Lecture 9:

Deep Learning for Medical Imaging

- AI revolution in radiology
- Breakthrough examples
- FDA approvals timeline

Introduction to Biomedical Data Science

Lecture Contents

Focus 1: CNN architectures

Focus 2: Medical applications

Focus 3: Clinical deployment

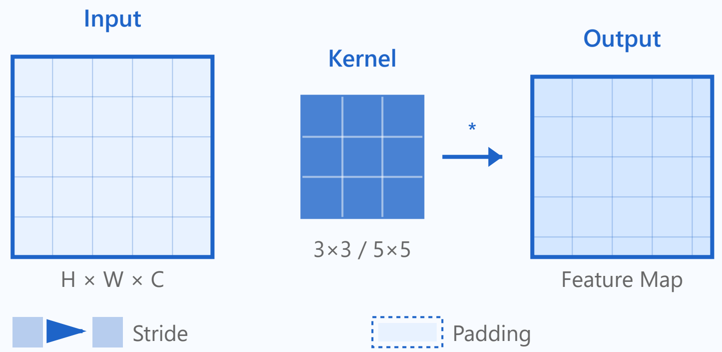
Part 1/3:

CNN Fundamentals

- Convolutional operations
- Network architectures
- Training strategies

Convolution Operation

Convolution Process



Kernel/Filter Concepts

Small learnable matrices that slide across input to extract features. Common sizes: 3×3, 5×5, 7×7

Stride and Padding

Stride: step size of kernel movement. Padding: adding borders to preserve spatial dimensions

Feature Map Generation

Output of convolution operation. Each filter produces one feature map detecting specific patterns

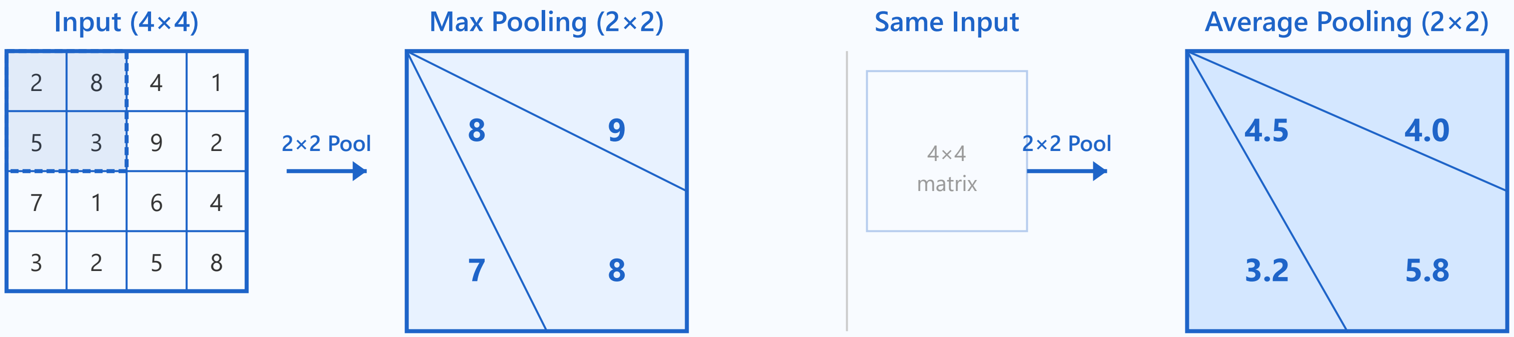
Receptive Fields

Region of input that affects a particular feature. Grows with network depth and kernel size

Special Case: **1×1 Convolutions** - Channel-wise operations for dimensionality reduction and cross-channel learning

Pooling Layers

Max vs Average Pooling



Max Pooling

Selects maximum value from each window. Preserves strongest activations and provides translation invariance

Average Pooling

Computes average of values in each window. Smoother downsampling, often used before classification layers

Global Pooling

Reduces entire feature map to single value per channel. Eliminates need for fixed input sizes

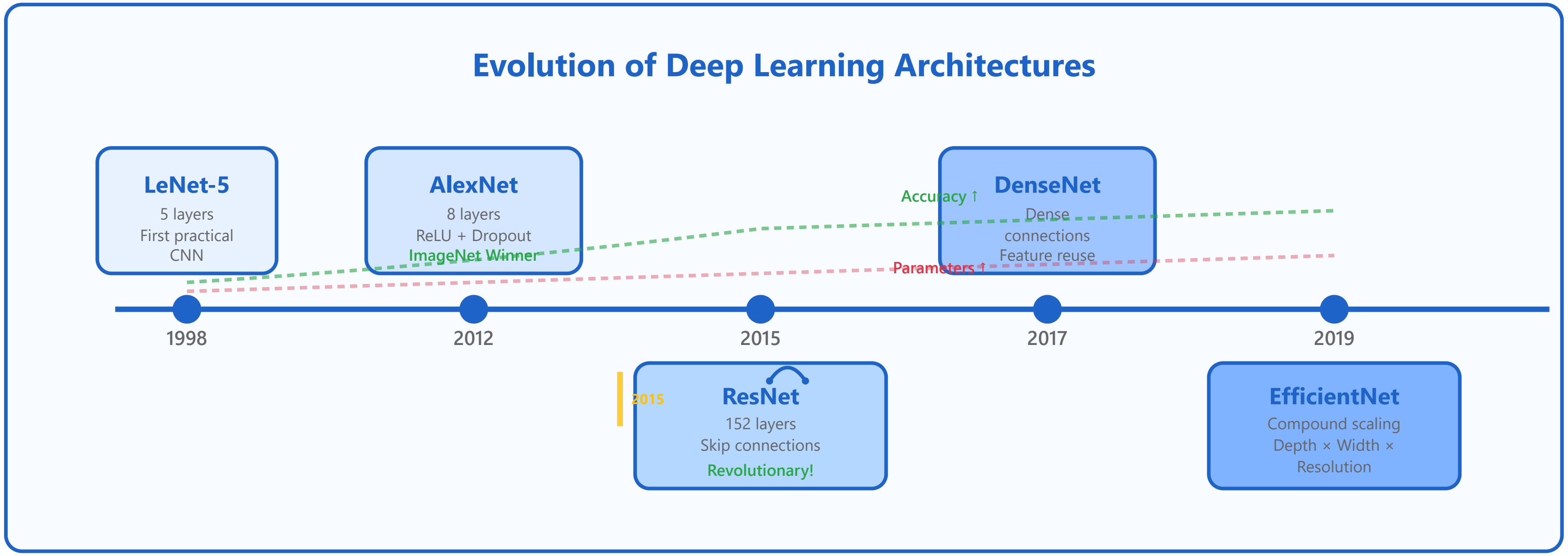
Adaptive Pooling

Outputs fixed size regardless of input dimensions. Automatically adjusts pooling window and stride

Modern Alternatives

Strided convolutions can replace pooling while learning optimal downsampling patterns. Some architectures eliminate pooling entirely

CNN Architectures Evolution



LeNet to AlexNet

Early pioneers (1998-2012): Basic convolution layers, introduced ReLU and dropout for deeper networks

ResNet & Skip Connections

Revolutionary residual connections enable 100+ layer networks. Solves vanishing gradient problem

DenseNet

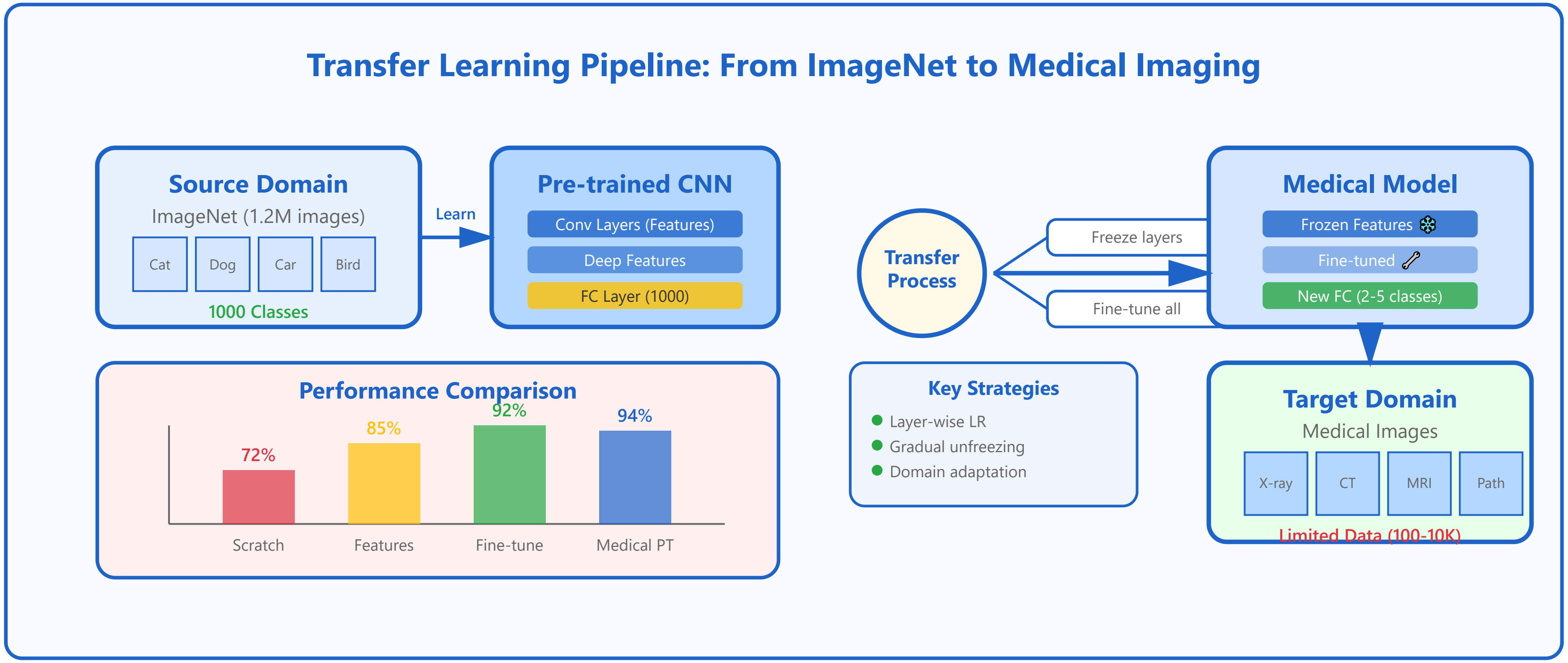
Dense connections between all layers. Enhanced feature propagation and parameter efficiency

EfficientNet

Compound scaling of depth, width, and resolution. Optimal accuracy-efficiency tradeoff

Modern Trend: **Neural Architecture Search (NAS)** - Automated discovery of optimal architectures for specific tasks

Transfer Learning



ImageNet Pretraining

Large-scale pretraining on natural images. Features transfer surprisingly well to medical domain

Fine-tuning Strategies

Full fine-tuning vs. feature extraction. Layer-wise learning rate scheduling for optimal transfer

Domain Adaptation

Techniques to bridge domain gap between natural and medical images. Adversarial and statistical methods

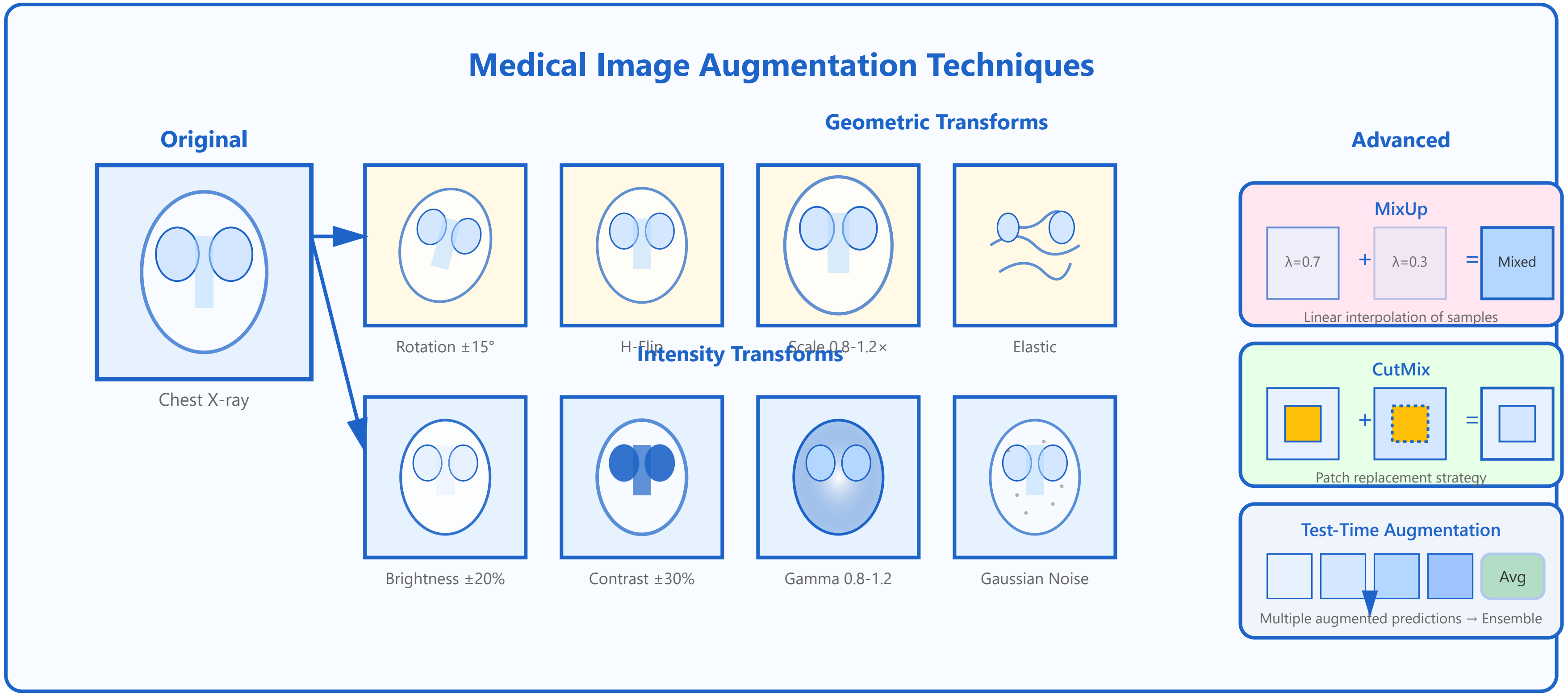
Medical Pretraining

Self-supervised learning on medical data. Models like MedCLIP and BioViL trained on radiology reports

Few-shot Learning

Learning from limited labeled data. Meta-learning and prototypical networks for rare diseases

Data Augmentation



Geometric Transforms

Rotation, flipping, scaling, elastic deformations. Must respect anatomical constraints

Intensity Transforms

Contrast adjustment, brightness, gamma correction. Simulates different scanner protocols

MixUp/CutMix

Medical-Specific

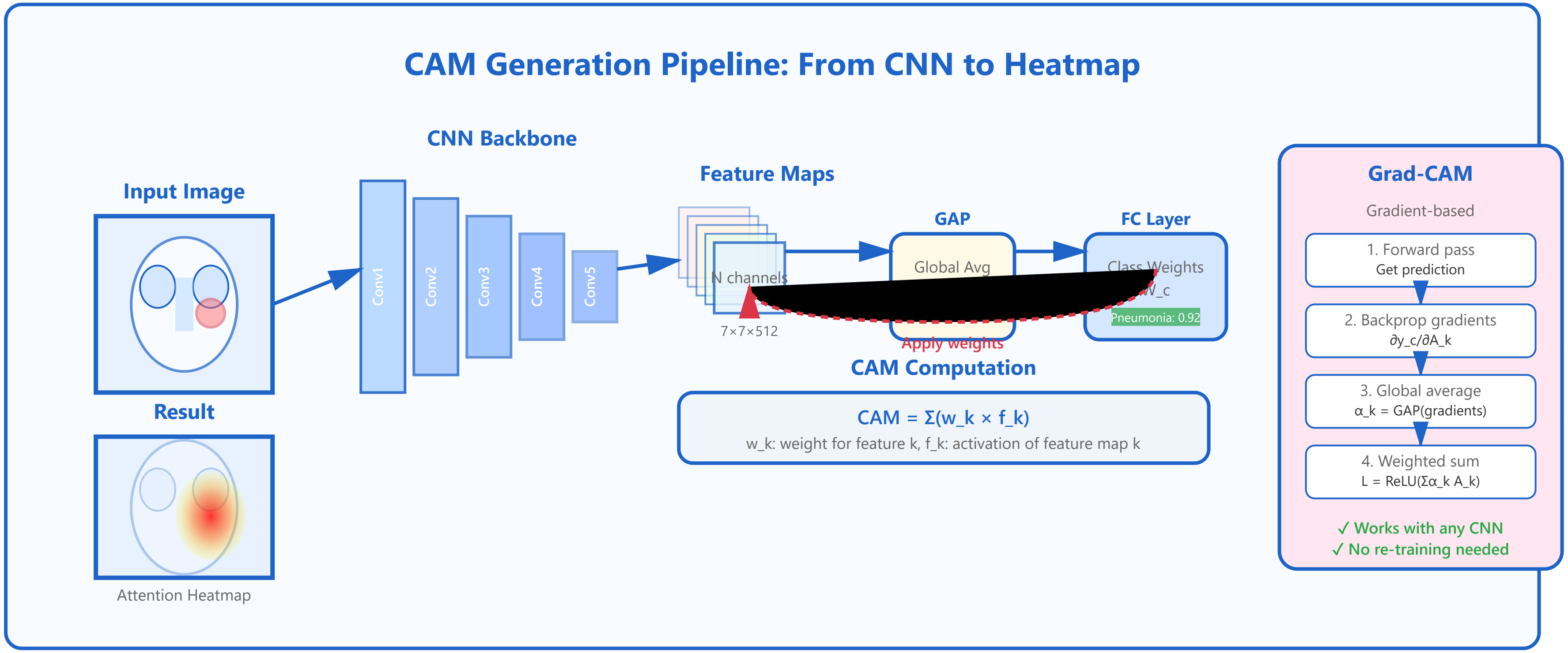
Mixing training examples. Creates synthetic samples for better generalization

Domain knowledge augmentation: simulating pathology, artifacts, different imaging protocols

Test-Time Augmentation

Multiple predictions on augmented test images. Ensemble for improved robustness

Class Activation Maps (CAM)



CAM Principles

Visualize important regions for classification. Linear combination of feature maps weighted by class weights

Grad-CAM

Gradient-based localization. Works with any CNN architecture without modification

Grad-CAM++

Improved weighted combination. Better localization for multiple objects and weak activations

Score-CAM

Gradient-free approach using forward passes. More stable and cleaner visualizations

Clinical Interpretation

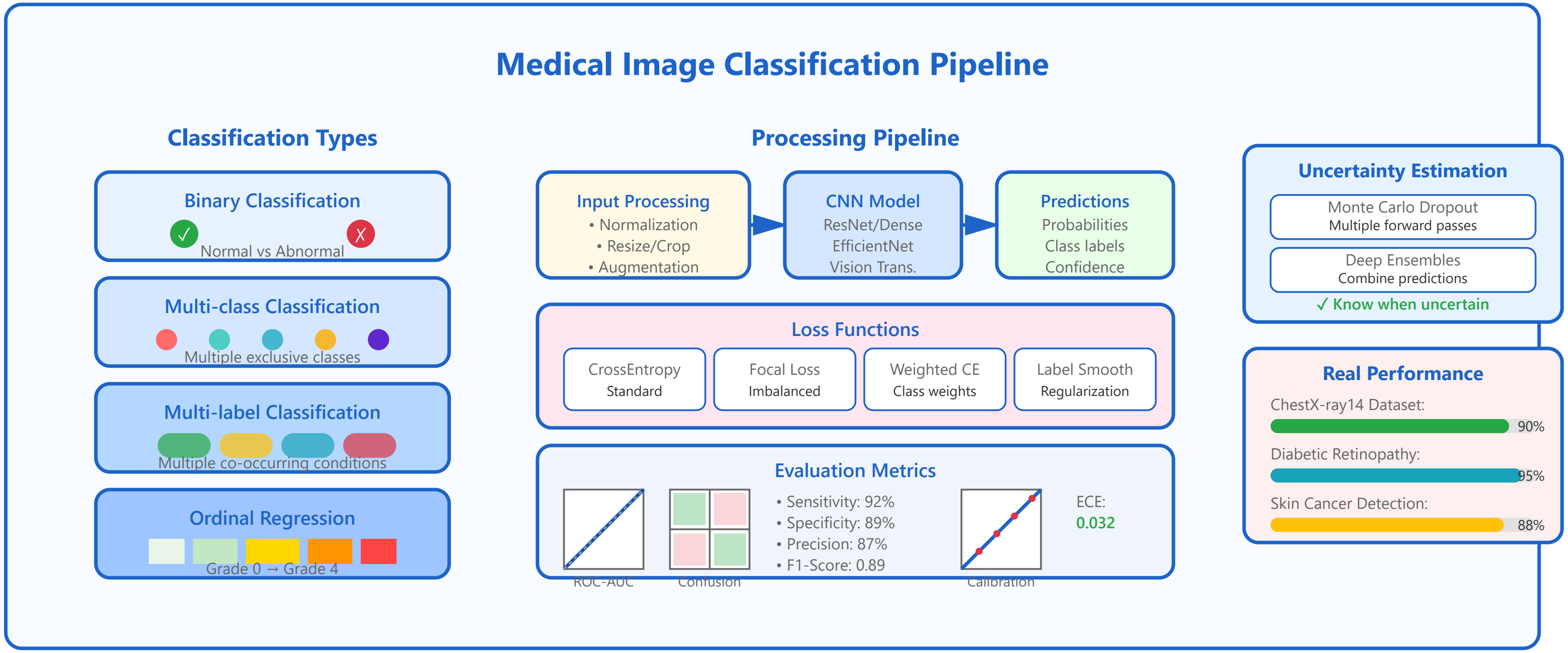
Essential for model validation and trust building. Helps radiologists understand AI decisions

Part 2/3:

Medical Applications

- Task categories
- Architecture selection
- Performance benchmarks

Classification Tasks



Disease Detection

Binary or multi-class classification. Pneumonia detection, cancer screening, retinopathy grading

Multi-label Classification

Multiple diseases per image. Thoracic diseases (14 classes in ChestX-ray14 dataset)

Ordinal Regression

Ordered categories (disease severity). Preserves ordering constraints in loss function

Uncertainty Estimation

Confidence in predictions. Monte Carlo dropout, ensembles, or Bayesian approaches

Ensemble Methods

Combining multiple models. Improves robustness and calibration of predictions

Detection Tasks

Object Detection Basics

Localizing and classifying objects. Bounding boxes around lesions, nodules, fractures

YOLO for Medical

Real-time detection. Fast inference for large 3D volumes or video

Faster R-CNN

Two-stage detector. Higher accuracy, commonly used in medical imaging

Anchor-Free Methods

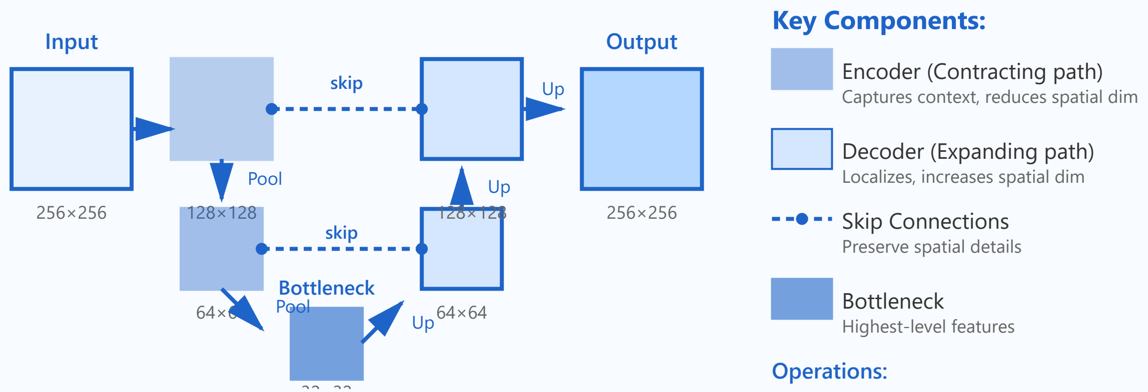
FCOS, CenterNet. Simpler pipelines without anchor design

3D Detection

Extending to volumetric data. 3D bounding boxes for CT/MRI lesions

Segmentation with U-Net

U-Net Architecture: Encoder-Decoder with Skip Connections



U-Net Architecture

Encoder-decoder with skip connections. Standard for medical image segmentation

Skip Connections

Combine low and high-level features. Preserve spatial details for precise boundaries

Loss Functions

Dice loss, focal loss, boundary loss. Address class imbalance and boundary precision

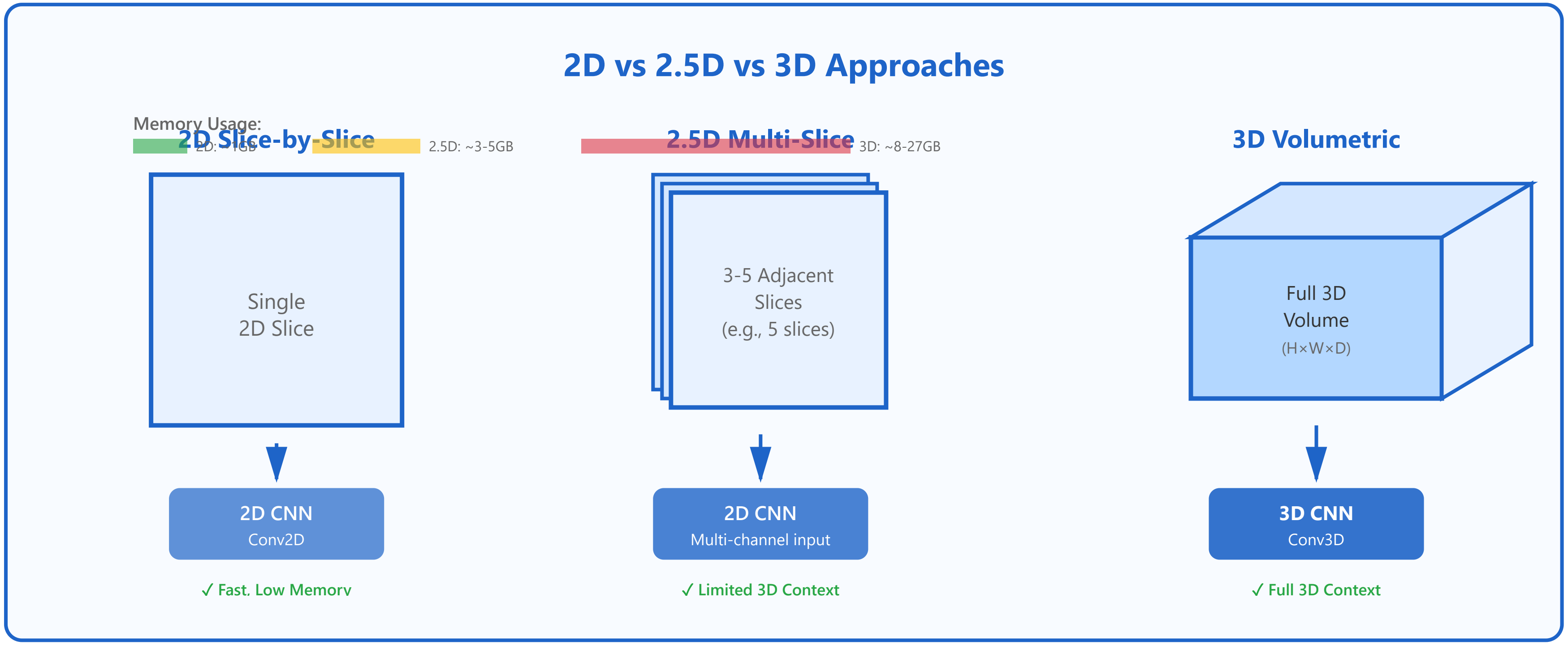
3D U-Net

Extension to volumetric data. Processes entire 3D volumes for organ/tumor segmentation

nnU-Net Framework

Self-configuring U-Net. Automatically adapts to dataset characteristics

3D Medical Imaging



2.5D vs 3D Approaches

2.5D: Multi-slice input. 3D: Full volumetric processing. Tradeoffs in memory and context

Memory Constraints

3D convolutions require 8-27x more memory. Careful batch size and patch size selection

Patch-Based Methods

Process small overlapping 3D patches. Enables processing of large volumes

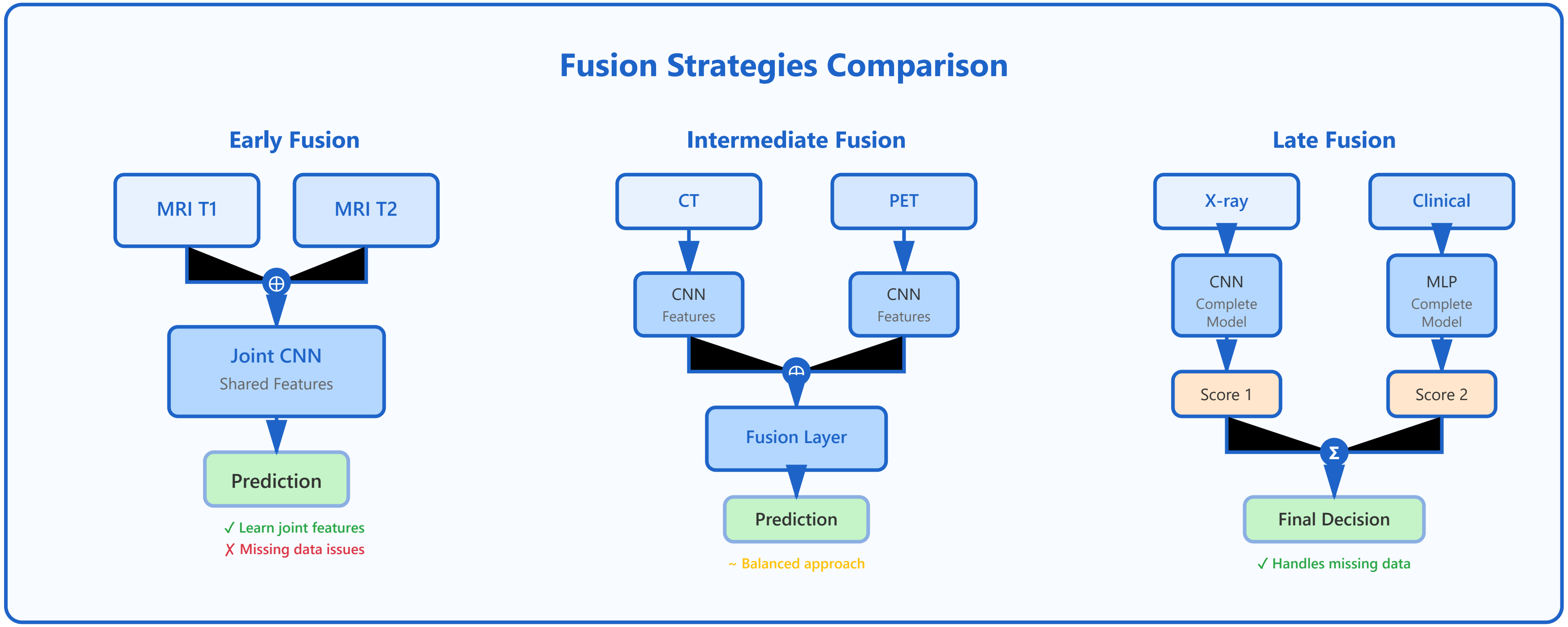
Sliding Window

Inference strategy for large volumes. Overlapping predictions with smoothing

Volumetric Networks

3D ResNet, V-Net, 3D U-Net. Leverage full 3D context for better accuracy

Multi-modal Fusion



Early vs Late Fusion

Early: Combine at input/features. Late: Combine predictions. Depends on modality complementarity

Attention Mechanisms

Learn importance of each modality. Dynamic weighting based on input

Cross-Modal Learning

Transfer knowledge between modalities. Co-training and contrastive learning

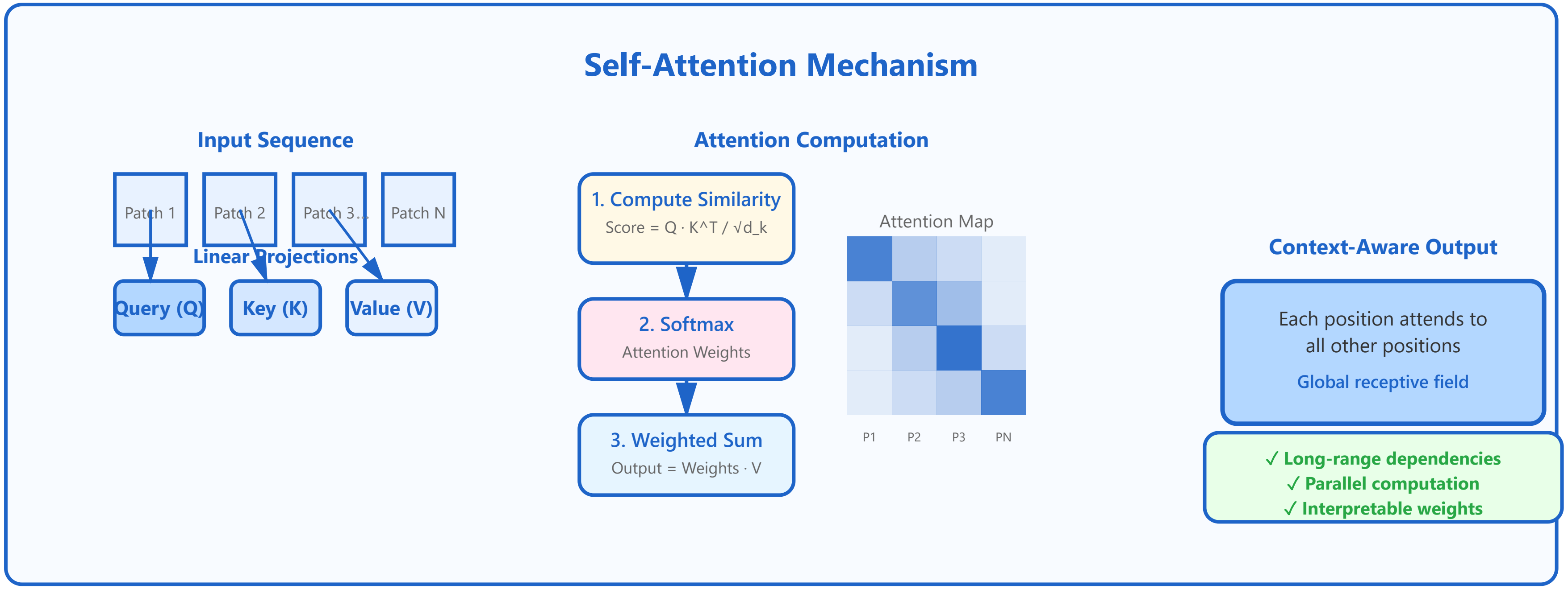
Missing Modalities

Handling incomplete data. Imputation or modality-specific pathways

Clinical Protocols

MRI sequences (T1, T2, FLAIR), PET-CT fusion. Each modality provides unique information

Attention Mechanisms



Self-Attention

Capture long-range dependencies. Every position attends to all others

Cross-Attention

Attend between different modalities or sequences. Query from one, key/value from another

Vision Transformers

Pure attention-based architecture. ViT, Swin Transformer for medical imaging

Hybrid Architectures

CNN backbone + Transformer head. CoAtNet, TransUNet combine local and global context

Interpretability Benefits

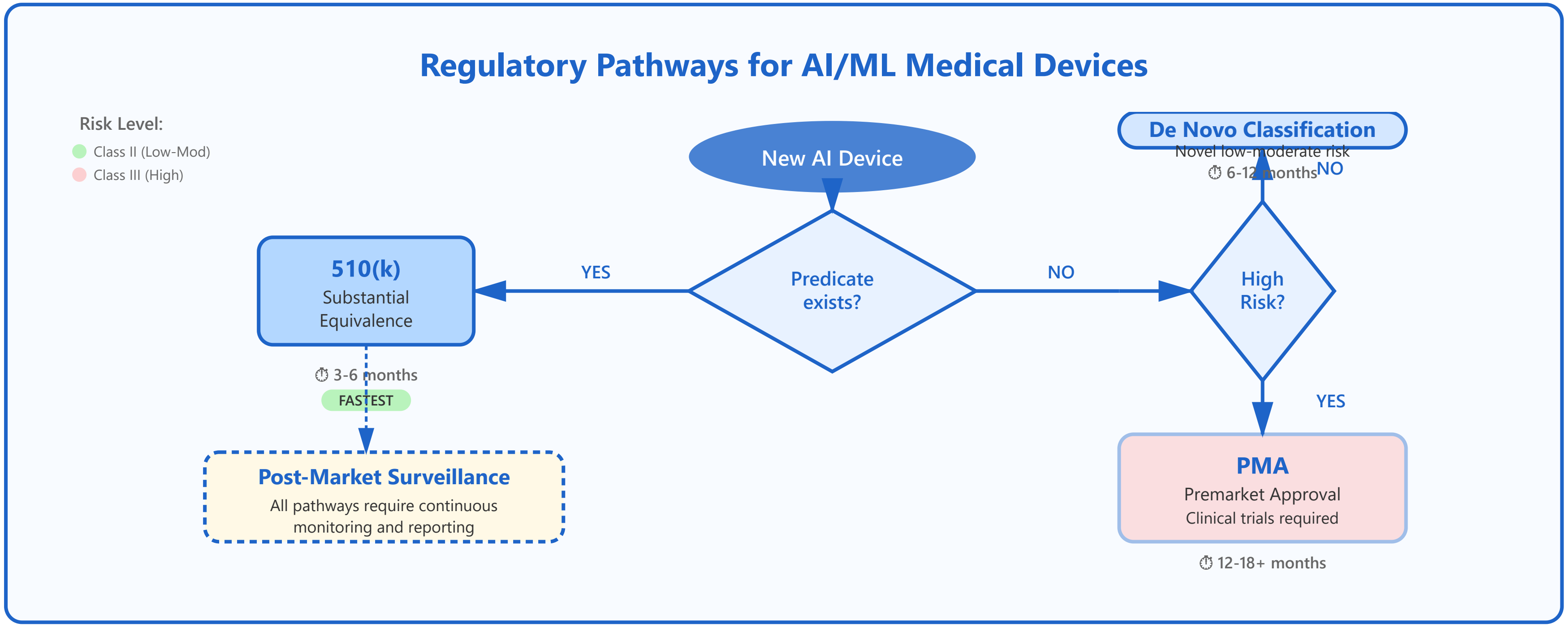
Attention maps show model focus. More intuitive than CNN activation maps

Part 3/3:

Clinical Implementation

- Regulatory pathway
- Integration challenges
- Quality assurance

FDA Approval Process



510(k) Pathway

Substantial equivalence to existing device. Fastest route, ~3-6 months if predicate exists

De Novo Classification

Novel low-to-moderate risk devices. Creates new device category, ~6-12 months

PMA Requirements

Premarket Approval for high-risk devices. Most rigorous, requires clinical trials

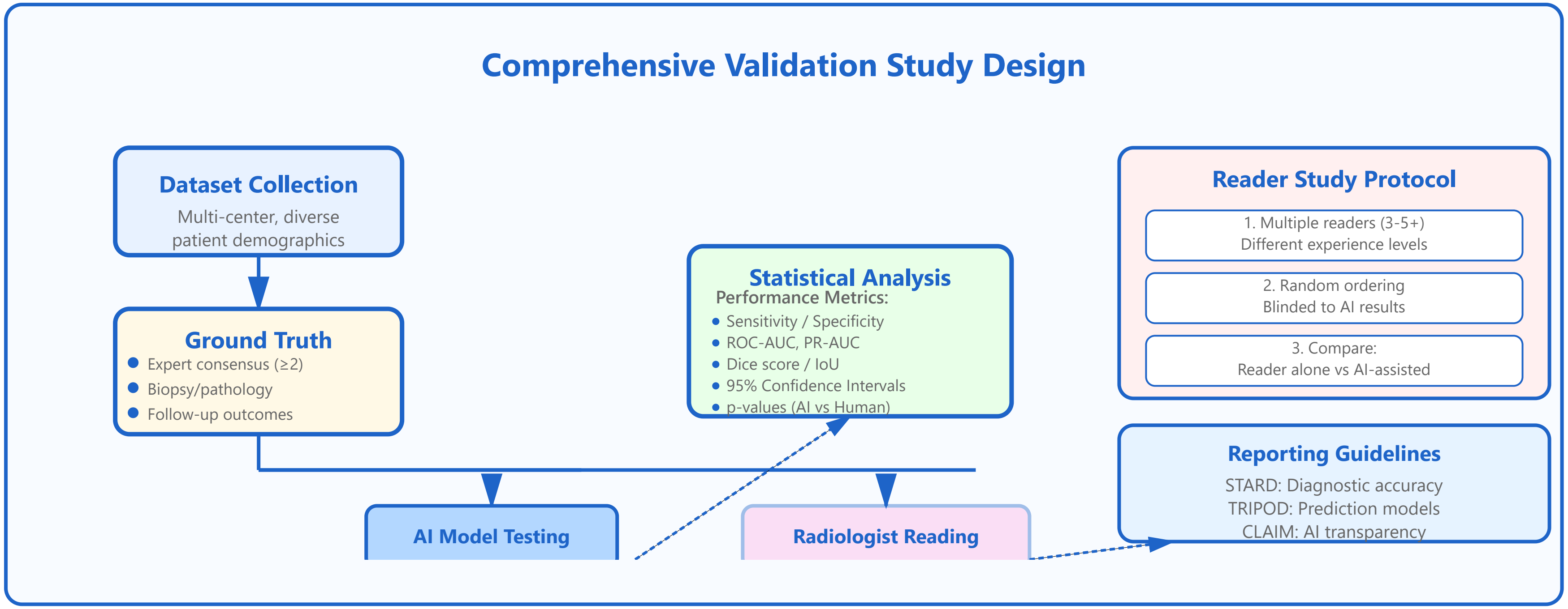
Software Modifications

When algorithm changes require new submission. Predetermined change control plans

Real-World Surveillance

Post-market monitoring. Detect performance drift or adverse events

Validation Studies



Study Design

Retrospective vs prospective. Multi-center validation for generalizability

Ground Truth

Reference standard definition. Expert consensus, biopsy confirmation, follow-up outcomes

Reader Studies

Compare AI to radiologists. Multiple readers, random ordering, statistical testing

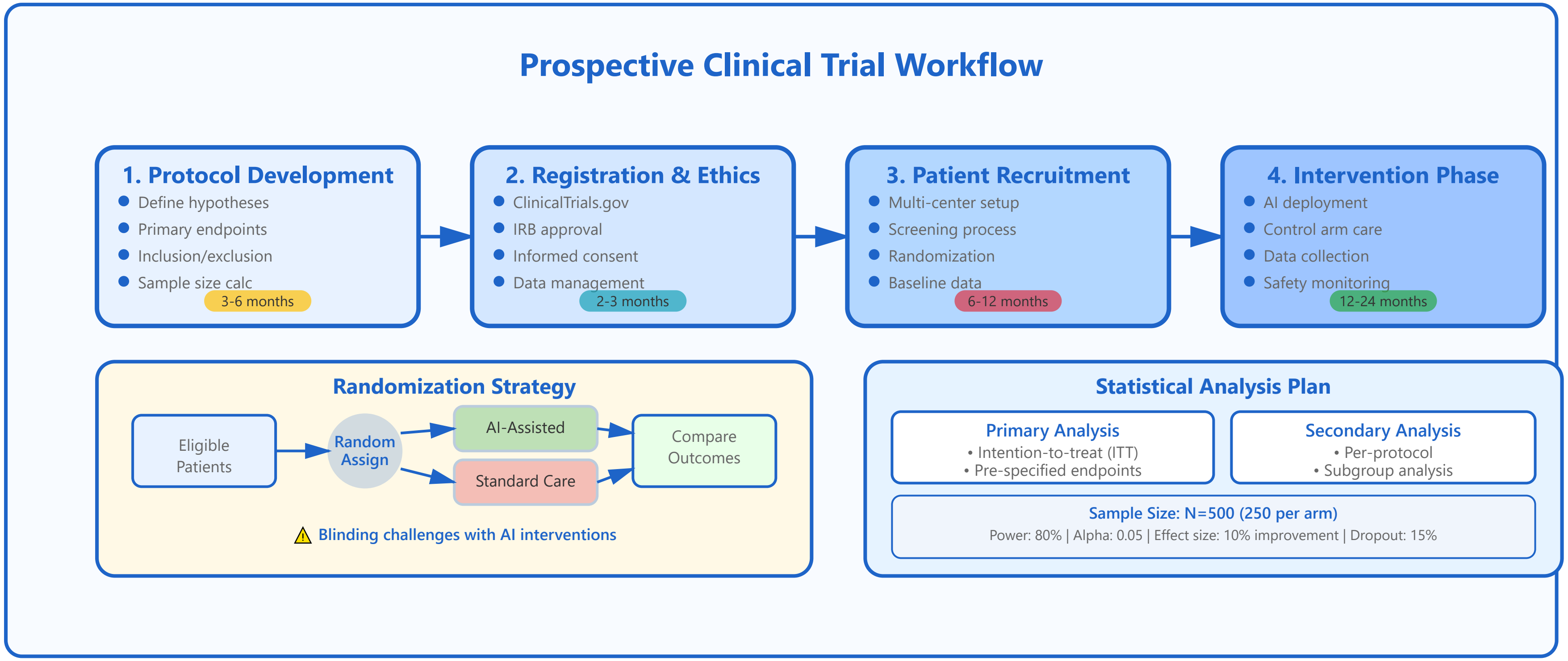
Statistical Analysis

ROC curves, sensitivity/specificity. Confidence intervals and significance testing

Reporting Guidelines

STARD, TRIPOD, CLAIM. Standardized reporting for reproducibility

Prospective Trials



Trial Protocols

Pre-specified hypotheses and endpoints. Registered in clinicaltrials.gov

Endpoint Selection

Diagnostic accuracy vs clinical outcomes. Hard outcomes (mortality) vs surrogate markers

Sample Size

Power analysis for adequate statistical power. Account for prevalence and effect size

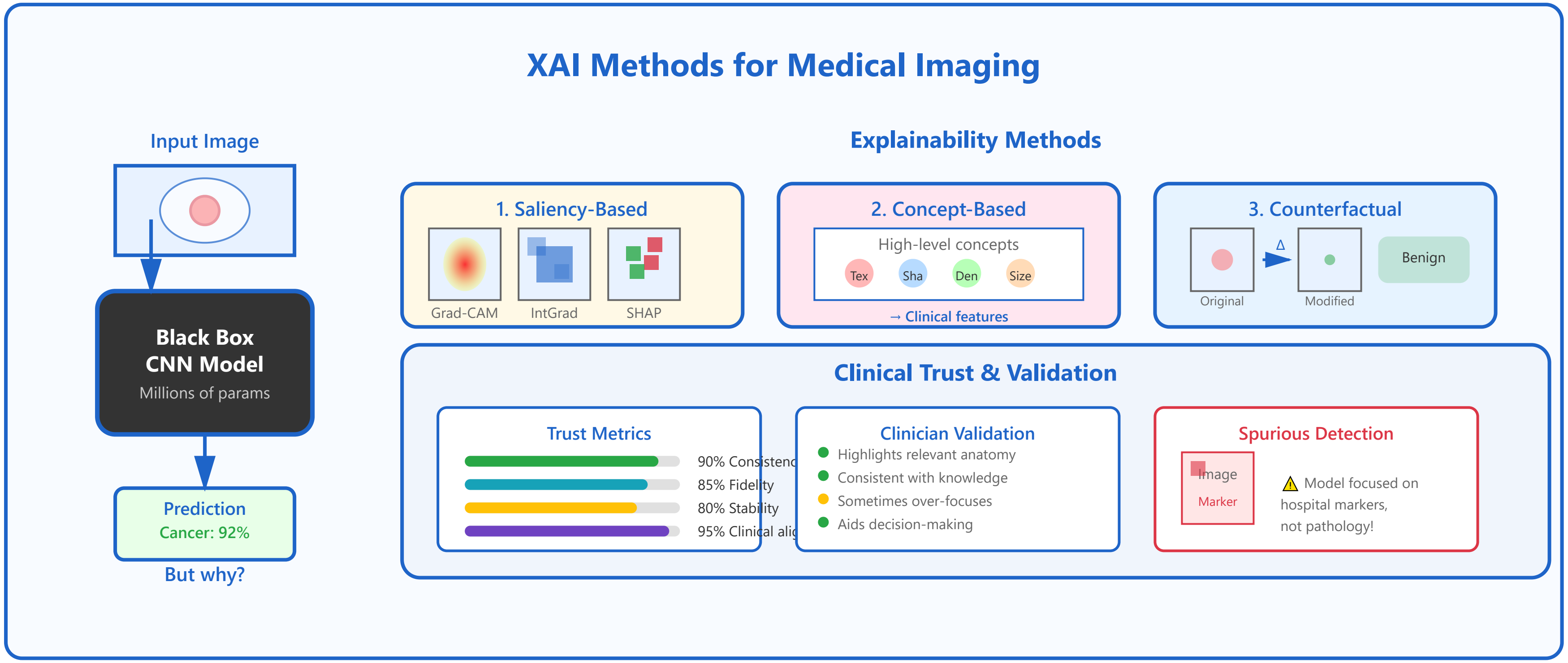
Randomization

AI-assisted vs standard of care. Cluster randomization by site to avoid contamination

Analysis Plans

Pre-specified statistical analysis. ITT vs per-protocol analysis

Explainable AI (XAI)



Interpretability Needs

Clinical trust and adoption. Regulatory requirements and liability concerns

Saliency Maps

Grad-CAM, attention maps. Highlight important image regions

Counterfactual Explanations

What changes would flip prediction. Minimal perturbations for opposite class

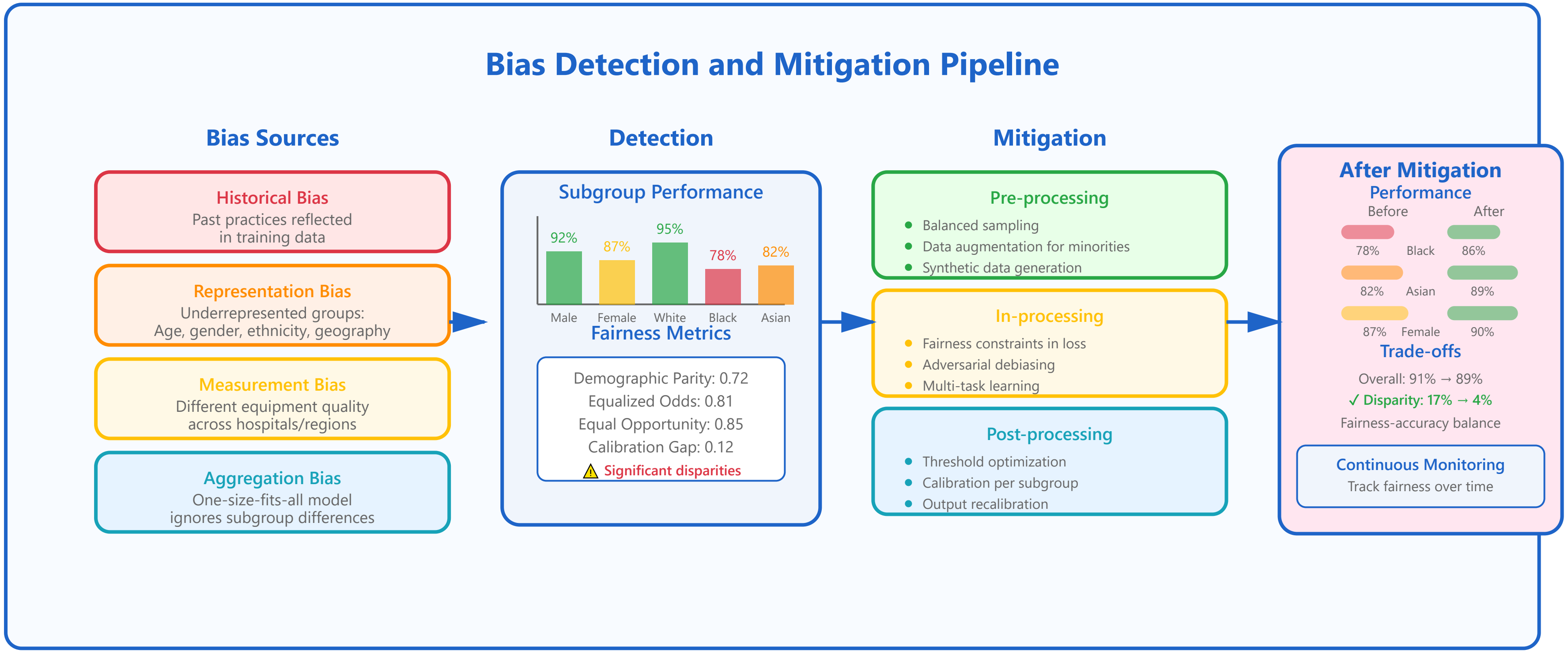
Concept Attribution

High-level concept importance. Relate to clinical features (texture, shape, density)

Trust Building

Consistent explanations aligned with clinical knowledge. Detect spurious correlations

Bias and Fairness



Dataset Bias

Selection bias, label bias. Underrepresentation of certain demographics

Demographic Disparities

Performance gaps across age, sex, race. Different disease prevalence and presentation

Fairness Metrics

Equalized odds, demographic parity. Group fairness vs individual fairness

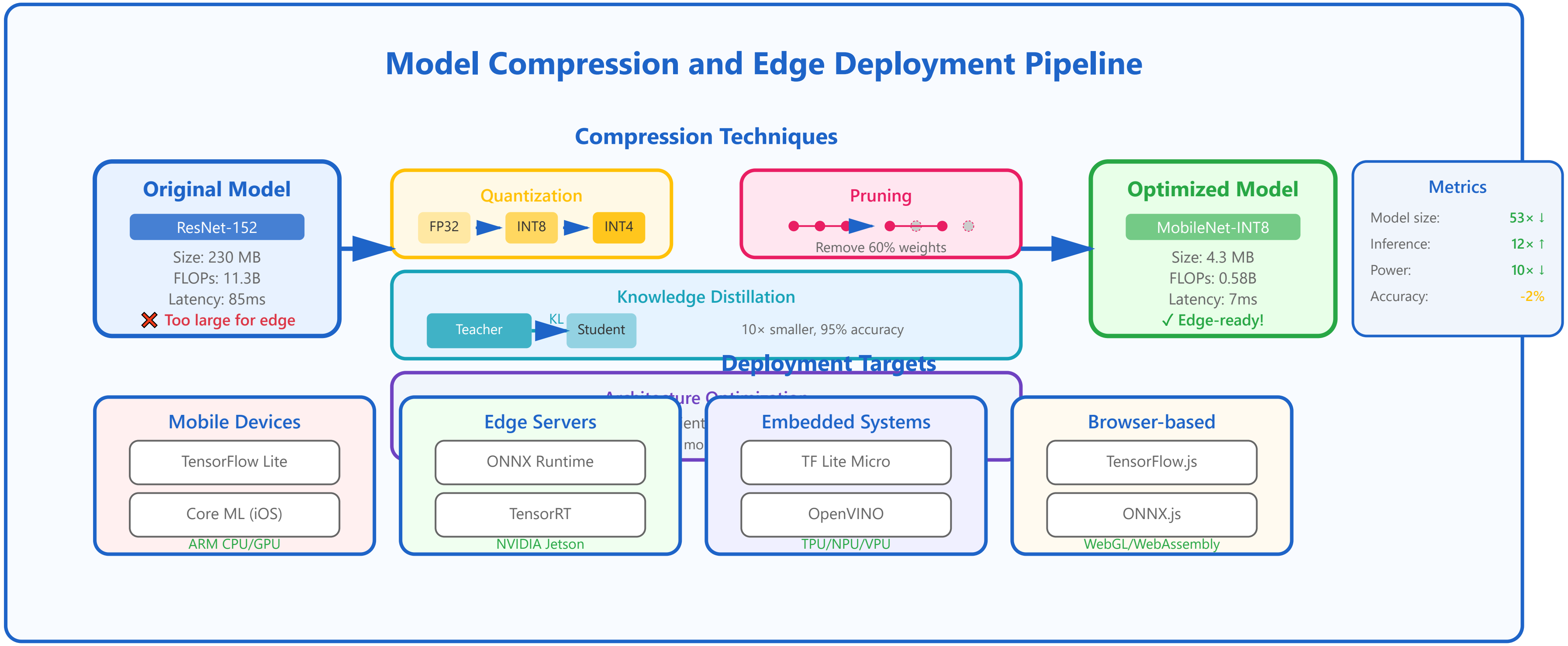
Mitigation Strategies

Diverse training data, reweighting, adversarial debiasing. Fairness constraints

Continuous Monitoring

Track performance by subgroup. Detect and address emerging disparities

Edge Deployment



Model Compression

Reduce model size and latency. Essential for edge devices and real-time applications

Quantization

INT8 or INT4 precision. 4x smaller models with minimal accuracy loss

Pruning

Remove redundant weights/neurons. Structured pruning for hardware efficiency

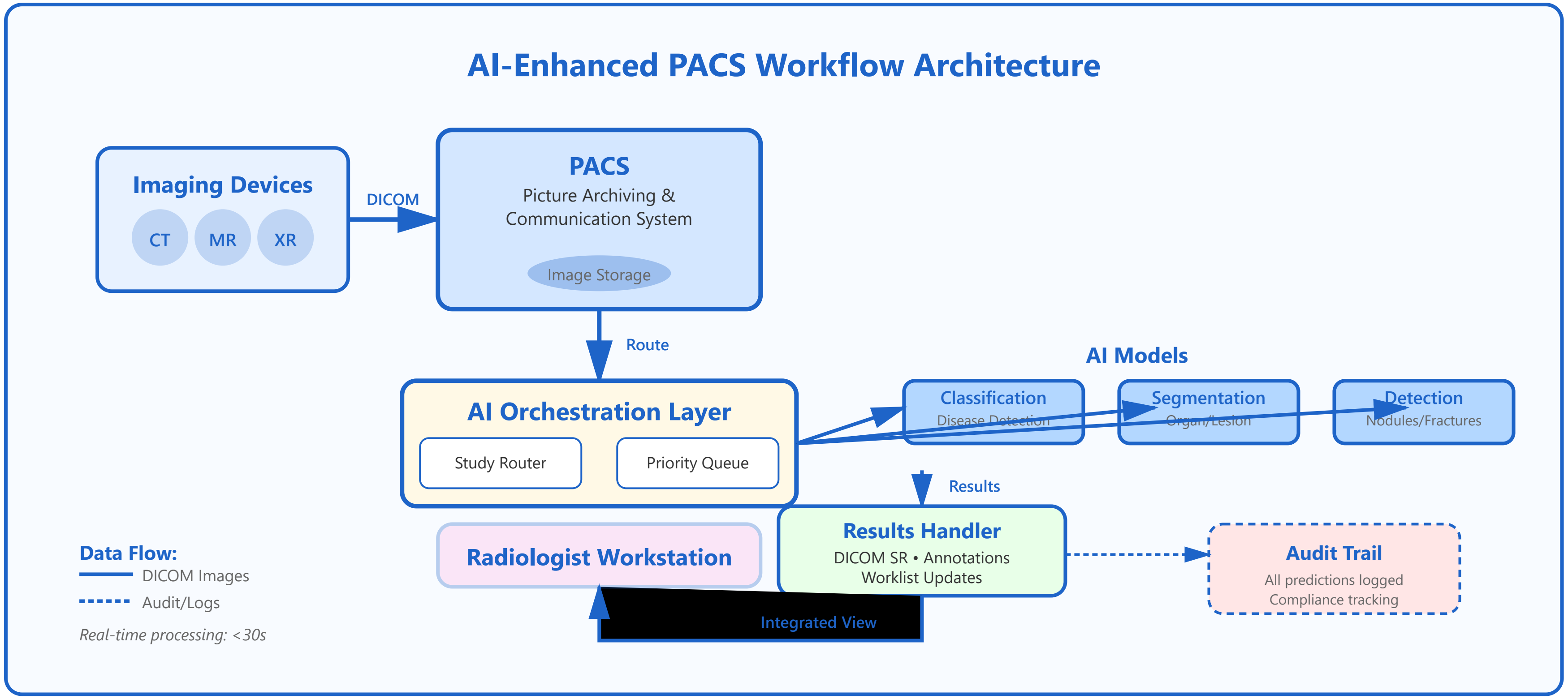
Knowledge Distillation

Train small student from large teacher. Maintains performance with fewer parameters

Hardware Acceleration

TensorRT, ONNX Runtime. GPU, TPU, or specialized medical imaging accelerators

PACS Integration



DICOM Workflows

Receive images, process, send results. Standard medical imaging communication

AI Orchestration

Routing studies to appropriate AI models. Manage multiple algorithms and priorities

Results Communication

DICOM SR, overlay annotations. Integration with radiology reporting systems

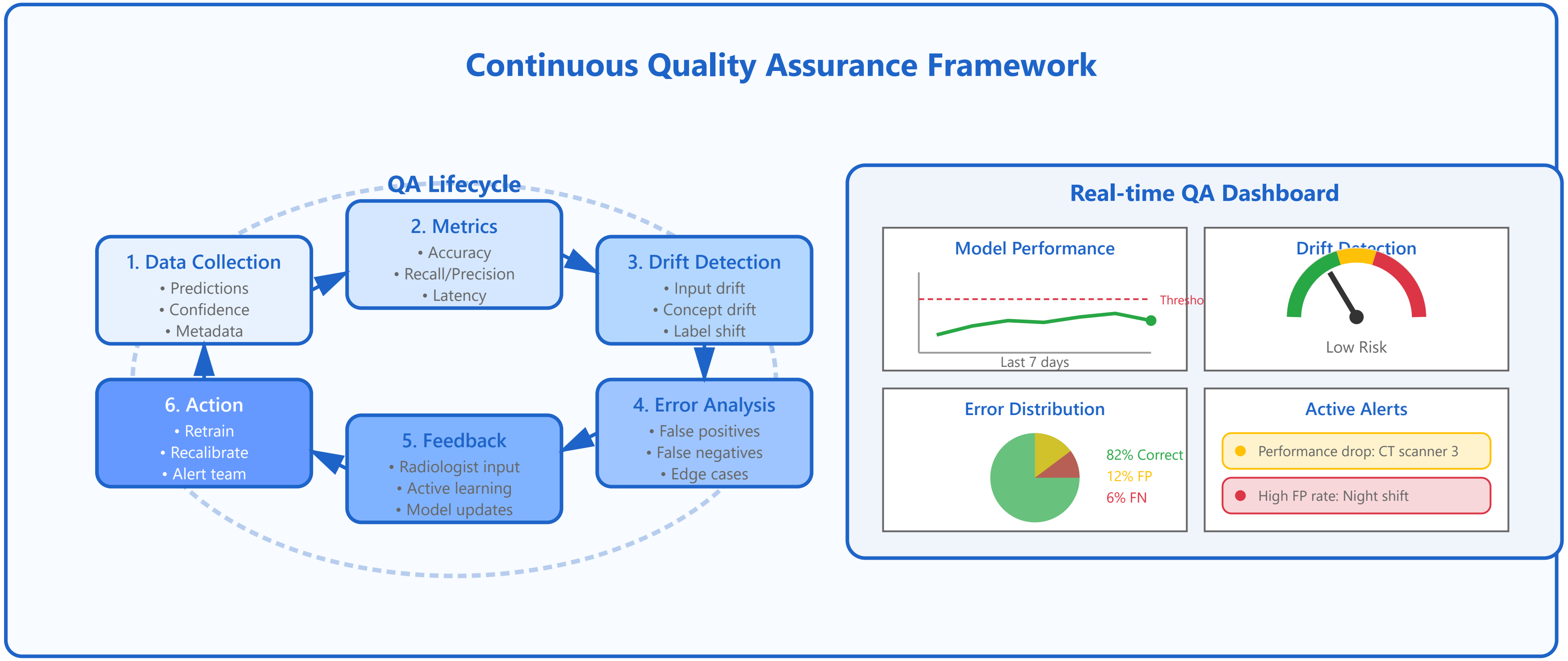
Worklist Prioritization

AI-driven triaging. Urgent findings flagged for immediate review

Audit Trails

Complete logging for compliance. Track every AI prediction and radiologist interaction

Quality Assurance



Performance Monitoring

Track accuracy, precision, recall over time. Automated dashboards

Drift Detection

Identify distribution shifts. Input drift (scanner changes) vs concept drift (disease patterns)

Error Analysis

Systematic review of failures. Identify error patterns and edge cases

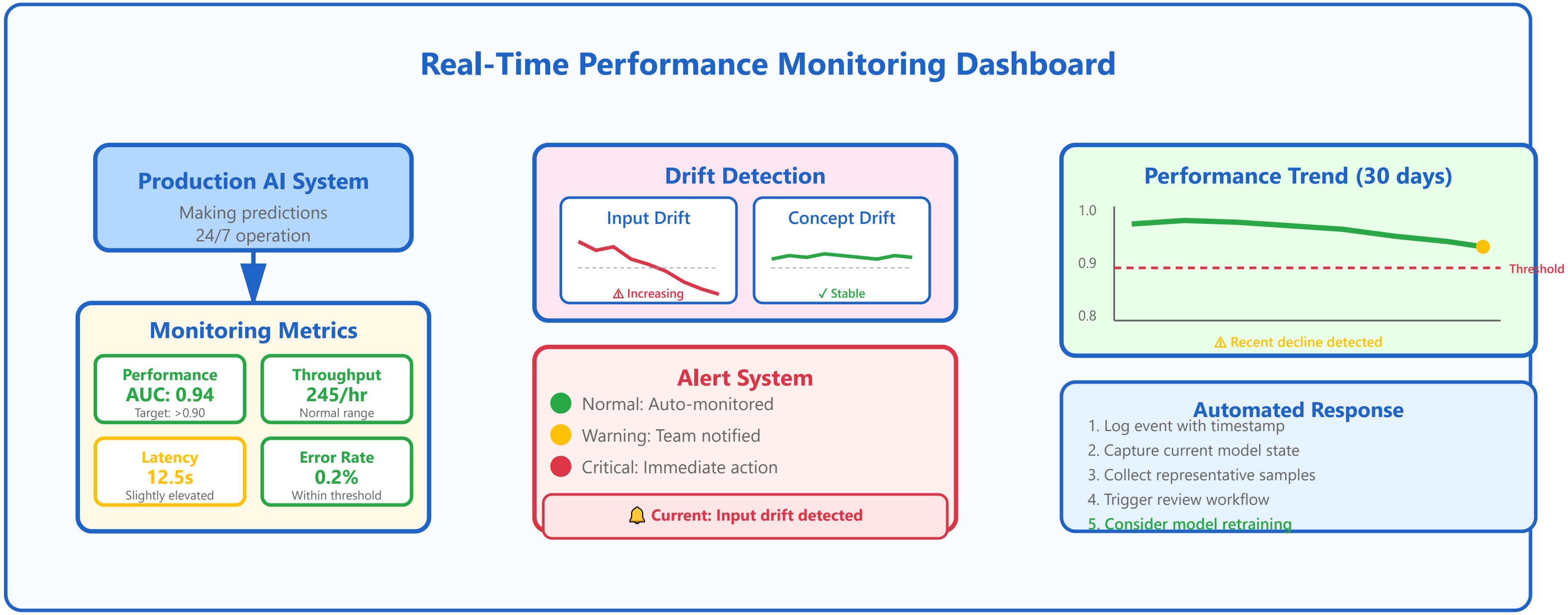
Feedback Loops

Radiologist corrections. Active learning to improve model from production data

Continuous Improvement

Iterative model updates. A/B testing of model versions

Continuous Monitoring



Real-World Metrics

Sensitivity, specificity in production. Compare to validation performance

Alert Systems

Automated alerts for anomalies. Performance degradation, unusual predictions

Performance Degradation

Detection of model staleness. Dataset shift from new equipment or protocols

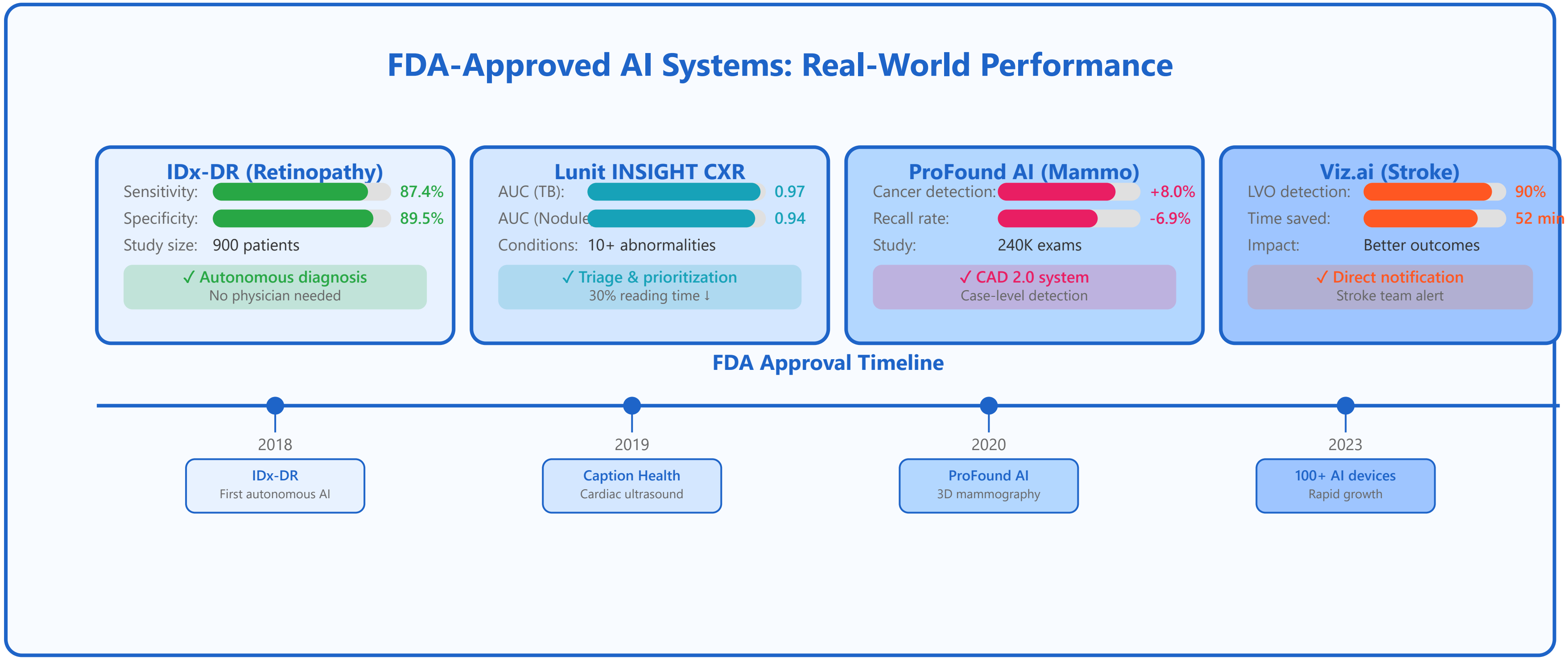
Update Strategies

When and how to retrain. Regulatory considerations for algorithm changes

Regulatory Compliance

Documentation for audits. Adverse event reporting to FDA

Clinical Case Studies



Diabetic Retinopathy

FDA-approved IDx-DR system. Autonomous diagnosis without physician review

Chest X-ray Screening

Qure.ai qXR, Lunit INSIGHT CXR. Detection of 20+ thoracic abnormalities

Mammography CAD

iCAD ProFound AI, Transpara. 5-8% increase in cancer detection rate

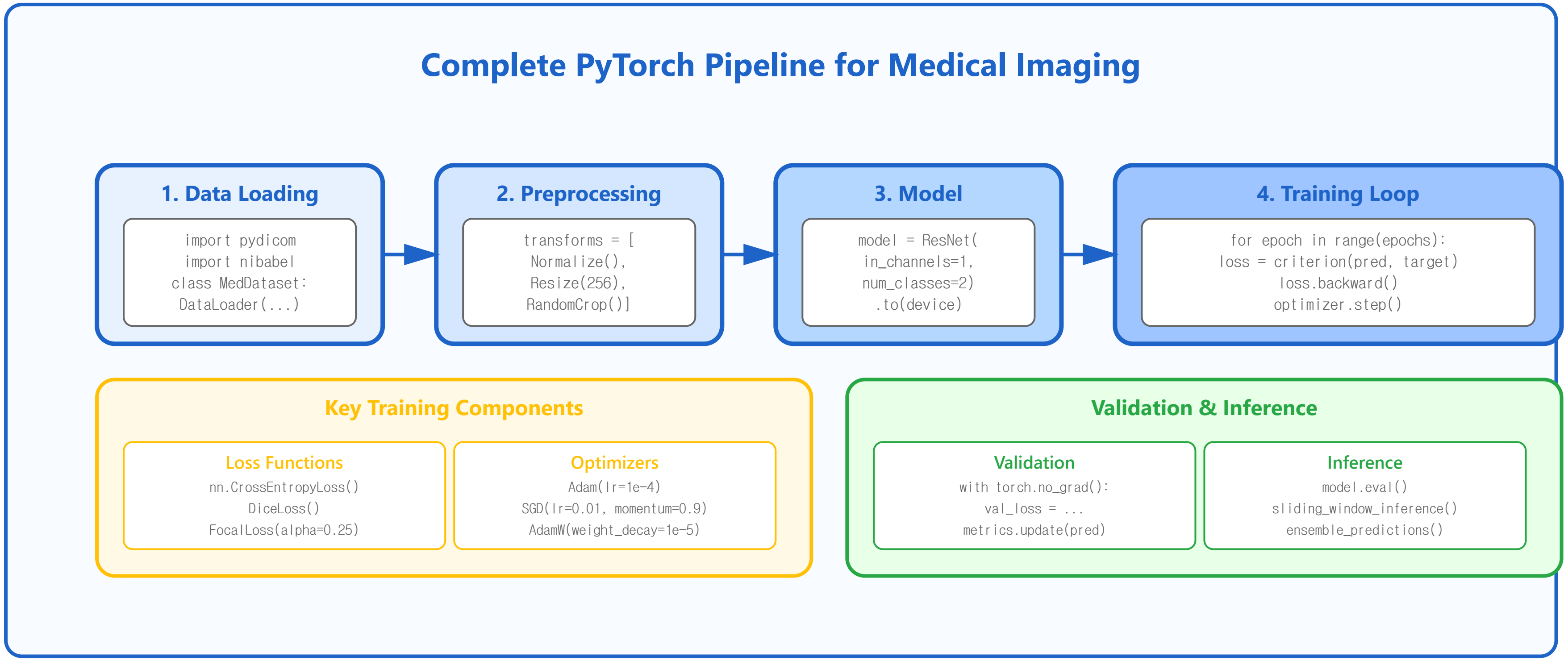
Stroke Detection

Viz.ai, RapidAI. Automated LVO detection and care team notification

Pathology Applications

Digital pathology with AI. Cancer detection in biopsies, PD-L1 scoring

Hands-on: PyTorch Medical Imaging



Data Loading

DICOM reading with pydicom, NIfTI with nibabel. Custom Dataset classes

Model Implementation

ResNet, U-Net from scratch or torchvision. Custom layers for medical imaging

Training Loops

Loss functions, optimizers, learning rate schedules. Mixed precision training

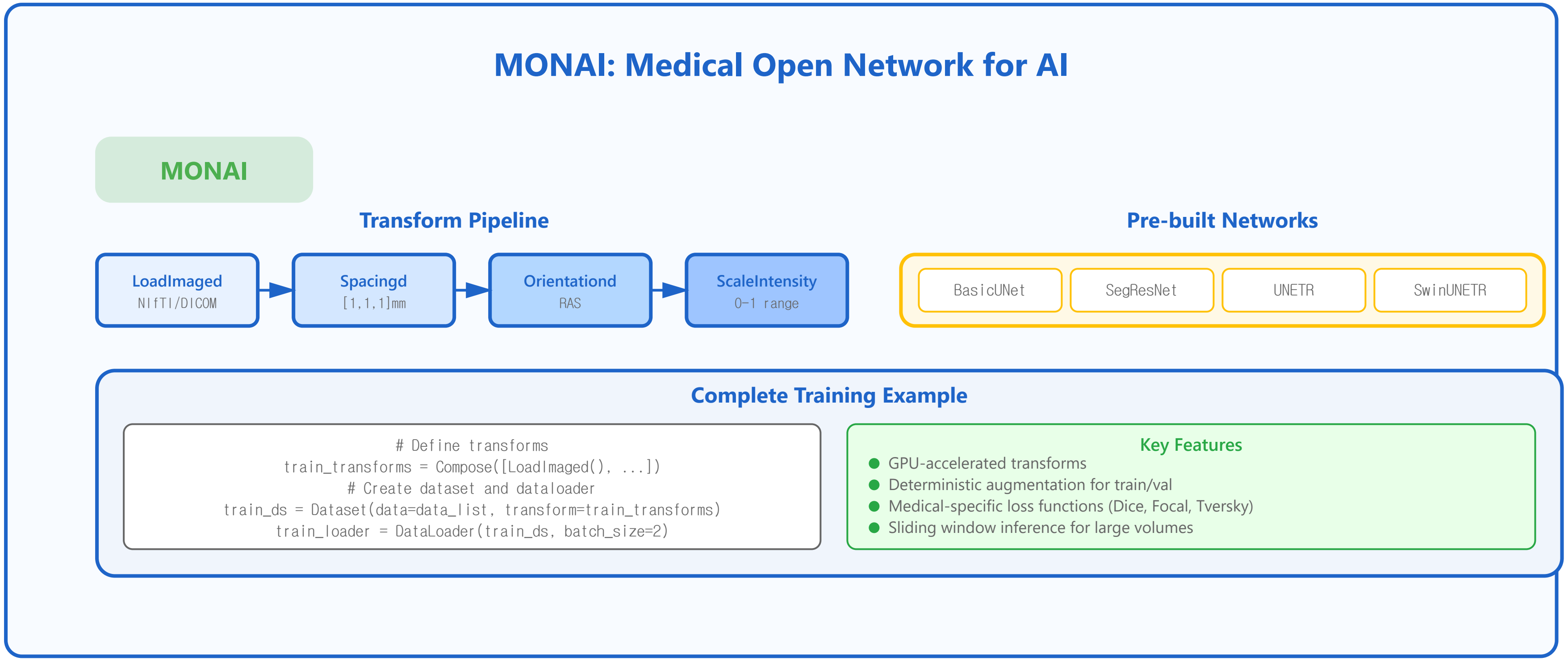
Validation

Metrics computation, checkpointing. Early stopping and model selection

Inference

Sliding window for large images. Batch processing and result aggregation

Hands-on: MONAI Framework



Medical Transforms

Specialized augmentation pipeline. Intensity normalization, resampling, cropping

Pre-built Networks

DenseNet, SegResNet, UNETR. Optimized for medical imaging

Loss Functions

DiceLoss, FocalLoss, TverskyLoss. Handle class imbalance

Metrics

Mean Dice, Hausdorff distance. Standard medical imaging metrics

Deployment

MONAI Deploy for production. Integration with PACS and inference servers

Thank You & Future Directions

Emerging Trends

Foundation models for medical imaging. Self-supervised learning at scale

Generative Models

Synthesis for data augmentation and privacy. Conditional generation for rare cases

Federated Learning

Collaborative learning without data sharing. Address data privacy and silos

Career Paths

Clinical AI researcher, ML engineer in healthcare. Regulatory affairs specialist