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# Ensemble Learning

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## Synonyms

Committee-based learning; Multiple classifier systems; Classifier combination

## Definition

Ensemble learning is a machine learning paradigm where multiple learners are trained to solve the same problem. In contrast to ordinary machine learning approaches which try to learn *one* hypothesis from training data, ensemble methods try to construct a *set* of hypotheses and combine them to use.

## Main Body Text

### Introduction

An ensemble contains a number of learners which are usually called *base learners*. The **generalization** ability of an ensemble is usually much stronger than that of base learners. Actually, ensemble learning is appealing because that it is able to boost *weak learners* which are slightly better than random guess to *strong learners* which can make very accurate predictions. So, “base learners” are also referred as “weak learners”. It is noteworthy, however, that although most theoretical analyses work on weak learners, base learners used in practice are not necessarily weak since using not-so-weak base learners often results in better performance.

Base learners are usually generated from training data by a *base learning algorithm* which can be decision tree, neural network or other kinds of machine learning algorithms. Most ensemble methods use a single base learning algorithm to produce *homogeneous* base learners, but there are also some methods which use multiple learning algorithms to produce *heterogeneous* learners. In the latter case there is no single base learning algorithm and thus, some people prefer calling the learners *individual learners* or *component learners* to “base learners”, while the names “individual learners” and “component learners” can also be used for homogeneous base learners.

It is difficult to trace the starting point of the history of ensemble methods since the basic idea of deploying multiple models has been in use for a long time, yet it is clear that the hot wave of research on ensemble learning since the 1990s owes much to two works. The first is an applied research conducted by Hansen and Salamon [1] at the end of 1980s, where they found that predictions made by the combination of a set of classifiers are often more accurate than predictions made by the best single classifier. The second is a theoretical research conducted in 1989, where Schapire [2] proved that *weak learners* can be boosted to *strong learners*, and the proof resulted in Boosting, one of the most influential ensemble methods.

### Constructing Ensembles

Typically, an ensemble is constructed in two steps. First, a number of base learners are produced, which can be generated in a *parallel* style or in a *sequential* style where the generation of a base learner has influence on the generation of subsequent





learners may be a better choice. The second reason is that, the search processes of the learning algorithms might be imperfect. For example, even if there exists a unique best hypothesis, it might be difficult to achieve since running the algorithms result in sub-optimal hypotheses. Thus, ensembles can compensate for such imperfect search processes. The third reason is that, the hypothesis space being searched might not contain the true target function, while ensembles can give some good approximation. For example, it is well-known that the classification boundaries of decision trees are linear segments parallel to coordinate axes. If the target classification boundary is a smooth diagonal line, using a single decision tree cannot lead to a good result yet a good approximation can be achieved by combining a set of decision trees. Note that those are intuitive instead of rigorous theoretical explanations.

There are many theoretical studies on famous ensemble methods such as Boosting and Bagging, yet it is far from a clear understanding of the underlying mechanism of these methods. For example, empirical observations show that Boosting often does *not* suffer from **overfitting** even after a large number of rounds, and sometimes it is even able to reduce the **generalization** error after the training error has already reached zero. Although many researchers have studied this phenomenon, theoretical explanations are still in arguing.

The **bias-variance decomposition** is often used in studying the performance of ensemble methods [9, 12]. It is known that Bagging can significantly reduce the variance, and therefore it is better to be applied to learners suffered from large variance, e.g., unstable learners such as decision trees or neural networks. Boosting can significantly reduce the bias in addition to reducing the variance, and therefore, on weak learners such as decision stumps, Boosting is usually more effective.

## Applications

Ensemble learning has already been used in diverse applications such as optical character recognition, text categorization, face recognition, computer-aided medical diagnosis, gene expression analysis, etc. Actually, ensemble learning can be used wherever machine learning techniques can be used.

## Summary

Ensemble learning is a powerful machine learning paradigm which has exhibited apparent advantages in many applications. By using multiple learners, the **generalization** ability of an ensemble can be much better than that of a single learner. A serious deficiency of current ensemble methods is the lack of comprehensibility, i.e., the knowledge learned by ensembles is not understandable to the user. Improving the comprehensibility of ensembles [15] is an important yet largely understudied direction. Another important issue is that currently no diversity measures is satisfying [4] although it is known that diversity plays an important role in ensembles. If those issues can be addressed well, ensemble learning will be able to contribute more to more applications.

## Related Entries

Boosting, Classifier design, Machine learning, Multiple classifier systems, Multiple experts.

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## Definitional Entries

### Bias-Variance Decomposition

An important tool for analyzing machine learning approaches. Given a learning target and the size of training data set, it breaks the expected error of a learning approach into the sum of three non-negative quantities, i.e., the *intrinsic noise*, the *bias* and the *variance*. The intrinsic noise is a lower bound on the expected error of any learning approach on the target; the bias measures how closely the average estimate of the learning approach is able to approximate the target; the variance measures how much the estimate of the learning approach fluctuates for the different training sets of the same size.

### Cross-Validation

A popular approach to estimating how well the result learned from a given training data set is going to generalize on unseen new data. It partitions the training data set into  $k$  subsets with equal size, and then uses the union of  $k - 1$  subsets for training while the remaining subset for performance evaluation. The final estimate is obtained by averaging after every subset has been used for evaluation once. A popular settings of  $k$  is 10 and in this case it is called as *10-fold cross-validation*; another popular setting of  $k$  is the number of training examples and in this case it is called as LOO (i.e., *Leave-One-Out*) test.

### Generalization

The most central concept in machine learning, which characterizes how well the result learned from a given training data set can be applied to unseen new data.

### Overfitting

The phenomenon that the learning result performs very good on training data but poorly on unseen new data, which is caused by that the learning approach has fit the training data too much such that some malign particularities that prevents a good generalization has also been captured by the learning result.