PREDICTING FETAL HEALTH WITH MACHINE LEARNING: HEART RATE VARIABILITY AS A NON-INVASIVE MARKER OF AUTONOMIC NERVOUS SYSTEM MATURATION

By Shane Bollinger 8/8/2025

PROJECT OVERVIEW

- Used fetal health dataset to train ML models on CTG features.
- Gradient Boosting model: **95%** training, **90%** test accuracy.
- Interpreted key features like **HRV** as markers of **ANS development**.
- Bridges **machine learning** and **neurophysiology** for clinical and research use.

Dataset Columns

- Accelerations: Number of accelerations per second
- Fetal_movement: Number of fetal movements per second
- Uterine contractions: Number of uterine contractions per second
- Severe_decelerations: Number of severe decelerations per second
- Prolonged_decelerations: Number of prolonged decelerations per second
- Abnormal_short_term_variability: Percentage of time with abnormal short-term variability.
- Mean_value_of_short_term_variability
- Percentage_of_time_with_abnormal_long_term_variability
- Mean_value_of_long_term_variability
- Histogram_width: Range between the highest and lowest histogram values
- Histogram_min: Lowest value in the histogram
- Histogram_max: Highest value in the histogram
- Histogram_number_of_peaks: Count of distinct peaks in the histogram
- Histogram_number_of_zeroes: Number of zero-frequency bins in histogram
- Histogram_mode: Most frequent value in the histogram
- Histogram_mean: Average value of histogram data
- Histogram_median: Middle value of histogram data
- Histogram_median *(duplicate)*: Same as above
- Histogram_variance: Spread of values in the histogram
  Histogram_tendency: Skew or direction of histogram distribution
- Fetal_health: 1 - Normal; 2 - Suspect; 3 - Pathological

RESEARCH QUESTIONS

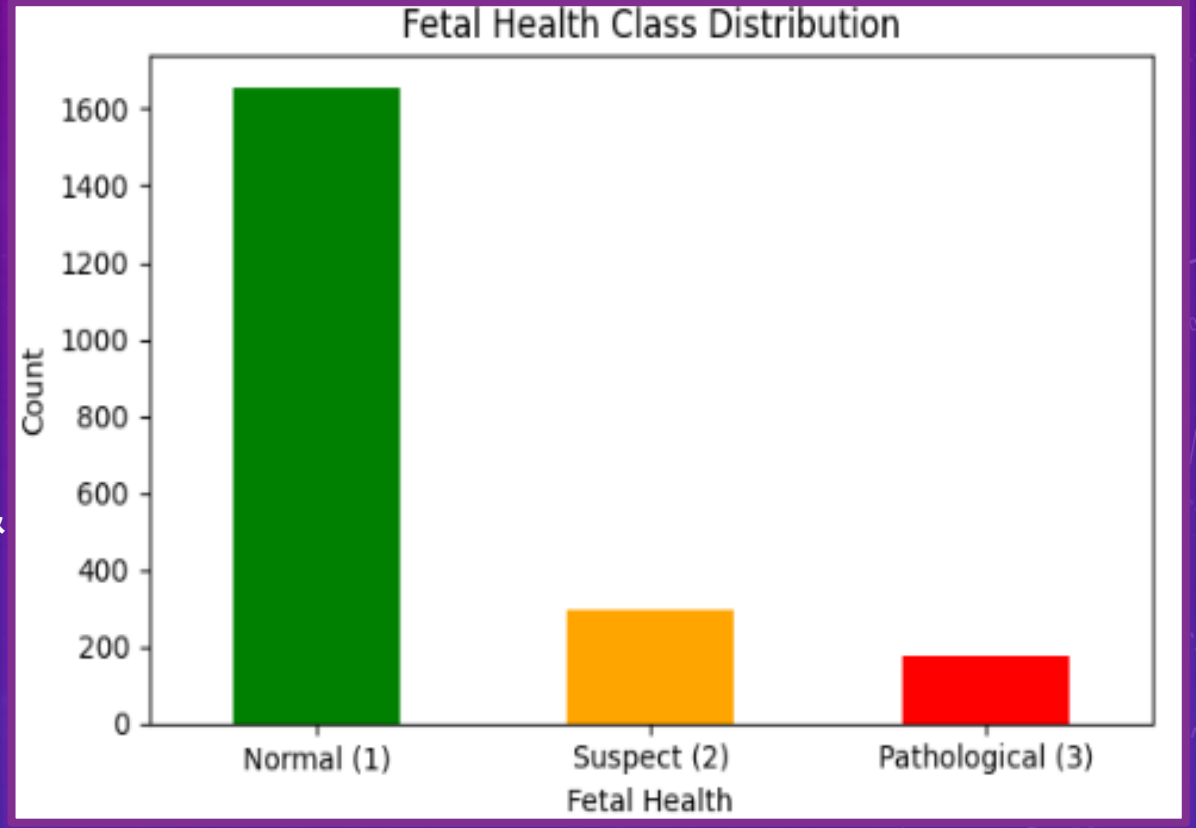
Research Question #1: Can we accurately predict fetal health status using cardiotocographic features?

Research Question #2: Can variability measures in fetal heart rate be non-invasive indicators of autonomic nervous system (ANS) maturation?

EXPLORATORY DATA ANALYSIS

Top 5 Most Correlated Features (Excluding Histograms)

- Mean_value_of_short_term_variability & light decelerations **56%**
- Fetal_health & prolongued_decelerations **48%**
- Abnormal_short_term_variability & fetal_health **47%**
- percentage_of_time_with_abnormal_long_term_variability & mean_value_of_short_term_variability **47%**
- percentage_of_time_with_abnormal_long_term_variability abnormal_short_term_variability **46%**



Dropped the most correlated feature due to collinearity that can lead to redundant information and model overfitting.

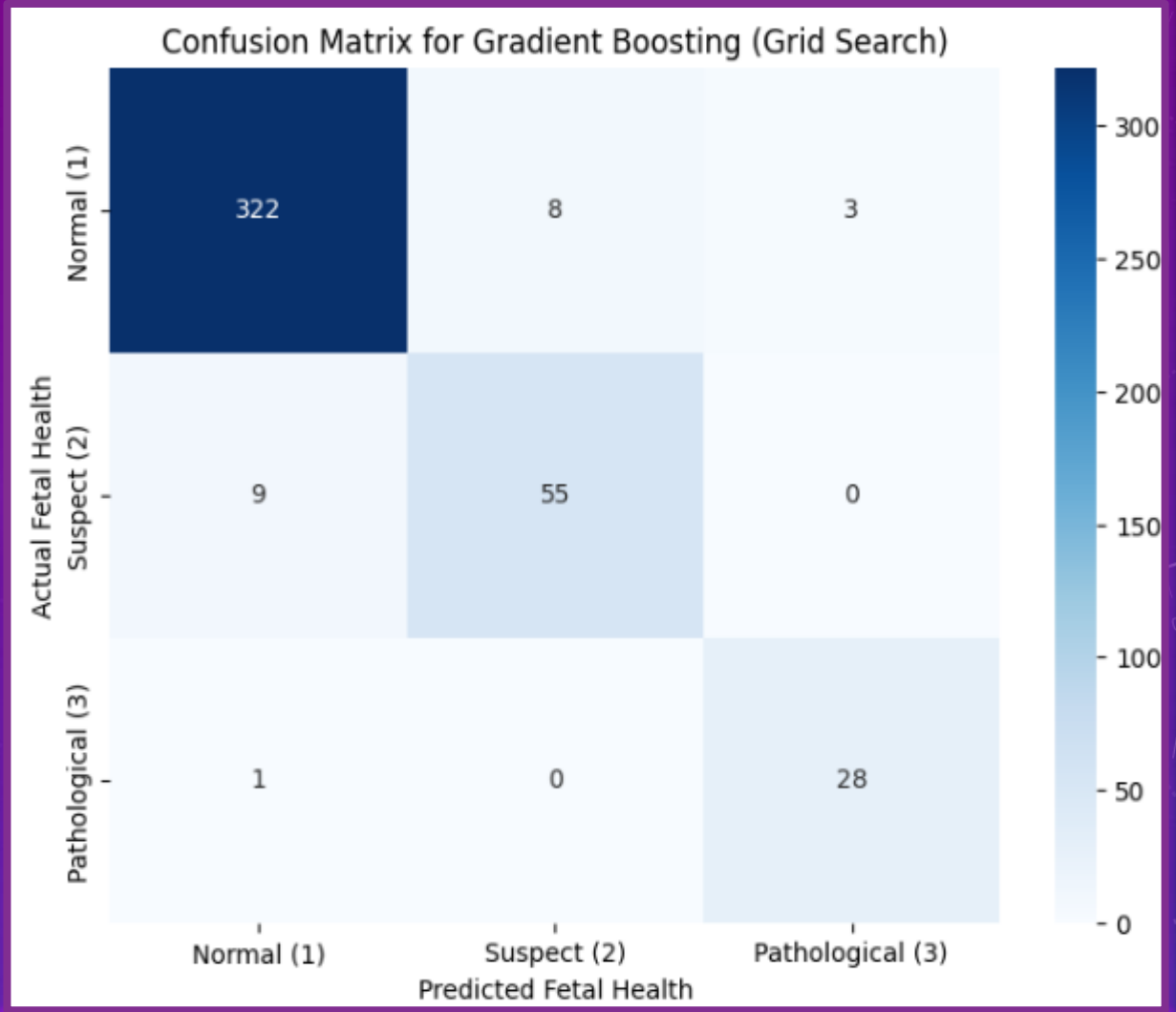
MODEL TRAINING & RESULTS

K-Folds Cross-Validation splits the dataset into *k* equal parts; the model trains on *k-1* parts and validates on the remaining part, rotating until every part has been used for validation, providing a reliable estimate of model performance.

K Folds Cross Validation Accuracy Score 90%

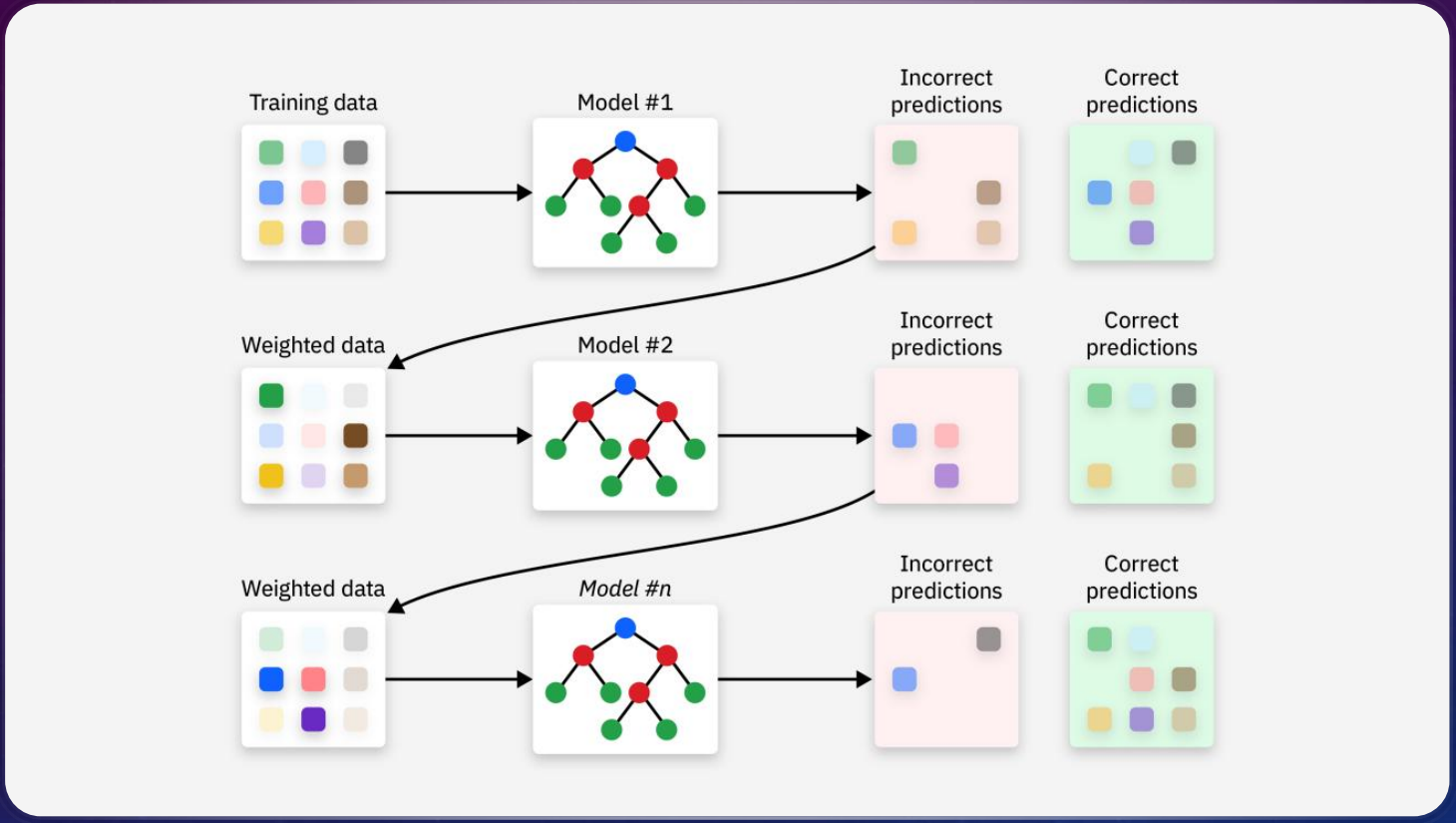
GridSearchCV tests multiple hyperparameter combinations through cross-validation to find the best-performing model settings, improving accuracy and generalization.

No statistically significant difference between models (all t-test p-values > 0.05).



	Accuracy	Precision (weighted)	Recall (weighted)	F1-score (weighted)
KNN (k=4)	0.899061	0.899935	0.899061	0.898674
Decision Tree	0.922535	0.924926	0.922535	0.923522
Random Forest	0.946009	0.944710	0.946009	0.944523
Gradient Boosting	0.948357	0.947965	0.948357	0.948015
Gradient Boosting (Grid Search)	0.950704	0.950790	0.950704	0.950667

GRADIENT BOOSTING IN DETAIL

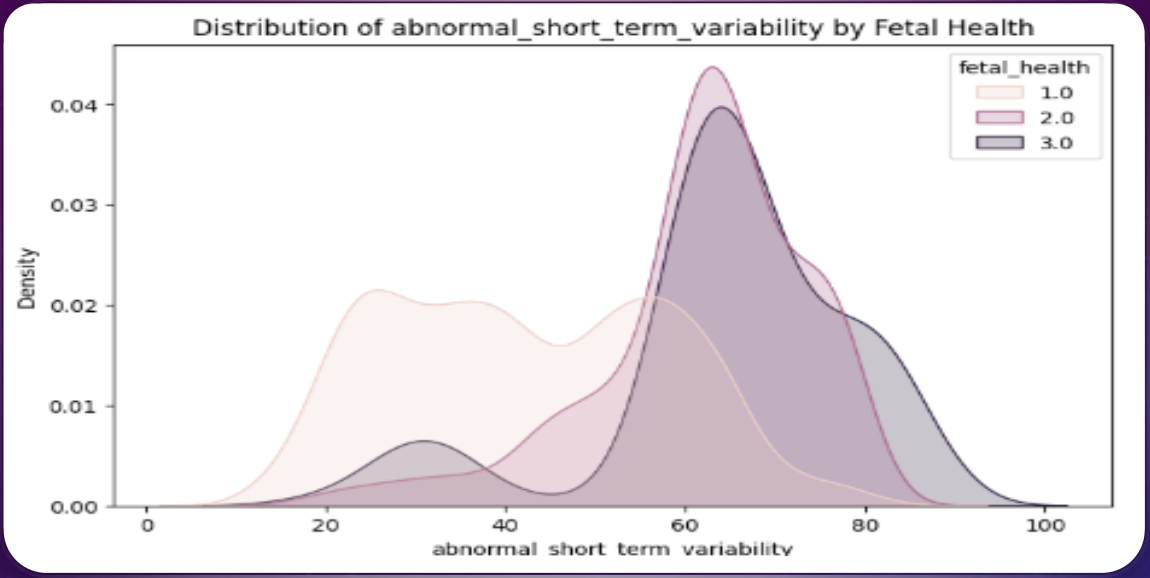


Combines many weak learners (shallow decision trees)

Gradient Boosting is an ensemble method that builds models sequentially, where each new model corrects the errors of the previous ones using gradient descent to minimize prediction loss.

An Ensemble Method is a ML technique that combines multiple models to improve overall prediction accuracy by using their collective strengths and reducing individual errors.

Research Question Part #2



Gradient Boosting Classification Report (Variability Features Only):

	precision	recall	f1-score	support
1.0	0.94	0.97	0.95	333
2.0	0.87	0.75	0.81	64
3.0	0.92	0.79	0.85	29
accuracy			0.93	426
macro avg	0.91	0.84	0.87	426
weighted avg	0.93	0.93	0.93	426

Feature Importances (Variability Features Only):

abnormal_short_term_variability	0.394155
percentage_of_time_with_abnormal_long_term_variability	0.238546
mean_value_of_short_term_variability	0.188468
mean value of long term variability	0.178830

Only used columns that measured Heart Rate variability

Key Insight: HRV as a Marker of ANS Maturation

- Abnormal Short-Term Variability was the most important feature for predicting fetal health.
- Supports the hypothesis that HRV reflects autonomic nervous system development.
- HRV is controlled by the ANS, which regulates heart rate accelerations and decelerations.
- Abnormal HRV patterns indicate dysfunction or immaturity in ANS regulation.
- Thus, HRV features serve as non-invasive indicators of fetal neurological development

PART #2 CONNECTION TO SCIENTIFIC RESEARCH

Study Reference: Schneider et al. (2009) Physiological Measurement
Investigated whether fetal heart rate variability reflects the different time scales of sympathetic and parasympathetic (vagal) development before and after 32 weeks gestation.

- **Before 32 Weeks:** Progressive parasympathetic (vagal) activation
- **After 32 Weeks:** Sympathetic dominance appears

- **Non-Accelerative Patterns**: Increased SDNN/RMSSD ratio indicates parasympathetic maturation. RMSSD highlights short-term, vagally-mediated rhythms.

- **Accelerative Patterns:** Sympathetic dominance shown through changes in mean heart rate, SDNN, and SDNN/RMSSD.

Conclusion: The period before 32 weeks gestation is critical for parasympathetic development.
- HRV parameters (SDNN, RMSSD, LF/HF) provide non-invasive biomarkers of ANS maturation.
- Supports the use of HRV analysis in assessing fetal neurological development.

CONCLUSIONS

- ***(Answer to Part #1)*** We can accurately predict fetal health using CTG features in the given dataset - achieved 90% test accuracy with new data, showing that CTG measurements contain reliable predictive information about fetal health

- **(Answer to Part #2)** HRV serves as a marker of ANS maturation because the autonomic nervous system directly controls heart rate variability patterns - our ML model validated this by identifying abnormal short-term variability as one of the most predictive features of fetal health

- **Future Directions:** Validate findings on larger datasets, implement the model in clinical monitoring systems, and explore additional HRV parameters for enhanced prediction accuracy

- **Impact:** This work enables earlier detection of fetal neurological issues, supports development of automated prenatal screening tools, and advances personalized care by bridging machine learning with clinical understanding of fetal development

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Reference Paper: Schneider et al. (2009). *Fetal heart rate variability reveals differential dynamics in ANS development.* Physiological Measurement. PubMed