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Neuroinspired Computing (Prof. Dr. Abigail Morrison)

Deterministic Recurrent Neural Networks

Seminar Thesis

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1 Introduction

In recent years, machine learning has rapidly evolved, with neural networks emerging as a powerful tool for a wide range of applications. Artificial neural networks, initially inspired by the structure and function of the human brain, have evolved into a diverse family of models, each adapted to specific tasks. Recurrent Neural Networks (RNNs) have significantly transformed the processing of sequential data. They have enabled tasks such as language modelling [13], machine translation [3], and speech recognition [7]. This paper explores the architecture and operation of RNNs, with a particular focus on Long Short-Term Memory networks. These networks are designed to learn long-term dependencies more effectively than standard RNNs. We also discuss the Neural Turing Machine, which is a type of recurrent neural network that is augmented with an external memory bank.

1.1 Feedforward Neural Networks

Before discussing RNNs, it is important to understand the basics of feedforward neural networks. These networks, also called multilayer perceptrons, process input data through interconnected layers of nodes. Each layer consists of a set of nodes that perform a weighted sum of the inputs, followed by the application of an activation function. Each layer's output serves as input to the next layer, producing a final output. To train a feedforward neural network, the weights of the connections between neurons are adjusted to minimize the difference between predicted and actual outputs. This is typically done using the backpropagation algorithm and gradient descent [14].

Feedforward neural networks are limited in their ability to process sequential data due to their design for fixed-size input and output vectors. This makes them unsuitable for tasks where the length of input and output sequences may vary, such as natural language processing [18]. Furthermore, feedforward neural networks do not have an internal state, which means they cannot remember information from previous inputs. As a result, they struggle to capture the sequential dependencies that are present in many real-world datasets. To overcome these limitations, we turn to Recurrent Neural Networks.

2 Recurrent Neural Networks

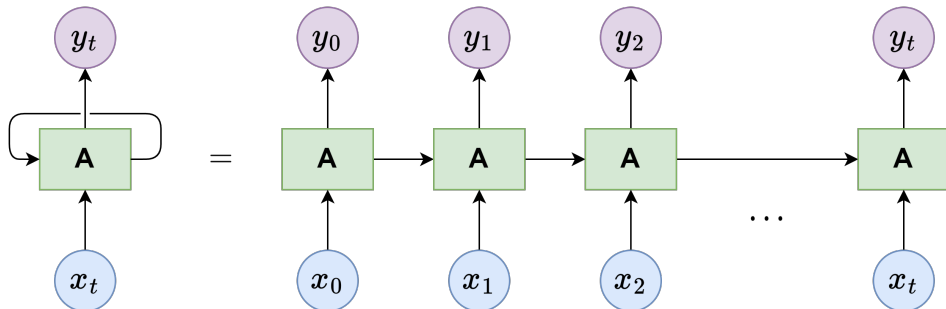


Figure 1: A recurrent neural network unrolled into a sequence of layers. The input sequence x_0, x_1, \dots, x_t is shown in blue, the network layer in green and the output sequence y_0, y_1, \dots, y_t in purple.

Recurrent Neural Networks (RNNs) are a type of neural network specifically designed to handle sequential data by maintaining an internal state. Unlike feedforward neural networks, which process the entire input at once, RNNs process the input elements one at a time, capturing dependencies over time.

The structure of an RNN is similar to a feedforward neural network, but with the addition of a feedback loop to maintain an internal state. This state is updated at each time step, enabling the network to remember information from previous inputs. The output of the network at each time step is influenced by both the current input and the internal state. The repeating module in an RNN can be unrolled into a sequence of layers, so that sequences of arbitrary length can be processed, as shown in Figure 1. This unrolling shows that RNNs are closely related to sequences and lists, making them a useful architecture for processing data of this form.

2.1 Categories of Applications

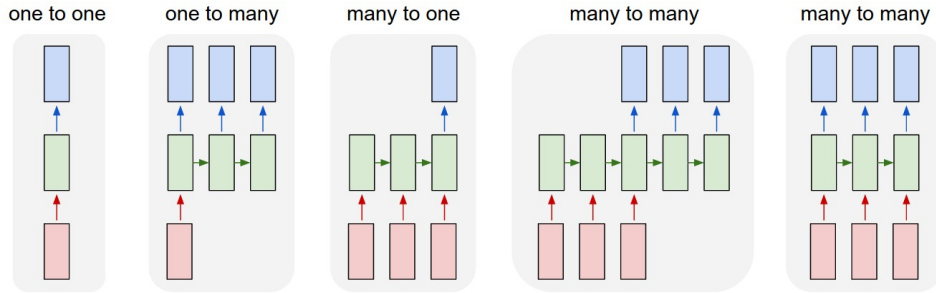


Figure 2: Ways of applying RNNs to different types of data. Both the input and output can be a fixed-size vector or a sequence of vectors. If both are sequences, the input and output vectors can either be regarded as pairs or as unrelated sequences of different lengths. [11]

The applications of RNNs can be categorized based on the length of the input and output sequences and the relationship between them, as shown in Figure 2. For instance, for tasks like image classification, where the input and output sequences have a fixed length, RNNs can be used in a way similar to feedforward neural networks (one-to-one). They can also be used for tasks such as image captioning, where the input is a fixed-size image and the output is a sequence of words (one-to-many). Additionally, RNNs can be applied to tasks such as sentiment analysis, where the input is a sequence of words and the output is a single value (many-to-one). Tasks, where both the input and output are sequences of variable length (many-to-many), can be divided into two subtypes. For example, in machine translation, the input sequence is processed first, and then the output sequence is generated. In contrast, video classification generates the output simultaneously with the input, making it possible for the network to use the previous frames as context. This demonstrates the flexibility of RNNs in handling a wide range of tasks involving sequential data.

2.2 Internal Structure

To understand the structure of an RNN, we compare a single layer feedforward NN with a single layer RNN. As shown in Figure 3, a feedforward NN transforms the input vector

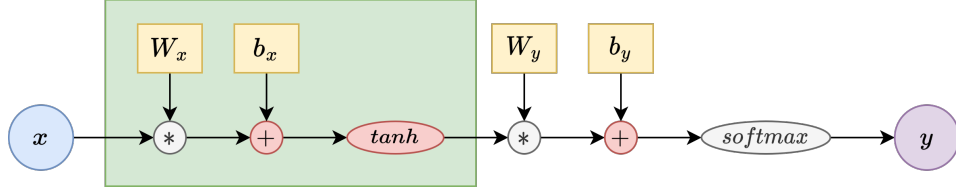


Figure 3: The internal structure of a feedforward neural network with a single layer (in green) and an example for output processing.

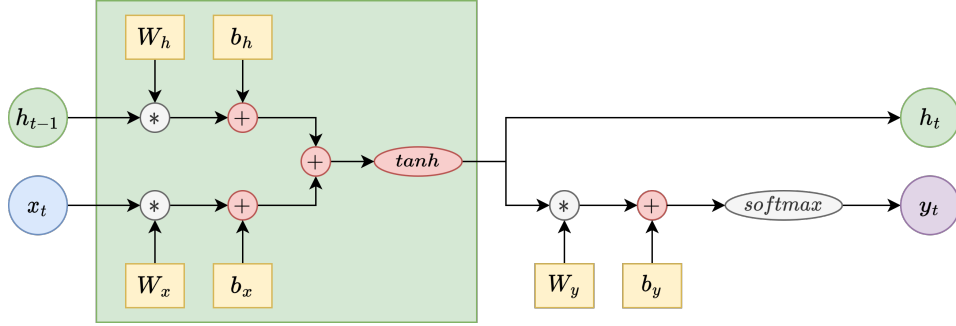


Figure 4: The internal structure of a recurrent neural network with a single layer (in green) and an example for output processing.

x by a linear transformation and an activation function to produce the output of a single layer. In contrast, as shown in Figure 4, an RNN first concatenates the input vector x with the previous state vector h_{t-1} before transforming the concatenated vector in the same way as a feedforward NN. The resulting state vector h_t is then used as the input for the next time step. In the first iteration of the RNN, the previous state vector is usually initialized to a vector of zeros. However, it can also be learned during the training process, which can improve the network's performance in some cases [19].

2.3 Backpropagation

RNNs are usually trained using the backpropagation through time (BPTT) algorithm, an extension of the backpropagation algorithm for feedforward neural networks. As an example, consider a single layer feedforward NN, like the green box in Figure 3. Let

- x be the input vector,
- W the weight matrix,
- b the bias vector,
- y the output vector,
- t the target vector (ground truth)
- σ the activation function, and
- $L = \frac{1}{2} \sum_{i=1}^n (t_i - y_i)^2$ the loss function (e.g. mean squared error).

We first do a forward pass to compute the output $y = \sigma(Wx + b)$ and compare it to the target t by the loss function L . Then, we do a backward pass to compute the gradient of the loss function with respect to the weights and biases of the network. Here, we use the chain rule of calculus:

$$\frac{\partial L}{\partial W} = \frac{\partial L}{\partial y} \frac{\partial y}{\partial W} \quad (1)$$

$$= \frac{\partial L}{\partial y} \frac{\partial y}{\partial(Wx + b)} \frac{\partial(Wx + b)}{\partial W} \quad (2)$$

$$= -(t - y) \cdot \sigma'(Wx + b) \cdot x^T \quad (3)$$

The gradient for the bias vector $\frac{\partial L}{\partial b}$ can be computed similarly. For a network with multiple layers, the gradients are computed layer by layer using the chain rule, starting from the output layer and moving backwards through the network. In the final step, the weights and biases are updated in the direction that minimizes the loss: $W \leftarrow W - \alpha \frac{\partial L}{\partial W}$ and $b \leftarrow b - \alpha \frac{\partial L}{\partial b}$, where α is the learning rate. This is usually done using an optimization algorithm such as stochastic gradient descent [6].

The BPTT algorithm extends this approach to RNNs by unrolling the network into a sequence of connected layers. The forward pass is performed as usual, with the output of each time step serving as the input to the next time step. The backward pass then accumulates the gradients over the entire sequence and updates the weights and biases accordingly. This enables the network to capture the dependencies between the input elements and learn from the entire sequence, rather than just the current input. The main distinction between BPTT and standard backpropagation is that the RNN weights are shared across time steps, and the number of steps is determined by the length of the input sequence, rather than the number of layers. For long sequences, this can result in problems such as vanishing or exploding gradients, which can make training difficult [2].

2.4 The Problem of Long-Term Dependencies

One of the key challenges in training RNNs is the problem of long-term dependencies. To illustrate this, consider a simplified RNN that takes an input sequence x_0, x_1, \dots, x_n and produces a sequence of outputs/hidden states h_0, h_1, \dots, h_n . It is defined by the function F for each time step $t \in \{0, 1, \dots, n\}$:

$$h_t = F(h_{t-1}, x_t) = W_h \tanh h_{t-1} + W_x x_t + b \quad (4)$$

Then the gradient with respect to the hidden state at time step t is given by:

$$\nabla_h F(h_{t-1}, x_t) = W_h \text{diag}(\tanh'(h_{t-1})) \quad (5)$$

For the backward pass, we need to compute the gradient of the loss function, which in this case is given by

$$\partial L = \nabla_h L(h_n, x_1, \dots, x_n) \cdot \sum_{t=1}^n \prod_{k=n-t+1}^n \nabla_h F(h_{k-1}, x_k) \quad (6)$$

where each term in the sum is the gradient of the current layer. The sum can be written as:

$$\begin{aligned}
& \sum_{t=1}^n \prod_{k=n-t+1}^n \nabla_h F(h_{k-1}, x_k) \\
&= \nabla_h F(h_{n-1}, x_n) \\
&+ \nabla_h F(h_{n-1}, x_n) \cdot \nabla_h F(h_{n-2}, x_{n-1}) \\
&+ \nabla_h F(h_{n-1}, x_n) \cdot \nabla_h F(h_{n-2}, x_{n-1}) \cdot \nabla_h F(h_{n-3}, x_{n-2}) \\
&+ \dots
\end{aligned} \tag{7}$$

With Equation (5) and Equation (7), we can see that the gradient for time step t is predominantly influenced by W_h^{n-t+1} . If the largest singular value of W_h is less than 1, the gradient will vanish as t increases. If it is greater than 1, the gradient will explode [17]. This makes it difficult for the network to learn long-term dependencies, as the gradients become too small or too large to be useful. This is known as the problem of long-term dependencies, and it is a fundamental limitation of standard RNNs.

Multiple approaches have been proposed to address this problem, for example, clipping the gradient to prevent it from becoming too large [17]. Let $\nabla_W L$ be the gradient of the loss function and ϵ be a small constant. Then the clipped gradient ∇ is

$$\nabla = \begin{cases} \nabla_W L & \text{if } \|\nabla_W L\| < \epsilon \\ \epsilon \cdot \frac{\nabla_W L}{\|\nabla_W L\|} & \text{otherwise} \end{cases} \tag{8}$$

This technique prevents the gradient from growing indefinitely, but it does not solve the issue of vanishing gradients. Another approach is to use Rectified Linear Unit (ReLU) activation functions [5]. ReLU functions do not saturate for positive inputs because their derivative is 1. However, the problem of vanishing gradients still remains for negative inputs. Additionally, there are methods proposed to initialize the network weights in a way that prevents the gradients from vanishing or exploding [12]. While these methods can partially mitigate the issue of long-term dependencies, they do not offer a complete solution. A more effective approach is to use Long Short-Term Memory networks, which were specifically developed to address the problem of vanishing and exploding gradients in RNNs.

3 Long Short-Term Memory Networks

Long Short-Term Memory (LSTM) networks are a special type of RNN designed to learn long-term dependencies more effectively than standard RNNs. They were introduced by Hochreiter and Schmidhuber in 1997 [10] and have since become popular for various applications, such as language generation, medical diagnosis, sentiment analysis, and video processing. The main concept behind LSTMs is the use of a memory cell, which allows the network to store and access information over long time scales. This section looks at the architecture and operation of LSTMs, as well as some of the variants that have been developed to improve their performance.

3.1 Architecture

The architecture of an LSTM network is based on a repeating module containing four interacting layers, as shown in Figure 5. The central feature of LSTMs is the cell state

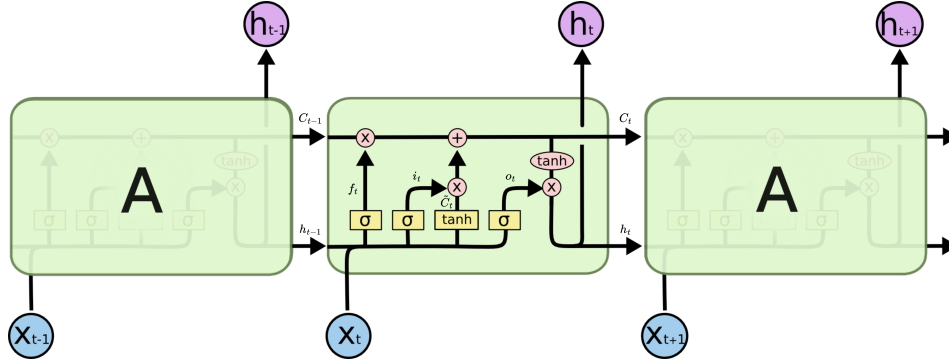


Figure 5: The repeating module of an LSTM network. Each yellow box represents a neural network layer with its activation function and the pink circles represent pointwise operations. The lines merging denote concatenation, while a line forking denotes its content being copied. The output is denoted by h_t . [15]

C_t , which runs straight down the entire chain with only minor linear interactions. This allows information to flow unchanged along the cell state, making it easy for the network to remember information over long time scales. The cell state is controlled by structures called gates, which are made up of neural network layers and pointwise operations. The gates enable the network to remember or forget information as needed.

3.1.1 Forget Gate

The first step in the operation of an LSTM is to decide which information from the cell state to forget. This is done by a sigmoid layer which takes the previous hidden state h_{t-1} and the current input x_t as input and outputs a number between 0 and 1 for each element in the cell state C_{t-1} . A value of 0 indicates that the corresponding element should be forgotten, while a value of 1 indicates that it should be retained. The network can then filter out unimportant information and focus on what matters.

$$f_t = \sigma(W_f \cdot [h_{t-1}, x_t] + b_f) \quad (9)$$

3.1.2 Input Gate

The next step is to decide what new information to store in the cell state. It has two parts. First, a sigmoid layer decides which values to update. Next, a tanh layer creates a vector of new candidate values \tilde{C}_t that could be added to the state. The input gate layer outputs a number between 0 and 1 for each element in the cell state, indicating how much of the new candidate values should be added to the state. Thus, the network can selectively update the cell state with new information.

$$i_t = \sigma(W_i \cdot [h_{t-1}, x_t] + b_i) \quad (10)$$

$$\tilde{C}_t = \tanh(W_C \cdot [h_{t-1}, x_t] + b_C) \quad (11)$$

3.1.3 Update Cell State

The next step is to update the old cell state C_{t-1} into the new cell state C_t . First, the old state is multiplied by the forget gate f_t , forgetting the things that were decided to forget earlier. Then, the new candidate values \tilde{C}_t are added to the state, scaled by how much the input gate decided to update each state value.

$$C_t = f_t \cdot C_{t-1} + i_t \cdot \tilde{C}_t \quad (12)$$

3.1.4 Output Gate

Finally, the network needs to decide what to output. This output will be based on the cell state, but will be a filtered version. First, a sigmoid layer decides which parts of the cell state to output. Then the cell state is run through a tanh function to shift the values between -1 and 1 , and multiplied by the output of the sigmoid gate. The result is the output of the network at the current time step h_t , which can be used for further processing or as the final output of the network.

$$o_t = \sigma(W_o \cdot [h_{t-1}, x_t] + b_o) \quad (13)$$

$$h_t = o_t \cdot \tanh(C_t) \quad (14)$$

3.2 Variants

LSTMs have been the subject of extensive research, leading to the development of several variants [9]. One popular variant, introduced by Gers and Schmidhuber in 2000 [4], adds peephole connections to the LSTM architecture. These connections allow the cell to control the gates more precisely, making it easier for the network to learn precise timing. In addition, the output activation function is omitted, as there is no evidence that it is essential for solving the problems on which LSTMs have been tested so far.

Another variant, called Dynamic Cortex Memory (DCM), was introduced by Otte et al. in 2014 [16]. DCM adds several new trainable connections to the LSTM model, improving the error carousel and the internal interplay between gates. These connections make direct signal transmission between the gates possible, resulting in faster convergence than LSTM under the same training conditions. Furthermore, DCMs outperform LSTMs in generalisation, as shown for several supervised problems, including precise value storage, addition, and context-sensitive grammar learning.

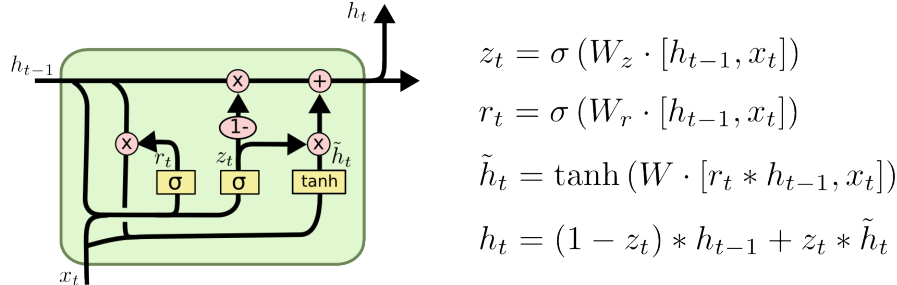


Figure 6: The structure of a Gated Recurrent Unit (GRU) network. [15]

One of the best known variants of the LSTM architecture is the Gated Recurrent Unit (GRU), which was proposed by Cho et al. in 2014 [3]. The GRU simplifies the LSTM architecture by removing the output gate and the cell state, and combining the input and forget gates into a single update gate. This reduces the number of parameters in the network and makes it easier to train. The internal structure of a GRU network is shown in Figure 6. While the GRU has been shown to perform comparably to the LSTM for many tasks, it has the advantage of being simpler and more efficient, making it a popular choice for many applications [21].

4 Neural Turing Machines

While LSTMs and their variants have proven effective for a wide range of tasks, they are still limited in their ability to perform complex operations that require explicit memory access. To address this limitation, Graves et al. introduced the Neural Turing Machine (NTM) in 2014 [8]. The NTM is augmented with an external memory bank to combine the power of neural networks with the capability to store and retrieve information. Unlike operations on a computer’s memory, the NTM’s operations are designed to be fully differentiable and can be trained using backpropagation and gradient-based optimisation algorithms.

The approach is inspired by the structure and operation of a Turing machine, which is a theoretical model of a computer that can read from and write to an infinite tape of memory. A computer program uses three basic mechanisms: elementary operations (such as arithmetic), logical flow control (branching), and external memory that can be written to and read from during computation [20]. In human cognition, the process that most closely resembles algorithmic operation is known as working memory, which is understood as the capacity for short-term storage of information and its rule-based manipulation [1].

4.1 Architecture

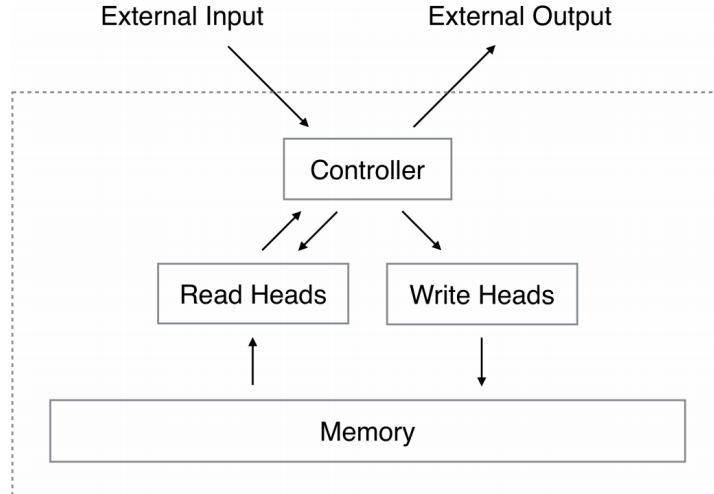


Figure 7: The architecture of a Neural Turing Machine.

The architecture of an NTM, as shown in Figure 7, consists of two main components: a controller and a memory bank. The controller is an LSTM, which is responsible for processing the input data and interacting with the memory bank. The memory bank for time step t is a matrix \mathbf{M}_t of size $N \times M$, where N is the number of memory locations and M is the size of each memory location. The memory bank can be read from and written to by the controller. It interacts with the memory bank using read heads and write heads, which are responsible for reading and writing information from and to the memory bank. They use an attention mechanism to select the memory locations, allowing the network to focus on specific parts of the memory.

4.2 Addressing Mechanism

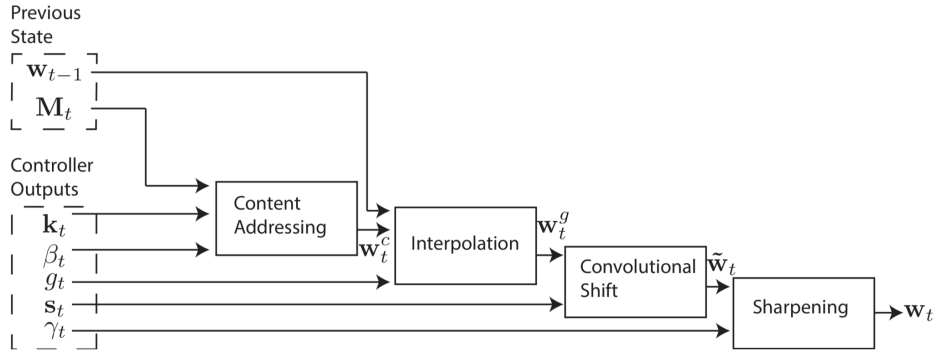


Figure 8: Flow diagram of the addressing mechanism in a Neural Turing Machine. [8]

The addressing mechanism of an NTM is responsible for selecting the memory locations to read from and write to. It combines both content-based and location-based addressing and consists of four main steps: content addressing, interpolation, convolutional shift and sharpening, as shown in Figure 8. The addressing mechanism is performed at each time step, providing a dynamic and flexible way for the controller to interact with the memory bank.

4.2.1 Content Addressing

The first step of the addressing mechanism is content addressing, which selects memory locations based on the content of the cells. It takes as input the current memory bank \mathbf{M}_t , the key vector \mathbf{k}_t , and the key strength β_t . The key vector is used to calculate the similarity between the key and each memory location using the cosine similarity measure $K[\cdot, \cdot]$. The parameter β_t amplifies the precision of the attention weights, enforcing high sparsity in the weights.

$$\mathbf{w}_t^c = \text{softmax}(\beta_t K[\mathbf{M}_t, \mathbf{k}_t]) \quad (15)$$

4.2.2 Interpolation

The next step is interpolation, which lets the network iteratively access subsequent memory locations. It uses the previous attention weights \mathbf{w}_{t-1} , the content-based attention weights

\mathbf{w}_t^c , and the interpolation gate $g_t \in (0, 1)$. For a value of $g_t = 0$ the previous weights are retained, while for a value of $g_t = 1$ the current weights are used. This enables the network to blend between them based on the value of g_t .

$$\mathbf{w}_t^g = g_t \mathbf{w}_t^c + (1 - g_t) \mathbf{w}_{t-1} \quad (16)$$

4.2.3 Convolutional Shift

After interpolation, each head produces a shift weighting \mathbf{s}_t that is used as the kernel for a convolutional shift operation. It convolves the new attention weights with the kernel \mathbf{s}_t , allowing the network to shift the attention if needed. This is useful for accessing memory locations dynamically. All indices are modulo N to ensure that the shift operation is circular.

$$\tilde{\mathbf{w}}_t(i) \leftarrow \sum_{j=0}^{N-1} \mathbf{w}_t^g(j) \mathbf{s}_t(i - j) \quad (17)$$

4.2.4 Sharpening

The final step of the addressing mechanism is sharpening, which amplifies the focus of the attention weights. It takes the convolved attention weights $\tilde{\mathbf{w}}_t$ and the sharpening parameter $\gamma_t \geq 1$ as input and applies a power function to the weights, increasing large weights and decreasing small weights. The effect of sharpening increases with higher values of γ_t .

$$\mathbf{w}_t(i) = \frac{\tilde{\mathbf{w}}_t(i)^{\gamma_t}}{\sum_j \tilde{\mathbf{w}}_t(j)^{\gamma_t}} \quad (18)$$

4.3 Comparison with LSTMs

To compare the performance of the NTM with LSTMs, Graves et al. conducted a series of experiments on a set of simple algorithmic tasks, such as copying and sorting data sequences. The aim was to show that the NTM is able to solve the problems by learning compact internal programs. For example, the researchers tested whether a network trained to copy sequences up to 20 in length could copy a sequence up to 120 in length without further training. The results of the experiments showed that the NTM was able to learn much faster than LSTMs and converged to a lower cost. In addition, the NTM was able to generalise well beyond the range of the training data, while the LSTM degraded rapidly beyond length 20. This suggests that the NTM, unlike the LSTM, had learned some form of copying algorithm. The researchers also examined the interaction between the controller and memory, and concluded that the NTM had learned how to create and iterate through arrays. The focus-sharpening mechanism was also found to be essential, as without it the weightings would lose precision over time.

5 Conclusion

In this paper we have explored the architecture and operation of Recurrent Neural Networks, Long Short-Term Memory networks and Neural Turing Machines, focusing on their ability to store and retrieve information over long time scales. We looked at their internal structure, the back-propagation algorithm used to train them, the problem of long-term

dependencies in standard RNNs, and introduced LSTMs as a solution to this problem. We also discussed the architecture of LSTMs and their variants and introduced the Neural Turing Machine built on top of the LSTM architecture. The results of experiments comparing the performance of LSTMs and NTMs on a set of simple algorithmic tasks were presented, showing that the NTM was able to learn these specific tasks much faster with higher accuracy than LSTMs. Overall, the field of RNNs and their variants is a rapidly developing area of research, and we expect to see many more exciting developments in the future.

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