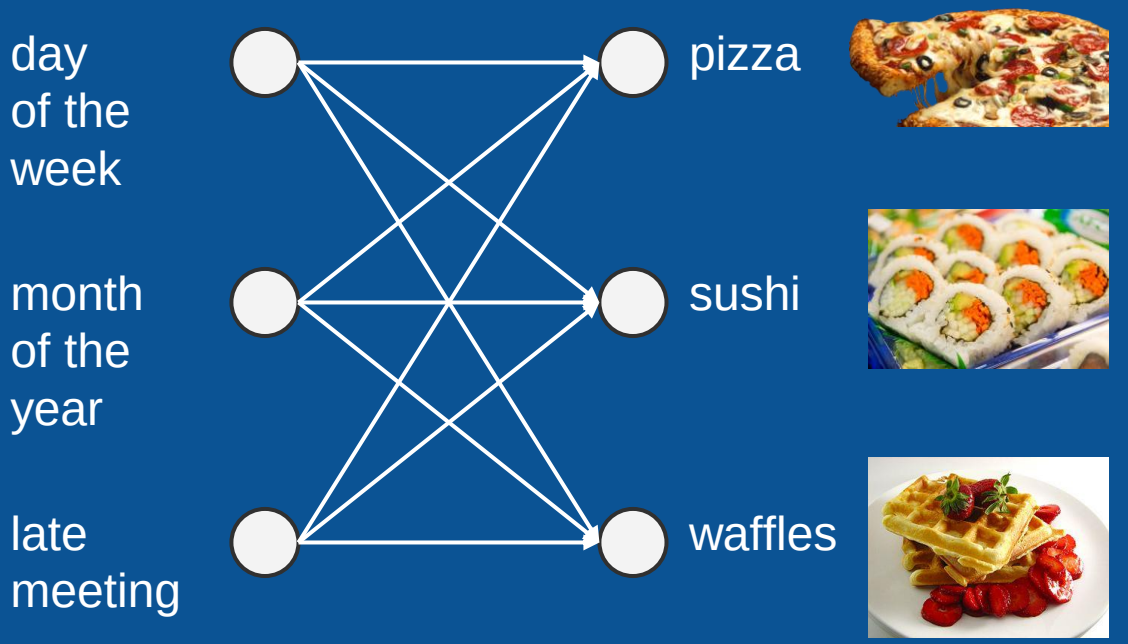
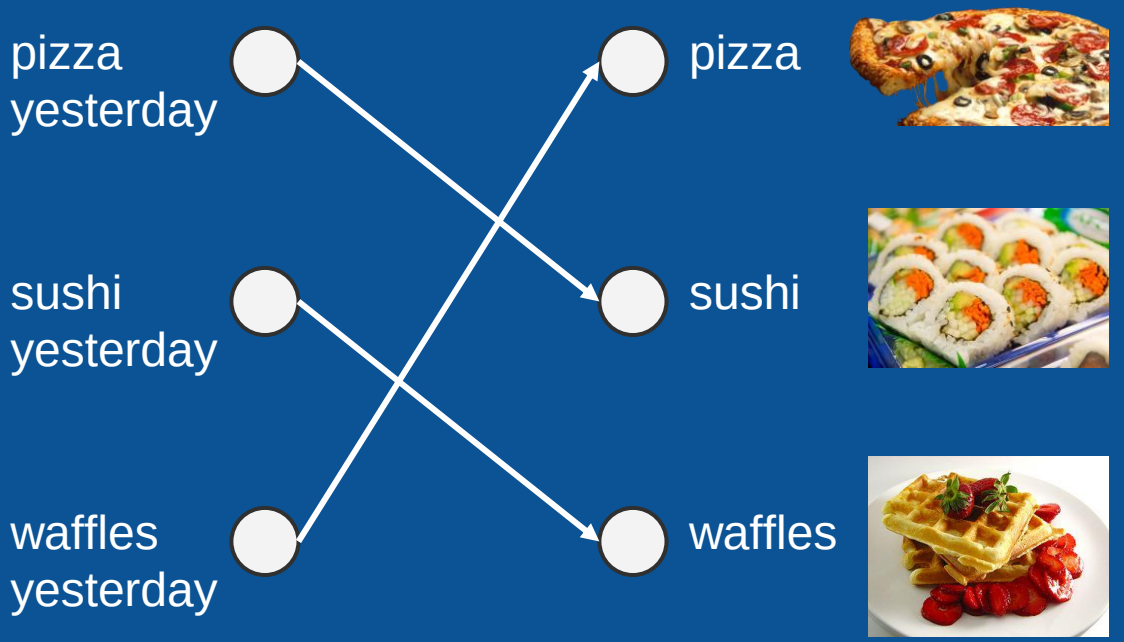
How Long Short-Term Memory (LSTM) and Recurrent Neural Networks (RNNs) work

Brandon Rohrer

What’s for dinner?



What’s for dinner?




predicted pizza for yesterday
predicted sushi for yesterday
predicted waffles for yesterday
pizza yesterday
sushi yesterday
waffles yesterday
pizza
sushi
waffles

A vector is a list of values

“High is 67 F.
Low is 43 F.
Wind is 13 mph.
.25 inches of rain.
Relative humidity
is 83%.”

=

High temperature	67
Low temperature	43
Wind speed	13
Precipitation	.25
Humidity	.83

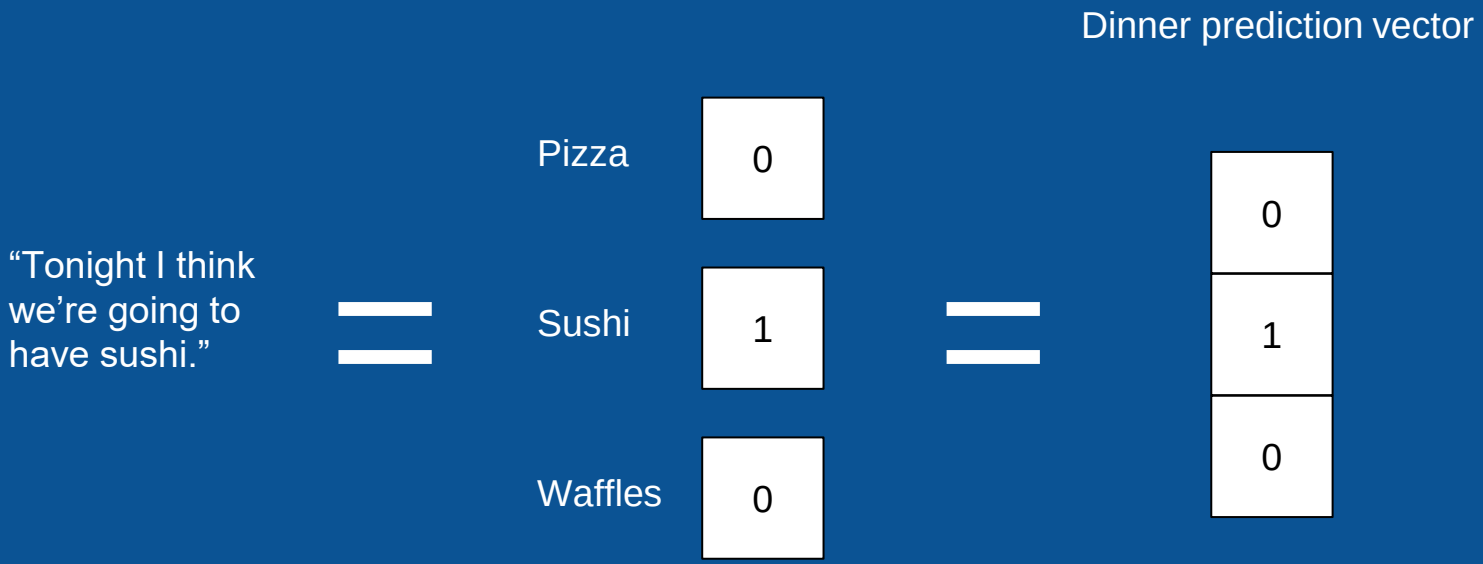
=

Weather vector

67
43
13
.25
.83

A vector is a list of values

A vector is a list of values



predicted pizza for yesterday

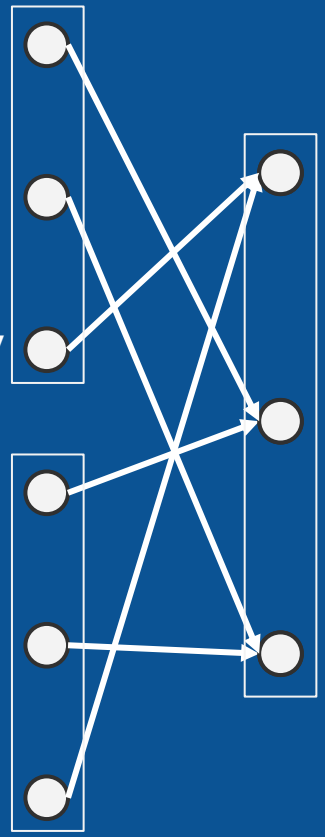
predicted sushi for yesterday

predicted waffles for yesterday

pizza yesterday

sushi yesterday

waffles yesterday



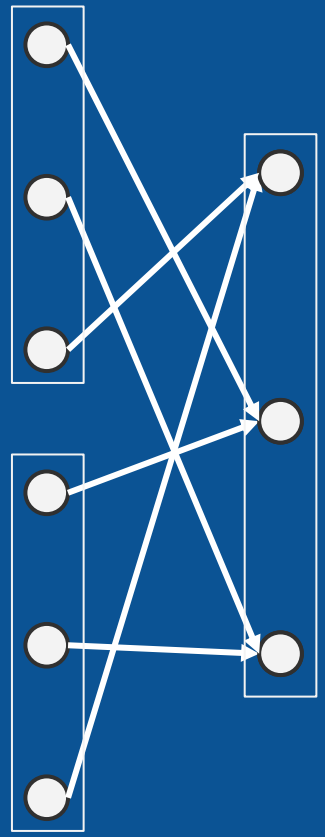
pizza

sushi

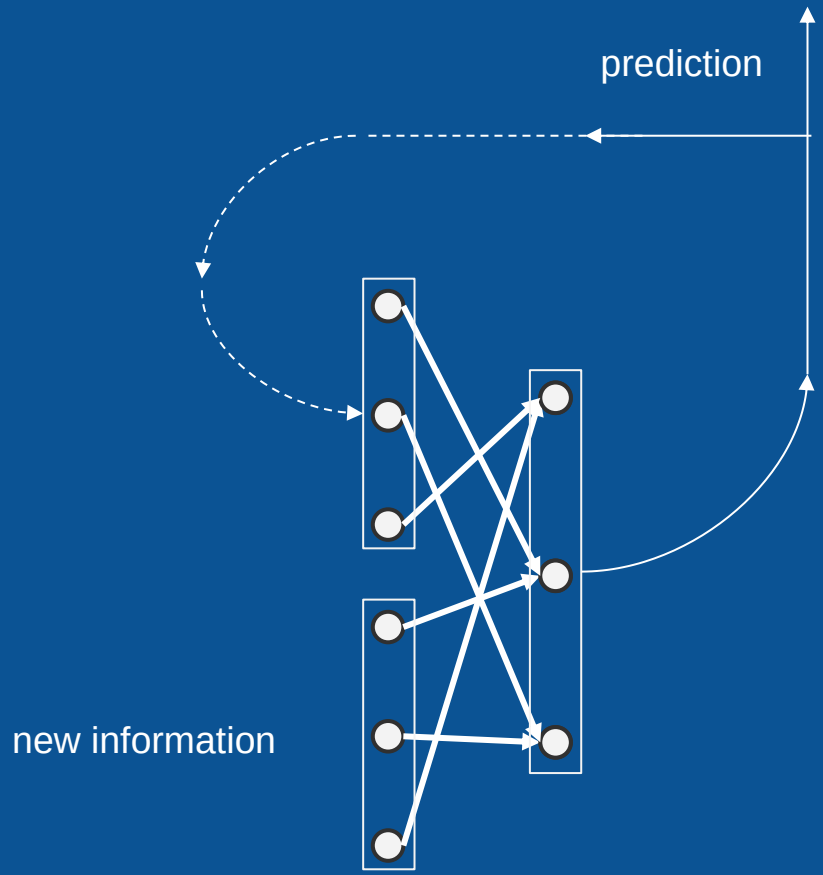
waffles

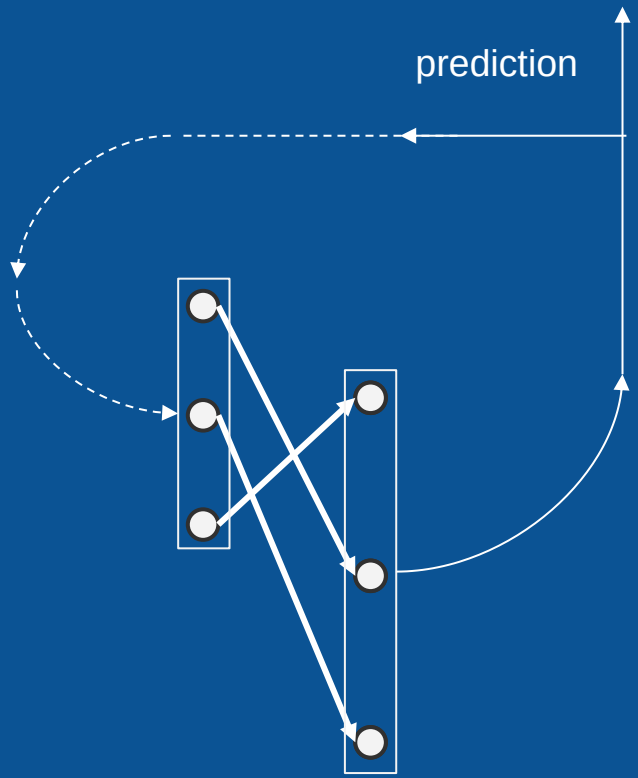
predictions for yesterday

dinner yesterday

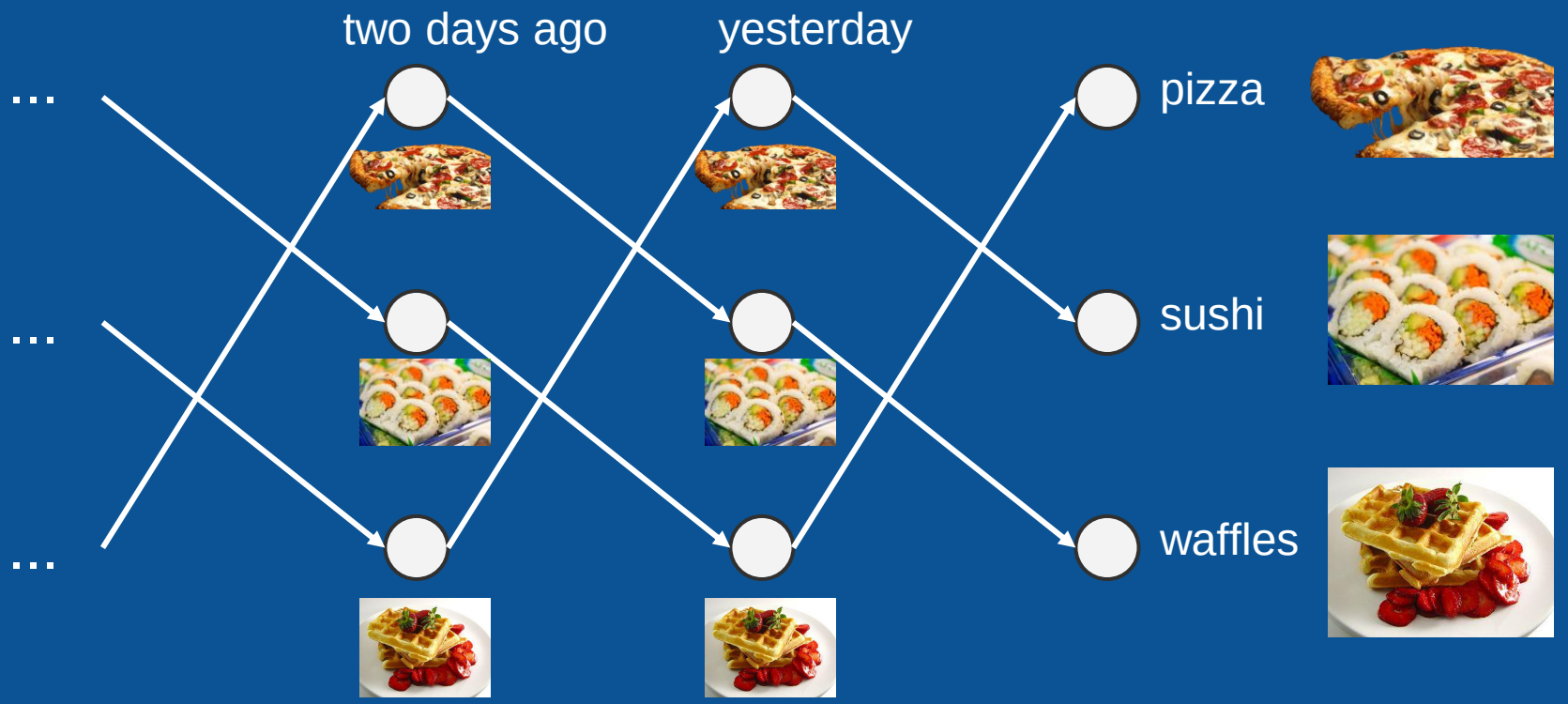


prediction for today


prediction
new information


prediction

Unrolled predictions



Write a children’s book

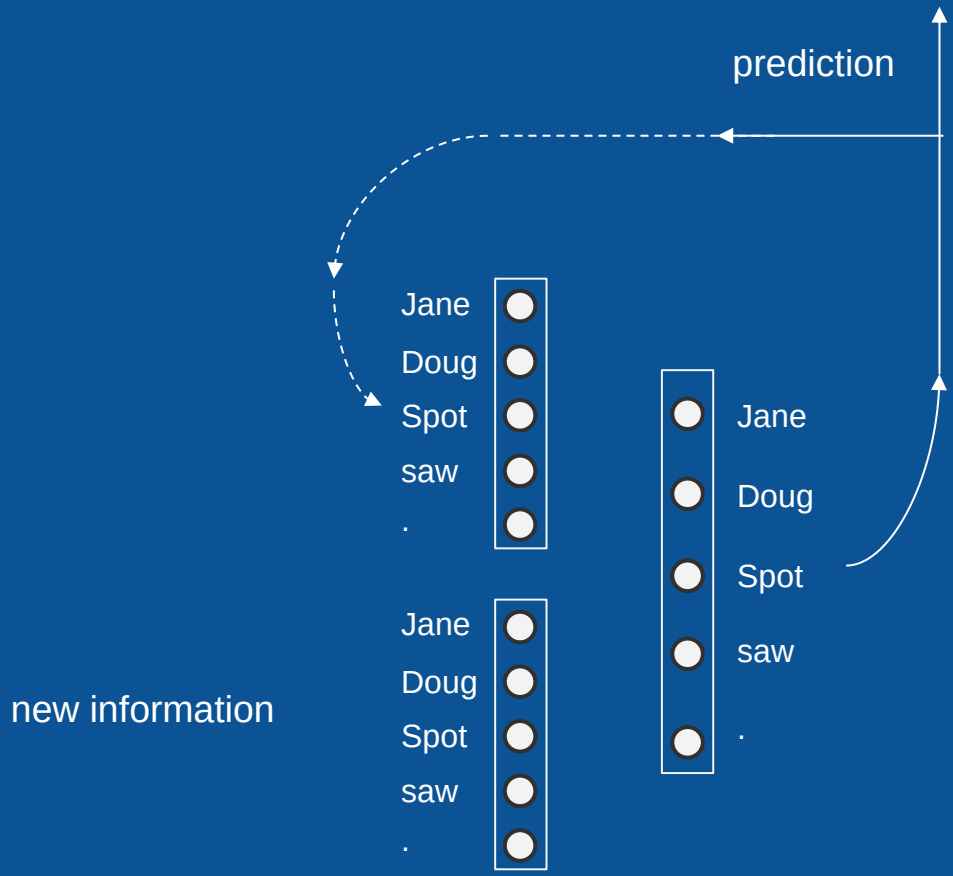
Doug saw Jane.

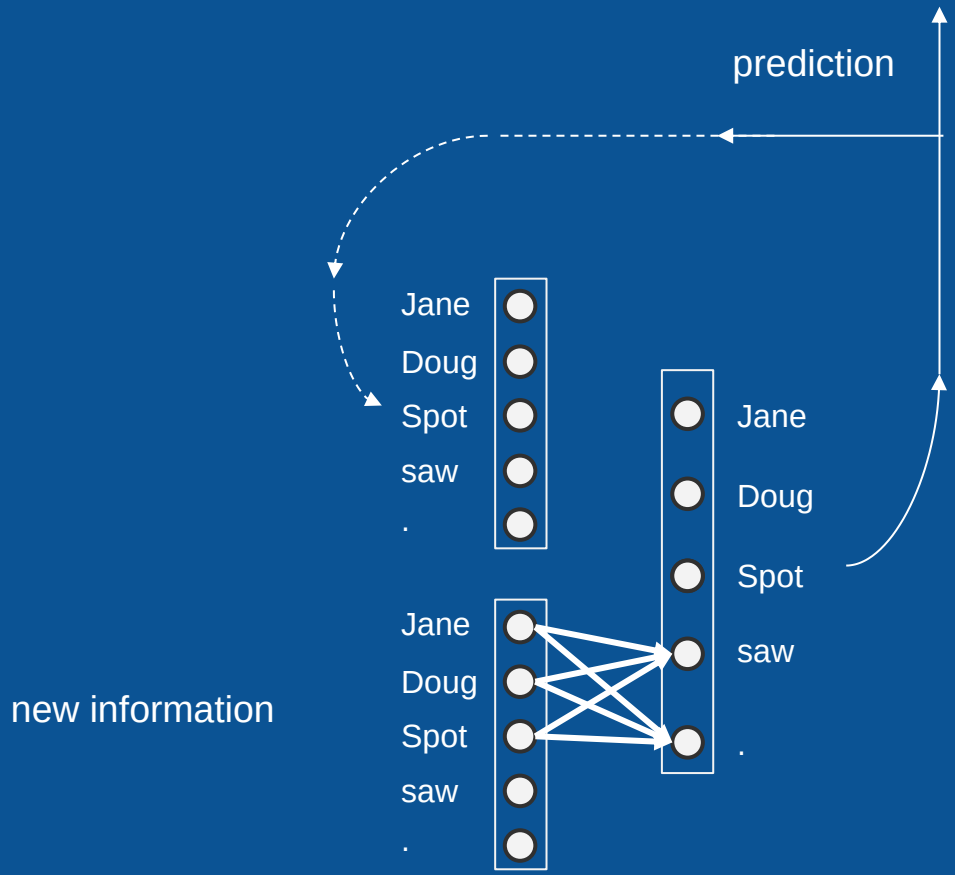
Jane saw Spot.

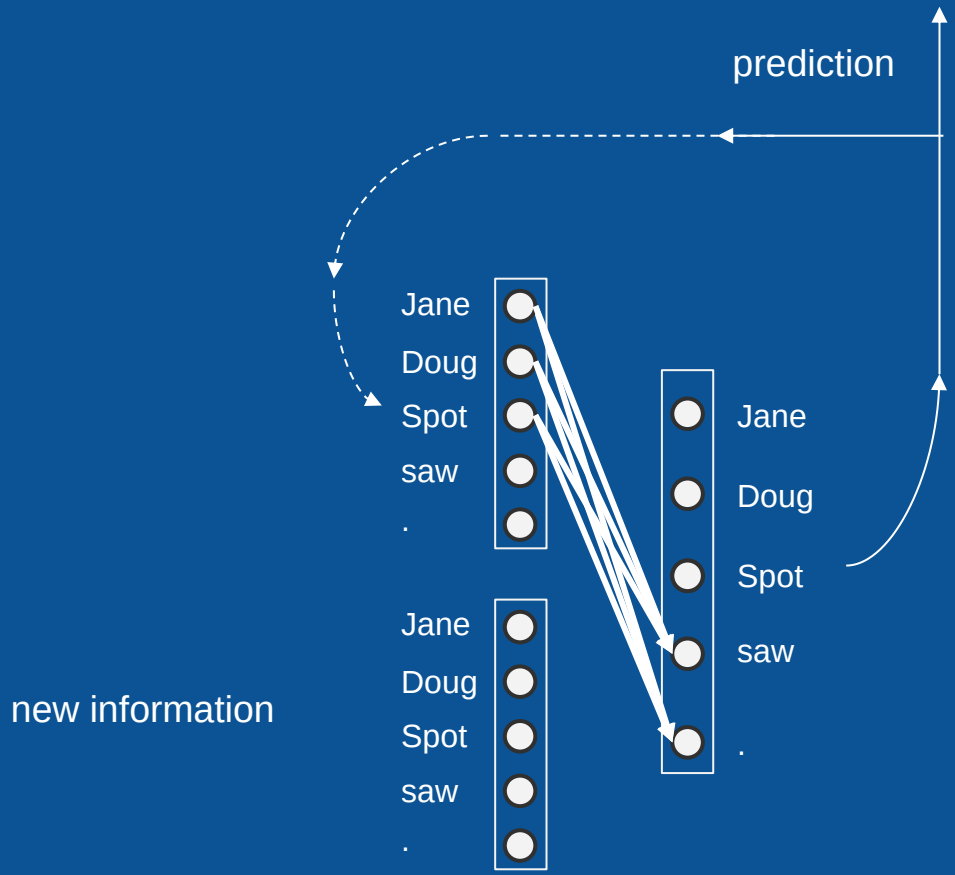
Spot saw Doug.

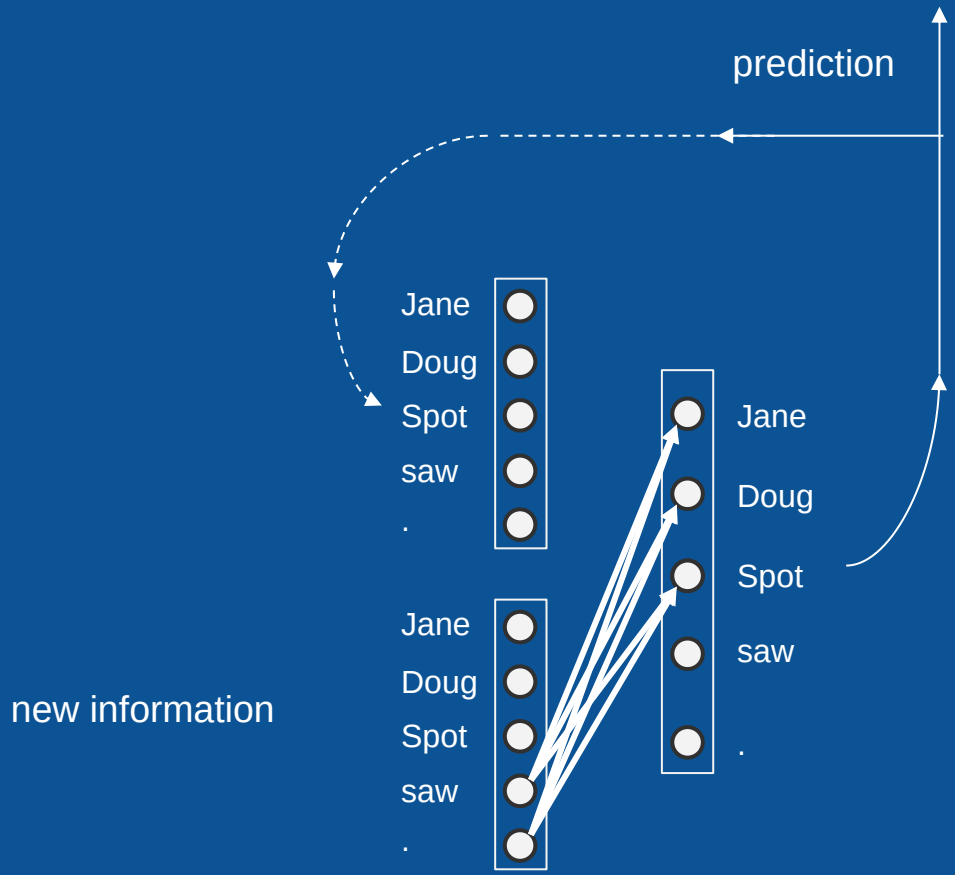
...

Your dictionary is small: {Doug, Jane, Spot, saw, .}

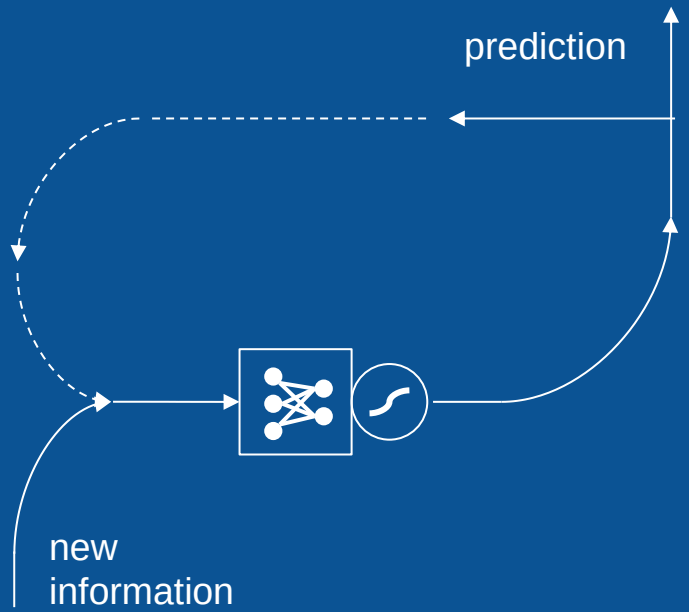

prediction
Jane
Doug
Spot
saw
.
Jane
Doug
Spot
saw
.
Jane
Doug
Spot
saw
.
new information


prediction
Jane
Doug
Spot
saw
.
Jane
Doug
Spot
saw
.
Jane
Doug
Spot
saw
.
new information

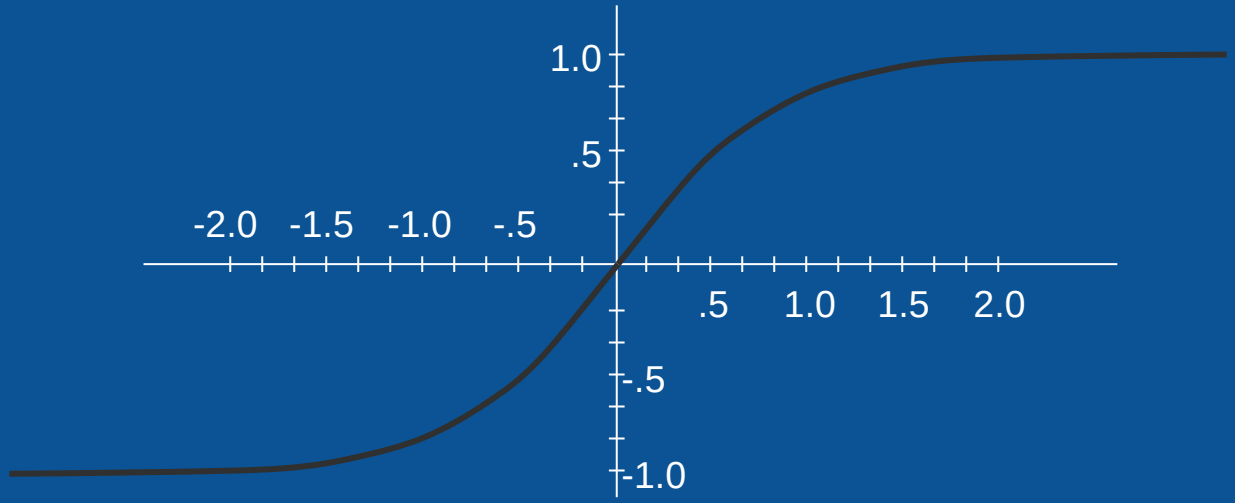

prediction
Jane
Doug
Spot
saw
.
Jane
Doug
Spot
saw
.
Jane
Doug
Spot
saw
.
new information


prediction
Jane
Doug
Spot
saw
.
Jane
Doug
Spot
saw
.
Jane
Doug
Spot
saw
.
new information

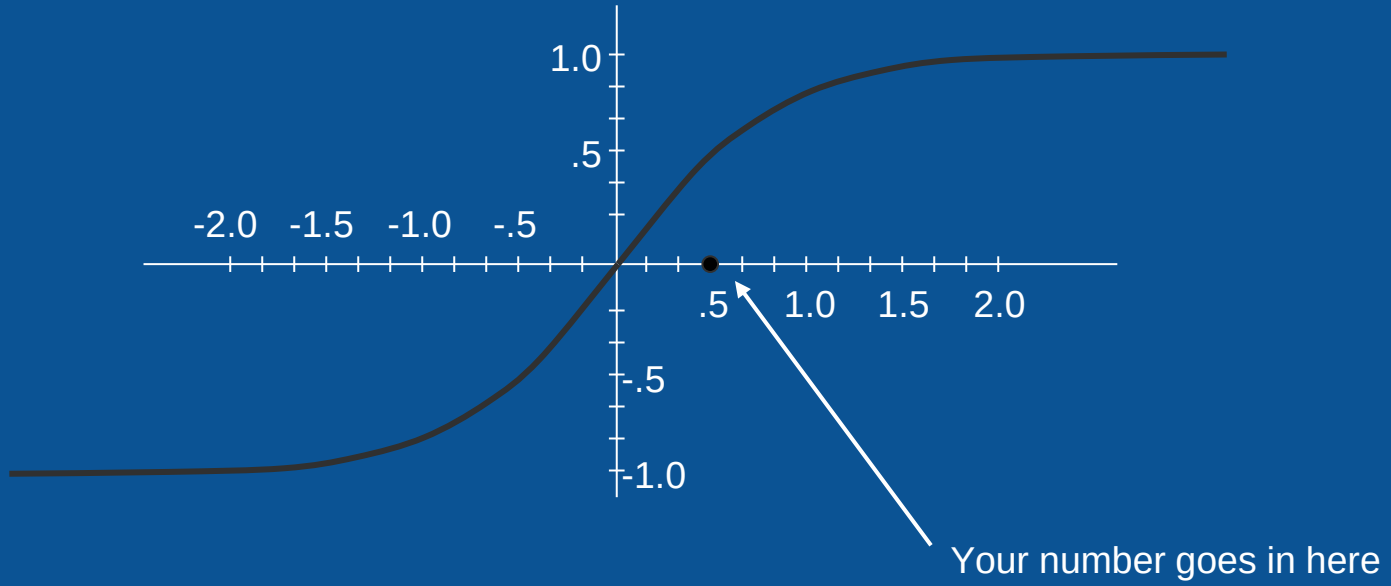
recurrent neural network



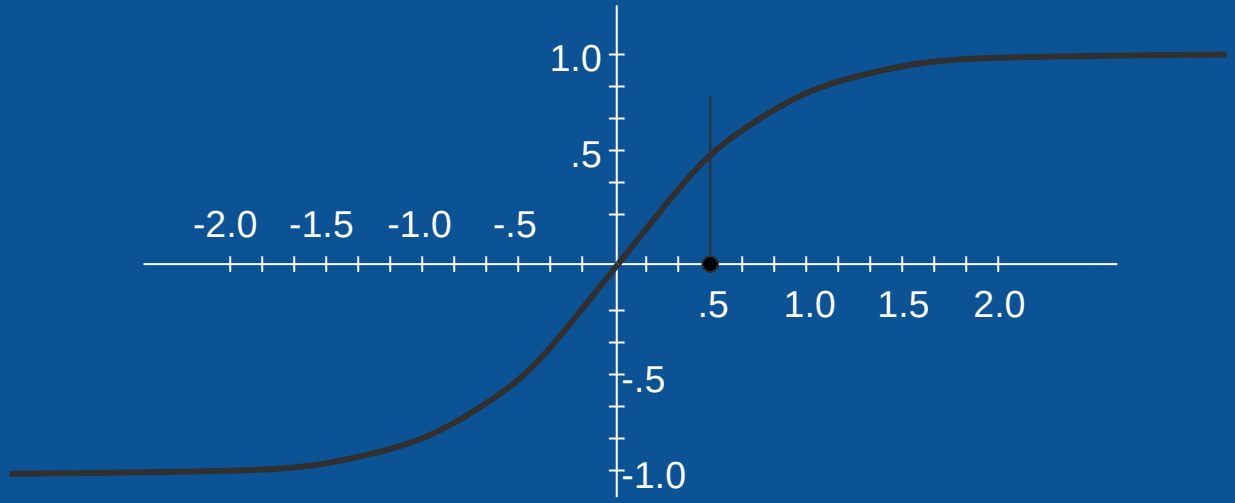
Hyperbolic tangent (tanh) squashing function



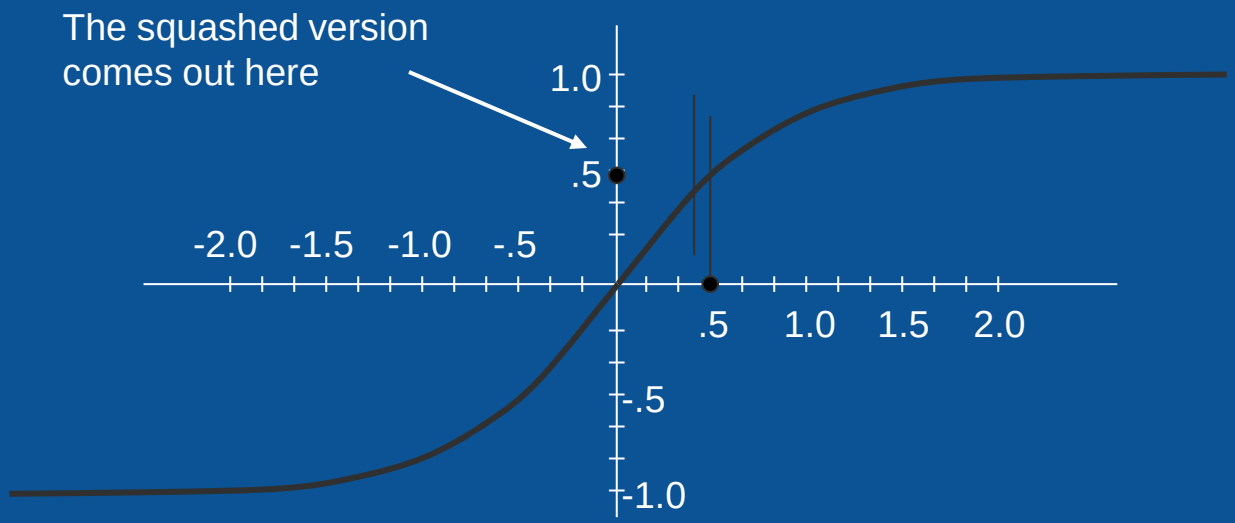
tanh squashing function



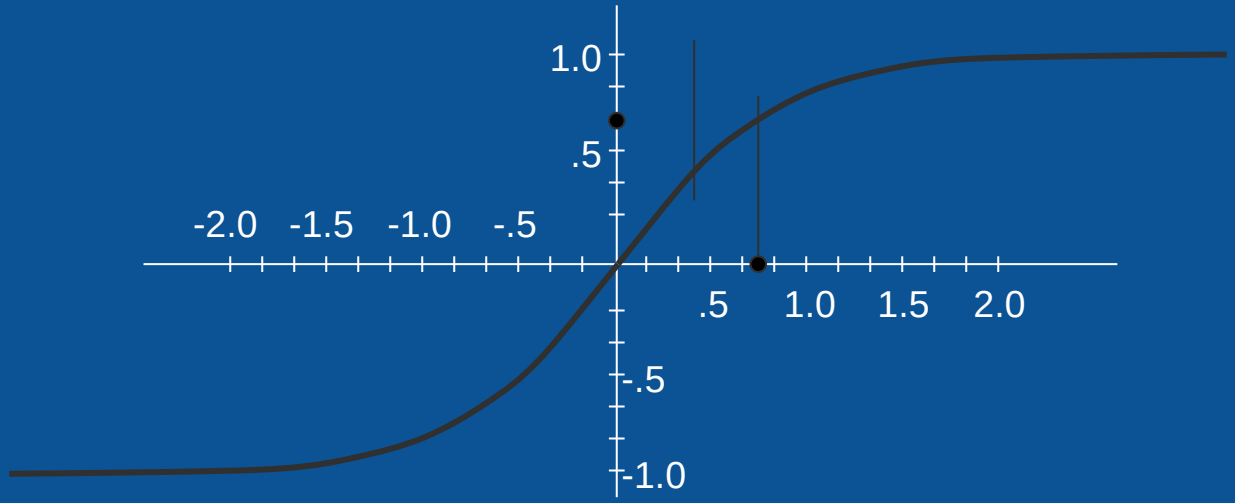
tanh squashing function



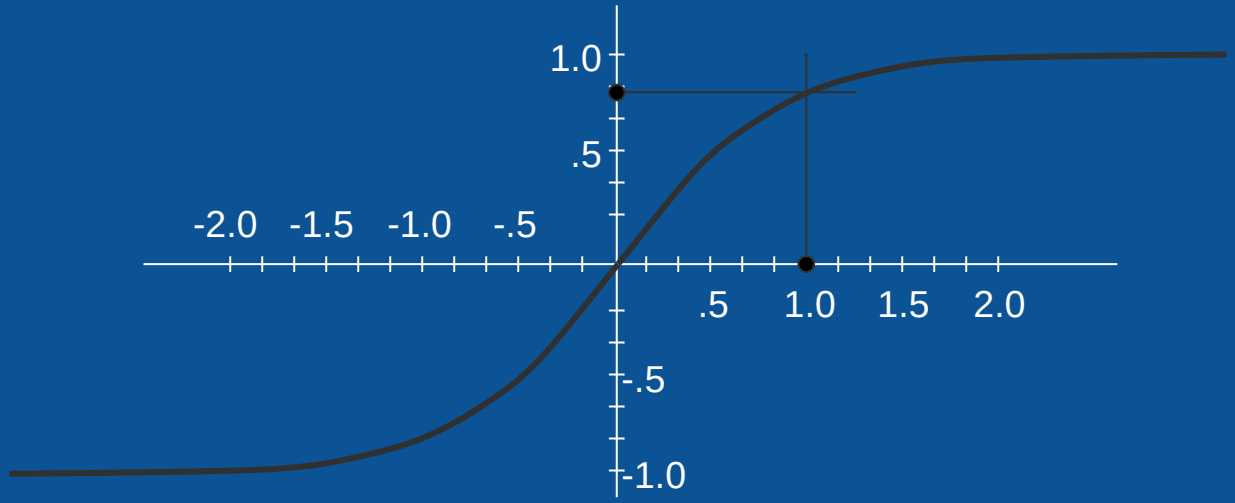
tanh squashing function



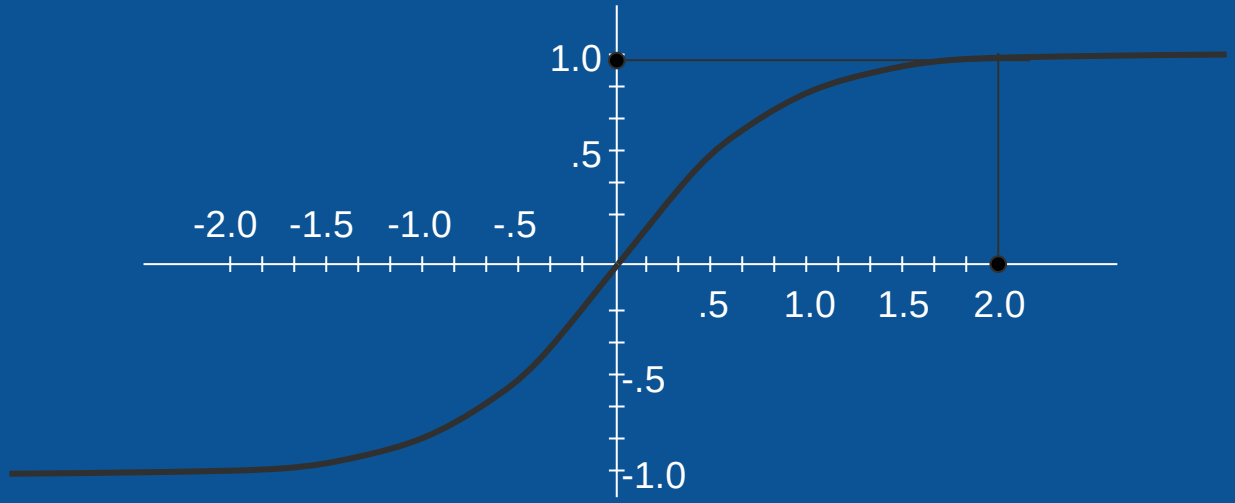
tanh squashing function



tanh squashing function

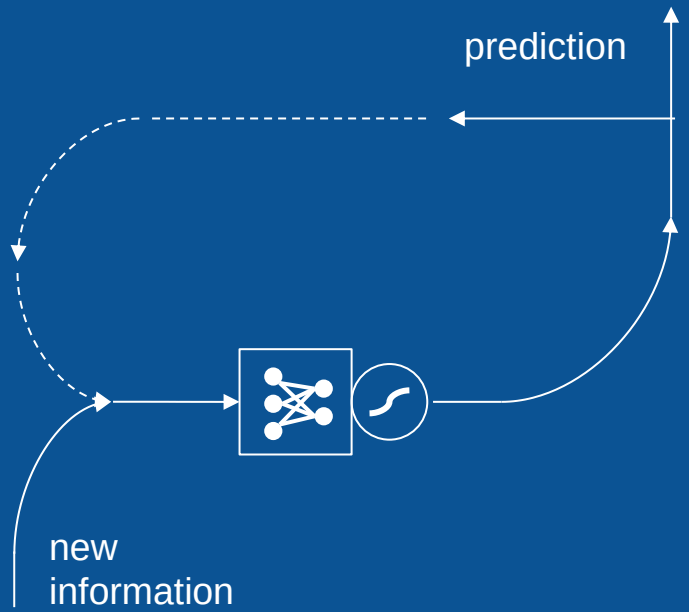


tanh squashing function



No matter what you start with, the answer stays between -1 and 1.

recurrent neural network



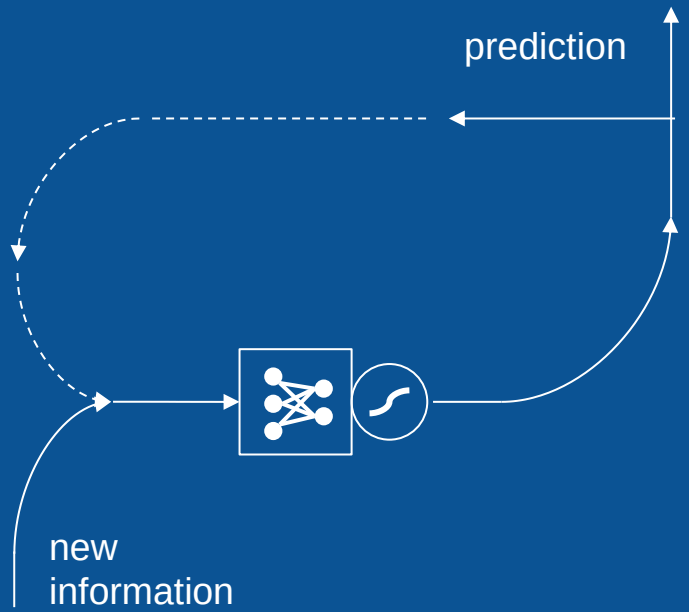
Mistakes an RNN can make

Doug saw Doug.

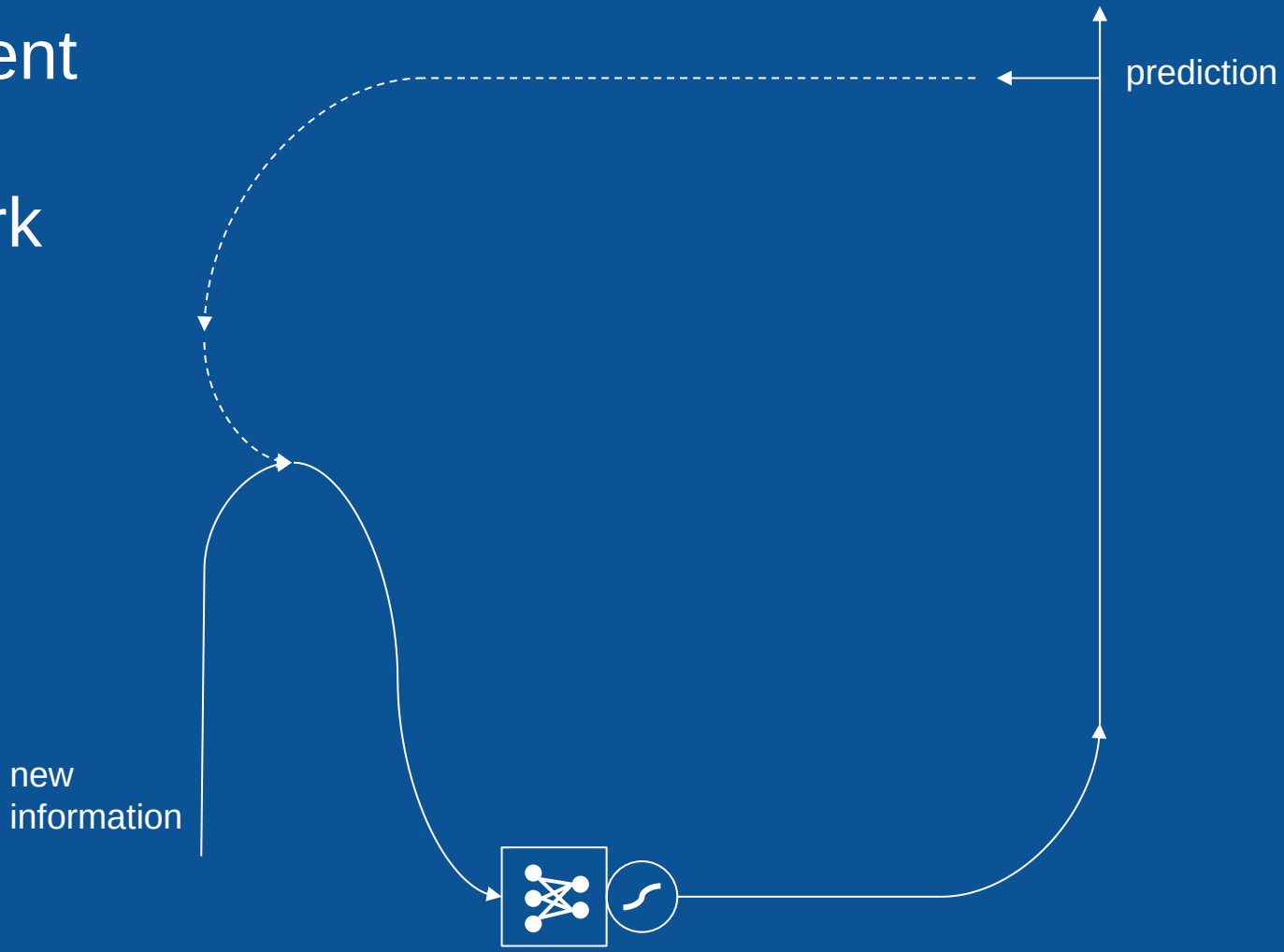
Jane saw Spot saw Doug saw …

Spot. Doug. Jane.

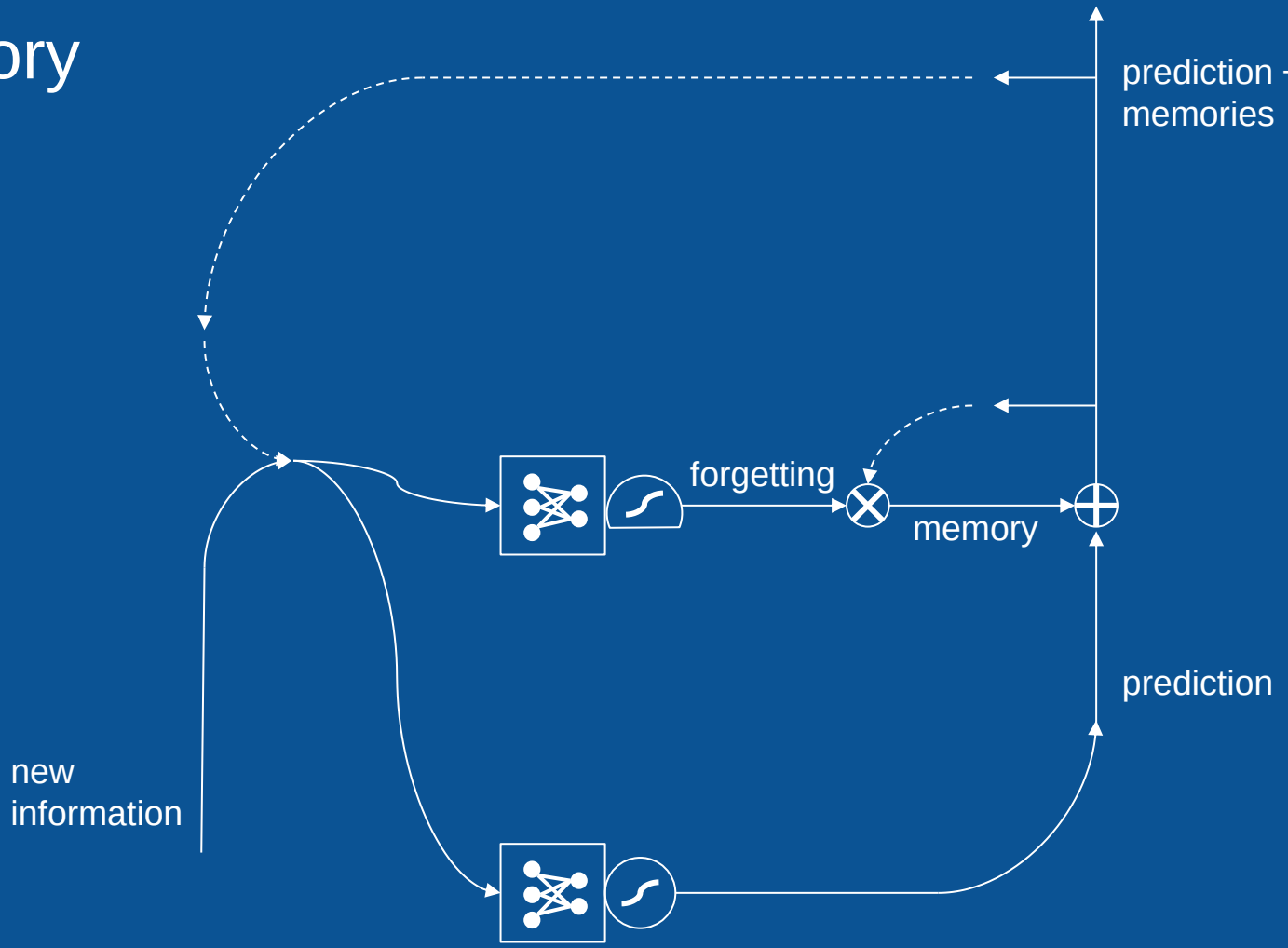
recurrent neural network



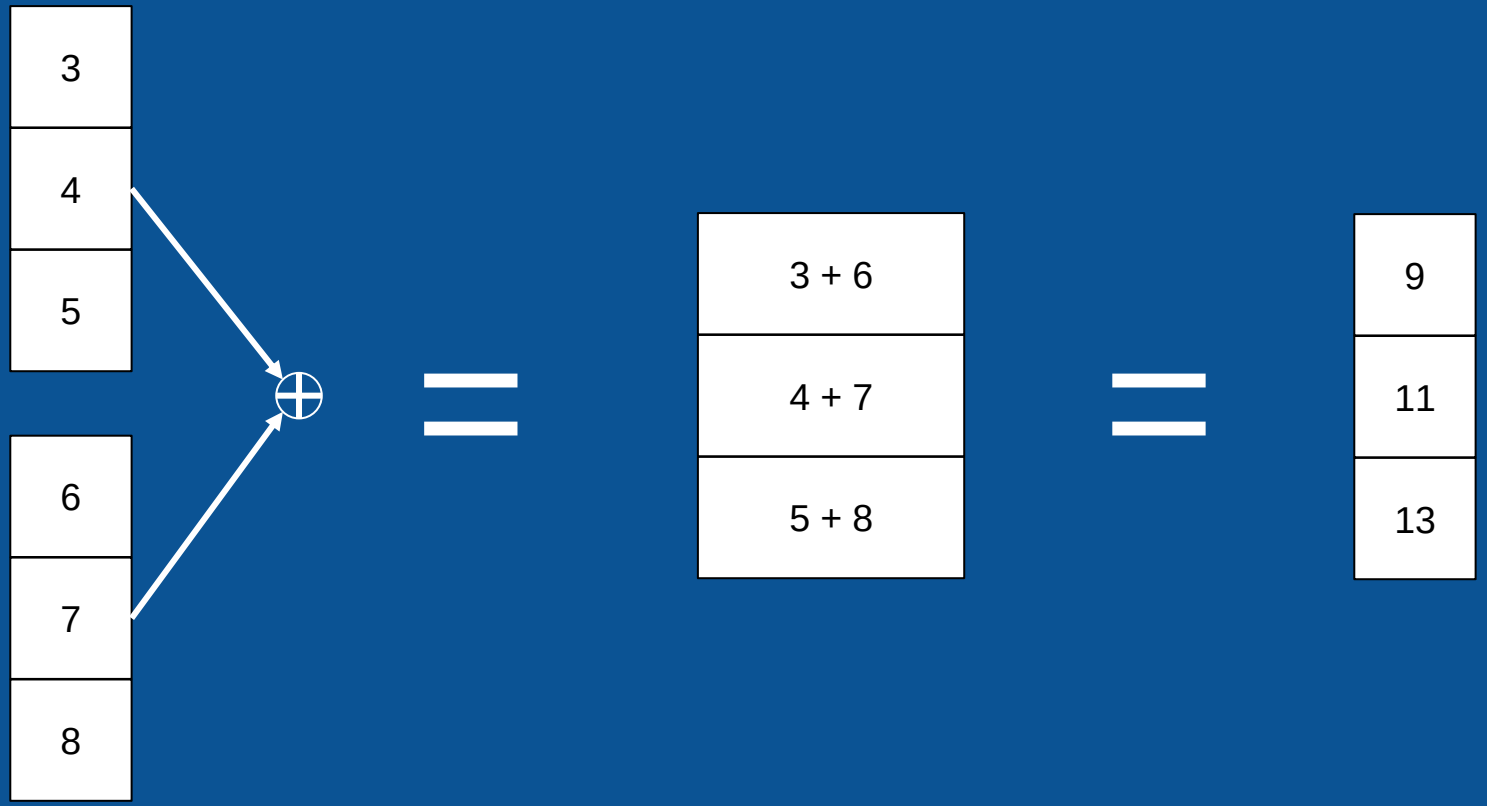
recurrent neural network



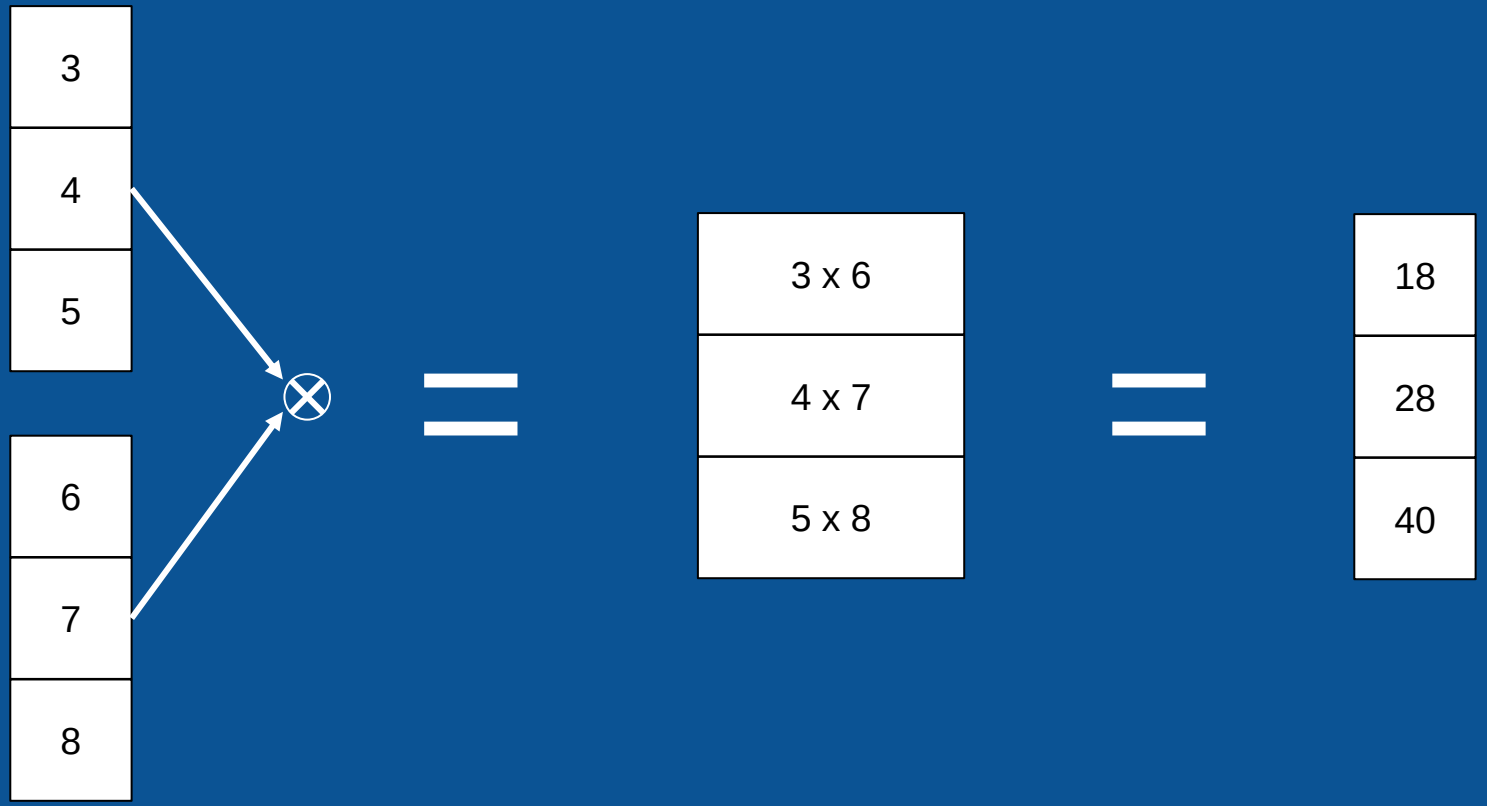
memory


prediction +
memories
forgetting
memory
prediction
new
information

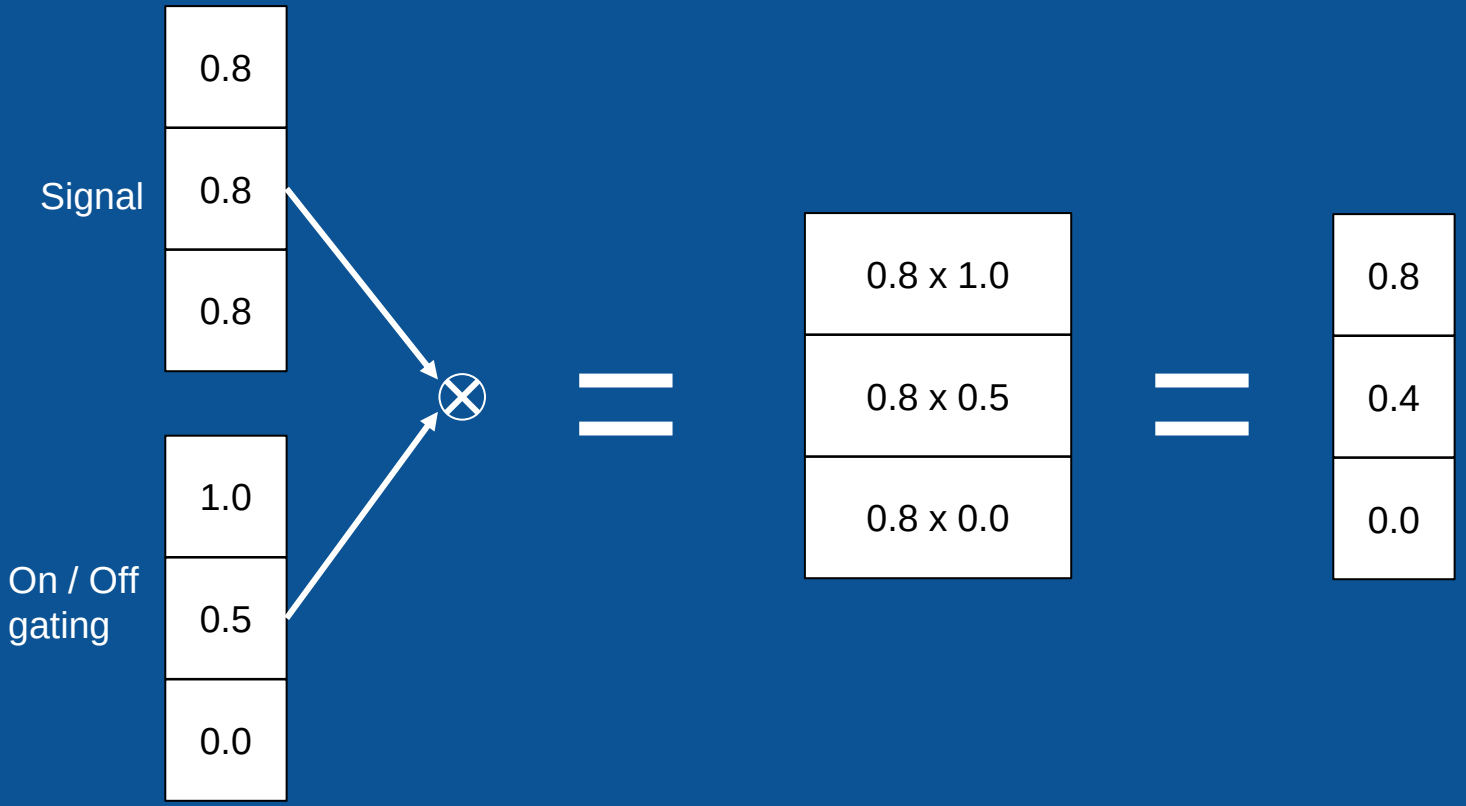
Plus junction: element-by-element addition



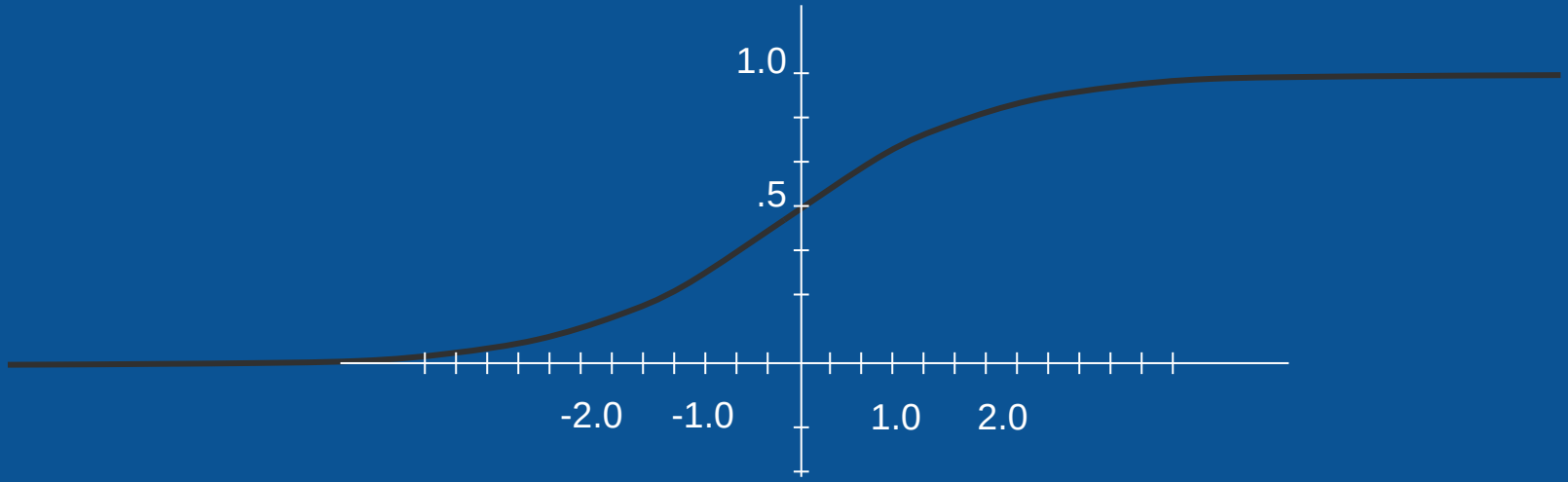
Times junction: element-by-element multiplication



Gating

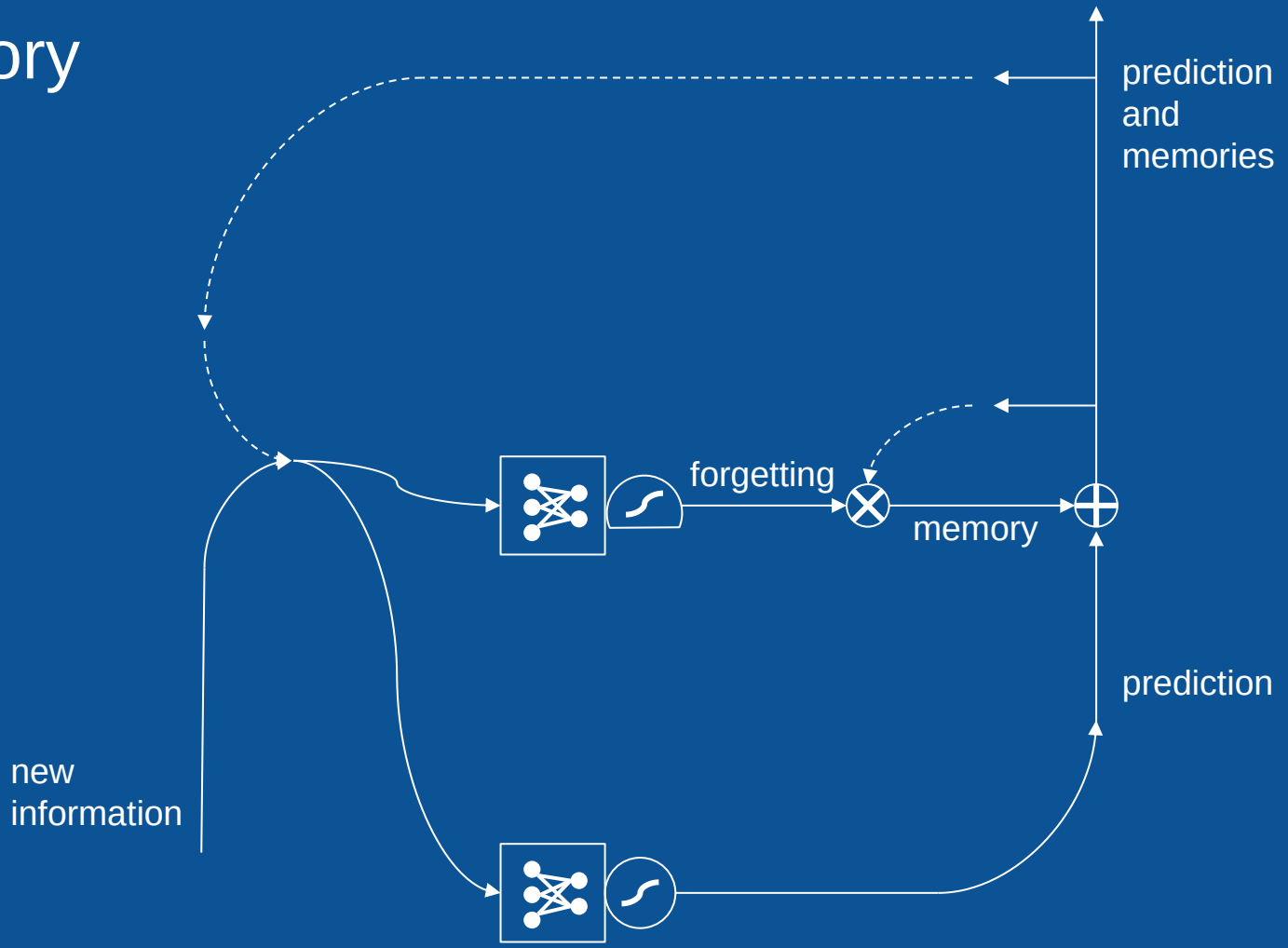

Signal
0.8
0.8
0.8
On / Off gating
1.0
0.5
0.0
0.8 x 1.0
0.8 x 0.5
0.8 x 0.0
0.8
0.4
0.0

Logistic (sigmoid) squashing function

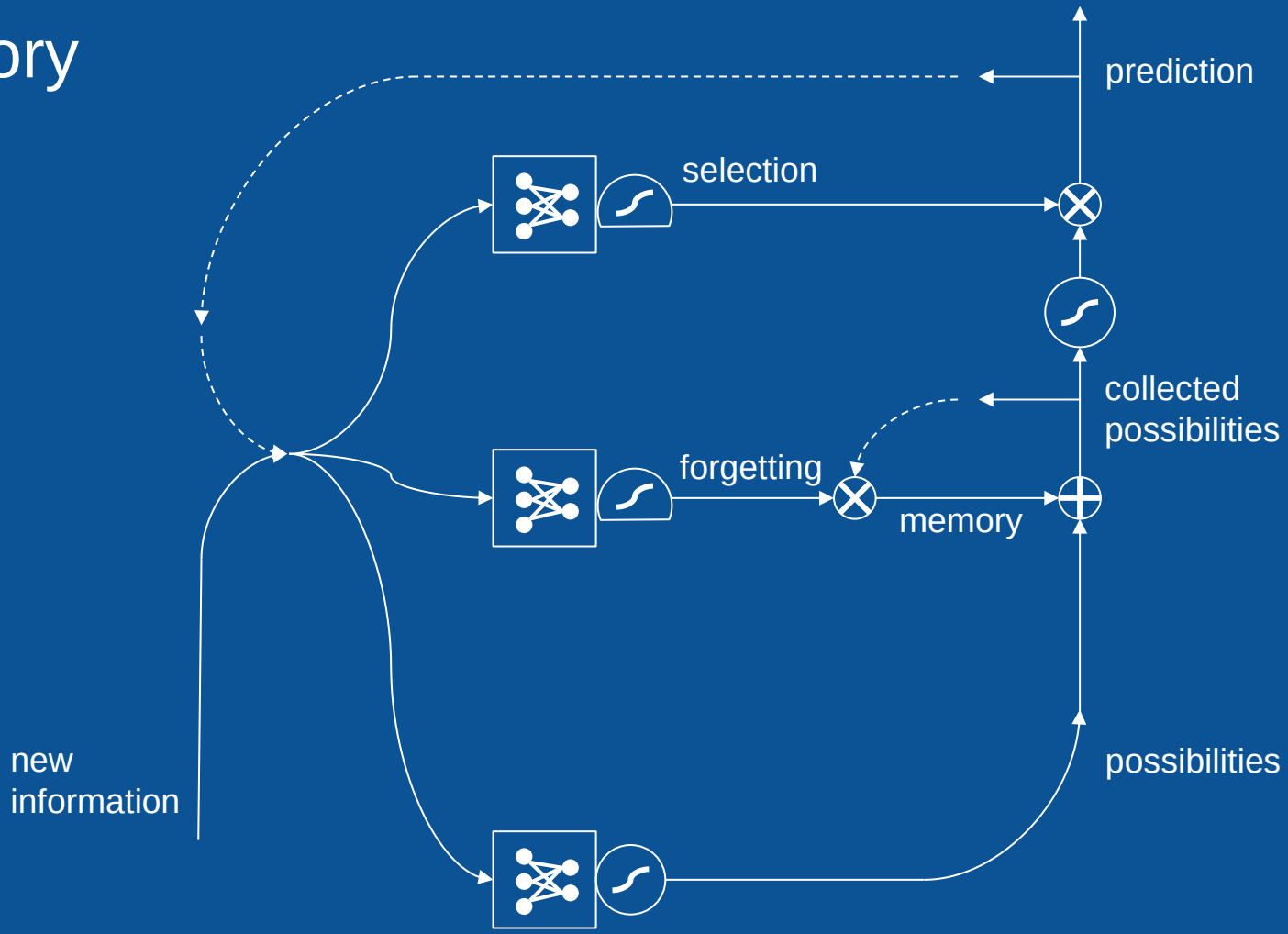


No matter what you start with, the answer stays between 0 and 1.

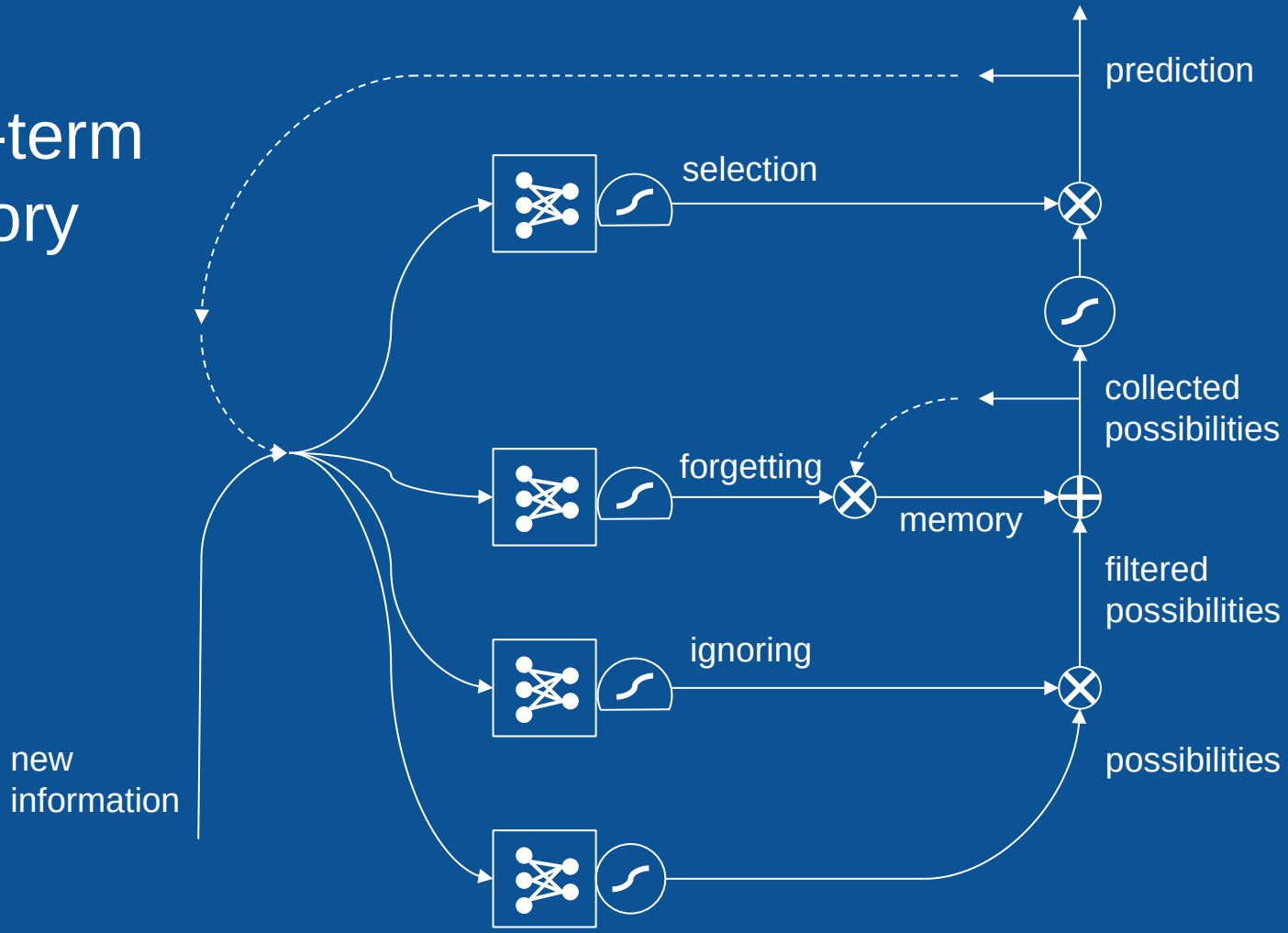
memory


prediction
and
memories
forgetting
memory
prediction
new
information

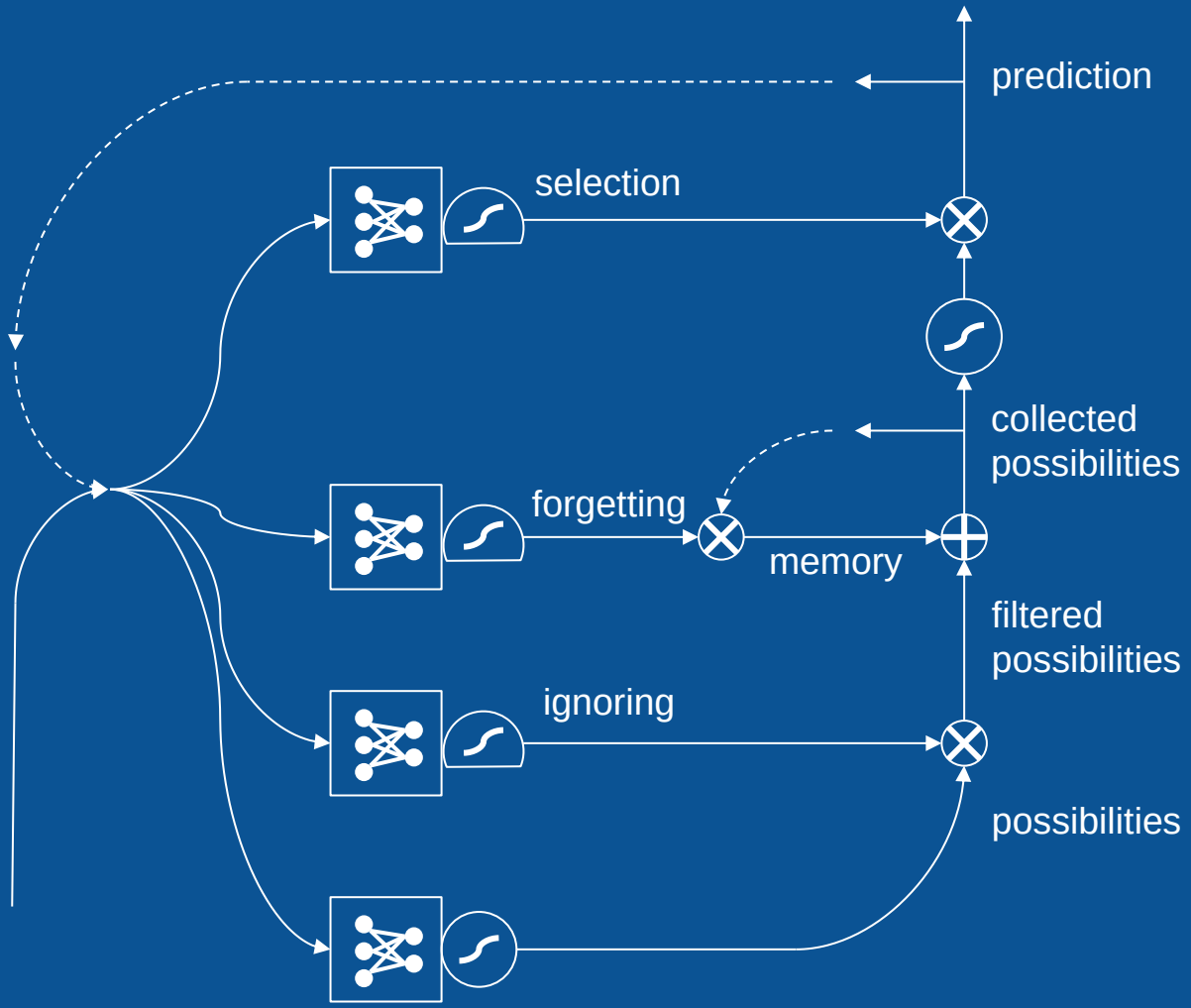
memory


prediction
selection
collected
possibilities
forgetting
memory
new
information
possibilities

long short-term memory

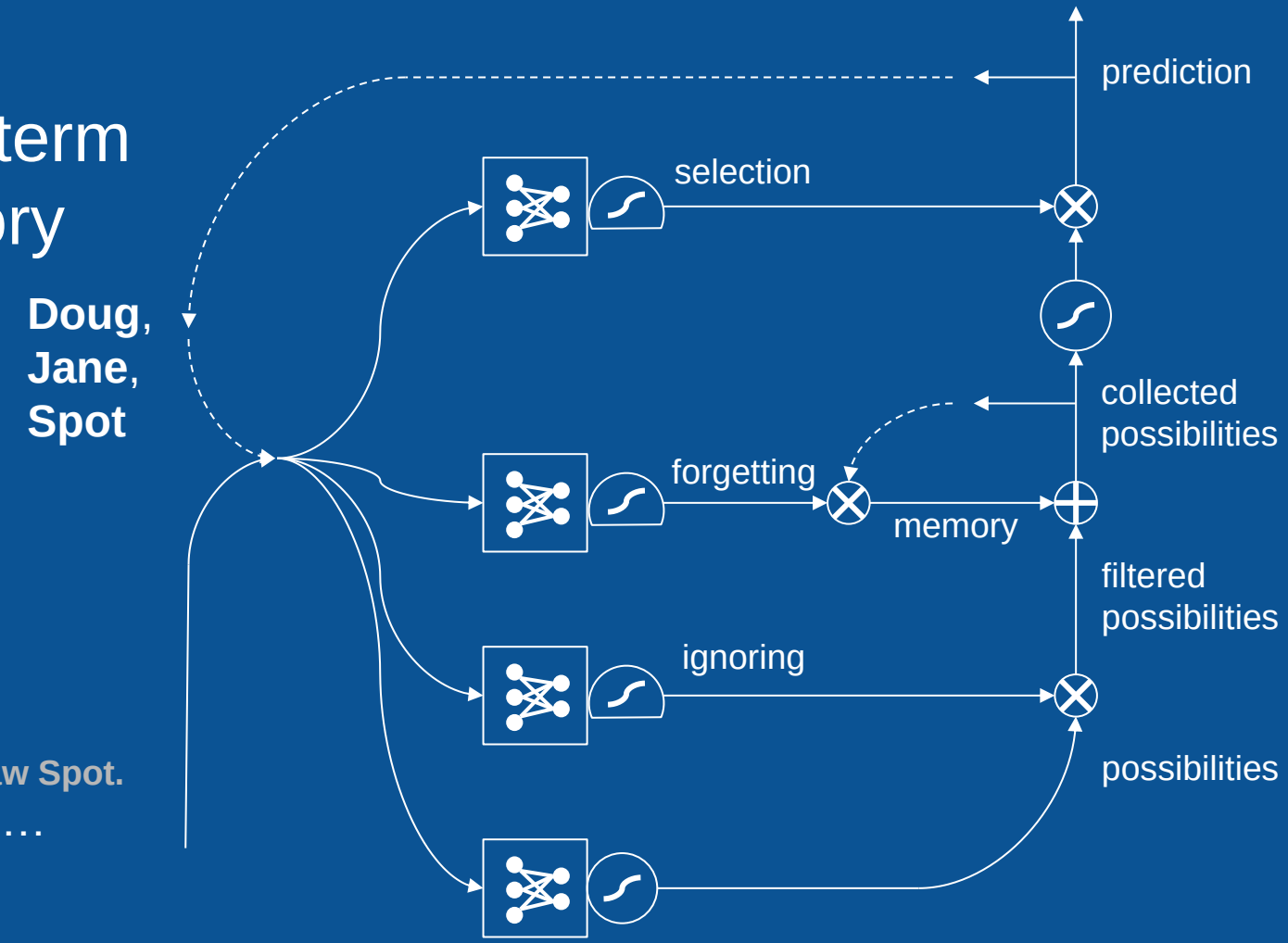


long short-term memory

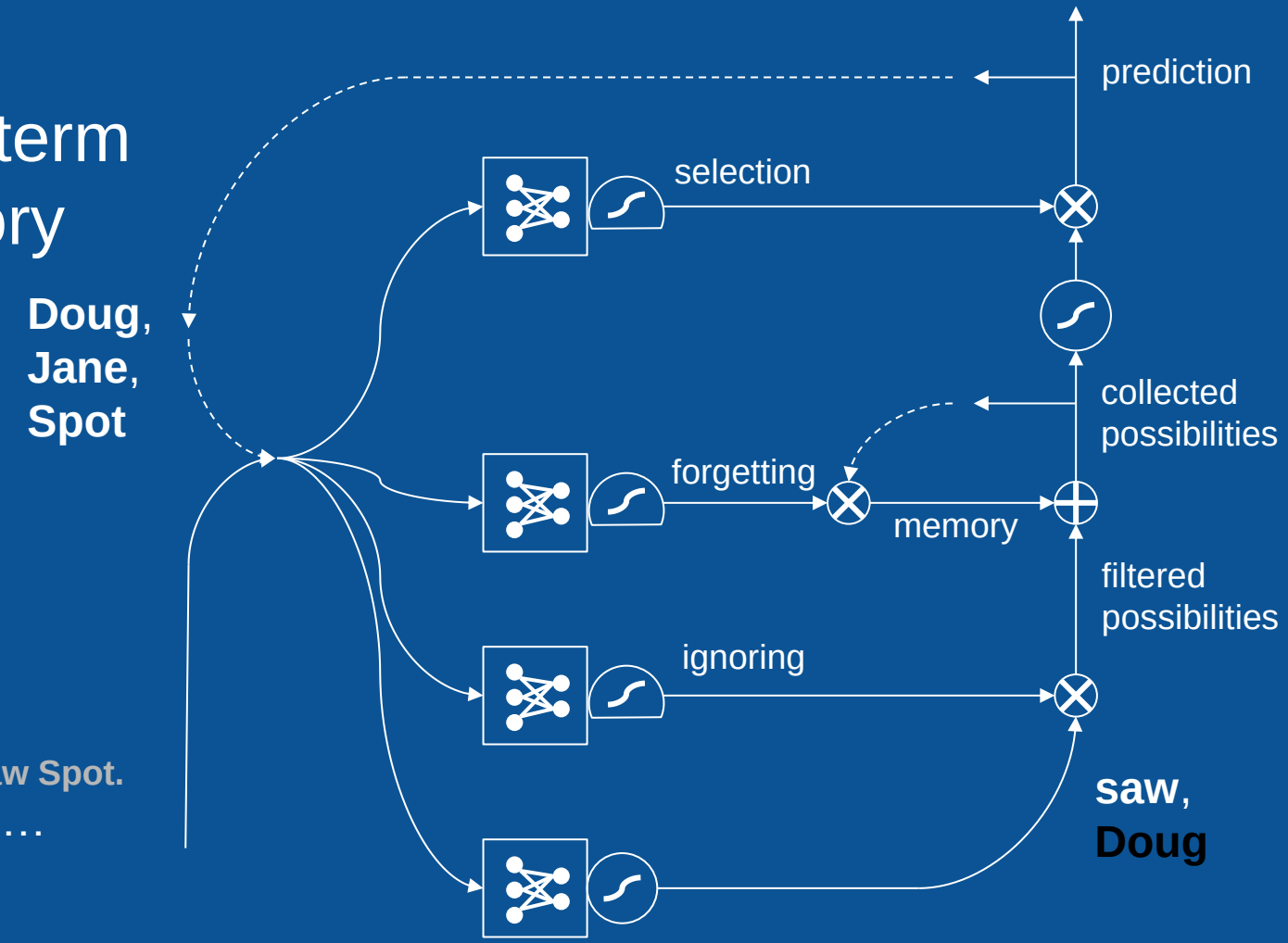


Jane saw Spot.
Doug …

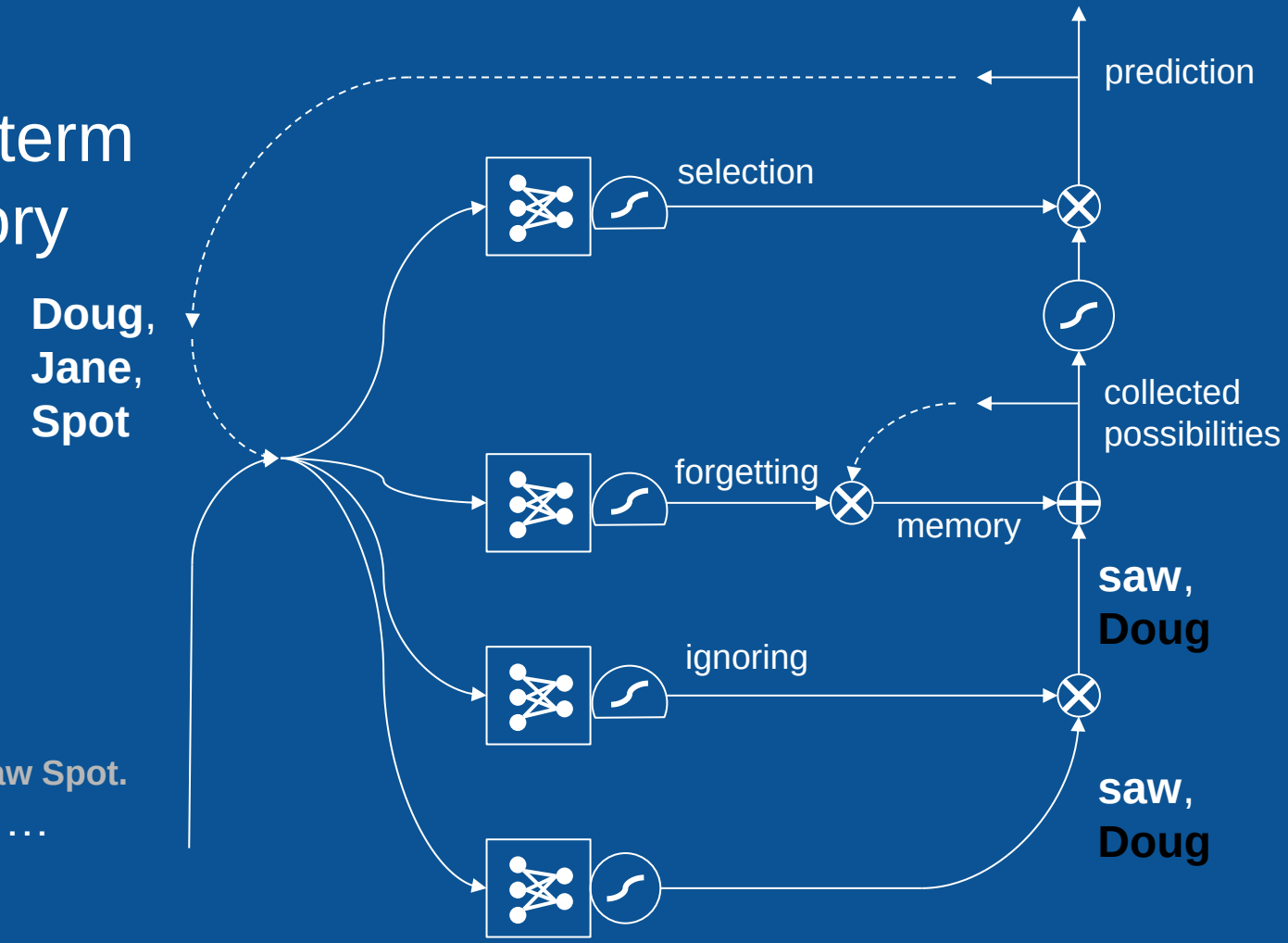
long short-term memory



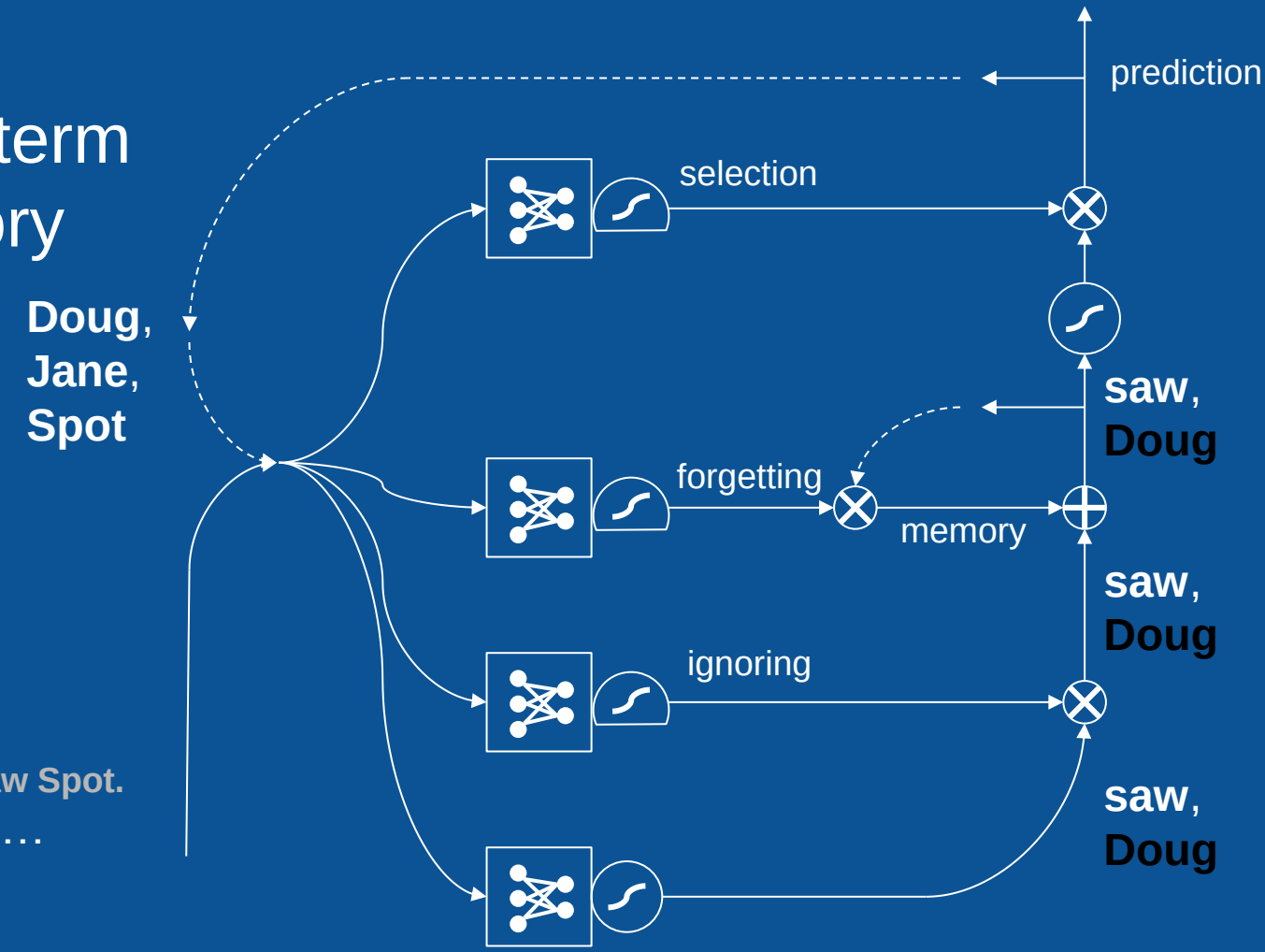
long short-term memory



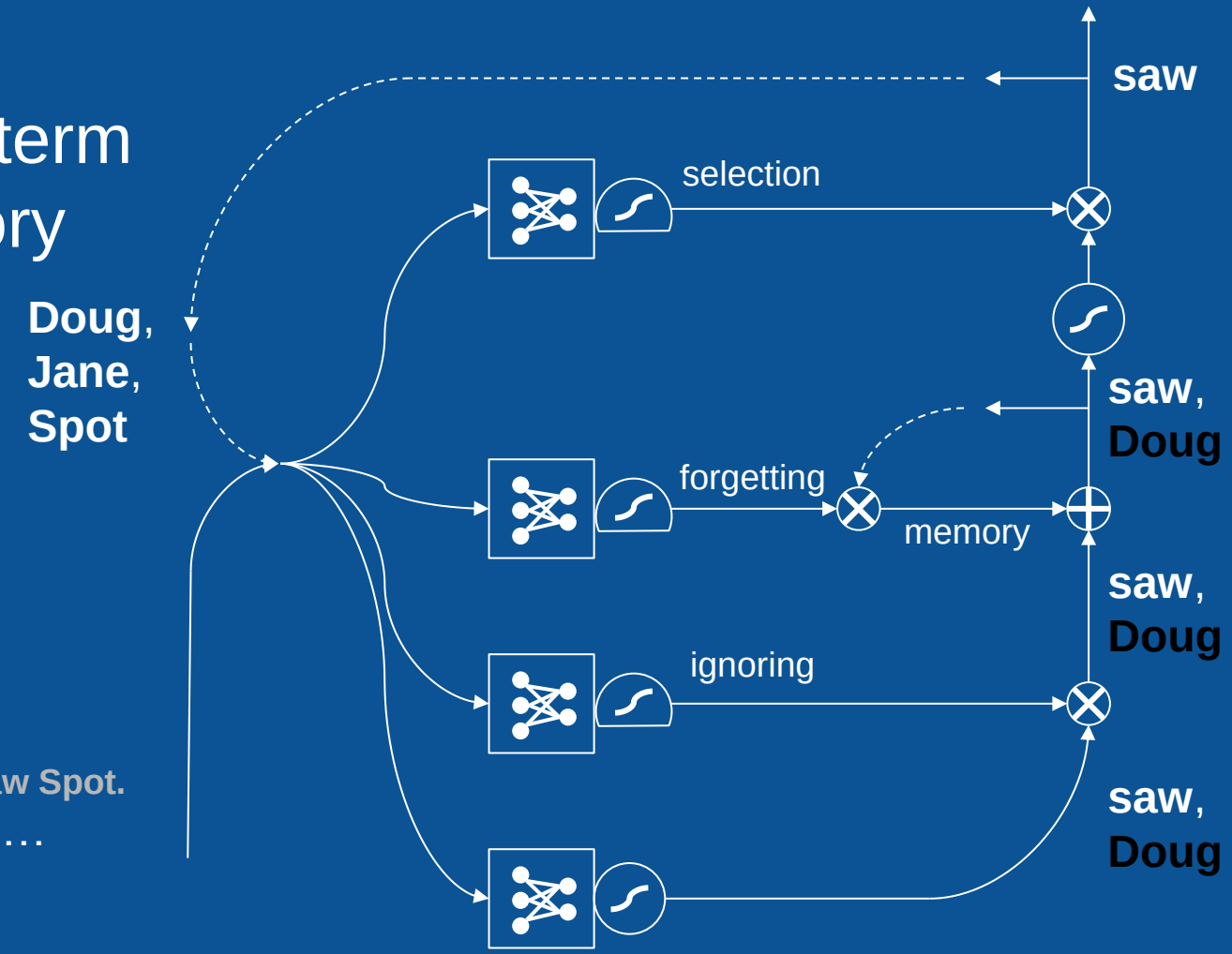
long short-term memory



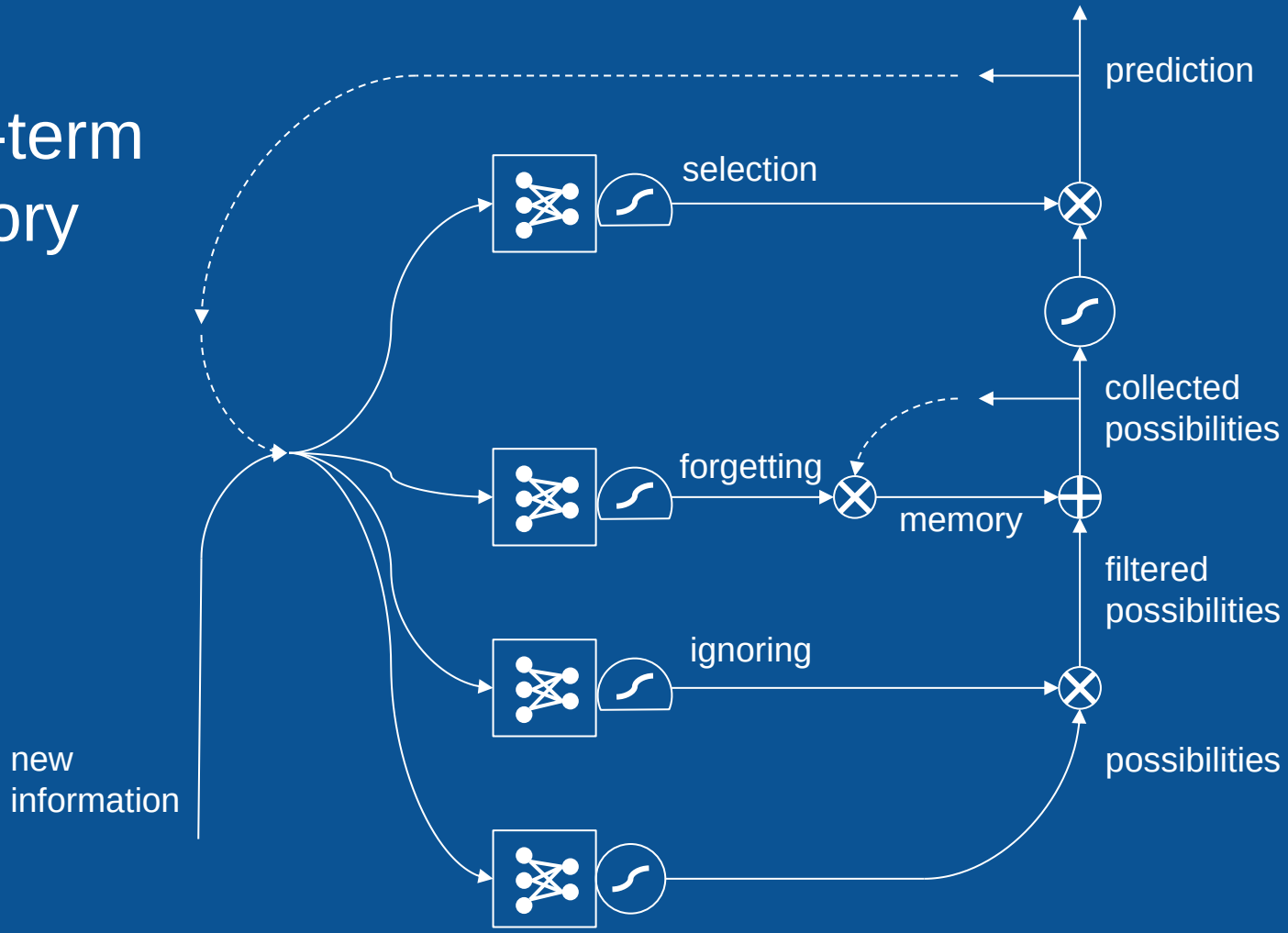
long short-term memory



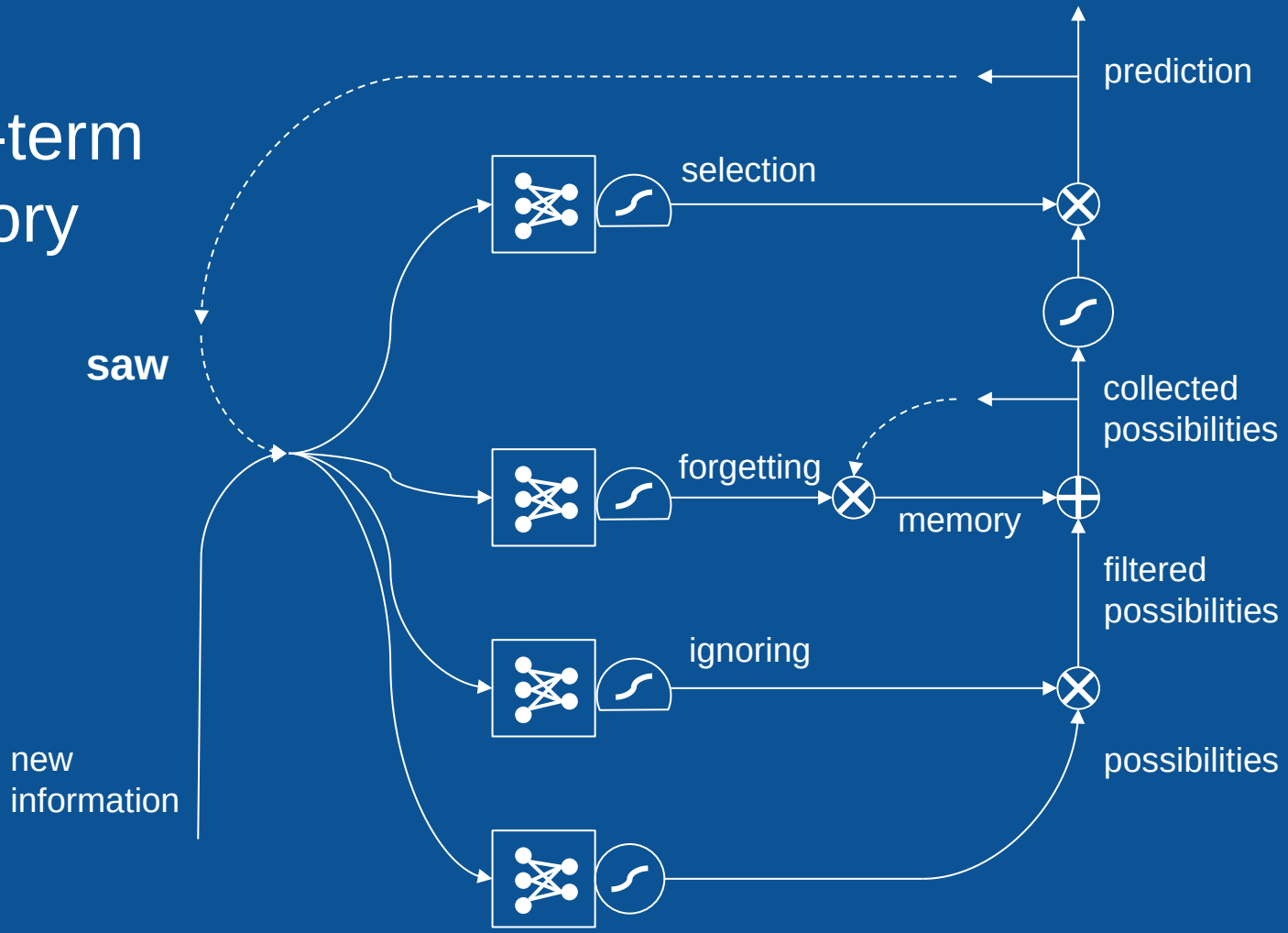
long short-term memory



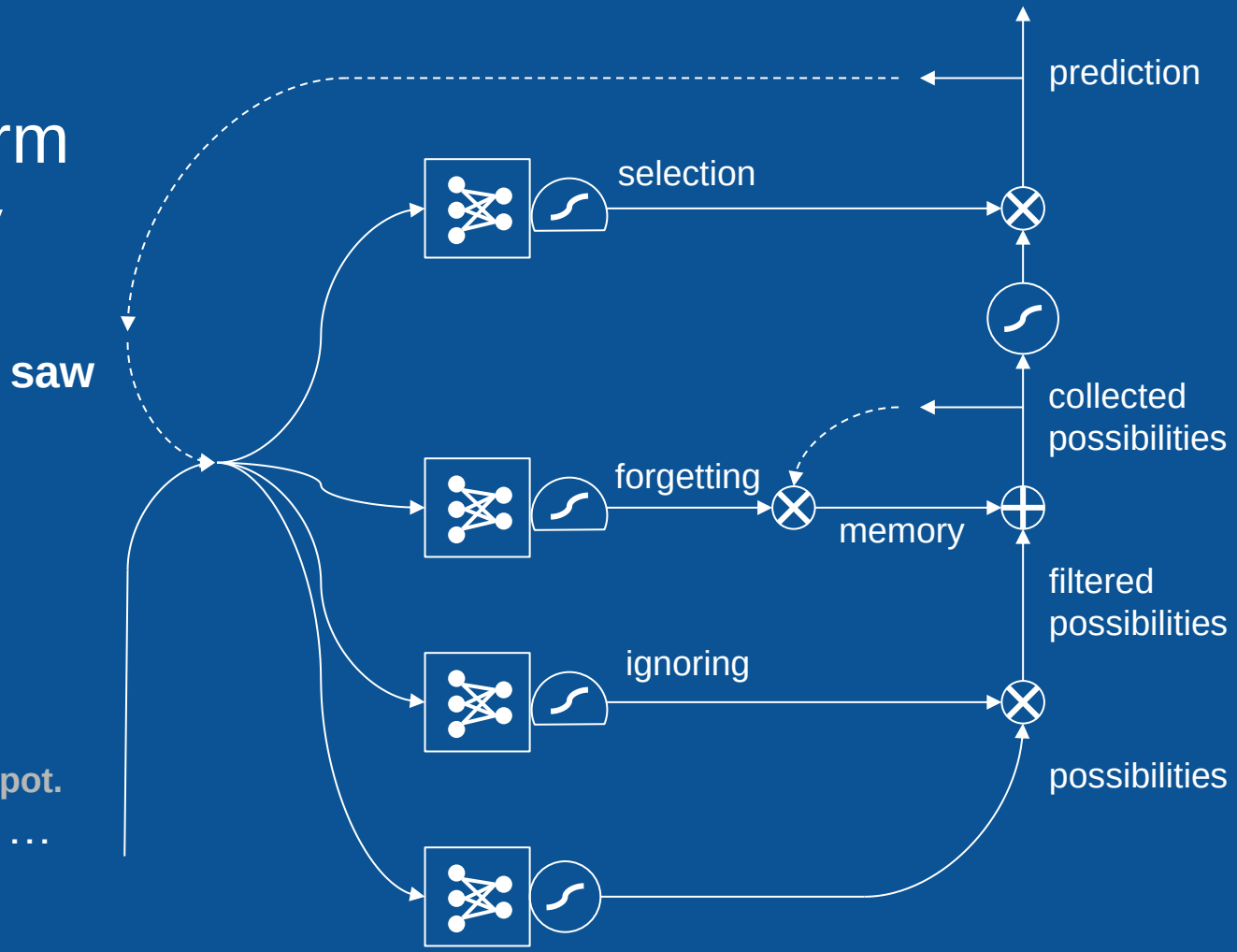
long short-term memory



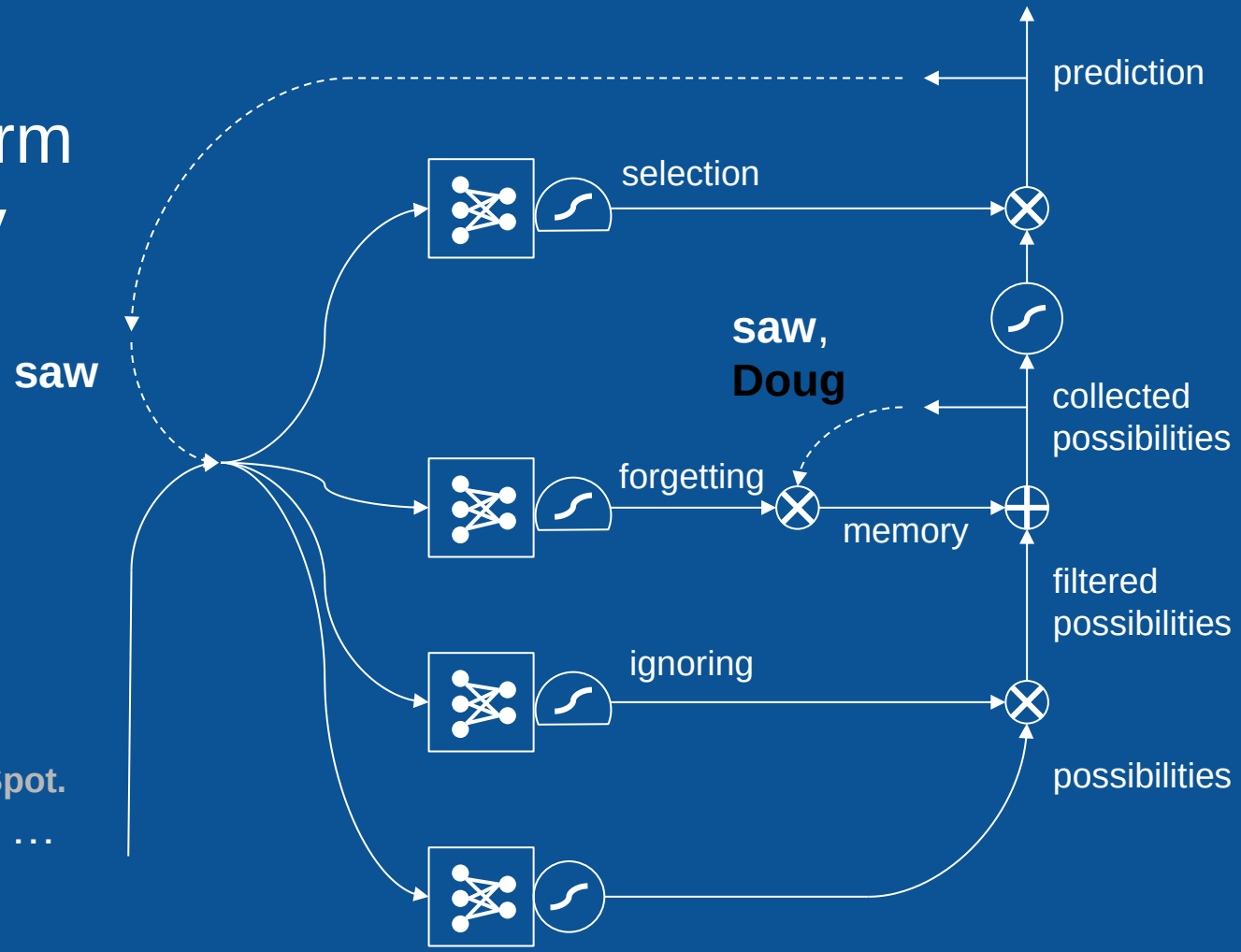
long short-term memory



long short-term memory

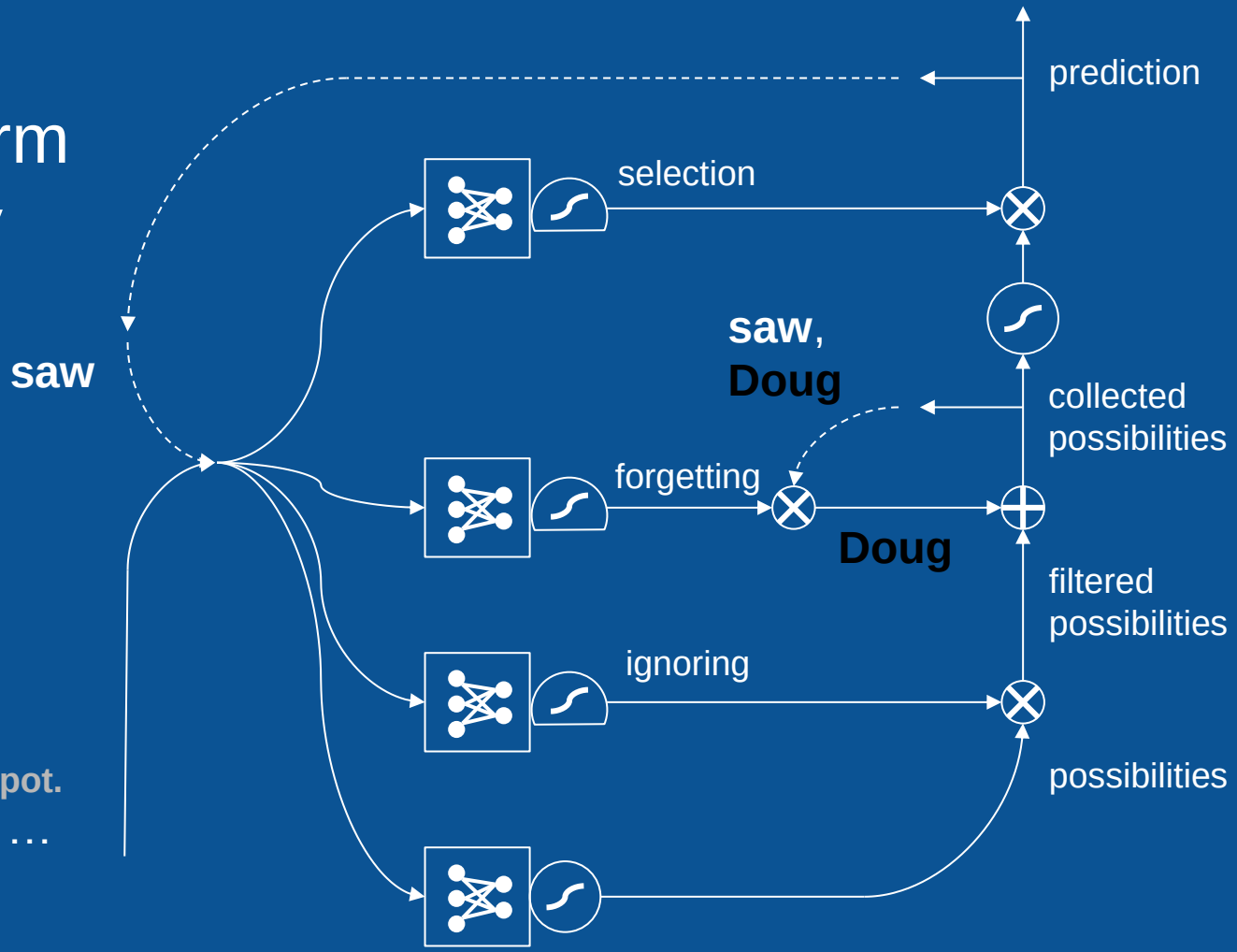


long short-term memory



Jane saw Spot.
Doug **saw** …

long short-term memory



Jane saw Spot.
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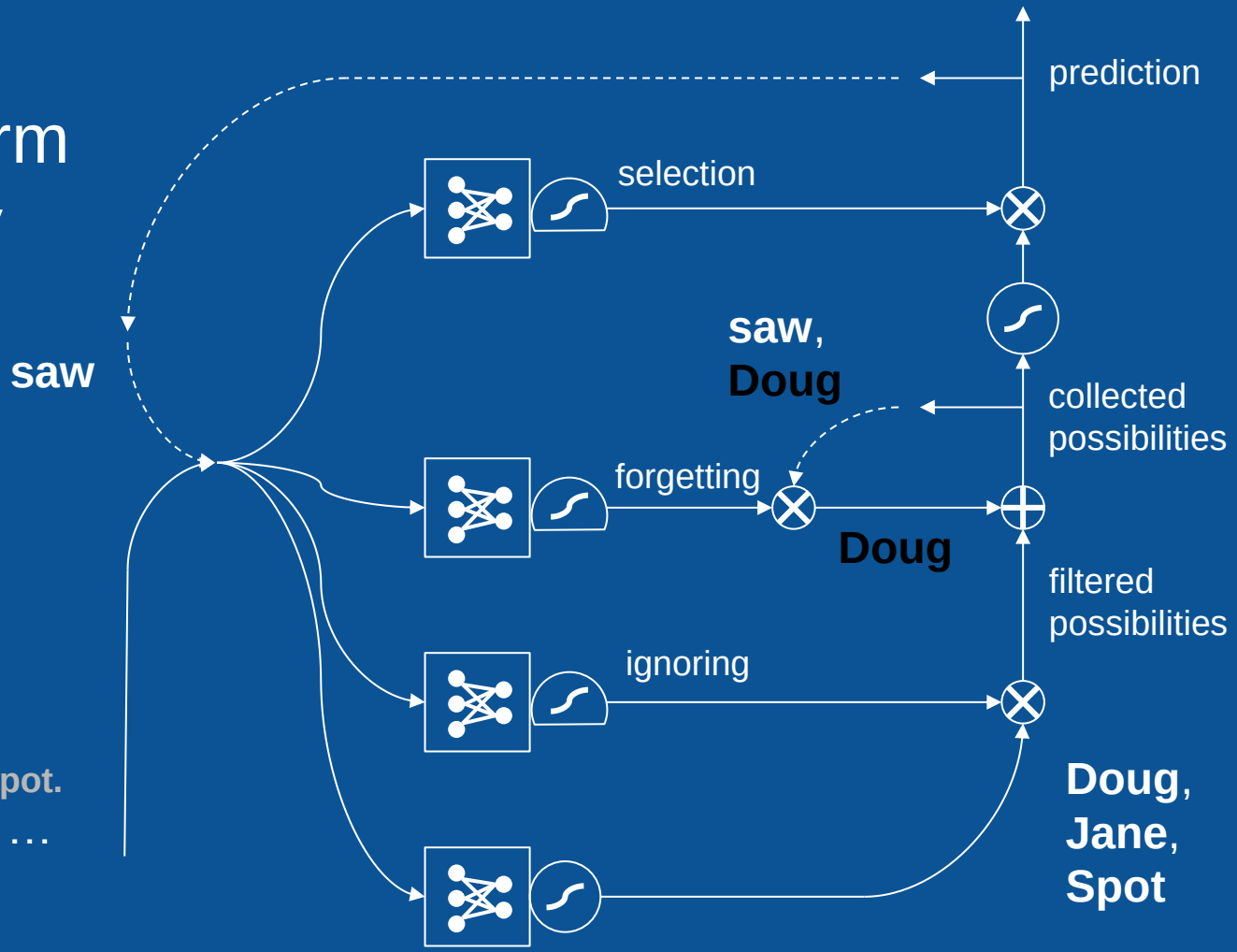
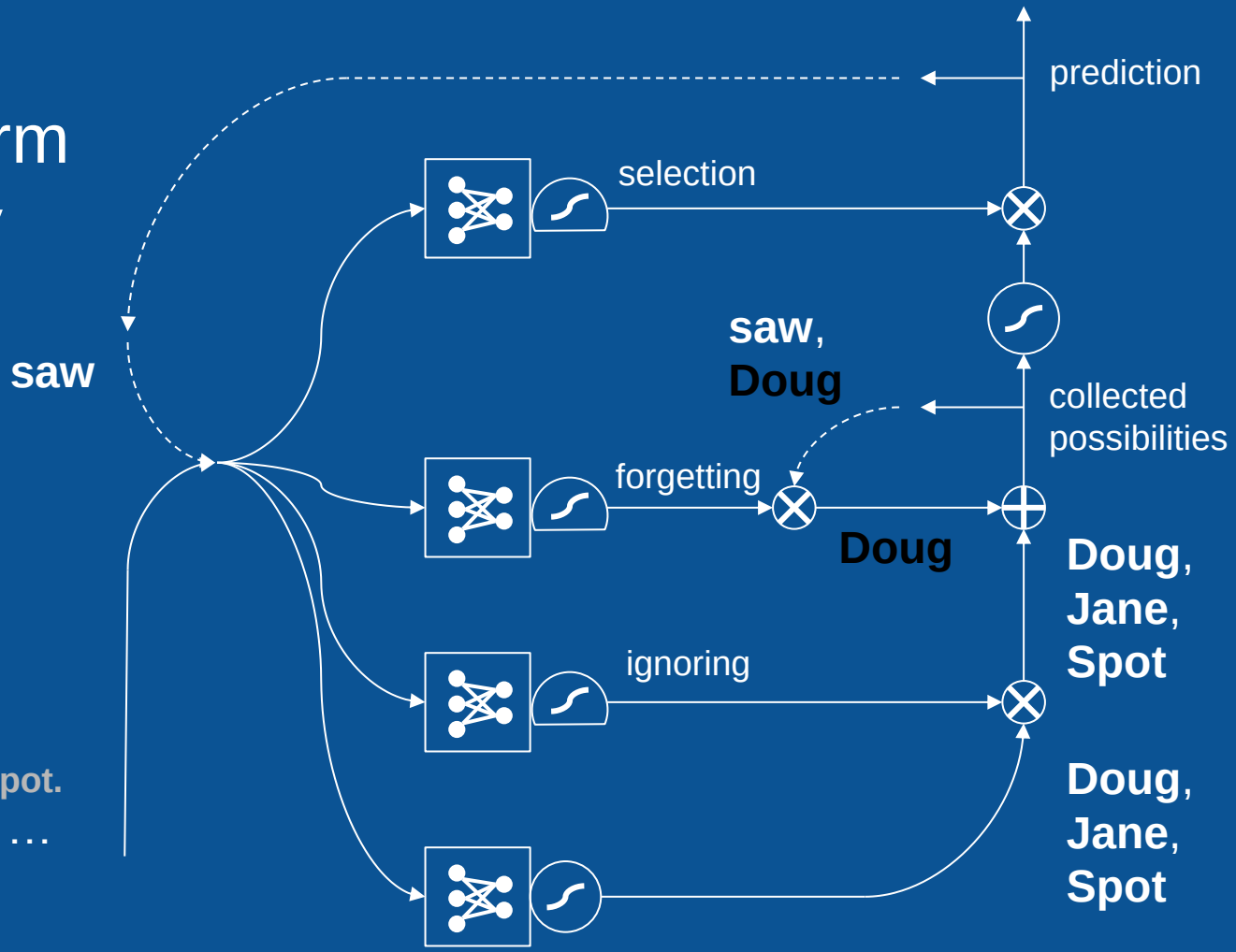
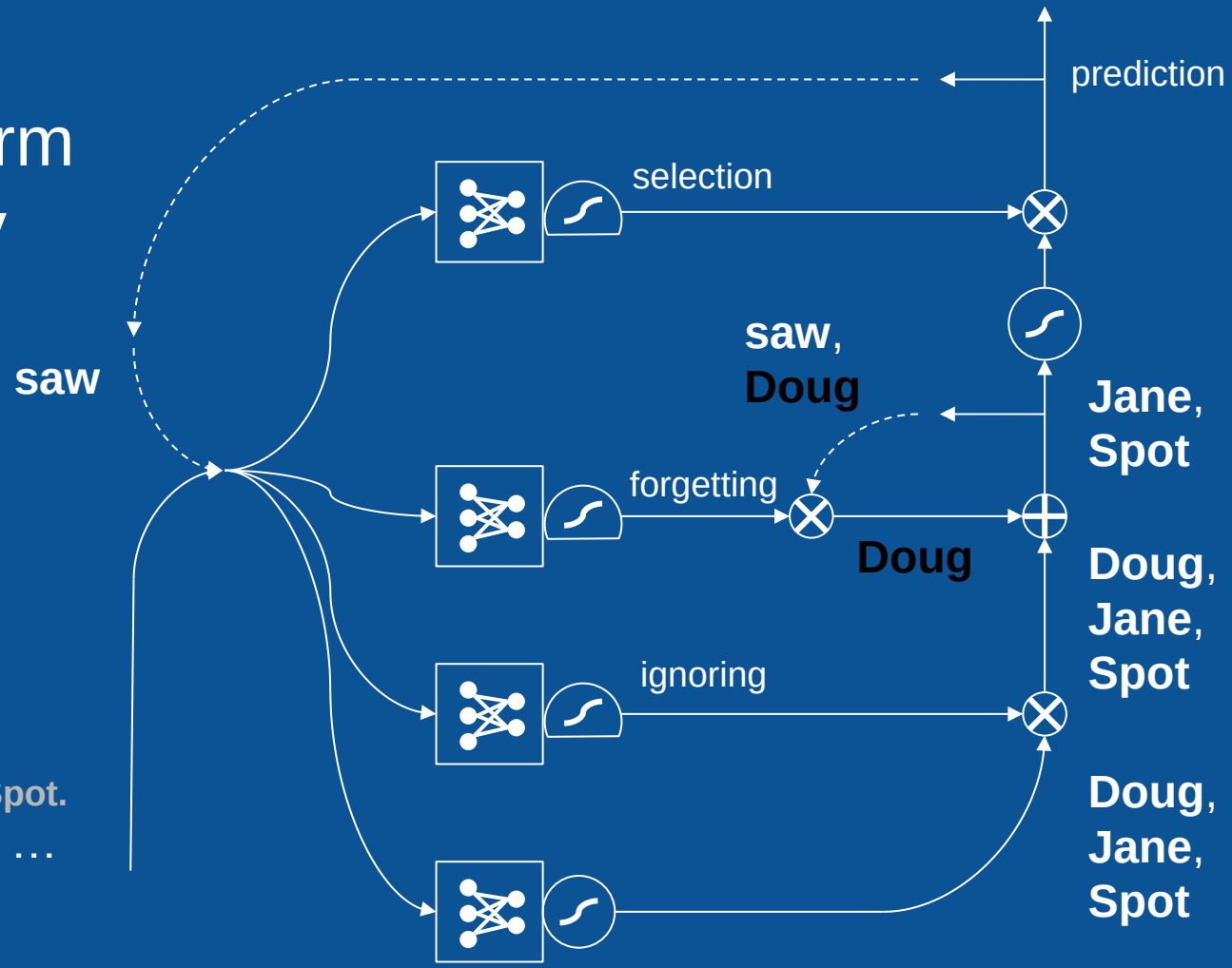
long short-term memory



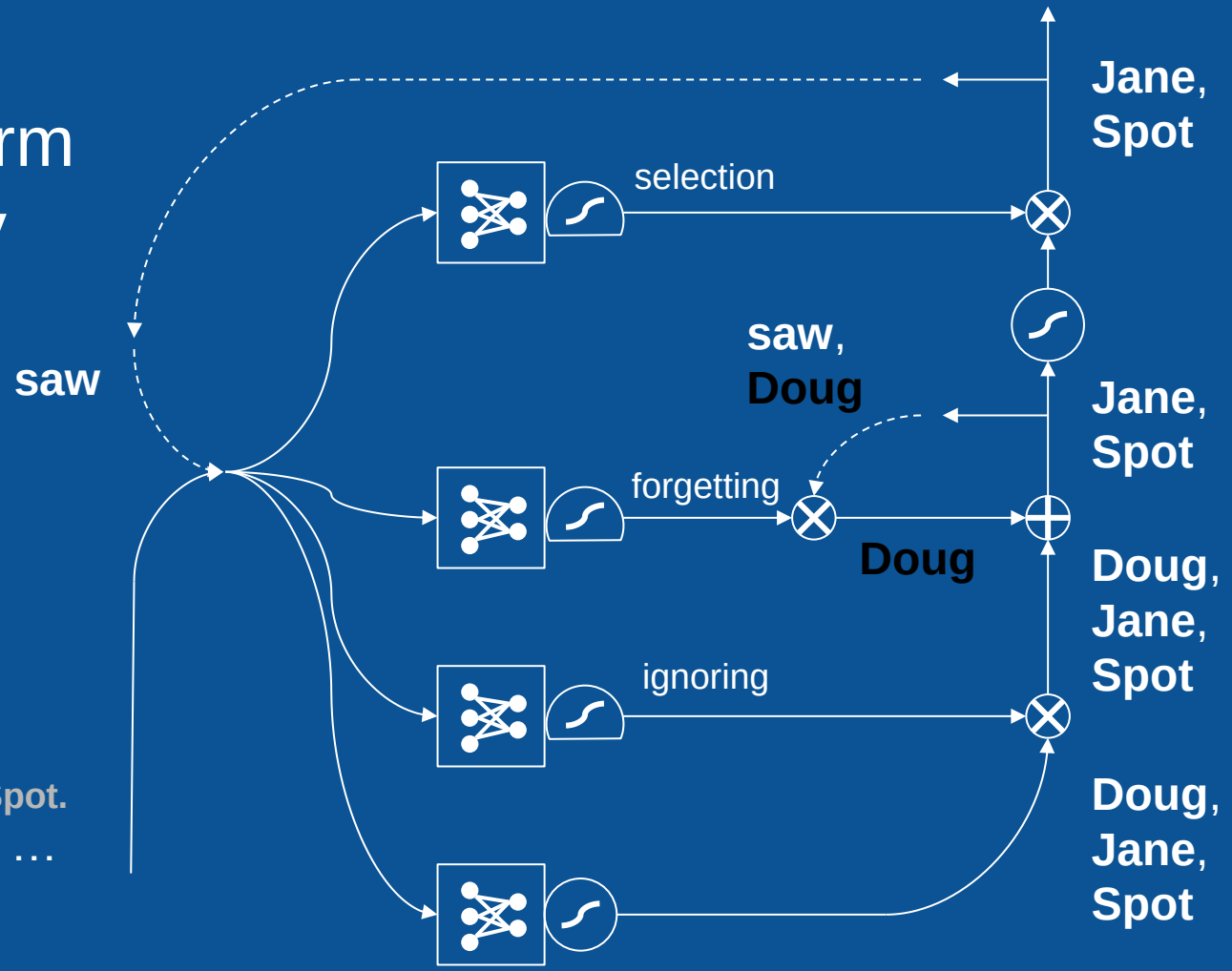
long short-term memory



long short-term memory



long short-term memory



Sequential patterns

Text

Speech

Audio

Video

Physical processes

Anything embedded in time (almost everything)

Traditional LSTM with forget gates.[2][3]

Initial values: $c_0 = 0$ and $h_0 = 0$. The operator $\circ$ denotes the Hadamard product (entry-wise product).

$$
\begin{aligned}
f_t &= \sigma_g(W_f x_t + U_f h_{t-1} + b_f) \\
i_t &= \sigma_g(W_i x_t + U_i h_{t-1} + b_i) \\
o_t &= \sigma_g(W_o x_t + U_o h_{t-1} + b_o) \\
c_t &= f_t \circ c_{t-1} + i_t \circ \sigma_c(W_c x_t + U_c h_{t-1} + b_c) \\
h_t &= o_t \circ \sigma_h(c_t)
\end{aligned}
$$

Variables

- x_t: input vector
- h_t: output vector
- c_t: cell state vector
- W, U and b: parameter matrices and vector
- f_t, i_t and o_t: gate vectors
  - f_t: Forget gate vector. Weight of remembering old information.
  - i_t: Input gate vector. Weight of acquiring new information.
  - o_t: Output gate vector. Output candidate.

Activation functions

- σ_g: The original is a sigmoid function.
- σ_c: The original is a hyperbolic tangent.
- σ_h: The original is a hyperbolic tangent, but the peephole LSTM paper suggests $\sigma_h(x) = x$.[18][19]

Resources

Chris Olah's tutorial

Andrej Karpathy's

Blog post

RNN code

Stanford CS231n lecture

The DeepLearning 4J tutorial has some helpful discussion and a longer list of good resources.

How Neural Networks Work [video]

Credits (all images CC0)

Pizza image

Sushi image

Waffles image