

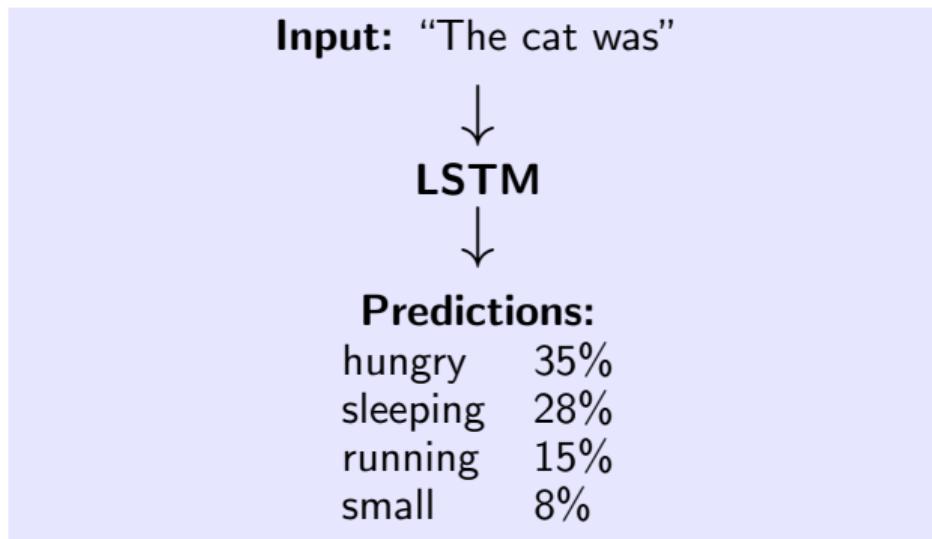
# LSTM - Long Short-Term Memory

## Understanding Through a Complete Example

# What Is This About?

## The Core Task: Predict the Next Word

Simple Example:



How does it work?

Must remember "cat" to predict appropriate adjective/verb!

Why This Matters:

- **Autocomplete**

Your phone keyboard

- **Translation**

Google Translate (2016)

- **Text Generation**

Write stories, code

- **Voice Assistants**

Siri, Alexa

- **Chatbots**

Customer service

### Checkpoint: The Challenge

To predict well, the model must REMEMBER earlier words in the sentence.

That's what LSTM does brilliantly!

# The Challenge and The Solution

## THE PROBLEM

### RNNs Cannot Remember

- Vanishing gradients
- $0.5^{50} \approx 0$  (information dies)
- Forgets early context
- Cannot handle long sentences

#### Example:

*"I grew up in Paris. I speak fluent ..."*

RNN forgets "Paris" after 20 words

Cannot predict "French"

## THE SOLUTION

### LSTM Controls Memory

- Three gates (0-1 values)
- Addition path (not multiplication)
- Preserves gradients
- Remembers 100+ steps

#### The Method:

##### Three Independent Gates:

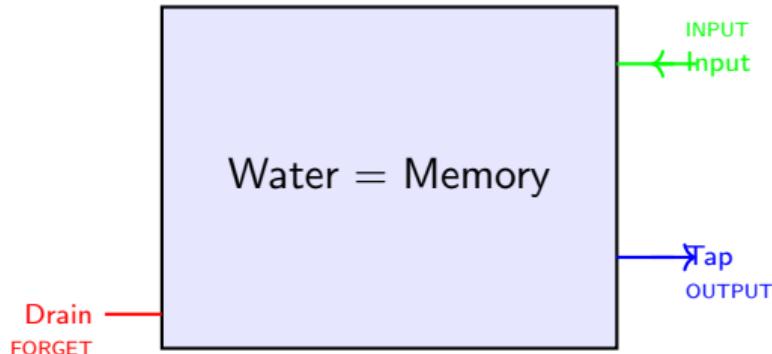
- **FORGET**: What to erase
- **INPUT**: What to add
- **OUTPUT**: What to use

Let's see how this works with a simple analogy...

# Understanding The Idea: Water Tank Analogy

## Think of Memory as a Water Tank with Three Valves

### The Tank System:



#### How Each Valve Works:

##### FORGET = Drain Valve

Controls how much water flows OUT

0.1 = Open 10% → 90% drains away

Removes old water (old memory)

##### INPUT = Input Valve

Controls how much new water flows IN

0.9 = Open 90% → lots added

Adds fresh water (new memory)

##### OUTPUT = Outout Tap

### Real Examples:

At period “.” in sentence:

- Drain: 90% (0.1 forget)
- Input: 40% (0.4 input)
- Tap: 30% (0.3 output)

→ Tank mostly empties!

At noun “dog”:

- Drain: 30% (0.7 forget)
- Input: 90% (0.9 input)
- Tap: 90% (0.9 output)

→ Tank fills up!

### Intuition: The Key Insight

Three INDEPENDENT valves on ONE tank!

Each valve controls a different aspect:

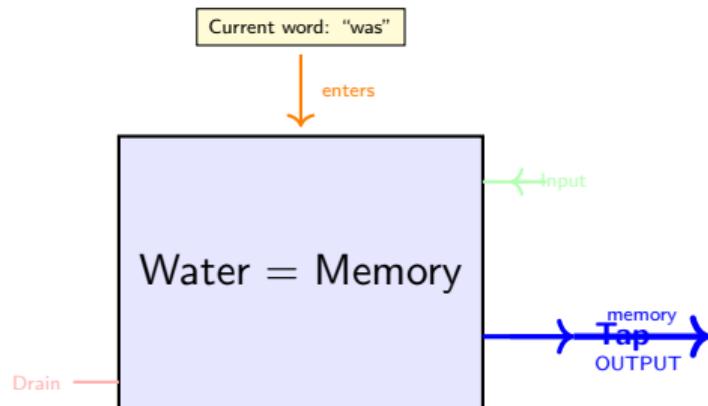
- **Drain:** How much OLD to remove
- **Input:** How much NEW to add
- **Tap:** How much to USE now

This is EXACTLY what LSTM does!

# Where Does The Tap Water Go?

## Continuing The Analogy: From Tank to Predictions

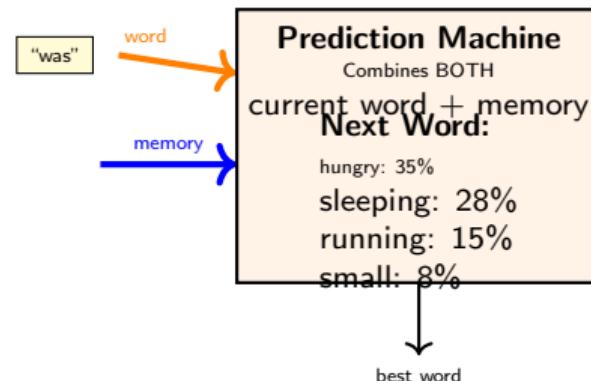
The Complete System:



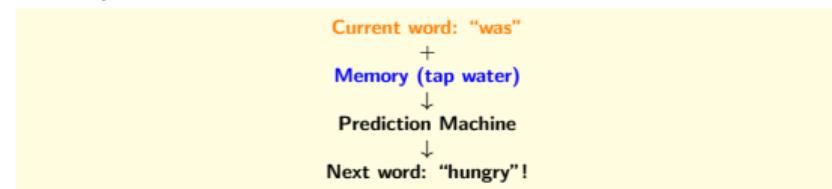
Two Things Happening:

- Current word enters system
- Memory (tap water) flows out
- BOTH go to prediction!

Where They Go:



The Complete Flow:



Checkpoint: Key Insight!

# What Are “Gates”?

**Three Gates Control Memory Like Volume Knobs (0 to 1)**

**FORGET**



**REMOTES**  
old information

Value 0-1:

- 0.0 = erase all
- 0.5 = keep half
- 1.0 = keep all

**Example:**  
0.1 at period  
→ Erase 90%!

**INPUT**



**ADDS**  
new information

Value 0-1:

- 0.0 = add nothing
- 0.5 = add half
- 1.0 = add all

**Example:**  
0.9 on "cat"  
→ Store lots!

**OUTPUT**



**REVEALS**  
stored information

Value 0-1:

- 0.0 = hide all
- 0.5 = show half
- 1.0 = show all

**Example:**  
0.9 at "was"  
→ Use memory!

## How They Work Together:

$$\text{New Memory} = (\text{Forget} \times \text{Old Memory}) + (\text{Input} \times \text{New Info})$$
$$\text{Output} = \text{Output Gate} \times \text{Memory}$$

Now let's see these gates in action with concrete numbers...

# The 4-Step Process (Part 1): Erase Old, Add New

## Updating Memory From “cat” to “dog”

### Starting Point:

Old Memory: [0.8, 0.6, 0.4]

Contains “cat” information

### Step 1: FORGET Gate = 0.1

**What it does:** Multiply old memory by 0.1

$$[0.8, 0.6, 0.4] \times 0.1 = [0.08, 0.06, 0.04]$$

**Result:** 90% erased! “cat” mostly removed.

**Why?** At period, we need fresh start for new sentence.

### Step 2: INPUT Gate = 0.9

**What it does:** Filter new candidate info

Create candidate: [0.7, 0.5, 0.9]

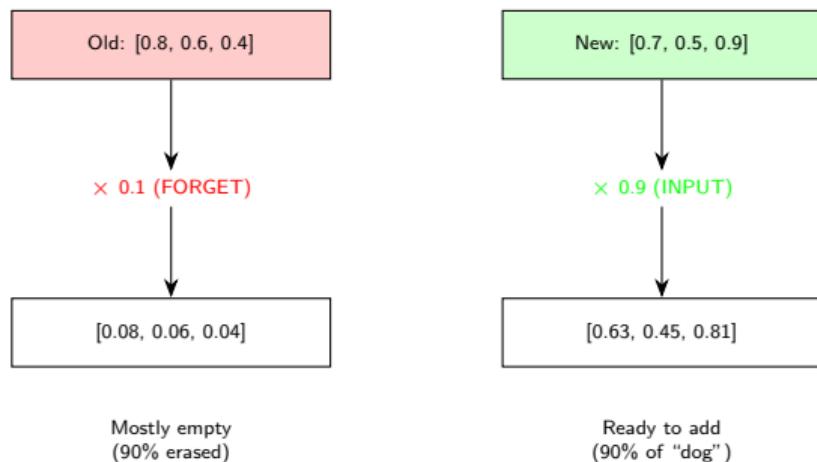
Multiply by 0.9:  $[0.7, 0.5, 0.9] \times 0.9$

$$= [0.63, 0.45, 0.81]$$

**Result:** 90% of “dog” info ready to add.

**Why?** “dog” is new subject, very important!

### Visual Flow (Steps 1-2):



### Checkpoint: Key Point

Two INDEPENDENT operations:

- FORGET decides what OLD to keep
- INPUT decides what NEW to add
- They don't interfere!

# The 4-Step Process (Part 2): Combine and Use

## From Separate Results to Final Output

### Where We Left Off:

- Erased old: [0.08, 0.06, 0.04]
- Filtered new: [0.63, 0.45, 0.81]

### Step 3: COMBINE (Addition!)

**What it does:** Add the two results together

$$[0.08, 0.06, 0.04] + [0.63, 0.45, 0.81] \\ = [0.71, 0.51, 0.85]$$

**Result:** Updated memory = “dog” info

**Why addition?** Preserves gradients! This is the key innovation that prevents vanishing.

### Step 4: OUTPUT Gate = 0.9

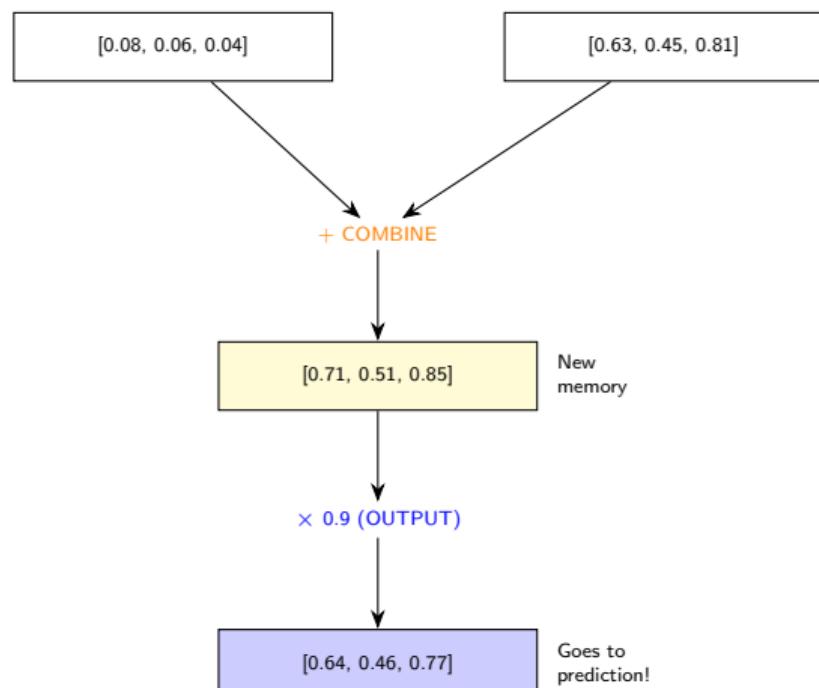
**What it does:** Filter what network sees

$$[0.71, 0.51, 0.85] \times 0.9 \\ = [0.64, 0.46, 0.77]$$

**Result:** 90% revealed to next layer

**Why?** At “was”, we NEED subject info for verb prediction!

### Visual Flow (Steps 3-4):



# What Do We Do With The Output?

## From Hidden State to Prediction

### Recap: Output Gate Result

From Step 4: [0.64, 0.46, 0.77]

This is the **hidden state**  $h_t$

### Where Does It Go?

#### ① To Prediction Layer

$h_t \rightarrow \text{Linear} \rightarrow \text{Softmax} \rightarrow \text{Probabilities}$

Example at "was": Predict next word

#### ② To Next Time Step

$h_t$  feeds into next LSTM cell

Used to compute next gates

#### ③ Optional: To Attention

In seq2seq models, decoder attends to these  $h_t$  values

### Key Distinction:

- $C_t$  = Long-term memory (protected)
- $h_t$  = Working memory (filtered output)

Now let's see why we need three separate gates...

### Concrete Example:

At word "was" in "The dog was sleeping":

Memory  $C_t$  contains: [dog, context]

Output gate: 0.9 (reveal 90%)

Hidden state  $h_t$ : [0.64, 0.46, 0.77]

Prediction layer receives  $h_t$ :

$h_t \rightarrow \text{Linear}(512 \rightarrow \text{vocab}) \rightarrow \text{Softmax}$

Top predictions:

- "sleeping": 0.35 (verb matches dog)
- "running": 0.18
- "eating": 0.12

The subject info ("dog") in  $h_t$  helps predict appropriate verb!

### Intuition: Why Filter?

Not all memory is relevant NOW.

Examples:

- At "The": Output gate low (0.2) → hide memory, article doesn't need context
- At "was": Output gate high (0.9) → reveal memory, verb needs subject!

The OUTPUT gate is smart about WHEN to use memory.

# Why Three Separate Gates? Real Scenarios

## Reading: “The cat sat. The dog...”

### Scenario 1: At “cat”

#### Gate Values:

- F = 0.8 (keep)
- I = 0.9 (STORE!)
- O = 0.8 (show)

#### What Happens:

- Keep previous context
- STORE subject strongly
- Show it to network

#### Goal:

Remember “cat” for rest of sentence

#### Memory:

→ [cat, context]

### Scenario 2: At “.”

#### Gate Values:

- F = 0.1 (ERASE!)
- I = 0.4 (small)
- O = 0.3 (HIDE)

#### What Happens:

- ERASE old sentence
- Small punctuation add
- HIDE memory

#### Goal:

Clean slate for new sentence

#### Memory:

→ [mostly empty]

### Scenario 3: At “dog”

#### Gate Values:

- F = 0.7 (keep some)
- I = 0.9 (NEW!)
- O = 0.9 (REVEAL!)

#### What Happens:

- Keep some context
- STORE new subject
- REVEAL all info

#### Goal:

New focus, need it NOW

#### Memory:

→ [dog, some context]

#### Key Insight: Each situation needs DIFFERENT gate values!

That's why LSTM has three independent gates, not just one.

The network LEARNS which values to use for each word.

Now let's watch these gates in action on a real sentence...

# 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

Notice the patterns? Let's explore what you observed...

# What Did You Notice?

## Common Observations:

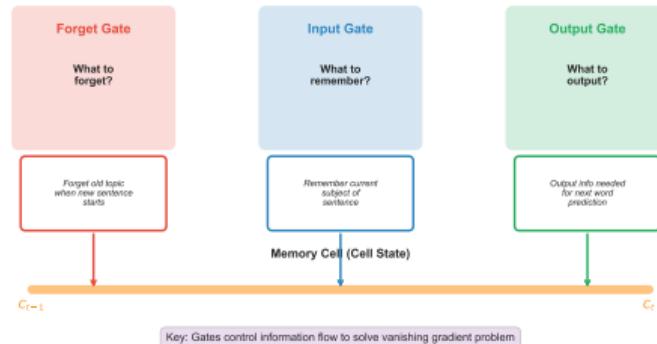
Students usually notice:

- “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?

LSTM Solution: Three Smart Gates



## 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?

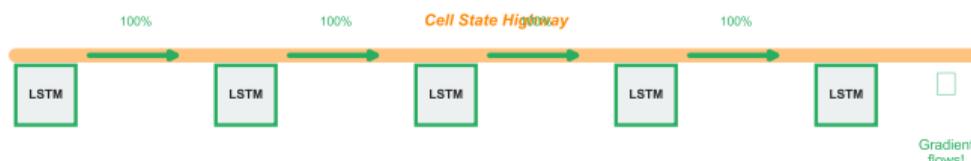
## The Vanishing Gradient Problem

Standard RNN:



Gradient vanishes!

LSTM:



Gradient flows!

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"

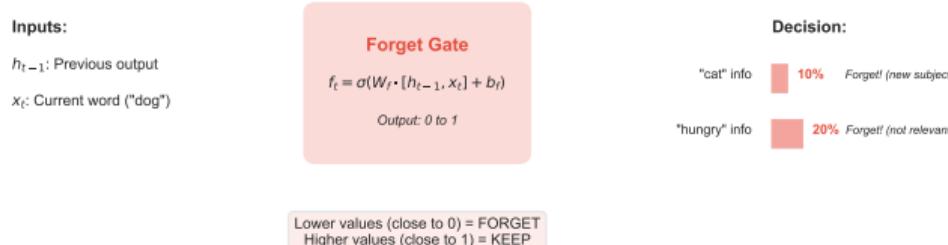
LSTM Solution:

- 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

## Forget Gate: What to Erase?

Example: "The cat was hungry. The dog ..."



Intuition: When you see "dog", forget information about "cat"

Back to Our Table - Row 5:

Word	Forget
"."	<b>0.1</b>

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  $\rightarrow$  output 0 to 1

Cell State Update:

# Input Gate: How We Get That 0.9

## Input Gate: What to Remember?

Example: "The dog was sleeping ..."

### Inputs:

- $h_{t-1}$ : Previous output
- $x_t$ : Current word ("sleeping")



### Decision:



### New info to add:

$$i_t * \tilde{C}_t$$

Intuition: Remember "dog is sleeping" for future predictions

Back to Our Table - Row 7:

Word	Input
"dog"	0.9

### The Formulas (Two Parts):

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

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

What This 0.9 Means:

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

Why at "dog"?

### How It Works:

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

# Output Gate: When to USE Memory

## Output Gate: What to Output?

Example: "The dog was sleeping and ..." → predict next word

### Cell State:

Contains: dog, sleeping, etc.

Question: What's relevant NOW?

### Output Gate

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

How much to output?

### Decision:

"dog" info  90% Output (subject)

"sleeping" info  70% Output (state)

old context  10% Hide (not needed)

### Final Output:

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



To next layer / prediction

Intuition: Only share relevant parts of memory for current prediction

Back to Our Table - Row 8:

Word	Output
"was"	0.9

### The Formulas:

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

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

What This 0.9 Means:

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

Why at "was"?

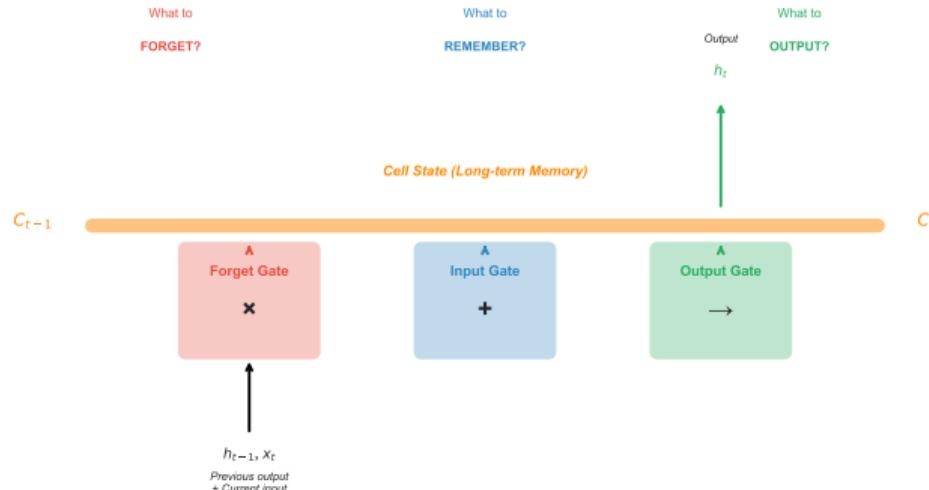
### How It Works:

- Look at cell state (has "dog" info)
- Decide what's relevant NOW
- Filter memory through gate (0.9)
- Send  $h_t$  to prediction layer

### Key Insight:

# The Big Picture: Three Gates Working Together

## LSTM Architecture: Three Smart Gates



### The Cell State Highway:

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

### At Each Time Step:

- Forget:** Erase old ( $0.1 \rightarrow$  erase "cat")
- Input:** Add new ( $0.9 \rightarrow$  add "dog")

### Intuition: Visual Analogy

Think of LSTM like a notebook:

- Forget Gate** = Eraser  
(Clear old notes at period)
- Input Gate** = Pen  
(Only write new notes)

# 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 **Intuition:** Water tank analogy  
(Three valves on one tank)
- ② **Concepts:** What gates are  
(Volume knobs from 0 to 1)
- ③ **Mechanics:** How they work  
(4-step process with real numbers)
- ④ **Usage:** What happens to output  
(Hidden state → prediction layer)
- ⑤ **Mastery:** Complete understanding  
(Table makes perfect sense now!)

## 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?