"Missing Is Useful": Missing Values in Cost-Sensitive Decision Trees

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Abstract—Many real-world data sets for machine learning and data mining contain missing values and much previous research regards it as a problem and attempts to impute missing values before training and testing. In this paper, we study this issue in cost-sensitive learning that considers both test costs and misclassification costs. If some attributes (tests) are too expensive in obtaining their values, it would be more cost-effective to miss out their values, similar to skipping expensive and risky tests (missing values) in patient diagnosis (classification). That is, "missing is useful" as missing values actually reduces the total cost of tests and misclassifications and, therefore, it is not meaningful to impute their values. We discuss and compare several strategies that utilize only known values and that "missing is useful" for cost reduction in cost-sensitive decision tree learning.

Index Terms—Induction, knowledge acquisition, machine learning.

1 Introduction

Machine learning and data mining reply heavily on a large amount of data to build learning models and make predictions and, thus, the quality of data is ultimately important. Though there is no formal measure on the quality of data, it can be intuitively quantified by the inclusion of relevant attributes, the errors in attribute values, and the amount of missing values in data sets. This paper studies the issue of missing attribute values in training and test data sets.

Indeed, many real-world data sets contains missing values and it is often regarded as a difficult problem to cope with. Sometimes, values are missing due to unknown reasons or errors and omissions when data are recorded and transferred. As many statistical and learning methods cannot deal with missing values directly, examples with missing values are often deleted. However, deleting cases can result in the loss of a large amount of valuable data. Thus, much previous research has focused on filling or imputing the missing values before learning and testing is applied to.

In this paper, we study missing data in cost-sensitive learning in which both misclassification costs and test costs are considered. That is, there is a known cost associated with each attribute (variable or test) when obtaining its values. This is true in most real-world applications where it costs money to obtain new information. For example, in medical diagnosis, it costs money (to the patient, lab, or health insurance) to request blood tests, X-rays, or other types of tests, some of which can be quite expensive and even risky to patient life (which can also be converted to cost). Doctors often have to balance the cost effectiveness of the tests and the accuracy of the diagnosis (prediction) to decide what tests should be performed. That is, if a test is too expensive compared to the potential reduction in misclassification cost, it is desirable to skip the test. In other words, if the goal is to minimize the total cost of tests and misclassifications, some attribute values *should* be missing and doctors did not need to know the missing values in their diagnosis (prediction or classification).

Thus, cost-sensitive learning algorithms should make use of only known values. Of course, the learners may not know exactly how the known values were acquired—were all of them necessary for prediction? In any case, we can assume that the known values may be useful for prediction, but the unknown values are certainly not. Thus, under cost-sensitive learning, there is no need to impute values of any missing data and the learning algorithms should make use of only known values and that "missing is useful" to minimize the total cost of tests and misclassifications.

The rest of the paper is organized as follows: In Section 2, we review previous techniques for dealing with missing values and a recent cost-sensitive decision tree algorithm based on which we will discuss our missing-value strategies. We will discuss and compare four missing-value strategies that utilize only known data in Section 3. We experimentally compare the four strategies using real-world data sets in Section 4. Our conclusions and future work occupy Section 5.

2 Review of Previous Work

The issue of missing values (or missing data) has been studied extensively in the statistical and machine learning literature. According to the missing data mechanisms, statisticians have identified three classes of missing data [16]: *missing completely at random (MCAR)*, *missing at random (MCR)*, and *not missing at random (NMAR)*. MCAR is when the probability of missing a value is the same for all variables, MCR is when the probability of missing a value is only dependent on other variables, and NMAR is when the probability of missing a value is also dependent on the

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value of the missing variable. MCR has received the most attentions, for which various "imputation" methods have been designed to predict the missing values before building models. In machine learning, the missing value issue has been dealt with mostly in decision tree learning and rule learning. Various imputation methods have also been tried, such as imputation by the most common value [6], clustering [7], and other learning models [2]. In C4.5 [19], [20], a different approach is used in which a test example with missing values is distributed into branches probabilistically (see Section 3.4). A comparison of various imputation methods has also been published [15]. The approaches we discuss in this paper do not impute any missing values as it is regarded as unnecessary for cost-sensitive learning that also considers the test costs.

This paper deals with missing values in cost-sensitive learning. Turney [22] presents an excellent survey on different types of costs in cost-sensitive learning, among which misclassification costs and test costs are singled out as most important. Much work has been done in recent years on nonuniform misclassification costs (alone), such as [9], [10], [14]. Some previous work, such as [18], [21], considers the test cost alone without incorporating misclassification cost, which is obviously an oversight. A few researchers [5], [13], [23], [24] consider both misclassification and test costs, but their methods are less computationally efficient as our approach is based on decision trees. Ling et al. [17] propose a decision-tree learning algorithm that uses minimum total cost of tests and misclassifications as the attribute split criterion and it is the basis of the four missing-value strategies to be presented in Section 3. Basically, given a set of training examples, the total cost without further splitting and the total cost after splitting on an attribute can be calculated and the difference of the two is called cost reduction. The attribute with the maximum, positive cost reduction is chosen for growing the tree. All examples with missing values of an attribute stay at the internal node of that attribute. The method produces decision trees with minimal total cost of tests and misclassifications on the training data [17].

In the next section, we will discuss several different missing-value strategies, all of which use the maximum cost reduction strategy described above to build cost-sensitive decision trees.

3 Dealing with Missing Values in Cost-Sensitive Decision Trees

As we discussed in Section 1, in cost-sensitive learning which attempts to minimize the total cost of tests and misclassifications, missing data can be useful for cost reduction and imputing missing values should be unnecessary. Thus, cost-sensitive decision tree learning algorithms should utilize only known values. In the following sections, we will describe four such missing-value techniques. These strategies have been proposed previously, but their performance in cost-sensitive learning has not been studied. In Section 4, we will perform empirical experiments to compare the four strategies on real-world data sets by the total cost.

3.1 The Known Value Strategy

The first tree building and test strategy for "missing is useful" is called the Known Value Strategy. It utilizes only the known attribute values in the tree building for each test example. For each test example, a new (and probably different) decision tree is built from the training examples with only those attributes whose values are known in the test example. That is, the new decision tree only uses attributes with known values in the test example and, thus, when the tree classifies the test example, it will never encounter any missing values.

The Known Value Strategy was proposed in [17], but its ability to handle unknown values was not studied. Clearly, the strategy utilizes all known attributes and avoids any missing data directly. It is a lazy tree method [12] where a tree is built during test process. The main drawback of the Known Value Strategy is its relatively high computation cost as different trees may be built for different test examples. This is usually not a problem as the tree building process is very efficient. In addition, we can save frequent trees and use them directly in testing for test examples with the same subsets of known attributes because decision trees for the same subsets of known attributes are the same. We can use space to trade off the speed, if necessary.

3.2 The Null Strategy

As values are missing for a certain reason—unnecessary and too expensive to test—it might be a good idea to assign a special value, often called "null" in databases [8], to missing data. The null value is then treated just as a regular known value in the tree building and test processes. This strategy has also been proposed in machine learning [1], but its ability in cost-sensitive learning has not been studied.

One potential problem with the Null Strategy is that it does not deliberately utilize the original known values as missing values are treated as equally as a known value. Another potential drawback is that there might be more than one situation where values are missing. Replacing all missing values by one value (null) may not be adequate. In addition, subtrees can be built under the "null" branch, oddly suggesting that the unknown is more discriminating than the known values. The advantage of this strategy is its simplicity and high efficiency compared to the Known Value Strategy as only one decision tree is built for all test examples.

3.3 The Internal Node Strategy

This strategy, as proposed in [17] and reviewed in Section 2, keeps examples with missing values in internal nodes and does not build branches for them during tree building. When classifying a test example, if the tree encounters an attribute whose value is unknown, then the class probability of training examples falling at the internal node is used to classify it. As unknown values are dealt with by internal nodes, we call this strategy the Internal Node Strategy.

As there might be several different situations where values are missing, leaving the classification to the internal nodes may be a natural choice. This strategy is also quite efficient as only one tree is built for all test examples.

3.4 The C4.5 Strategy

C4.5 [19], [20] does not impute missing values explicitly and it is shown to be quite effective [4]. Here, C4.5's missing-value strategy is applied directly in cost-sensitive trees. During training, an attribute is chosen by the maximum cost reduction discounted by the probability of missing values of that attribute. During testing, a test example with missing value is split into branches according to the portions of training examples falling into those branches and goes down to leaves simultaneously. The class of the test example is the weighted classification of all leaves.

TABLE 1
Data Sets Used in the Experiments

	No. of Attributes	No. of Examples	Class distribution (N/P)
Ecoli	6	332	230/102
Breast	9	683	444/239
Heart	8	161	98/163
Thyroid	24	2000	1762/238
Australia	15	653	296/357

4 Experiment Comparisons

In this section, we will compare the four missing-value strategies discussed in Section 3. We start with a description of the data sets used in the experiments.

4.1 Data Sets

We choose five real-world data sets from the UCI Machine Learning Repository [3] and compare the four missing-value strategies discussed earlier. These data sets are chosen because they have at least some discrete attributes, binary class, and a good number of examples. The original data sets have only a few missing values and we will select values to be missing (see later) to simulate different situations with missing values. The numerical attributes in the data sets are first discretized using the minimal entropy method [11] as the cost-sensitive decision tree learning can currently only deal with discrete attributes. This limitation can be moved easily. The data sets are listed in Table 1.

The five original data sets do not have test costs and misclassification costs, so we simply make assumptions on the costs. We assume that test costs and misclassification costs are based on the same unit, such as US dollars. We randomly assign random numbers between 0 and 100 to each attribute as test costs. We also assign 200 for false positive and 600 for false negative misclassification costs. The cost of true positives and true negatives is set to 0. These assumptions are reasonable as attributes do have some costs in the real world and we compare the four missing-value strategies based on the same test and misclassification costs.

4.2 Comparing the Four Missing-Value Strategies

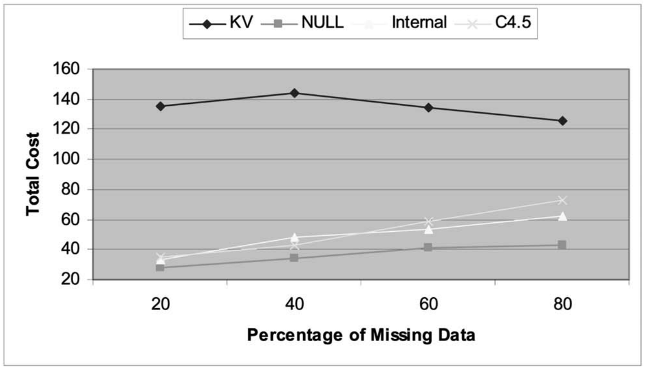
To simulate missing values in data sets, we randomly select certain percentages (20 percent, 40 percent, 60 percent, and 80 percent) of attribute values in the whole data set to be missing and those missing values are distributed into each attribute proportional to its cost as more expensive attributes usually have more missing values. Each data set is then split into training and test sets using 10-fold cross validation (thus, test sets also have the same percentages of missing values). For each split, a decision tree is built from the training data set and is applied to the test examples using the Null Strategy, the Internal Node Strategy, and the C4.5 Strategy. For the Know Value Strategy, a lazy tree is built for each test example.

The performance of the four missing-value strategies is measured by the average total cost of tests and misclassifications of test examples in the 10-fold cross-validation. Here, the test cost is the total cost of the tests (attributes) in actually classifying test examples. That is, it is the “effective” test cost, not the sum of test costs of known attributes in test examples. As we discussed in Section 1, some tests may be unnecessary for prediction, as doctors may subscribe more tests than needed for diagnosis. Therefore, we use the “effective” test cost to better measure each strategy’s actual performance. The misclassification cost is calculated as usual: If the prediction is correct, the misclassification cost is 0; otherwise, it is either the false positive cost or false negative cost, depending on the true class of the test examples. Table 2 lists the average total cost with different missing-value strategies under different percentages of missing values in the data sets. Figs. 1a, 1b, 1c, 1d, and 1e illustrate the results of Table 2 visually.

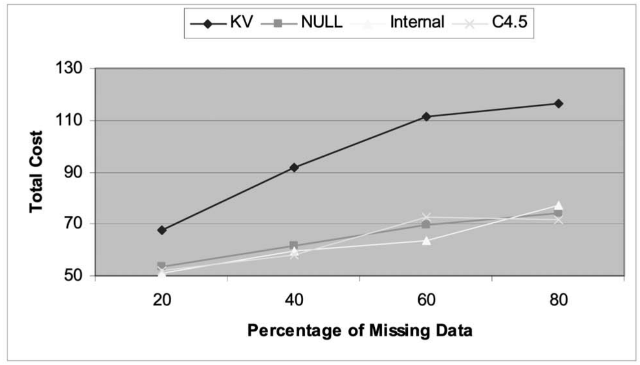
We can draw the following interesting conclusions from the results. First of all, the Known Value Strategy (KV) is

TABLE 2
Average Total Cost with Different Missing-Value Strategies under Different Percentages of Missing Values in the Data Sets

	20%	40%	60%	80%
The Ecoli Dataset				
The Known Value Strategy	135.1	144.5	134.2	125.8
The Null Strategy	28.3	33.9	41.4	42.5
The Internal Node Strategy	33.2	48.6	53.5	62.3
The C4.5 Strategy	35.0	42.5	58.9	72.6
The Breast Dataset				
The Known Value Strategy	67.6	91.9	111.3	116.2
The Null Strategy	53.3	61.4	69.8	74.2
The Internal Node Strategy	51.0	59.6	63.5	77.3
The C4.5 Strategy	52.2	57.8	72.6	71.4
The Heart Dataset				
The Known Value Strategy	146.6	126.0	98.2	121.9
The Null Strategy	90.3	88.6	103.7	98.8
The Internal Node Strategy	86.6	85.3	83.2	88.2
The C4.5 Strategy	88.2	87.6	83.2	88.9
The Thyroid Dataset				
The Known Value Strategy	169.4	153.7	138.9	108.5
The Null Strategy	66.6	72.7	76.1	73.3
The Internal Node Strategy	64.4	70.7	71.8	71.7
The C4.5 Strategy	64.4	72.3	90.5	72.4
The Australia Dataset				
The Known Value Strategy	174.2	143.0	106.3	107.4
The Null Strategy	115.3	99.2	121.0	113.1
The Internal Node Strategy	97.1	90.7	94.4	96.8
The C4.5 Strategy	98.1	94.0	109.4	96.2



(a)



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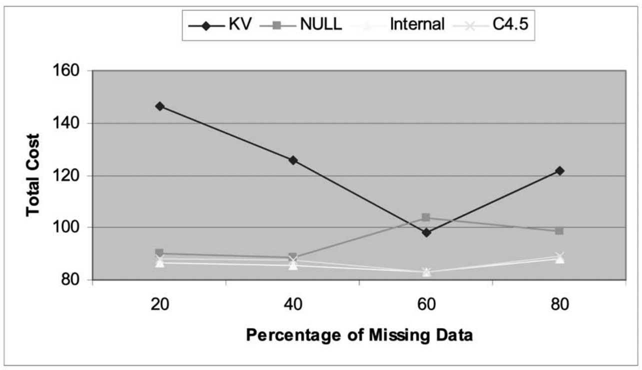

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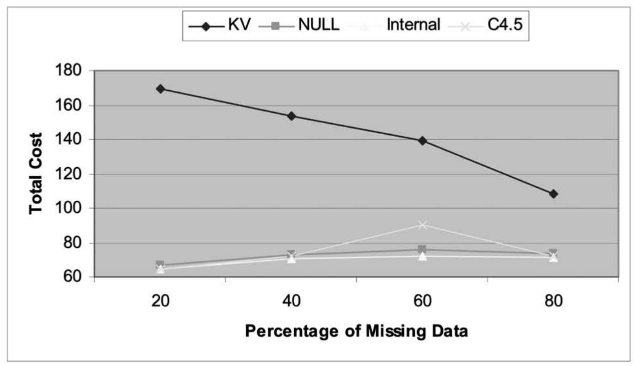

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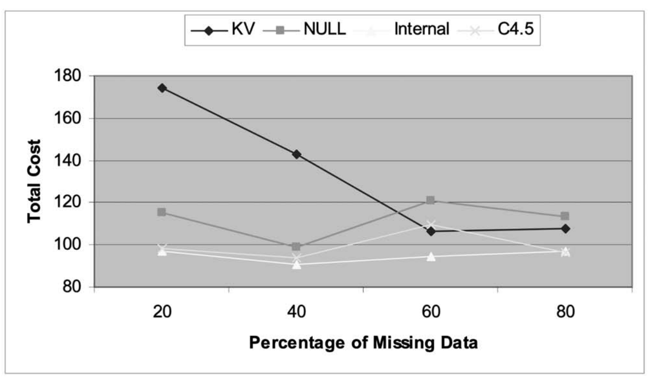

(e)

Fig. 1. (a) Total costs for Ecoli. (b) Total costs for Breast. (c) Total costs for Heart. (d) Total cost for Thyroid. (e) Total costs for Australia.

almost always the worst. This is because deleting attributes with missing values in the test example loses useful information in the data sets. Thus, this strategy should be avoided in the future. Second, in only one data set (Ecoli) is the Null Strategy slightly better than others; in other data sets, it is either similar (in Breast and Thyroid) or worse (in Heart and Australia). This shows that the Null Strategy, although very simple, is often not suitable. Third, the Internal Node Strategy is often comparable with the C4.5 Strategy (in Ecoli, Breast, and Heart) and is better than C4.5 in Thyroid and Australia. This indicates that, overall, the Internal Node Strategy is better than the C4.5 Strategy. Thus, we can conclude from our experiments that the Internal Node Strategy is the best, followed closely by the C4.5 Strategy and followed by the Null Strategy. The Known Value Strategy is the worst.

It might be slightly counterintuitive why the C4.5 Strategy, which obtains weighted classifications from leaves, is not better than the Internet Node Strategy, which uses the internal node directly. This is because when it weighs the leaves' classifications, there is a loss of information. If it weighs the leaves' probabilities, it can be easily shown that the result is equivalent to the class probability in the internal node in the Internal Node Strategy. Thus, the Internal Node Strategy is better than the C4.5 Strategy.

In Figs. 1a, 1b, 1c, 1d, and 1e, "KV" stands for the Known Value Strategy, "NULL" for the Null Strategy, "Internal" for the Internal Node Strategy, and "C4.5" for the C4.5 Strategy.

5 Conclusions and Future Work

Missing values are traditionally regarded as a tough problem and must be imputed before learning is applied. In this paper, we break away from this tradition and argue that in cost-sensitive learning that also considers test costs, it is actually desirable to have missing values to reduce the total cost of tests and misclassifications. Thus, cost-sensitive decision tree learning algorithms would only need the known values and take advantage of "missing is useful" for cost reduction. We compare four such strategies and conclude that the Internet Node Strategy, originally proposed in [17], is the best. In our future work, we plan to apply those strategies to data sets with real costs and missing values.

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