

MLP, CNN, RNN, and Transformer

Answers to the Same Question

How do we make a machine understand a sentence?

A sentence is a **sequence** — order matters.

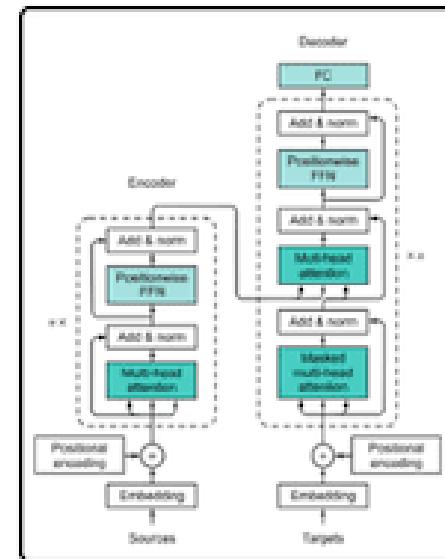
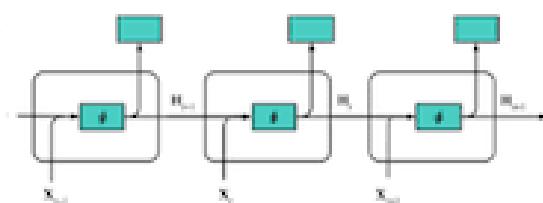
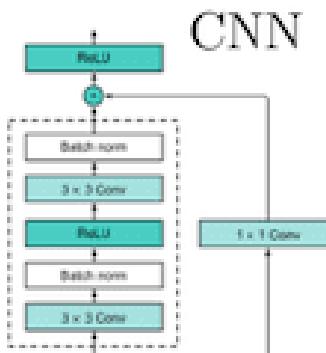
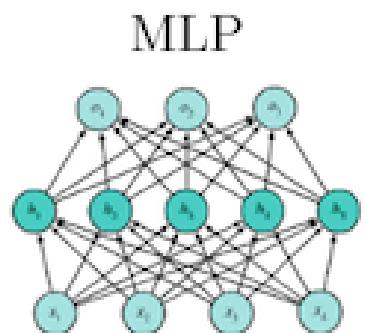
"Alice will eat pizza" means something very different from "Pizza will eat Alice."

Any model that processes language must answer:

How do we capture the **meaning** and
relationships between words in a sequence?

These are popular architecute:

Popular Architectures



1. MLP (Multi-Layer Perceptron) — the basic building block of all neural networks.
2. Convolutional Neural Networks (CNNs) — good for images, not ideal for sequences.
3. Recurrent Neural Networks (RNNs) — designed to handle sequences by maintaining a hidden state.
4. Transformers — use self-attention to capture relationships between all words at once.

1. The Shared Foundation: Perceptrons

Everything Starts Here: The Perceptron

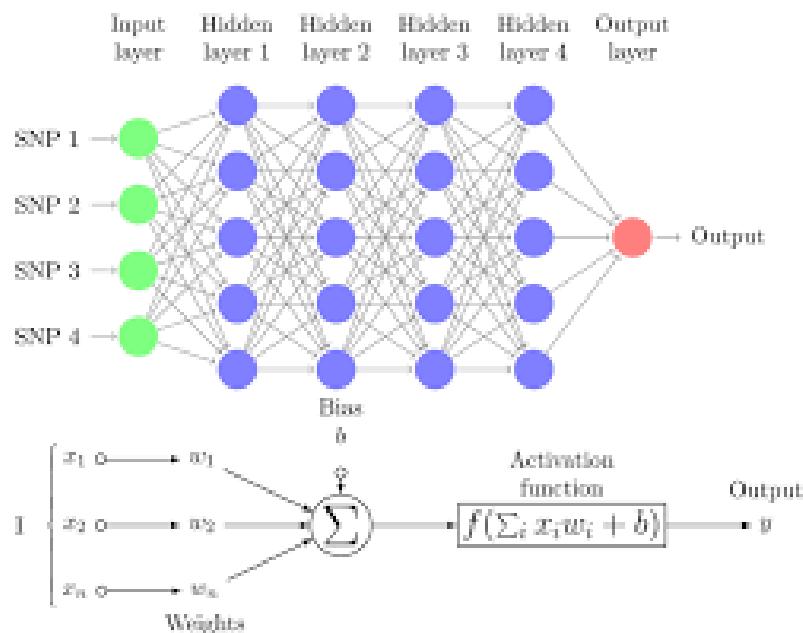
Before either RNNs or Transformers, there is the **perceptron** – the basic building block of all neural networks.

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

Symbol	Meaning
x_i	input values
w_i	learned weights
b	bias
f	activation function (e.g. ReLU, sigmoid)

From Perceptron to MLP

Stack multiple perceptrons into **layers** and you get a **Multi-Layer Perceptron (MLP)**:



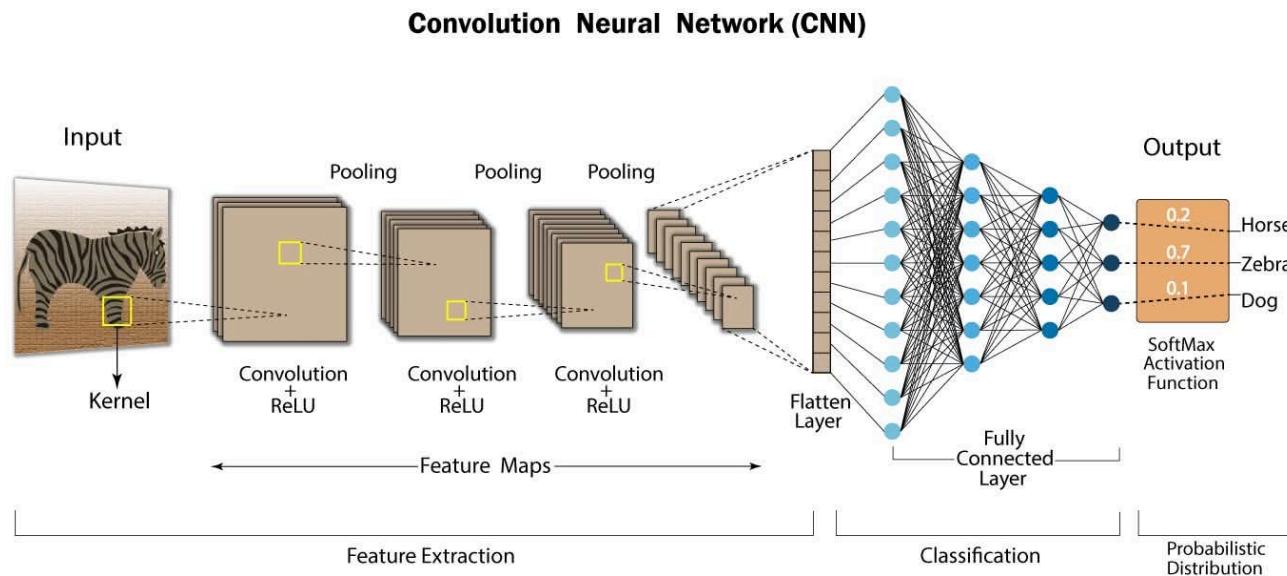
Each layer learns increasingly abstract features.
MLPs are excellent for fixed-size inputs — but
sentences vary in length.

Neither RNNs nor Transformers throw away the
perceptron.
They both **use MLPs inside** — but add different
mechanisms to handle sequences.

2. CNN: Perceptrons with Local Receptive Fields

The Core Idea of a CNN

A CNN (Convolutional Neural Network) applies the **same small perceptron** (called a filter or kernel) repeatedly across the input.

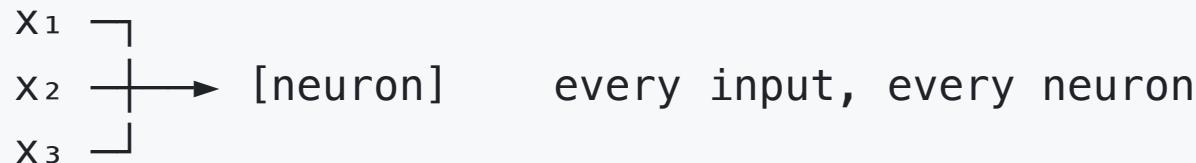


Instead of connecting every input to every neuron (like MLP), each neuron only looks at a **small local region** — its **receptive field**.

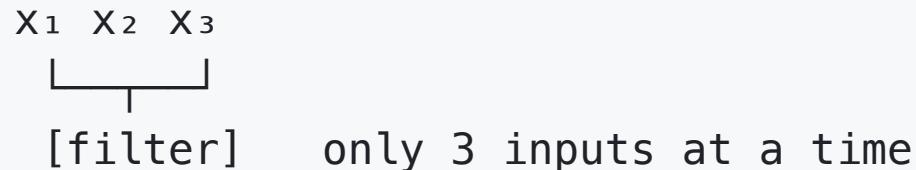
Key insight: nearby pixels (or nearby words) are often more related than distant ones.

From MLP to CNN – What Changes?

MLP: every input connects to every neuron



CNN: each neuron connects to only a small window



The same filter **slides** across the entire input — this is called **convolution**.

The Convolution Operation

A filter is just a small set of weights. It slides across the input and produces one output number per position:

$$z_i = f\left(\sum_{k=0}^{K-1} w_k \cdot x_{i+k} + b\right)$$

Symbol	Meaning
x_{i+k}	input values in the current window
w_k	filter weights (learned)
K	filter size (e.g. 3x3 for images)
b	bias
f	activation function (ReLU)

The same w_k is used at **every position** – this is called **weight sharing across space**.

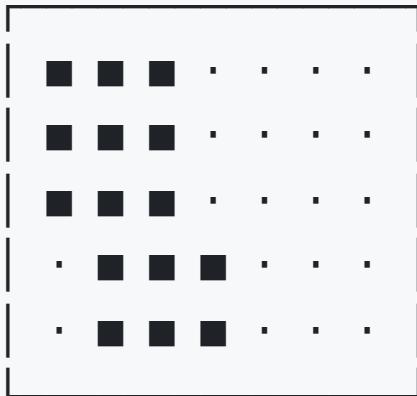
CNN on an Image — Step by Step

For a 5×5 image with a 3×3 filter:

Image patch: Filter (learned): Output:

$$\begin{array}{ccc} 1 & 2 & 3 \\ 0 & 1 & 0 \\ 2 & 1 & 3 \end{array} \quad \times \quad \begin{array}{ccc} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{array} \quad = \quad \begin{array}{c} \text{one} \\ \text{number} \end{array}$$

The filter slides across **every** 3×3 patch of the image:



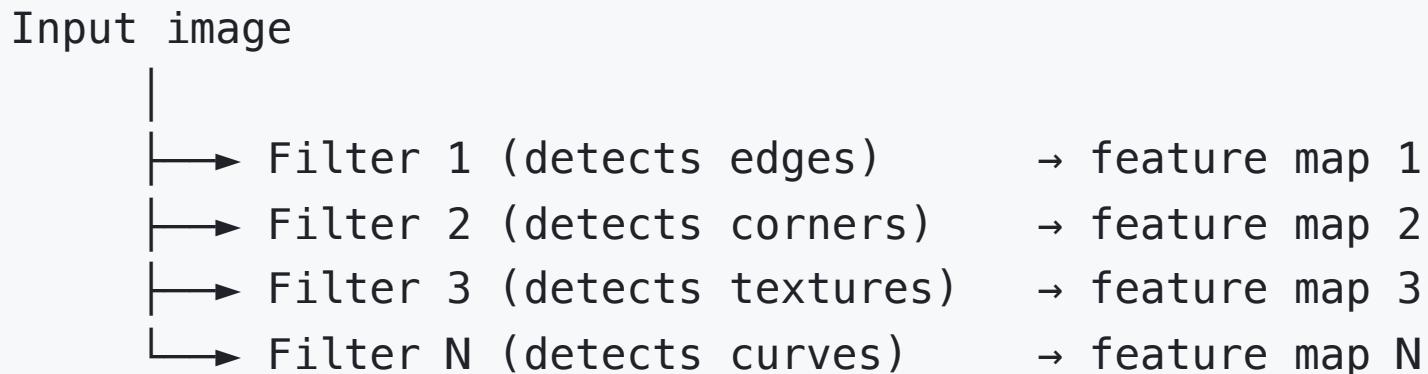
filter here → z_1

filter slides → z_2

Each position produces one value — together they form a **feature map**.

Multiple Filters = Multiple Features

One filter detects one kind of pattern. CNNs use **many filters in parallel**:



In practice a single CNN layer might have **64, 128, or 512 filters** — each learning to detect a different visual pattern.

Stacking multiple layers builds increasingly **abstract features**:

- Layer 1: edges and colors
- Layer 2: shapes and textures
- Layer 3: object parts (eyes, wheels)
- Layer 4+: whole objects (face, car)

Pooling: Reducing Size

After convolution, a **pooling** layer shrinks the feature map by summarizing local regions:

Max pooling (2×2):

$$\begin{matrix} 1 & 3 & 2 & 4 \\ 5 & 6 & 1 & 2 \\ 0 & 2 & 3 & 1 \\ 4 & 1 & 0 & 2 \end{matrix} \quad \rightarrow \quad \begin{matrix} 3 & 4 \\ 6 & 3 \end{matrix}$$

Max pooling keeps the **strongest activation** in each region.

Pooling makes the CNN **translation-invariant** — it recognizes a cat whether it is in the top-left or bottom-right of the image.

CNN Strengths and Weaknesses

Strengths	Weaknesses
Excellent for spatial data (images, video)	Needs large amounts of labeled image data
Weight sharing drastically reduces parameters	Poor at capturing long-range global relationships
Translation invariant — position does not matter	Fixed receptive field — context window is limited
Fast and parallelizable	Not naturally suited for sequences (text, time series)

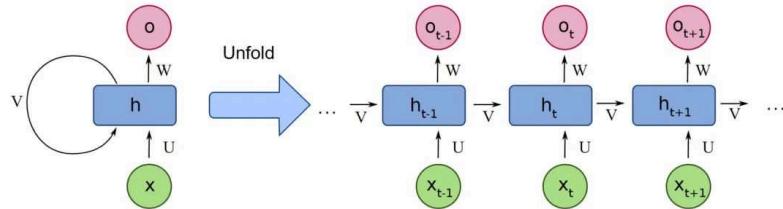
CNN vs MLP – Key Difference

	MLP	CNN
Connectivity	Every input to every neuron	Each neuron sees only a local window
Weight sharing	No — each connection has its own weight	Yes — same filter reused across all positions
Good for	Fixed-size tabular data	Spatial data (images, grids)
Parameters	Many (grows with input size)	Few (filter size is fixed, small)
Spatial awareness	None	Built in via local receptive fields

Example: A 28×28 image (784 pixels) into a 512-neuron MLP needs $784 \times 512 = 401,408$ weights for one layer. A 3×3 CNN filter needs only 9 weights — reused 784 times.

3. RNN: Perceptrons Chained Through Time

The Core Idea of an RNN



An RNN processes a sentence **one word at a time**, left to right.

- At each step, the same perceptron layer runs — but it also receives a **hidden state** from the previous step.

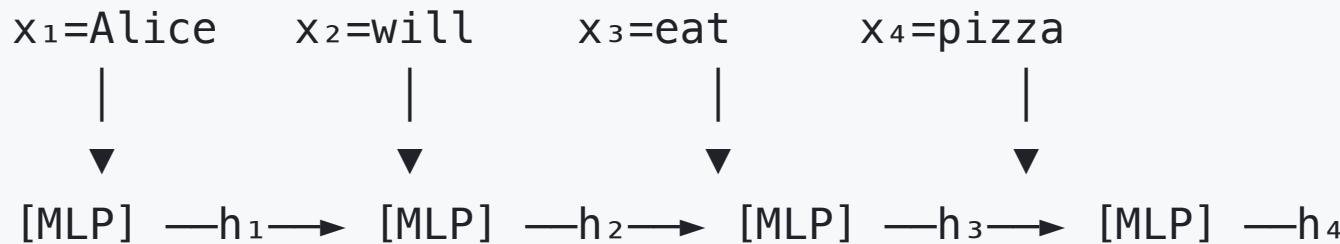
$$h_t = f(W_h \cdot h_{t-1} + W_x \cdot x_t + b)$$

Symbol	Meaning
x_t	current word vector
h_{t-1}	hidden state from previous step (memory)
W_h, W_x	learned weight matrices
h_t	new hidden state (updated memory)

The hidden state h_t is the RNN's "**running memory**" of everything seen so far.

RNN: Step by Step

For the sentence "Alice will eat pizza":



- h_1 contains: "I've seen Alice"
- h_2 contains: "I've seen Alice, will"
- h_3 contains: "I've seen Alice, will, eat"
- h_4 contains: everything – but Alice's signal has faded

Each step uses the **same weight matrices** – just applied again with the new hidden state.
The perceptron is reused at every time step.

The Vanishing Gradient Problem

The further back a word is, the weaker its influence becomes on the final hidden state.

$$h_4 \approx f(W_h \cdot f(W_h \cdot \underbrace{f(W_h \cdot h_1))}_{\text{fading...}}))$$
$$\underbrace{\hspace{10em}}_{\text{fading...}}$$

By the time we reach "eat", the signal from "Alice" has passed through multiple nonlinear functions — it is **diluted**.

This is the **vanishing gradient problem**:
gradients shrink as they travel back through time,
making early words hard to learn from.

LSTM (Long Short-Term Memory) was invented to
address this — using gates to selectively remember
or forget — but the fundamental sequential
bottleneck remained.

RNN: What the Perceptron Does

In an RNN, the perceptron (MLP) plays one role:

Given the current word and the accumulated memory, produce the next memory state.



The same MLP weights are used at **every time step**.

This is called **weight sharing across time**.

RNN Strengths and Weaknesses

Strengths	Weaknesses
Naturally handles variable-length sequences	Must process words one at a time — slow
Small memory footprint	Long-range dependencies fade (vanishing gradient)
Conceptually simple	Cannot be parallelized during training
Works well on short sequences	Performance degrades on long sentences

3. Transformer: Perceptrons Across Space

The Core Idea of a Transformer

A Transformer processes **all words simultaneously**.

- Instead of passing a hidden state forward in time, it computes **relationships between all word pairs at once** using self-attention.

One Transformer layer has two components: Self-Attention and a Feed-Forward Network (FFN)

Input (all words at once)



Self-Attention

← "Who should I pay attention to?"



FFN

← MLP applied per word (perceptrons!)



Output (all words, enriched)

Self-Attention: Computing Relationships

For every word, self-attention computes three vectors:

$$Q = xW_Q \quad K = xW_K \quad V = xW_V$$

The Feed-Forward Network (FFN): Perceptrons Return

After attention has gathered relational information, each word's representation is passed through an **MLP independently**:

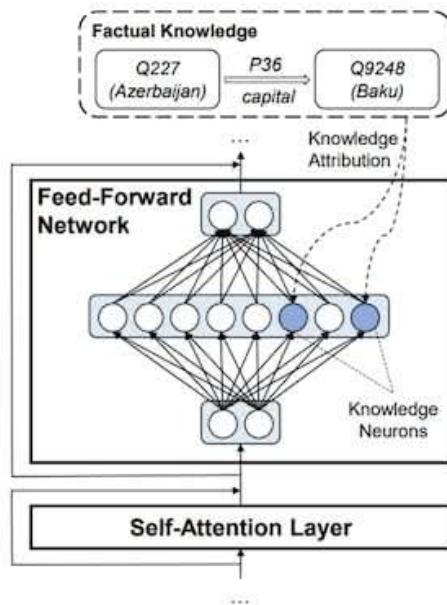


Figure 1: We aim to identify knowledge neurons correlated to a relational fact through knowledge attribution.

$$\text{FFN}(x) = \text{ReLU}(xW_1 + b_1) W_2 + b_2$$

This is a standard **2-layer perceptron** — applied identically to every word position.

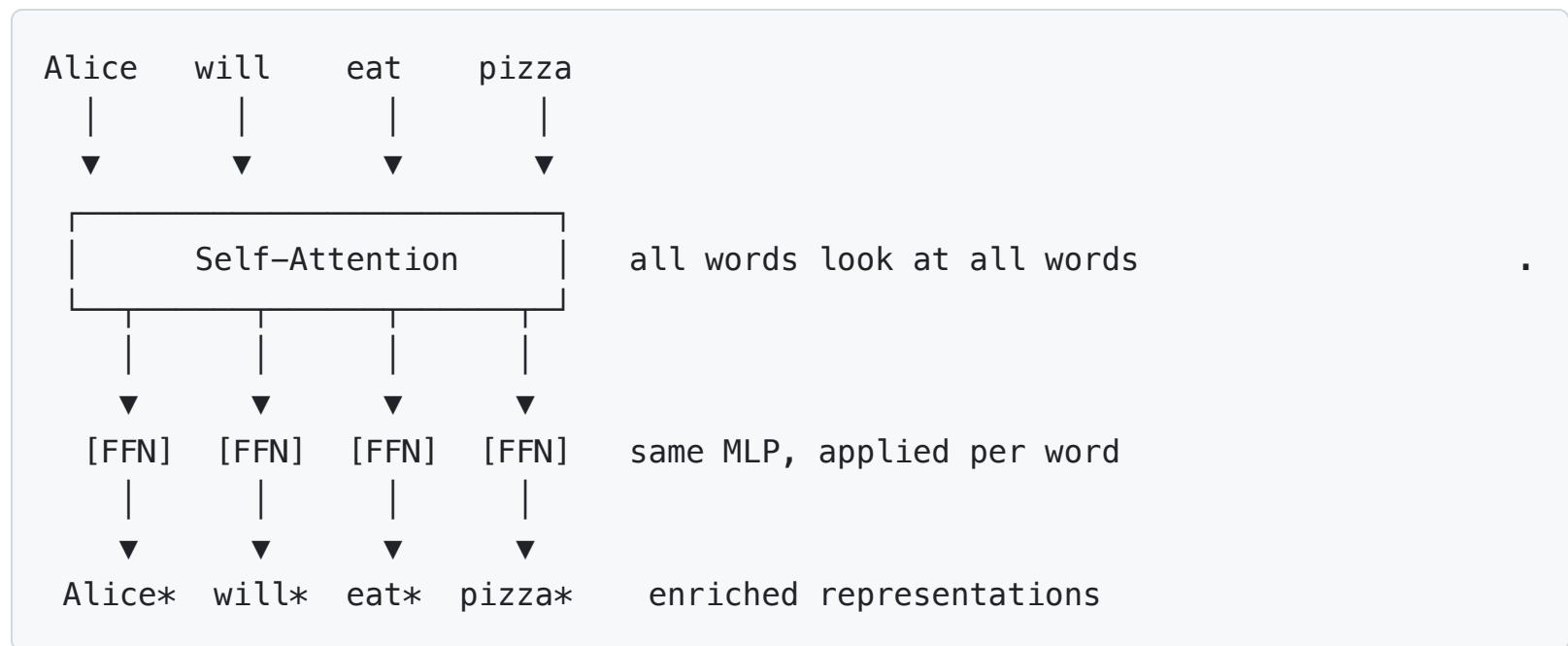
Attention answers: "**Which words matter to me?**"

FFN answers: "**What do I do with the information I gathered?**"

The FFN is where the Transformer stores and retrieves **factual knowledge** — researchers have found that facts like "Paris is the capital of France" live in the FFN weights.

Transformer: Step by Step

For the sentence "Alice will eat pizza":



Every word is updated **in parallel** — no waiting.

"eat*" already knows about "Alice" after just one layer.

Transformer Strengths and Weaknesses

Strengths	Weaknesses
Processes all words in parallel — fast training	Attention cost grows as $O(n^2)$ with sequence length
Captures long-range dependencies directly	Needs positional encoding (no inherent word order)
Scales extremely well with data and compute	Much larger memory footprint than RNNs
Highly parallelizable on GPUs	Harder to interpret than RNNs

Why the Transformer Won

When "Attention Is All You Need" was published (2017), the community saw three key advantages:

- 1. Parallelism** — RNNs could not use GPU hardware efficiently because each step depends on the previous one. Transformers process everything at once.

2. **Long-range dependencies** — A Transformer connects word 1 to word 500 with the same single attention operation. An RNN must pass a signal through 499 intermediate states.
3. **Scalability** — Transformer performance scales smoothly with more data, more parameters, and more compute — following the scaling laws that enabled GPT-3, GPT-4, and beyond.

CNNs/RNNs were not wrong — they were the best solution available.

Transformers were simply **a better answer** to the same question.

4. What They Share

Similarities Run Deep

Despite looking very different on the surface, RNNs and Transformers share the same foundations:

Shared Concept	How RNN Uses It	How Transformer Uses It
Perceptrons (MLP)	Main computation unit at each step	FFN after attention in each layer
Weight matrices	W_h, W_x shared across time steps	W_Q, W_K, W_V, W_1, W_2 shared across positions
Learned embeddings	Word → vector before processing	Word → vector before processing
Backpropagation	Gradients flow backward through time	Gradients flow backward through layers
Activation functions	ReLU, tanh in hidden layers	ReLU in FFN layers
Loss function	Cross-entropy for next-word prediction	Cross-entropy for next-word prediction

Both are trained the same way: predict the next word, measure the error, adjust the weights.

The Perceptron Never Left

A common misconception: "Transformers replaced perceptrons with attention."

This is wrong. Attention is not a perceptron — it has no activation function and no learned bias in the traditional sense. It is pure **weighted averaging**.

The perceptron (FFN) is still essential:

- Attention handles **relationships between words** (relational reasoning)
- FFN handles **transformation of each word's representation** (local processing)

Remove the FFN from a Transformer and performance drops significantly.

The Transformer is **attention + perceptrons**, not **attention instead of perceptrons**.

Evolution, Not Revolution

```
1943 Perceptron (McCulloch & Pitts)
      |
1980s Multi-Layer Perceptron (MLP)
      |
1986 Backpropagation (Rumelhart et al.)
      |
1989 CNN – MLP + local filters + weight sharing (LeCun et al.)
      .
      |
1990s RNN – MLP + hidden state across time
      |
1997 LSTM – RNN + gating mechanism
      |
2012 AlexNet – CNN dominates image recognition (ImageNet)
      |
2014 Seq2Seq + Attention (Bahdanau et al.)
      |
2017 Transformer – Attention + MLP, no recurrence
      |
2018+ BERT, GPT, Claude, LLaMA...
```

Each step **built on** the previous one. The perceptron from 1943 is still inside GPT-4.