Medical/Bio Research Topics Ⅰ: Week 01 (4 March 2025)

Overview of Brain Imaging-based Artificial Intelligence Models

뇌영상 기반 인공지능 모델 개요

Course Introduction

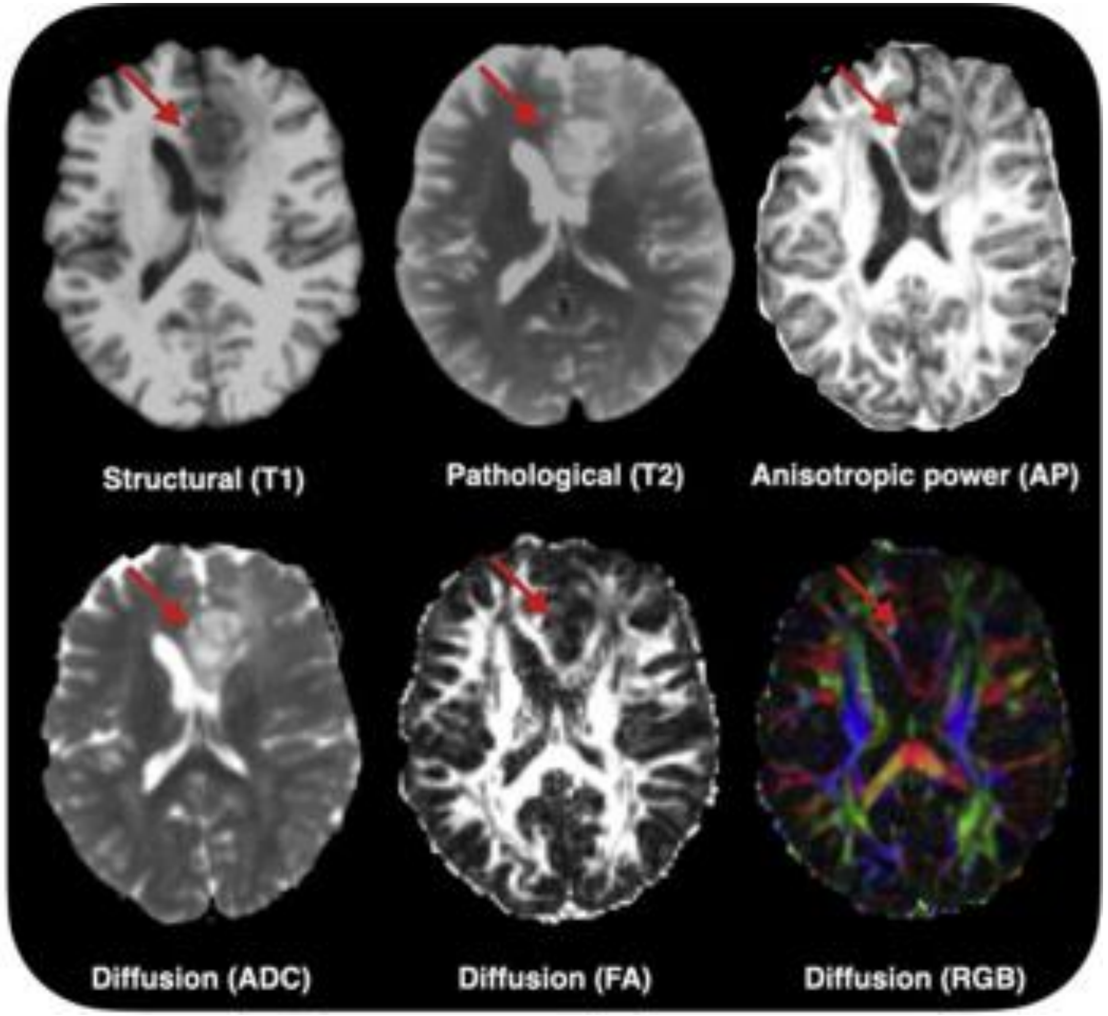
- Course: AI Convergence Medical/Bio Research Topics I
  - Introduction to brain imaging data as medical data
  - Explanation for processing brain imaging data
  - Hands-on practice in developing brain imaging-based AI models
- Objectives
  - To understand the clinical utility of brain imaging
  - To secure knowledge and experience in developing brain imaging-based AI models

- Format
  - Lecture: 70%
  - Presentation/discussion: 30%
- Evaluation
  - Midterm exam: 30 points
    - Overall understanding of course content
  - Presentation/discussion: 60 points
    - AI model development
  - Participation: 10 points

- Course schedule
  - Weeks 1-2: Overview
  - Weeks 3-8: Brain imaging
  - Week 9: Midterm exam
  - Weeks 11-12: Brain imaging-based AI models
  - Weeks 13-14: Presentation/discussion
  - Week 15: Summary and review

Brain Imaging Practices in Radiology

- Precise diagnosis
  - Selecting imaging techniques (e.g., MRI, CT, PET) depending on the suspected condition
  - Identifying abnormalities such as tumors, strokes, hemorrhages, inflammation, and structural anomalies, aiding in the accurate diagnosis of the underlying condition



Brain Lesion Detection

- Informed prognosis
  - Evaluating disease progression by assessing the extent and severity of brain abnormalities, for example, the size and spread of tumors or the extent of stroke damage
  - Identifying biomarkers that help predict disease progression and outcomes, particularly in degenerative diseases and brain injuries
  - Monitoring changes in the brain over time by regular imaging, helping to predict how a patient is responding to treatment and adjust prognosis accordingly

- Effective treatment planning
  - Guiding surgery or other interventions by providing detailed maps of the brain to ensure that treatments target the correct areas while avoiding critical structures
  - Delineating tumor boundaries and planning targeted radiation therapy, minimizing exposure to healthy brain tissue, in oncology
  - Evaluating whether certain treatments are viable options based on the location, size, and nature of brain lesions

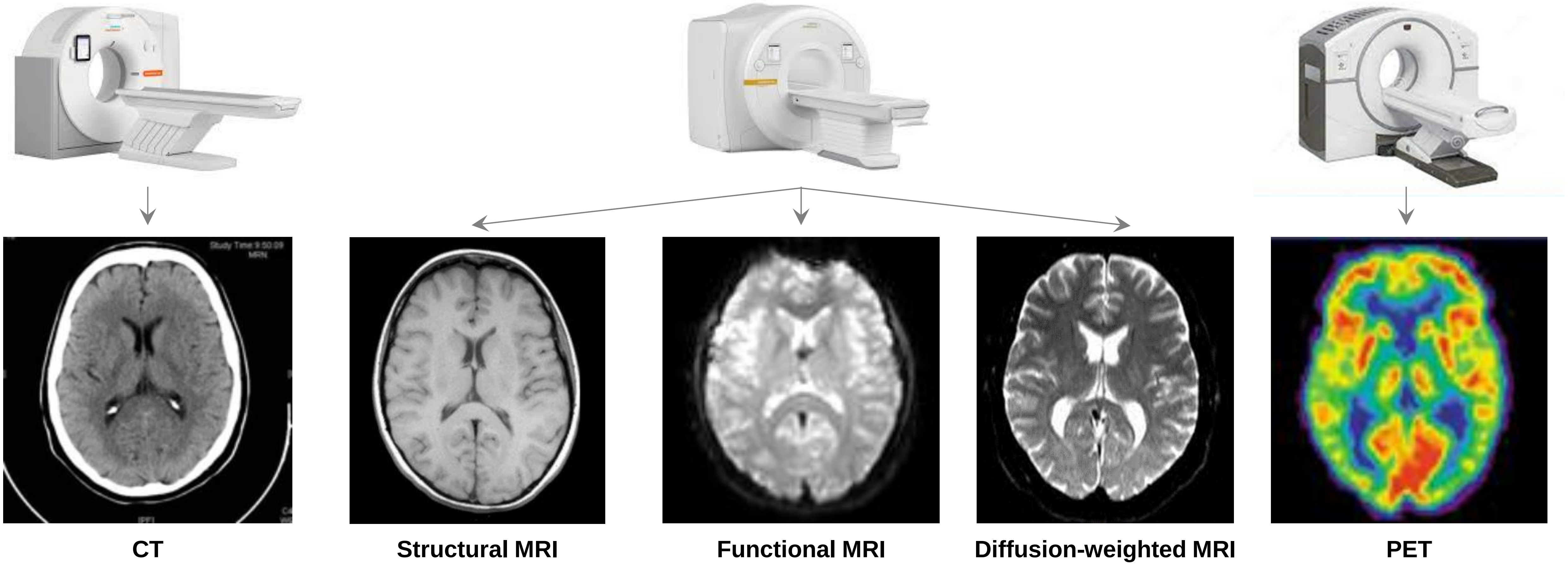
- Ongoing management
  - Assessing the effectiveness of treatments, such as the shrinkage of tumors in response to chemotherapy or changes in inflammatory markers after medication adjustments
  - Detecting complications arising from the disease or treatment, such as bleeding post-surgery or radiation-induced changes, allowing for timely intervention
  - Regular imaging for long-term surveillance to detect recurrence or manage chronic diseases effectively

- General process for brain imaging in radiology
  - Referral
    - From a healthcare provider, who identifies the need for brain imaging based on the patient's symptoms, medical history, and physical examination
    - Choice of modality, often in consultation with a radiologist
  - Preparation
    - Patient instructions, such as fasting or withholding certain medications
    - Safety screening, particularly for contraindications to MRI, such as implanted metal devices or claustrophobia
    - Contrast agent, which may be administered to enhance the visibility of certain structures or abnormalities

- Imaging procedure
  - Positioning on the scanning table, ensuring comfort and the correct posture for optimal imaging of the brain
  - Scanning in the imaging device (e.g., the gantry of a CT scanner or the bore of an MRI machine) for the duration which can vary from a few minutes to an hour, depending on the modality and the extent of imaging required
  - Monitoring throughout the procedure
- Post-procedure
  - Immediate care, especially if a contrast agent was used
  - Instructions, such as hydration to help eliminate a contrast agent

- Analysis and reporting
  - Processing for optimal visualization, including adjustments of brightness, contrast, and in some cases, 3D reconstructions
  - Image review to identify any abnormalities or relevant findings
  - Reporting of the findings, interpretations, and any recommended further imaging or evaluations
  - Communication back to the referring provider, who will discuss the results with the patient and plan any further treatment or investigation needed
- Collaboration and follow-up
  - Interdisciplinary collaboration with other specialists (e.g., neurologists, neurosurgeons) in complex cases to provide a comprehensive interpretation of the imaging results
  - Follow-up imaging recommended to monitor changes over time or to investigate any anomalies further

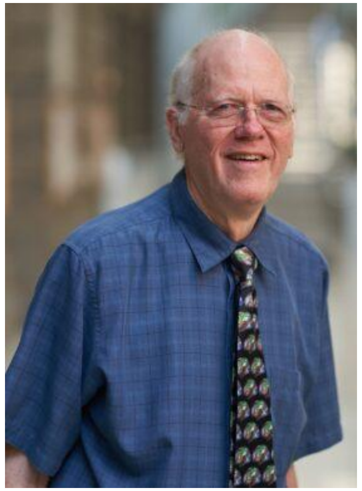
Brain Imaging



- Computed tomography (CT)
  - Uses X-rays to create detailed cross-sectional images of the brain
  - Fast and widely available, making it a first-line imaging technique in emergencies
- Magnetic resonance imaging (MRI)
  - Uses a magnetic field and radio waves to produce detailed images of the brain
  - Does not use ionizing radiation

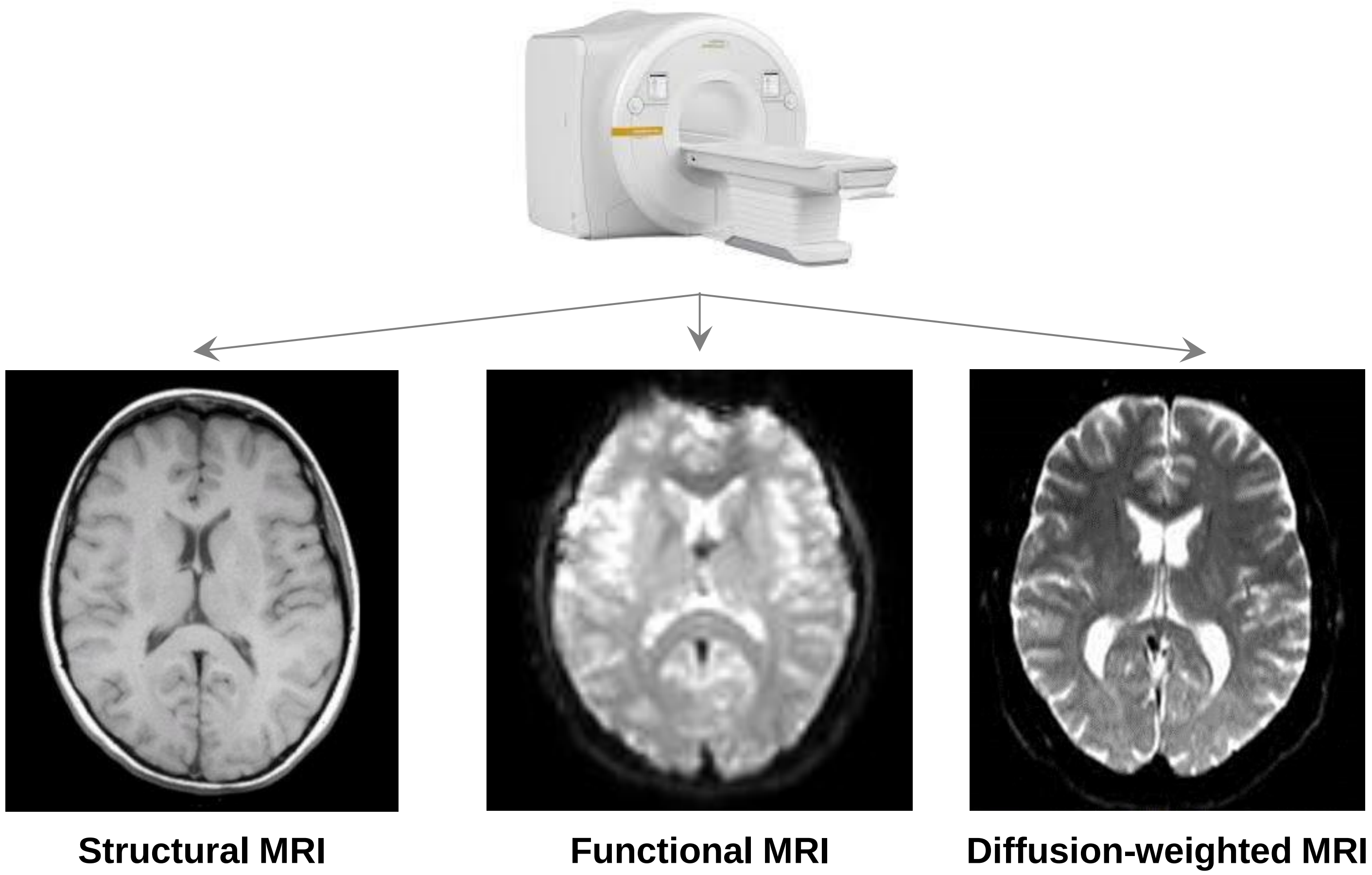
- Positron emission tomography (PET)
  - Involves the injection of a radioactive tracer into the bloodstream, which is then taken up by active brain tissue
  - Visualizes metabolic activity within the brain by detecting the radiation emitted by the tracer
- The choice of imaging techniques depends on:
  - Patient's condition
  - Specific clinical question to be answered
  - Imaging facilities available

MRI



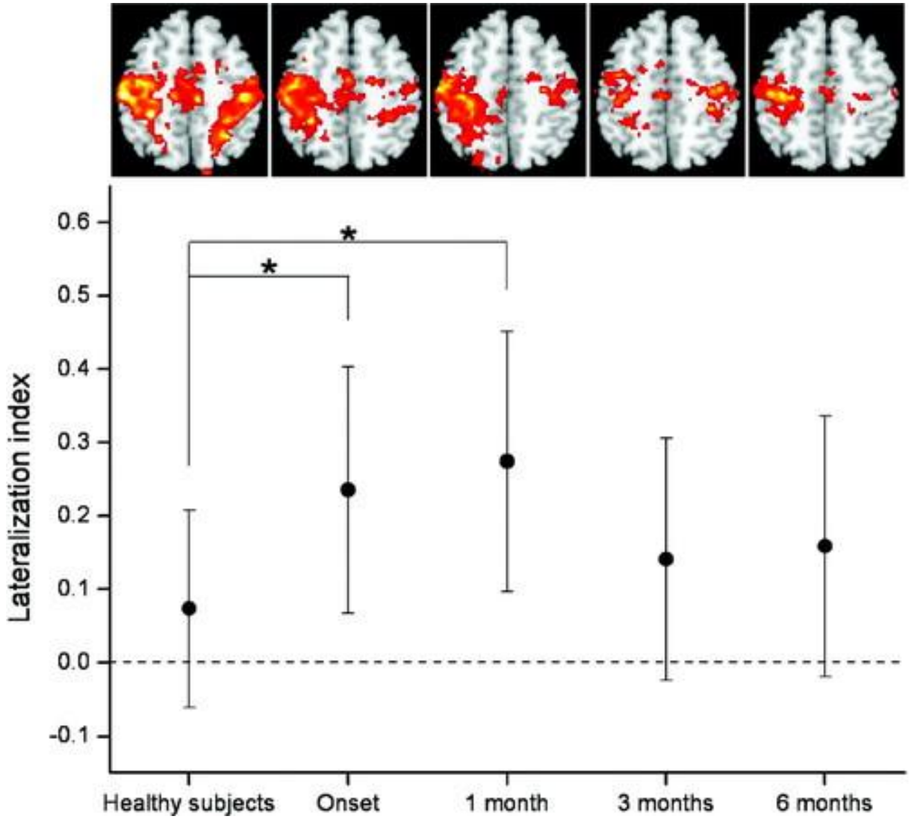
- "*A workhorse technology because of the diversity of information attainable using the same scanner to acquire images*" (D.C. Van Essen)

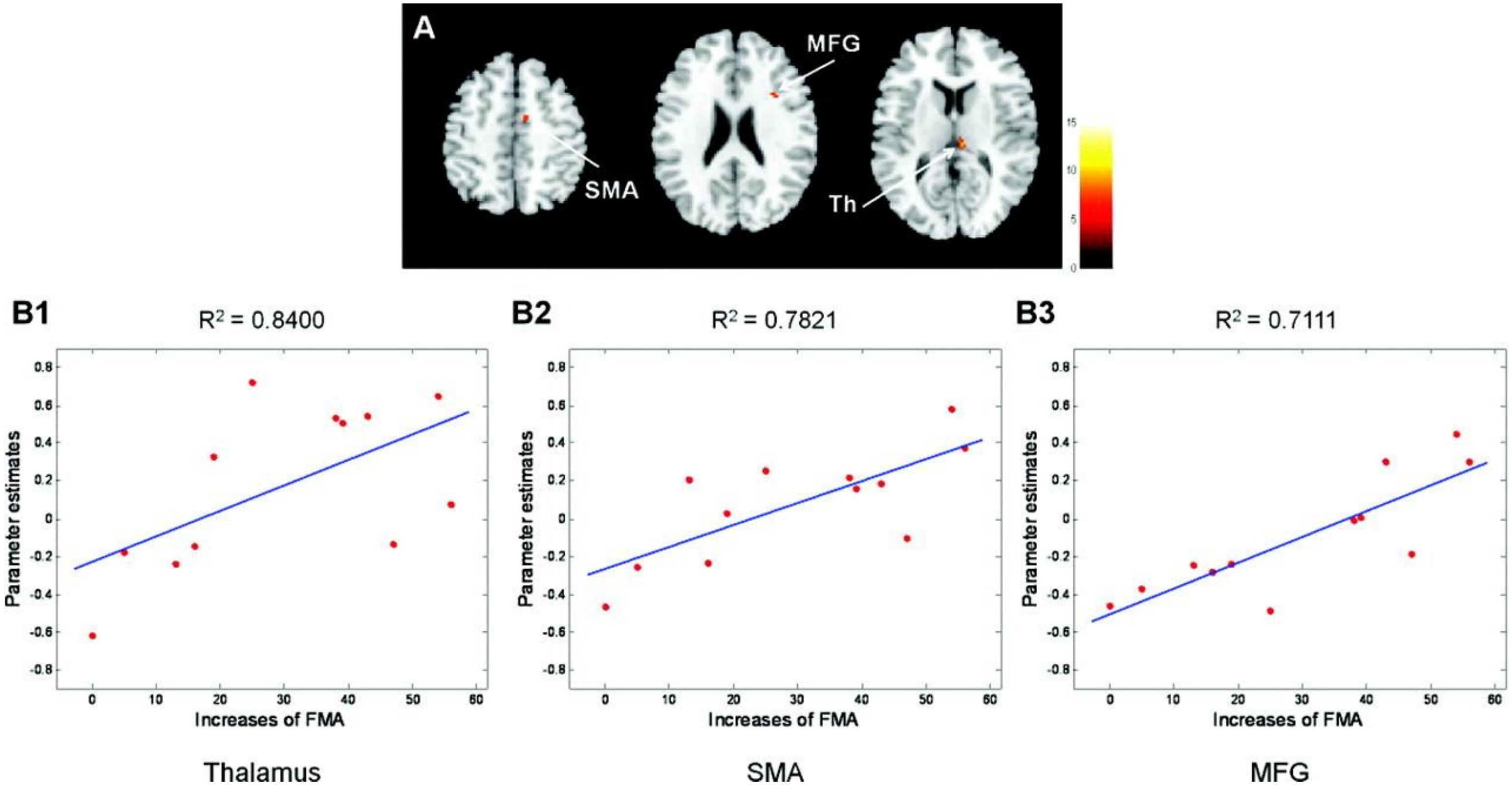
- Three main types of MRI
  - Structural MRI
  - Functional MRI
  - Diffusion-weighted MRI


Structural MRI
Functional MRI
Diffusion-weighted MRI

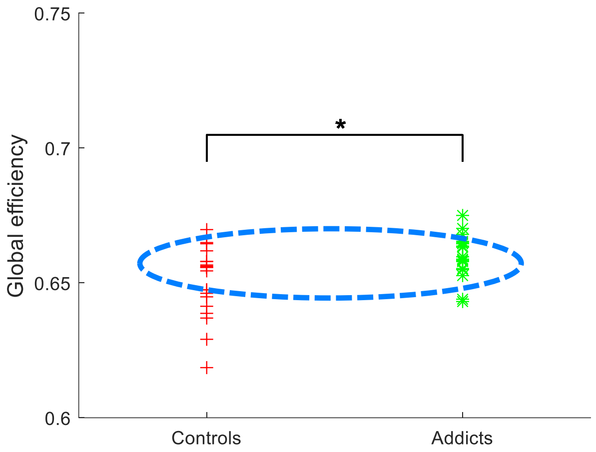
Clinical MRI Studies

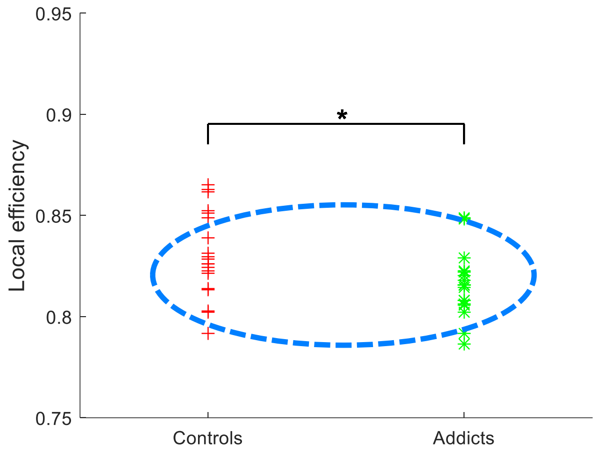
- Brain changes in recovery after stroke [Park et al, 2011]

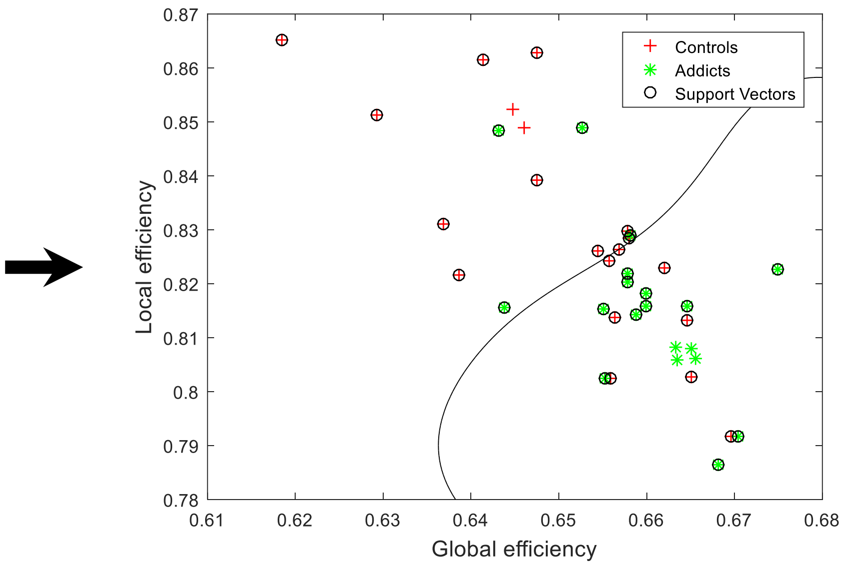



A
MFG
SMA
Th
B1
R^2 = 0.8400
Parameter estimates
Increases of FMA
B2
R^2 = 0.7821
B3
R^2 = 0.7111
Thalamus
SMA
MFG

- Classification beyond describing group differences







Machine Learning (ML)

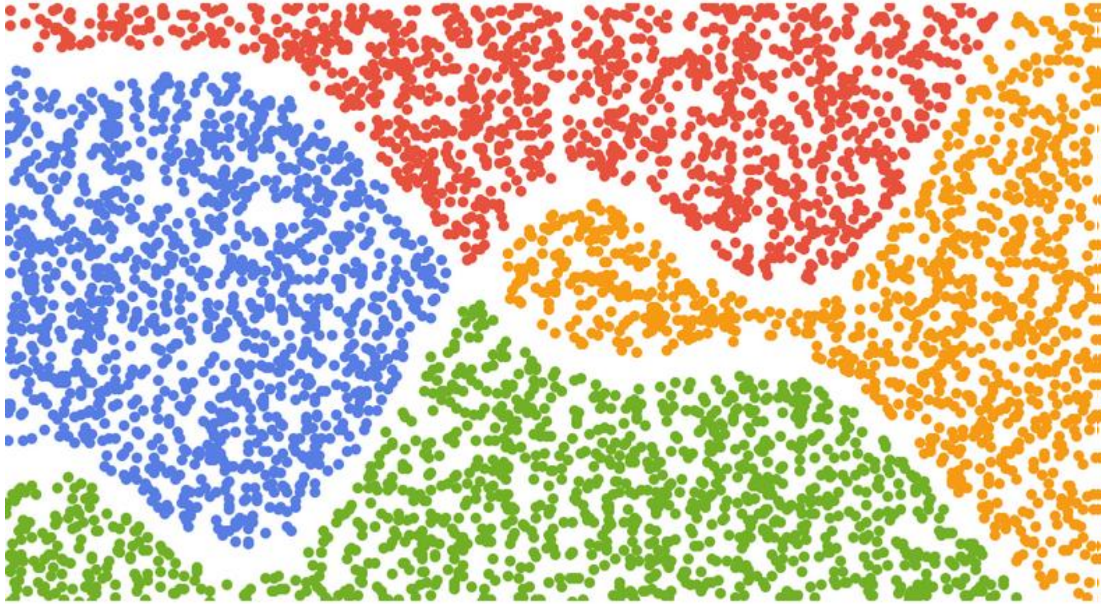
- Subset of AI that enables systems to learn patterns from data and make predictions or decisions without being explicitly programmed
- Key characteristics:
  - [Data-driven learning] Learns from structured or unstructured data rather than relying on rule-based programming
  - [Generalization ability] Aims to generalize from training data to unseen data, making accurate predictions on new inputs

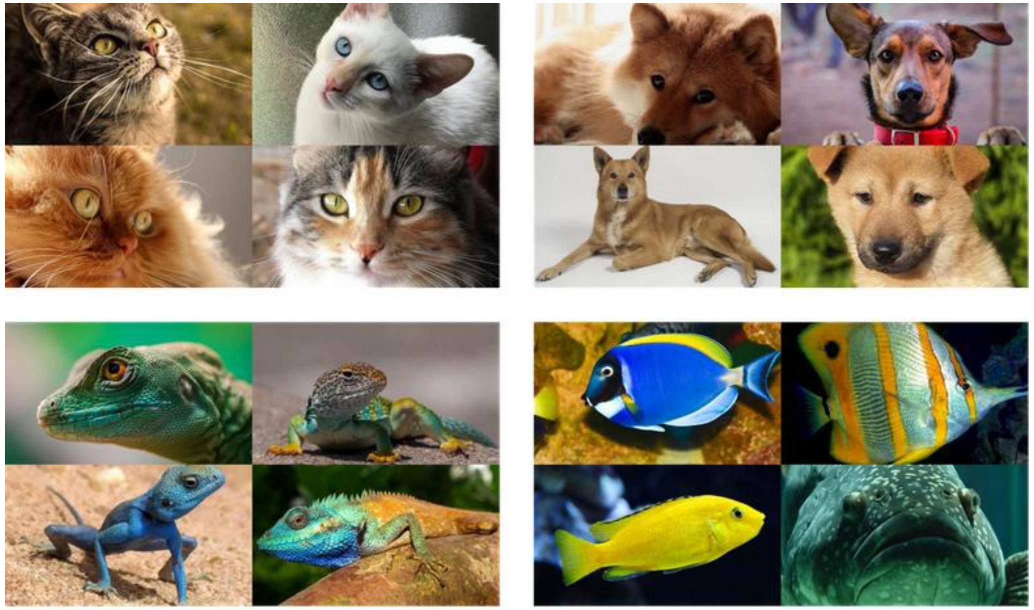
- Based on learning paradigm
  - Supervised learning
    - Learns from labeled data to make predictions
  - Unsupervised learning
    - Discovers patterns and structures in unlabeled data
  - Semi-supervised learning
    - Uses a mix of a small amount of labeled data and a large amount of unlabeled data
  - Reinforcement learning
    - Learns through interaction with the environment through rewards and penalties

- Based on data supervision
  - Online learning
    - Learns incrementally from continuously arriving data
  - Batch learning (offline learning)
    - Trains on entire dataset at once
- Based on model purpose
  - Discriminative models
    - Learns the direct mapping from inputs to outputs by estimating $P(Y|X)$
  - Generative models
    - Learns the joint probability distribution $P(X,Y)$, enabling to generate new data samples by drawing from the estimated distribution

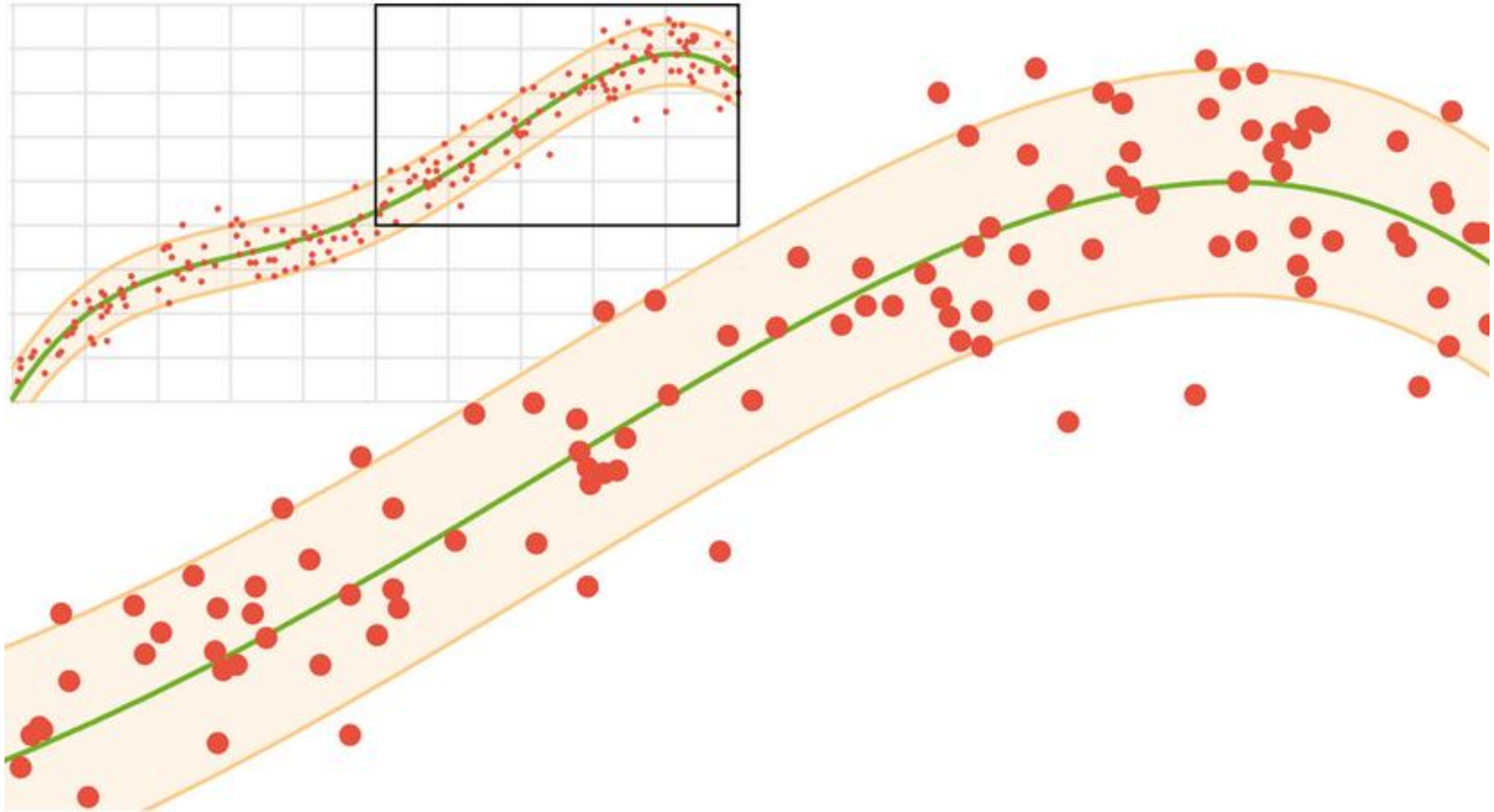
- Based on model architecture
  - Traditional ML (shallow learning)
    - Relies on statistical methods and simpler architectures
    - Often requires manual feature extraction and engineering
    - Linear models (linear regression, logistic regression), tree-based models (decision trees, random forest, gradient boosting machines (GBMs) like XGBoost, LightGBM, CatBoost), support vector machines (SVMs), etc.
  - Deep learning
    - Composed of multiple hidden layers
    - Capable of learning hierarchical features automatically
    - Feedforward neural networks (FNNs), convolutional neural networks (CNNs), recurrent neural networks (RNNs), transformers, etc.

- Based on application domains
  - Predictive modeling
  - Computer vision
  - Clustering
  - Dimensionality reduction
  - Anomaly detection
  - Natural language processing (NLP)
  - Speech processing

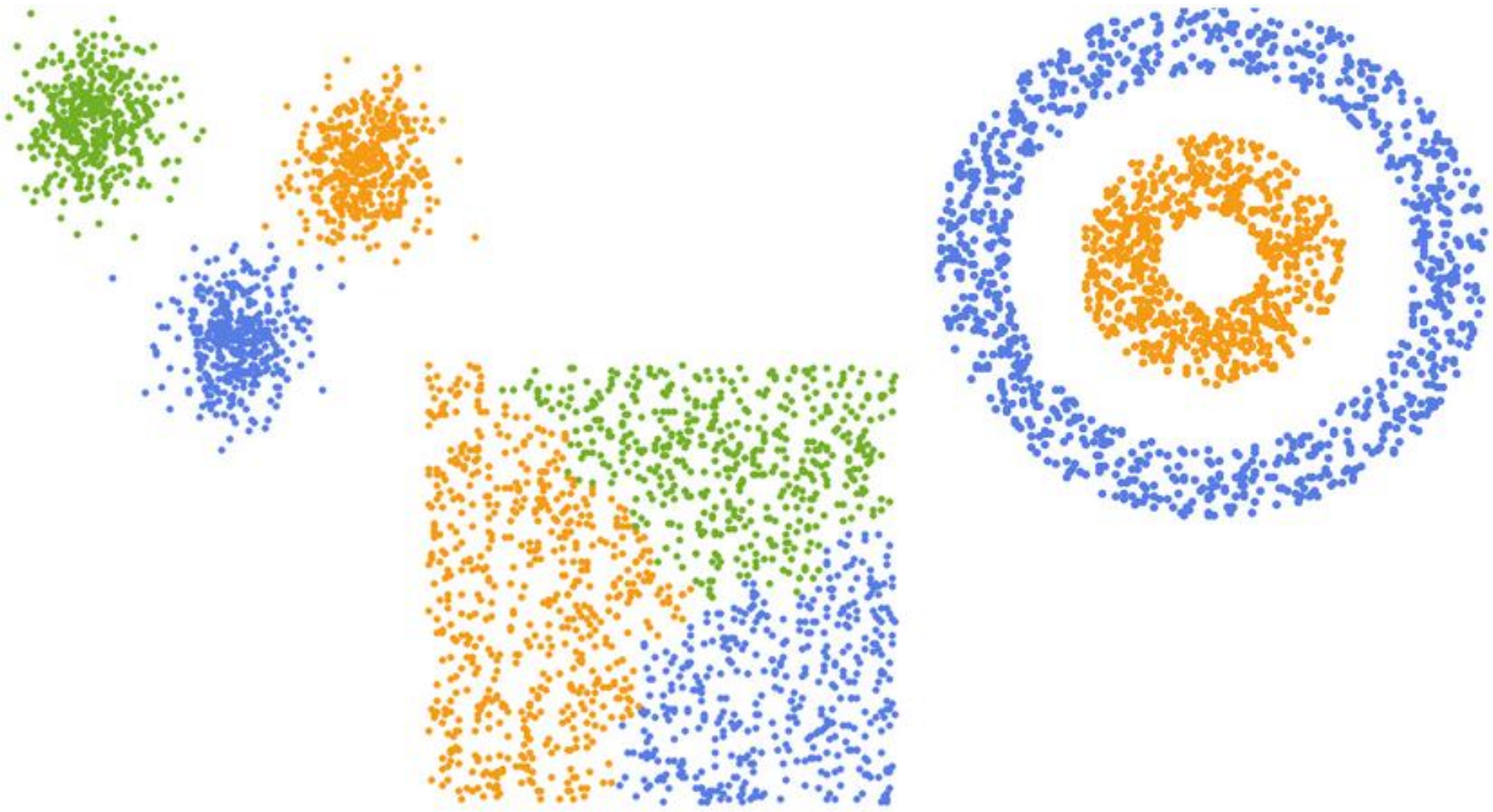




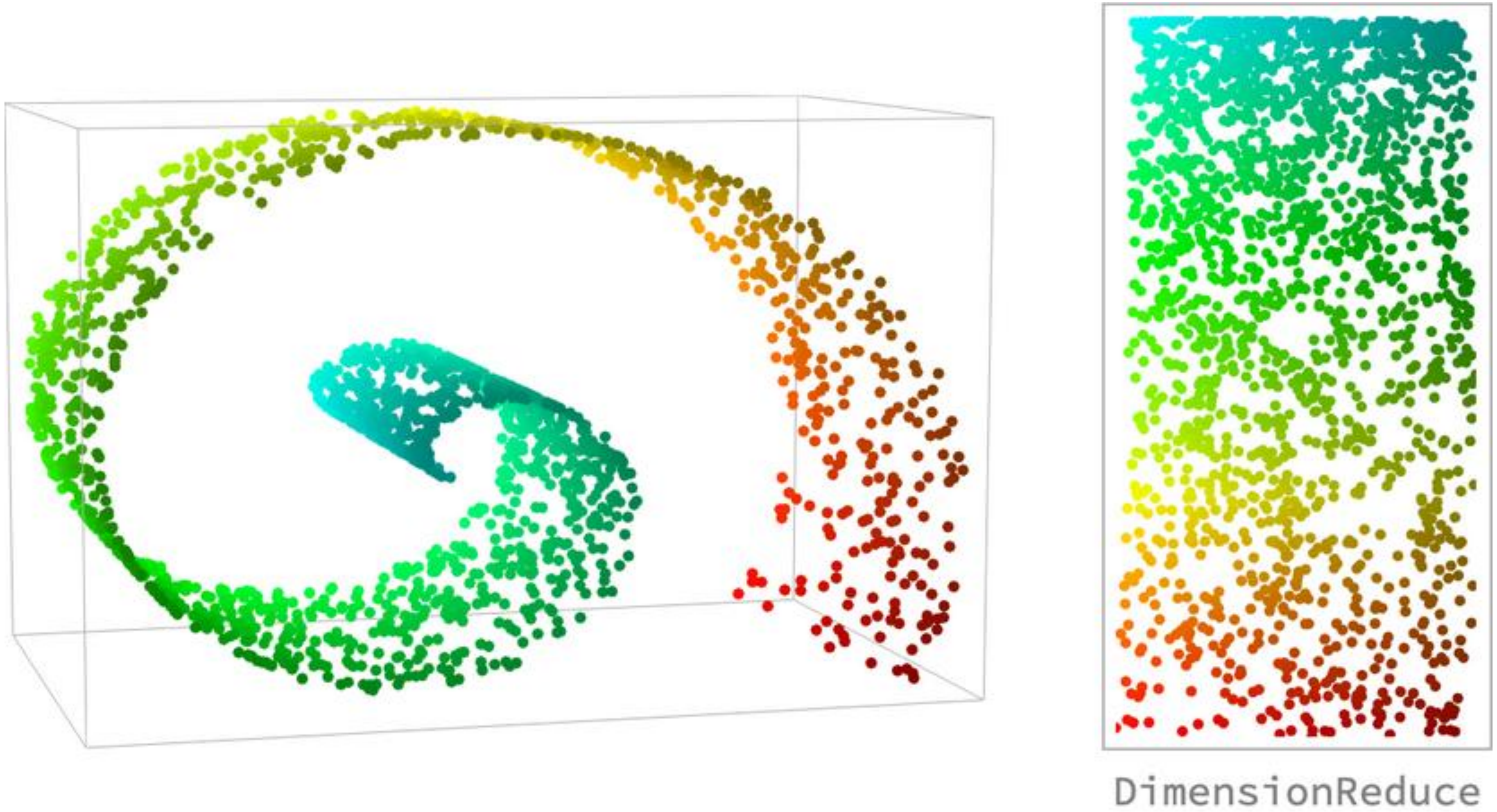
Predictive Modeling: Classification



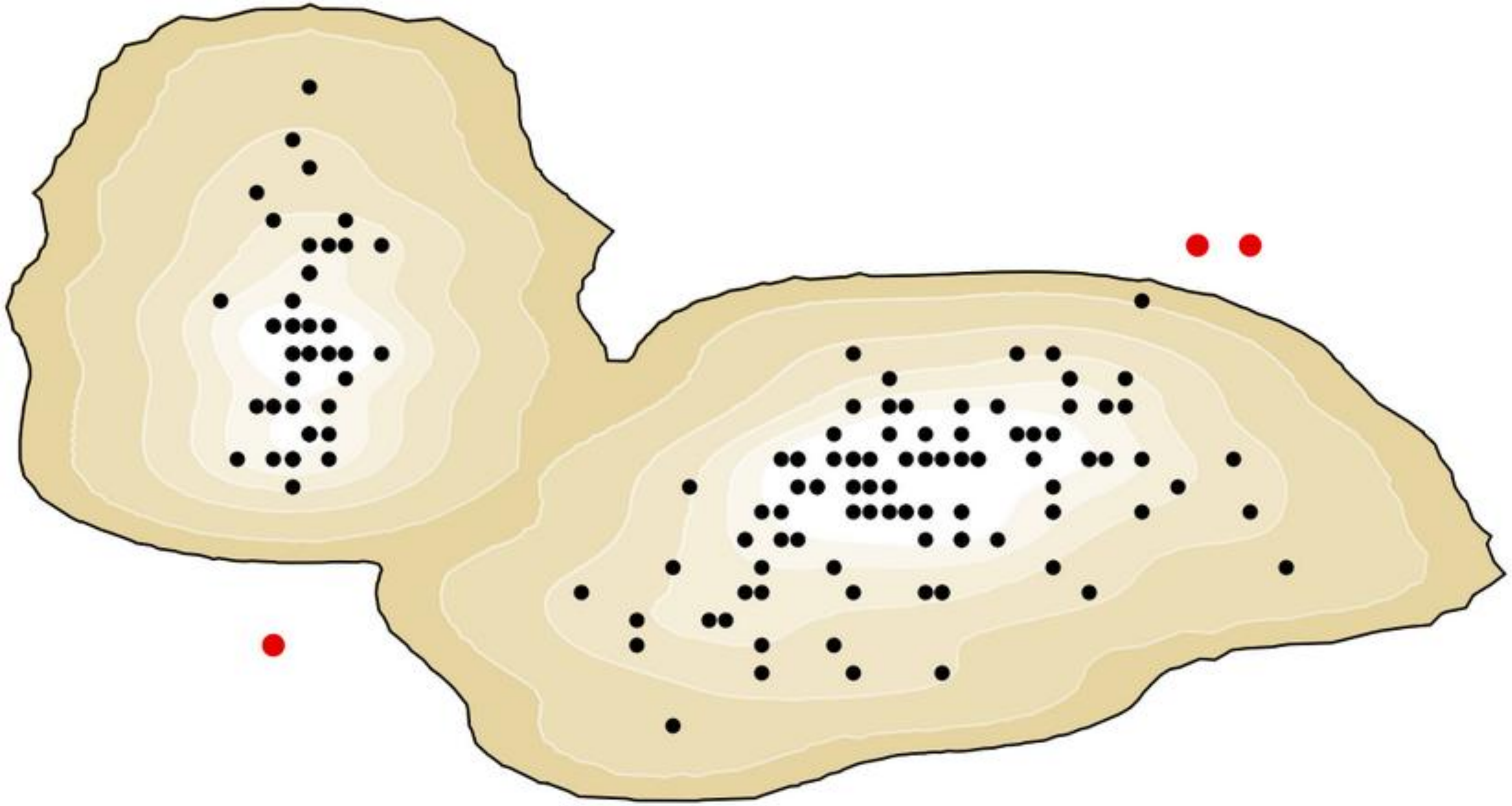
Predictive Modeling: Regression



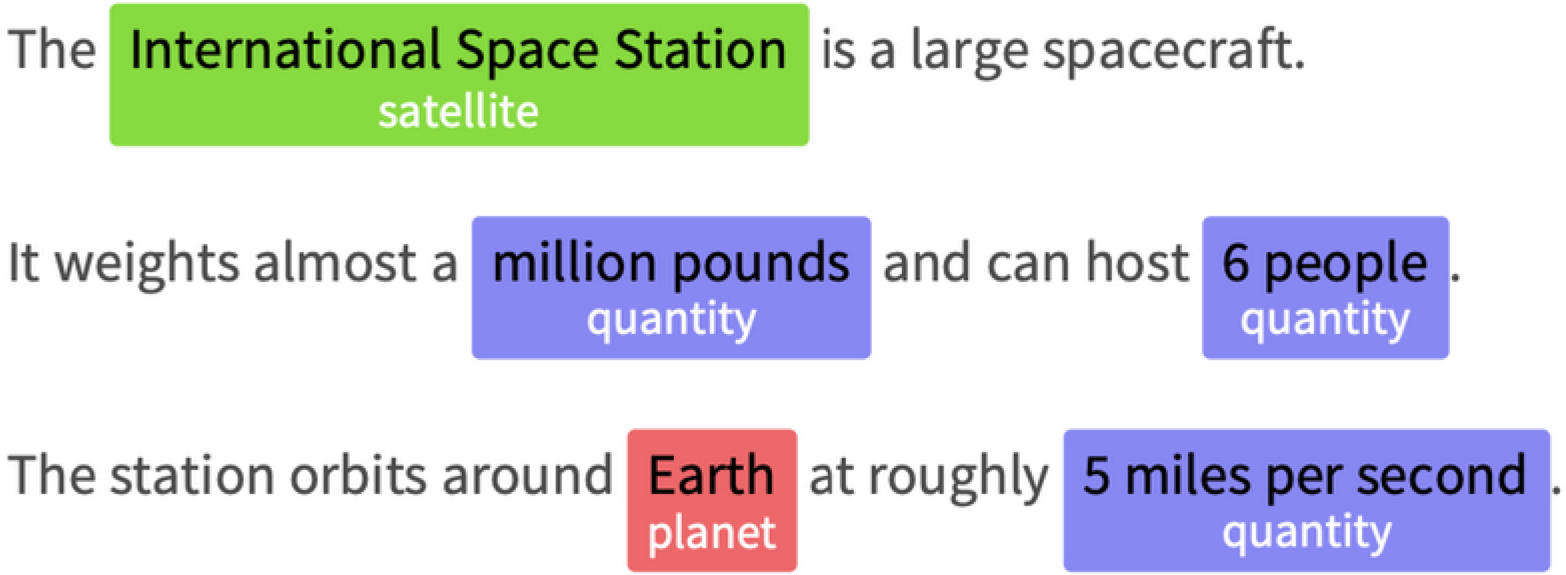
Clustering



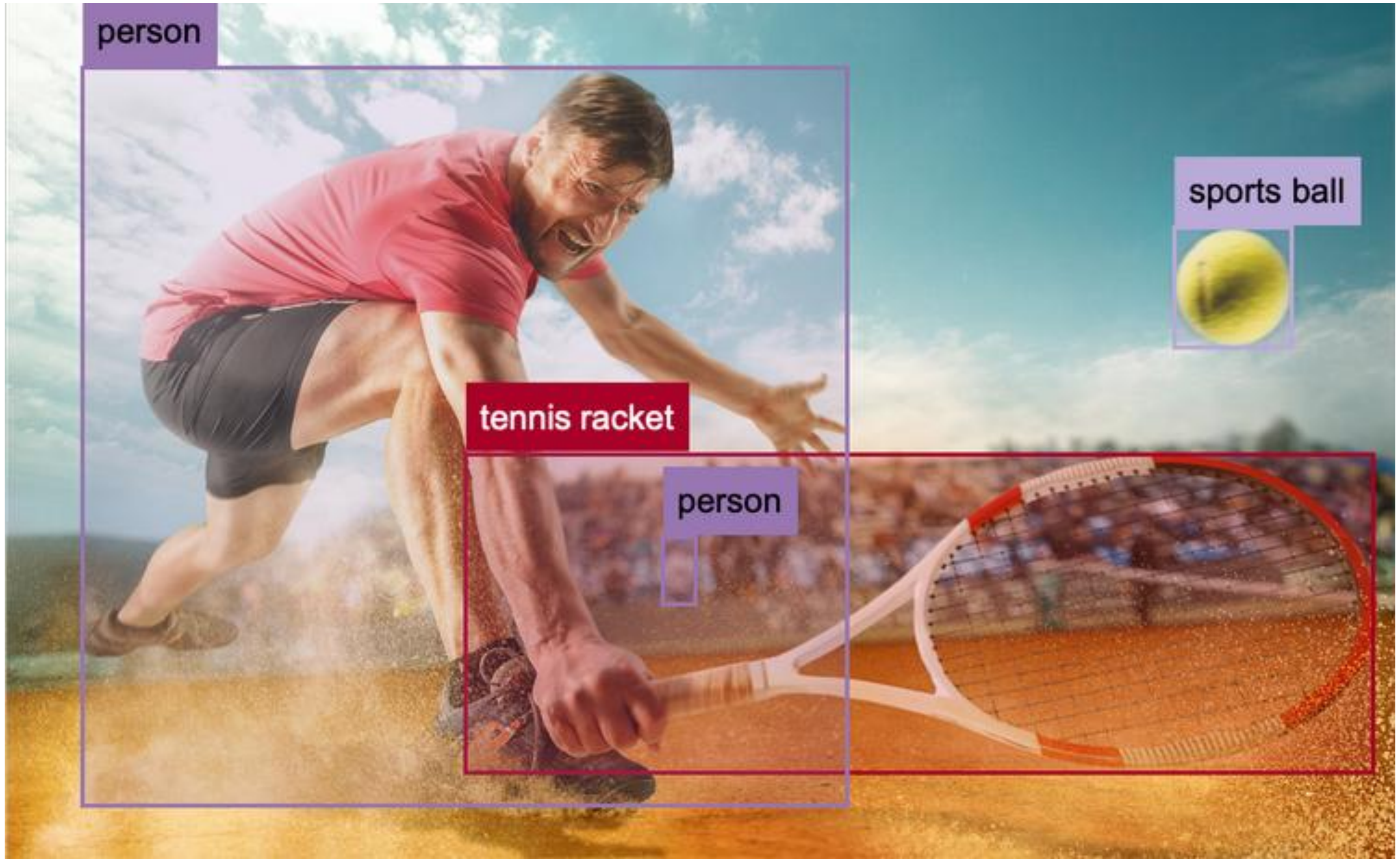
Dimensionality Reduction



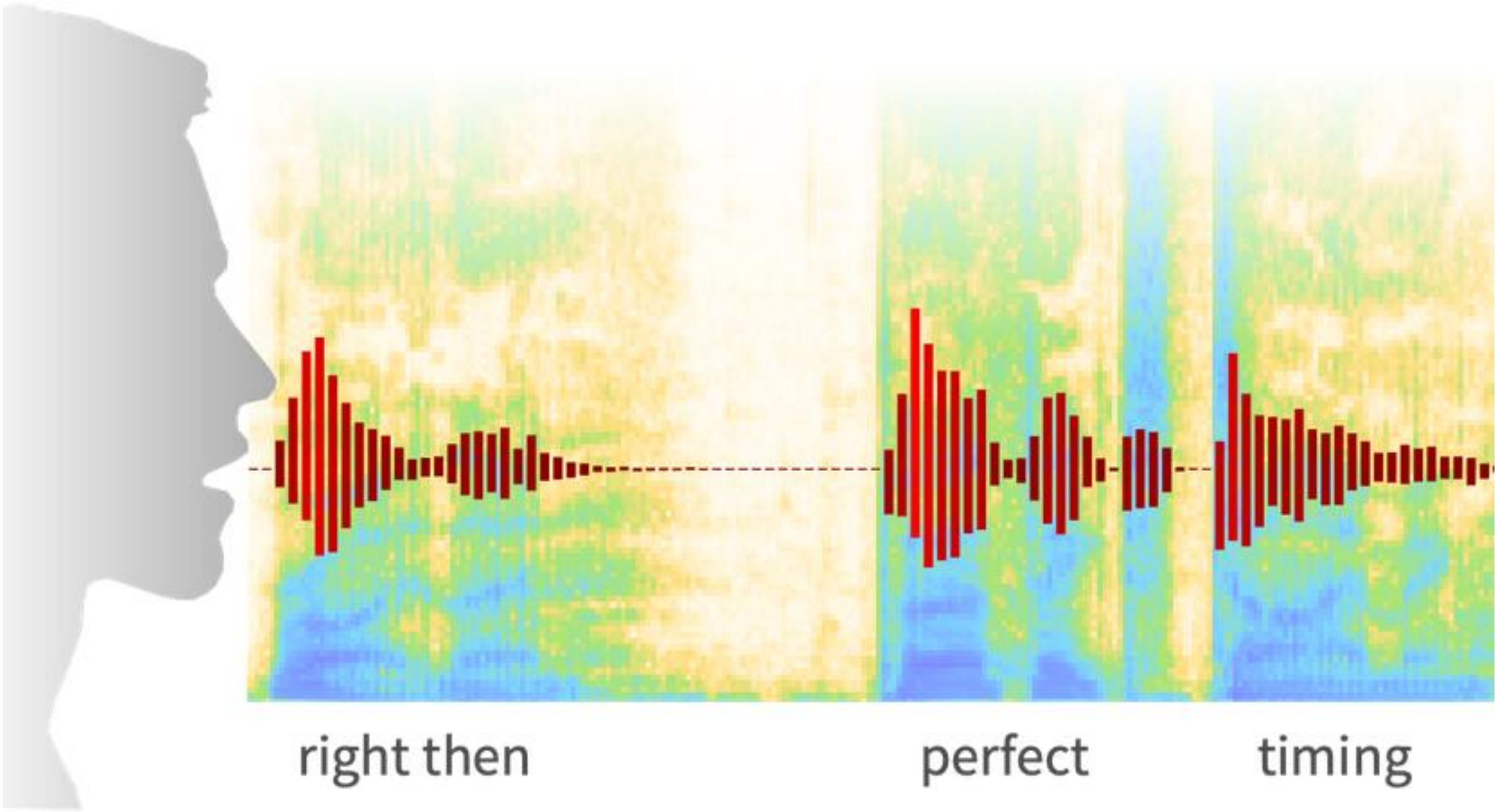
Anomaly Detection



Natural Language Processing



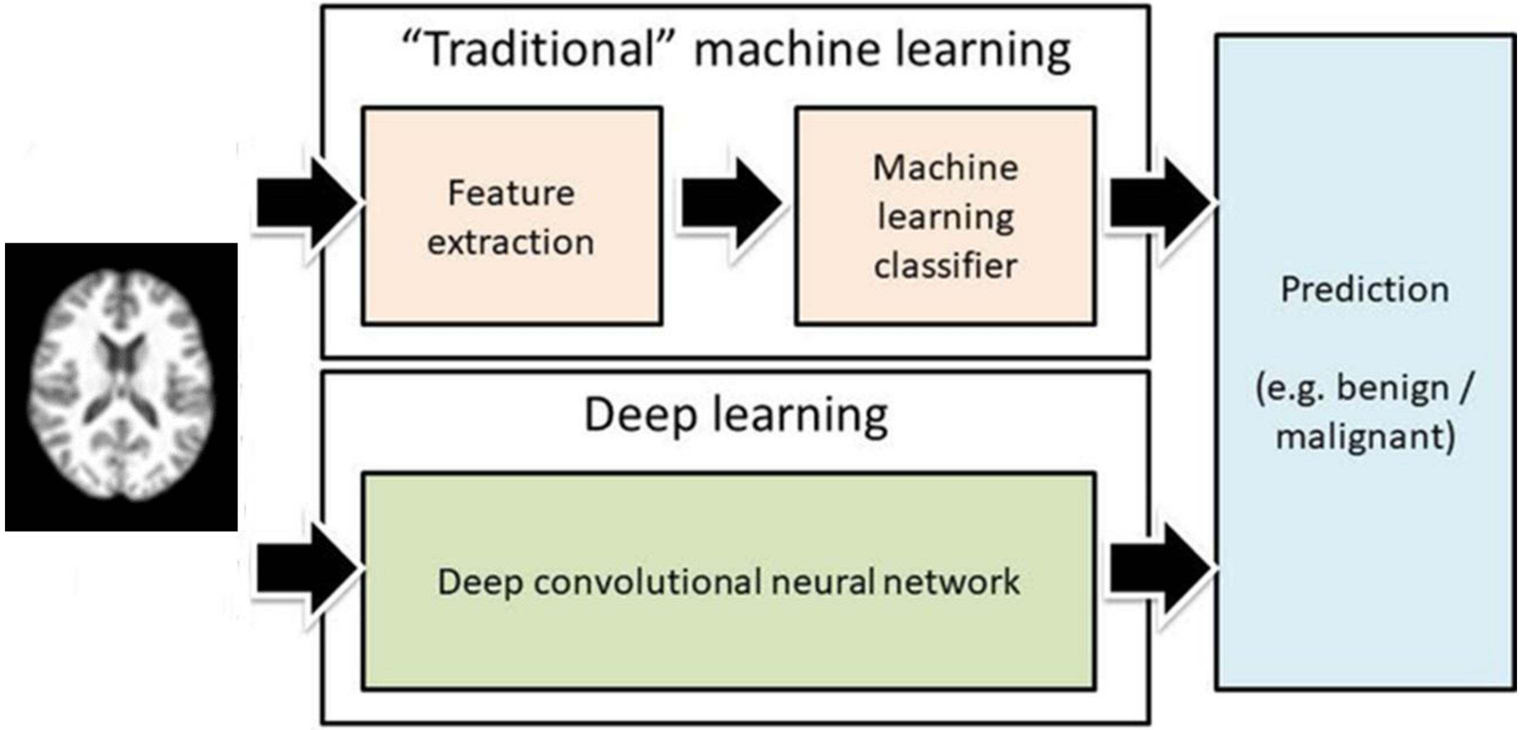
Computer Vision



Speech Processing

- ML models to be covered in this course
  - Based on learning paradigm: Supervised learning
  - Based on data supervision: Batch learning
  - Based on model purpose: Discriminative models
  - Based on model architecture: Traditional ML and deep learning
  - Based on application domains: Predictive modeling

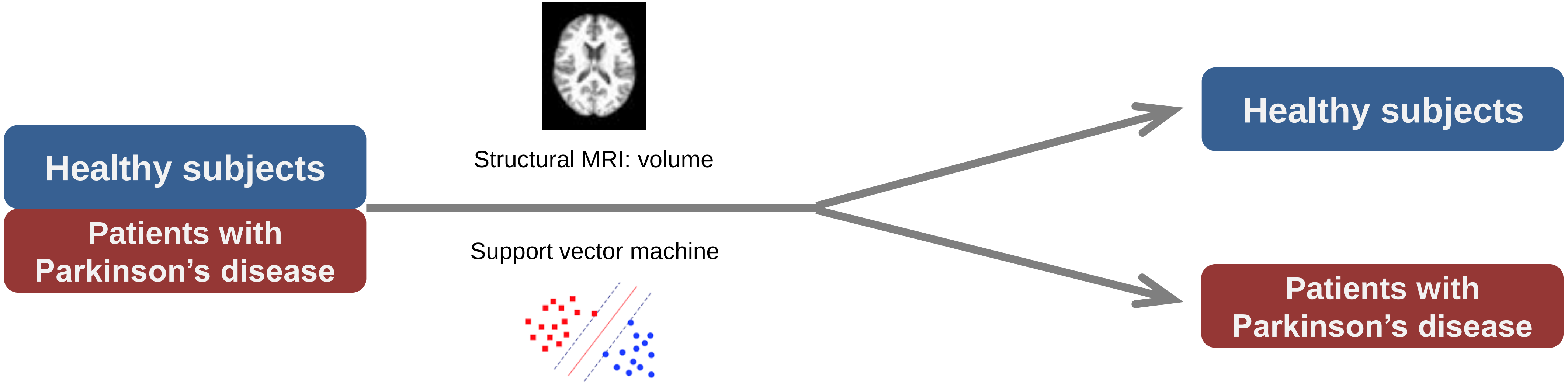
MRI-based ML Studies



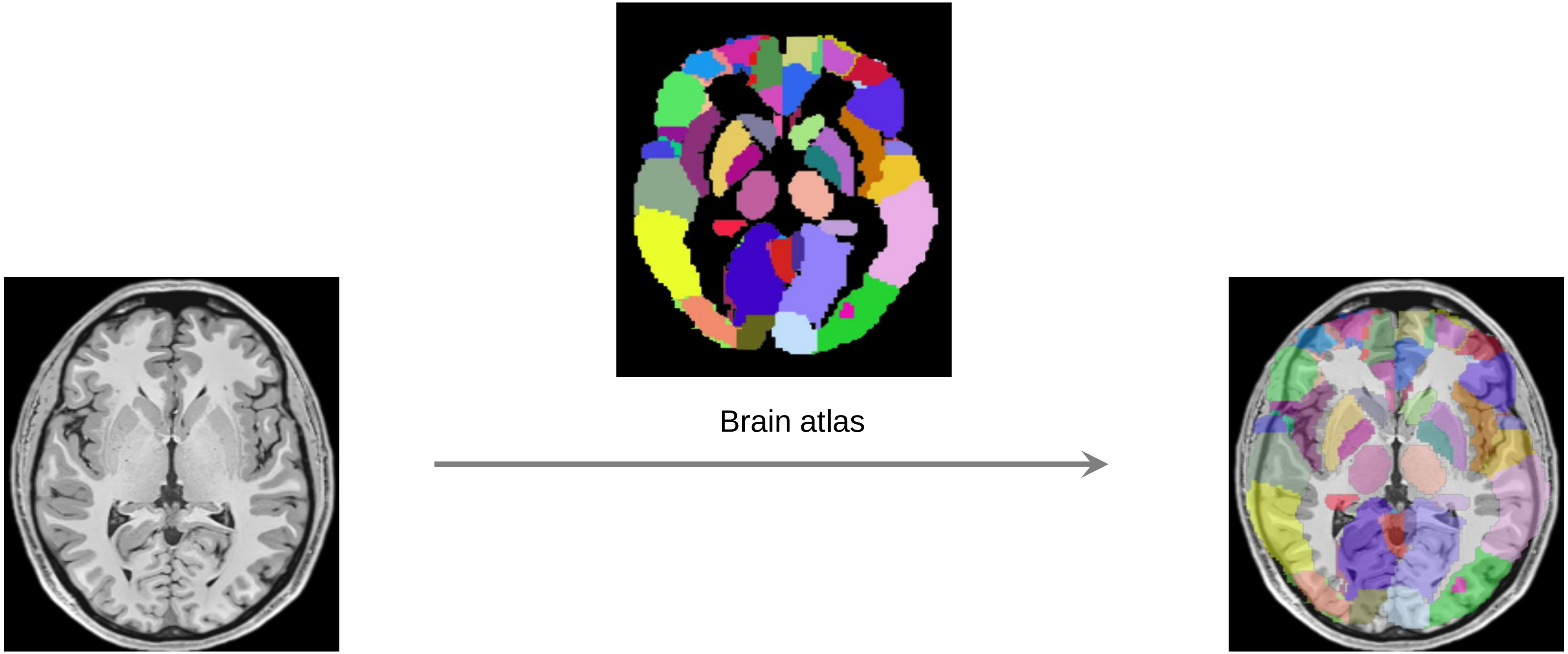
[Mazurowski et al., 2018]

Difference between Traditional ML and Deep Learning

- Classification



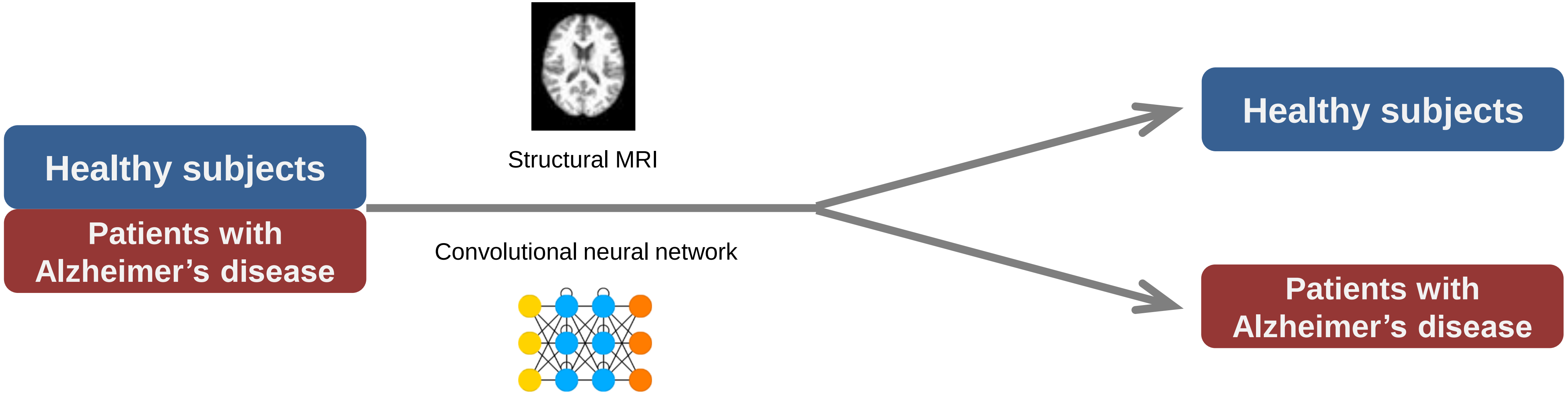
[Park et al., 2020]



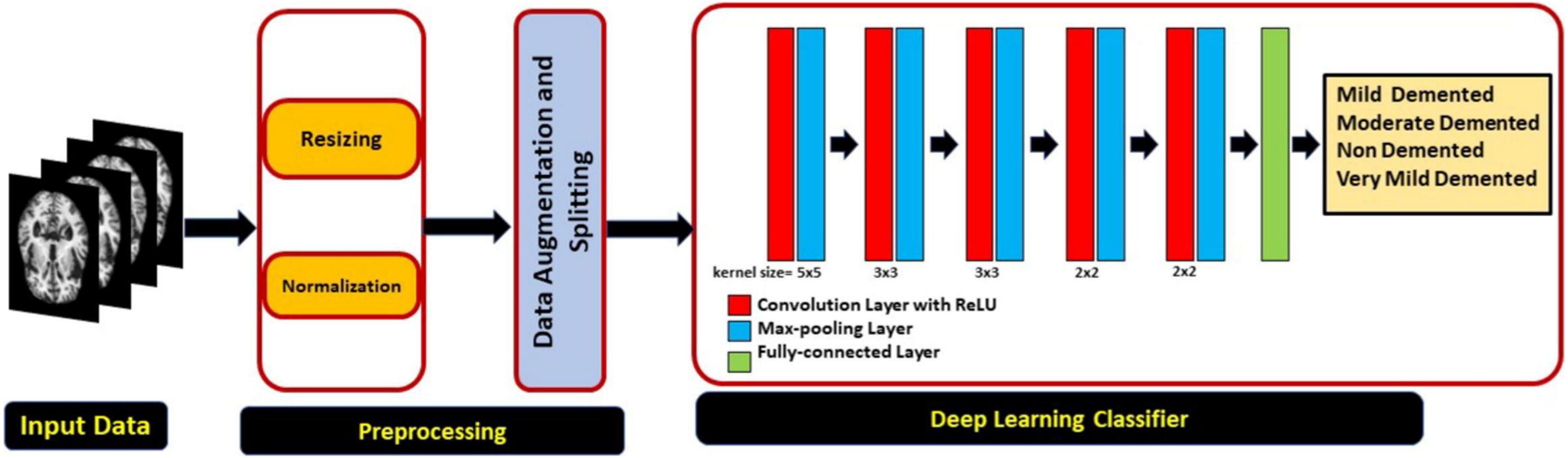
Features

Samples

	Brain area 1 volume	Brain area 2 volume	Brain area 3 volume	…
Subject 1	-	-	-	-
Subject 2	-	-	-	-
Subject 3	-	-	-	-
⋮	-	-	-	-



[EL-Geneedy et al., 2023]



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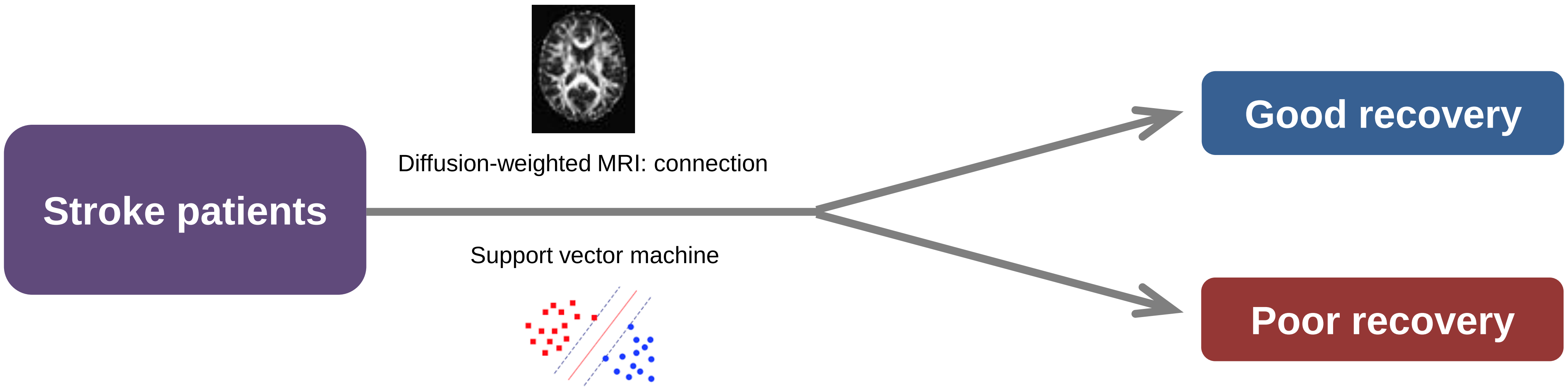
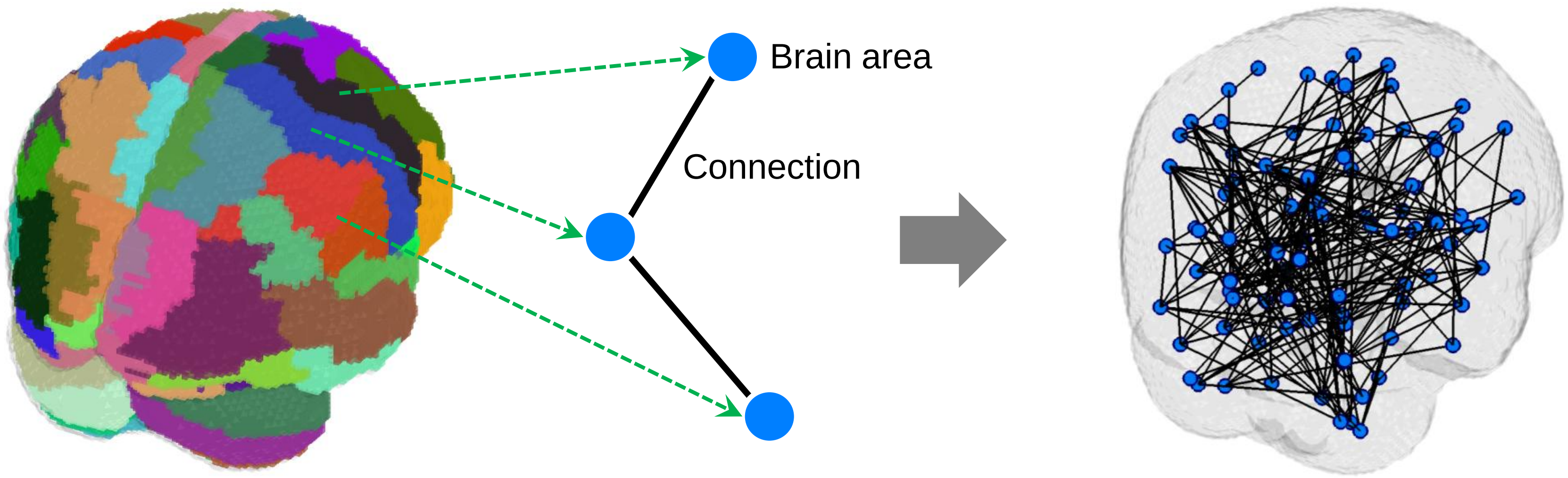


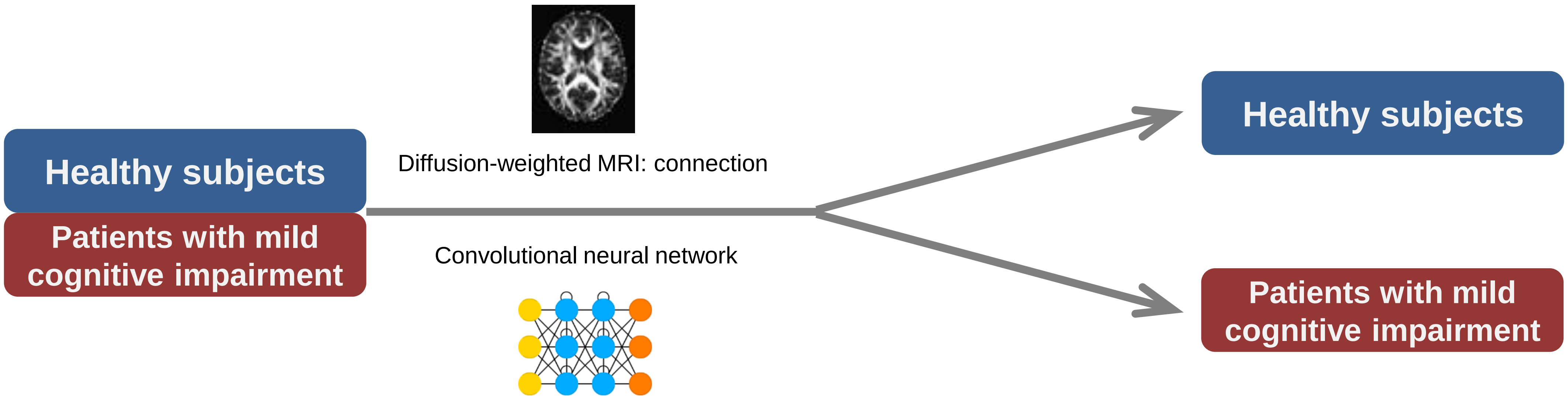
[Koch et al., 2021]



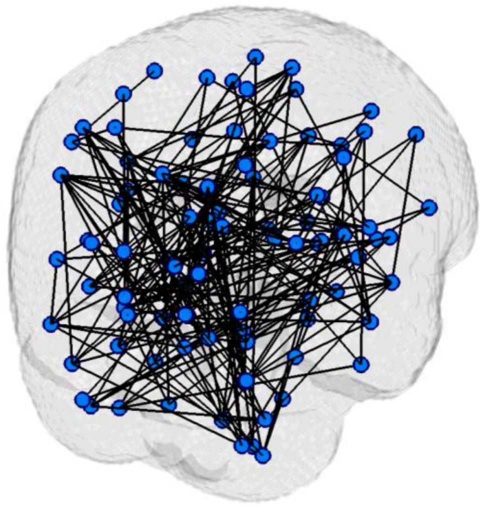
Features

Samples

	Brain areas 1 – 2 connection	Brain areas 1 – 3 connection	Brain areas 1 – 4 connection	…
Subject 1	-	-	-	-
Subject 2	-	-	-	-
Subject 3	-	-	-	-
⋮	-	-	-	-



[Kolahkaj et al., 2023]



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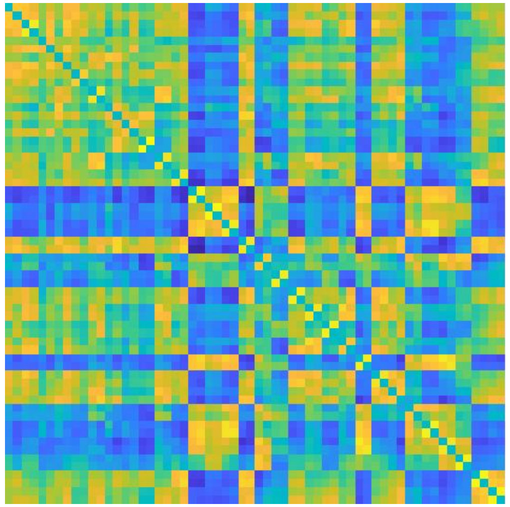
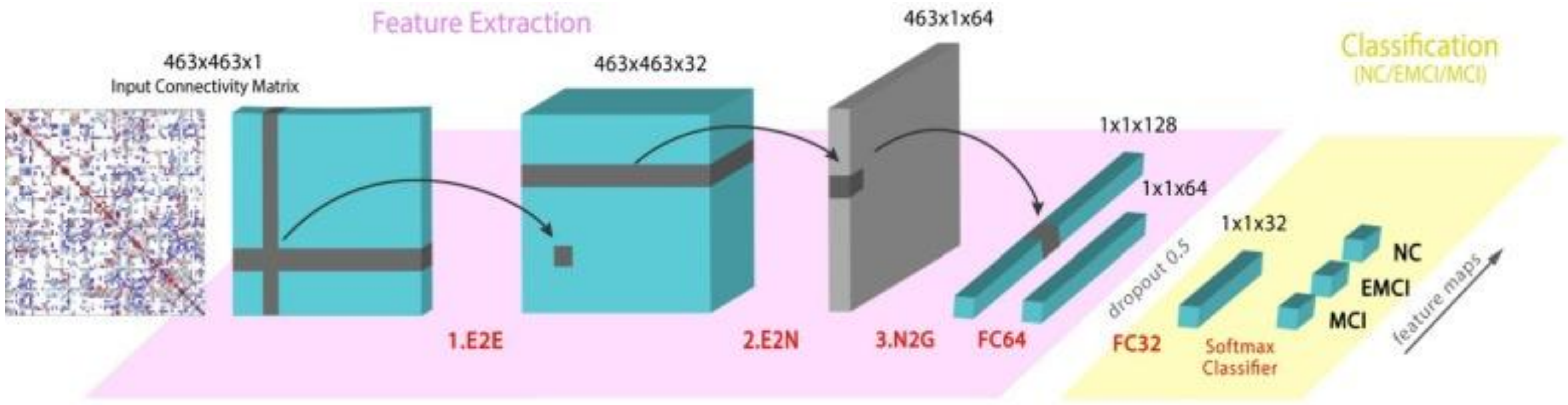
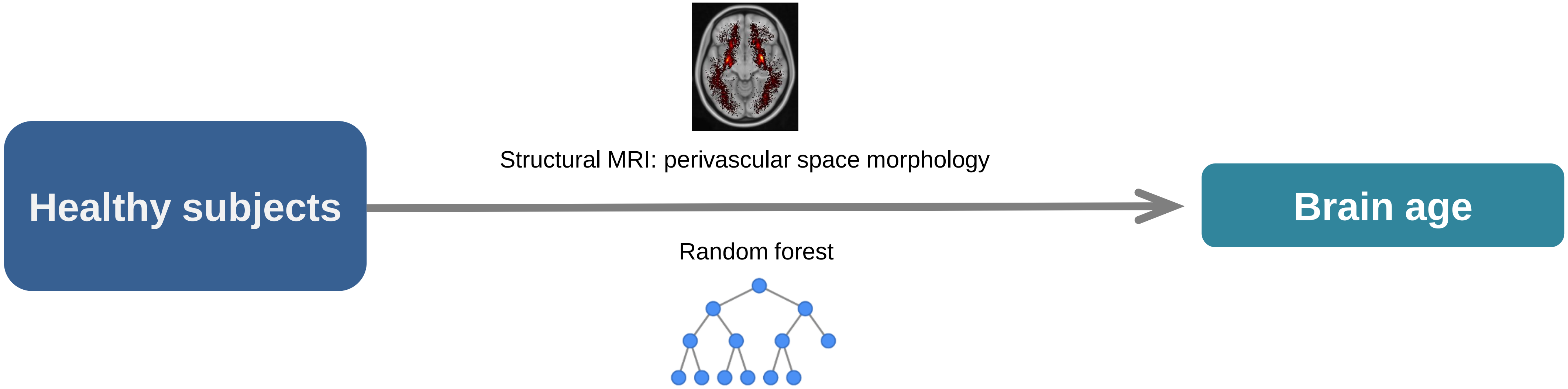


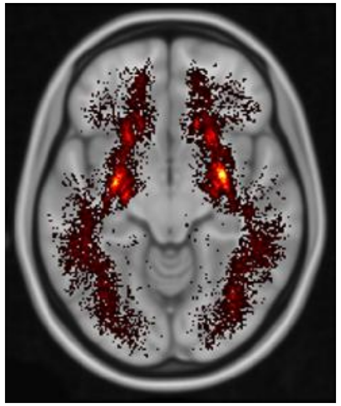


[Kolahkaj et al., 2023]

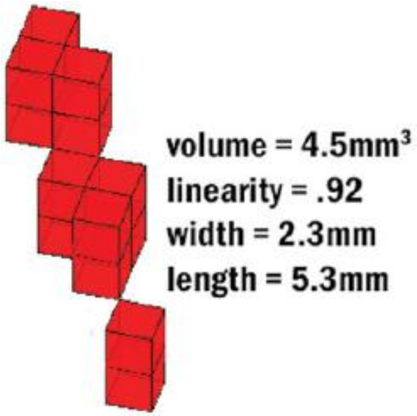
- Regression



[Park et al., 2023]



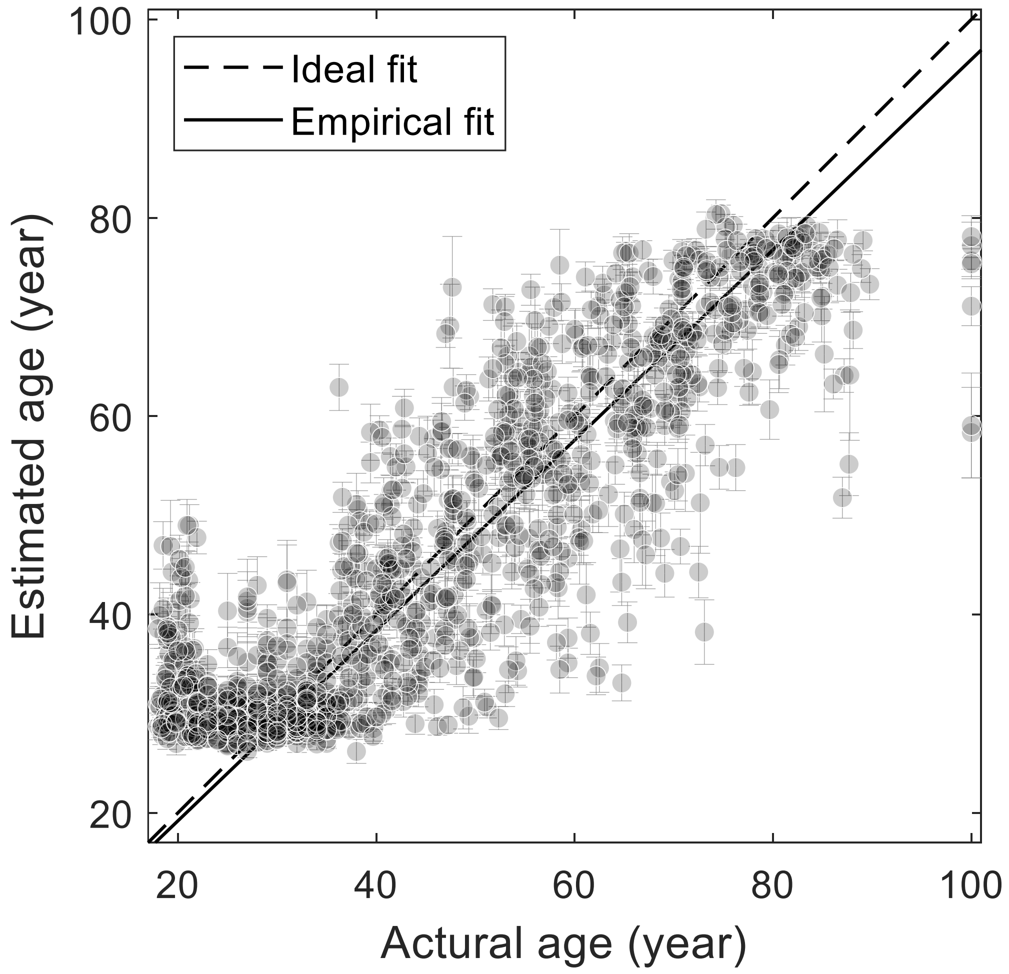
Perivascular space (PVS)



Features

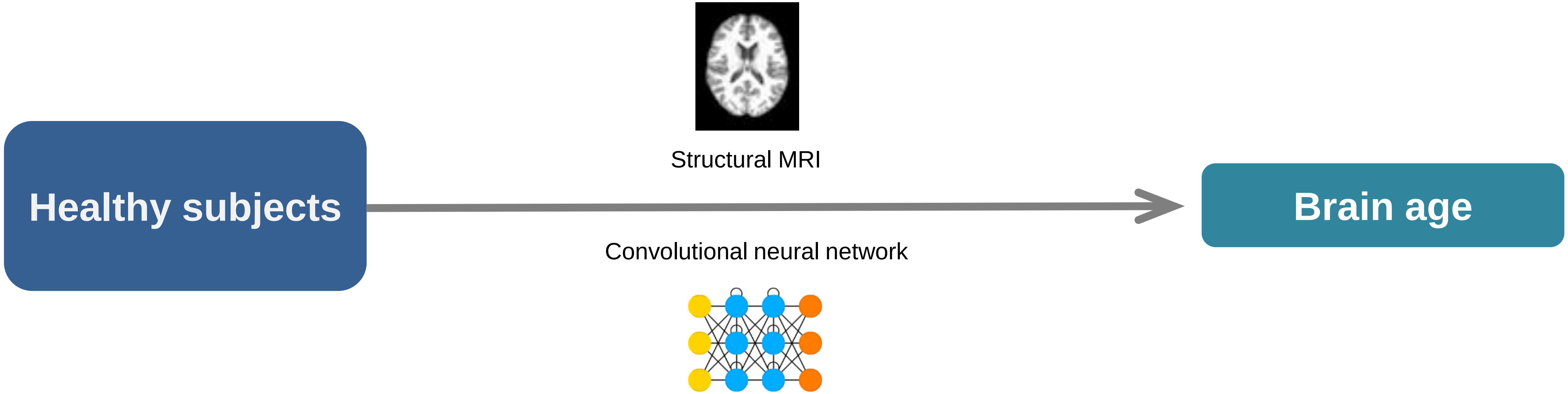
Samples

	Brain area 1 PVS volume	Brain area 1 PVS linearity	Brain areas 1 PVS width	…
Subject 1	-	-	-	-
Subject 2	-	-	-	-
Subject 3	-	-	-	-
⋮	-	-	-	-

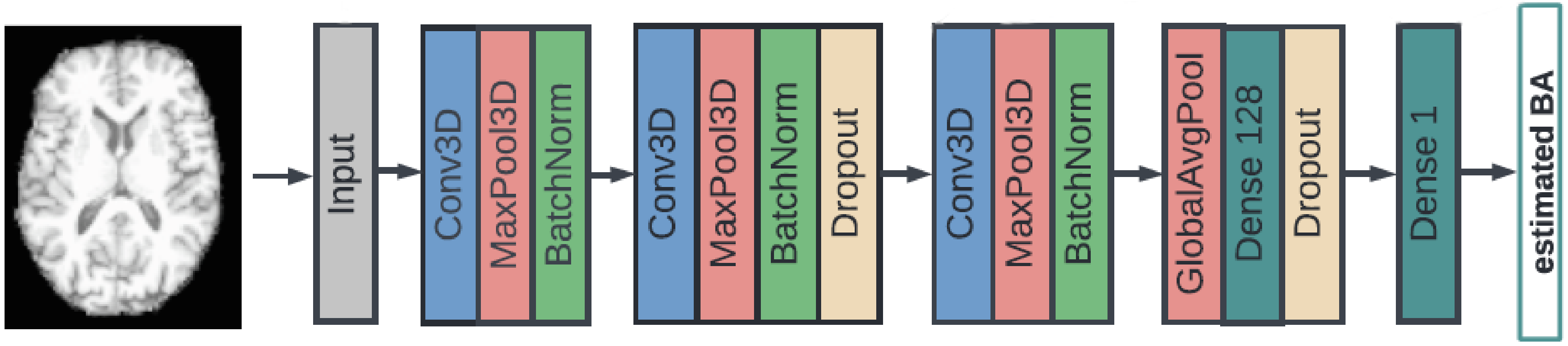


[Park et al., 2023]

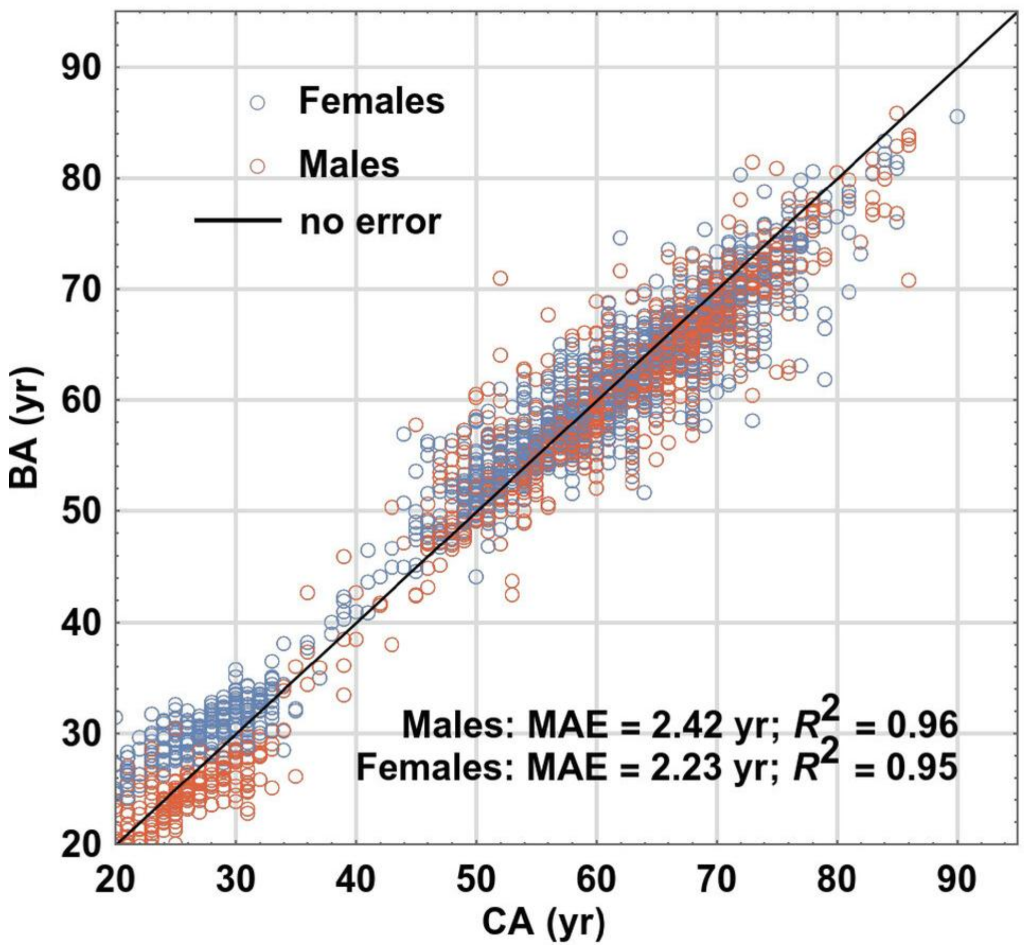
Actual Age (Chronological Age) vs. Estimated Age (Brain Age)



[Yin et al., 2023]



[Yin et al., 2023]



[Yin et al., 2023]

Actual Age (Chronological Age) vs. Estimated Age (Brain Age)

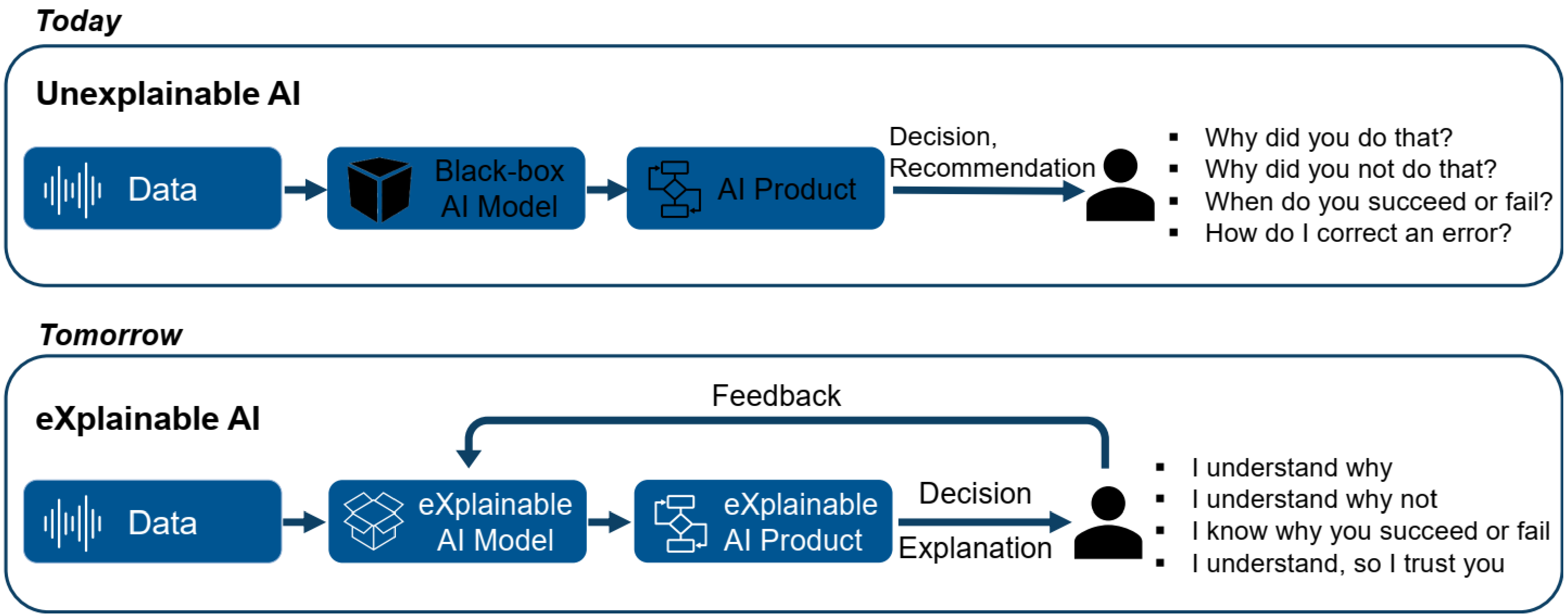
Demands for MRI-based ML

- Good Machine Learning Practices (GMLPs)
  - Standardized guidelines and best practices for developing, validating, and implementing ML systems in healthcare
- Explainable AI (XAI)
  - AI systems designed to make their decisions transparent and interpretable to humans

Checklist of GMLPs for brain MRI		
1.	Are neuroradiologists, neuroimaging scientists, MR technician and data scientist working together throughout the whole life cycle of the product?	
2.	Is the patient's personal information anonymous in the brain MR images?	
3.	Is the metadata being filled for each patient scan with proper details of all parameters?	
4.	Does training and testing MR datasets contain different scans? There shouldn't be any common scan in both datasets.	
5.	Does reference MR dataset for validation of model have completely unique scans with same parameters as training and testing dataset?	
6.	Are you using the model for segmenting brain structures from the specific contrast for which it has been trained for? If so, don't use it for other contrasts.	
7.	Is the output of the model accepted and readable by the neuroradiologist?	
8.	Has the model been tested in the neuroradiology department under the supervision of an expert neuroradiologist before deployment?	
9.	Are the precautions and potential dangers of using the model explicitly mentioned?	
10.	Is the model being updated frequently for incorporating the changes in the new scans that may occur naturally?	

[Aggarwal et al., 2023]

GLMPs for brain MRI

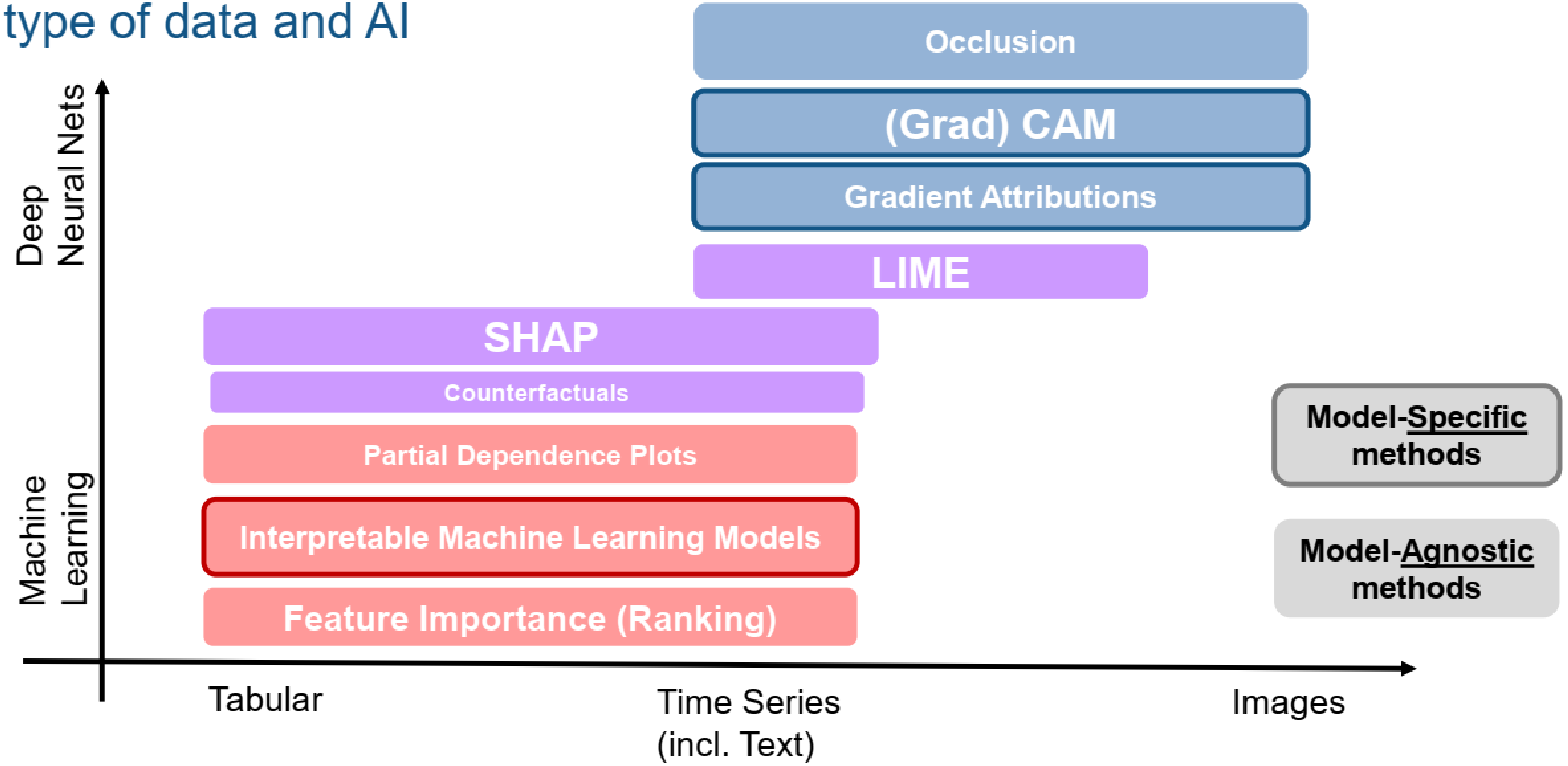


[MathWorks Online Seminar: eXplainable AI and AI V&V]

Unexplainable AI vs XAI

- Critical importance of XAI in healthcare
  - Clinical trust
    - Helps medical professionals trust AI recommendations
    - Enables validation of AI decisions
  - Regulatory compliance
    - Meets healthcare regulations such as EU Patients' Rights Directive (2011/24/EU) and US Informed Consent Laws
    - Supports medical decision accountability
  - Error detection
    - Helps identify potential biases
    - Enables troubleshooting of incorrect outputs

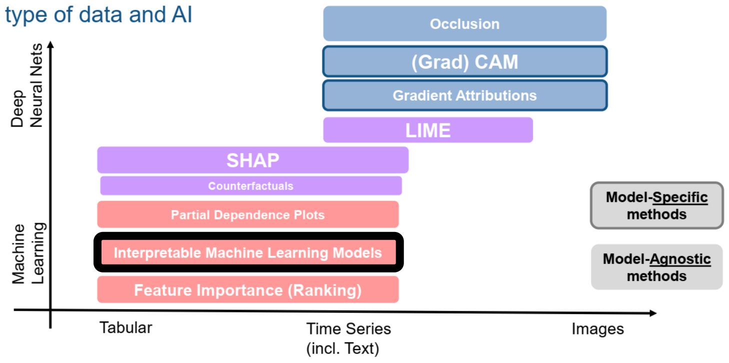
Wide range of techniques with varying applicability depending on type of data and AI

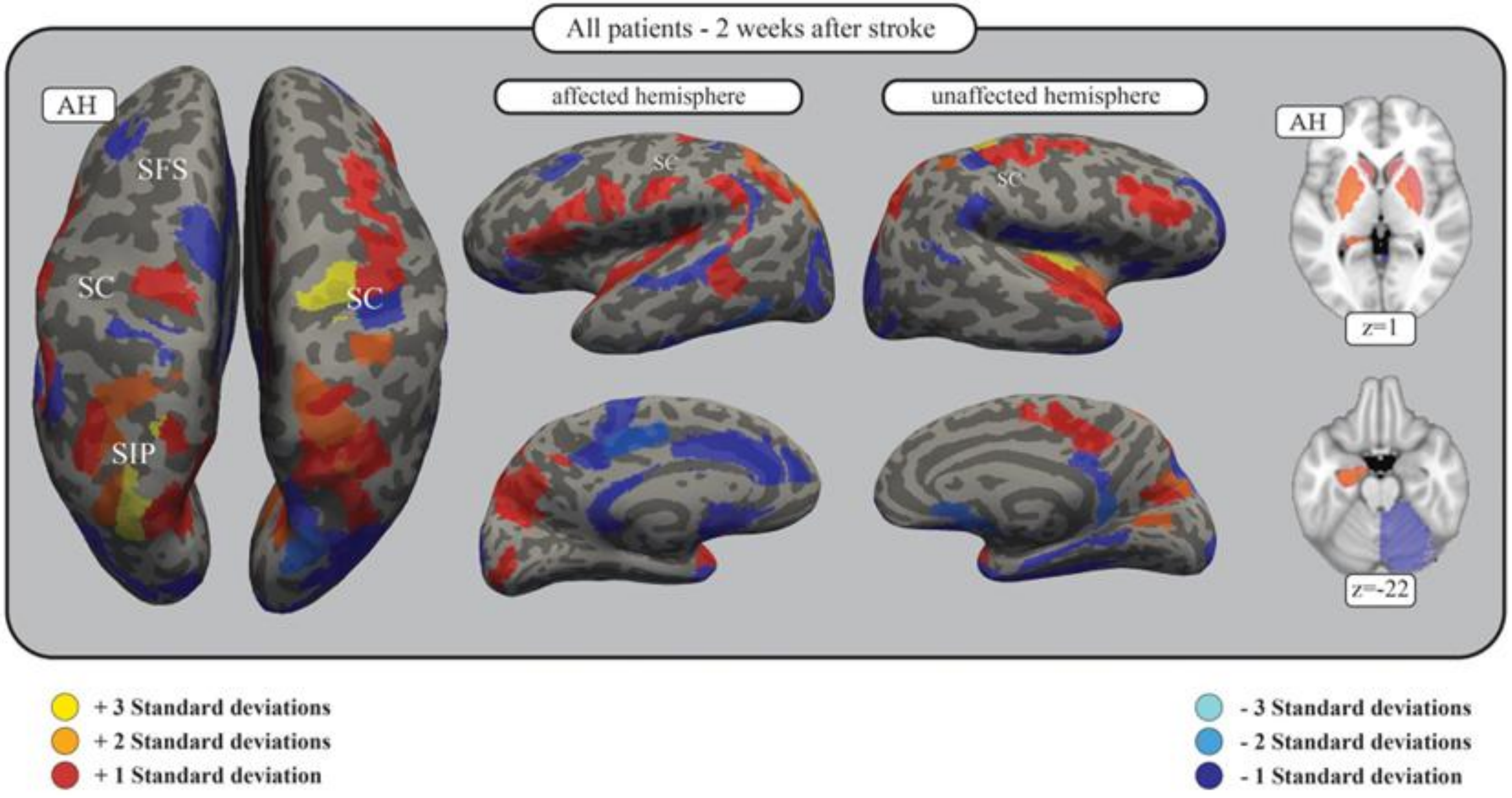


[MathWorks Online Seminar: eXplainable AI and AI V&V]]

Techniques for XAI

Wide range of techniques with varying applicability depending on type of data and AI

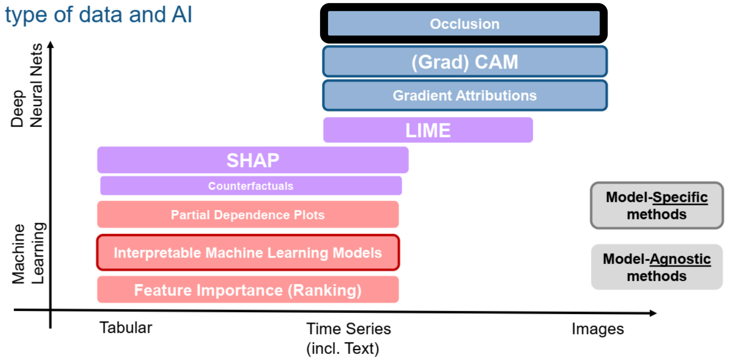


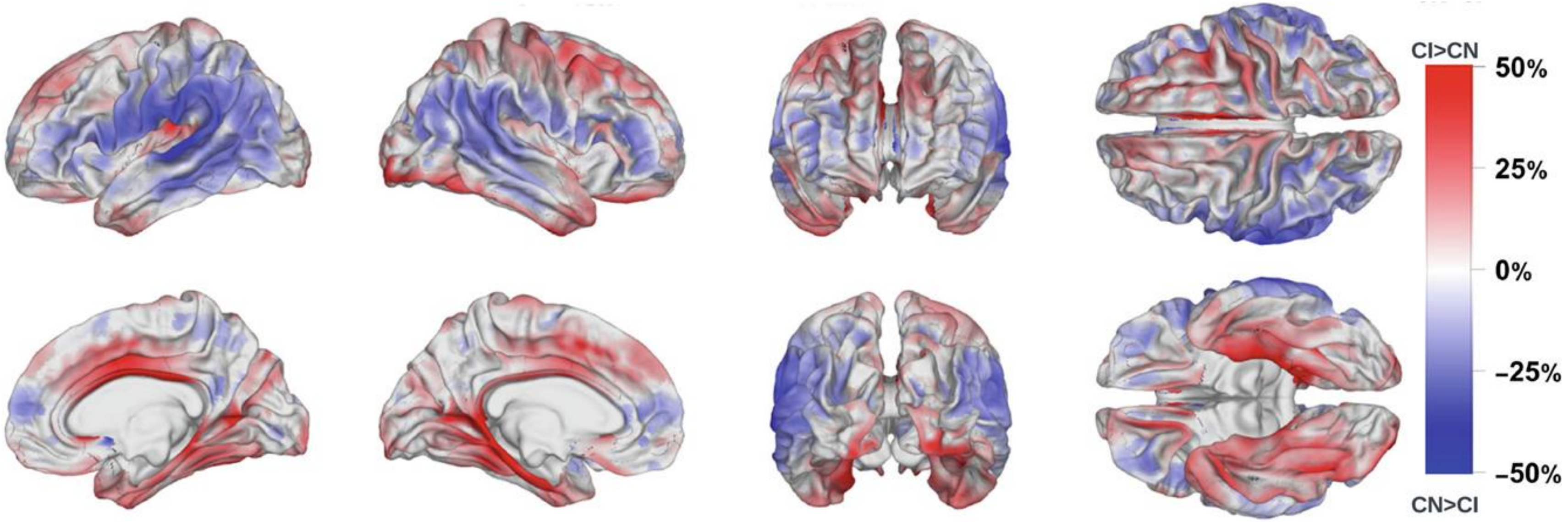


[Koch et al., 2021]]

XAI using Intrinsic Model Interpretability

Wide range of techniques with varying applicability depending on type of data and AI

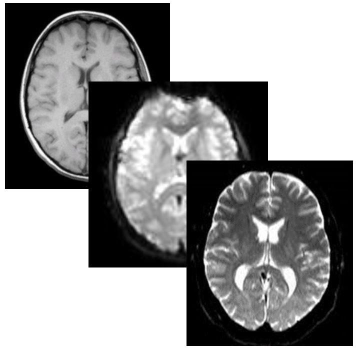


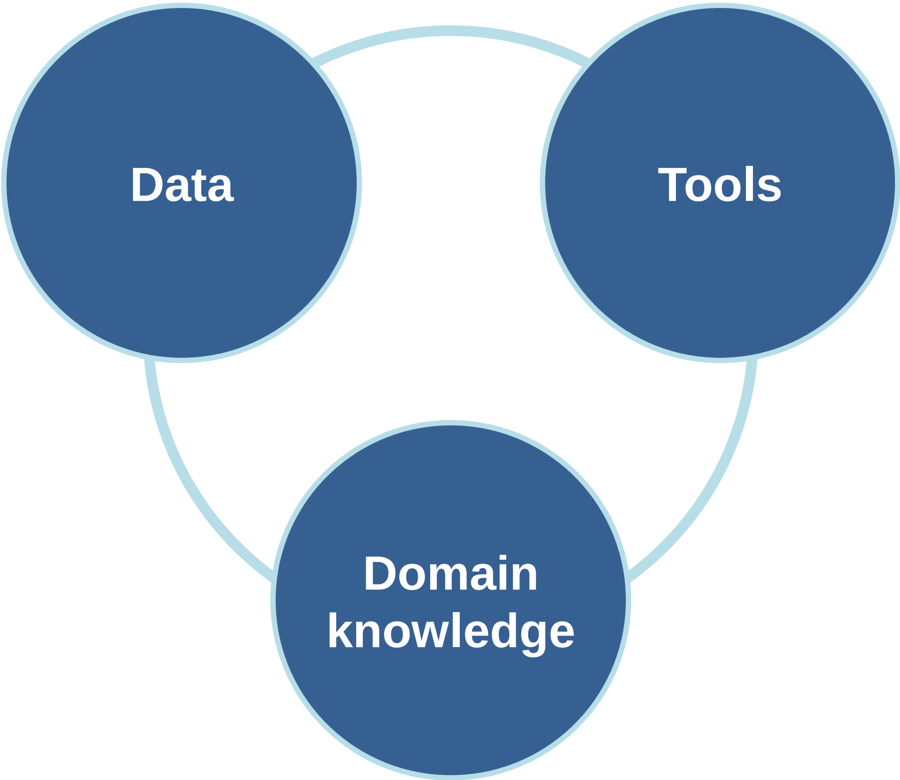


[Yin et al., 2023]]

XAI through Sensitivity Analysis

Summary: MRI-based Predictive Analytics





python™

MATLAB

R