Foundation models for EEG analysis

From raw EEG to robust insights

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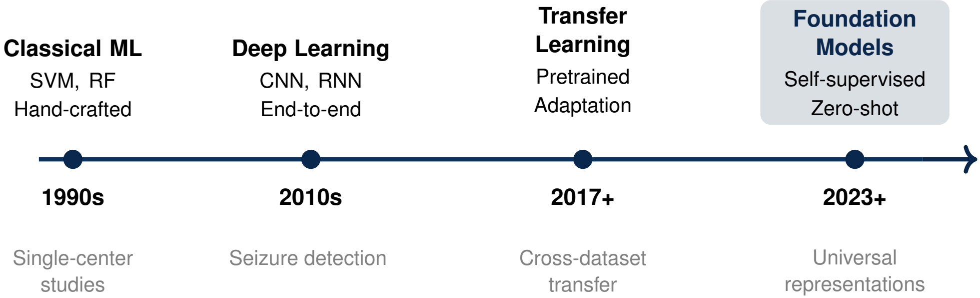
December 15, 2025

1. Motivation

Evolution of AI in Clinical EEG Analysis



From task-specific models to **general-purpose** representations that transfer across datasets and clinical applications.

Problem Statements

Approach	Complex Patterns	Low Label Requirement	Cross-Dataset Transfer	Zero-Shot Capability	Multimodal Integration
Classical ML (SVM, RF)	✗	✗	✗	✗	✗
CNN / RNN	✓	✗	✗	✗	✗
Transfer Learning	✓	✓	✓	✗	✗
Self-Supervised	✓	✓	✓	✗	✗
Foundation Model	✓	✓	✓	✓	✓

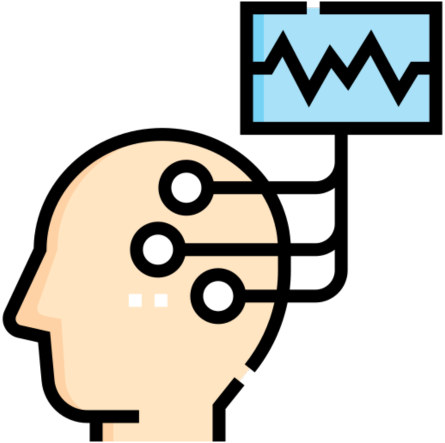
Foundation models leverage large-scale self-supervised pretraining, enabling strong generalization, zero-shot inference, and multimodal integration capabilities.

2. What is EEG?

What is EEG?

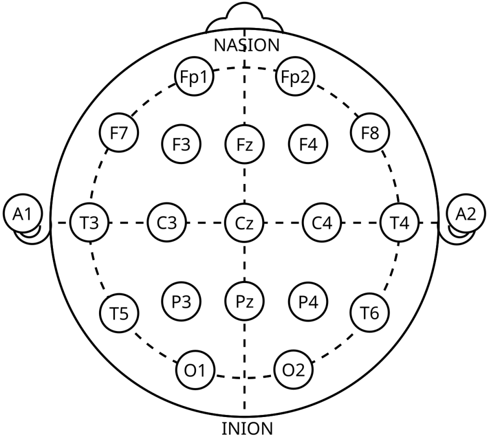
Electrical brain activity recorded from scalp electrodes. High temporal resolution, non-invasive measurement of neural dynamics.

Band	Range
Delta	0.5–4 Hz
Theta	4–8 Hz
Alpha	8–12 Hz
Beta	12–30 Hz
Gamma	$>$30 Hz



EEG Analysis Examples

- Motor Imagery
- Impulsivity Detection
- Brain-Computer Interfaces
- Sleep Stage Classification
- Emotion Recognition
- Seizure Detection



Data preprocessing pipeline

Filtering

- Bandpass filter (1-50 Hz)
- Notch filter (50/60 Hz)

Artifact Removal

- Independent Component Analysis (ICA)
- Automatic algorithms
- Manual inspection

Segmentation

- Epoching based on events
- Fixed-length windows
- Overlap handling

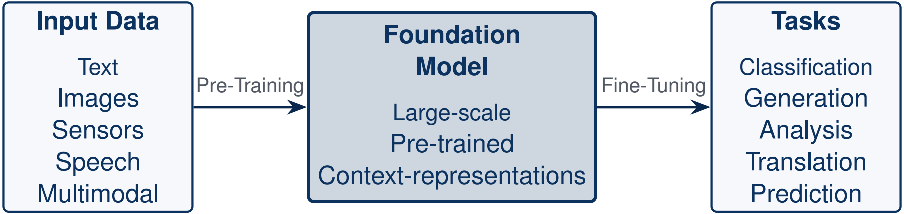
Normalization

- Z-score normalization
- Min-max scaling
- Power normalization

3. What is a Foundation Model?

Foundation Models

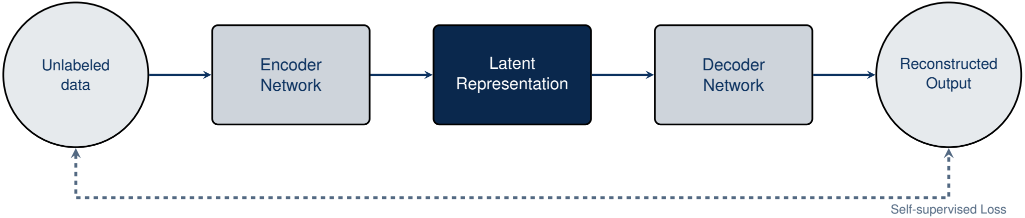
Foundation models are large-scale machine learning models trained on vast amounts of data across various domains and modalities. They can be fine-tuned for specific downstream tasks with relatively small-labeled datasets.



That is, learn general representations during pre-training that can be transferred to various specific tasks during fine-tuning.

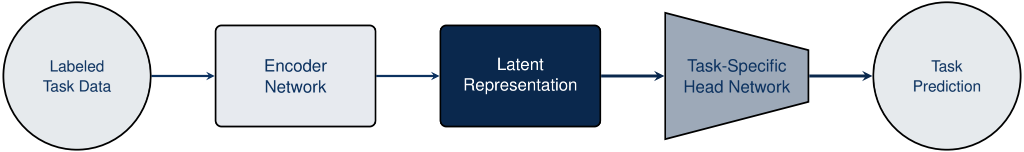
Breaking Down Foundation Models: Pre-training

The model is trained on a large and diverse dataset using self-supervised learning techniques. This allows the model to learn general features and patterns from the data.



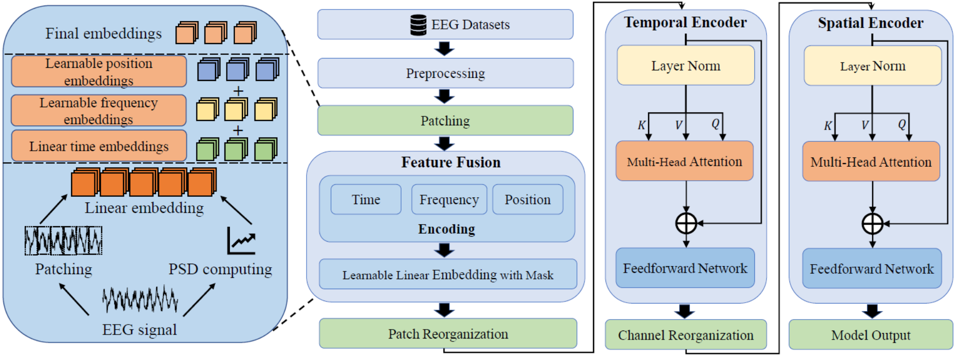
Breaking Down Foundation Models: Fine-tuning

The pre-trained model is then adapted to specific tasks using smaller labeled datasets. This process leverages the knowledge acquired during pre-training to improve performance on the target task.



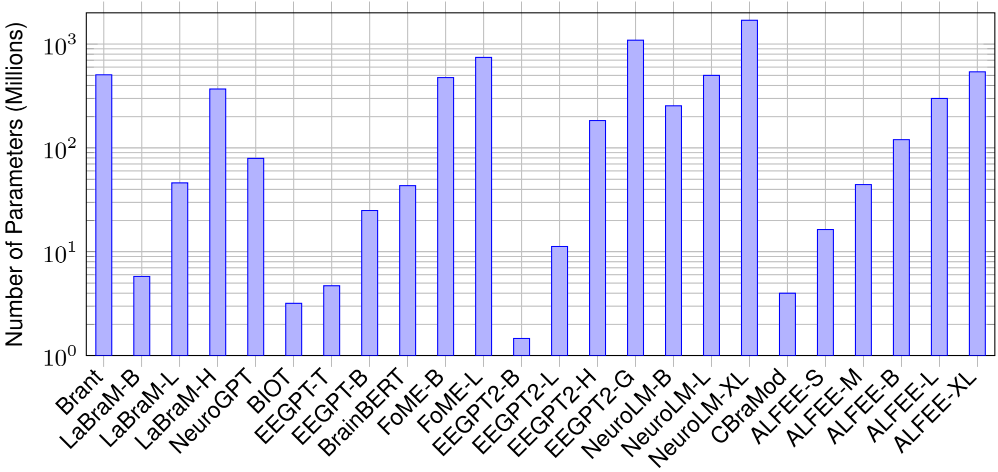
4. State of Art models

Overview of the architecture and workflow of general EEG-FM Encoder

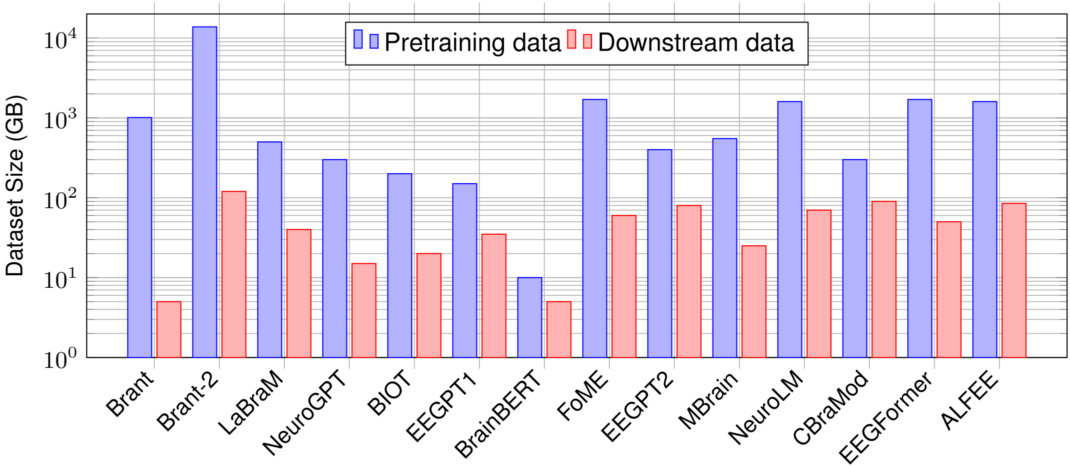


Source: [Lai et al., 2025]

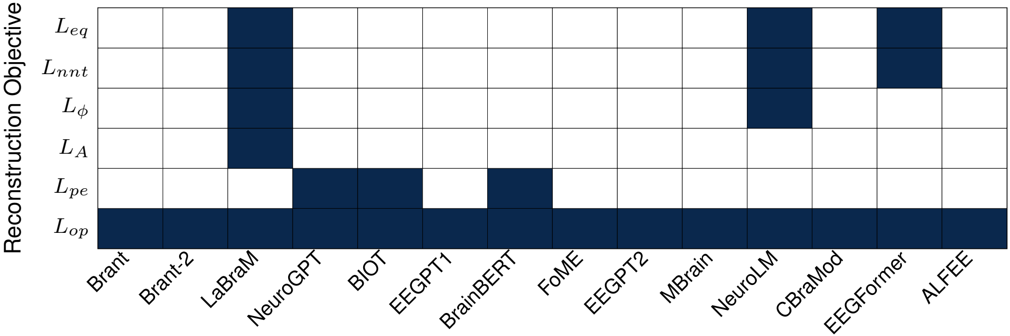
Model Sizes of EEG Foundation Models



Pretraining vs Downstream Data Scale



Binary Heatmap of Pretraining Objectives



Reconstruction tasks used during pretraining for different models: $\boldsymbol{L_{op}}$, patch reconstruction; $\boldsymbol{L_{pe}}$, embedding reconstruction; $\boldsymbol{L_A/L_\phi}$, Fourier amplitude/phase regression; $\boldsymbol{L_{nnt}/L_{eq}}$, neural-tokenizer codebook/commitment prediction.

Downstream Task Performance Summary

Model	Task	Dataset	Accuracy (%)
Clinical Applications [Authors, 2024]			
LaBraM	Abnormal detection	TUAB	83.8
BENDR	Epilepsy detection	Epilepsy	74.0
NeuroGPT	Epilepsy detection	Epilepsy	73.4
LaBraM	OCD classification	OCD	74.0
LaBraM	Stress classification	Real-world	90.5
BCI Applications - Cross-subject Transfer [Wu et al., 2025]			
CBraMod	Mental workload	EEGMAT	88.9
LaBraM	Mental workload	EEGMAT	85.8
CBraMod	Sleep staging	SHHS	73.5
BIOT	Sleep staging	SHHS	72.2

Current Challenges in EEG Foundation Models

Preprocessing & Normalization

Minimal preprocessing; unclear impact of noise, outliers, and data variability.

Evaluation & Benchmarking

No common benchmarks; limited out-of-distribution and few-shot/zero-shot testing.

Long-Term Context Modeling

Difficulty handling diverse timescales (ms ERPs to hours-long sleep stages).

Trustworthiness & Interpretability

No focus on interpretability; essential for clinical trust in high-stakes diagnoses.

5. Proposed Research

Proposed EEG Foundation Model: Handling Variability and Uncertainty

Objective

Develop a foundation model for EEG analysis that handles **input variability** and provides **uncertainty quantification** for reliable decision-making.

- **Input Adaptability:** Handle variable channel configurations and sampling frequencies across heterogeneous EEG datasets.
- **Uncertainty Estimation:** Produce calibrated confidence scores to support clinical decision-making.
- **Multi-Modal Pretraining:** Pretrain on diverse biological signals (EEG, ECG, EMG) for robust representations.

We gratefully acknowledge the support of

Ciencias

This work has been possible thanks to the collaboration of these institutions.

[Authors, 2024] Authors, M. (2024).
Eeg-bench: A benchmark for eeg foundation models in clinical applications.
arXiv preprint arXiv:2512.08959.
Reports LaBraM 83.8% on TUAB abnormal detection, BENDR 74.0% and NeuroGPT 73.4% on epilepsy detection.

[Lai et al., 2025] Lai, J., Wei, J., Yao, L., and Wang, Y. (2025).
A simple review of eeg foundation models: Datasets, advancements and future perspectives.

[Wu et al., 2025] Wu, J., Ren, Z., Wang, J., Zhu, P., Song, Y., Liu, M., Zheng, Q., Bai, L., Ouyang, W., and Song, C. (2025).
Adabrain-bench: Benchmarking brain foundation models for brain-computer interface applications.
arXiv preprint arXiv:2507.09882.
Cross-subject: CBraMod 88.9%, LaBraM 85.8% on EEGMAT. Multi-subject: LaBraM 70.9%, CBraMod 70.3% on SEED.