LSTM - Long Short-Term Memory

Understanding Through a Complete Example

Watch LSTM Process a Sentence

Sentence: "The cat was hungry. The dog was sleeping."

Word	Forget	Input	Output	Memory State
The	0.9	0.3	0.2	*article*
cat	0.8	**0.9**	0.8	*subject: cat*
was	0.9	0.7	0.9	*cat + verb*
hungry	0.8	0.8	0.7	*cat is hungry*
.	**0.1**	0.4	0.3	*sentence ends*
The	0.1	0.8	0.2	*new article*
dog	0.7	**0.9**	0.9	*subject: dog*
was	0.9	0.8	**0.9**	*using dog info*

0.1 = Forget

0.9 = Store/Use

Period → Reset

Just observe for now. Notice any patterns? We'll explain HOW in a moment...

What Did You Notice?

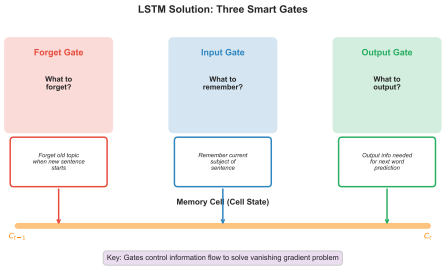
Common Observations:

Students usually notice:

- **"It drops to 0.1 at the period!"**
- **"It's 0.9 on important words (cat, dog)"**
- "The memory changes from cat to dog"
- "It resets between sentences"
- "Three different columns of numbers"

Key Questions:

1. HOW does it know to forget at period?
2. HOW does it know cat and dog are important?
3. HOW does it decide when to use memory?



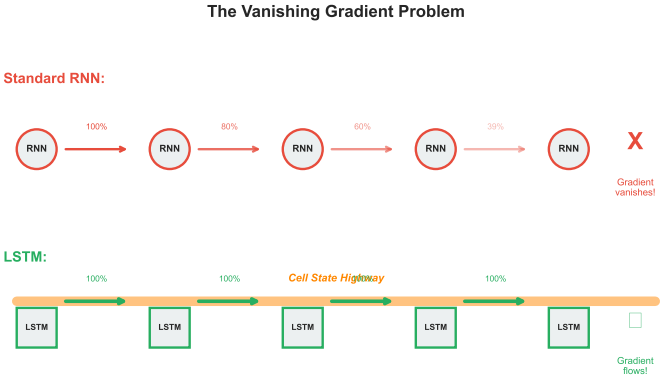
Checkpoint: The Big Reveal

Those three columns are called **GATES**:

- Forget Gate: Controls what to erase
- Input Gate: Controls what to store
- Output Gate: Controls what to use

But WHY do we need gates?

Why Do We Need Controlled Memory?



Key: LSTM uses addition (cell state) instead of multiplication (RNN hidden state)

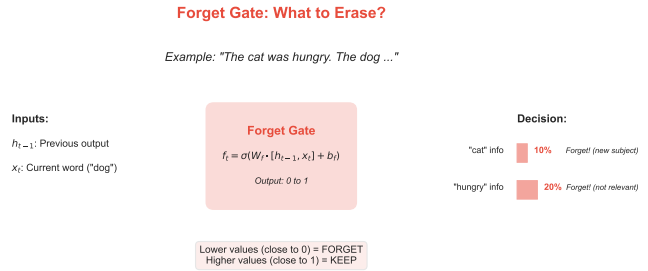
RNN Problem:

- Gradients vanish ($0.5^{50} \approx 0$)
- Forgets early information
- Can't handle long dependencies
- Would lose "cat" by "dog"

LSTM Solution:

- Cell state highway (addition not multiplication)
- Three gates for CONTROL
- Can preserve info for 100+ steps
- Then ERASE when sentence ends

Forget Gate: How We Get That 0.1



Back to Our Table - Row 5:

Word	Forget
"."	**0.1**

What This 0.1 Means:

- 0.0 = forget everything
- 1.0 = keep everything
- 0.1 = forget 90% (keep only 10%)

Why at period?

The Formula That Produces 0.1:

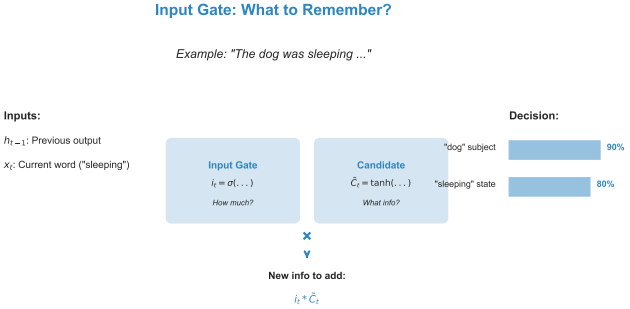
$$f_t = \sigma(W_f \cdot [h_{t-1}, x_t] + b_f)$$

How It Decides:

1. Look at current word (".")
2. Look at previous hidden state
3. Compute weighted sum
4. Apply sigmoid $\longrightarrow$ output 0 to 1

Cell State Update:

Input Gate: How We Get That 0.9



Back to Our Table - Row 7:

Word	Input
"dog"	**0.9**

What This 0.9 Means:

- 0.0 = add nothing
- 1.0 = add everything
- 0.9 = add 90% of candidate

Why at "dog"?

The Formulas (Two Parts):

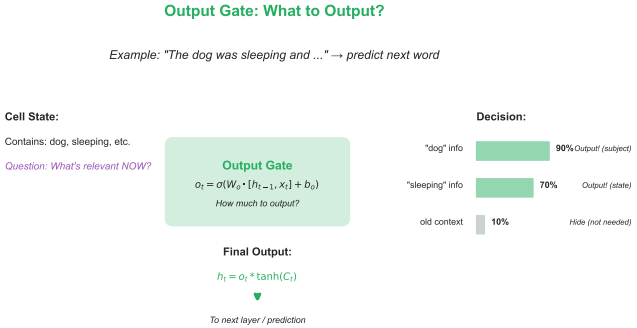
$$i_t = \sigma(W_i \cdot [h_{t-1}, x_t] + b_i)$$

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

How It Works:

1. Create candidate info ($\tilde{C}_t$) with tanh
2. Decide how much to use ($i_t = 0.9$)
3. Multiply: 0.9 × candidate
4. Add to cell state

Output Gate: When to USE Memory



Back to Our Table - Row 8:

Word	Output
"was"	**0.9**

What This 0.9 Means:

- 0.0 = hide everything
- 1.0 = reveal everything
- 0.9 = output 90% of memory

Why at "was"?

The Formulas:

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

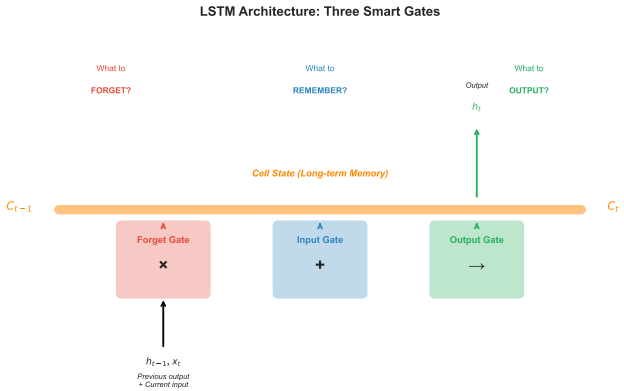
$$h_t = o_t \odot \tanh(C_t)$$

How It Works:

1. Look at cell state (has "dog" info)
2. Decide what's relevant NOW
3. Filter memory through gate (0.9)
4. Send h_t to prediction layer

Key Insight:

The Big Picture: Three Gates Working Together



The Cell State Highway:

- Protected memory channel
- Information flows easily
- Gates control entry/exit
- Gradients don't vanish!

At Each Time Step:

1. **Forget:** Erase old (0.1 → erase "cat")
2. **Input:** Add new (0.9 → add "dog")

Intuition: Visual Analogy

Think of LSTM like a notebook:

- Forget Gate = Eraser
  (Clear old notes at period)
- Input Gate = Pen

Now Look Again - You Understand EVERYTHING!

Sentence: "The cat was hungry. The dog was sleeping."

Word	Forget	Input	Output	What LSTM "Thinks"
The	0.9 (keep)	0.3 (weak)	0.2 (hide)	Article seen, nothing special yet
cat	0.8 (keep)	**0.9** (STORE!)	0.8 (show)	Subject! Important noun!
was	0.9 (keep)	0.7 (add)	0.9 (need!)	Verb connects to cat
hungry	0.8 (keep)	0.8 (add)	0.7 (show)	Describes the cat's state
.	**0.1** (ERASE!)	0.4 (end)	0.3 (hide)	Sentence over! Clear memory!
The	0.1 (clear)	0.8 (new!)	0.2 (hide)	NEW sentence starts fresh
dog	0.7 (keep)	**0.9** (NEW!)	0.9 (use!)	NEW subject! (forgot cat)
was	0.9 (keep)	0.8 (add)	**0.9** (USE!)	Using DOG info for prediction

Checkpoint: The Magic Transition

Watch rows 4→5→6→7: **hungry** → **.** → **The** → **dog**
Memory Evolution: [cat, hungry] → FORGET (0.1) → [end] → ADD (0.9) → [dog]
This intelligent memory control is what RNNs cannot do! LSTM uses gates to:

- Preserve important info (0.9 on subject nouns)
- Erase when context changes (0.1 at sentence boundaries)
- Reveal info when needed (0.9 output for predictions)

Summary: From Table to Understanding

Your Learning Journey:

1. **Observed:** Patterns in the table
   (0.1 at period, 0.9 on important words)
2. **Understood WHY:** Vanishing gradients
   (RNNs can't remember long-term)
3. **Learned HOW:** Gate equations
   (Sigmoid produces those 0.1 and 0.9 values)
4. **Mastered:** Complete picture
   (Gates control memory intelligently)

Key Equations:

$$f_t = \sigma(W_f[h_{t-1}, x_t] + b_f)$$
$$i_t = \sigma(W_i[h_{t-1}, x_t] + b_i)$$
$$o_t = \sigma(W_o[h_{t-1}, x_t] + b_o)$$
$$C_t = f_t \odot C_{t-1} + i_t \odot \tilde{C}_t$$
$$h_t = o_t \odot \tanh(C_t)$$

Real World: Where LSTMs Excel

Applications (2015-2020):

- Machine Translation (Google Translate)
- Speech Recognition (Siri, Alexa)
- Text Generation (early GPT)
- Video Analysis
- Music Generation
- Handwriting Recognition

Modern Context (2024):
Transformers now dominate NLP, but LSTMs:

- Still used in time series
- Efficient for streaming data
- Foundation for understanding attention

The Core Insight:
That table showed you *exactly* how gates work. Every 0.1 and 0.9 has a purpose. That's the real magic of LSTMs!

Questions?