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KANs: KOLMOGOROV-ARNOLD NETWORKS

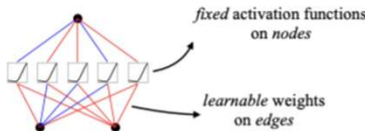
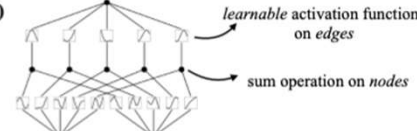
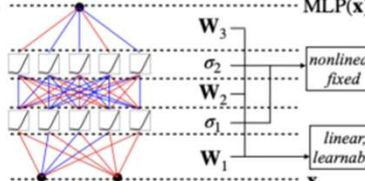
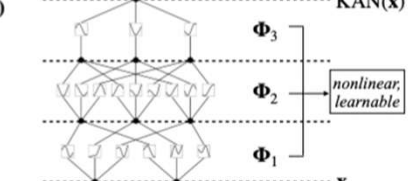
Project of Numerical Analysis for Machine Learning
Master's degree in Computer Science Engineering

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Introduction to Kolmogorov-Arnold Networks (KANs)

- KANs are inspired by the Kolmogorov-Arnold theorem.
- They provide a valid alternative to Multi-Layer Perceptrons (MLPs).
- Their key innovation lies in using learnable spline-based activation functions
- Advantages: enhanced accuracy, improved interpretability, and greater scalability.

Model	Multi-Layer Perceptron (MLP)	Kolmogorov-Arnold Network (KAN)
Theorem	Universal Approximation Theorem	Kolmogorov-Arnold Representation Theorem
Formula (Shallow)	$f(\mathbf{x}) \approx \sum_{i=1}^{N(c)} a_i \sigma(\mathbf{w}_i \cdot \mathbf{x} + b_i)$	$f(\mathbf{x}) = \sum_{q=1}^{2n+1} \Phi_q \left(\sum_{p=1}^n \phi_{q,p}(x_p) \right)$
Model (Shallow)	(a)  fixed activation functions on nodes learnable weights on edges	(b)  learnable activation functions on edges sum operation on nodes
Formula (Deep)	$\text{MLP}(\mathbf{x}) = (\mathbf{W}_3 \circ \sigma_2 \circ \mathbf{W}_2 \circ \sigma_1 \circ \mathbf{W}_1)(\mathbf{x})$	$\text{KAN}(\mathbf{x}) = (\Phi_3 \circ \Phi_2 \circ \Phi_1)(\mathbf{x})$
Model (Deep)	(c)  MLP(x) \mathbf{W}_3 σ_2 nonlinear, fixed \mathbf{W}_2 σ_1 linear, learnable \mathbf{W}_1 \mathbf{x}	(d)  KAN(x) Φ_3 Φ_2 nonlinear, learnable Φ_1 \mathbf{x}

Kolmogorov-Arnold Theorem

The theorem states that any multivariate continuous function on a bounded domain can be expressed as a finite composition of univariate continuous functions and additions.

Theorem 2.1 (Kolmogorov-Arnold representation theorem [4]). *Let f be an arbitrary multivariate continuous function on a bounded domain $f : [0, 1]^n \rightarrow \mathbb{R}$, then f :*

$$f(\mathbf{x}) = f(x_1, x_2, \dots, x_n) = \sum_{q=1}^{2n+1} \Phi_q\left(\sum_{p=1}^n \phi_{q,p}(x_p)\right)$$

with continuous one-dimensional inner functions $\phi_{q,p} : [0, 1] \rightarrow \mathbb{R}$ and continuous one-dimensional outer functions $\Phi_q : \mathbb{R} \rightarrow \mathbb{R}$.

- The advantage: Only a polynomial number of 1D functions must be learned.
- The disadvantage: These 1D functions can be non-smooth or fractal and challenging to learn directly, spline functions can approximate them effectively, achieving the desired accuracy.



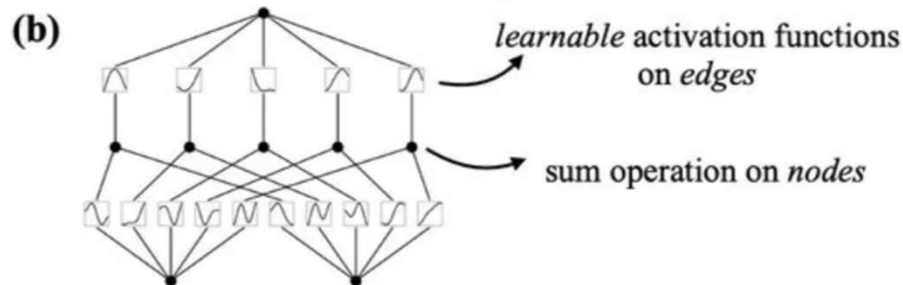
From Theorem to 2-Layers KAN

Starting from the theorem, we define the matrix representation that replaces the summation with two matrices

$$f(\mathbf{x}) = \Phi_{out} \times \Phi_{in} \times \mathbf{x}$$

where:

$$\Phi_{in} = \begin{pmatrix} \phi_{1,1}(\cdot) & \dots & \phi_{1,n}(\cdot) \\ \vdots & & \vdots \\ \phi_{2n+1,1}(\cdot) & \dots & \phi_{2n+1,n}(\cdot) \end{pmatrix}, \quad \Phi_{in} = (\Phi_1(\cdot) \dots \Phi_{2n+1}(\cdot))$$

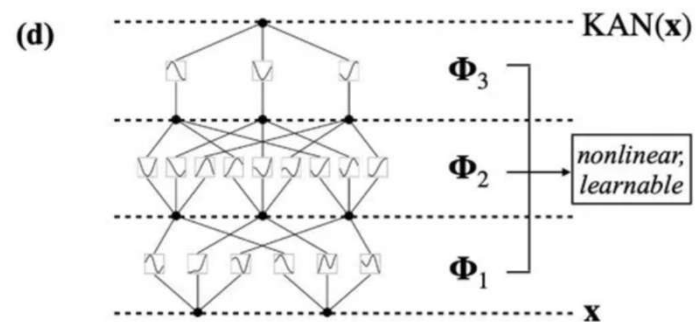


BUT Kolmogorov-Arnold networks are more expressive than their basic formulation from the Kolmogorov-Arnold representation theorem ...



KANs Layer Structure

... in practice, we can design networks with different topologies by stacking layers from the input to the output.



A general KAN layer maps its input to the output through the matrix ϕ

$$\mathbf{x}_{l+1} = \Phi \times \mathbf{x}_l \Rightarrow \mathbf{x}_{l+1} = \begin{pmatrix} \phi_{1,1}(\cdot) & \dots & \phi_{1,n_{in}}(\cdot) \\ \vdots & & \vdots \\ \phi_{n_{out},1}(\cdot) & \dots & \phi_{n_{out},n_{in}}(\cdot) \end{pmatrix} \mathbf{x}_l$$

Then the whole network will be represented by:

$$KAN(\mathbf{x}) = \Phi_{L-1} \times \dots \times \Phi_1 \times \Phi_0 \times \mathbf{x}$$



KANs Activation Functions

The most efficient technique involves leveraging spline functions. These functions are particularly effective for approximating the complexity and the non-linearities of the 1D functions associated with the KAN layers

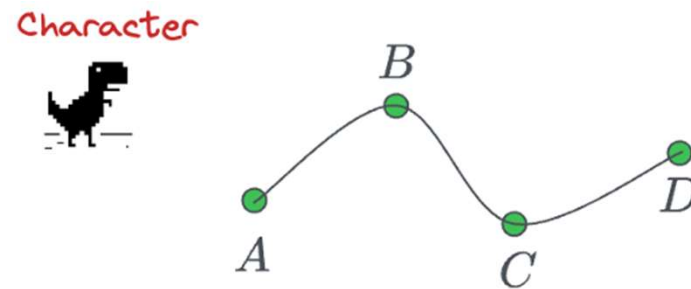
Every activation function is defined as follows:

$$\phi(x) = w_b b(x) + w_s \text{spline}(x)$$

- w_b and w_s are learnable weights
- $b(x)$ is the residual connection function defined by the silu function. It is the counterpart of the bias in MLPs
- $\text{spline}(x)$ is the learnable function where the real power of KANs came from. In most of the cases is parametrized as a linear combination of B-splines functions

B-splines (1)

The problem we are going to solve is that the spline function should pass through some tag points that will be adjusted during the training phase.



The naive way to implement it is to solve a n-dim linear system.

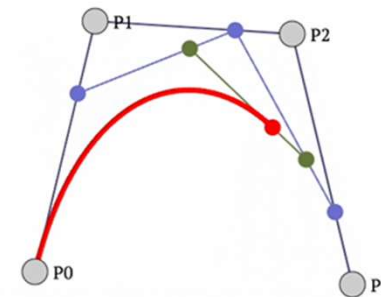
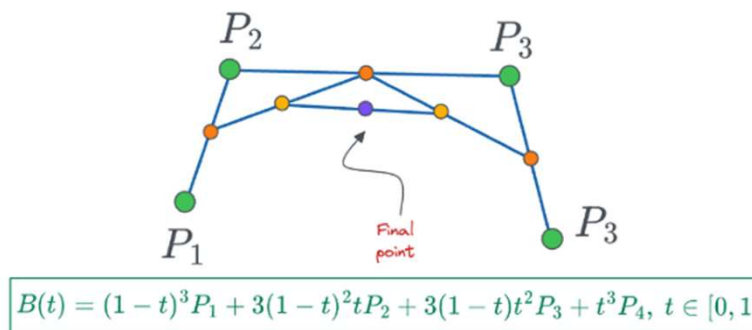
$$h(x) = a_{n-1}x^{n-1} + a_{n-2}x^{n-2} + \dots + a_1x + a_0$$

Solving such a system of linear equations will be computationally expensive and almost infeasible for KANs.



B-splines (2)

Bézier curves solve the problem more smartly: the smooth curve passes near a set of control points without needing to solve a large system of equations



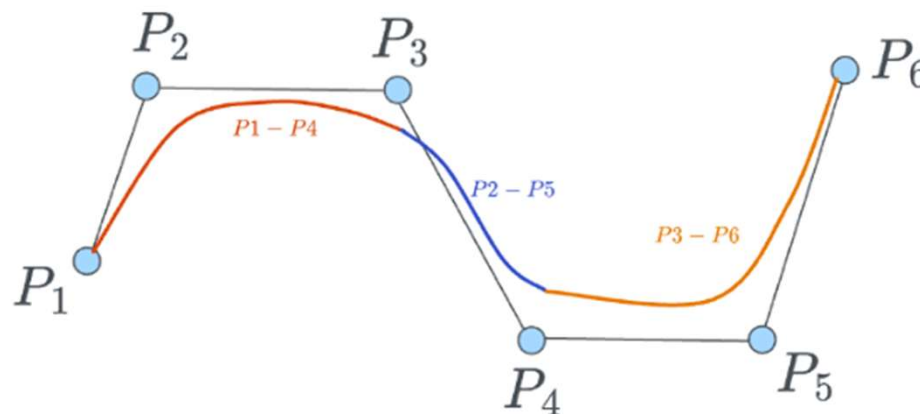
However, the problem is still the same as before. Having N data points will result in a polynomial of degree $N - 1$, which will be computationally expensive

$$\mathbf{b}(t) = \sum_{i=0}^n \binom{n}{i} (1-t)^{n-i} t^i \mathbf{P}_i, \quad t \in [0, 1]$$



B-splines (3)

B-splines use a series of lower-degree polynomial segments, which are connected smoothly. In other words, instead of extending Bézier curves to tens of hundreds of data points, which leads to an equally high degree of the polynomial, we use multiple lower-degree polynomials and connect them to form a smooth curve



$$\mathbf{B}_i(x) = \sum_{i=0}^n P_i N_{i,k} \Rightarrow \text{splines}(x) = \sum_{i=0}^k c_i B_i(x) = \sum_{i=0}^k c_i \sum_{i=0}^n P_i N_{i,k}$$



Hyperparameters

The hyperparameters of a Kolmogorov-Arnold Network (KAN) are as follows:

- L : the depth of the KAN
- $N \in \{n_0, \dots, n_l\}$: the width of each layer
- k : the number of B-splines used in the linear combination of each spline.
- G : the number of control points for each B-spline

Given these hyperparameters L , N , G , and k , and considering N as the largest $n \in N$ the total number of parameters in a KAN can be expressed as

$$O(N^2 L (G + k)) \simeq O(N^2 L G)$$

In contrast, a multi-layer perceptron (MLP) with hyperparameters L , N requires only

$$O(N^2 L)$$

However, KANs typically require much smaller values of N compared to MLPs



Inizialization and Training

KANs can be initialized and trained just like any other neural network.

Specifically for Training:

- Forward propagation: Compute

$$KAN(\mathbf{x}) = \Phi_{L-1} \times \cdots \times \Phi_1 \times \Phi_0 \times \mathbf{x}$$

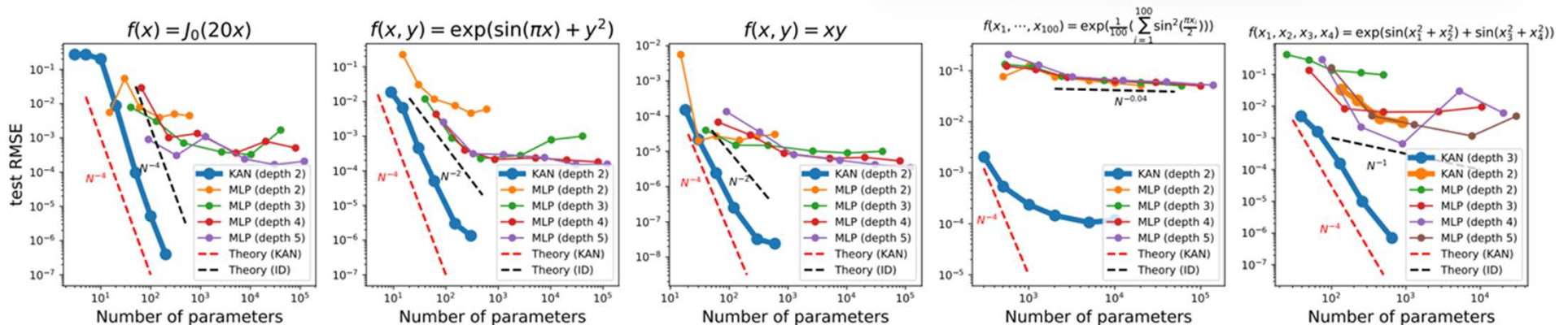
- Backward propagation: Compute the loss using LSM or cross-entropy, and then adjust the weights and splines using optimization methods such as Gradient Descent (GD), Stochastic Gradient Descent (SGD), Newton's Method (NM), BFGS, or others.



Accuracy

KANs consistently outperform MLPs, achieving significantly lower test loss across a range of parameters, and at much lower network depth (number of layers).

The performance of MLPs almost stagnates as the number of parameters increases.



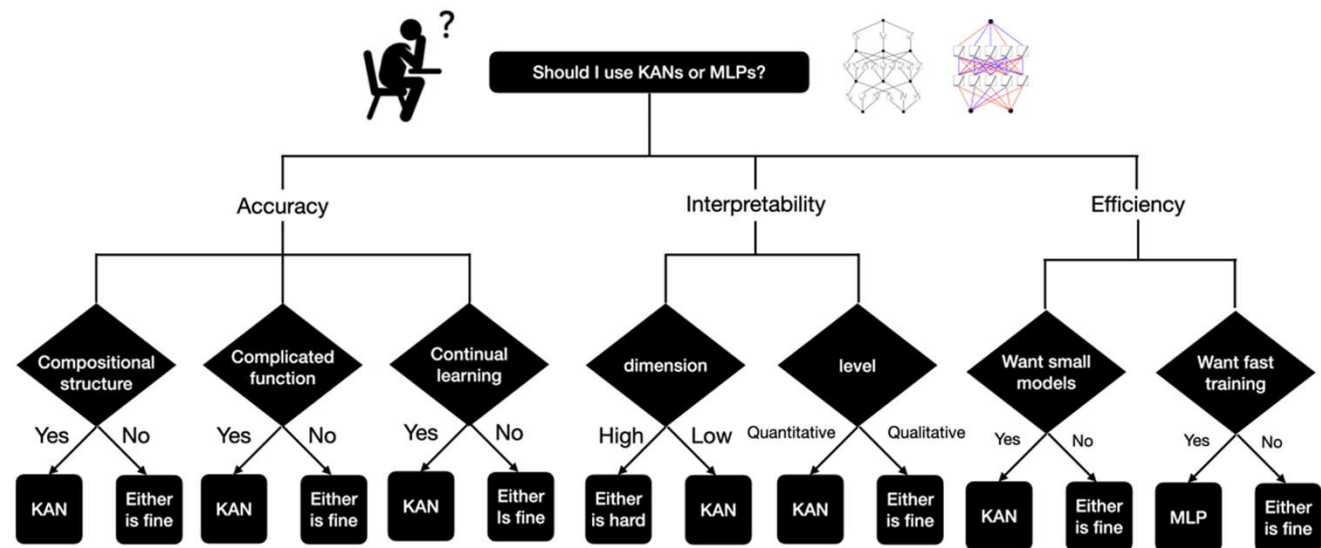
Drawbacks

Currently, the biggest bottleneck of KANs lies in their slow training.

KANs are typically 10 times slower than MLPs, given the same number of parameters (though KANs require fewer parameters than MLPs to accomplish the same task).

This is primarily caused by the complex reshaping of $\text{spline}(x)$, particularly on B-spline control points.

When should
we use KANs?



Advanced: Sparsification (1)

For MLPs, L1 regularization of linear weights is used to promote sparsity, thereby improving predictions. KANs can adopt this high-level concept by modifying it to achieve the same result.

The L1 norm of an activation function ϕ as its average magnitude over its N_p inputs:

$$|\phi|_1 \equiv \frac{1}{N_p} \sum_{s=1}^{N_p} |\phi(x^{(s)})|$$

The L1 norm of a layer is the sum of all the activation functions norm :

$$|\Phi|_1 \equiv \sum_{i=1}^{n_{in}} \sum_{j=1}^{n_{out}} |\phi_{i,j}|_1$$



Advanced: Sparsification (2)

Experimentally, we find that L1 regularization alone is insufficient for sparsification. Instead, additional entropy regularization encourages the model to use activation functions with lower complexity and fewer degrees of freedom

$$S(\Phi) \equiv - \sum_{i=1}^{n_{in}} \sum_{j=1}^{n_{out}} \frac{|\phi_{i,j}|_1}{|\Phi|_1} \log\left(\frac{|\phi_{i,j}|_1}{|\Phi|_1}\right)$$

Then the final regularization will be:

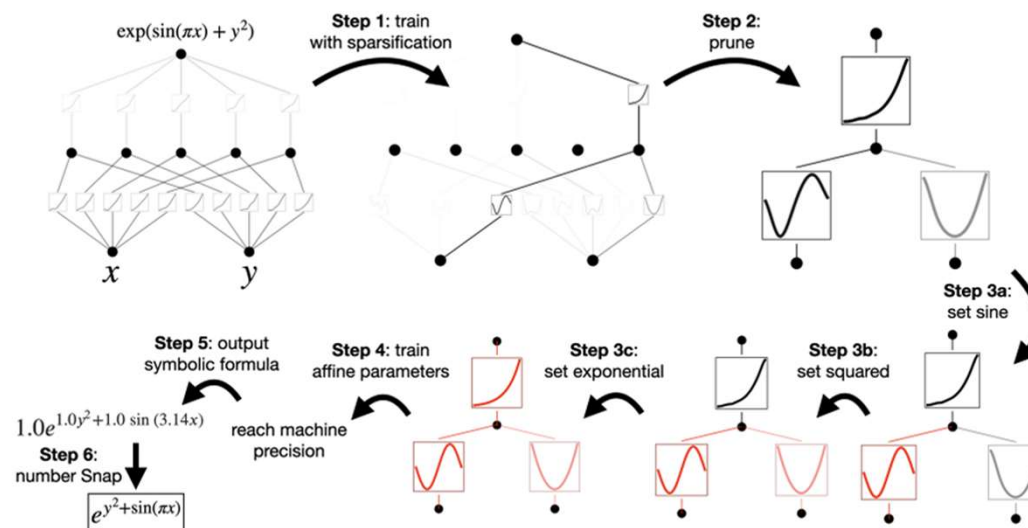
$$l_{total} = l_{pred} + \lambda(\mu_1 \sum_{l=0}^{L-1} |\Phi_l|_1 + \mu_2 \sum_{l=0}^{L-1} S(\Phi_l))$$



Advanced: Pruning and Symbolification

PRUNING: We may also want to prune the network to a smaller subnetwork by eliminating all the non-essential nodes. In matrix form, these nodes will be represented as 0.

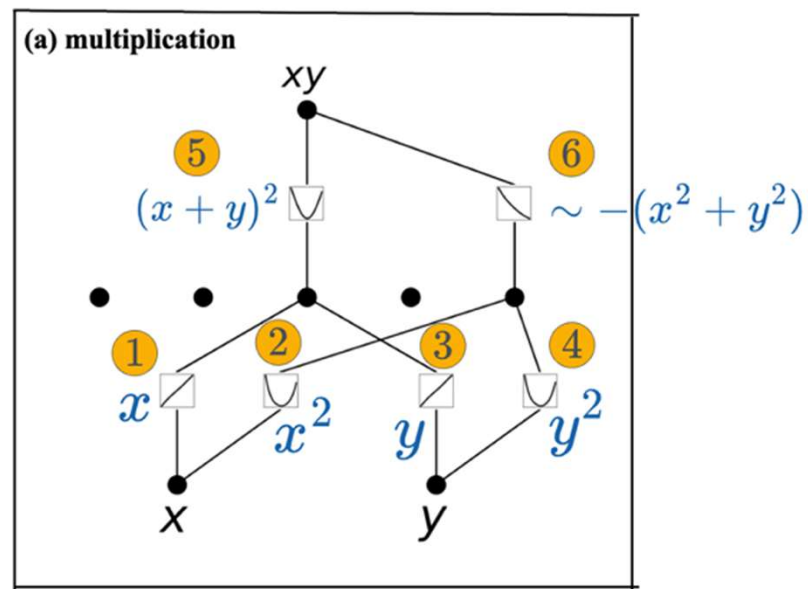
SYMBOLIFICATION: In some cases, after pruning, we suspect that some activation functions are very similar to symbolic functions then symbolification provides an interface to set the symbolic ϕ to their specified symbolic form



Interpretability

Kolmogorov-Arnold networks are interpretable since they learn univariate functions at all levels and it is relatively easy to determine the structure learned

Interpretation of $f(x, y) = xy$



Proof:
$$\frac{1}{2}(x+y)^2 - \frac{1}{2}(x^2+y^2) = \frac{1}{2}x^2 + \frac{1}{2}y^2 + xy - \frac{1}{2}x^2 - \frac{1}{2}y^2 = xy$$

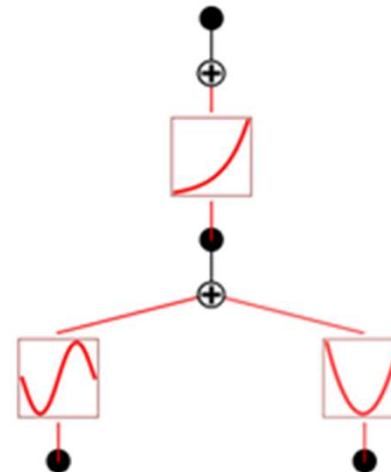
Code: Symbolic Regression

The regression task involves training a Kolmogorov Arnold Network (KAN) to learn a non-linear function using symbolic regression enhancing interpretability.

Accuracy:

- Training Accuracy: 1
- Test Accuracy: 1

$$f(x, y) = e^{\sin(\pi x) + y^2}$$



Cancer Analysis

The cancer analysis task involves training a Kolmogorov Arnold Networks (KAN) to predict cancer outcomes based on clinical and pathological data from the Wisconsin Breast Cancer Dataset from sklearn.

Accuracy:

- Training Accuracy: 0.978
- Test Accuracy: 0.974



Conclusions

KANs are not merely an alternative to MLPs but represent a paradigm shift toward more expressive, transparent, and efficient neural network architectures.

KANs in Practice:

- Outperform MLPs: Achieving lower test loss with reduced depth and complexity.
- Application: Superiority in non-linear regression, function approximation tasks, ...

Challenges with KANs:

- Computational Overhead: Spline activation functions slow down the process.
- Optimization: Lack of optimization strategies for spline-based architectures.

Future of KANs:

- Improvement: Accelerated training methods and efficient spline representations.
- Broader Adoption: Scalable regularization techniques for various tasks.

