

Ensemble learning

Daniel Lawson University of Bristol

Lecture 05.2 (v1.0.1)

Signposting

- ▶ In 05.1 we introduced key classification methods including:
 - ▶ Logistic Regression,
 - ▶ Linear Discriminant Analysis,
 - ▶ Support Vector Machines
- ▶ Other core methods based on trees and forests and in Block 06.
- ▶ This lecture is not about specific methods, but how they can be combined using **ensemble learning** (also called **meta-methods**).

Intended Learning Outcomes

- ▶ ILO1 Be able to access and process cyber security data into a format suitable for mathematical reasoning
- ▶ ILO2 Be able to **use and apply basic machine learning** tools
- ▶ ILO3 Be able to make and report appropriate inferences from the results of applying basic tools to data

Theory and Practice

- ▶ All of the practical work is done in the Workshop.
- ▶ **Activity I** of the Workshop is about making a standardized interface for classifiers.
- ▶ This is an essential first step for using classifiers as building blocks for more complex operations.
- ▶ It tends to be where the Python Package SciKit Learn shines over R, though there are still inconsistencies

Broad approaches to combining learners

- ▶ The goal is “Meta Learning”, i.e. combining multiple “learners”
 - ▶ learner = machine learning algorithms that consume data and make predictions
 - ▶ generalisation of a classifier
- ▶ There are two main approaches:
- ▶ **Parallel** approaches:
 - ▶ Run independently
 - ▶ Exploits independence structure between learners
- ▶ **Sequential** approaches:
 - ▶ Run dependently
 - ▶ Exploits dependence structure between learners
 - ▶ i.e. focus on what the previous set of learners are bad at

Core topics

- ▶ Bagging
- ▶ Boosting
- ▶ Stacking

Bagging

- ▶ The algorithm for bagging is straightforward - simply taking the average of bootstrapped learners
- ▶ In parallel, B times:
 - ▶ Form data sample $\{X\}_b$, e.g. by sampling with replacement, or leaving out a random subset of data
 - ▶ Learn a classifier $f_b(x)$
- ▶ Output: A “bagged” classifier $f(x) = \frac{1}{B} \sum_{b=1} f_m(x)$

Bagging comments

- ▶ Bagging reduces overfitting to the data, and therefore works well on complex classifiers
- ▶ Same rules for resampling apply as in statistics: e.g. it works well when you respect the correlation structure
- ▶ In theory under certain assumptions, the **distribution of bagged learners** give a distribution on:
 - ▶ “what I could have seen if I obtained new data”
 - ▶ From the same distribution I got my data
- ▶ Usually little reason not to try it in practice

Boosting

- ▶ The general idea of **Boosting** is:
 - ▶ Build a classifier, predict the data
 - ▶ Treat the residuals as “new data”
 - ▶ Repeat
- ▶ Boosting sounds like it should work for arbitrary classifiers, but because of the iterative nature it is applied to single classifiers.
- ▶ There are many boosting algorithms, amongst which are:
 - ▶ Majority vote (Early and weak)¹
 - ▶ Adaboost² (Adaptive boosting - first game-changer)
 - ▶ xgboost³ (exploits sparsity and gradients, current Kaggle winner)

¹ Kearns M and Valiant L (1989). Symp. Theor. Comp. ACM. 21: 433-444

² Freund and Schapire in 1996

³ Chen T and Carlos G (2016) KDD 2016.

Boosted feature splitter

- ▶ A very simple way to use boosting is to allow classifiers only from **single features**:
- ▶ Initialise weights of each **data sample** (uniformly)
- ▶ For T iterations:
 - ▶ Normalise weights
 - ▶ Train a classifier on every feature individually
 - ▶ Choose the best classifier, i.e. feature
 - ▶ Update the data weights by upweighting correct decisions and downweighting wrong decisions
- ▶ The boosted classifier uses a weighted sum of the selected classifiers

Adaboost

- ▶ **Given:** N data $(x_1, y_1), \dots, (x_N, y_N); x_i \in \mathcal{X}, y_i \in \{-1, 1\}$
- ▶ Set data weights $D_{t=1}(n) = 1/N$. For $t = 1 \dots T$:
 - ▶ **Train M “weak” classifiers** $h_{mt}(x_t) : \mathcal{X} \rightarrow \{-1, 1\} \in \mathcal{H}$
 - ▶ With weighted **prediction error**
$$\epsilon_{mt} = \sum_{i=1}^N D_t(i)(h_{mt}(x_i) - y_i)/2$$
 - ▶ Choose the best classifier $h_t = \operatorname{argmin}_m \epsilon_{mt}(h_{mt})$ with error ϵ_t
 - ▶ Evaluate $\alpha_t = \log([1 - \epsilon_t]/\epsilon_t)$
 - ▶ Update the **weights**:

$$D_{t+1}(i) = \frac{D_t(i) \exp(\alpha_t \mathcal{I}(y_i \neq h_t(x_i)))}{Z_t}$$

- ▶ Where Z_t re-normalises weights D_{t+1} to sum to 1.
- ▶ **Output:** Boosted classifier:

$$H(x) = \operatorname{sign} \left(\sum_{m=1}^M \theta_m h_m(x) \right)$$

Boosting comments

- ▶ α grows (towards infinity) as ϵ shrinks (towards zero)
- ▶ The weighting process is chosen to ensure that the sign operation ensures correct classification
- ▶ Boosting is **computed** as a “decision tree” describing which classifier to use
- ▶ But outputs a mixture solution!
- ▶ All information about previous decisions is encoded into the weights
- ▶ When there is no residual error left for a data point, its weight is set to zero
- ▶ h can be thought of as “features” and $\mathcal{H} = \{h(x)\}$ can be large or infinite.
- ▶ Implementations in practice usually restrict weak classifiers h to a single, simple class (e.g. decision tree, perceptron)
- ▶ Weak classifiers are often generated by subsetting features, e.g. one at a time

Stacking

- ▶ Stacking is a different way to combine multiple weak learners. It is more appropriate to combining “good classifiers” to make a meta-classifier.
- ▶ In theory a stacked classifier will always outperform its constituents if implemented appropriately⁴.
 - ▶ Cross-validation and asymptotics are required for this guarantee but in practice many approaches work.

⁴van der Laan, M, Polley E, Hubbard A, “Super Learner” (2007) Statistical Applications in Genetics and Molecular Biology, Volume 6.

Super learner

- ▶ **Set up** the ensemble:
 - ▶ Specify L base classifiers.
 - ▶ Specify a metalearning algorithm.
- ▶ **Train** the ensemble:
 - ▶ Train the L base algorithms on the N training data. Use k -fold cross-validation for these learners.
 - ▶ For the $N \times L$ matrix of predictions. Form the “level one” data with this matrix and the raw data.
 - ▶ Train the metalearning algorithm on the “level one” data.
- ▶ **Predict** on new data:
 - ▶ Generate predictions from the base classifiers.
 - ▶ Feed those predictions into the meta-learner to generate the ensemble prediction.

More Stacking

- ▶ Related approaches:
 - ▶ Run any number of classification algorithms
 - ▶ Use their predictions as features
 - ▶ Use the data in addition to the predictions
- ▶ Pass this new feature set to any classification algorithm
- ▶ In practice, the best algorithm will be the one that generalises best in the test dataset. Common techniques:
 - ▶ Majority vote: use the prediction that most classifiers choose
 - ▶ Regularisation
 - ▶ Boosting-like prediction combination

Wrapup

- ▶ Key to high prediction accuracy are:
 - ▶ **Complexity**: Non-linearity helps dramatically
 - ▶ **Bias control**: Don't overfit
 - ▶ **Meta-learning**: Boosting and stacking are essential for the final few percent.

Reflection

- ▶ By the end of the course, you should:
 - ▶ Be able to use Bagging, Boosting and Stacking
 - ▶ Be able to describe their advantages and disadvantages at a high level

Signposting

- ▶ Next Block: Random Forests and decision trees and more practice using classification.
- ▶ Next Lecture: The workshop Lecture going over Bagging, Stacking and Boosting in practice.
- ▶ **References:**
- ▶ Ensemble learning in general:
 - ▶ Vadim Smolyakov, MIT: ML-perspective on Ensemble Methods
 - ▶ Stacked Ensembles by H2O, a Commercial AI Company focussing on Deployable AI
 - ▶ StackExchange: Stacking vs Bagging vs Boosting
 - ▶ Super Learners: van der Laan, M, Polley E, Hubbard A, “Super Learner” (2007) Statistical Applications in Genetics and Molecular Biology, Volume 6.

Signposting (2)

- ▶ **More References:**

- ▶ Boosting:

- ▶ AdaBoost paper: Experiments with a New Boosting Algorithm Freund and Schapire (1996).
- ▶ Explaining AdaBoost, Rob Schapire, Empirical Inference (2013) pp 37-52.
- ▶ xgboost Chen T and Carlos G (2016) KDD 2016.
- ▶ xgboost explained, a blog post about Didrik Nilsen's paper Tree Boosting With XGBoost: Why Does XGBoost Win "Every" Machine Learning Competition?