

# Module 1: The Birth of Neural Computing

## From Biological Inspiration to the Perceptron (1943-1969)

Neural Networks for Finance

BSc Lecture Series

November 28, 2025

## How Does a Committee Make Decisions?

Imagine an investment committee evaluating a stock:

- **Analyst A:** “Strong earnings growth” (+1 vote)
- **Analyst B:** “High debt levels” (-1 vote)
- **Analyst C:** “Good momentum” (+1 vote)
- **Senior Partner:** “Market risk is elevated” (-2 votes)

## The Decision Process:

1. Gather evidence from each analyst
2. Weight opinions by seniority/expertise
3. Sum the weighted votes
4. If total > threshold: **Buy**

## Weighted Voting

Analyst	Vote	Weight
Analyst A	+1	1.0
Analyst B	-1	1.0
Analyst C	+1	1.0
Senior Partner	-1	2.0
Weighted Sum		-1.0

**Decision: Don't Buy**

**Finance Hook:** This is exactly how a perceptron works!

# What If Machines Could Decide?

## The Central Question

In 1943, scientists asked:

*“Can we build a machine that learns to make decisions like a brain?”*

## Why This Matters for Finance:

- Humans are slow and biased
- Markets process millions of data points
- Pattern recognition at scale
- Consistent, emotionless decisions

## The Promise

If we could capture how neurons compute:

- Automatic stock screening
- Risk assessment at scale
- Pattern detection in market data
- Learning from historical decisions

## The Challenge

How do we translate biological processes into mathematical operations?

*This module tells the story of how scientists attempted this translation.*

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The fundamental question that started neural network research

## The Complete Journey (4 Modules)

### 1. The Perceptron (Today)

- Single neuron foundations
- 1943-1969 history

### 2. Multi-Layer Perceptrons

- Stacking layers, activation functions

### 3. Training Neural Networks

- Backpropagation, optimization

### 4. Applications in Finance

- Stock prediction case study

## Today's Module Structure

### 1. Historical Context (1943-1969)

- McCulloch-Pitts, Hebb, Rosenblatt

### 2. Biological Inspiration

- From neurons to mathematics

### 3. The Perceptron

- Intuition, then math

### 4. Learning Algorithm

- How it adjusts weights

### 5. Limitations

- XOR problem, AI Winter

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Your journey through neural network fundamentals

By the end of this module, you will be able to:

**1. Understand biological inspiration**

- How real neurons inspired artificial ones
- What we kept and what we simplified

**2. Master the perceptron model**

- Inputs, weights, sum, activation
- The decision-making unit

**3. Interpret decision boundaries**

- Geometric meaning of weights
- Linear separability concept

**4. Apply the learning algorithm**

- Weight update rule
- Convergence conditions

**5. Recognize limitations**

- XOR problem
- Why single layers are not enough

**Finance Connection:** Throughout, we'll use stock classification as our running example.

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By the end of this module, you will be able to...

# 1943: The Mathematical Neuron

## Warren McCulloch & Walter Pitts

In 1943, a neurophysiologist and a logician asked:

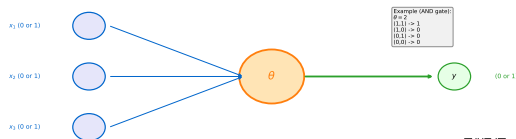
*"Can we describe what neurons do using mathematics?"*

Their paper: "A Logical Calculus of Ideas Immanent in Nervous Activity"

### Key Insight:

- Neurons have binary states (fire or not)
- This is like TRUE/FALSE in logic
- Networks of neurons can compute any logical function

McCulloch-Pitts Neuron (1943): Binary Threshold Logic



Example (AND gate):  
 $\theta = 2$   
 $(1,1) \rightarrow 1$   
 $(1,0) \rightarrow 0$   
 $(0,1) \rightarrow 0$   
 $(0,0) \rightarrow 0$

McCulloch-Pitts Rule:  
 $y = 1$  if  $\sum x_i \geq \theta$   
 $y = 0$  otherwise

Key Properties:  
- All inputs are binary (0 or 1)  
- All weights are equal ( $=1$ )  
- Single threshold parameter  
- No learning (fixed weights)

Warren McCulloch and Walter Pitts

"A Logical Calculus of Ideas Immanent in Nervous Activity" (1943)

mcculloch.pitts.diagram

Warren McCulloch and Walter Pitts: "A Logical Calculus of Ideas Immanent in Nervous Activity"

## What McCulloch & Pitts Proposed

The brain performs computation through:

### 1. Binary Signals

- Neurons either fire (1) or don't (0)
- Like bits in a computer

### 2. Threshold Logic

- Sum of inputs exceeds threshold  $\rightarrow$  fire
- Otherwise  $\rightarrow$  stay quiet

### 3. Network Composition

- Complex behaviors from simple units
- AND, OR, NOT gates from neurons

## Logical Operations with Neurons

**AND Gate** (threshold = 2):

- Both inputs = 1  $\rightarrow$  output = 1
- Otherwise  $\rightarrow$  output = 0

**OR Gate** (threshold = 1):

- Any input = 1  $\rightarrow$  output = 1
- All inputs = 0  $\rightarrow$  output = 0

**Implication:** If neurons compute logic, and computers compute logic, then we can build artificial brains!

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If neurons compute, can we build artificial ones?

## Donald Hebb's Insight

McCulloch-Pitts neurons were fixed. But how does the brain *learn*?

## Hebb's Rule (1949):

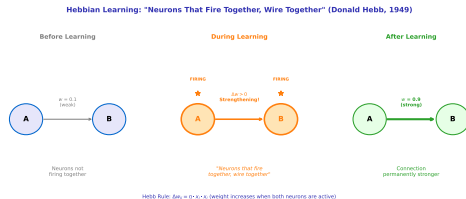
*"Neurons that fire together, wire together."*

### In Plain Terms:

- If neuron A consistently activates neuron B
- The connection  $A \rightarrow B$  grows stronger
- Repeated patterns reinforce pathways

### Finance Analogy:

An analyst who repeatedly identifies winning stocks gains more influence in the committee.



hebb\_learning\_visualization

Donald Hebb: "Neurons that fire together, wire together"



# 1958: The Perceptron is Born

## Frank Rosenblatt at Cornell

Combined McCulloch-Pitts neurons with Hebbian learning into a machine that could *learn from examples*.

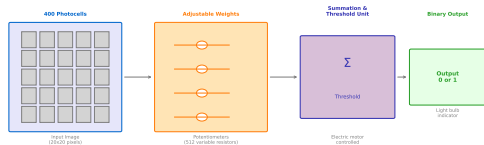
### The Perceptron:

- A single artificial neuron
- Adjustable connection weights
- Learns to classify patterns
- Implemented in hardware (Mark I)

### Key Innovation:

Not just fixed logic gates, but a system that **learns** the right weights from training data.

Mark I Perceptron (1958): First Neural Network Hardware



Specifications (1958):  
- Weights: 2 bits  
- Scale: Motor-sized  
- 512 motor-driven potentiometers (weights)  
- Could recognize simple shapes  
- Training: Electric motor adjusted weights

Frank Rosenblatt, Cornell University (funded by U.S. Navy)



The Mark I Perceptron used 400 photocells connected to a single layer of neurons with adjustable weights.

Frank Rosenblatt creates a machine that can learn

## July 8, 1958 - The New York Times

*"New Navy Device Learns By Doing; Psychologist Shows Embryo of Computer Designed to Read and Grow Wiser"*

### The Promises Made:

- Machines that recognize faces
- Automatic translation of languages
- Systems that "perceive" like humans
- The Navy predicted: walking, talking, self-reproducing machines

### The Reality:

The perceptron could classify simple patterns, but the gap between promise and capability was vast.

## Lessons for Today

### Sound Familiar?

- "AI will replace all jobs"
- "Machines will be smarter than humans by 20XX"
- "This changes everything"

### Pattern:

1. Genuine breakthrough
2. Media amplification
3. Overpromising
4. Disappointment
5. "AI Winter"

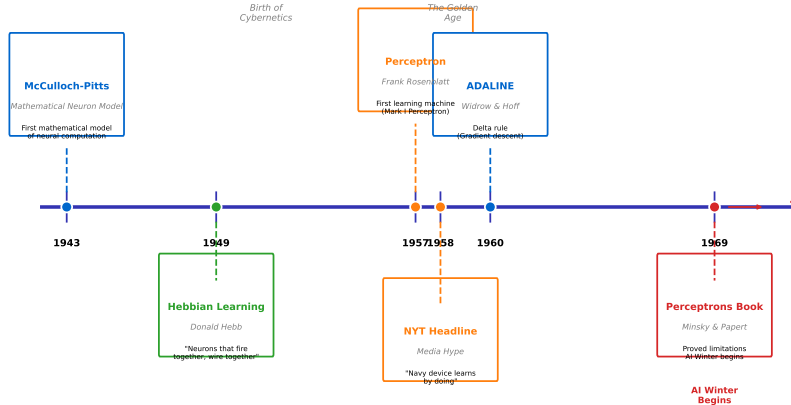
*History repeats...*

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"New Navy Device Learns By Doing" - The hype cycle begins

# Timeline: The Early Years

## Neural Networks: The Early Years (1943-1969)



From mathematical model to practical machine to fundamental limitations



timeline\_1943-1969

*“The perceptron was funded by the US Navy for military applications. How does funding source shape research direction? Are there parallels in modern AI development?”*

**Consider:**

- Military vs. commercial vs. academic funding
- What problems get prioritized?
- Open vs. closed research
- Today: Tech giants fund most AI research
- Government initiatives (CHIPS Act, etc.)
- Startup ecosystem influence

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**Think-Pair-Share: 3 minutes**

## Anatomy of a Real Neuron

1. **Dendrites (Input)**
  - Tree-like branches
  - Receive signals from other neurons
  - Thousands of connections
2. **Cell Body (Soma) (Processing)**
  - Integrates incoming signals
  - Contains the nucleus
  - Determines if neuron fires
3. **Axon (Output)**
  - Long fiber carrying output signal
  - Connects to other neurons
  - All-or-nothing signal

## How It Works

1. Signals arrive at dendrites
2. Soma sums the inputs
3. If sum exceeds threshold: neuron **fires**
4. Action potential travels down axon
5. Signal reaches next neurons

## Key Numbers:

- Human brain: ~86 billion neurons
- Each neuron: ~7,000 connections
- Total synapses: ~100 trillion

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Dendrites receive, soma processes, axon transmits

## Mathematical Abstraction

1. **Inputs** ( $x_1, x_2, \dots, x_n$ )
  - Numerical values (features)
  - Replace dendrites
2. **Weights** ( $w_1, w_2, \dots, w_n$ )
  - Importance of each input
  - Replace synapse strength
3. **Weighted Sum**
  - $z = \sum_{i=1}^n w_i x_i + b$
  - Replace soma integration
4. **Activation Function**
  - $y = f(z)$
  - Replace firing decision

## The Complete Model

$$y = f \left( \sum_{i=1}^n w_i x_i + b \right)$$

### Components:

- $x_i$ : Input features
- $w_i$ : Learnable weights
- $b$ : Bias (threshold adjustment)
- $f$ : Activation function
- $y$ : Output (prediction)

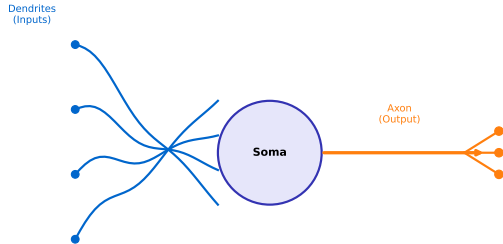
**Key Point:** The weights are what the network *learns*.

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From biology to mathematics: the abstraction trade-off

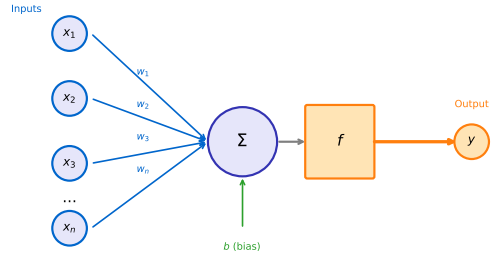
# Biological vs. Artificial: Side by Side

## Biological Neuron



*Processes information  
and generates output signal*

## Artificial Neuron



$$y = f\left(\sum_i w_i x_i + b\right)$$



biological\_vs\_artificial\_neuro

What did we keep? What did we simplify?

## A Financial Analyst as a Neuron

Biology	Finance
Dendrites	Market data feeds
Synapses	Data reliability weights
Soma	Analyst's judgment
Threshold	Conviction level
Axon	"Buy" recommendation

### The Process:

1. Receive multiple data points
2. Weight by source quality
3. Aggregate into overall view
4. If conviction  $>$  threshold: recommend

## Example: Stock Screening

### Inputs (Data):

- $x_1$ : P/E ratio = 15
- $x_2$ : Revenue growth = 20%
- $x_3$ : Debt/Equity = 0.5

### Weights (Importance):

- $w_1 = 0.3$  (value focus)
- $w_2 = 0.5$  (growth priority)
- $w_3 = -0.2$  (debt penalty)

### Decision:

$$z = 0.3(15) + 0.5(20) - 0.2(0.5) = 14.4$$

If  $z > 10$ : **Buy**

Inputs (data) -  $\rightarrow$  Weights (importance) -  $\rightarrow$  Decision (output)



## Benefits of Simplification

### 1. Mathematical Tractability

- We can write equations
- Analyze behavior formally
- Prove theorems

### 2. Computability

- Easy to implement in code
- Fast computation
- Scales to millions of units

### 3. Trainability

- Can adjust weights systematically
- Gradient-based optimization
- Learn from data

## What We Can Now Do

- Define learning algorithms
- Compute exact outputs
- Train on historical data
- Make predictions on new data
- Analyze decision boundaries

## Scale Comparison:

	Brain	GPU
Operations/sec	$10^{16}$	$10^{15}$
Power	20W	300W
Training time	Years	Hours

Different trade-offs, different capabilities.

Simplification enables computation

## Biological Complexity We Ignored

### 1. Temporal Dynamics

- Real neurons have timing
- Spike patterns carry information
- We use static activations

### 2. Structural Complexity

- Dendrites have local computation
- Different neuron types
- We use uniform units

### 3. Neurochemistry

- Neurotransmitters vary
- Modulatory systems
- We use simple multiplication

## Implications

### What ANNs Cannot Do (Well):

- Energy efficiency of brain
- One-shot learning
- Continuous adaptation
- Common sense reasoning

### The Trade-off:



*Artificial neurons are inspired by biology, not copies of it.*

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The brain does far more than our models capture

## What is a Perceptron?

The simplest possible neural network:

- One artificial neuron
- Multiple inputs, one output
- Binary decision: Yes or No

## Think of it as:

- A filter for data
- A simple classifier
- A linear decision maker

## Finance Application:

Stock screener that outputs “Buy” or “Don’t Buy” based on financial metrics.

## Real-World Examples

### Email Spam Filter:

- Inputs: word frequencies
- Output: spam or not spam

### Loan Approval:

- Inputs: income, credit score, debt
- Output: approve or reject

### Stock Screening:

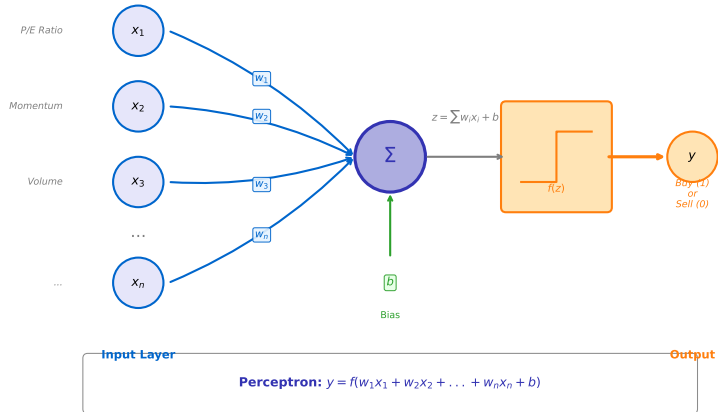
- Inputs: P/E, momentum, volume
- Output: buy or pass

All these are binary classification problems that a perceptron can solve (if the data is linearly separable).

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A single perceptron is a stock screening filter

## The Perceptron: Architecture



perceptron.architectur

## Problem Setup

You want to build a simple stock screener:

- **Goal:** Decide Buy or Pass
- **Data:** Historical financial metrics
- **Method:** Perceptron classifier

## Available Features:

1. P/E Ratio (valuation)
2. 6-month momentum (%)
3. Average daily volume
4. Debt-to-Equity ratio
5. Earnings surprise (%)

## The Question

Given these features for a new stock, should we add it to our portfolio?

## Example Stock:

- $P/E = 18$
- $Momentum = +12\%$
- $Volume = 2M \text{ shares}$
- $D/E = 0.8$
- $Surprise = +5\%$

## Traditional Approach:

Analyst manually weighs factors and decides.

## Perceptron Approach:

Learn the weights from historical winners/losers.

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Given financial indicators, should we buy this stock?

## What Are Inputs?

Each input  $x_i$  is a numerical feature:

- A measurement
- A statistic
- A signal

## In Finance:

- Price-based: returns, volatility
- Fundamental: P/E, ROE, debt ratios
- Technical: RSI, moving averages
- Sentiment: news scores, analyst ratings

## Key Requirement:

All inputs must be **numerical**. Categorical data needs encoding.

## Notation

For a stock with  $n$  features:

$$\mathbf{x} = \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix}$$

## Example (n=3):

$$\mathbf{x} = \begin{pmatrix} 18 \\ 0.12 \\ 0.8 \end{pmatrix} = \begin{pmatrix} \text{P/E} \\ \text{Momentum} \\ \text{D/E} \end{pmatrix}$$

**Note:** Features often need **normalization** (covered in Module 3).

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What data feeds into our decision?

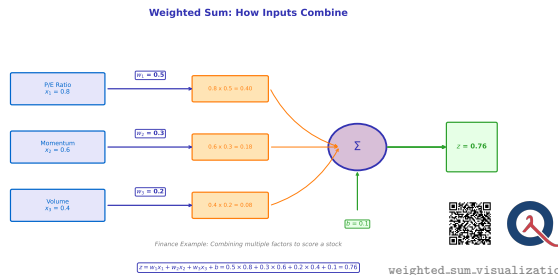
## What Are Weights?

Each weight  $w_i$  represents:

- Importance of input  $x_i$
- Direction of influence
- Learned from data

## Interpretation:

- $w_i > 0$ : Higher  $x_i$  pushes toward “Buy”
- $w_i < 0$ : Higher  $x_i$  pushes toward “Sell”
- $|w_i|$  large: Strong influence
- $|w_i|$  small: Weak influence



“Not all data is equally important” - weights encode importance

*“If you could only look at 3 metrics for a stock, which would you choose and why? How would you weight them?”*

**Consider:**

**Value Investor Might Choose:**

- P/E ratio ( $w = 0.5$ )
- Book value ( $w = 0.3$ )
- Dividend yield ( $w = 0.2$ )

**Growth Investor Might Choose:**

- Revenue growth ( $w = 0.5$ )
- Momentum ( $w = 0.3$ )
- Market share ( $w = 0.2$ )

**Key Insight:** Different investors would assign different weights. The perceptron *learns* these weights from historical performance.

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**Think-Pair-Share: 3 minutes**



# The Weighted Sum: Adding Up Evidence

## Computing the Weighted Sum

$$z = \sum_{i=1}^n w_i x_i + b = w_1 x_1 + w_2 x_2 + \cdots + w_n x_n + b$$

### What This Means:

- Multiply each input by its weight
- Sum all the products
- Add the bias term  $b$
- Result: a single “score”

### The Bias $b$ :

- Shifts the decision threshold
- Like a “base rate” or prior
- Can be thought of as  $w_0 \cdot x_0$  where  $x_0 = 1$

Combine all weighted inputs into a single score

## Worked Example

### Inputs:

- $x_1 = 0.8$  (normalized P/E)
- $x_2 = 0.6$  (normalized momentum)

### Weights:

- $w_1 = 0.5$
- $w_2 = 0.7$
- $b = -0.3$

### Calculation:

$$\begin{aligned} z &= w_1 x_1 + w_2 x_2 + b \\ &= (0.5)(0.8) + (0.7)(0.6) + (-0.3) \\ &= 0.4 + 0.42 - 0.3 \\ &= \mathbf{0.52} \end{aligned}$$

## The Perceptron as a Committee

Member	Vote	Weight	Contribution
P/E analyst	+1	0.5	+0.5
Momentum	+1	0.7	+0.7
Bias (skeptic)	-1	0.3	-0.3
Total			+0.9

If Total > 0: Committee recommends **Buy**

### Key Insight:

The perceptron is just a weighted voting system where the weights are learned from data.

## Why This Works

### Traditional Committee:

- Human experts set weights
- Based on experience/intuition
- May have biases
- Hard to scale

### Perceptron Committee:

- Weights learned from data
- Based on historical performance
- Consistent application
- Scales to any volume

**Trade-off:** Data-driven weights may not capture regime changes or rare events.

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Some votes count more than others

# The Threshold: Making the Call

## The Activation Function

After computing  $z$ , we need a final decision.

### Step Function:

$$f(z) = \begin{cases} 1 & \text{if } z \geq 0 \\ 0 & \text{if } z < 0 \end{cases}$$

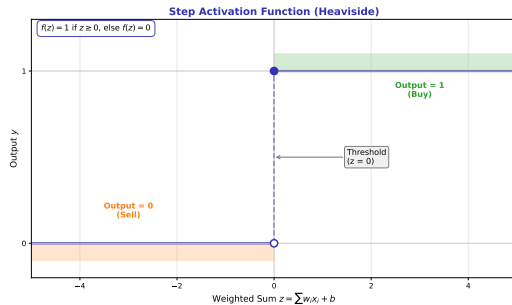
### Interpretation:

- $z \geq 0$ : Evidence favors “Buy” → output 1
- $z < 0$ : Evidence favors “Sell” → output 0

### Why Step Function?

- Binary classification needs binary output
- Mimics neuron firing (all-or-nothing)
- Simple to implement

Above threshold = Buy, Below threshold = Sell



step\_function

# The Complete Perceptron Flow

## The Pipeline

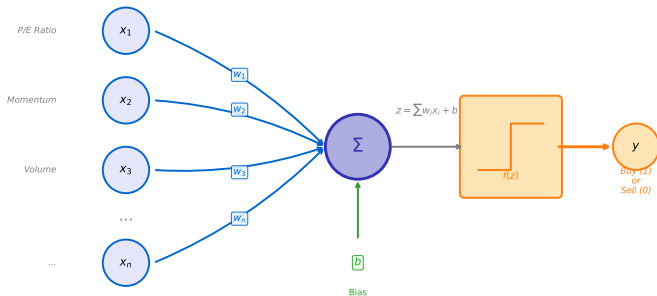
1. **Input:** Receive features  $\mathbf{x}$
2. **Weight:** Multiply by  $\mathbf{w}$
3. **Sum:** Add all products + bias
4. **Activate:** Apply step function
5. **Output:** Return prediction

## Compact Notation:

$$y = f(\mathbf{w}^T \mathbf{x} + b)$$

where  $\mathbf{w}^T \mathbf{x} = \sum_i w_i x_i$

## The Perceptron: Architecture



Input Layer

$$\text{Perceptron: } y = f(w_1 x_1 + w_2 x_2 + \dots + w_n x_n + b)$$



perceptron\_architecture

Inputs -  $i$  Weights -  $i$  Sum -  $i$  Threshold -  $i$  Decision

# Now Let's Formalize

## What You Already Know

From the intuition section:

- Inputs are weighted
- Weights encode importance
- Sum is compared to threshold
- Output is binary

## What's Next

- Precise mathematical notation
- Geometric interpretation
- Foundation for learning algorithm

## Why Math Matters

### Without Math:

- “The network kind of learns”
- “Adjust weights somehow”
- “It works, probably”

### With Math:

- Precise learning rules
- Convergence guarantees
- Understanding of limitations

*The next 8 slides formalize what you already understand intuitively.*

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**You understand the intuition. Let's write it precisely.**

# The Perceptron Equation

## Scalar Form

$$y = f \left( \sum_{i=1}^n w_i x_i + b \right)$$

where  $f$  is the step function:

$$f(z) = \begin{cases} 1 & \text{if } z \geq 0 \\ 0 & \text{otherwise} \end{cases}$$

## Vector Form

$$y = f(\mathbf{w}^T \mathbf{x} + b)$$

where:

- $\mathbf{w} = (w_1, \dots, w_n)^T$
- $\mathbf{x} = (x_1, \dots, x_n)^T$

## Alternative Notation

We can absorb the bias into weights:

$$\tilde{\mathbf{w}} = \begin{pmatrix} b \\ w_1 \\ \vdots \\ w_n \end{pmatrix}, \quad \tilde{\mathbf{x}} = \begin{pmatrix} 1 \\ x_1 \\ \vdots \\ x_n \end{pmatrix}$$

Then:

$$y = f(\tilde{\mathbf{w}}^T \tilde{\mathbf{x}})$$

**Note:** This “bias trick” simplifies notation but they are equivalent.

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The complete mathematical model

## Term by Term

Symbol	Meaning
$x_i$	Input feature $i$
$w_i$	Weight for feature $i$
$b$	Bias (threshold shift)
$z$	Weighted sum (pre-activation)
$f$	Activation function
$y$	Output prediction
$n$	Number of features

## Dimensions:

- $\mathbf{x} \in \mathbb{R}^n$
- $\mathbf{w} \in \mathbb{R}^n$
- $b, z, y \in \mathbb{R}$

Each symbol has a meaning

## What Gets Learned?

### Learned (trainable):

- Weights  $w_1, \dots, w_n$
- Bias  $b$

### Fixed (architecture):

- Number of inputs  $n$
- Activation function  $f$

### Given (data):

- Input values  $x_1, \dots, x_n$
- Target labels (for training)

**Total Parameters:**  $n + 1$

(For a 3-feature perceptron: 4 parameters)

## What Does Bias Do?

Without bias ( $b = 0$ ):

$$z = \mathbf{w}^T \mathbf{x}$$

The decision boundary passes through origin.

With bias ( $b \neq 0$ ):

$$z = \mathbf{w}^T \mathbf{x} + b$$

The decision boundary can be anywhere.

## Interpretation:

- $b > 0$ : Default toward “Buy”
- $b < 0$ : Default toward “Sell”
- Like a prior belief

## Finance Analogy

### Without Bias:

“I have no opinion until I see data”

### With Positive Bias:

“I’m generally bullish; you need to convince me to sell”

### With Negative Bias:

“I’m skeptical by default; you need strong evidence to buy”

**Key Point:** Bias shifts the “bar” that evidence must clear. It’s learned from data just like weights.

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Bias shifts the decision threshold



# The Step Activation Function

## Formal Definition

The Heaviside step function:

$$f(z) = \mathbf{1}_{z \geq 0} = \begin{cases} 1 & \text{if } z \geq 0 \\ 0 & \text{if } z < 0 \end{cases}$$

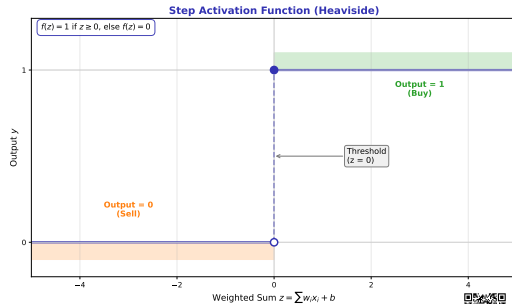
## Properties:

- Output  $\in \{0, 1\}$
- Discontinuous at  $z = 0$
- Not differentiable (problem for gradient-based learning!)

## Variants:

- Sign function: outputs  $\{-1, +1\}$
- Same idea, different labels

Binary output: yes or no



**Preview:** The non-differentiability of the step function is why we'll need smoother activations (sigmoid, ReLU) in later modules.



## The Perceptron as a Hyperplane

The equation  $\mathbf{w}^T \mathbf{x} + b = 0$  defines a hyperplane:

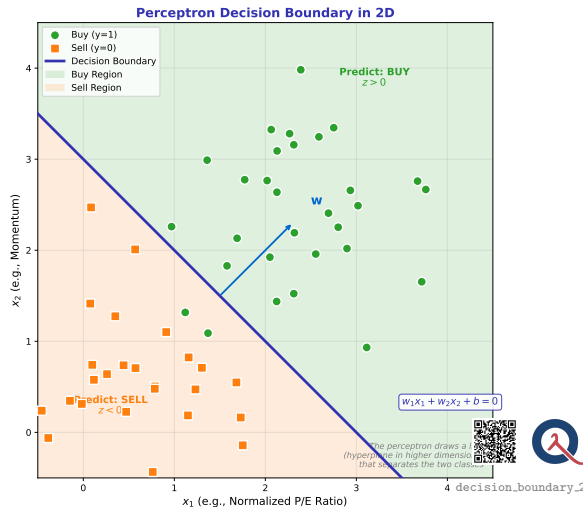
- In 2D: a line
- In 3D: a plane
- In  $n$ D: a hyperplane

## Regions:

- $\mathbf{w}^T \mathbf{x} + b > 0$ : Class 1 (Buy)
- $\mathbf{w}^T \mathbf{x} + b < 0$ : Class 0 (Sell)
- $\mathbf{w}^T \mathbf{x} + b = 0$ : Decision boundary

## Weight Vector Direction:

$\mathbf{w}$  is perpendicular to the decision boundary, pointing toward the positive class.



## Two-Feature Stock Screener

Features:

- $x_1$ : P/E ratio (normalized)
- $x_2$ : 6-month momentum (%)

Classes:

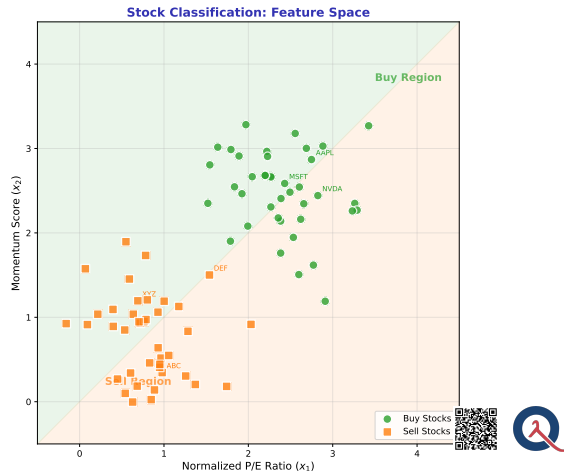
- **Green**: Outperformed (Buy)
- **Red**: Underperformed (Sell)

Goal:

Find  $w_1, w_2, b$  such that:

$$w_1 \cdot \text{P/E} + w_2 \cdot \text{Momentum} + b = 0$$

separates the classes.



Challenge: Can we draw a single line to separate Buy from Sell?

Separating “good” stocks from “bad” stocks

# The Decision Boundary Formula

## In 2D: The Line Equation

From  $w_1x_1 + w_2x_2 + b = 0$ :

$$x_2 = -\frac{w_1}{w_2}x_1 - \frac{b}{w_2}$$

This is a line with:

- Slope:  $-\frac{w_1}{w_2}$
- Intercept:  $-\frac{b}{w_2}$

## Example:

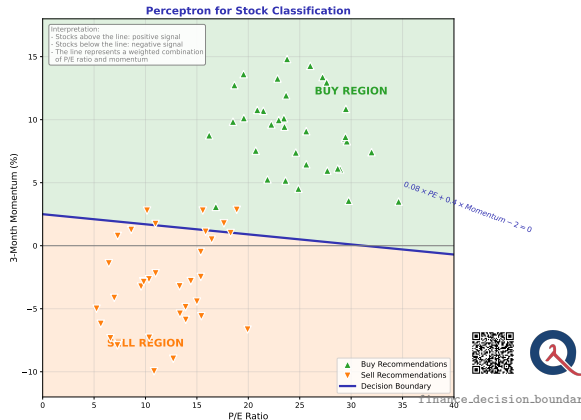
If  $w_1 = 2$ ,  $w_2 = 1$ ,  $b = -3$ :

$$x_2 = -2x_1 + 3$$

Stocks above this line: Buy

Stocks below this line: Sell

The line that separates buy from sell



# How Does the Perceptron Learn?

## The Learning Problem

### Given:

- Training data:  $\{(\mathbf{x}^{(i)}, y^{(i)})\}_{i=1}^m$
- Each  $\mathbf{x}^{(i)}$ : feature vector
- Each  $y^{(i)} \in \{0, 1\}$ : true label

### Find:

- Weights  $\mathbf{w}$
- Bias  $b$
- Such that predictions match labels

### The Approach:

Start with random weights, then iteratively adjust based on mistakes.

## The Core Idea

### If prediction is correct:

Do nothing. Weights are fine.

### If prediction is wrong:

Adjust weights to make this example more likely to be correct next time.

### Repeat:

Keep cycling through training data until no mistakes (or convergence).

**Key Insight:** Learning = adjusting weights based on errors.

---

Learning = adjusting weights based on mistakes

## Two Types of Errors

**False Negative** ( $\hat{y} = 0, y = 1$ ):

- Predicted Sell, should be Buy
- The score  $z$  was too low
- Need to *increase* score for this  $x$
- Solution: Add  $x$  to  $w$

**False Positive** ( $\hat{y} = 1, y = 0$ ):

- Predicted Buy, should be Sell
- The score  $z$  was too high
- Need to *decrease* score for this  $x$
- Solution: Subtract  $x$  from  $w$

---

Each mistake is a learning opportunity

## Visual Intuition

**Before update:**

Point is on wrong side of boundary.

**After update:**

Boundary moves to include the point on the correct side.

**The Update Rule:**

$$w_{\text{new}} = w_{\text{old}} + (y - \hat{y}) \cdot x$$

**Check:**

- If  $y = 1, \hat{y} = 0$ : add  $x$
- If  $y = 0, \hat{y} = 1$ : subtract  $x$
- If  $y = \hat{y}$ : no change

# The Learning Rule: Intuition

## Why Adding $x$ Works

For a false negative (missed Buy):

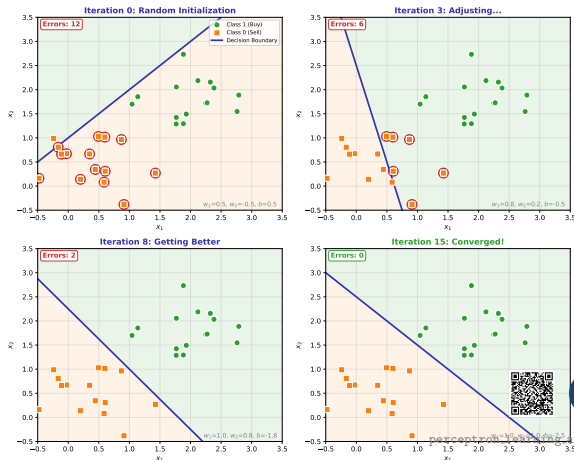
- Current:  $\mathbf{w}^T \mathbf{x} + b < 0$
- After adding  $\mathbf{x}$  to  $\mathbf{w}$ :
- New score:  $(\mathbf{w} + \mathbf{x})^T \mathbf{x} + b$
- $= \mathbf{w}^T \mathbf{x} + \mathbf{x}^T \mathbf{x} + b$
- $= \mathbf{w}^T \mathbf{x} + \|\mathbf{x}\|^2 + b$

Since  $\|\mathbf{x}\|^2 > 0$ , the new score is higher!

## Geometrically:

Adding  $\mathbf{x}$  rotates the decision boundary toward classifying  $\mathbf{x}$  correctly.

Perceptron Learning: Decision Boundary Adjusts Until Convergence



If wrong, move the boundary

# The Perceptron Learning Rule

## The Update Equations

For each training example  $(\mathbf{x}, y)$ :

**Weight update:**

$$\mathbf{w} \leftarrow \mathbf{w} + \eta(y - \hat{y})\mathbf{x}$$

**Bias update:**

$$b \leftarrow b + \eta(y - \hat{y})$$

where:

- $\eta > 0$  is the learning rate
- $\hat{y} = f(\mathbf{w}^T \mathbf{x} + b)$  is prediction
- $y$  is true label

## The Complete Algorithm

1. Initialize  $\mathbf{w} = \mathbf{0}$ ,  $b = 0$
2. repeat:
  - a. For each  $(\mathbf{x}^{(i)}, y^{(i)})$  in training set:
  - b. Compute  $\hat{y}^{(i)} = f(\mathbf{w}^T \mathbf{x}^{(i)} + b)$
  - c. If  $\hat{y}^{(i)} \neq y^{(i)}$ :
$$\mathbf{w} \leftarrow \mathbf{w} + \eta(y^{(i)} - \hat{y}^{(i)})\mathbf{x}^{(i)}$$
$$b \leftarrow b + \eta(y^{(i)} - \hat{y}^{(i)})$$
3. until no errors (or max iterations)

---

The mathematical update rule



## What is $\eta$ ?

The learning rate controls step size:

- How much weights change per update
- Typical values: 0.01 to 1.0
- For perceptron: often  $\eta = 1$

## Effects:

### $\eta$ too small:

- Very slow learning
- Many iterations needed
- But stable

### $\eta$ too large:

- May overshoot
- Oscillate around solution
- But faster initially

## For the Perceptron

### Good news:

For linearly separable data, the perceptron converges regardless of  $\eta > 0$ .

### Why?

The convergence theorem (next slides) guarantees finding a solution if one exists.

### In Practice:

$\eta = 1$  is common for perceptron. Learning rate matters more for:

- Gradient descent (Module 3)
- Non-separable data
- Multi-layer networks

---

Step size matters: too big or too small both cause problems

# Worked Example: Stock Classification

## Setup

Two stocks, two features:

- $\mathbf{x}^{(1)} = (0.5, 0.8)$ ,  $y^{(1)} = 1$  (Buy)
- $\mathbf{x}^{(2)} = (0.2, 0.3)$ ,  $y^{(2)} = 0$  (Sell)

Initialize:  $\mathbf{w} = (0, 0)$ ,  $b = 0$ ,  $\eta = 1$

## Iteration 1: Example 1

- $z = 0 \cdot 0.5 + 0 \cdot 0.8 + 0 = 0$
- $\hat{y} = f(0) = 1$  (threshold at 0)
- $y = 1$ , correct! No update.

## Iteration 1: Example 2

- $z = 0$ ,  $\hat{y} = 1$
- $y = 0$ , wrong!
- $\mathbf{w} \leftarrow (0, 0) + 1(0 - 1)(0.2, 0.3) = (-0.2, -0.3)$
- $b \leftarrow 0 + 1(0 - 1) = -1$

## Iteration 2: Example 1

- $z = -0.2(0.5) - 0.3(0.8) - 1 = -1.34$
- $\hat{y} = 0$
- $y = 1$ , wrong!
- $\mathbf{w} \leftarrow (-0.2, -0.3) + (0.5, 0.8) = (0.3, 0.5)$
- $b \leftarrow -1 + 1 = 0$

## Iteration 2: Example 2

- $z = 0.3(0.2) + 0.5(0.3) + 0 = 0.21$
- $\hat{y} = 1$ ,  $y = 0$ , wrong!
- $\mathbf{w} \leftarrow (0.3, 0.5) - (0.2, 0.3) = (0.1, 0.2)$
- $b \leftarrow 0 - 1 = -1$

Continue until convergence...

---

Following the math with real numbers

# Convergence: Does It Always Work?

## The Perceptron Convergence Theorem

### Theorem (Rosenblatt, 1962):

If the training data is **linearly separable**, the perceptron learning algorithm will find a separating hyperplane in a **finite** number of updates.

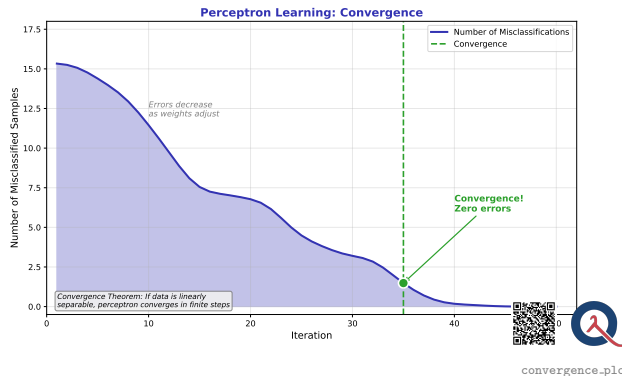
### Key Conditions:

- Data must be linearly separable
- Learning rate  $\eta > 0$
- Cycling through all examples

### Bound on Updates:

$$\text{mistakes} \leq \frac{R^2}{\gamma^2}$$

where  $R = \text{max norm}$ ,  $\gamma = \text{margin}$



The perceptron convergence theorem guarantees finding a solution IF one exists

*“What happens when data isn’t linearly separable in financial markets? Can you think of examples?”*

**Consider:**

**Examples of Non-Separable Data:**

- High P/E growth stocks AND low P/E value stocks both outperform
- Medium-risk investments underperform both conservative and aggressive
- “Buy the rumor, sell the news” patterns

**What Happens to the Perceptron?**

- Never converges
- Oscillates forever
- Best we can do: minimize errors
- Need something more powerful...

**Foreshadowing:** This is exactly why we need **multi-layer** networks (Module 2).

---

**Think-Pair-Share: 3 minutes**

# The XOR Problem

## The Exclusive OR Function

$x_1$	$x_2$	XOR
0	0	0
0	1	1
1	0	1
1	1	0

### In Words:

Output is 1 if inputs are *different*, 0 if inputs are *same*.

### The Challenge:

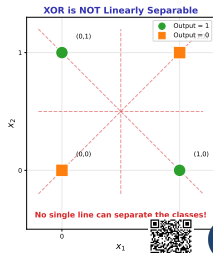
Try to draw a single line that separates the 1s from the 0s...

## The XOR Problem: Why Single-Layer Perceptrons Fail

XOR Truth Table

$x_1$	$x_2$	XOR	Output
0	0	0 XOR 0	0
0	1	0 XOR 1	1
1	0	1 XOR 0	1
1	1	1 XOR 1	0

"Same inputs = 0, Different inputs = 1"



xor\_problem

Some patterns cannot be separated by a single line

# Why XOR Cannot Be Solved

## Geometric Impossibility

### Perceptron decision boundary:

$$w_1x_1 + w_2x_2 + b = 0$$

This is always a **straight line**.

### XOR requires:

A boundary that curves or has multiple segments.

### Linear vs Non-Linear

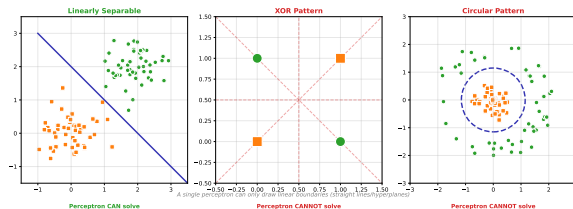
#### Linearly Separable:

- AND, OR, NAND, NOR
- One line can separate

#### Not Linearly Separable:

- XOR, XNOR
- No single line works

Linear vs Non-Linear Decision Boundaries



linear\_vs\_nonlinear\_pattern

No single hyperplane can separate XOR

# 1969: The Critique That Changed Everything

## Minsky and Papert's Book

"Perceptrons: An Introduction to Computational Geometry" (1969)

### Key Arguments:

1. Single-layer perceptrons cannot compute XOR
2. Many important functions are non-linear
3. No known training algorithm for multi-layer networks
4. Scaling limitations

### The Impact:

The book was rigorous and influential. It convinced funding agencies that neural networks were a dead end.

## The Controversy

### Valid Points:

- Single layers *are* limited
- XOR problem is real
- No training algorithm existed (then)

### Overstated Points:

- "Neural networks can't work"
- Implied multi-layer networks wouldn't help
- Discouraged research for 15+ years

**Lesson:** Valid criticism of current methods shouldn't stop research into future improvements.

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Marvin Minsky and Seymour Papert: "Perceptrons" book

# The First AI Winter Begins

## The Collapse

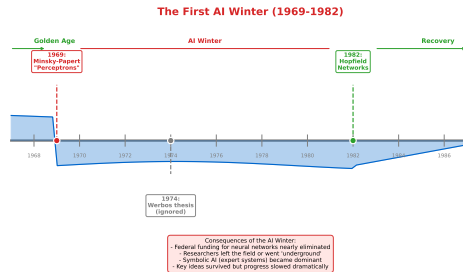
After 1969:

- Funding dried up
- Researchers left the field
- “Neural networks don’t work”
- Symbolic AI took over

**Duration:** 1969 to ~1982

## What Survived:

- A few dedicated researchers
- Theoretical work continued quietly
- Hopfield networks (1982)
- Backpropagation (1986)



ai\_winter\_timelin

**1969-1982: The dark ages of neural network research**



## What We Learned

### 1. Historical Foundation

- McCulloch-Pitts (1943): neurons compute
- Hebb (1949): learning strengthens connections
- Rosenblatt (1958): perceptron learns

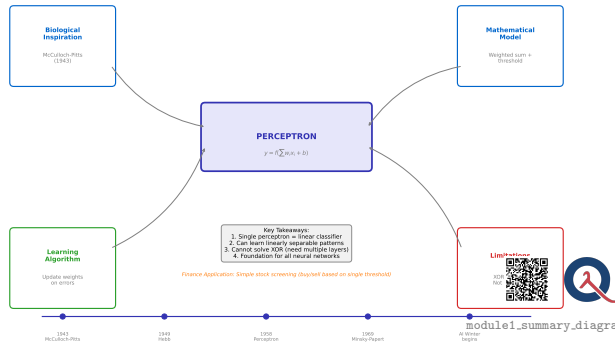
### 2. The Perceptron Model

- Weighted sum + threshold
- Linear decision boundary
- Learns from mistakes

### 3. Limitations

- Only linearly separable problems
- XOR is impossible
- Led to AI Winter

Module 1 Summary: The Birth of Neural Computing



From biological inspiration to mathematical limitation

### *“What if we stack multiple perceptrons?”*

#### **The Problem We Face**

Single perceptrons can only solve linearly separable problems. Real financial data is rarely that simple.

#### **The Solution Preview:**

- Add “hidden” layers
- Non-linear activation functions
- Multi-Layer Perceptrons (MLPs)

#### **Coming in Module 2:**

- How XOR gets solved
- MLP architecture
- Activation functions (sigmoid, ReLU)
- Universal Approximation Theorem
- Loss functions

**Spoiler:** Adding just one hidden layer changes everything.

**Mathematical details for this module: See Appendix A (Perceptron Convergence Proof)**

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**Next: Solving XOR with Multi-Layer Perceptrons**

# Module 1: The Birth of Neural Computing

## From Biological Inspiration to the Perceptron (1943-1969)

Neural Networks for Finance

BSc Lecture Series

November 28, 2025

## Module 1 Summary

We learned that a single perceptron:

- Takes weighted inputs
- Applies a threshold
- Outputs a binary decision
- Can only draw **linear** boundaries

## The Perceptron Equation:

$$y = f \left( \sum_{i=1}^n w_i x_i + b \right)$$

## The Problem

The perceptron cannot solve XOR or any non-linearly separable problem.

## The AI Winter:

- Minsky-Papert (1969) critique
- Funding dried up
- “Neural networks don’t work”

## Today’s Question:

What if we stack multiple perceptrons together?

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The perceptron: powerful but limited

# The XOR Problem Revisited

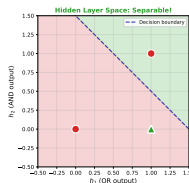
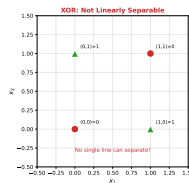
## Why One Line Isn't Enough

$x_1$	$x_2$	XOR
0	0	0
0	1	1
1	0	1
1	1	0

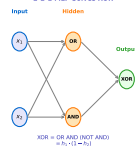
## The Geometry:

- Opposite corners have same label
- No single line can separate them
- We need *multiple* boundaries

XOR Solution: Hidden Layer Creates Linearly Separable Representation



2-2-1 MLP Solves XOR



xor\_solution.ml

Some patterns require more than a single line

## Single Analyst (Perceptron)

One junior analyst screening stocks:

- Looks at a few metrics
- Applies simple rules
- Makes direct decisions
- Limited perspective

### Limitation:

“Buy if  $P/E < 15$  AND momentum  $> 0$ ”

This is a single linear rule.

**Key Insight:** Hierarchical processing enables complex pattern recognition.

## Investment Team (MLP)

A hierarchical team:

- Junior analysts find patterns
- Senior analysts synthesize
- CIO makes final call
- Complex reasoning emerges

### Capability:

“Consider value metrics, momentum signals, AND market regime together”

Multiple non-linear patterns.

---

A single analyst sees simple patterns. A team sees complex ones.

## What We'll Cover

### 1. Historical Context

- AI Winter survival
- Backprop rediscovery (1986)

### 2. MLP Architecture

- Intuition: The firm analogy
- Math: Matrix notation

### 3. Activation Functions

- Why non-linearity matters
- Sigmoid, Tanh, ReLU

### 4. Universal Approximation

- The fundamental theorem
- Implications and limits

### 5. Loss Functions

- MSE for regression
- Cross-entropy for classification

## Learning Objectives:

- Understand MLP architecture
- Master matrix notation
- Know when to use which activation
- Appreciate universal approximation

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From single perceptron to universal function approximation

# The AI Winter (1969-1982)

## After Minsky-Papert

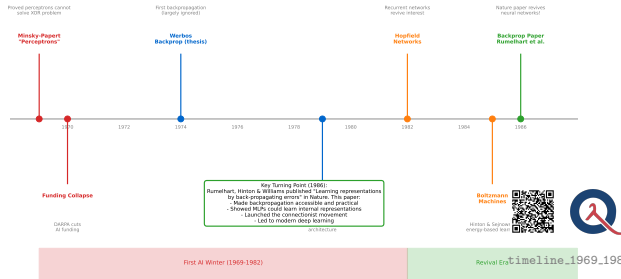
The neural network winter:

- Government funding cut
- Researchers moved to other fields
- “Connectionism is dead”
- Symbolic AI dominated

## The Mood:

- Perceptrons can't solve XOR
- Multi-layer networks exist but...
- No efficient training algorithm
- Why bother?

### From Darkness to Light: 1969-1986



After Minsky-Papert, neural network research nearly died



## Paul Werbos (1974)

PhD thesis at Harvard:

- Derived backpropagation
- For general non-linear systems
- Applied to neural networks
- Largely ignored

## Why Ignored?

- Published in economics, not CS
- AI winter was at its coldest
- No computational power to test
- No community to spread ideas

## Parallel Discoveries

### 1970s:

- Linnainmaa: automatic differentiation
- Control theory: similar ideas

### 1980s:

- Parker (1982): rediscovery
- LeCun (1985): independent work
- Rumelhart/Hinton/Williams (1986): fame

**Lesson:** Good ideas can be discovered multiple times before they “take off.”

---

The key ideas existed but were ignored

## John Hopfield

A physicist (not AI researcher) revived interest:

- Connected neural networks to physics
- Energy-based formulation
- Published in PNAS (prestigious)
- Showed neural nets could store memories

## The Impact:

- Legitimized neural network research
- Attracted physicists to the field
- New mathematical tools
- Funding started returning

## Why Physics Helped

### Physics Connection:

- Neurons  $\leftrightarrow$  spins in magnets
- Learning  $\leftrightarrow$  energy minimization
- Networks  $\leftrightarrow$  statistical mechanics

### Finance Parallel:

Physicists would later apply similar ideas to:

- Option pricing
- Market dynamics
- Risk modeling
- Quantitative finance

---

John Hopfield: Physicist rediscovers neural networks

# 1986: The Backpropagation Paper

## The Paper That Changed Everything

Rumelhart, Hinton, Williams in Nature (1986):

“Learning representations by back-propagating errors”

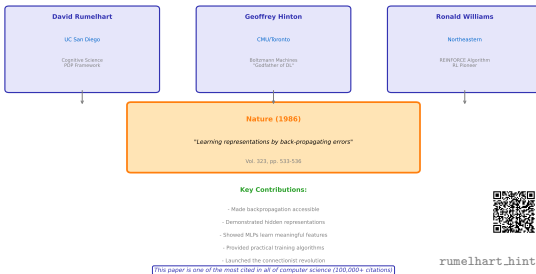
### Key Contributions:

- Clear algorithm presentation
- Demonstrated on real problems
- Published in high-impact journal
- Well-communicated to broad audience

### The Result:

Neural network renaissance begins.

#### The 1986 Breakthrough: Rumelhart, Hinton & Williams



Nature paper: “Learning representations by back-propagating errors”

# What Made 1986 Different?

## Werbos (1974)

- + Correct algorithm
- + General framework
- Wrong field (economics)
- No demonstrations
- No community
- No computers

## Lesson for Researchers:

Being right isn't enough. You need:

- The right timing
- The right communication
- The right audience
- The right technology

## Rumelhart et al. (1986)

- + Correct algorithm
- + Clear presentation
- + Compelling demos
- + High-profile venue (Nature)
- + Growing community
- + Computers available

---

The right idea at the right time with the right people

*“Backpropagation was discovered multiple times (1974, 1982, 1986). Why do some discoveries get ignored while others take off? What role did timing play?”*

**Consider:**

- Publication venue matters
- Community readiness
- Computational infrastructure
- Demonstration quality
- Today: transformers (2017) exploded
- LSTMs existed since 1997
- What changed?

---

**Think-Pair-Share: 3 minutes**

## After 1986

Neural networks were back:

- Funding returned
- New conferences (NIPS, now NeurIPS)
- “Connectionism” movement
- Real applications emerged

## Key Milestones:

- 1989: LeNet for digit recognition
- 1990s: Speech recognition
- 1990s: Financial applications begin

## But Challenges Remained

Not everything worked:

- Deep networks hard to train
- Vanishing gradients
- Limited compute power
- Another “winter” in 2000s

## True Revolution: 2012

AlexNet on ImageNet marked the deep learning era.  
(Module 4)

*But first, we need to understand the architecture...*

---

Neural networks are back - and this time they can learn

## Hierarchical Decision Making

### Level 1: Junior Analysts (Hidden Layer 1)

- Look at raw data
- Find basic patterns
- “This looks like a value stock”
- “This has momentum”

### Level 2: Senior Analysts (Hidden Layer 2)

- Combine junior reports
- Higher-level synthesis
- “Value + momentum = quality”

### Level 3: CIO (Output Layer)

- Final buy/sell decision
- Combines all analyses
- Single decision point

### Key Properties:

1. Information flows upward
2. Each level adds abstraction
3. Later layers see patterns in patterns
4. Final layer integrates everything

**This is an MLP!**

---

Hierarchical decision making

## The Input Layer

What it does:

- Receives raw data
- One neuron per feature
- No computation
- Just passes data forward

## In Finance:

- P/E ratio
- Momentum (returns)
- Volume
- Volatility
- Sector indicators
- Market cap

## Notation

$$\mathbf{x} = \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix}$$

where:

- $n$  = number of features
- $x_i$  = value of feature  $i$

## Example (n=4):

$$\mathbf{x} = \begin{pmatrix} 15 \\ 0.08 \\ 1.2M \\ 0.25 \end{pmatrix} = \begin{pmatrix} \text{P/E} \\ \text{Return} \\ \text{Volume} \\ \text{Vol} \end{pmatrix}$$

---

The input layer receives raw information



# Hidden Layers: The Pattern Finders

## What Hidden Layers Do

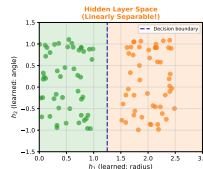
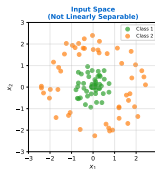
They discover intermediate patterns:

- Not explicitly programmed
- Emerge from training
- Often uninterpretable
- But highly useful

## Each Hidden Neuron:

- Receives weighted inputs
- Applies activation function
- Outputs a single number
- “Detects” a specific pattern

Hidden Layers: Learning Useful Representations



## What Hidden Layers Learn

**Raw Features:**  $x_1, x_2$   
Original inputs

**Hidden Features:**  $h_1 = f(W \cdot x)$   
Learned combinations

**Useful Patterns:** Radius, angles, edges, textures...

**Linear Separability:** Transform until classes separable

*Network learns this!*



hidden\_layer\_representation

“They see things in the data you didn’t explicitly ask for”

## Hypothetical Hidden Neurons

### Hidden Neuron 1: “Value Detector”

- Positive weight on low P/E
- Positive weight on high book value
- Activates for value stocks

### Hidden Neuron 2: “Momentum Detector”

- Positive weight on recent returns
- Positive weight on volume
- Activates for trending stocks

### Hidden Neuron 3: “Risk Detector”

- Positive weight on volatility
- Positive weight on debt
- Activates for risky stocks

---

Hidden neurons learn abstract concepts

## The Output Layer

Combines hidden neuron outputs:

$$\text{Buy} = f(w_1 \cdot \text{Value} + w_2 \cdot \text{Momentum} - w_3 \cdot \text{Risk})$$

### Key Insight:

We never told the network what “value” or “momentum” means. It *discovered* these concepts from data.

### Caveat:

Real hidden neurons may not be this interpretable. They might detect patterns we can't name.

## The Output Layer

Takes hidden representations and produces:

- Classification: probability of class
- Regression: continuous prediction
- Multiple outputs possible

### For Binary Classification:

Single output neuron with sigmoid:

$$\hat{y} = \sigma(w^T h + b)$$

Output  $\in (0, 1)$  interpreted as probability.

### For Regression:

Single output neuron with no activation (or linear):

$$\hat{y} = w^T h + b$$

Output is predicted value.

---

The output layer synthesizes everything into a decision

## Finance Examples

### Buy/Sell Classification:

- Output:  $P(\text{Buy})$
- If  $> 0.5$ : recommend Buy
- If  $< 0.5$ : recommend Sell

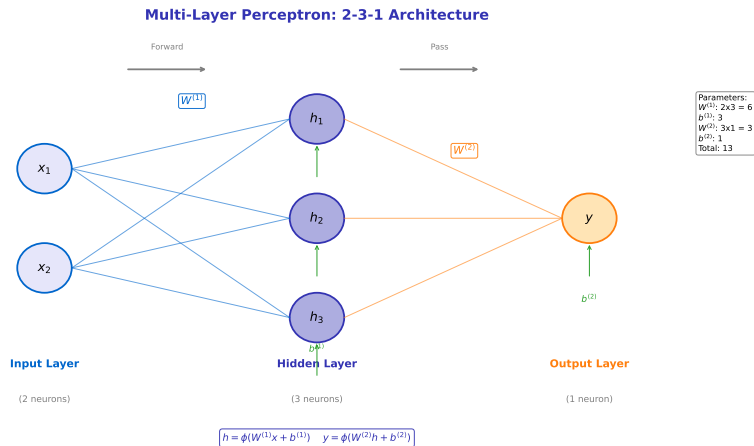
### Return Prediction:

- Output: predicted return
- Could be next-day, next-month
- Continuous value

### Multi-Class (Sector):

- Multiple output neurons
- Softmax activation
- Each output = probability of sector

# The Full MLP Architecture



mlp\_architecture\_2.3\_

# Why Are They Called “Hidden”?

## We Don't Observe Them Directly

### Observable:

- Input layer: the features we provide
- Output layer: the prediction we get

### Hidden:

- Internal representations
- Not directly specified
- Learned automatically
- “Hidden” from us

## We Don't Tell Them What to Learn

### Traditional ML:

“Here are features: P/E, momentum, volume”  
We engineer the features.

### Deep Learning Philosophy:

“Here is raw data. Find useful patterns.”  
Network discovers features.

### Trade-off:

More automatic, but less interpretable.

---

Hidden layers discover features automatically

## The Two-Hidden-Neuron Solution

### Hidden Neuron 1:

Learns: "Is it in the upper-right region?"

$$h_1 = \sigma(w_{11}x_1 + w_{12}x_2 + b_1)$$

### Hidden Neuron 2:

Learns: "Is it in the lower-left region?"

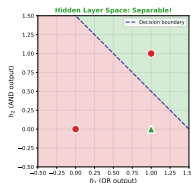
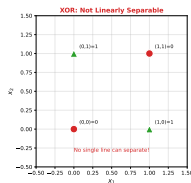
$$h_2 = \sigma(w_{21}x_1 + w_{22}x_2 + b_2)$$

### Output Neuron:

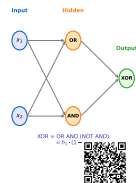
Combines: "If  $h_1$  XOR  $h_2$ , output 1"

Each hidden neuron draws *one* line. Together, they create a non-linear boundary.

XOR Solution: Hidden Layer Creates Linearly Separable Representation



2-2-1 MLP Solves XOR



xor\_solution.ml

Multiple decision boundaries working together

*“If hidden layers find features automatically, why do we still need feature engineering in finance?”*

**Consider:**

**Arguments for Feature Engineering:**

- Domain knowledge helps
- Less data needed
- More interpretable
- Faster training

**Reality:** In finance, hybrid approaches often work best.

**Arguments Against:**

- Human biases
- Miss non-obvious patterns
- Deep learning works on raw data
- ImageNet revolution

---

**Think-Pair-Share: 3 minutes**

# Universal Approximation: The Big Promise

## A Remarkable Theorem

With just *one* hidden layer and enough neurons, an MLP can approximate **any** continuous function to arbitrary accuracy.

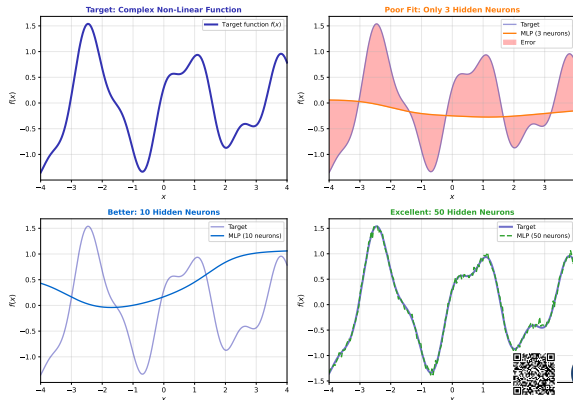
### Implications:

- MLPs are universal function approximators
- No pattern is too complex (in theory)
- The architecture is not the bottleneck

### Caveats:

- “Enough neurons” may be exponential
- Finding the right weights is hard
- Theory vs practice gap

Universal Approximation: MLPs Can Learn Any Function



Universal Approximation Theorem (Cybenko, 1989): A feedforward network with a single hidden layer containing a finite number of neurons can approximate any continuous function on compact subsets of  $\mathbb{R}^n$

MLPs can learn ANY pattern (in theory)



## What You Already Know

From the intuition section:

- Layers process sequentially
- Each layer transforms its input
- Hidden layers find patterns
- Output layer makes predictions

## What's Next

- Matrix notation for efficiency
- Precise forward pass equations
- Parameter counting
- Worked numerical examples

## Why Matrix Notation?

### Without Matrices:

Write  $n \times m$  separate equations for each weight.

### With Matrices:

$$\mathbf{h} = f(\mathbf{W}\mathbf{x} + \mathbf{b})$$

One equation captures everything.

### Benefits:

- Compact notation
- Efficient computation (GPUs)
- Easier to implement
- Clearer understanding

---

You understand the intuition. Let's write it precisely.

# Matrix Notation: Why Matrices?

## Single Neuron (Scalar)

$$h = f(w_1x_1 + w_2x_2 + w_3x_3 + b)$$

## As Dot Product:

$$h = f(\mathbf{w}^T \mathbf{x} + b)$$

where  $\mathbf{w}, \mathbf{x} \in \mathbb{R}^3$

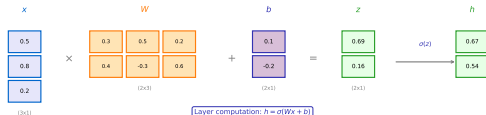
## Multiple Neurons (Matrix):

$$\mathbf{h} = f(\mathbf{W}\mathbf{x} + \mathbf{b})$$

where  $\mathbf{W} \in \mathbb{R}^{m \times n}$

Each *row* of  $\mathbf{W}$  is the weights for one hidden neuron.

Neural Network Layer as Matrix Multiplication



Computation Details

$$\begin{aligned} z_1 &= w_{11}x_1 + w_{12}x_2 + w_{13}x_3 + b_1 = 0.3(0.5) + 0.5(0.8) + 0.2(0.2) + 0.1 = 0.69 \\ z_2 &= w_{21}x_1 + w_{22}x_2 + w_{23}x_3 + b_2 = 0.4(0.5) + (-0.3)(0.8) + 0.6(0.2) + (-0.2) = 0.16 \end{aligned}$$



matrix\_multiplication\_visualization

Matrices make neural network math elegant

# The Weight Matrix

## Weight Matrix $\mathbf{W}^{(l)}$

For layer  $l$ :

$$\mathbf{W}^{(l)} \in \mathbb{R}^{n_l \times n_{l-1}}$$

where:

- $n_l$  = neurons in layer  $l$
- $n_{l-1}$  = neurons in layer  $l - 1$

**Entry  $w_{ij}^{(l)}$ :**

Weight from neuron  $j$  in layer  $l - 1$  to neuron  $i$  in layer  $l$ .

## Bias Vector $\mathbf{b}^{(l)}$

$$\mathbf{b}^{(l)} \in \mathbb{R}^{n_l}$$

One bias per neuron in layer  $l$ .

### Example: 4-3 Layer

Input: 4 neurons, Hidden: 3 neurons

$$\mathbf{W}^{(1)} = \begin{pmatrix} w_{11} & w_{12} & w_{13} & w_{14} \\ w_{21} & w_{22} & w_{23} & w_{24} \\ w_{31} & w_{32} & w_{33} & w_{34} \end{pmatrix}$$

Size:  $3 \times 4$  (12 weights)

$\mathbf{b}^{(1)} \in \mathbb{R}^3$  (3 biases)

---

Each layer has its own weight matrix

## One Layer Computation

$$\mathbf{z}^{(l)} = \mathbf{W}^{(l)} \mathbf{a}^{(l-1)} + \mathbf{b}^{(l)}$$

$$\mathbf{a}^{(l)} = f(\mathbf{z}^{(l)})$$

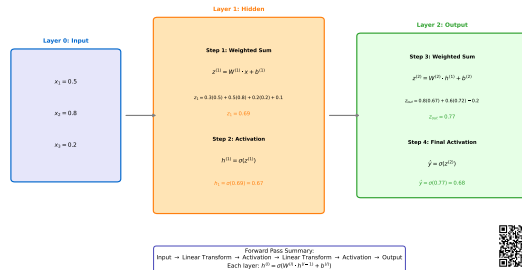
where:

- $\mathbf{z}^{(l)}$ : pre-activation (weighted sum)
- $\mathbf{a}^{(l)}$ : activation (after  $f$ )
- $\mathbf{a}^{(0)} = \mathbf{x}$ : input

## The Steps:

1. Matrix multiply:  $\mathbf{W}^{(l)} \mathbf{a}^{(l-1)}$
2. Add bias:  $+\mathbf{b}^{(l)}$
3. Apply activation:  $f(\cdot)$

Forward Pass: Layer-by-Layer Computation



layer\_by\_layer\_computation

Computing outputs one layer at a time

## For an L-Layer Network

Input:

$$\mathbf{a}^{(0)} = \mathbf{x}$$

Hidden Layers ( $l = 1, \dots, L - 1$ ):

$$\mathbf{z}^{(l)} = \mathbf{W}^{(l)}\mathbf{a}^{(l-1)} + \mathbf{b}^{(l)}$$

$$\mathbf{a}^{(l)} = f(\mathbf{z}^{(l)})$$

Output Layer:

$$\mathbf{z}^{(L)} = \mathbf{W}^{(L)}\mathbf{a}^{(L-1)} + \mathbf{b}^{(L)}$$

$$\hat{\mathbf{y}} = g(\mathbf{z}^{(L)})$$

where  $g$  may differ from  $f$ .

## Example: 2-Layer Network

Layer 1 (hidden):

$$\mathbf{z}^{(1)} = \mathbf{W}^{(1)}\mathbf{x} + \mathbf{b}^{(1)}$$

$$\mathbf{a}^{(1)} = \text{ReLU}(\mathbf{z}^{(1)})$$

Layer 2 (output):

$$\mathbf{z}^{(2)} = \mathbf{W}^{(2)}\mathbf{a}^{(1)} + \mathbf{b}^{(2)}$$

$$\hat{\mathbf{y}} = \sigma(\mathbf{z}^{(2)})$$

Compact Form:

$$\hat{\mathbf{y}} = \sigma(\mathbf{W}^{(2)}\text{ReLU}(\mathbf{W}^{(1)}\mathbf{x} + \mathbf{b}^{(1)}) + \mathbf{b}^{(2)})$$

---

Chaining layer computations together

## Dimension Checking

For  $\mathbf{z} = \mathbf{W}\mathbf{x} + \mathbf{b}$ :

$\mathbf{W}$ :  $(n_{\text{out}} \times n_{\text{in}})$

$\mathbf{x}$ :  $(n_{\text{in}} \times 1)$

$\mathbf{W}\mathbf{x}$ :  $(n_{\text{out}} \times 1)$

$\mathbf{b}$ :  $(n_{\text{out}} \times 1)$

$\mathbf{z}$ :  $(n_{\text{out}} \times 1)$

### Rule:

Inner dimensions must match.

$$(m \times n) \times (n \times p) = (m \times p)$$

## Example: 4-3-1 Network

### Layer 1:

- $\mathbf{W}^{(1)}$ :  $3 \times 4$

- $\mathbf{x}$ :  $4 \times 1$

- $\mathbf{z}^{(1)}$ :  $3 \times 1$

### Layer 2:

- $\mathbf{W}^{(2)}$ :  $1 \times 3$

- $\mathbf{a}^{(1)}$ :  $3 \times 1$

- $\mathbf{z}^{(2)}$ :  $1 \times 1$  (scalar)

**Common Error:** Transposed matrices. Always check dimensions!

---

Matrix dimensions must be compatible

## Worked Example: 2-3-1 Network

### Network Setup

Input:  $\mathbf{x} = \begin{pmatrix} 0.5 \\ 0.8 \end{pmatrix}$

Layer 1 weights:

$$\mathbf{W}^{(1)} = \begin{pmatrix} 0.2 & 0.4 \\ 0.3 & 0.1 \\ 0.5 & 0.2 \end{pmatrix}$$

$$\mathbf{b}^{(1)} = \begin{pmatrix} 0.1 \\ -0.1 \\ 0.0 \end{pmatrix}$$

Layer 2 weights:

$$\mathbf{W}^{(2)} = (0.6 \quad 0.3 \quad 0.4)$$

$$b^{(2)} = -0.2$$

### Forward Pass

Layer 1:

$$\mathbf{z}^{(1)} = \begin{pmatrix} 0.2(0.5) + 0.4(0.8) + 0.1 \\ 0.3(0.5) + 0.1(0.8) - 0.1 \\ 0.5(0.5) + 0.2(0.8) + 0.0 \end{pmatrix} = \begin{pmatrix} 0.52 \\ 0.13 \\ 0.41 \end{pmatrix}$$

$$\mathbf{a}^{(1)} = \text{ReLU}(\mathbf{z}^{(1)}) = \begin{pmatrix} 0.52 \\ 0.13 \\ 0.41 \end{pmatrix}$$

Layer 2:

$$z^{(2)} = 0.6(0.52) + 0.3(0.13) + 0.4(0.41) - 0.2 = 0.315$$

$$\hat{y} = \sigma(0.315) = 0.578$$

**Output: 57.8% probability of class 1**

---

Following the numbers through the network

## Parameters per Layer

For layer  $l$  with  $n_{l-1}$  inputs and  $n_l$  outputs:

**Weights:**  $n_l \times n_{l-1}$

**Biases:**  $n_l$

**Total:**  $n_l \times n_{l-1} + n_l = n_l(n_{l-1} + 1)$

**Network Total:**

$$\text{Params} = \sum_{l=1}^L n_l(n_{l-1} + 1)$$

## Example: 4-10-5-1 Network

**Layer 1** ( $4 \rightarrow 10$ ):

$$10 \times 4 + 10 = 50$$

**Layer 2** ( $10 \rightarrow 5$ ):

$$5 \times 10 + 5 = 55$$

**Layer 3** ( $5 \rightarrow 1$ ):

$$1 \times 5 + 1 = 6$$

**Total: 111 parameters**

For 100 training samples:  $< 2$  samples per parameter.  
Risk of overfitting!

---

How many weights does your network have?



*“A 4-10-5-1 network has how many parameters? Calculate and discuss: is this a lot or a little for stock prediction?”*

**Answer: 111 parameters**

**Consider:**

**Stock Data Context:**

- Daily data:  $\sim 252$  days/year
- 10 years = 2,520 samples
- 111 params: 23 samples/param
- Seems okay...

**But Also Consider:**

- Financial regimes change
- Not all data equally relevant
- Need train/val/test split
- Model complexity vs data size

---

**Exercise: 3 minutes**

## A Realistic Setup

### Input Features (10):

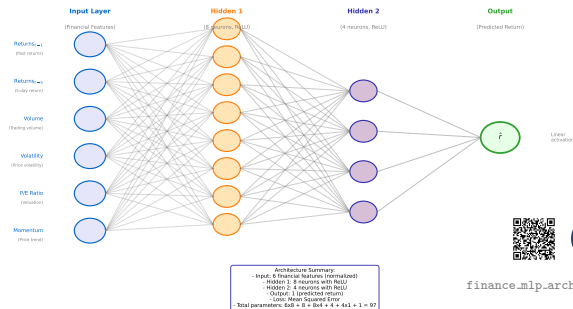
- P/E, P/B, EV/EBITDA (value)
- 1m, 3m, 6m returns (momentum)
- 20d volatility (risk)
- Volume ratio (liquidity)
- Sector one-hot (2 features)

### Architecture:

- Hidden 1: 20 neurons (ReLU)
- Hidden 2: 10 neurons (ReLU)
- Output: 1 neuron (sigmoid)

**Total: 441 parameters**

MLP for Stock Return Prediction



Multiple factors combined through hidden layers

# Why Non-Linearity?

## The Core Problem

Without activation functions:

$$\mathbf{a}^{(1)} = \mathbf{W}^{(1)}\mathbf{x} + \mathbf{b}^{(1)}$$

$$\hat{\mathbf{y}} = \mathbf{W}^{(2)}\mathbf{a}^{(1)} + \mathbf{b}^{(2)}$$

Substituting:

$$\begin{aligned}\hat{\mathbf{y}} &= \mathbf{W}^{(2)}(\mathbf{W}^{(1)}\mathbf{x} + \mathbf{b}^{(1)}) + \mathbf{b}^{(2)} \\ &= (\mathbf{W}^{(2)}\mathbf{W}^{(1)})\mathbf{x} + (\mathbf{W}^{(2)}\mathbf{b}^{(1)} + \mathbf{b}^{(2)}) \\ &= \mathbf{W}'\mathbf{x} + \mathbf{b}'\end{aligned}$$

**Result:** A single linear transformation!

## The Solution

Non-linear activation functions:

$$\mathbf{a}^{(l)} = f(\mathbf{z}^{(l)})$$

where  $f$  is non-linear.

## Why This Works:

- Non-linearity breaks the collapse
- Composition of non-linear functions
- Can approximate any function

## Key Insight:

Non-linearity is what makes deep networks “deep” in a meaningful sense.

---

Non-linearity is essential for learning complex patterns

## Mathematical Proof

For any number of linear layers:

$$y = W^{(L)}W^{(L-1)} \dots W^{(1)}x$$

Since matrix multiplication is associative:

$$= (W^{(L)}W^{(L-1)} \dots W^{(1)})x$$

$$= W^{\text{eff}}x$$

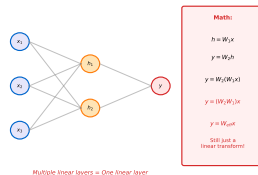
## Conclusion:

100 linear layers = 1 linear layer.

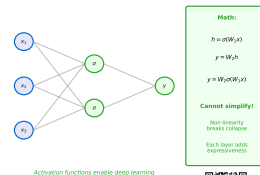
No benefit from depth without non-linearity.

## Why Non-Linear Activations Are Essential

### Without Non-Linear Activation



### With Non-Linear Activation



linear\_collapse\_proof

Stacked linear layers = single linear layer

# The Sigmoid Function

## Definition

$$\sigma(z) = \frac{1}{1 + e^{-z}}$$

## Properties:

- Range: (0, 1)
- Smooth and differentiable
- $\sigma(0) = 0.5$
- Symmetric:  $\sigma(-z) = 1 - \sigma(z)$

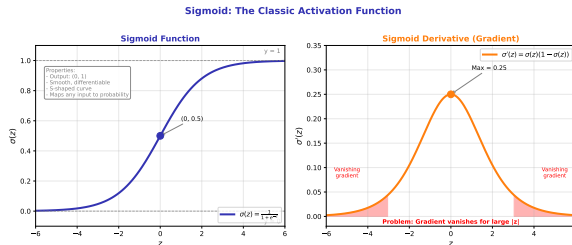
## Derivative:

$$\sigma'(z) = \sigma(z)(1 - \sigma(z))$$

## Use Cases:

- Binary classification (output)
- Probability interpretation
- Historical (hidden layers)

The classic activation: squashes to probability



sigmoid\_function

## Advantages

- + Bounded output (0, 1)
- + Smooth gradient
- + Probability interpretation
- + Historically important

## Disadvantages

### - Vanishing gradients

For  $|z| > 4$ :  $\sigma'(z) \approx 0$

Gradients become tiny

Deep networks can't learn

### - Not zero-centered

All positive outputs

Zig-zag weight updates

### - Computationally expensive

Requires exp function

Smooth and bounded, but gradients can vanish

## The Vanishing Gradient Problem

When  $z$  is very positive or negative:

$z$	$\sigma'(z)$
0	0.25
2	0.10
4	0.018
6	0.0025

Gradients shrink exponentially through layers!

**Result:** Early layers learn very slowly in deep networks.  
This limited deep learning until ReLU.

# The Tanh Function

## Definition

$$\tanh(z) = \frac{e^z - e^{-z}}{e^z + e^{-z}} = 2\sigma(2z) - 1$$

## Properties:

- Range:  $(-1, 1)$
- Zero-centered
- $\tanh(0) = 0$
- Odd function:  $\tanh(-z) = -\tanh(z)$

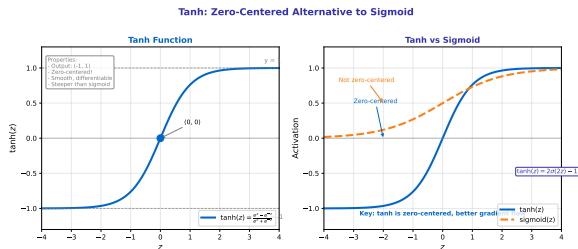
## Derivative:

$$\tanh'(z) = 1 - \tanh^2(z)$$

## Advantage over Sigmoid:

Zero-centered outputs lead to more stable gradient updates.

Zero-centered: range  $(-1, 1)$



tanh\_function

## Definition

$$\text{ReLU}(z) = \max(0, z) = \begin{cases} z & z > 0 \\ 0 & z \leq 0 \end{cases}$$

## Properties:

- Range:  $[0, \infty)$
- Not bounded above
- Not differentiable at  $z = 0$
- Piecewise linear

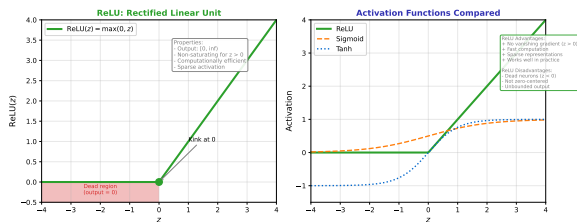
## Derivative:

$$\text{ReLU}'(z) = \begin{cases} 1 & z > 0 \\ 0 & z \leq 0 \end{cases}$$

The Modern Default for hidden layers.

Simple but powerful: the modern default

ReLU: The Modern Default Activation



relu.function



## Advantages

- + **No vanishing gradient**  
Gradient is 1 for  $z > 0$   
Signal propagates through layers
- + **Computationally cheap**  
Just comparison and assignment  
No exponentials  
6x faster than sigmoid
- + **Sparse activation**  
Many neurons output 0  
Efficient representation
- + **Biological plausibility**  
Neurons can be “off”

## Disadvantages

- **“Dying ReLU” problem**  
If  $z < 0$  always: gradient = 0  
Neuron never updates  
Can “die” permanently
- Not zero-centered
- Unbounded (can explode)

## Variants:

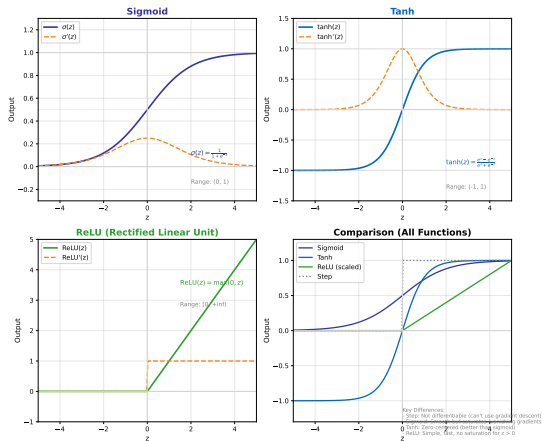
- Leaky ReLU:  $\max(0.01z, z)$
- ELU:  $z$  if  $z > 0$ ,  $\alpha(e^z - 1)$  otherwise
- GELU: used in transformers

---

Cheap to compute, gradients don't vanish (for positive inputs)

# Activation Functions: Comparison

Activation Functions: Function and Derivative



activation\_comparison

Different functions for different problems

*“Which activation function would you use for: (a) predicting stock returns, (b) buy/sell classification? Why?”*

**Consider:**

**(a) Stock Returns (Regression)**

- Output: continuous value
- Can be positive or negative
- Hidden: ReLU or tanh
- Output: **Linear (none)**
- Returns are unbounded

**(b) Buy/Sell (Classification)**

- Output: probability  $\in (0, 1)$
- Two mutually exclusive classes
- Hidden: ReLU
- Output: **Sigmoid**
- Or softmax for multi-class

---

**Think-Pair-Share: 3 minutes**

## Hidden Layer Guidelines

### Default: ReLU

- Works well in most cases
- Fast and stable

### If dying ReLU: Leaky ReLU

- Small negative slope
- Prevents dead neurons

### For RNNs: Tanh

- Bounded outputs help stability
- Zero-centered

## Output Layer Guidelines

Task	Activation
Binary class	Sigmoid
Multi-class	Softmax
Regression	Linear
Bounded regression	Sigmoid/tanh
Positive only	ReLU

### Finance Examples:

- Return prediction: Linear
- Direction prediction: Sigmoid
- Sector classification: Softmax
- Volatility: ReLU or Softplus

Output layer choice depends on your problem type

## How Powerful Are Neural Networks?

We've seen that MLPs can:

- Solve XOR (non-linear patterns)
- Combine features hierarchically
- Learn from data

## But a Deeper Question:

Are there functions that MLPs fundamentally *cannot* represent?

Or can they approximate *anything*?

## Why This Matters

### If MLPs are limited:

- Need to check if problem is solvable
- Architecture constraints matter
- Some patterns impossible

### If MLPs are universal:

- Architecture is not the bottleneck
- Challenges are elsewhere (data, training)
- Theoretical guarantee of capability

**Spoiler:** MLPs are universal approximators!

---

Just how powerful are neural networks?

## The Theorem (Informal)

A feedforward network with:

- One hidden layer
- Sufficient hidden neurons
- Non-linear activation (e.g., sigmoid)

can approximate any continuous function on a compact domain to arbitrary accuracy.

## Key Contributors:

- Cybenko (1989): sigmoid
- Hornik (1991): general activations
- Further extensions since

## Formal Statement

Let  $f : [0, 1]^n \rightarrow \mathbb{R}$  be continuous.

For any  $\epsilon > 0$ , there exists an MLP  $\hat{f}$  with:

$$|\hat{f}(\mathbf{x}) - f(\mathbf{x})| < \epsilon$$

for all  $\mathbf{x} \in [0, 1]^n$ .

## In Plain English:

No matter how complex the pattern, an MLP with enough hidden neurons can match it as closely as you want.

---

With enough hidden neurons, you can approximate any continuous function

# What Universal Approximation Means

## The Good News

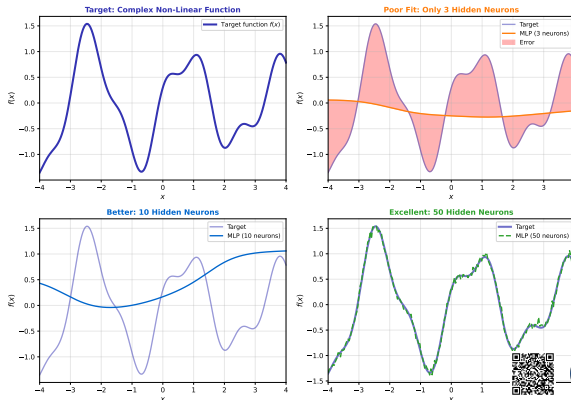
- No function is “too complex”
- MLPs are theoretically complete
- Architecture is not the limit
- One hidden layer is enough (in theory)

## Visual Intuition:

Each hidden neuron contributes a “bump” or “step.”  
With enough bumps, you can approximate any shape.

Think of it like approximating a curve with many small line segments.

Universal Approximation: MLPs Can Learn Any Function



Universal Approximation Theorem (Cybenko, 1989): A feedforward network with a single hidden layer containing a finite number of neurons can approximate any continuous function on compact subsets of  $\mathbb{R}^n$

universalapproximation.dem

More neurons = better approximation

## Common Misconceptions

### “Any network can learn anything”

**No.** Need enough neurons

- May need exponentially many

### “Training will find the solution”

**No.** Theorem is about existence

- Says nothing about finding weights
- Optimization may fail

### “One layer is always enough”

**Usually no.**

- Deep networks often more efficient
- Fewer parameters for same accuracy

## The Gap: Existence vs Construction

**The theorem says:**

“A good approximation exists.”

**It does NOT say:**

- How many neurons you need
- How to find the right weights
- How much data is required
- How long training takes
- Whether it will generalize

**Analogy:**

“There exists a needle in this haystack” doesn't help you find it.

---

Existence of a solution does not mean we can find it



## Theoretical Guarantees

Universal approximation says:

- Given infinite neurons: perfect fit
- Given infinite data: find the function
- Given infinite compute: optimize

## Practical Reality

We have:

- Finite neurons: limited capacity
- Finite data: must generalize
- Finite compute: approximate solutions

## What Matters More in Practice

1. **Data quality and quantity**
  - More important than architecture
2. **Regularization**
  - Prevent overfitting
3. **Optimization**
  - Finding good weights
4. **Generalization**
  - Performance on new data

**Module 3** will address these practical challenges.

---

Universal approximation is necessary but not sufficient

## The Optimistic View

If markets have patterns, MLPs can learn them:

- Non-linear relationships? Possible.
- Complex interactions? Possible.
- Hidden factors? Possible.

## Theoretical Capability:

“An MLP could, in principle, capture any market pattern.”

## The Realistic View

### Challenges Remain:

- Signal-to-noise ratio is low
- Markets are non-stationary
- Past patterns may not repeat
- Data is limited (especially for crashes)
- Overfitting is easy

### The EMH Counterargument:

If markets are efficient, there's nothing systematic to learn.

*Module 4 will explore this tension.*

---

In theory, yes. In practice, many challenges remain.

# Why Loss Functions?

## Learning Requires an Objective

To train a neural network, we need:

1. A way to measure errors
2. A number that decreases as we improve
3. A signal for weight updates

## The Loss Function:

$\mathcal{L}(\hat{y}, y)$  measures how wrong our predictions are.

## Goal of Training:

Find weights that minimize  $\mathcal{L}$ .

## Finance Analogy

### Profit & Loss (P&L):

- Measures trading performance
- Negative P&L = bad trades
- Optimize to maximize P&L

### Loss Function:

- Measures prediction errors
- High loss = bad predictions
- Optimize to minimize loss

**Note:** “Loss” is the opposite of “profit” – we minimize loss!

---

To learn, we must measure mistakes

# Mean Squared Error (MSE)

## Definition

$$\mathcal{L}_{\text{MSE}} = \frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2$$

## Properties:

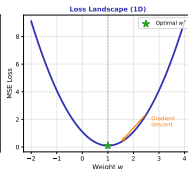
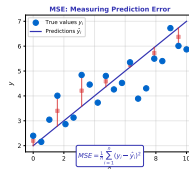
- Always non-negative
- Zero only if perfect predictions
- Penalizes large errors heavily
- Differentiable everywhere

## Use Case:

- Regression problems
- Predicting continuous values
- Stock returns, prices, etc.

The standard loss for predicting continuous values

Mean Squared Error: The Classic Regression Loss



### MSE Properties

**Convex:** Single global minimum for linear models

**Differentiable:** Smooth gradients everywhere

**Scale-sensitive:** Large errors penalized more (squared)

**Outlier-sensitive:** Outliers amplify outlier impact

**Best for:**  
Regression problems with  
normally distributed errors



mse\_visualization

## Binary Cross-Entropy

$$\mathcal{L}_{\text{BCE}} = -\frac{1}{n} \sum_{i=1}^n [y_i \log(\hat{y}_i) + (1 - y_i) \log(1 - \hat{y}_i)]$$

### Properties:

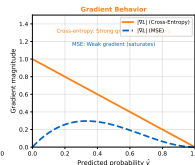
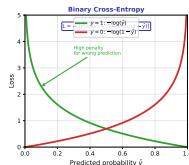
- For probability outputs
- Heavily penalizes confident wrong answers
- Connected to information theory

### Use Case:

- Classification problems
- Buy/sell decisions
- Any yes/no prediction

The standard loss for classification

Cross-Entropy: The Standard Classification Loss



### Cross-Entropy Properties

**Probability-based:** measures information difference

**Strong gradients:** fast learning from mistakes

**No saturation:** Always learns from errors

**Natural for classifications:** softmax output

#### Why use Cross-Entropy over MSE?

- Stronger gradients for confident wrong predictions
- Information-theoretic foundation
- Standard for classification tasks



cross\_entropy\_visualization

# The Loss Landscape

## Loss as a Function of Weights

$$\mathcal{L}(\mathbf{W}, \mathbf{b})$$

For every choice of weights, there's a loss value.

### The Landscape:

- High regions: bad weights
- Low regions: good weights
- Global minimum: best weights
- Local minima: traps

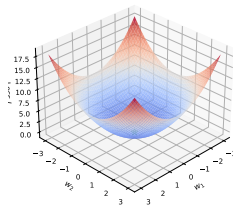
### Training =

Finding the lowest point in this landscape.

Training = finding the lowest point in this landscape

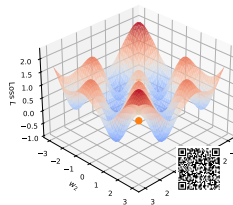
### Loss Landscape: Why Deep Networks Are Hard to Train

Convex Loss Surface  
(Single Layer)



Easy: One global minimum  
Gradient descent always finds it

Non-Convex Loss Surface  
(Deep Network)



Hard: Many local minima  
May get stuck in suboptimal solutions

## Task-Specific Loss Functions

Task	Loss
Return prediction	MSE
Direction prediction	Cross-entropy
Volatility forecast	MSE
Multi-class sector	Categorical CE

## Beyond Standard Losses:

- Sharpe ratio optimization
- Asymmetric losses (penalize losses more than gains)
- Custom finance metrics

## Important Consideration

### MSE vs Business Metric:

A model with low MSE may still lose money!

### Example:

- Predict returns with 5% MSE
- But wrong on big moves
- Transaction costs eat profits
- Risk-adjusted return is poor

### Lesson:

Statistical accuracy  $\neq$  Trading profitability  
Module 4 explores this gap.

---

Different problems, different loss functions

## What We Learned

### 1. Historical Context

- AI Winter (1969-1982)
- Backprop renaissance (1986)
- Right idea + right time

### 2. MLP Architecture

- Hidden layers find patterns
- Matrix notation for computation
- Parameter counting

### 3. Activation Functions

- Non-linearity is essential
- ReLU for hidden, task-specific for output

### 4. Universal Approximation

- MLPs can learn any function
- But existence  $\neq$  construction

### 5. Loss Functions

- MSE for regression
- Cross-entropy for classification
- Loss landscape visualization

## The Big Picture:

We now have powerful architectures. But how do they *learn*?

---

From single perceptron to universal function approximator



*“We have the architecture. But how does it LEARN?”*

### The Missing Piece

We know:

- How to compute forward pass
- What loss functions measure
- That good weights exist

We don't know:

- How to find good weights
- How errors update weights
- How to avoid overfitting

**Mathematical details: See Appendix B (Backpropagation Derivation)**

### Coming in Module 3:

- Gradient descent (intuition)
- Backpropagation (the magic)
- Training dynamics
- Overfitting and regularization
- Practical training tips

**The Key:** Backpropagation – the algorithm that made deep learning possible.

---

Next: The magic of backpropagation

# Module 1: The Birth of Neural Computing

## From Biological Inspiration to the Perceptron (1943-1969)

Neural Networks for Finance

BSc Lecture Series

November 28, 2025

*“We have the architecture. How does it LEARN?”*

## What We Know:

- MLP architecture (Module 2)
- Forward pass computation
- Loss functions measure error
- Good weights exist (universal approximation)

## What We Don't Know:

- How to find good weights
- How errors guide updates
- Why training sometimes fails
- How to avoid overfitting

**This module bridges the gap from architecture to learning.**

---

**The fundamental challenge of neural network training**

## How Traders Improve

A trader's learning process:

1. Make a trade (forward pass)
2. Wait for P&L (loss function)
3. Analyze what went wrong (gradient)
4. Adjust strategy (weight update)
5. Repeat thousands of times (epochs)

## Key Insight:

Mistakes are information. Each error tells you how to adjust.

## Neural Network Training

Trading	Neural Net
Trade execution	Forward pass
P&L calculation	Loss function
Post-trade analysis	Backpropagation
Strategy adjustment	Weight update
Experience	Training epochs

Both learn by **iteratively correcting mistakes**.

---

How does a trader improve? By analyzing what went wrong.

## Today's Journey

### 1. Loss Functions (Review)

- Measuring prediction error
- MSE intuition

### 2. Gradient Descent

- Finding the minimum
- Learning rate tuning

### 3. Backpropagation

- Credit assignment
- Chain rule in action

### 4. Training Dynamics

- Batch vs. stochastic
- Epochs and convergence

### 5. Overfitting

- The enemy of generalization
- The backtest trap

## Learning Objectives:

- Understand gradient descent intuitively
- Grasp backpropagation as “blame assignment”
- Recognize and prevent overfitting

---

From measuring error to updating weights

## The Challenge

### Given:

- Training data:  $\{(\mathbf{x}^{(i)}, y^{(i)})\}_{i=1}^m$
- Network architecture
- Loss function  $\mathcal{L}$

### Find:

- Weights  $\mathbf{W}$  and biases  $\mathbf{b}$
- That minimize  $\mathcal{L}$
- And generalize to new data

### Scale of the Problem:

A 4-10-5-1 network: 111 parameters

A ResNet-50: 25 million parameters

## Why Is This Hard?

### Dimensionality:

- Millions of weights to tune
- Exponentially many combinations
- Can't try them all

### Non-Convexity:

- Many local minima
- Saddle points
- Flat regions

### The Solution:

Gradient-based optimization

“Move downhill in weight space”

---

Thousands of weights to tune - how do we find the right values?

## Yann LeCun at Bell Labs

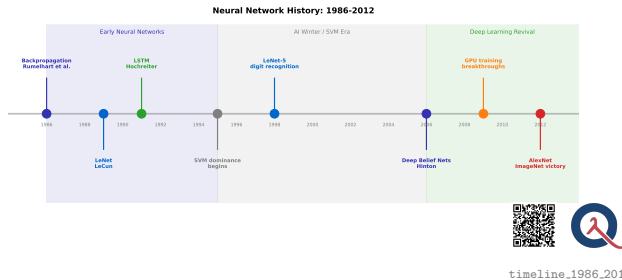
First commercially deployed neural network:

- Handwritten digit recognition
- Used by US Postal Service
- Read millions of checks
- Proved neural nets could work

## Key Innovations:

- Convolutional architecture
- Shared weights
- Backprop through convolutions

Yann LeCun: First commercially deployed neural network



# 1991: The Vanishing Gradient Problem

## The Discovery

Sepp Hochreiter (1991) identified why deep networks fail:

## The Problem:

- Gradients multiply through layers
- Sigmoid derivative: max 0.25
- Through 10 layers:  $0.25^{10} \approx 10^{-6}$
- Early layers learn nothing

## Symptoms:

- Later layers learn quickly
- Early layers stuck at random
- Network never converges

## Why Sigmoid Causes Problems

For sigmoid:  $\sigma'(z) = \sigma(z)(1 - \sigma(z))$

Maximum value:  $\sigma'(0) = 0.25$

Layers	Max Gradient
1	0.25
5	$10^{-3}$
10	$10^{-6}$
20	$10^{-12}$

**Implication:** Deep networks seemed impossible until ReLU (2010).

Deep networks couldn't learn - gradients disappeared



## Long Short-Term Memory

Hochreiter & Schmidhuber solution:

- Designed for sequences
- Explicit “memory” cells
- Gating mechanisms
- Gradients can flow unchanged

## Key Innovation:

The “constant error carousel” – a path where gradients don’t decay.

## Applications:

- Speech recognition
- Machine translation
- Time series prediction

## Finance Relevance

LSTMs became popular for:

- Stock price prediction
- Volatility forecasting
- Sentiment analysis
- Algorithmic trading

## Why LSTM for Finance?

- Financial data is sequential
- Long-term dependencies matter
- Regime changes persist

**Note:** Now largely replaced by Transformers (2017).

---

Hochreiter and Schmidhuber: Long Short-Term Memory

## AlexNet Wins ImageNet

Alex Krizhevsky, Ilya Sutskever, Geoffrey Hinton:

- 15.3% error rate
- Second place: 26.2%
- **40% relative improvement**
- Used GPUs for training

## What Made It Work:

1. ReLU activation (not sigmoid)
2. Dropout regularization
3. GPU training (60x faster)
4. Large dataset (1.2M images)
5. Data augmentation

## Why This Was Different

### Previous Attempts:

- Shallow networks
- Hand-crafted features
- Small datasets
- CPU training

### AlexNet:

- 8 layers deep
- Learned features
- Massive data
- GPU parallelism

**The Result:** Deep learning became the dominant paradigm. Every major AI company pivoted.

---

AlexNet: Deep learning proves its superiority

# What Changed Between 1990 and 2012?

## The Ingredients for Success

### 1. Big Data

- ImageNet: 1.2M labeled images
- Internet made data collection possible
- 1990: thousands of samples

### 2. Compute Power

- GPUs: 100x speedup
- Moore's law compounding
- Training in days, not years

### 3. Algorithmic Improvements

- ReLU: no vanishing gradients
- Dropout: better generalization
- Batch normalization (2015)

### 4. Open Research Culture

- arXiv preprints
- Open-source frameworks
- Reproducibility

**Key Insight:** The core ideas from 1986 worked – they just needed scale and engineering.

---

Big data + GPUs + ReLU + dropout = breakthrough

# What Does “Wrong” Mean?

## Quantifying Prediction Error

We need a function that:

- Takes predictions and labels
- Returns a single number
- Higher = worse predictions
- Differentiable (for gradients)

## The Loss Function:

$$\mathcal{L}(\hat{y}, y)$$

## Properties We Want:

- $\mathcal{L} \geq 0$  (non-negative)
- $\mathcal{L} = 0$  iff perfect prediction
- Smooth (for optimization)

We need a way to measure how wrong our predictions are

## Different Tasks, Different Losses

Task	Loss
Regression	MSE
Binary classification	Cross-entropy
Multi-class	Categorical CE
Ranking	Hinge loss

## Finance Examples:

- Return prediction: MSE
- Buy/sell: Binary CE
- Sector classification: Categorical CE

## P&L as a Loss Function

For traders:

- P&L = realized gain/loss
- Negative P&L = bad trades
- Goal: maximize P&L

## Connection to ML Loss:

- ML loss = prediction error
- Higher loss = worse model
- Goal: minimize loss

## Key Difference:

P&L is a *performance* metric.

ML loss is an *optimization* target.

They may not align perfectly!

## When P&L $\neq$ Loss

A model might have:

- Low MSE (accurate predictions)
- But low P&L (wrong on big moves)

Or:

- High MSE (noisy predictions)
- But high P&L (right when it matters)

## Implication:

Consider using custom loss functions that better align with trading goals.

*Module 4 explores this tension.*

---

P&L is the loss function of trading

## Total Loss Over Dataset

For  $m$  training examples:

$$\mathcal{L}(\mathbf{W}) = \frac{1}{m} \sum_{i=1}^m \ell(\hat{y}^{(i)}, y^{(i)})$$

where:

- $\ell$ : loss per example
- $\hat{y}^{(i)} = f(\mathbf{x}^{(i)}; \mathbf{W})$ : prediction
- $y^{(i)}$ : true label
- $\mathbf{W}$ : all network weights

**Goal:**

$$\mathbf{W}^* = \arg \min_{\mathbf{W}} \mathcal{L}(\mathbf{W})$$

---

The loss function quantifies prediction error

## Why Average?

### Sum vs Average:

- Sum: scales with dataset size
- Average: comparable across datasets
- Gradient magnitude consistent

### The Optimization Landscape:

$\mathcal{L}(\mathbf{W})$  defines a surface over weight space.

- High regions: bad weights
- Low regions: good weights
- We seek the lowest point

## The Formula

$$\mathcal{L}_{MSE} = \frac{1}{m} \sum_{i=1}^m (y^{(i)} - \hat{y}^{(i)})^2$$

## In Words:

1. Compute error:  $y - \hat{y}$
2. Square it:  $(y - \hat{y})^2$
3. Average over all samples

## Why Squaring?

- Makes all errors positive
- Penalizes large errors heavily
- Mathematically convenient

## Example

$y$	$\hat{y}$	$(y - \hat{y})^2$
5%	3%	4
-2%	1%	9
8%	7%	1
<b>MSE</b>		<b>4.67</b>

Units: (percentage points)<sup>2</sup>

**RMSE:**  $\sqrt{MSE} = 2.16\%$

“On average, we’re off by about 2%”

“How far off were we, on average?”

## Squared Errors as Areas

Each error  $(y - \hat{y})^2$  is the area of a square with side length  $|y - \hat{y}|$ .

**MSE = Average Square Area**

## Why This Matters:

- Error of 4 is 16x worse than error of 1
- Large errors dominate
- Outliers have huge impact

## Alternative: MAE

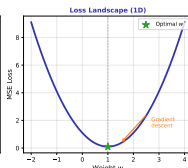
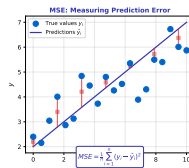
Mean Absolute Error:

$$\mathcal{L}_{MAE} = \frac{1}{m} \sum |y - \hat{y}|$$

More robust to outliers.

**Squaring emphasizes large errors**

Mean Squared Error: The Classic Regression Loss



### MSE Properties

**Convex:** Single global minimum for linear models

**Differentiable:** Smooth gradients everywhere

**Scale-sensitive:** Large errors penalized more (squared)

**Outlier-sensitive:** Squares amplify outlier impact

**Best for:** Regression problems with normally distributed errors



## Worked Example

### Predictions for 5 Stocks:

Stock	$\hat{y}$	$y$	Error <sup>2</sup>
AAPL	+5%	+2%	9
MSFT	+3%	+4%	1
GOOG	-1%	+2%	9
AMZN	+4%	+4%	0
META	+2%	-3%	25
<b>MSE</b>			<b>8.8</b>

$$\text{RMSE} = 2.97\%$$

## Interpretation

“On average, our return predictions are off by about 3 percentage points.”

### Is This Good?

Depends on context:

- Market daily vol:  $\sim 1\%$
- $3\% \text{ RMSE} = 3 \text{ std devs}$
- **Not very predictive**

### Reality Check:

Even small predictability ( $\text{RMSE slightly} < \text{volatility}$ ) can be valuable in trading.

---

Worked example with stock returns

*“Why might we want to penalize large errors more than small ones in stock prediction?”*

**Consider:**

**Arguments For (Use MSE):**

- Big errors are costlier
- Crashes matter more than small moves
- Position sizing affected
- Risk management

**Arguments Against (Use MAE):**

- Markets have fat tails
- Outliers can dominate MSE
- May optimize for rare events
- Robustness to noise

**Reality:** Many practitioners use MAE or Huber loss (combines both) for financial applications.

---

**Think-Pair-Share: 3 minutes**

## Loss as a Function of Weights

$$\mathcal{L}(\mathbf{W})$$

For every choice of weights, there's a loss value.

**In 2D (two weights):**

A surface we can visualize.

**In High Dimensions:**

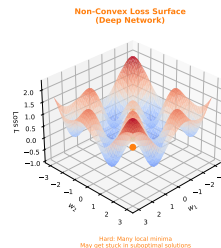
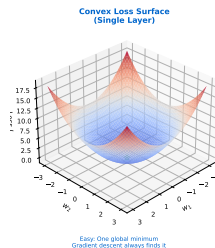
A hypersurface we navigate blindly.

**Features:**

- Global minimum (best)
- Local minima (traps)
- Saddle points
- Flat regions (plateaus)

Finding the minimum of a high-dimensional function

Loss Landscape: Why Deep Networks Are Hard to Train



## The Challenge

Find:

$$\mathbf{W}^* = \arg \min_{\mathbf{W}} \mathcal{L}(\mathbf{W})$$

## Difficulties:

- Millions of dimensions
- Non-convex landscape
- No closed-form solution
- Can't try all possibilities

## We Need:

An *iterative* algorithm that gradually improves weights.

## Possible Approaches

### Random Search:

- Try random weights
- Keep best so far
- **Hopelessly slow**

### Grid Search:

- Try all combinations
- $10^{100}$  possibilities
- **Impossible**

### Gradient-Based:

- Use local slope information
- Move toward improvement
- **Tractable!**

---

How do we find the weights that minimize loss?

# The Blind Hiker Analogy

## The Scenario

Imagine you're:

- Blindfolded
- On a mountainside
- Trying to reach the valley
- Can only feel the local slope

## What Would You Do?

1. Feel the ground around you
2. Determine which way is downhill
3. Take a step in that direction
4. Repeat until you reach a valley

## Neural Network Translation

Hiker	Network
Position	Weights $\mathbf{W}$
Altitude	Loss $\mathcal{L}$
Slope	Gradient $\nabla \mathcal{L}$
Step	Weight update
Valley	Minimum loss

## Key Insight:

We don't need to see the whole landscape. Local slope is enough!

"You're blindfolded on a mountain. How do you find the valley?"

## The Strategy

1. Compute the slope (gradient)
2. Move opposite to the slope
3. Repeat until convergence

## Why Opposite?

- Gradient points uphill
- We want to go downhill
- Move in negative gradient direction

## The Update Rule:

$$\mathbf{W} \leftarrow \mathbf{W} - \eta \nabla_{\mathbf{W}} \mathcal{L}$$

---

Move in the direction that goes down

## Gradient Descent Algorithm

1. Initialize  $\mathbf{W}$  randomly
2. **repeat**:
  - a. Compute loss  $\mathcal{L}(\mathbf{W})$
  - b. Compute gradient  $\nabla \mathcal{L}$
  - c. Update:  $\mathbf{W} \leftarrow \mathbf{W} - \eta \nabla \mathcal{L}$
3. **until** convergence

$\eta$  = learning rate (step size)

# The Gradient: Direction of Steepest Ascent

## What Is the Gradient?

The gradient  $\nabla \mathcal{L}$  is a vector of partial derivatives:

$$\nabla_{\mathbf{w}} \mathcal{L} = \begin{pmatrix} \frac{\partial \mathcal{L}}{\partial w_1} \\ \frac{\partial \mathcal{L}}{\partial w_2} \\ \vdots \\ \frac{\partial \mathcal{L}}{\partial w_n} \end{pmatrix}$$

## Each Component:

$\frac{\partial \mathcal{L}}{\partial w_i}$  = How much does loss change if we change  $w_i$  slightly?

## Properties

### Direction:

- Points toward steepest increase
- $-\nabla \mathcal{L}$  points toward steepest decrease

### Magnitude:

- $\|\nabla \mathcal{L}\|$  = slope steepness
- Near minimum: gradient  $\approx 0$

### At a Minimum:

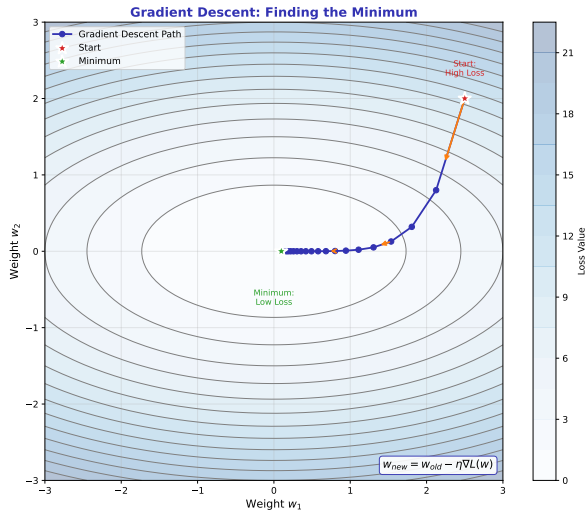
$$\nabla \mathcal{L} = \mathbf{0}$$

No direction goes further down.

---

The gradient tells us which way is “up”

# Gradient Descent: Move Downhill



gradient.descent.contour



## Portfolio Adjustment

Similar iterative process:

1. Evaluate current portfolio
2. Estimate sensitivities (“greeks”)
3. Adjust positions to reduce risk
4. Repeat periodically

## Delta Hedging:

- Measure option delta
- Adjust stock position
- Move toward neutral

## Comparison

GD	Portfolio
Loss	Risk/Variance
Weights	Positions
Gradient	Sensitivities
Learning rate	Trading aggressiveness
Convergence	Optimal allocation

## Key Difference:

Markets change continuously. Portfolios must adapt.  
Neural networks train once (mostly).

Similar to iterative portfolio rebalancing

# The Learning Rate: Step Size

## The Hyperparameter $\eta$

$$\mathbf{W} \leftarrow \mathbf{W} - \eta \nabla \mathcal{L}$$

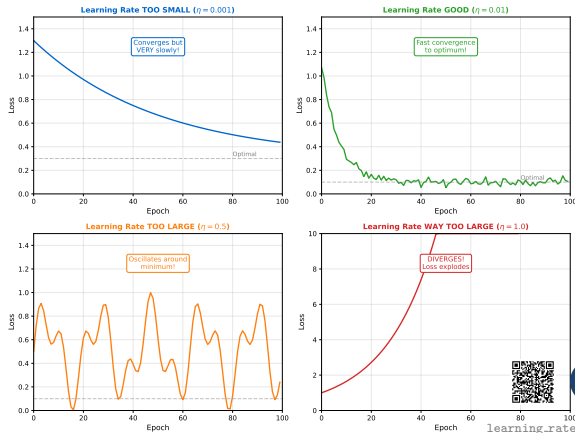
### $\eta$ Controls:

- Size of each weight update
- Speed of convergence
- Stability of training

### Typical Values:

- $10^{-4}$  to  $10^{-1}$
- Often starts at 0.01 or 0.001
- May decrease during training

### Learning Rate: The Most Important Hyperparameter



Rule of thumb: Start with 0.001-0.01 and adjust based on training dynamics

Learning rate controls how far we move each step

## The Problem

When  $\eta$  is too large:

- Steps overshoot the minimum
- May jump to worse regions
- Loss oscillates or explodes
- Training diverges

## Symptoms:

- Loss goes up, not down
- Loss becomes NaN
- Weights grow very large
- Erratic training curves

## Finance Analogy

### Overtrading:

- Adjusting positions too aggressively
- Chasing every signal
- Transaction costs accumulate
- Portfolio becomes unstable

### Solution:

Reduce learning rate until stable.

**Rule of Thumb:** If loss explodes, halve  $\eta$ .

---

Too big = overshoot the minimum

## The Problem

When  $\eta$  is too small:

- Steps are tiny
- Progress is slow
- May get stuck in flat regions
- Training takes forever

## Symptoms:

- Loss decreases very slowly
- Many epochs with little improvement
- May stop before reaching minimum
- Wasted computation

## Finance Analogy

### Underreacting:

- Ignoring market signals
- Missing opportunities
- Portfolio drifts from target
- Slow adaptation to regime changes

### Solution:

Increase learning rate or use adaptive methods.

**Modern Practice:** Adaptive optimizers (Adam, RMSprop) adjust  $\eta$  automatically.

---

Too small = converge too slowly

*“In trading, what’s analogous to learning rate? What happens if you adjust positions too aggressively or too conservatively?”*

**Consider:**

**Position Sizing:**

- How much to trade per signal
- Kelly criterion vs. fractional Kelly
- Risk management constraints

**Rebalancing Frequency:**

- How often to adjust
- Transaction cost vs. tracking error
- Market impact considerations

**Key Insight:** Both trading and ML require balancing responsiveness against stability.

---

**Think-Pair-Share: 3 minutes**

## The Challenge

We know:

- The output was wrong
- We need to update weights
- There are thousands of weights

## The Question:

*Which weights caused the error?*

## Credit Assignment:

Attributing output error to individual weights deep in the network.

## Why Is This Hard?

### Direct Attribution:

- Output layer weights: clear influence
- Hidden layer weights: indirect
- Early layers: very indirect

### The Chain of Influence:

$$w_1 \rightarrow h_1 \rightarrow h_2 \rightarrow \cdots \rightarrow \hat{y} \rightarrow \mathcal{L}$$

Each weight affects the loss through many intermediate steps.

---

The output was wrong. Which weights caused it?

## Attribution in Trading

A portfolio lost money. Why?

1. Macro call wrong?
2. Sector allocation off?
3. Stock selection bad?
4. Timing poor?
5. Execution costly?

## Performance Attribution:

- Decompose returns by factor
- Trace P&L to decisions
- Learn which calls were wrong

## Neural Network Attribution

Trading	Neural Net
Macro view	Early layers
Sector allocation	Hidden layers
Stock picks	Later layers
Final trades	Output
P&L	Loss

**Backpropagation** is the neural network's performance attribution algorithm.

“Which decisions led to this P&L?”

# Backpropagation: Blame Assignment

## The Algorithm

Backpropagation computes  $\frac{\partial \mathcal{L}}{\partial w}$  for every weight  $w$  in the network.

## Key Idea:

Work backward from output to input, propagating error attribution.

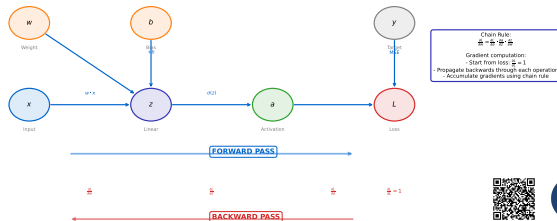
## Two Passes:

1. **Forward Pass:** Compute outputs
2. **Backward Pass:** Compute gradients

## Efficiency:

Computes ALL gradients in time proportional to one forward pass.

Computational Graph: Forward and Backward Pass



backprop.computational\_graph

Propagating error backward through the network



# The Chain Rule: Intuition

## The Core Mathematical Tool

If A affects B and B affects C:

$$\frac{\partial C}{\partial A} = \frac{\partial C}{\partial B} \cdot \frac{\partial B}{\partial A}$$

### Example:

Temperature  $\rightarrow$  Ice cream sales  $\rightarrow$  Profit

How does temperature affect profit?

$$\frac{\partial \text{Profit}}{\partial \text{Temp}} = \frac{\partial \text{Profit}}{\partial \text{Sales}} \cdot \frac{\partial \text{Sales}}{\partial \text{Temp}}$$

## Chain Rule: Foundation of Backpropagation

### Chain Rule: The Key to Backprop



Chain Rule:

$$\frac{d}{dx} f(g(x)) = \frac{df}{dg} \cdot \frac{dg}{dx}$$

Intuition: Rate of change multiplies through the chain

Example:

$$f(x) = x^2, \quad g(x) = 3x + 1$$
$$\frac{d}{dx} f(g(x)) = 2(3x + 1) \cdot 3 = 6(3x + 1)$$

### Multi-Variable Chain Rule



Total Derivative (sum over all paths):

$$\frac{dy}{dx} = \frac{\partial y}{\partial z_1} \frac{dz_1}{dx} + \frac{\partial y}{\partial z_2} \frac{dz_2}{dx}$$

In neural networks: gradients flow back through ALL paths



chain\_rule\_visualization

"If A affects B and B affects C, how does A affect C?"

## Chain of Effects

Fed Rate → Mortgages → Housing → Banks → Portfolio

## How does Fed rate affect your portfolio?

$$\frac{\partial \text{Portfolio}}{\partial \text{Fed}} = \frac{\partial P}{\partial B} \cdot \frac{\partial B}{\partial H} \cdot \frac{\partial H}{\partial M} \cdot \frac{\partial M}{\partial F}$$

## Each Link:

- Fed → Mortgages: rate sensitivity
- Mortgages → Housing: demand elasticity
- Housing → Banks: credit exposure
- Banks → Portfolio: position size

## Neural Network Parallel

Finance	Neural Net
Fed rate	Input x
Mortgages	Hidden layer 1
Housing	Hidden layer 2
Banks	Hidden layer 3
Portfolio	Output

## Backprop does this automatically:

Chains together all the local sensitivities to get the total effect of each input/weight on the loss.

Effects propagate through chains of influence

### At the Output

For output weight  $w^{(L)}$ :

$$\frac{\partial \mathcal{L}}{\partial w^{(L)}} = \frac{\partial \mathcal{L}}{\partial \hat{y}} \cdot \frac{\partial \hat{y}}{\partial z^{(L)}} \cdot \frac{\partial z^{(L)}}{\partial w^{(L)}}$$

### Each Term:

- $\frac{\partial \mathcal{L}}{\partial \hat{y}}$ : How loss changes with output
- $\frac{\partial \hat{y}}{\partial z^{(L)}}$ : Activation derivative
- $\frac{\partial z^{(L)}}{\partial w^{(L)}}$ : Input from previous layer

### For MSE + Sigmoid:

$$\frac{\partial \mathcal{L}}{\partial w^{(L)}} = (\hat{y} - y) \cdot \hat{y}(1 - \hat{y}) \cdot a^{(L-1)}$$

At the output, error attribution is straightforward

### Output Error ( $\delta^{(L)}$ )

Define the “error signal”:

$$\delta^{(L)} = \frac{\partial \mathcal{L}}{\partial z^{(L)}}$$

For MSE loss + sigmoid:

$$\delta^{(L)} = (\hat{y} - y) \cdot \sigma'(z^{(L)})$$

Then:

$$\frac{\partial \mathcal{L}}{\partial w^{(L)}} = \delta^{(L)} \cdot a^{(L-1)}$$

This is just error  $\times$  input!

## The Key Insight

Hidden layer error comes from downstream:

$$\delta^{(l)} = ((W^{(l+1)})^T \delta^{(l+1)}) \odot \sigma'(z^{(l)})$$

## In Words:

1. Take error from next layer ( $\delta^{(l+1)}$ )
2. Multiply by weights connecting to next layer
3. Scale by local activation derivative

## Error Flows Backward:

Output  $\rightarrow$  Last hidden  $\rightarrow \dots \rightarrow$  First hidden

## Why This Works

Chain rule connects layers:

$$\frac{\partial \mathcal{L}}{\partial z^{(l)}} = \sum_j \frac{\partial \mathcal{L}}{\partial z_j^{(l+1)}} \cdot \frac{\partial z_j^{(l+1)}}{\partial z^{(l)}}$$

## Gradient for Hidden Weight:

$$\frac{\partial \mathcal{L}}{\partial w^{(l)}} = \delta^{(l)} \cdot a^{(l-1)}$$

Same formula as output layer!

---

Hidden layer gradients require the chain rule

## One Training Step

### 1. Forward Pass

- Compute all activations
- Get prediction  $\hat{y}$

### 2. Compute Loss

- $\mathcal{L} = \ell(\hat{y}, y)$

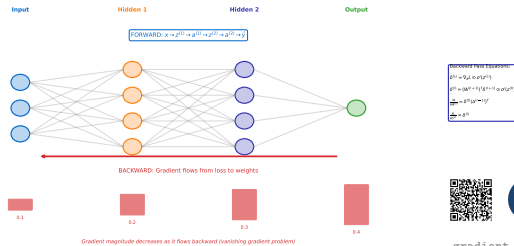
### 3. Backward Pass

- Compute  $\delta^{(L)}$  at output
- Propagate backward to get all  $\delta^{(l)}$
- Compute all weight gradients

### 4. Update Weights

- $\mathbf{W} \leftarrow \mathbf{W} - \eta \nabla \mathcal{L}$

Gradient Flow Through a 3-Layer MLP



gradient\_flow.ml

Forward pass, compute loss, backward pass, update weights

# Why “Backpropagation”?

## The Name

“Back-propagation of errors”

## Information Flow:

### Forward:

- Data flows input  $\rightarrow$  output
- Activations computed layer by layer

### Backward:

- Errors flow output  $\rightarrow$  input
- Gradients computed layer by layer

## Symmetry:

Each layer: one forward operation, one backward operation.

## Historical Note

### The Algorithm:

- Werbos (1974): first derivation
- Rumelhart et al. (1986): popularized
- Now standard in all deep learning

### Modern Perspective:

Backprop is just automatic differentiation applied to neural networks.

### Frameworks (PyTorch, TensorFlow):

Compute gradients automatically – you just specify the forward pass!

---

Error information flows from output to input

*“Why do deeper networks make training harder? What happens to gradients as they flow backward through many layers?”*

**Consider:**

**Vanishing Gradients:**

- Sigmoid: max derivative 0.25
- Through 10 layers:  $0.25^{10}$
- Early layers get tiny gradients
- Learn extremely slowly

**Exploding Gradients:**

- If derivatives  $> 1$
- Gradients grow exponentially
- Weights become huge
- Training diverges

**Solutions:** ReLU, batch normalization, residual connections, careful initialization.

---

**Think-Pair-Share: 3 minutes**

## Definition

Use **all** training data to compute gradient:

$$\nabla \mathcal{L} = \frac{1}{m} \sum_{i=1}^m \nabla \ell(\hat{y}^{(i)}, y^{(i)})$$

Then update weights once.

## Advantages:

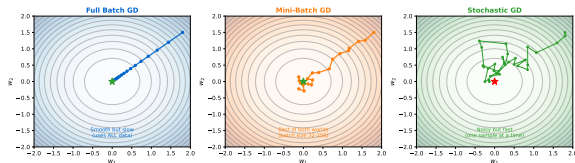
- + Stable gradient estimate
- + Deterministic updates
- + Guaranteed descent direction

## Disadvantages:

- Slow for large datasets
- Must load all data in memory
- One update per full pass

Compute gradient using the entire dataset

Gradient Descent Variants: Trading Off Speed vs Stability



Full Batch: Stable gradients, slow updates | Mini-Batch: Good balance, standard choice | SGD: Fast updates, noisy gradients



batch\_vs\_stochasti



## Definition

Update after **each** single example:

$$\nabla \mathcal{L} \approx \nabla \ell(\hat{y}^{(i)}, y^{(i)})$$

One sample = one update.

## Advantages:

- + Very fast updates
- + Can handle huge datasets
- + Noise helps escape local minima
- + Online learning possible

## Disadvantages:

- Noisy gradient estimate
- Erratic convergence
- May not settle at minimum

## Why “Stochastic”?

Random sampling of training examples introduces randomness into gradient.

## Expected Value:

$$\mathbb{E}[\nabla \ell^{(i)}] = \nabla \mathcal{L}$$

On average, SGD points in the right direction.

## Variance:

Individual updates are noisy, but noise can help exploration.

---

Update after each single example

## Definition

Use small batches of  $B$  examples:

$$\nabla \mathcal{L} \approx \frac{1}{B} \sum_{i=1}^B \nabla \ell(\hat{y}^{(i)}, y^{(i)})$$

Typical  $B$ : 32, 64, 128, 256

## Advantages:

- + Reduced variance vs SGD
- + GPU parallelization
- + Reasonable memory usage
- + Frequent updates

## The Modern Default

Balance between efficiency and noise

## Batch Size Trade-offs

Size	Noise	Speed
1 (SGD)	High	Fast updates
32-256	Medium	Best practice
Full batch	Low	Slow updates

## Large Batch Issues:

- May converge to sharp minima
- Worse generalization
- Need learning rate scaling

# Epochs: Full Passes Through Data

## Definition

**Epoch** = one complete pass through all training data.

## With Mini-Batches:

- 10,000 samples
- Batch size 100
- 100 updates per epoch

## Typical Training:

- 10-1000 epochs
- Monitor loss curve
- Stop when converged

## Training Timeline

Stage	Behavior
Early epochs	Loss drops quickly
Middle epochs	Progress slows
Late epochs	Diminishing returns

## When to Stop?

- Loss stops improving
- Validation loss increases (overfitting!)
- Resource constraints

---

Training typically requires multiple epochs

# Training Curves

## What to Plot

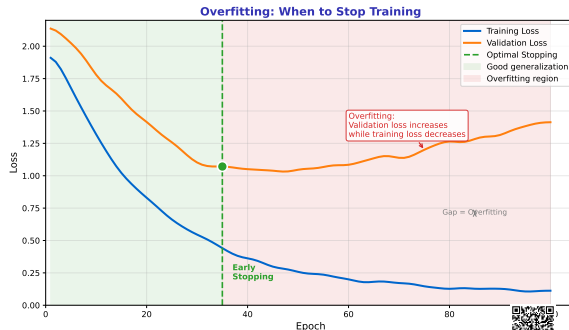
- Training loss vs. epoch
- Validation loss vs. epoch
- Learning rate schedule
- Gradient norms (debugging)

## Healthy Training:

- Both losses decrease
- Validation tracks training
- Smooth convergence

## Warning Signs:

- Training drops, validation rises
- Loss oscillates wildly
- Loss becomes NaN



Finance Analogy: Like backtesting a strategy that works perfectly on historical data but fails in live trading



overfitting\_curve

## Monitoring progress during training

## Worked Example: One Training Step

### Simple 2-2-1 Network

#### Given:

- Input:  $\mathbf{x} = (0.5, 0.8)^T$
- Target:  $y = 1$
- Current weights (simplified)

#### Forward Pass:

$$z^{(1)} = W^{(1)}\mathbf{x} + b^{(1)}$$

$$a^{(1)} = \sigma(z^{(1)})$$

$$z^{(2)} = W^{(2)}a^{(1)} + b^{(2)}$$

$$\hat{y} = \sigma(z^{(2)}) = 0.62$$

### Loss and Backward

#### Loss:

$$\mathcal{L} = \frac{1}{2}(y - \hat{y})^2 = \frac{1}{2}(1 - 0.62)^2 = 0.072$$

#### Backward Pass:

$$\begin{aligned}\delta^{(2)} &= (0.62 - 1) \cdot 0.62(1 - 0.62) \\ &= -0.089\end{aligned}$$

#### Weight Gradient:

$$\frac{\partial \mathcal{L}}{\partial W^{(2)}} = \delta^{(2)} \cdot a^{(1)}$$

#### Update:

$$W^{(2)} \leftarrow W^{(2)} - 0.1 \cdot \nabla W^{(2)}$$

---

Following the numbers through one training step

# The Vanishing Gradient Problem

## The Problem

Gradients shrink as they flow backward:

$$\delta^{(l)} \propto \prod_{k=l}^{L-1} \sigma'(z^{(k)})$$

For sigmoid:  $\sigma'(z) \leq 0.25$

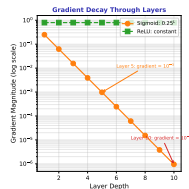
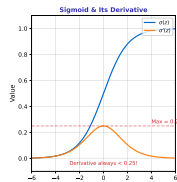
Through 10 layers: gradient  $\times 10^{-6}$

## Symptoms:

- Early layers don't learn
- Deep networks fail to train
- Loss plateaus quickly

Deep networks: gradients can become vanishingly small

Vanishing Gradients: Why Deep Networks Were Hard to Train



## The Vanishing Gradient Problem

**Problem:** Gradients shrink exponentially with depth

**Cause:** Sigmoid/tanh derivatives are  $< 1$

**Effect:** Early layers don't learn (gradients  $\sim 0$ )

1. Use ReLU activation (gradient = 1 for  $z > 0$ )

**Solutions:**

2. Careful weight initialization (He, Xavier)

3. Batch normalization

4. Residual connections (skip connections)

5. LSTM/GRU for recurrent networks

Key insight: ReLU solved this for feedforward networks!



vanishing\_gradient\_demo

## This Module: Intuition

We covered:

- Why backprop works (chain rule)
- How errors flow backward
- Update rule intuition
- Training dynamics

## What We Skipped:

- Full mathematical derivation
- Matrix calculus details
- Vectorized implementations
- Automatic differentiation theory

## Appendix B Contains:

1. Chain rule setup
2. Output layer error derivation
3. Hidden layer recursion formula
4. Complete gradient equations
5. Weight and bias gradients
6. Algorithm pseudocode

## For the mathematically curious:

The appendix provides the rigorous derivation with all matrix calculus steps.

---

See Appendix B for complete backpropagation derivation

# What Is Overfitting?

## Definition

**Overfitting:** When a model learns the training data too well, including its noise, and fails to generalize.

## Analogy:

A student who memorizes exam answers but doesn't understand the material.

## Symptoms:

- Training loss: very low
- Test loss: high
- Model is “too confident”

## Why It Happens

### Model Complexity:

- Too many parameters
- Can fit any training data perfectly
- Including noise

### Limited Data:

- Not enough examples
- Training set not representative
- Noise gets learned as signal

### Training Too Long:

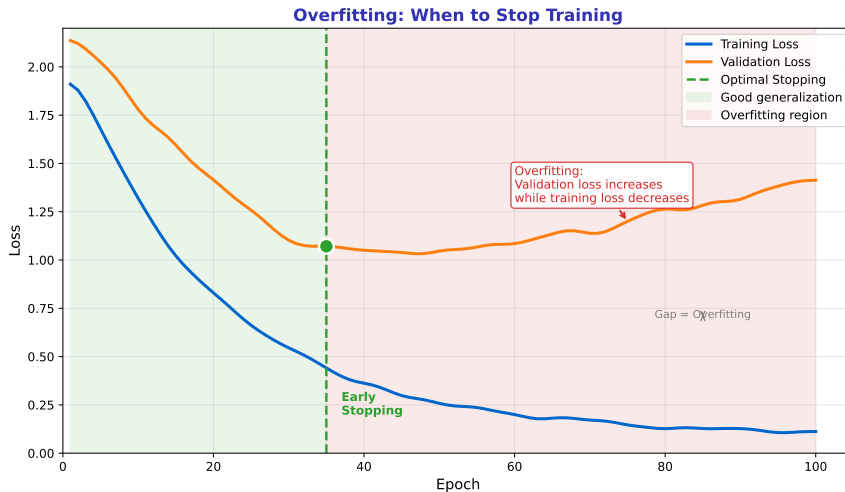
- Model eventually memorizes
- Needs early stopping

---

When your model memorizes instead of learns



# Training vs Validation Loss



Finance Analogy: Like backtesting a strategy that works perfectly on historical data but fails in live trading



overfitting\_curve

## The Trap

Every trading strategy looks good on historical data – that's how you found it!

## The Process:

1. Try many strategies
2. Keep the one that worked best
3. By construction, it fits the past
4. Future performance? Unknown.

## Multiple Testing:

- Try 1000 random strategies
- Best one has Sharpe 2.0
- Is it skill or luck?

## Why Finance Overfits Easily

### 1. Limited Data

- 20 years = 5000 trading days
- Few independent observations

### 2. Low Signal-to-Noise

- Markets are noisy
- Easy to fit noise

### 3. Non-Stationarity

- Regimes change
- Past may not predict future

### 4. Look-Ahead Bias

- Using future information
- Subtle but deadly

---

“Every strategy looks good on historical data”

## Data Limitations

Domain	Samples
ImageNet	1,200,000
MNIST	60,000
Stock returns (daily, 10y)	2,520
Stock returns (monthly, 50y)	600
Market crashes	~10

### The Problem:

Neural networks have thousands of parameters but only thousands of data points.

## Signal vs Noise

### Image Classification:

- A cat is always a cat
- Signal is strong and consistent
- $R^2$  can reach 99%+

### Stock Prediction:

- Returns are mostly random
- Signal is weak and changing
- $R^2$  of 1% is excellent!

### Implication:

Standard ML practices don't directly transfer to finance.

---

Limited data, high noise, non-stationary markets

## Train/Validation/Test Split

1. **Training Set** (60-80%)
  - Used to fit weights
2. **Validation Set** (10-20%)
  - Used to tune hyperparameters
  - Monitor for overfitting
3. **Test Set** (10-20%)
  - Final evaluation only
  - Touch only once!

## Key Rule:

Never use test data for decisions.

---

Always monitor out-of-sample performance

## Warning Signs

### Overfitting Indicators:

- Training loss  $\ll$  validation loss
- Validation loss starts increasing
- Model predictions are “too confident”
- Performance degrades out-of-sample

### For Finance:

- Backtest Sharpe  $\gg$  live Sharpe
- Strategy “stops working”
- Drawdowns worse than expected

*“How would you know if your stock prediction model is overfitting? What specific symptoms would you look for?”*

**Consider:**

**In Training:**

- Training/validation gap
- Validation loss trend
- Prediction confidence

**In Production:**

- Live vs. backtest performance
- Regime sensitivity
- Transaction cost impact

**Best Practice:** Always maintain a truly out-of-sample test set that you evaluate only once.

---

**Think-Pair-Share: 3 minutes**

## Solutions (Module 4)

1. **L1/L2 Regularization**
  - Penalize large weights
  - Simpler models
2. **Dropout**
  - Randomly disable neurons
  - Ensemble effect
3. **Early Stopping**
  - Stop before overfitting
  - Use validation loss
4. **Data Augmentation**
  - Create more training data
  - Finance: bootstrap?

## Finance-Specific

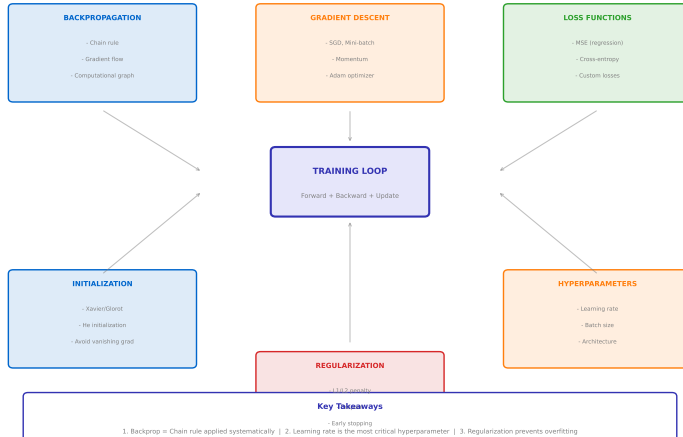
1. **Walk-Forward Validation**
  - Respect time ordering
  - Rolling windows
2. **Cross-Validation Variants**
  - Purged CV
  - Combinatorial CV
3. **Ensemble Methods**
  - Average multiple models
  - Reduce variance

*Module 4 will cover these in detail.*

---

Module 4 will cover solutions: regularization, dropout, early stopping

## Module 3 Summary: Training Neural Networks



module3\_summary\_diagram

## What We Learned

### 1. Loss Functions

- Measure prediction error
- MSE, cross-entropy
- Define what “good” means

### 2. Gradient Descent

- Follow the slope downhill
- Learning rate matters
- Batch vs stochastic

### 3. Backpropagation

- Chain rule for credit assignment
- Error flows backward
- Enables efficient gradient computation

### 4. Training Dynamics

- Epochs and batches
- Monitoring with curves
- Vanishing gradients

### 5. Overfitting

- Memorizing vs learning
- Train/val/test split
- Finance-specific challenges

## The Big Picture:

We can now train neural networks. But making them work well requires more...

---

From measuring error to updating weights



## Modules 1-3 Foundation

### 1. Module 1: Architecture

- Perceptron basics
- Linear decision boundaries
- Limitations (XOR)

### 2. Module 2: MLPs

- Hidden layers
- Non-linear activation
- Universal approximation

### 3. Module 3: Training

- Gradient descent
- Backpropagation
- Overfitting awareness

## You Can Now:

- Explain how neural networks compute
- Understand the training process
- Recognize overfitting
- Follow the math (or know where to look)

## What's Missing:

- Practical regularization
- Real-world applications
- Finance case studies
- Modern developments

---

Modules 1-3: The complete neural network foundation

**Think about these as you move to Module 4:**

**1. Loss vs. Profit:**

Why might minimizing MSE not maximize trading profit? What loss function would better align with trading goals?

**2. Overfitting in Finance:**

With only 20 years of daily data, how many parameters can we safely learn? What's the ratio of samples to parameters you'd be comfortable with?

**3. Non-Stationarity:**

If market regimes change, what does that mean for our training strategy? Should we weight recent data more heavily?

**4. The Efficient Market Hypothesis:**

If markets are efficient, can neural networks find persistent patterns? What would success look like?

---

Reflect on the learning process

*“Theory meets practice. How do we actually use neural networks in finance?”*

### Coming Up:

- Regularization techniques
  - L1/L2, dropout, early stopping
- Financial data challenges
  - Non-stationarity, noise
- Complete case study
  - Stock prediction end-to-end

### Also:

- Modern architectures overview
  - CNN, RNN, Transformers
- Limitations and ethics
  - Black-box decisions
  - Regulatory concerns
- Future directions
  - Where the field is heading

**Mathematical details: See Appendix B-D for derivations**

---

**Next: Regularization, case studies, and modern developments**

# Module 1: The Birth of Neural Computing

## From Biological Inspiration to the Perceptron (1943-1969)

Neural Networks for Finance

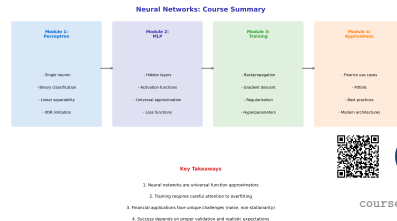
BSc Lecture Series

November 28, 2025

## What We've Covered:

- **Module 1:** The Perceptron
  - Single neuron, decision boundaries
  - XOR limitation → AI Winter
- **Module 2:** Multi-Layer Perceptrons
  - Hidden layers, activation functions
  - Universal Approximation Theorem
- **Module 3:** Training
  - Gradient descent, backpropagation
  - Overfitting warning signs

## The Foundation is Complete



Perceptron → MLP → Training: The complete foundation

*“How do we actually use this for stock prediction?”*

**From theory to practice:**

- How do we prevent overfitting in finance?
- What makes financial data different?
- Does this actually work?
- What are the ethical considerations?

---

**Theory meets practice**

1. **Historical Context (2012-Present)**
  - The deep learning revolution
2. **Regularization Techniques**
  - L1/L2, dropout, early stopping
3. **Financial Data Challenges**
  - Non-stationarity, regime changes, biases
4. **Case Study: Stock Prediction**
  - S&P 500 direction prediction (realistic assessment)
5. **Modern Architectures**
  - CNN, RNN, Transformer overview
6. **Limitations and Ethics**
  - What neural networks can and cannot do

---

From theory to real-world applications

## Theory is Clean:

- Data is stationary
- Training set represents test set
- Patterns persist
- No transaction costs
- Unlimited computing power

## Finance is Messy:

- Markets change constantly
- Past may not predict future
- Regime changes happen
- Costs eat into profits
- Latency matters

**Warning:** Paper profits  $\neq$  Real profits

---

“Theory is clean. Finance is messy.”

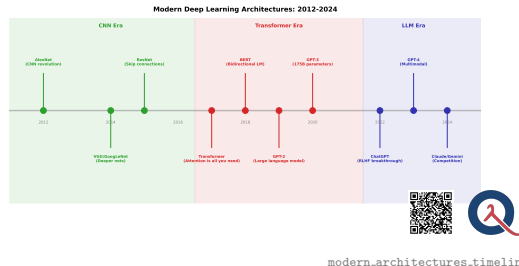


## AlexNet (Krizhevsky et al., 2012):

- ImageNet competition: 1.2M images, 1000 classes
- **Error rate: 15.3%** (vs. 26.2% second place)
- Deep convolutional neural network (8 layers)

## Why This Mattered:

- 10+ percentage points better than alternatives
- Proved deep learning works at scale
- GPU training (2x NVIDIA GTX 580)
- Started the deep learning “gold rush”



AlexNet: When deep learning proved its superiority

# What Made Deep Learning Work?

## Three Factors Converged in the 2010s:

### 1. Big Data

- ImageNet: 14M+ images
- Internet scale data
- Labeled datasets
- In finance: tick data, alternative data

### 2. GPU Computing

- Parallel matrix operations
- 100x speedup vs CPU
- CUDA programming
- Cloud GPU access

### 3. Better Algorithms

- ReLU activation
- Dropout regularization
- Batch normalization
- Better optimizers (Adam)

**All three were necessary; none was sufficient alone**

---

The convergence of data, compute, and algorithms

## The Transformer Architecture (Vaswani et al., 2017):

- Originally for machine translation
- Key innovation: **Self-attention mechanism**
- No recurrence needed → parallelizable

## Self-Attention Intuition:

- Each position “attends” to all other positions
- Learns which inputs are relevant to each other
- “The cat sat on the mat because *it* was tired”
- Attention reveals that “it” refers to “cat”

## Attention Formula:

$$\text{Attention}(Q, K, V) = \text{softmax}\left(\frac{QK^T}{\sqrt{d_k}}\right) V$$

- $Q$ : Query (what am I looking for?)
- $K$ : Key (what do I have?)
- $V$ : Value (what do I return?)

---

Vaswani et al.: The architecture that changed everything

## Scaling Laws and Foundation Models:

### Key Developments:

- GPT-2 (2019): 1.5B parameters
- GPT-3 (2020): 175B parameters
- GPT-4 (2023): rumored 1T+ parameters
- ChatGPT: Conversational interface

### Scaling Discovery:

- Performance scales predictably with:
  - Model size
  - Dataset size
  - Compute budget

### Impact on Finance:

- Sentiment analysis from news/social media
- Document understanding (10-K filings)
- Natural language queries for data
- Automated research summarization

### But: LLMs don't predict stock prices

- Different problem domain
- Time series  $\neq$  language patterns

---

From GPT-2 to GPT-4 and beyond

*“Why did neural networks succeed in 2012 but not in 1990?”*

*What changed?”*

- Was it just computing power?
- What role did data play?
- Were the algorithms fundamentally different?
- Could we have predicted this breakthrough?

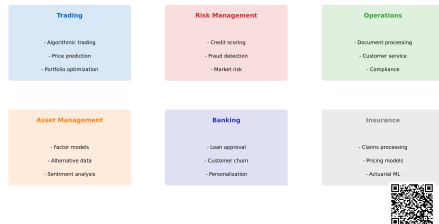
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**Think-Pair-Share: 3 minutes**

## Major Players:

- **Renaissance Technologies**
  - Medallion Fund: 66% avg. return (1988-2018)
  - Highly secretive, physics/math PhDs
- **Two Sigma**
  - \$60B+ AUM
  - Heavy ML/AI focus
- **Citadel**
  - Market making + hedge fund
  - ML for high-frequency trading

## AI/ML Applications in Finance



**Common Applications:** Signal generation, portfolio optimization, risk management, alternative data analysis, [i.applications.finance](#)

Renaissance, Two Sigma, Citadel: Industry adoption

## What's Actually Working:

- Risk management and fraud detection
- High-frequency market making
- Alternative data processing
- Portfolio optimization
- Credit scoring
- Sentiment analysis

## What's Mostly Hype:

- “AI that beats the market consistently”
- Perfect stock price prediction
- Fully automated trading for retail
- “Guaranteed returns” from AI

**Red Flag:** If someone claims their AI consistently beats the market, ask why they're selling it instead of using it.

---

Separating reality from marketing

# The Overfitting Problem Revisited

## Recall from Module 3:

- Model learns training data too well
- Memorizes noise instead of patterns
- Fails on new, unseen data

## In Finance, This Is Critical:

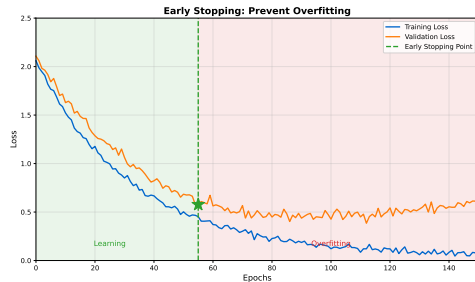
- Backtest shows 40% annual returns
- Live trading shows -15%
- This happens constantly

## Why Module 4 Focuses on This:

- Overfitting is the #1 failure mode
- Financial data is especially prone
- Must master regularization techniques

Overfitting: The greatest challenge in financial ML

## The Overfitting Gap:



earlystopping.ai



# Why Finance Overfits So Easily

## Limited Data:

- 20 years of daily data = 5,000 samples
- Compare to ImageNet: 14,000,000 images
- Regime changes reduce effective samples further

## High-Dimensional Features:

- 50 technical indicators  $\times$  10 lookbacks = 500 features
- More parameters than data points = guaranteed overfitting

## Low Signal-to-Noise:

- Daily stock returns: 95%+ noise
- Real patterns are tiny

### Challenges with Financial Data for ML



These challenges make financial ML harder than typical ML applications



financial.data.challenge

Limited data, high noise, changing regimes

# L2 Regularization (Ridge)

**The Idea:** Add penalty for large weights

$$\mathcal{L}_{reg} = \mathcal{L} + \frac{\lambda}{2} \|\mathbf{W}\|_2^2 = \mathcal{L} + \frac{\lambda}{2} \sum_i w_i^2$$

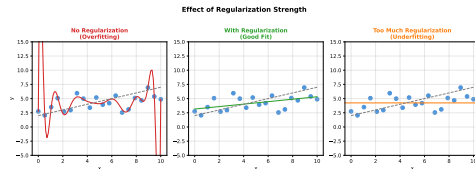
**Effect on Optimization:**

- Original gradient:  $\nabla_w \mathcal{L}$
- With L2:  $\nabla_w \mathcal{L} + \lambda w$
- Weights decay toward zero each update
- Also called “weight decay”

**Hyperparameter  $\lambda$ :**

- $\lambda = 0$ : No regularization
- $\lambda$  large: All weights  $\rightarrow 0$
- Typical:  $10^{-4}$  to  $10^{-2}$

Push weights to be small



regularization\_effect.pdf

### Why Does Penalizing Large Weights Help?

#### Mathematical View:

- Large weights  $\rightarrow$  extreme predictions
- Small changes in input  $\rightarrow$  big output changes
- High sensitivity = memorization
- L2 forces smoother functions

#### Bayesian View:

- $L2 = \text{Gaussian prior on weights}$
- Prior belief: weights should be small
- More data  $\rightarrow$  prior matters less

#### Finance Analogy:

- Large weight on one feature = “betting everything on one stock”
- Risky: what if that feature stops working?
- L2 forces diversification across features
- No single feature dominates the prediction

#### Key Insight:

- L2 doesn't eliminate features
- Just reduces their influence
- All features contribute, but moderately

---

Don't let any single feature dominate

# L1 Regularization (Lasso)

**The Idea:** Penalty proportional to absolute value

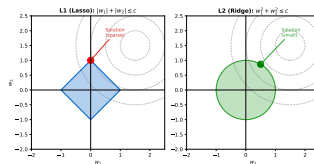
$$\mathcal{L}_{reg} = \mathcal{L} + \lambda \|\mathbf{W}\|_1 = \mathcal{L} + \lambda \sum_i |w_i|$$

**Key Difference from L2:**

- L1 pushes weights to **exactly zero**
- Creates sparse models (feature selection)
- Automatically identifies irrelevant features

**Why Sparsity?**

- L1 gradient is  $\pm\lambda$  (constant)
- Small weights get pushed to zero
- L2 gradient is  $\lambda w$  (proportional)
- Small weights shrink slowly, never reach zero



L1 vs L2 Comparison

Property	L1 (Lasso)	L2 (Ridge)
Constraint	Diamond	Circle
Sparsity	Yes (zeros)	No
Feature Selection	Automatic	No
Correlated Features	Kicks one	Shrinks all
Computational	Harder	Easier



11\_vs\_1

Push some weights to exactly zero: feature selection

## L1 vs L2: Comparison

Property	L1 (Lasso)	L2 (Ridge)
Penalty term	$\lambda \sum  w_i $	$\frac{\lambda}{2} \sum w_i^2$
Effect on weights	Some become exactly 0	All shrink toward 0
Feature selection	Yes (automatic)	No
Correlated features	Picks one arbitrarily	Shares weight among them
Sparsity	Sparse solutions	Dense solutions
Computation	Non-differentiable at 0	Smooth, differentiable
Use when	Few features matter	All features may matter

**Elastic Net:** Combine both:  $\lambda_1 \|W\|_1 + \lambda_2 \|W\|_2^2$

Best of both worlds for correlated features

L1 for sparsity, L2 for shrinkage

## The Idea (Hinton et al., 2012):

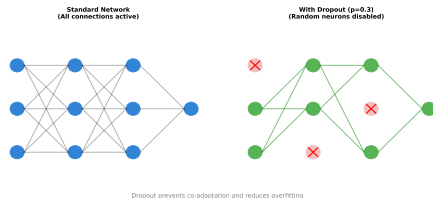
- During training: randomly “drop” neurons
- Each neuron has probability  $p$  of being set to 0
- Typically  $p = 0.5$  for hidden,  $p = 0.2$  for input

## Training:

- Each mini-batch sees different network
- Forces redundancy in learned features
- No neuron can become a “crutch”

## Inference:

- Use all neurons (no dropout)
- Scale outputs by  $(1 - p)$  or use “inverted dropout”



dropout\_visualization

“No single neuron becomes a crutch”

*“How is dropout like diversifying a portfolio?”*

- What happens if you bet everything on one stock?
- What happens if a neural network relies on one neuron?
- How does diversification protect against failure?
- How does dropout force the network to diversify?

---

**Think-Pair-Share: 3 minutes**

## Ensemble Interpretation:

- Network with  $n$  neurons has  $2^n$  possible subnetworks
- Dropout trains all subnetworks simultaneously
- Each mini-batch samples a different subnetwork
- Final prediction: average of all subnetworks

## Why Ensembles Work:

- Different models make different errors
- Averaging reduces variance
- More robust to noise

## Finance Parallel:

- One analyst: high variance predictions
- Committee of analysts: more stable
- Dropout = “committee of networks”

## Practical Notes:

- Dropout slows convergence
- Needs more epochs to train
- Don't use with batch normalization (debate)
- Less common in CNNs today

---

Dropout approximates training an ensemble of networks



## The Simplest Regularization:

- Monitor validation loss during training
- Stop when validation loss stops improving
- Use the model from the best epoch

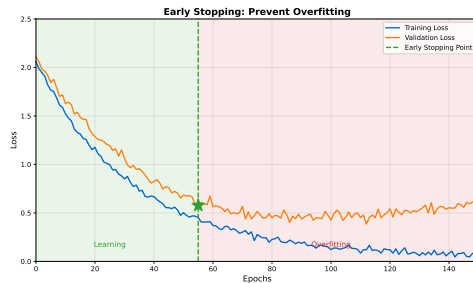
## Implementation:

- Track best validation loss
- Patience: wait  $k$  epochs before stopping
- Save checkpoint at each improvement
- Restore best checkpoint at end

## Why It Works:

- Early epochs: learning real patterns
- Later epochs: memorizing training noise
- Sweet spot: generalization peak

Stop training when validation loss stops improving



Typical patience: 5-20 epochs



early\_stoppin

## Standard Cross-Validation: **WRONG** for Time Series

- Random splits leak future information
- Model sees 2024 data, predicts 2023
- Guaranteed overfitting

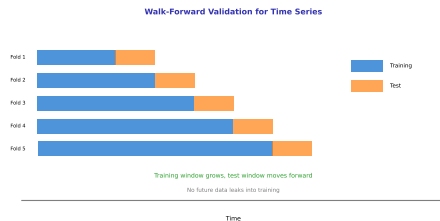
## Walk-Forward Validation:

- Train on [2010-2015], validate on [2016]
- Train on [2010-2016], validate on [2017]
- Train on [2010-2017], validate on [2018]
- Always: train on past, validate on future

## Anchored vs Rolling Window:

- Anchored: always start from same date
- Rolling: fixed window slides forward

Train on past, validate on future (never the reverse)



walk\_forward\_validation.com

Technique	Mechanism	When to Use
L2 (Ridge)	Penalize large weights	Always (as baseline)
L1 (Lasso)	Push weights to zero	Feature selection needed
Dropout	Random neuron deactivation	Deep networks
Early Stopping	Stop before overfitting	Always (free)
Walk-Forward	Time-respecting validation	Time series only

### Practical Recommendation for Finance:

1. Always use walk-forward validation
2. Start with L2 regularization
3. Add early stopping (patience=10)
4. Try dropout (0.2-0.5) for deep networks
5. Use L1 if you need interpretable feature importance

### Multiple defenses against overfitting

## Financial Data is Fundamentally Different:

### Images/Text:

- Patterns are stable over time
- Cat in 2020 looks like cat in 2010
- English grammar doesn't change daily
- High signal-to-noise ratio
- Abundant labeled data

### Financial Markets:

- Patterns change constantly
- Strategies that work get arbitrated away
- Regime changes (bull/bear/crisis)
- Extremely low signal-to-noise
- Limited history, no "labels" for future

**Key Insight:** Success in image recognition doesn't translate to finance.  
The problems are fundamentally different.

---

Financial data is fundamentally different from images or text

## Definition:

- Statistical properties change over time
- Mean, variance, correlations all shift
- Model trained on past may fail on future

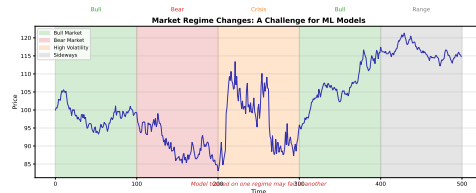
## Causes in Finance:

- Central bank policy changes
- Market structure evolution (HFT, ETFs)
- Regulatory changes
- Technology disruption
- Global events (pandemics, wars)

## Implication:

- Models have “shelf life”
- Need regular retraining
- “What worked”  $\neq$  “what will work”

The patterns that worked yesterday may not work tomorrow



regime-change

## Markets Switch Between Fundamentally Different Behaviors:

### Bull Market:

- Upward trend
- Low volatility
- Mean reversion works
- Risk-on behavior
- Correlations low

### Bear Market:

- Downward trend
- High volatility
- Momentum works
- Risk-off behavior
- Correlations spike

### Crisis:

- Extreme moves
- “All correlations go to 1”
- Historical patterns break
- Liquidity disappears
- Fat tails dominate

**Challenge:** You don't know which regime you're in until it's over.

**Solution:** Train separate models or use regime detection.

---

Markets switch between fundamentally different behaviors

## Signal-to-Noise Ratio (SNR):

- Daily stock returns:  $\text{SNR} \approx 0.05$
- Speech recognition:  $\text{SNR} \approx 10\text{-}20$
- 200-400x harder!

## What This Means:

- 95%+ of price movement is random
- True patterns are tiny
- Easy to find spurious patterns
- Need massive data to detect signal

## Example:

- Average daily return: 0.04%
- Daily standard deviation: 1%
- $\text{Signal} = \text{return} / \text{std} = 0.04$

---

Most price movement is noise, not signal

## Implications for ML:

- Models will find patterns in noise
- Backtests look amazing
- Live performance disappoints
- Need extreme skepticism

## Reality Check:

- If returns were 50% predictable, you'd be a billionaire in months
- Markets are efficient enough that small edges are huge
- 55% accuracy is actually impressive

**Definition:** Using information that wasn't available at decision time.

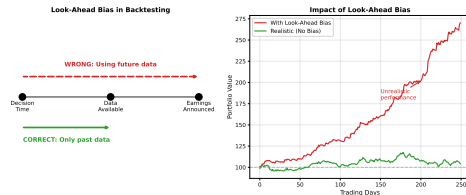
## Common Mistakes:

- Using today's adjusted close to trade at today's open
- Normalizing with full dataset statistics
- Including stocks that didn't exist yet
- Using restated (revised) financial data
- Feature engineering with future data

## Example:

- Train on 2020-2023
- Normalize: subtract mean, divide by std
- **Problem:** Mean includes 2023!
- In 2020, you didn't know 2023 stats

The silent killer of backtests



## Prevention:

- Point-in-time data
- Rolling normalization
- Careful feature engineering



look\_ahead\_bias



**Definition:** Only successful companies remain in the dataset.

## The Problem:

- S&P 500 today has survivors
- Enron, Lehman, Bear Stearns are gone
- Your model never sees failures
- Learns patterns of survivors only

## Impact:

- Overstates historical returns
- “Average stock returned 10%/year”
- Actually includes only winners

## Real Example:

- Study: “Value stocks beat growth”
- Used current value stocks list
- Many value stocks went bankrupt
- True effect was much smaller

## Solution:

- Point-in-time constituent lists
- Include delisted companies
- Use survivorship-bias-free databases
- Account for delisting returns

---

**Your dataset doesn't include the failures**

*“What makes financial prediction harder than image recognition?”*

- A cat is always a cat. Is a bull market always a bull market?
- ImageNet has 14 million labeled images. How many “market crashes” exist?
- If everyone uses the same model, what happens?
- Does finding patterns in finance make them disappear?

---

**Think-Pair-Share: 3 minutes**

## Essential Preprocessing Steps:

### Normalization:

- Z-score:  $\frac{x-\mu}{\sigma}$
- Use rolling window (e.g., 252 days)
- Never use future data!

### Missing Data:

- Forward fill (most common)
- Linear interpolation
- Drop if too many missing
- **Never: backward fill**

### Outlier Handling:

- Winsorize at 1%/99% percentile
- Or use robust statistics (median)
- Don't remove outliers blindly!
- Crashes are real data

### Feature Engineering:

- Returns not prices (stationarity)
- Log returns for mathematical convenience
- Technical indicators as features
- Lag features appropriately

---

Proper preprocessing is essential

## A Realistic Example from Start to Finish

### Goal:

- Predict S&P 500 next-day direction
- Binary: Up or Down?
- Use only information available at market close

### Why This Problem:

- Simple, well-defined target
- Abundant data
- Common industry problem
- Illustrates key challenges

### Our Approach:

1. Define features and target
2. Choose architecture
3. Set up walk-forward validation
4. Train and evaluate
5. Reality check the results

**Spoiler:** Results will be modest.  
That's the honest truth about financial ML.

---

A realistic example from start to finish

## Target Variable:

$$y_t = \begin{cases} 1 & \text{if } R_{t+1} > 0 \\ 0 & \text{if } R_{t+1} \leq 0 \end{cases}$$

where  $R_{t+1} = \frac{P_{t+1} - P_t}{P_t}$  is next-day return.

## Baseline:

- Random guess: 50% accuracy
- Actual: S&P 500 up 53% of days (long-term)
- “Always predict up”: 53% accuracy

## Goal:

- Beat 53% consistently
- Out-of-sample (not just backtest)
- After transaction costs

## Data:

- Period: 2000-2023 (24 years)
- Frequency: Daily
- Samples:  $\sim 6,000$  trading days

## Important Notes:

- This is harder than it sounds
- Small edge = big money
- Markets are highly efficient
- Most published research overfits

---

Binary classification: Up or Down?

## Technical Indicators (15 features):

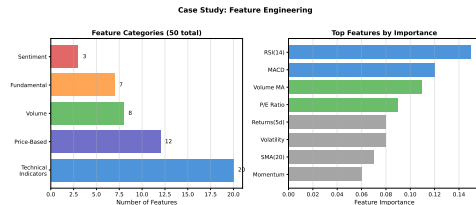
- Returns: 1-day, 5-day, 20-day
- Moving averages: 10/50/200-day ratios
- Volatility: 20-day rolling std
- RSI (14-day), MACD
- Bollinger Band position
- Volume ratio (vs 20-day avg)

## Market Factors (5 features):

- VIX level and change
- Treasury yield (10Y)
- Credit spread
- Put/Call ratio

**Preprocessing:** Rolling z-score (252-day window), clip at  $\pm 3$

15 technical indicators + 5 market factors



**Total: 20 input features**



case\_study\_feature

## Network: 20-16-8-1

- Input: 20 features
- Hidden 1: 16 neurons (ReLU)
- Hidden 2: 8 neurons (ReLU)
- Output: 1 neuron (Sigmoid)

## Why This Architecture?

- Relatively shallow (avoid overfitting)
- Decreasing width (funnel shape)
- Total parameters:  $\sim 500$
- Parameters  $\ll$  samples (6,000)

## Regularization:

- L2:  $\lambda = 0.001$
- Dropout: 0.2 (after each hidden layer)
- Early stopping: patience=10

Balancing model capacity with overfitting risk

Case Study: Stock Return Prediction Architecture



Total Parameters:  $\sim 15,000$   
Loss Function: MSE  
Optimizer: Adam ( $\alpha=0.001$ )  
Batch Size: 64  
Early Stopping: patience=10



case\_study\_architectur

## Walk-Forward Validation:

### Data Split:

- Training: 10 years (2,500 days)
- Validation: 2 years (500 days)
- Test: 2 years (500 days)
- Roll forward by 1 year, retrain

### Training Details:

- Optimizer: Adam ( $\text{lr}=0.001$ )
- Loss: Binary cross-entropy
- Batch size: 64
- Max epochs: 200
- Early stopping:  $\text{patience}=10$

10 years training, 2 years validation, 2 years test

### Walk-Forward Windows:

Train	Valid	Test
2000-09	2010-11	2012-13
2001-10	2011-12	2013-14
2002-11	2012-13	2014-15
...	...	...
2010-19	2020-21	2022-23

**Total:** 10 test

windows

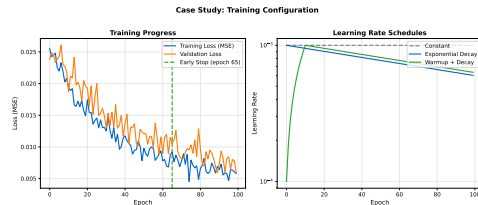


## Typical Training Run (2010-2019 → 2022-23):

- Training loss decreases smoothly
- Validation loss: decreases, then flat
- Early stopping at epoch 45-80
- Gap between train/val loss: moderate

## Observations:

- **Good:** Not severe overfitting
- **Good:** Validation loss improves
- **Moderate:** Some train-val gap
- Training accuracy: 58-62%
- Validation accuracy: 54-56%



case\_study\_trainin

## Monitoring the training process

## Out-of-Sample Results (2012-2023):

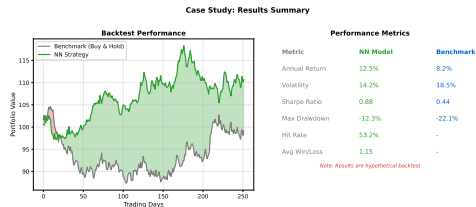
- Average test accuracy: **54.2%**
- Range across windows: 51.8% - 56.7%
- Baseline (always up): 53.1%
- **Edge over baseline: +1.1%**

## By Year:

- Best: 2017 (56.7%) - low volatility
- Worst: 2020 (51.8%) - COVID crash
- Average bull market: 55.1%
- Average bear market: 52.4%

Is 54.2% good? It depends on costs and execution...

54.2% accuracy - is this good?



case\_study\_result

*"If a model is 54% accurate at predicting direction,  
is it profitable?"*

- What if each trade costs 0.1% in fees and slippage?
- What if you trade once per day vs once per month?
- Does accuracy equal profitability?
- What other metrics matter?

---

**Think-Pair-Share: 3 minutes**

## Accuracy $\neq$ Profitability

### What Accuracy Misses:

- Size of wins vs losses
- 54% accuracy with small wins, large losses = loss
- Timing of predictions
- Risk taken to achieve returns

### Better Metrics:

- **Sharpe Ratio:**  $\frac{\text{Return} - R_f}{\text{Volatility}}$
- **Max Drawdown:** Largest peak-to-trough loss
- **Win/Loss Ratio:** Avg win / Avg loss

### Our Case Study:

- Annual return: 8.2% (vs 9.5% buy-hold)
- Volatility: 12.1% (vs 18.2% buy-hold)
- Sharpe: 0.68 (vs 0.52 buy-hold)
- Max drawdown: 18% (vs 34% buy-hold)

### Interpretation:

- Lower return than buy-hold
- But much lower risk
- Better risk-adjusted performance
- Before costs!

---

Accuracy is not the same as profitability

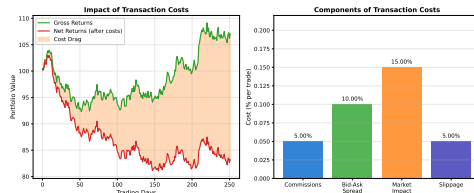
## Types of Costs:

- Commission: \$0-10 per trade (retail)
- Bid-ask spread: 0.01%-0.1%
- Market impact: depends on size
- Slippage: execution vs expected price

## Our Strategy:

- Trades: 252 days/year (daily)
- Round-trip cost: 0.1% (conservative)
- Annual cost:  $252 \times 0.1\% = 25.2\%$
- Gross return: 8.2%
- **Net return: -17%**

**Lesson:** Daily trading requires extremely high accuracy to be profitable.



transaction.costs

Costs can eliminate paper profits entirely

# The Efficient Market Hypothesis

## EMH (Fama, 1970):

“Prices fully reflect all available information”

### Three Forms:

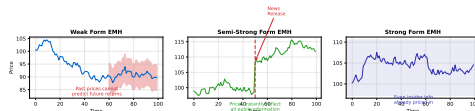
- **Weak:** Can't profit from past prices
- **Semi-strong:** Can't profit from public info
- **Strong:** Can't profit from any info

### Implications for ML:

- If EMH true: all patterns are noise
- If EMH false: patterns exist but are small
- Reality: markets are “mostly efficient”
- Small, temporary inefficiencies exist

Markets are (mostly) efficient

Efficient Market Hypothesis (EMH) Forms



### Grossman-Stiglitz Paradox:

If markets were perfectly efficient, no one would do research, so they couldn't be efficient.



emh.visualization

## What Works (Maybe):

- Risk management and hedging
- Alternative data processing
- High-frequency market making
- Factor model enhancement
- Portfolio optimization
- Regime detection

## Where NNs Add Value:

- Complex non-linear relationships
- High-dimensional feature spaces
- Alternative data (satellite, NLP)
- Execution optimization

## What Doesn't Work:

- "Predicting stock prices" (directly)
- Black-box trading systems
- Complex models on small data
- Ignoring transaction costs
- Overfitting to backtests

## Honest Expectations:

- Small edges are valuable
- 55% accuracy is impressive
- Risk management > alpha generation
- Domain knowledge essential

---

Setting appropriate expectations for neural networks in finance

## The MLP Foundation:

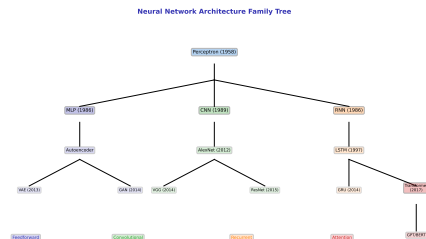
- Everything we learned applies to modern architectures
- Backpropagation: same algorithm
- Activation functions: same choices
- Regularization: same techniques

## Key Modern Architectures:

1. **CNN:** Convolutional Neural Networks
2. **RNN/LSTM:** Recurrent Networks
3. **Transformer:** Attention-based

## Common Thread:

All contain feedforward (MLP) components!



architecture\_family\_tree

MLPs are the foundation for everything that followed



## Key Idea: Learnable pattern detectors

- Convolutional filters slide over input
- Detect local patterns (edges, shapes)
- Weight sharing reduces parameters
- Hierarchical feature learning

## For Time Series:

- 1D convolutions over time
- Detect patterns in price/volume sequences
- Filter learns what to look for
- E.g., “head and shoulders” pattern

## Architecture:

Conv1D → ReLU → Pool

→ Conv1D → ReLU → Pool

→ Flatten → MLP → Output

## Finance Use Cases:

- Technical pattern recognition
- Order book analysis
- Multi-asset correlation patterns

---

CNNs: Finding patterns with learnable filters

## Key Idea: Memory for sequences

- Process sequences one step at a time
- Maintain hidden state (memory)
- Output depends on current + past inputs
- Natural for time series

## RNN Update:

$$h_t = \tanh(W_{hh}h_{t-1} + W_{xh}x_t + b)$$

**Problem:** Vanishing gradients over long sequences

## LSTM Solution (1997):

- Forget gate: what to discard
- Input gate: what to add
- Output gate: what to reveal
- Cell state: long-term memory

## Finance Use Cases:

- Time series forecasting
- Sequence-to-sequence (prices)
- Combining with attention

---

RNNs and LSTMs: Designed for sequences

## Key Innovation: Self-attention

- Each position attends to all others
- No recurrence needed
- Parallelizable (fast training)
- Captures long-range dependencies

## Components:

- Multi-head attention
- Feedforward layers (MLPs!)
- Layer normalization
- Positional encoding

## Attention Formula:

$$\text{Attn} = \text{softmax} \left( \frac{QK^T}{\sqrt{d_k}} \right) V$$

## Finance Use Cases:

- News/sentiment analysis (NLP)
- Document understanding
- Multi-asset attention
- Temporal attention for prices

---

The architecture behind GPT and modern NLP

## Retrieval-Augmented Generation (RAG):

- Combines retrieval with generation
- Query  $x$  retrieves relevant documents  $z$
- Model generates answer  $y$  conditioned on both

## The RAG Formula:

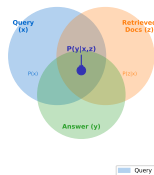
$$P(y|x) = \sum_z P(y|x, z) \cdot P(z|x)$$

- $P(z|x)$ : Retriever finds relevant docs
- $P(y|x, z)$ : Generator produces answer
- Marginalizes over retrieved documents

**Finance Application:** Retrieve relevant filings/news, then generate analysis conditioned on context.

RAG Formula: A Concrete Example

RAG: Conditional Probability Spaces



Concrete Example: Question Answering



## Every Modern Architecture Contains MLPs:

### CNN:

- Conv layers: shared MLPs
- Final classifier: MLP
- Same activation functions

### RNN/LSTM:

- Gate computations: MLPs
- Output layer: MLP
- Same backprop algorithm

### Transformer:

- FFN after attention: MLP
- Position-wise: MLP
- 2/3 of parameters in MLPs!

**What you learned in this course is the foundation for all of deep learning.**

Perceptron → MLP → CNN/RNN/Transformer

---

Every modern architecture contains feedforward components

*"If you were building a financial AI startup today,  
what architecture and problem would you focus on?"*

- Direct price prediction vs risk management?
- Traditional features vs alternative data?
- Simple MLP vs complex Transformer?
- Retail product vs institutional tool?

---

**Think-Pair-Share: 3 minutes**

## The Interpretability Challenge:

- Neural networks: millions of parameters
- No simple explanation for decisions
- “Why did you sell?” - “Because weight 47,823 was 0.0032”

## Why This Matters in Finance:

- Regulatory requirements (explainability)
- Risk management needs understanding
- Client trust requires explanation
- Debugging requires insight

## Partial Solutions:

- SHAP values, LIME
- Attention visualization
- Simpler models where possible

Neural networks are often difficult to interpret

## Trade-off:

Simple	Complex
Interpretable	Black box
Linear	Non-linear
Stable	May overfit
Lower accuracy	Higher accuracy

## Question:

Is 1% more accuracy worth losing all interpretability?

## Key Regulations:

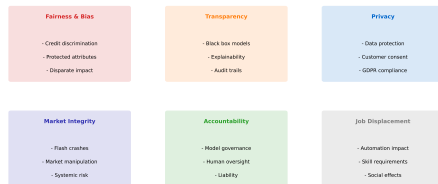
- **MiFID II (EU)**: Best execution, transparency
- **GDPR**: Right to explanation for automated decisions
- **SR 11-7 (US)**: Model risk management
- **Basel III**: Capital requirements, risk models

## Explainability Mandates:

- Credit decisions must be explainable
- Trading algorithms need documentation
- Model validation required
- Audit trails essential

**Trend:** Increasing regulation of algorithmic decision-making

### Ethical Considerations in AI/ML for Finance



Responsible AI: Balance innovation with societal impact



ethical\_consideration

Regulations increasingly demand explainable AI



## What if everyone uses similar models?

### The Problem:

- Similar training data
- Similar architectures
- Similar features
- $\Rightarrow$  Similar predictions
- $\Rightarrow$  Correlated trades
- $\Rightarrow$  Amplified market moves

### Historical Example:

- August 2007: Quant meltdown
- Many funds used similar strategies
- All deleveraged simultaneously
- Massive losses in days

### Flash Crash Risk:

- May 6, 2010: Dow dropped 1000 points in minutes
- Algorithmic trading implicated
- Feedback loops between systems

### Mitigations:

- Circuit breakers
- Position limits
- Diversity requirements
- Human oversight
- Stress testing for crowding

---

Correlated AI trading could amplify market instability

**“All models are wrong, some are useful” - George Box**

## **Types of Model Risk:**

- **Specification risk:** Wrong model type
- **Implementation risk:** Coding bugs
- **Data risk:** Bad inputs
- **Usage risk:** Misapplication

## **Famous Failures:**

- LTCM (1998): Model assumptions failed
- Knight Capital (2012): \$440M in 45 minutes
- London Whale (2012): VAR model issues

## **Governance Framework:**

- Independent model validation
- Documentation requirements
- Regular backtesting
- Stress testing
- Change management
- Clear ownership

## **Key Principle:**

Never deploy a model you don't understand well enough to know when it might fail.

---

**Responsible deployment requires proper oversight**

## AI Has Seen Hype Cycles Before:

### The Pattern:

1. Breakthrough discovery
2. Excessive optimism/funding
3. Over-promising
4. Failure to deliver
5. “AI Winter” backlash
6. Quiet progress
7. Next breakthrough...

### Examples:

- 1960s: “Machines will think in 20 years”
- 1980s: Expert systems will replace experts
- 2010s: “Deep learning solves everything”
- Today: “AGI is imminent”

### Lesson:

Hype damages the field. Responsible claims and honest assessment help it grow sustainably.

**Your Responsibility:** Be honest about what neural networks can and cannot do.

---

Hype cycles damage the field; responsible claims help it grow

## Realistic Assessment of Neural Networks in Finance:

### High Value Applications:

- **Risk Management**
  - Fraud detection
  - Credit scoring
  - Anomaly detection
- **Alternative Data**
  - Satellite imagery analysis
  - News sentiment
  - Social media signals
- **Execution**
  - Optimal order routing
  - Market making
  - Transaction cost analysis

### Lower Value (Often Overhyped):

- Direct price prediction
- “AI-powered” retail trading apps
- Fully automated strategies
- Complex models on limited data

### Key Insight:

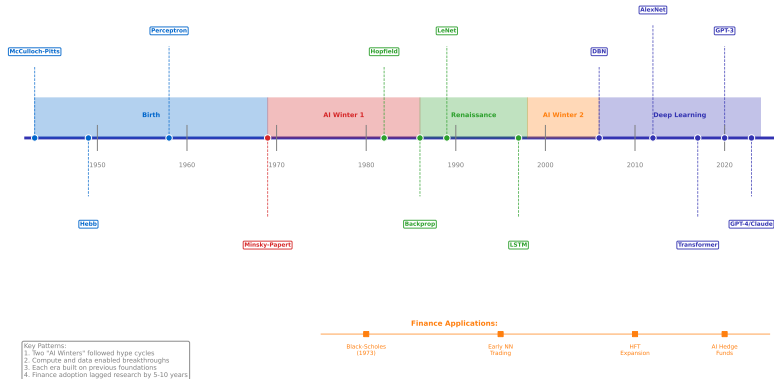
Neural networks work best when:

- Abundant data available
- Clear signal exists
- Domain expertise integrated
- Proper validation done

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Risk management, alternative data, market making

## Neural Networks: 80 Years of Progress (1943-2024)



full.timeline.1943\_2024

## Module 1 - Perceptron:

- Neuron as weighted voting
- Linear separability limits
- XOR problem → AI Winter

## Module 2 - MLPs:

- Hidden layers solve XOR
- Activation functions enable non-linearity
- Universal Approximation Theorem

## Module 3 - Training:

- Gradient descent finds minimum
- Backprop: efficient gradient computation
- Overfitting is the main enemy

## Module 4 - Practice:

- Regularization fights overfitting
- Financial data is uniquely challenging
- Honest assessment of capabilities

**The Foundation:** Everything in modern AI builds on these concepts.

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The essential concepts from all four modules

## Suggested Learning Path:

### Theory:

- Deep Learning (Goodfellow et al.)
- Neural Networks and Deep Learning (Nielsen) - free online
- Stanford CS231n (CNNs)
- Stanford CS224n (NLP)

### Practice:

- PyTorch or TensorFlow tutorials
- Kaggle competitions
- Personal projects
- Open-source contributions

### Finance-Specific:

- Advances in Financial ML (de Prado)
- Machine Learning for Asset Managers
- QuantConnect, Zipline (backtesting)
- Academic papers (SSRN, arXiv q-fin)

### Key Advice:

- Build things!
- Start simple, add complexity
- Focus on fundamentals
- Be skeptical of claims
- Domain knowledge matters

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Suggested resources for continued learning

**Thank You**

Neural Networks for Finance  
BSc Lecture Series

Questions?

See Mathematical Appendix for full derivations