idea also extends to generalized linear models (GLMs). In the code chunk below, we fit an LM to the simulated `trn` data set allowing for all main effects and two-way interactions, then use the `step()` function to perform backward elimination. The resulting VIP is displayed in Figure 3.

```
# Fit a LM
linmod <- lm(y ~ .^2, data = trn)
backward <- step(linmod, direction = "backward", trace = 0)

# Extract VI scores
vi(backward)
#> # A tibble: 21 x 3
#>   Variable Importance Sign
#>   <chr>          <dbl> <chr>
#> 1 X4             14.2 POS
#> 2 X2              7.31 POS
#> 3 X1              5.63 POS
#> 4 X5              5.21 POS
#> 5 X3:X5           2.46 POS
#> 6 X1:X10          2.41 NEG
#> 7 X2:X6           2.41 NEG
#> 8 X1:X5           2.37 NEG
#> 9 X10            2.21 POS
#> 10 X3:X4          2.01 NEG
#> # ... with 11 more rows

# Plot VI scores; by default, `vip()` displays the top ten features
vip(backward, num_features = length(coef(backward)),
    bar = FALSE, horizontal = FALSE)
```



**Figure 3:** Example VIP from a linear model fit to the simulated Friedman data.

One issue with computing VI scores for LMs using the *t*-statistic approach is that a score is assigned to each term in the model, rather than to each individual feature! We can solve this problem using one of the model-agnostic approaches discussed later.

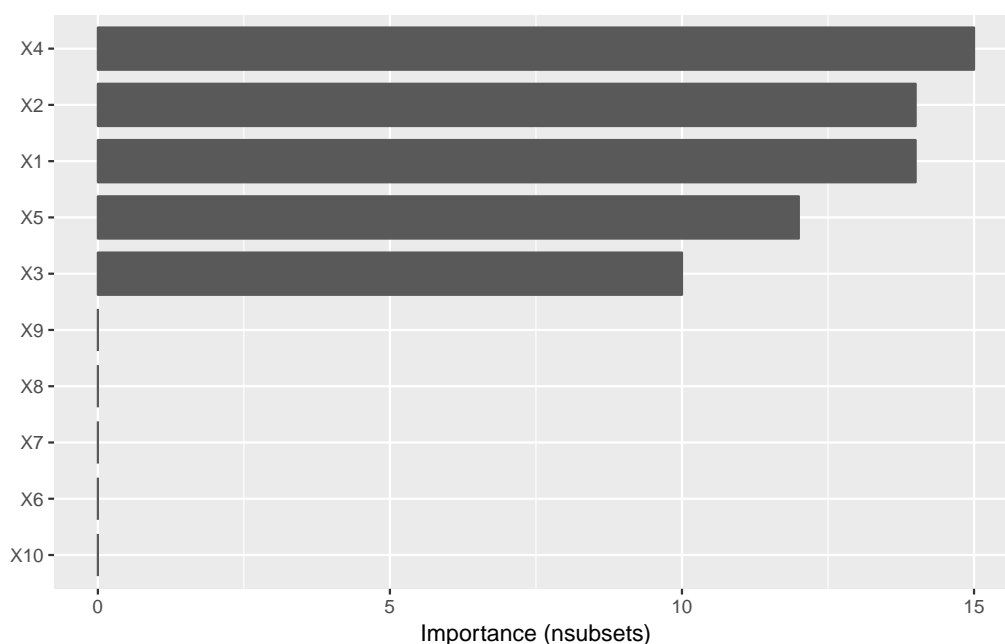
Multivariate adaptive regression splines (MARS), which were introduced in [Friedman \(1991\)](#), is an automatic regression technique and can be seen as a generalization of LMs and GLMs. In the MARS algorithm, the contribution (or VI score) for each predictor is determined using a generalized cross-validation (GCV) statistic (though, other statistics can also be used; see `'?vip::vi_model'` for details). An example using the [earth](#) package ([Milborrow, 2017](#)) is given below (the results are plotted in Figure 5):

```
# Load required packages
library(earth)
```

```
# Fit a MARS model
mars <- earth(y ~ ., data = trn, degree = 2, pmethod = "exhaustive")

# Extract VI scores
vi(mars, type = "gcv")
#> # A tibble: 10 x 2
#>   Variable Importance
#>   <chr>           <dbl>
#> 1 X4             100
#> 2 X1             83.2
#> 3 X2             83.2
#> 4 X5             59.3
#> 5 X3             43.5
#> 6 X6             0
#> 7 X7             0
#> 8 X8             0
#> 9 X9             0
#> 10 X10           0

# Plot VI scores
vip(mars)
```



**Figure 4:** Example VIP from a MARS model fit to the simulated Friedman data.

## Neural networks

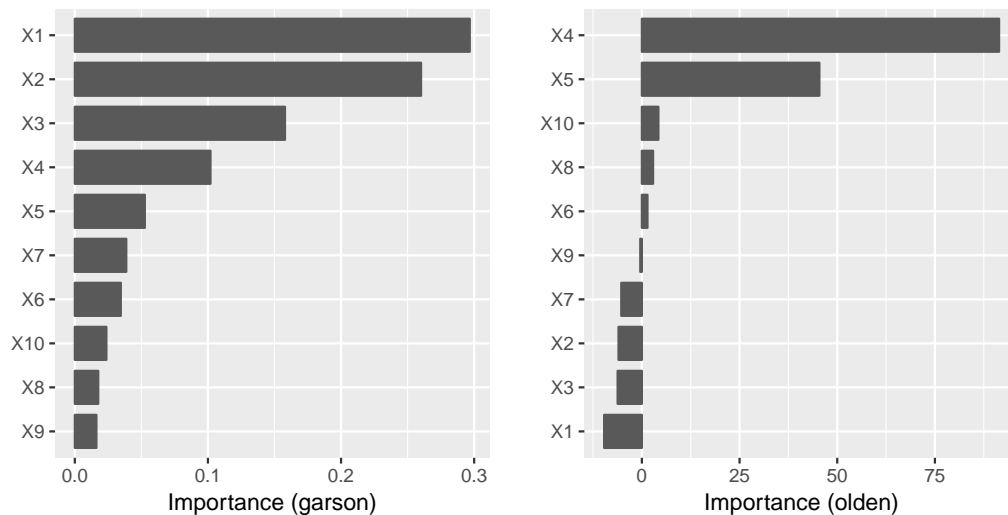
For neural networks (NNs), two popular methods for constructing VI scores are the Garson algorithm (Garson, 1991), later modified by Goh (1995), and the Olden algorithm (Olden et al., 2004). For both algorithms, the basis of these VI scores is the network's connection weights. The Garson algorithm determines VI by identifying all weighted connections between the nodes of interest. Olden's algorithm, on the other hand, uses the product of the raw connection weights between each input and output neuron and sums the product across all hidden neurons. This has been shown to outperform the Garson method in various simulations. For DNNs, a similar method due to Gedeon (1997) considers the weights connecting the input features to the first two hidden layers (for simplicity and speed); but this method can be slow for large networks. We illustrate these two methods below using `vip()` with the `nnet` package (Venables and Ripley, 2002) (see the results in Figure 5).

```
# Load required packages
library(nnet)
```

```
# Fit a neural network
set.seed(0803)
nn <- nnet(y ~ ., data = trn, size = 7, decay = 0.1, linout = TRUE)

# VIPs
p1 <- vip(nn, type = "garson")
p2 <- vip(nn, type = "olden")

# Figure X
grid.arrange(p1, p2, nrow = 1)
```



**Figure 5:** Example VIPs from a single-hidden-layer NN fit to the simulated Friedman data.

## Model-agnostic VI

Model-agnostic interpretability separates interpretation from the model. Compared to model-specific approaches, model-agnostic VI methods are more flexible and can be applied to any supervised learning algorithm. In this section, we discuss model-agnostic methods for quantifying global feature importance using three different approaches: 1) partial dependence plots (PDPs), 2) *individual conditional expectation* (ICE) curves, and 3) permutation-based feature importance. For details on approaches 1)–2), see [Greenwell et al. \(2018\)](#).

### PDP method

Our first model-agnostic approach is based on quantifying the "flatness" of the PDPs of each feature. PDPs help visualize the effect of low cardinality subsets of the feature space on the estimated prediction surface (e.g., main effects and two/three-way interaction effects.). PDPs provide model-agnostic interpretations and can be constructed in the same way for any supervised learning algorithm; for an overview, see [Greenwell \(2017\)](#). Below, we fit a projection pursuit regression (PPR) model and construct PDPs for each feature using the `pdp` package [Greenwell \(2017\)](#). The results are displayed in Figure 6. Notice how the PDPs for the uninformative features are relatively flat compared to the PDPs for features X1–X2!

```
# Load required packages
library(pdp)

# Fit a PPR model (nterms was chosen using the caret package with 5 repeats of
# 5-fold cross-validation)
pp <- ppr(y ~ ., data = trn, nterms = 11)

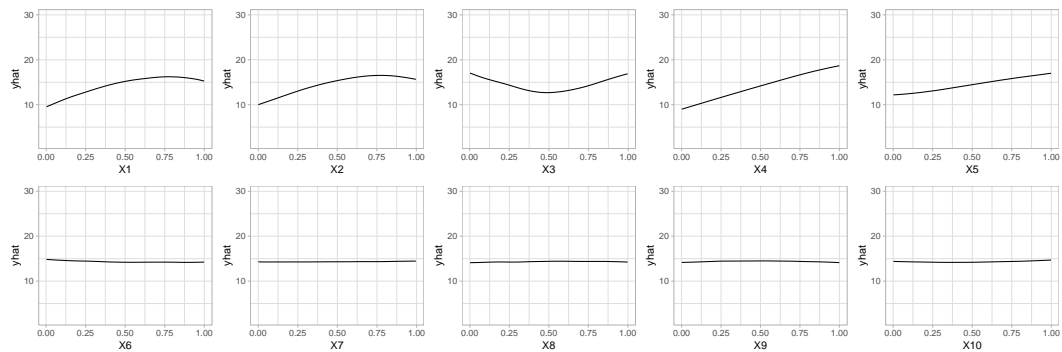
# PDPs for all 10 features
features <- paste0("X", 1:10)
```



```

pdps <- lapply(features, FUN = function(feature) {
  pd <- partial(pp, pred.var = feature)
  autoplot(pd) +
    ylim(range(trn$y)) +
    theme_light()
})
grid.arrange(grobs = pdps, ncol = 5)

```



**Figure 6:** PDPs of main effects in the PPR model fit to the simulated Friedman data.

Next, we compute PDP-based VI scores for the PPR and NN models. The PDP method constructs VI scores that quantify the "flatness" of each PDP (by default, this is defined by computing the standard deviation of the  $y$ -axis values for each PDP). To use the PDP method, specify `method = "pdp"` in the call to `vi()` or `vip()`:

```

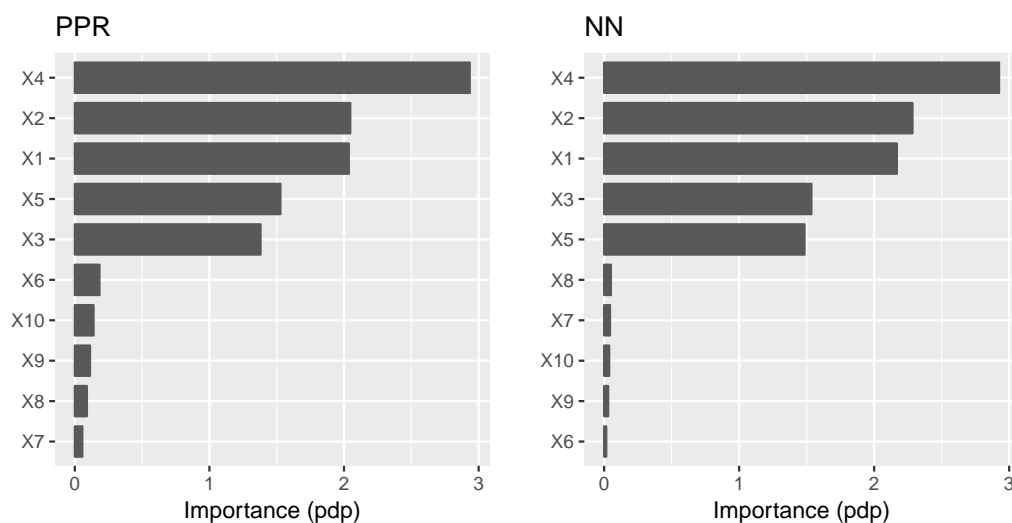
# Fit a PPR model (nterms was chosen using the caret package with 5 repeats of
# 5-fold cross-validation)
pp <- ppr(y ~ ., data = trn, nterms = 11)

# Plot VI scores
p1 <- vip(pp, method = "pdp") + ggtitle("PPR")
p2 <- vip(nn, method = "pdp") + ggtitle("NN")

# Figure X
grid.arrange(p1, p2, ncol = 2)

```

In Figure 7 we display the PDP-based feature importance for the previously obtained PPR and NN models. These VI scores essentially capture the variability in the partial dependence values for each main effect.



**Figure 7:** PDP-based feature importance for the PPR and NN models fit to the simulated Friedman data.

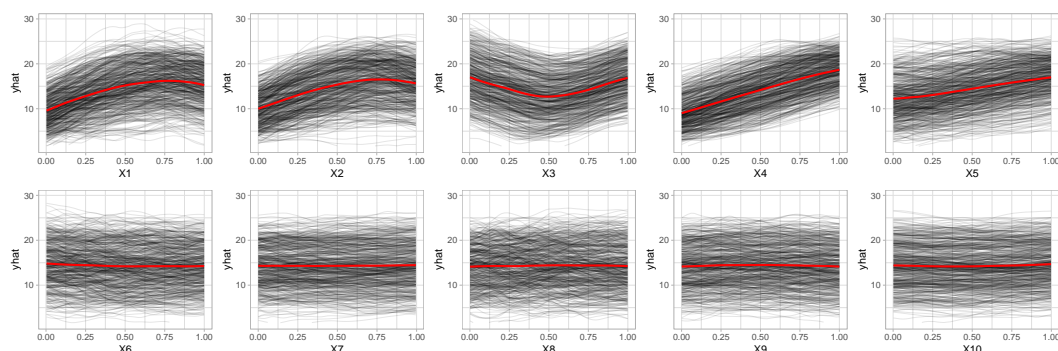
## ICE curve method

The ICE curve method is similar to the PDP method. The only difference is that we measure the "flatness" of each ICE curve and then aggregate the results (e.g., by averaging). If there are no (substantial) interaction effects, using `method = "ice"` will produce results similar to using `method = "pdp"`. However, if strong interaction effects are present, they can obfuscate the main effects and render the PDP-based approach less useful (since the PDPs for important features can be relatively flat when certain interactions are present; see Goldstein et al. (2015) for details). In fact, it is probably safest to always use `method = "ice"`.

Below, we display the ICE curves for each feature in the PPR model using the same  $y$ -axis scale; see Figure 8. Again, there is a clear difference between the ICE curves for features  $X_1$ – $X_5$  and  $X_6$ – $X_{10}$ ; the later being relatively flat by comparison. Also, notice how the ICE curves within each feature are relatively parallel (if the ICE curves within each feature were perfectly parallel, the standard deviation for each curve would be the same and the results will be identical to the PDP method). In this example, the interaction term between  $X_1$  and  $X_2$  does not obfuscate the PDPs for the main effects and the results are not much different.

```
# ICE curves for all 10 features
ice_curves <- lapply(features, FUN = function(feature) {
  ice <- partial(pp, pred.var = feature, ice = TRUE)
  autoplot(ice, alpha = 0.1) +
    ylim(range(trn$y)) +
    theme_light()
})

# Figure X
grid.arrange(grobs = ice_curves, ncol = 5)
```



**Figure 8:** ICE curves for each feature in the PPR model fit to the simulated Friedman data. The red curve represents the PDP (i.e., the averaged ICE curves).

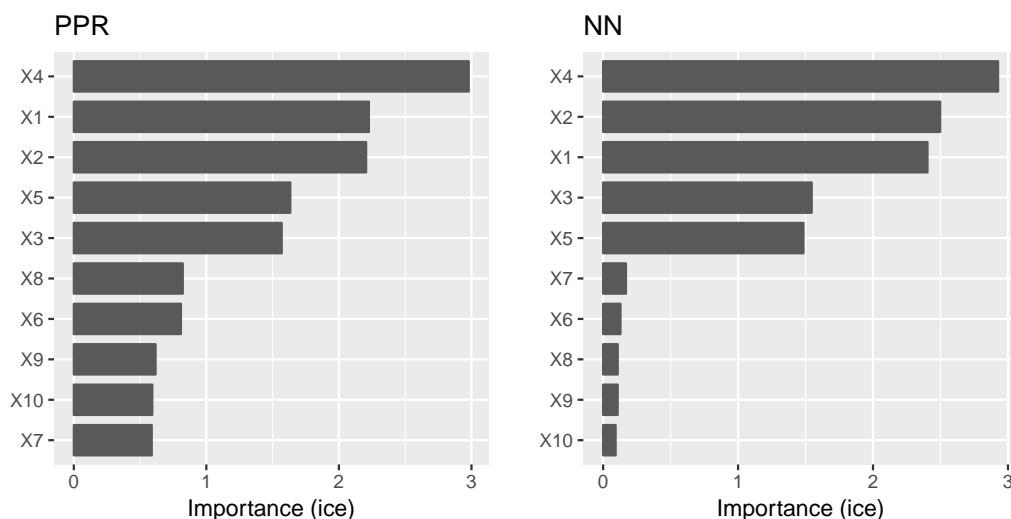
Obtaining the ICE-based feature importance scores is also straightforward. The results in Figure 9 are similar to those obtained using the PDP method.

```
# Plot VI scores
p1 <- vip(pp, method = "ice") + ggtitle("PPR")
p2 <- vip(nn, method = "ice") + ggtitle("NN")

# Figure X
grid.arrange(p1, p2, ncol = 2)
```

When using `method = "pdp"` or `method = "ice"`, the feature effect values are stored as attributes "pdp" and "ice", respectively. This is a convenience so that the feature effect plots (e.g., PDPs and ICE curves) can easily be reconstructed and compared with the VI scores, as demonstrated in the example below (see Figure 10):

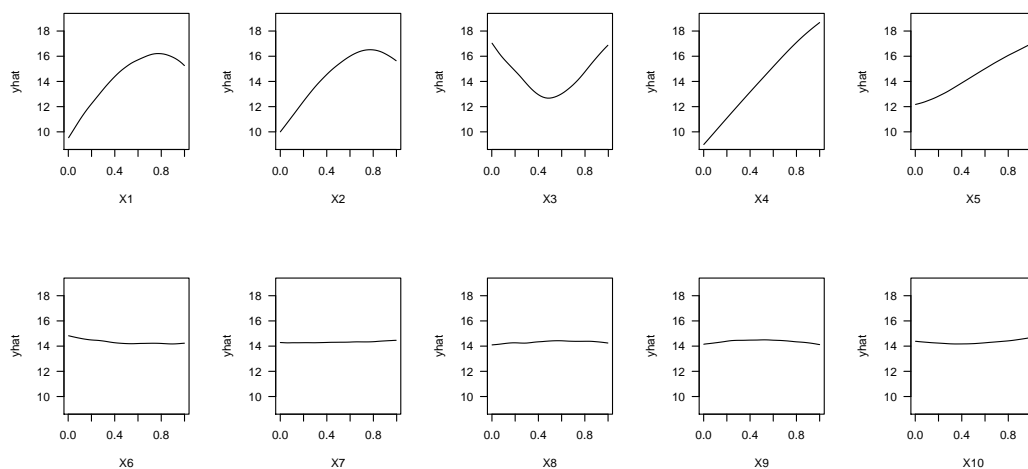
```
# Construct PDP-based variable importance scores
vis <- vi(pp, method = "pdp")
#> Warning message:
#> Setting `method = "pdp"` is experimental, use at your own risk!
vis
```



**Figure 9:** ICE-based feature importance for the PPR and NN models fit to the simulated Friedman data.

```
#> # A tibble: 10 x 2
#>   Variable Importance
#>   <chr>          <dbl>
#> 1 X4             2.93
#> 2 X2             2.05
#> 3 X1             2.04
#> 4 X5             1.53
#> 5 X3             1.38
#> 6 X6             0.183
#> 7 X10            0.139
#> 8 X9             0.113
#> 9 X8             0.0899
#> 10 X7            0.0558
```

```
# Reconstruct PDPs for all 10 features
par(mfrow = c(2, 5))
for (name in paste0("X", 1:10)) {
  plot(attr(vis, which = "pdp")[[name]], type = "l", ylim = c(9, 19), las = 1)
}
```



**Figure 10:** PDPs for all ten features reconstructed from the "pdp" attribute of the vis object.

## Permutation method

The permutation method exists in various forms and was made popular in [Breiman \(2001\)](#) for RFs, before being generalized and extended in [Fisher and Dominici \(2018\)](#). The permutation approach used in **vip** is quite simple and is outlined in Algorithm 1 below. The idea is that if we randomly permute the values of an important feature in the training data, the training performance would degrade (since permuting the values of a feature effectively destroys any relationship between that feature and the target variable). This of course assumes that the model has been properly tuned (e.g., using cross-validation) and is not over fitting. The permutation approach uses the difference between some baseline performance measure (e.g., training  $R^2$ , AUC, or RMSE) and the same performance measure obtained after permuting the values of a particular feature in the training data (**Note:** the model is NOT refit to the training data after randomly permuting the values of a feature). It is also important to note that this method may not be appropriate when you have, for example, highly correlated features (since permuting one feature at a time may lead to unlikely data instances).

Let  $X_1, X_2, \dots, X_j$  be the features of interest and let  $\mathcal{M}_{orig}$  be the baseline performance metric for the trained model; for brevity, we'll assume smaller is better (e.g., classification error or RMSE). The permutation-based importance scores can be computed as follows:

1. For  $i = 1, 2, \dots, j$ :
  - (a) Permute the values of feature  $X_i$  in the training data.
  - (b) Recompute the performance metric on the permuted data  $\mathcal{M}_{perm}$ .
  - (c) Record the difference from baseline using  $imp(X_i) = \mathcal{M}_{perm} - \mathcal{M}_{orig}$ .
2. Return the VI scores  $imp(X_1), imp(X_2), \dots, imp(X_j)$ .

**Algorithm 1:** A simple algorithm for constructing permutation-based VI scores.

Algorithm 1 can be improved or modified in a number of ways. For instance, the process can be repeated several times and the results averaged together. This helps to provide more stable VI measures, and also the opportunity to measure their variability. Rather than taking the difference in step (c), [Molnar \(2019, Chapter 5, Section 5.5.4\)](#) argues that using the ratio  $\mathcal{M}_{perm} / \mathcal{M}_{orig}$  makes the importance scores more comparable across different problems. It's also possible to assign importance scores to groups of features (e.g., by permuting more than one feature at a time); this would be useful if features can be categorized into mutually exclusive groups, for instance, categorical features that have been *one-hot-encoded*.

To use the permutation approach in **vip**, specify `method = "permute"` in the call to `vi()` or `vip()`. Note that using `method = "permute"` requires specifying a few additional arguments (e.g., the training data, target name, etc.); see `?vi_permute` for details.

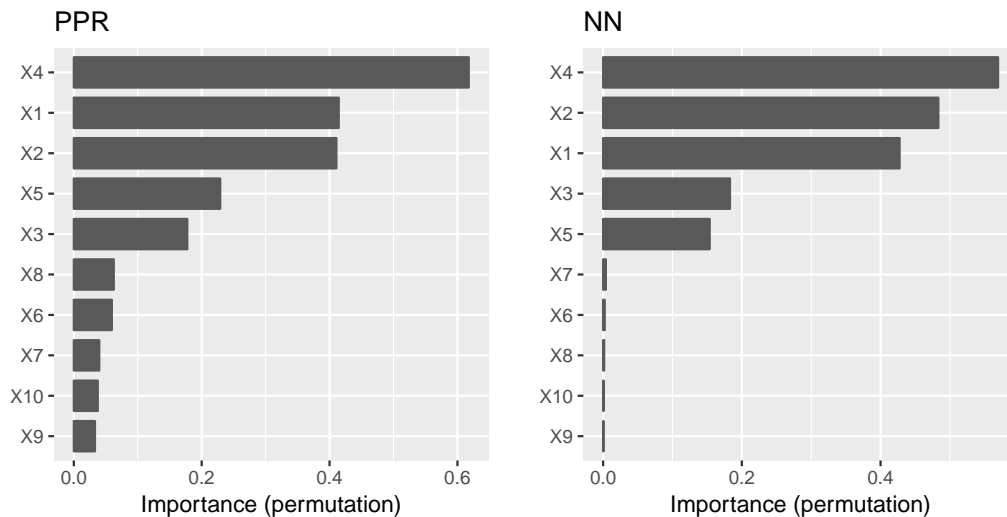
An example is given below for the previously fitted PPR and NN models. Here we use  $R^2$  (metric = "rsquared") as the evaluation metric. The result, which are displayed in Figure 11, agree with those obtained using the PDP- and ICE-based methods.

```
# Plot VI scores
set.seed(2021) # for reproducibility
p1 <- vip(pp, method = "permute", target = "y", metric = "rsquared",
          pred_wrapper = predict) + ggtitle("PPR")
p2 <- vip(nn, method = "permute", target = "y", metric = "rsquared",
          pred_wrapper = predict) + ggtitle("NN")

# Figure X
grid.arrange(p1, p2, ncol = 2)
```

The permutation approach introduces randomness into the procedure and therefore should be run more than once if computationally feasible. Fortunately, this also allows us to compute standard errors for the estimated VI scores, as illustrated in the example below where we specify `nsim = 10` to request that each feature be permuted 10 times and the results averaged together.

```
# A tibble: 10 x 3
#>   Variable Importance StDev
#>   <chr>          <dbl>   <dbl>
#> 1 X4            0.586  0.0188
```



**Figure 11:** Permutation-based feature importance for the PPR and NN models fit to the simulated Friedman data.

```
#> 2 X2      0.416 0.0184
#> 3 X1      0.377 0.0162
#> 4 X5      0.222 0.0155
#> 5 X3      0.183 0.00936
#> 6 X6      0.0620 0.00379
#> 7 X8      0.0603 0.00378
#> 8 X9      0.0389 0.00417
#> 9 X7      0.0373 0.00321
#> 10 X10    0.0348 0.00290
```

All available metrics for regression and classification can be listed using the `list_metrics()` function, for example:

```
#>   Metric      Description      Task
#> 1   auc      Area under (ROC) curve  Binary classification
#> 2   error    Misclassification error  Binary classification
#> 3 logloss      Log loss      Binary classification
#> 4   mauc  Multiclass area under (ROC) curve  Multiclass classification
#> 5 mlogloss    Multiclass log loss  Multiclass classification
#> 6   mse      Mean squared error      Regression
#> 7   r2      R squared      Regression
#> 8 rsquared    R squared      Regression
#> 9   rmse      Root mean squared error  Regression
```

We can also use a custom metric (i.e., loss function). Suppose for example you want to measure importance using the *mean absolute error* (MAE):

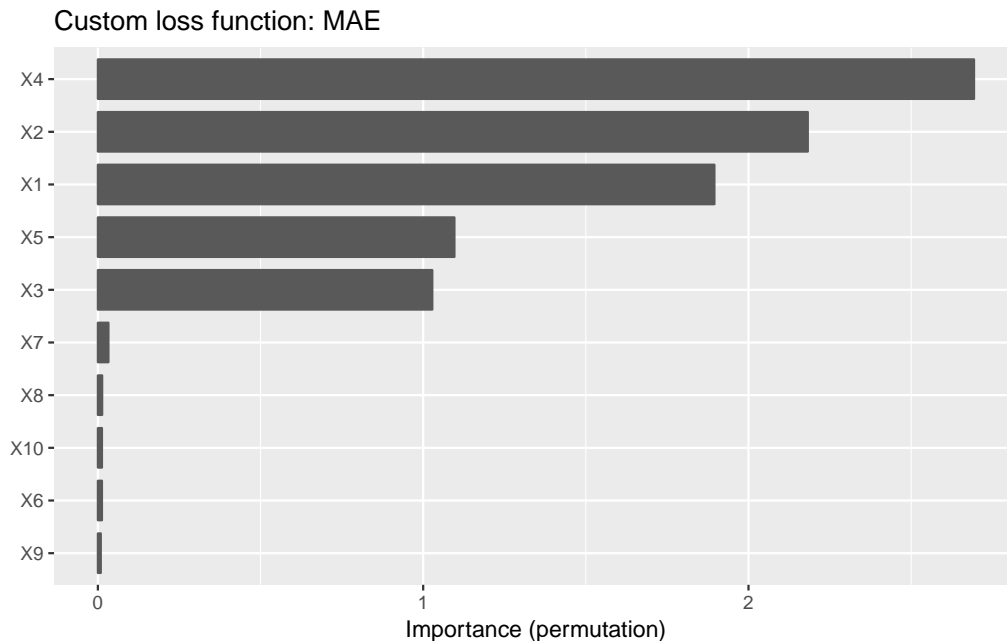
$$MAE = \frac{1}{n} \sum_{i=1}^n |Y_i - \hat{f}(X_i)|, \quad (2)$$

where  $\hat{f}(X_i)$  is the predicted value of  $Y_i$ . A simple function implementing this metric is given below (note that, according to the documentation in `?vi_permute`, this function requires two arguments: actual and predicted).

```
mae <- function(actual, predicted) {
  mean(abs(actual - predicted))
}
```

To use this for computing permutation-based VI scores just pass it to the `metric` argument (be warned, however, that the metric used for computing permutation importance should be the same as the metric used to train and tune the model). Also, since this is a custom metric, we need to specify whether a smaller value indicates better performance by setting `smaller_is_better = TRUE`. The results, which are displayed in Figure 13, are similar to those in Figure 11, albeit a different scale.

```
# Figure X
set.seed(2321) # for reproducibility
vip(nn, method = "permute", target = "y", metric = mae,
    smaller_is_better = TRUE, pred_wrapper = nnet::predict.nnet) +
  ggtitle("Custom loss function: MAE")
```



**Figure 12:** Permutation-based feature importance for the NN model fit to the simulated Friedman data. In this example, permutation importance is based on the MAE metric.

Although permutation importance is most naturally computed on the training data, it may also be useful to do the shuffling and measure performance on new data! This is discussed in depth in [Molnar \(2019\)](#)[Chapter 5, Section 5.2]. For users interested in computing permutation importance using new data, just supply it to the `train` argument in the call to `vi()`, `vip()`, or `vi_permute()`. For instance, suppose we wanted to only use a fraction of the original training data to carry out the computations. In this case, we could simply pass the sampled data to the `train` argument as follows:

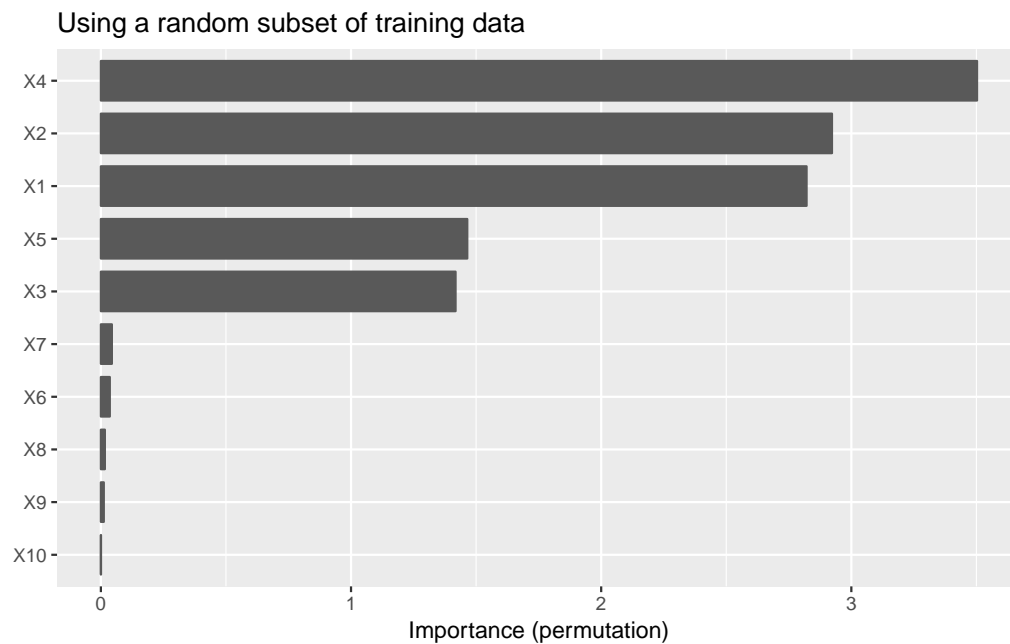
```
# Figure X
set.seed(2327) # for reproducibility
vip(nn, method = "permute",
    train = trn[sample(nrow(trn), size = 400), ], # sample 400 observations
    target = "y", metric = "rmse") +
  ggtitle("Using a random subset of training data")
```

When using the permutation method with `nsim > 1`, the default is to keep all the permutation scores as an attribute called `"raw_scores"`; you can turn this behavior off by setting `keep = FALSE` in the call to `vi_permute()`, `vi()`, or `vip()`. If `keep = TRUE` and `nsim > 1`, you can request all permutation scores to be plotted by setting `all_permutation = TRUE` in the call to `vip()` as demonstrated in the code chunk below (see Figure 13). This lets you visually inspect the variability in the permutation scores within each feature.

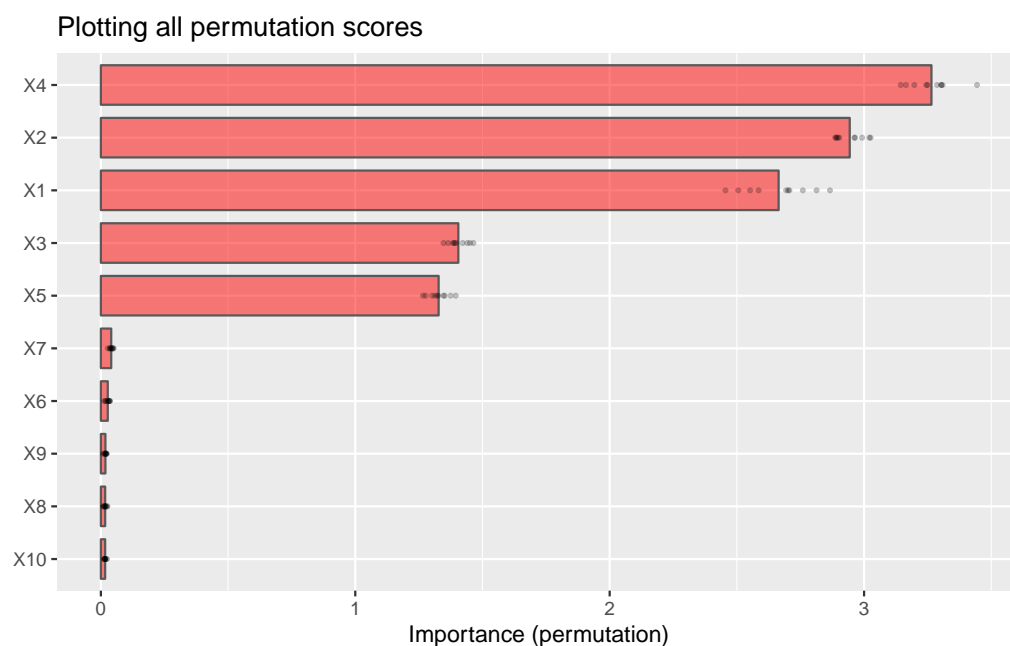
```
# Figure X
set.seed(8264) # for reproducibility
vip(nn, method = "permute", target = "y", metric = "rmse",
    all_permutations = TRUE) +
  ggtitle("Plotting all permutation scores")
```

## Use sparklines to characterize feature effects

Starting with `vip` 0.1.3, we have included a new function `add_sparklines()` for constructing HTML-based VI tables; however, this feature requires the `DT` package ([Xie et al., 2018](#)). The primary difference



**Figure 13:** Permutation-based feature importance for the NN model fit to the simulated Friedman data. In this example, permutation importance is based on a random sample of 400 training observations.



**Figure 14:** Permutation-based feature importance for the NN model fit to the simulated Friedman data. In this example, all the permutation importance scores (points) are displayed for each feature along with their average (bars).

between `vi()` and `add_sparklines()` is that the latter includes an `Effect` column that displays a sparkline representation of the partial dependence function for each feature. This is a concise way to display both feature importance and feature effect information in a single (interactive) table. See `?vip::add_sparklines` for details. We illustrate the basic use of `add_sparklines()` in the code chunks below.

```
# First, compute a tibble of variable importance scores using any method
var_imp <- vi(rfo, method = "permute", metric = "rmse", target = "y")
```

```
# Next, convert to an html-based data table with sparklines
```

```
add_sparklines(var_imp, fit = rfo)
```

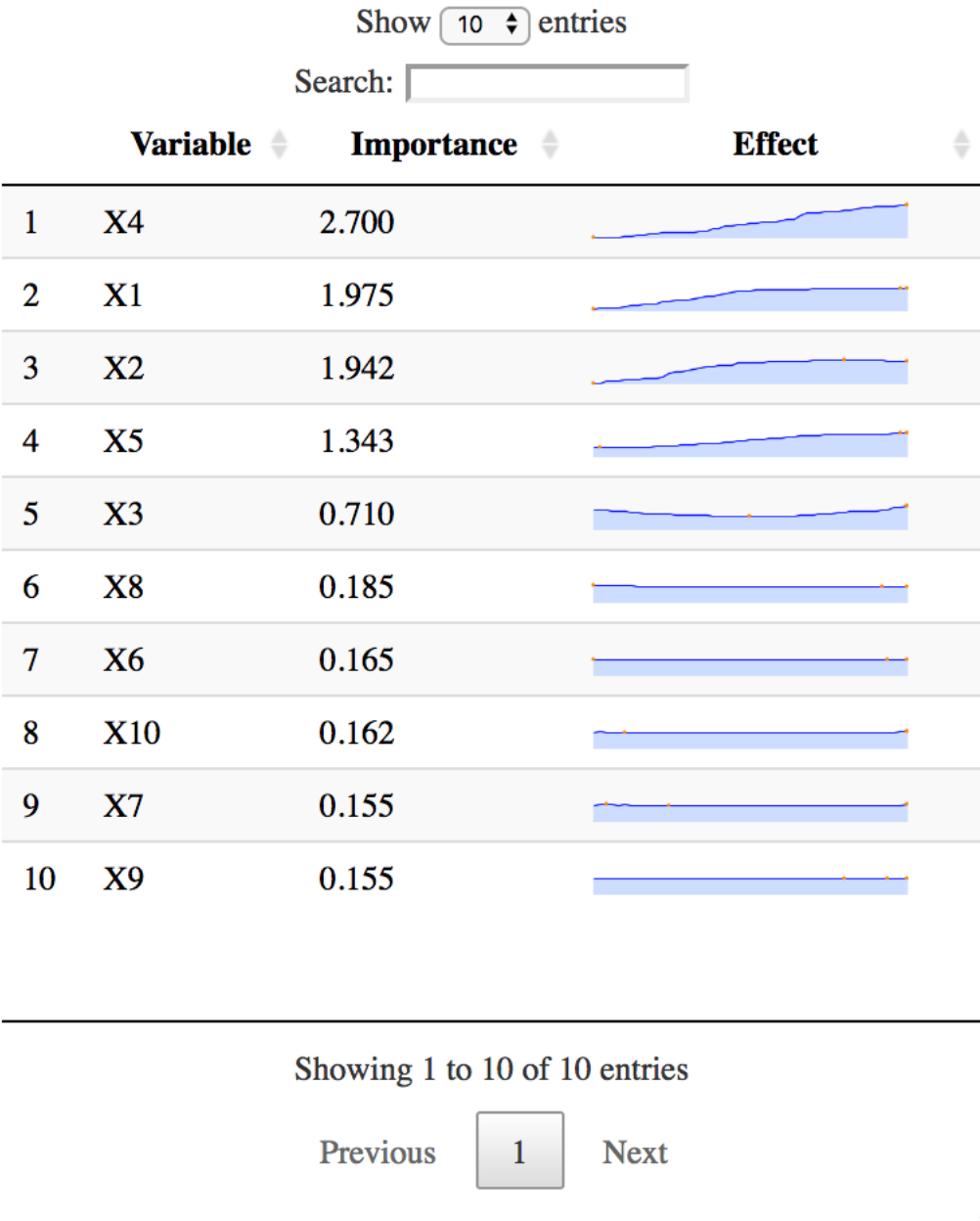


Figure 15: VIP with sparkline representation of feature effects fit to the simulated Friedman data.

Ames housing example

For illustration, we’ll use the Ames housing data set—a more contemporary version of the often cited Boston Housing data set—which are available in the [AmesHousing](#) package (Kuhn, 2017a). These data describe the sale of individual residential properties in Ames, Iowa from 2006–2010. The data set contains 2930 observations, 80 features (23 nominal, 23 ordinal, 14 discrete, and 20 continuous), and a continuous target giving the sale price of the home. The version we’ll load is a cleaned up version of the original data set and treats all categorical variables as nominal (see `?AmesHousing::make_ames` for details).

Using the R package [SuperLearner](#) (Polley et al., 2018), we trained five models using 5-fold cross-validation: a GBM using the [xgboost](#) package (Chen et al., 2017), an RF using the [ranger](#) package (Wright, 2017), a MARS model using the [earth](#) package, a GLMNET model using the [glmnet](#) package (Friedman et al., 2010), and a support vector regression model using the [kernlab](#) package (Karatzoglou



et al., 2004). The coefficients from the meta learner indicate that the GBM contributes the most to new predictions, followed by the MARS model, RF, and the GLMNET. The support vector regression model did not contribute to the ensemble.

```
# Load the Ames housing data
ames <- AmesHousing::make_ames()
X <- subset(ames, select = -Sale_Price)
y <- ames$Sale_Price

# Load required packages
library(SuperLearner)

# List of base learners
learners <- c("SL.xgboost", "SL.ranger", "SL.earth", "SL.glmnet", "SL.ksvm")

# Stack models
set.seed(840)
ctrl <- SuperLearner.CV.control(V = 5L, shuffle = TRUE)
sl <- SuperLearner(Y = y, X = X, SL.library = learners, verbose = TRUE,
                  cvControl = ctrl)

sl
#> Call:
#> SuperLearner(Y = y, X = X, SL.library = learners, verbose = TRUE,
#>   cvControl = ctrl)
#>
#>
#>
#>
#>
#>
```

	Risk	Coef
#> SL.xgboost_All	527111540	0.603160823
#> SL.ranger_All	658707534	0.111650583
#> SL.earth_All	731657510	0.276895806
#> SL.glmnet_All	884821443	0.008292788
#> SL.ksvm All	6782709110	0.000000000

In the code chunks below we request permutation-based VI scores and add sparkline representations of the PDPs for the top ten features. For this we need to define a couple of wrapper functions. One for computing predictions (for the permutation VI scores) and one for computing averaged predictions (for the PDPs):

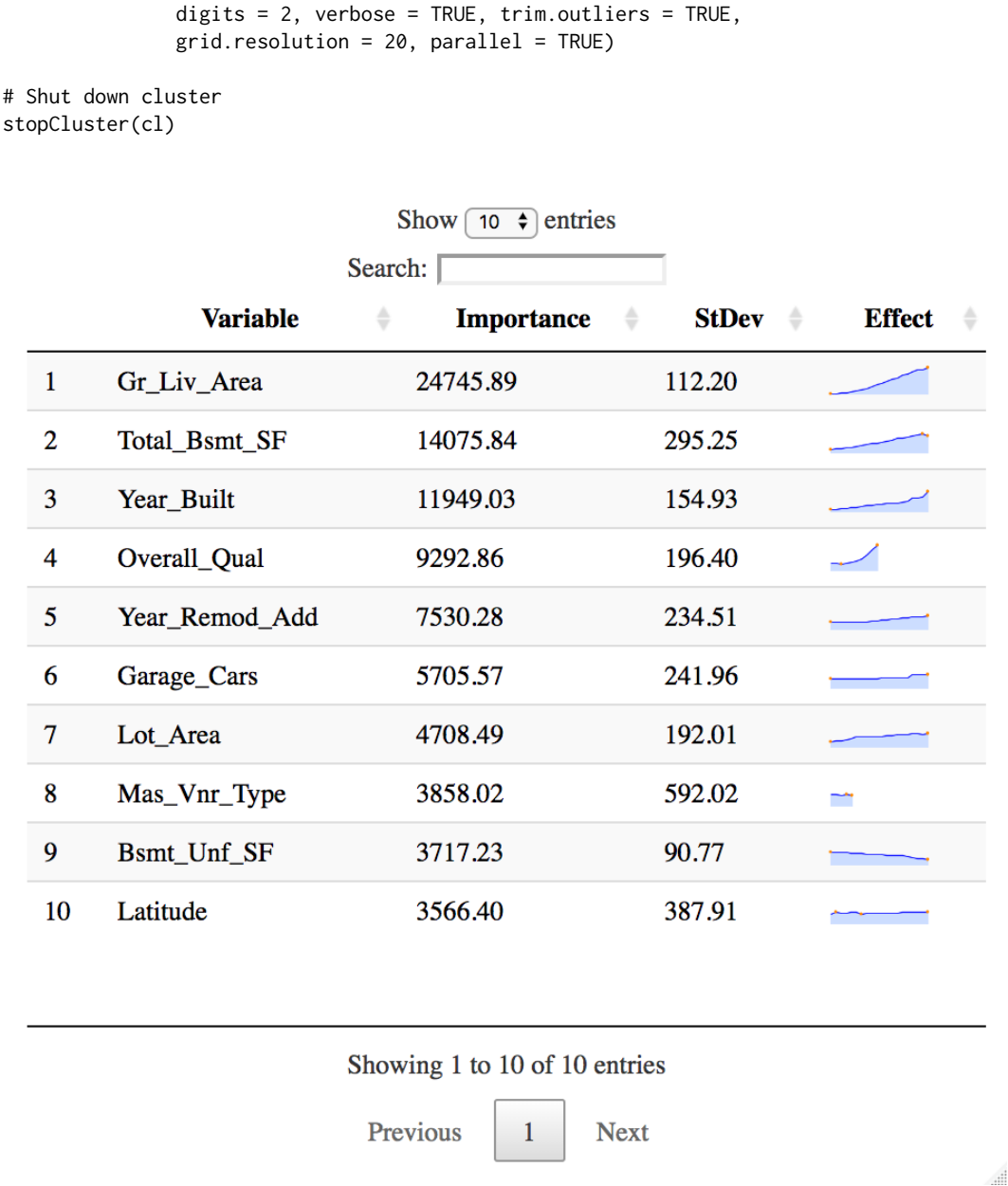
```
# Prediction wrapper functions
imp_fun <- function(object, newdata) { # for permutation-based VI scores
  predict(object, newdata = newdata)$pred
}
par_fun <- function(object, newdata) { # for PDPs
  mean(predict(object, newdata = newdata)$pred)
}
```

To speed up the process, we perform the computations in parallel by setting `parallel = TRUE` in the call to `vi()` and `add_sparklines()`. Note that we first need to set up a parallel backend for this to work. Both **vip** and **pdp** use **plyr** (Wickham, 2011)—which relies on **foreach** (Revolution Analytics and Weston, 2015b)—so any parallel backend supported by the **foreach** package should work. Below we use a **socket** approach with the **doParallel** backend (Revolution Analytics and Weston, 2015a) using a cluster of size five.

```
# Setup parallel backend
library(doParallel) # load the parallel backend
cl <- makeCluster(5) # use 5 workers
registerDoParallel(cl) # register the parallel backend

# Permutation-based feature importance
set.seed(278)
var_imp <- vi(s1, method = "permute", train = X, target = y, metric = "rmse",
             pred_wrapper = imp_fun, nsim = 5, parallel = TRUE)

# Add sparkline representation of feature effects
add_sparklines(var_imp[1L:10L, ], fit = s1, pred.fun = par_fun, train = X,
```



**Figure 16:** VIP with sparkline representation of feature effects for the top ten features from a Super Learner fit to the Ames housing data.

Summary

VIPs help to visualize the strength of the relationship between each feature and the response, while accounting for all the other features in the model. We’ve discussed two types of VI: model-specific and model-agnostic, as well as some of their strengths and weaknesses. In this paper, we showed how to construct VIPs for various types of “black box” models in R using the `vip` package. We also briefly discussed related approaches available in other R packages. Suggestions to avoid high execution times were discussed and demonstrated via examples. This paper is based on `vip` version 0.2.0. For updates that have occurred since then, see the package’s [NEWS file](#). In terms of future development, `vip` can be expanded in a number of ways. For example, we plan to allow group-based permutation scores in the near future. Although not discussed in this paper, the package also includes a promising statistic (similar to the PDP- and ICE-based VI scores previously discussed) for measuring the relative strength of interaction between features.

## Acknowledgments

TBD.

## Bibliography

- P. Biecek. Dalex: Explainers for complex predictive models in r. *Journal of Machine Learning Research*, 19(84):1–5, 2018. URL <http://jmlr.org/papers/v19/18-416.html>. [p1]
- B. Bischl, M. Lang, L. Kotthoff, J. Schiffner, J. Richter, E. Studerus, G. Casalicchio, and Z. M. Jones. mlr: Machine learning in r. *Journal of Machine Learning Research*, 17(170):1–5, 2016. URL <http://jmlr.org/papers/v17/15-066.html>. [p1]
- L. Breiman. Bagging predictors. *Machine Learning*, 8(2):209–218, 1996. URL <https://doi.org/10.1023/A:1018054314350>. [p2]
- L. Breiman. Random forests. *Machine Learning*, 45(1):5–32, 2001. URL <https://doi.org/10.1023/A:1010933404324>. [p12]
- L. Breiman, J. Friedman, and R. A. O. Charles J. Stone. *Classification and Regression Trees*. The Wadsworth and Brooks-Cole statistics-probability series. Taylor & Francis, 1984. ISBN 9780412048418. [p3]
- W. Chang. R6: Encapsulated Classes with Reference Semantics, 2019. URL <https://CRAN.R-project.org/package=R6>. R package version 2.4.0. [p1]
- T. Chen, T. He, and M. Benesty. xgboost: Extreme Gradient Boosting, 2017. URL <https://CRAN.R-project.org/package=xgboost>. R package version 0.6-4. [p16]
- W. S. Cleveland. Robust locally weighted regression and smoothing scatterplots. *Journal of the American Statistical Association*, 74(368):829–836, 1979. doi: 10.1080/01621459.1979.10481038. [p1]
- R. C. Fisher, A. and F. Dominici. Model class reliance: Variable importance measures for any machine learning model class, from the "rashomon" perspective. *arXiv preprint arXiv:1801.01489*, 2018. [p12]
- J. Friedman, T. Hastie, and R. Tibshirani. Regularization paths for generalized linear models via coordinate descent. *Journal of Statistical Software*, 33(1):1–22, 2010. URL <http://www.jstatsoft.org/v33/i01/>. [p16]
- J. H. Friedman. Multivariate adaptive regression splines. *The Annals of Statistics*, 19(1):1–67, 1991. URL <https://doi.org/10.1214/aos/1176347963>. [p2, 6]
- D. G. Garson. Interpreting neural-network connection weights. *Artificial Intelligence Expert*, 6(4):46–51, 1991. [p7]
- T. Gedeon. Data mining of inputs: Analysing magnitude and functional measures. *International Journal of Neural Systems*, 24(2):123–140, 1997. URL <https://doi.org/10.1007/s10994-006-6226-1>. [p7]
- A. Goh. Back-propagation neural networks for modeling complex systems. *Artificial Intelligence in Engineering*, 9(3):143–151, 1995. doi: [http://dx.doi.org/10.1016/0954-1810\(94\)00011-S](http://dx.doi.org/10.1016/0954-1810(94)00011-S). [p7]
- A. Goldstein, A. Kapelner, J. Bleich, and E. Pitkin. Peeking inside the black box: Visualizing statistical learning with plots of individual conditional expectation. *Journal of Computational and Graphical Statistics*, 24(1):44–65, 2015. URL <https://doi.org/10.1080/10618600.2014.907095>. [p10]
- B. Greenwell and B. Boehmke. vip: Variable Importance Plots, 2018. URL <https://CRAN.R-project.org/package=vip>. R package version 0.1.0. [p2]
- B. M. Greenwell. pdp: An r package for constructing partial dependence plots. *The R Journal*, 9(1): 421–436, 2017. URL <https://journal.r-project.org/archive/2017/RJ-2017-016/index.html>. [p8]
- B. M. Greenwell, B. C. Boehmke, and A. J. McCarthy. A simple and effective model-based variable importance measure. *arXiv preprint arXiv:1805.04755*, 2018. [p2, 8]
- T. Hastie, R. Tibshirani, and J. Friedman. *The Elements of Statistical Learning: Data Mining, Inference, and Prediction, Second Edition*. Springer Series in Statistics. Springer-Verlag, 2009. [p3]

- A. Karatzoglou, A. Smola, K. Hornik, and A. Zeileis. Kernlab – an S4 package for kernel methods in R. *Journal of Statistical Software*, 11(9):1–20, 2004. URL <https://doi.org/10.18637/jss.v011.i09>. [p16]
- M. Kuhn. *AmesHousing: The Ames Iowa Housing Data*, 2017a. URL <https://CRAN.R-project.org/package=AmesHousing>. R package version 0.0.3. [p16]
- M. Kuhn. *caret: Classification and Regression Training*, 2017b. URL <https://CRAN.R-project.org/package=caret>. R package version 6.0-76. [p1]
- M. Kuhn and K. Johnson. *Applied Predictive Modeling*. SpringerLink : Bücher. Springer New York, 2013. ISBN 9781461468493. [p1]
- F. Leisch and E. Dimitriadou. *mlbench: Machine Learning Benchmark Problems*, 2012. URL <https://CRAN.R-project.org/package=mlbench>. R package version 2.1-1. [p2]
- S. Milborrow. *earth: Multivariate Adaptive Regression Splines*, 2017. URL <https://CRAN.R-project.org/package=earth>. R package version 4.5.0. [p6]
- C. Molnar. *Interpretable Machine Learning*. 2019. <https://christophm.github.io/interpretable-ml-book/>. [p1, 12, 14]
- C. Molnar, B. Bischl, and G. Casalicchio. iml: An r package for interpretable machine learning. *JOSS*, 3(26):786, 2018. doi: 10.21105/joss.00786. URL <http://joss.theoj.org/papers/10.21105/joss.00786>. [p1]
- K. Müller and H. Wickham. *tibble: Simple Data Frames*, 2019. URL <https://CRAN.R-project.org/package=tibble>. R package version 2.1.1. [p2]
- J. D. Olden, M. K. Joy, and R. G. Death. An accurate comparison of methods for quantifying variable importance in artificial neural networks using simulated data. *Ecological Modelling*, 178(3):389–397, 2004. doi: <http://dx.doi.org/10.1016/j.ecolmodel.2004.03.013>. [p7]
- E. Polley, E. LeDell, C. Kennedy, and M. van der Laan. *SuperLearner: Super Learner Prediction*, 2018. URL <https://CRAN.R-project.org/package=SuperLearner>. R package version 2.0-24. [p16]
- Revolution Analytics and S. Weston. *doParallel: Foreach Parallel Adaptor for the ‘parallel’ Package*, 2015a. URL <https://CRAN.R-project.org/package=doParallel>. R package version 1.0.10. [p17]
- Revolution Analytics and S. Weston. *foreach: Provides Foreach Looping Construct for R*, 2015b. URL <https://CRAN.R-project.org/package=foreach>. R package version 1.4.3. [p17]
- G. Ridgeway. *gbm: Generalized Boosted Regression Models*, 2017. URL <https://CRAN.R-project.org/package=gbm>. R package version 2.1.3. [p1]
- W. N. Venables and B. D. Ripley. *Modern Applied Statistics with S*. Springer, New York, fourth edition, 2002. URL <http://www.stats.ox.ac.uk/pub/MASS4>. ISBN 0-387-95457-0. [p7]
- H. Wickham. The split-apply-combine strategy for data analysis. *Journal of Statistical Software*, 40(1): 1–29, 2011. URL <https://doi.org/10.18637/jss.v040.i01>. [p17]
- H. Wickham. *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York, 2016. ISBN 978-3-319-24277-4. URL <https://ggplot2.tidyverse.org>. [p2]
- M. N. Wright. *ranger: A Fast Implementation of Random Forests*, 2017. URL <https://CRAN.R-project.org/package=ranger>. R package version 0.7.0. [p16]
- Y. Xie, J. Cheng, and X. Tan. *DT: A Wrapper of the JavaScript Library ‘DataTables’*, 2018. URL <https://CRAN.R-project.org/package=DT>. R package version 0.5. [p14]

Brandon M. Greenwell  
 Department of Mathematics and Statistics  
 Wright State University  
 3640 Colonel Glenn Hwy  
 Dayton, OH 45435  
 United States of America  
 ORCID: 0000-0002-8120-0084  
[greenwell.brandon@gmail.com](mailto:greenwell.brandon@gmail.com)

*Bradley C. Boehmke*  
*University of Cincinnati*  
*2925 Campus Green Dr*  
*Cincinnati, OH 45221*  
*United States of America*  
ORCID: [0000-0002-3611-8516](https://orcid.org/0000-0002-3611-8516)  
[bradleyboehmke@gmail.com](mailto:bradleyboehmke@gmail.com)