**Binary and Multiclass Classification:**

**A Comparative Study on Breast Cancer Diagnosis and Data Science Job Experience Prediction**

Junyu Li and Lanjun Wang

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**Abstract**

This project explores the application of supervised machine learning to two classification problem: detecting breast cancer and predicting job experience levels in the data science filed. We selected one binary and one multiclass dataset to compare how various algorithms perform across different classiciation task. Though a complete pipleline involving preprocessing, model selection, and hyperparameter tuning, we evaluated models including logstic regression, decision tress, ensemble methods, and gradient boosting. The analysis emphasizes the importance of model choice, metric selection, and dataset charcteristics in shaping outcomes. The results provide insight into how different models, metric selection, and dataset characteristic in shaping outcomes. The results provide insight into how different models respons to domain-specific chanllenges such as feature overlap and class imbalance, and highlight practical consideration for real-world deployment.

**Introduction**

Supervised machine learning plays a crucial role in solving real-world classification problems across

**Datasets**

*Dataset 1: Breast Cancer Wisconsin Dataset (Binary Classification)*

The binary classification task uses the Breast Cancer Wisconsin (Diagnostic) dataset, which contains 455 samples and 32 numerical features derived from digitized images of fine needle aspirate (FNA) tests of breast masses. The target variable is diagnosis, encoded as 0 (benign) and 1 (malignant). The dataset has no missing values and exhibits a moderate class imbalance, with benign samples slightly more common than malignant.

To ensure reliable evaluation, the dataset was randomly split into training (80%) and testing (20%) subsets while preserving class ratios (stratified split). Feature scaling using standardization was applied to the training set to account for variation in measurement scales and improve model convergence.

Exploratory data analysis revealed that while some features (e.g., mean radius, mean texture) help differentiate between classes, there is substantial overlap in feature distributions. Additionally, the correlation heatmap showed that some features are highly collinear, while others are weakly related or redundant. These challenges make classification more difficult, especially for linear models.

*Dataset 2 – Data Science Job Salaries Dataset (Multiclass Classification)*

The multiclass classification task uses the Data Science Job Salaries dataset, which contains 606 records and 12 features. The goal is to predict the experience\_level of a data science professional, categorized into four classes: Entry-level (EN), Mid-level (MI), Senior-level (SE), and Executive (EX).

The dataset includes a mix of feature types: 5 categorical, 1 ordinal, 5 numerical, and 1 binary. Before modeling, categorical features were one-hot encoded and ordinal features were label-encoded. The dataset was split intro training (79%) and testing (21%) sets, and standard scaling was applied to the numerical features. No missing values were present.

A key challenge with this dataset is the weak correlation between most features and the target variable. Additionally, the class distribution is imbalanced, with senior-level positions compressing nearly half of the data and executive-level positions making up less than 5%. Some categorical features, such as job\_title, introduce semantic ambiguity. As different titles may reflect similar roles. These factors complicate model training and reduce predictive performance, particularly for underrepresented classes.

**Methods**

*Binary Classification*

We selected four supervised learning algorithms to model the binary classification task:

* Logistic Regression
* Support Vector Machine
* Random Forest Classifier
* XGBoost Classifier

These models were chosen to balance interpretability, robustness to noise, and performance on structured tabular data. Logistic regression serves as baseline linear model, while SVM is well-suited for high-dimensional features spaces. Random Forest and XGBoost, both ensemble methods, are expected to handle feature redundancy and class overlap more effectively.

Each model was integreated intro a pipeline that included StandardScaler for feature normalization. Hyperparameter tuning was performed using GridSearchCV with 3-fold cross-validation. For example, logistic regress was tuned on the regularization strength C and penalty type (L1, L2), while XGboost was tuned on parameters such max\_depth, learning\_rate, and regularization terms (reg\_alpha, reg\_lambda).

To evaluate performance, we prioritized recall and ROC AUC due to the medical context, where false negatives (missing malignant cases) are particularly costly. Recall ensures we capture the majority of positive cases, while ROC AUC provides a threshold-independent view of classification performance.

*Multiclass Classification*

For the multiclass classification task, the following four models were used:

* Decision Tree Classifier
* K-Nearest Neighbors
* Random Forest Classifier
* XGBoost Classifier

These models were selected to explore how distance-based, tree-based, and ensemble methods perform on a feature-diverse and moderately imbalanced dataset. Decision Trees and Random Forests can handle categorical data and non-linear interactions, while KNN captures local patterns. XGBoost was included for its strong performance on structured classification tasks and its built-in support for handling class imbalance.

Categorical variables were encoded using one-hot encoding, and numerical features were standardized using StandardScaler. Hyperparameter tuning was again conducted using GridSearchCV, focusing on model-specific parameters such as tree depth, number of neighbors, or learning rate.

Performance was evaluated using macro-averaged F1 score and accuracy. Macro F1 treats each class equally, making it suitable for imbalanced classification, while accuracy provides an overall performance reference. Together, these metrics offer a balanced view of model effectiveness across all experience levels.

**Hyperparameter Tuning**

*Binary Classification*

*Logistic Regression*

The Logistic Regression model was tuned across a range of regularization strengths (C ∈ {0.01, 0.1, 1, 10}) and penalty types (l1, l2). The best configuration was C = 1 with L2 regularization, achieving a cross-validated recall of 0.9588. As shown in the tuning plot (Figure 1), L2 regularization consistently outperformed L1, especially at moderate C values. Performance A graph of a graph with lines and numbers

AI-generated content may be incorrect.decreased at extreme values, likely due to under- or over-regularization. The tuning process was efficient, completing in 0.12 seconds.

Figure 1 – Logistic Regression Tuning Curves for Different Penalties and C values

This indicates that a moderate amount of regularization yields optimal sensitivity for this dataset.

A graph with a line

AI-generated content may be incorrect.*Support Vector Machine*

Figure 2 - SVM Recall across Different Values of C (Linear Kernal)

SVM was tuned over three hyperparameters: C ∈ {0.1, 1, 10}, kernel ∈ {'linear', 'rbf'}, and gamma ∈ {'scale', 'auto'}. The best-performing configuration used a linear kernel with C = 1 and gamma = scale, producing a cross-validated recall of 0.9529.

The tuning curve (Figure 2) shows that linear kernels performed consistently well, while higher C values slightly decreased recall, suggesting mild overfitting. The RBF kernel did not offer improvements, indicating that the dataset is linearly separable. The tuning process completed in 0.34 seconds, highlighting SVM’s computational efficiency on moderate-sized datasets.

*Random Forest*

A graph of different colored squares

AI-generated content may be incorrect.Random Forest was tuned on the number of trees (n\_estimators ∈ {50, 100, 200}) and maximum tree depth (max\_depth ∈ {None, 5, 10}). The optimal setting was n\_estimators = 50 with max\_depth = None, which achieved a cross-validated recall of 0.9294.

Figure 3 - Random Forest Heatmap Showing Recall by Depth and Number of Trees

The heatmap (Figure 3) shows that unrestricted depth yielded the highest recall across all values of n\_estimators. Shallower trees underperformed, suggesting that complex feature interactions are beneficial for this dataset. However, deeper trees may risk overfitting if not managed carefully. Tuning completed in 3.23 seconds.

*XGBoost*

A graph of a number of blue squares

AI-generated content may be incorrect.XGBoost was tuned over a wide range of hyperparameters, including learning rate ({0.01, 0.1, 0.2}), tree depth ({3, 5, 7}), and regularization parameters (reg\_alpha ∈ {0, 0.1}, reg\_lambda ∈ {1, 10}). The best configuration was found to be learning\_rate = 0.1, max\_depth = 3, reg\_alpha = 0, and reg\_lambda = 1, yielding a cross-validated recall of 0.9471. The tuning process required 10.77 seconds, the longest among the four models.

As shown in Figure 4, recall significantly improved as the learning rate increased from 0.01 to 0.1, with diminishing returns beyond that. Shallower and moderately deep trees (depth = 3 to 5) performed best, with a maximum recall of 0.941 achieved at learning\_rate = 0.2 and max\_depth = 5. In contrast, very shallow trees with low learning rates consistently underperformed. These results indicate that XGBoost benefits from moderate learning and structural complexity while avoiding overfitting through its regularization capabilities.

Figure 4 - XGBoost Tuning Heatmap Showing Recall by Learning Rate and Tree Depth

**Result**

*Binary Classification*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Model | Hyperparameters | Tuning Time (sec) | Test Recall (Class 1) | Test ROC AUC | Test Accuracy |
| Logistic Regression | C=1, penalty='l2' | 0.12 | 0.98 | 0.9997 | 0.99 |
| SVM | C=1, kernel='linear', gamma='scale' | 0.34 | 0.98 | 0.9997 | 0.98 |
| Random Forest | n\_estimators=50, max\_depth=None | 3.23 | 0.93 | 0.9950 | 0.96 |
| XGBoost | learning\_rate=0.1, max\_depth=3, reg\_alpha=0, reg\_lambda=1 | 10.77 | 0.90 | 0.9970 | 0.96 |

**Discussion**

*Binary Classification*

The binary classification task focused on predicting whether a breast tumor is benign or malignant, using the Breast Cancer Wisconsin dataset. Given the medical context, recall for class 1 (malignant tumors) was prioritized to minimize the risk of false negatives, which are particularly harmful in diagnostic settings.

Across all four models, performance on the test set was strong, with Logistic Regression and SVM emerging as top performers. Both achieved a recall of 0.98, a ROC AUC of 0.9997, and overall accuracy above 0.98. These results indicate that the decision boundary separating benign and malignant cases is largely linear, which explains why these relatively simple models performed as well as — or better than — more complex ensemble methods. Additionally, their short training times and interpretability make them strong candidates for deployment in real-world screening tools.

Ensemble models like Random Forest and XGBoost also demonstrated high overall performance, but with slightly lower recall (0.93 and 0.90, respectively). Despite achieving high ROC AUCs (0.9950 and 0.9970), their tendency to misclassify a few malignant cases reflects either increased model variance or conservative thresholding. XGBoost, in particular, showed robust ranking ability but less aggressive positive classification, suggesting it was more cautious in labeling tumors as malignant. This behavior may be beneficial in some settings but less desirable when missing malignant cases is costly.

Hyperparameter tuning revealed that linear models required minimal configuration — a moderate regularization (C=1) for Logistic Regression and linear kernel SVMs were sufficient. Ensemble methods benefited from deeper exploration: XGBoost performed best with shallow trees (max\_depth=3) and a learning rate of 0.1, while Random Forest favored more trees with unrestricted depth. Tuning times reflected this complexity, ranging from under 1 second for linear models to over 10 seconds for XGBoost.

In summary, simple linear classifiers not only generalized better but also aligned more directly with the primary goal of capturing all malignant cases. Ensemble models, while still strong, did not offer additional benefit in this context and were more computationally demanding. These findings reinforce the value of model simplicity and sensitivity-first evaluation when designing machine learning solutions for high-risk domains like healthcare.