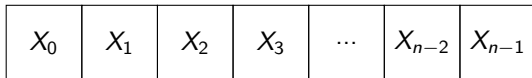# Using stigmergy as a computational memory in the design of recurrent neural networks
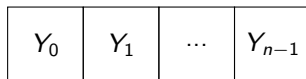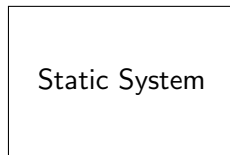
Federico A. Galatolo

20 February 2019

Time-Series Static Classification
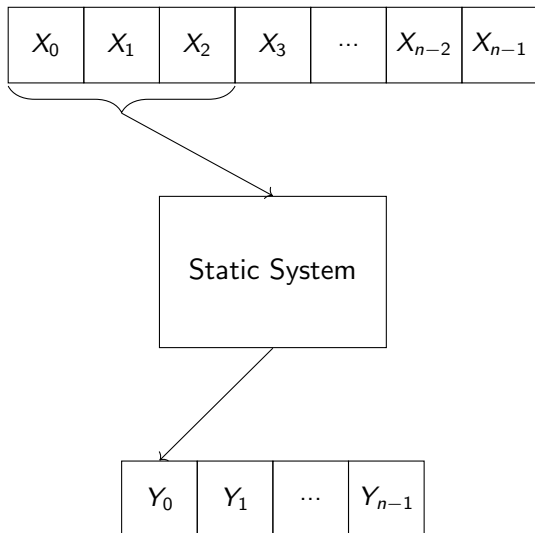
X_0	X_1	X_2	X_3	...	X_{n-2}	X_{n-1}

- MLP
- CNN
- ...

Static System

Y_0	Y_1	...	Y_{n-1}

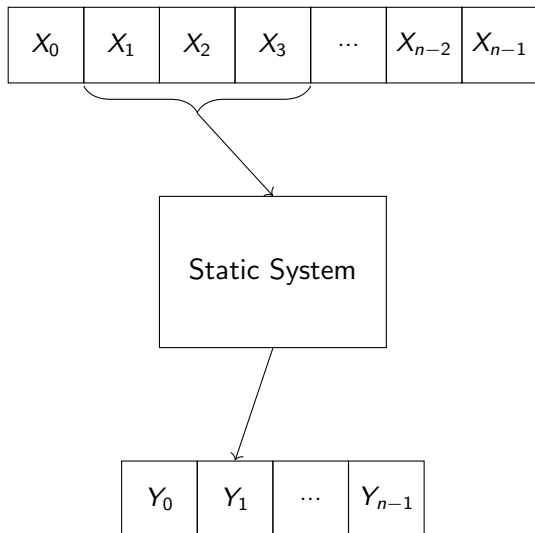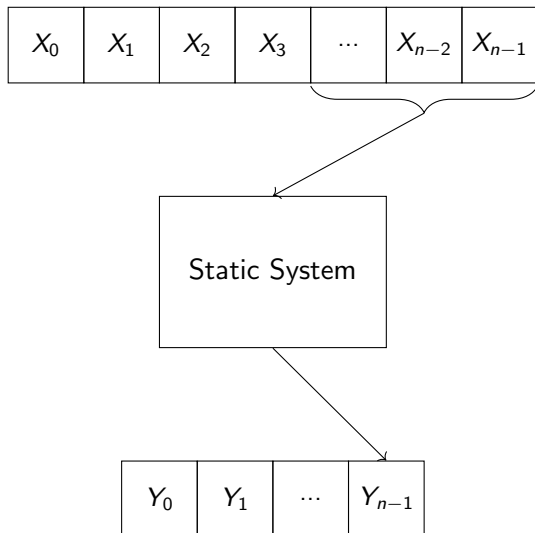# Time-Series Static Classification

- MLP
- CNN
- ...

Time-Series Static Classification

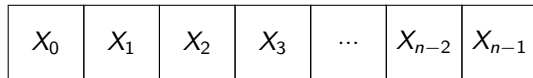
- MLP
- CNN
- ...

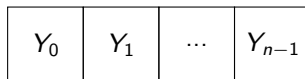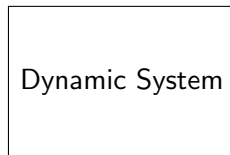# Time-Series Static Classification

- ▶ MLP
- ▶ CNN
- ▶ ...

Time-Series Static Classification

✓ You can use any existing ML Architecture

✗ Window size choice

✗ Long-lived relationships are impossible to infer

Time-Series Dynamic Classification

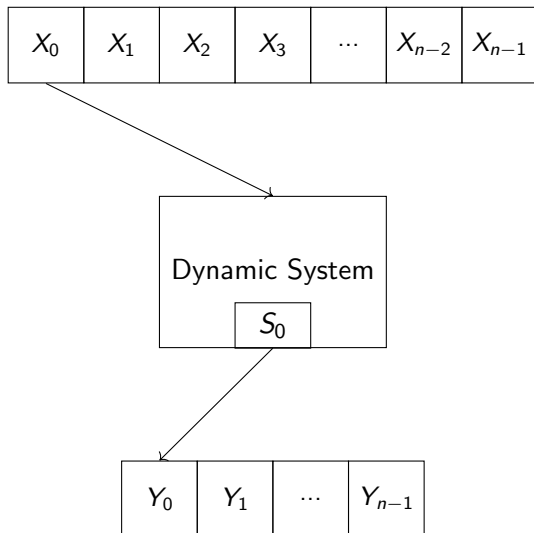| X_0	X_1	X_2	X_3	...	X_{n-2}	X_{n-1}

- ▶ RNN
- ▶ LSTM
- ▶ ...

Dynamic System

Y_0	Y_1	...	Y_{n-1}

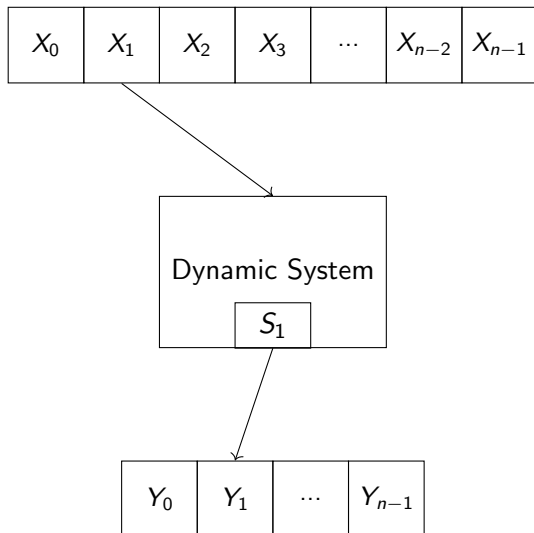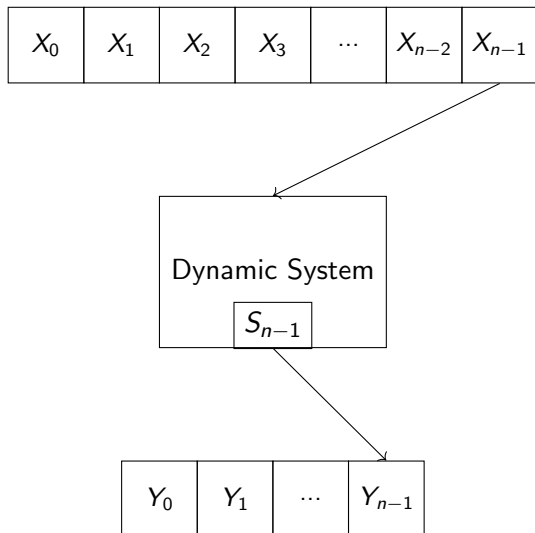# Time-Series Dynamic Classification

- RNN
- LSTM
- ...

Time-Series Dynamic Classification

- RNN
- LSTM
- ...

Time-Series Dynamic Classification


- ▶ RNN
- ▶ LSTM
- ▶ ...

Time-Series Dynamic Classification

- ✓ The system knows the concept of time
- ✓ Can autonomously decide what to remember and forget
- ✗ Ad-Hoc solutions
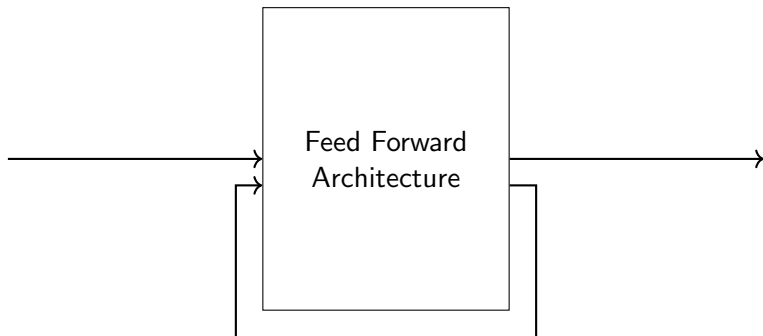- ✗ Highly engineered

RNN $\neq$ LSTM

- ▶ RNN and LSTM are often used as synonyms in literature
- ▶ Has been proven that "Vanilla recursion" performs poorly
- ▶ LSTM are the state of the art for Time Series Classification

Feed Forward Architecture
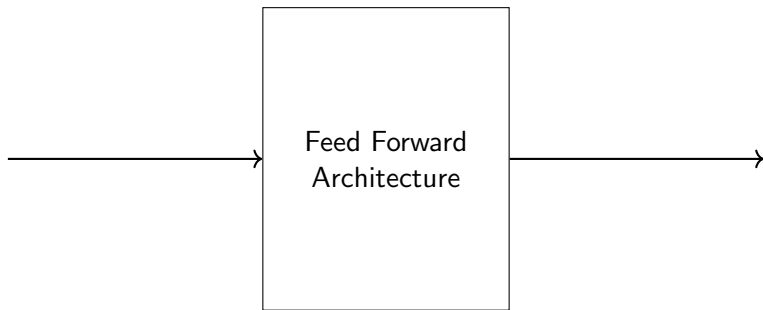
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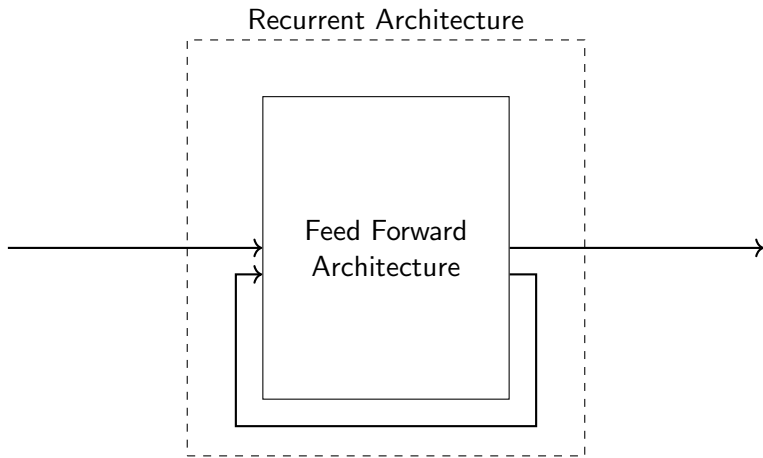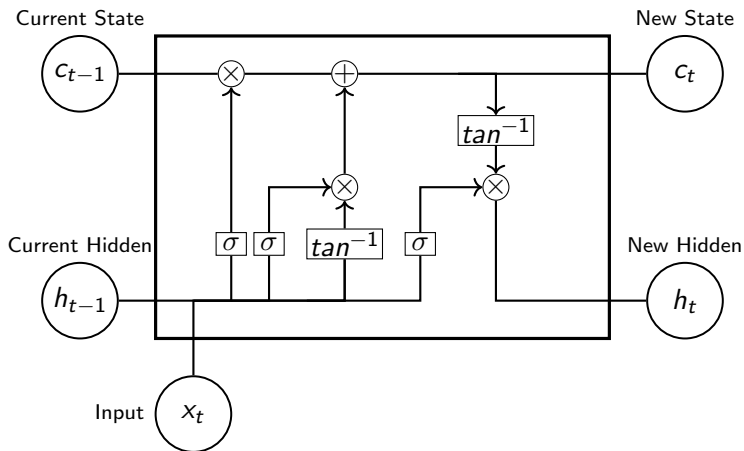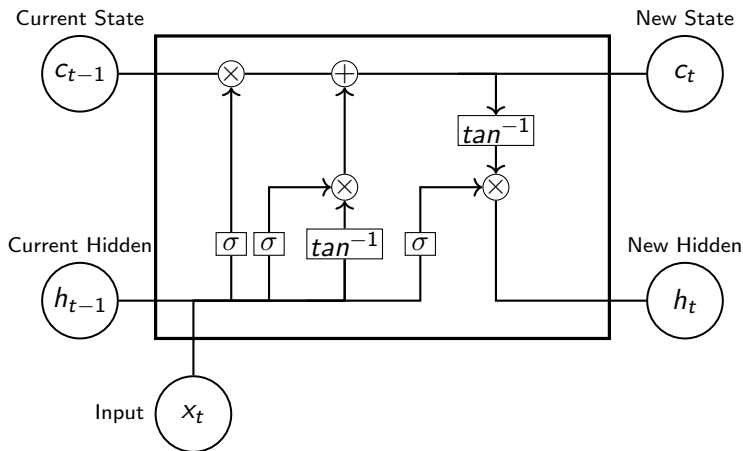

Recurrent Architecture

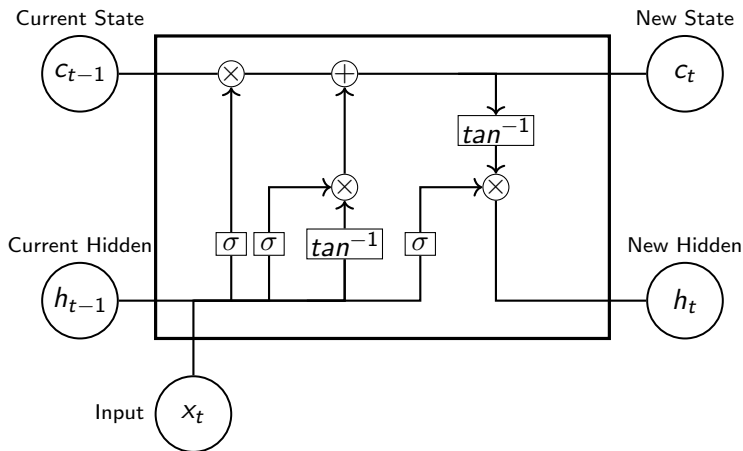Feed Forward Architecture

A deep look inside an LSTM cell

A deep look inside an LSTM cell
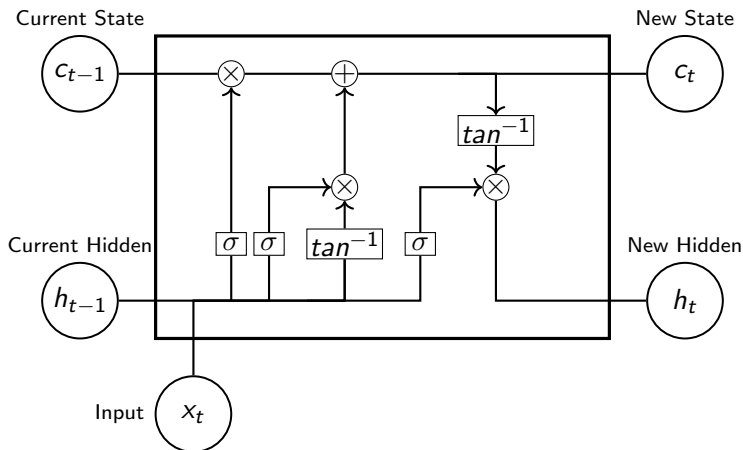

- $f_t = \sigma(W_f x_t + U_f h_t + b_f)$

A deep look inside an LSTM cell

- $f_t = \sigma(W_f x_t + U_f h_t + b_f)$
- $i_t = \sigma(W_i x_t + U_i h_t + b_i)$
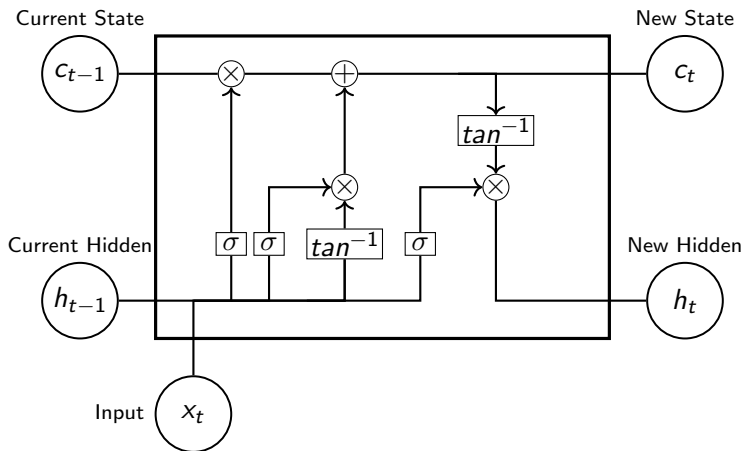
A deep look inside an LSTM cell

- $f_t = \sigma(W_f x_t + U_f h_t + b_f)$
- $i_t = \sigma(W_i x_t + U_i h_t + b_i)$

- $i_c = tan^{-1}(W_c x_t + U_c h_t + b_c)$

A deep look inside an LSTM cell

- $f_t = \sigma(W_f x_t + U_f h_t + b_f)$
- $i_t = \sigma(W_i x_t + U_i h_t + b_i)$

- $i_c = tan^{-1}(W_c x_t + U_c h_t + b_c)$
- $c_t = f_t \circ c_{t-1}$

A deep look inside an LSTM cell
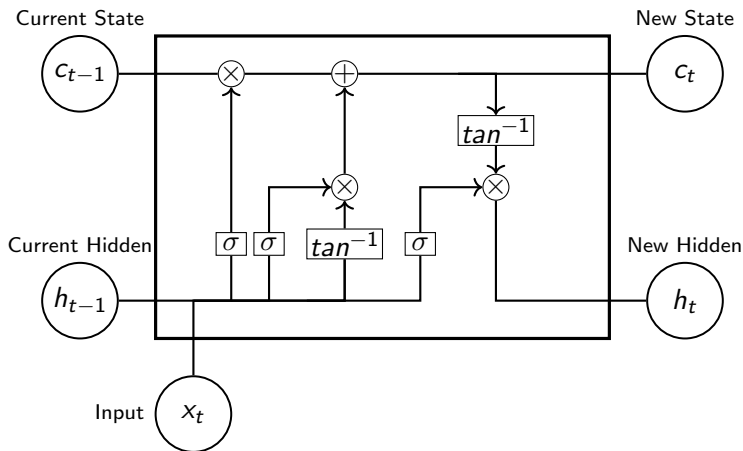
- $f_t = \sigma(W_f x_t + U_f h_t + b_f)$
- $i_t = \sigma(W_i x_t + U_i h_t + b_i)$
- $i_c = tan^{-1}(W_c x_t + U_c h_t + b_c)$
- $c_t = f_t \circ c_{t-1} + i_t \circ i_c$

A deep look inside an LSTM cell

- $f_i = \sigma(W_f x_i + U_f h_{i-1} + b_f)$
- $i_i = \sigma(W_i x_i + U_i h_{i-1} + b_i)$
- $o_i = \sigma(W_o x_i + U_o h_{i-1} + b_o)$
- $c_i = \sigma(f_i \circ c_{i-1} + i_i \circ \tan^{-1}(W_c X_i + U_c h_{i-1} + b_c))$
- $h_t = o_i * \tan^{-1}(c_i)$

Using

- $W_f,\ W_i,\ W_o,\ W_C \in R^{n \times h}$
- $U_f,\ U_i,\ U_o,\ U_c \in R^{h \times h}$
- $b_f,\ b_i,\ b_o,\ b_c \in R^{h}$

A deep look inside an LSTM cell

- $f_i = \sigma(W_f x_i + U_f h_{i-1} + b_f)$
- $i_i = \sigma(W_i x_i + U_i h_{i-1} + b_i)$
- $o_i = \sigma(W_o x_i + U_o h_{i-1} + b_o)$
- $c_i = \sigma(f_i \circ c_{i-1} + i_i \circ \tan^{-1}(W_c X_i + U_c h_{i-1} + b_c))$
- $h_t = o_i * \tan^{-1}(c_i)$

Using

- $W_f, W_i, W_o, W_C \in R^{n \times h}$
- $U_f, U_i, U_o, U_c \in R^{h \times h}$
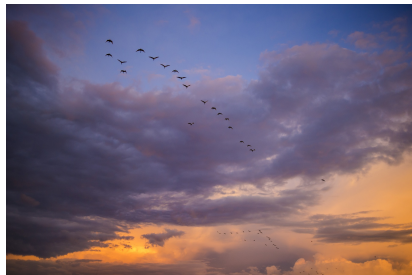- $b_f, b_i, b_o, b_c \in R^h$

Can we do better?

A deep look inside an LSTM cell

- $f_i = \sigma(W_f x_i + U_f h_{i-1} + b_f)$
- $i_i = \sigma(W_i x_i + U_i h_{i-1} + b_i)$
- $o_i = \sigma(W_o x_i + U_o h_{i-1} + b_o)$
- $c_i = \sigma(f_i \circ c_{i-1} + i_i \circ tan^{-1}(W_c X_i + U_c h_{i-1} + b_c))$
- $h_t = o_i * tan^{-1}(c_i)$

Using
- $W_f, W_i, W_o, W_C \in R^{n \times h}$
- $U_f, U_i, U_o, U_c \in R^{h \times h}$
- $b_f, b_i, b_o, b_c \in R^h$

Can we do better?

Can we do **simpler**?

Let's take a step back

Let's take a step back

Let's take a step back

Let's take a step back

- ▶ Complex behaviors can **emerge** from simple ones
- ▶ Emergence is a key phenomenon in nature
- ▶ **Stigmergy** is one of the tools nature uses to achieve emergence

Let's take a step back

- Complex behaviors can **emerge** from simple ones
- Emergence is a key phenomenon in nature
- **Stigmergy** is one of the tools nature uses to achieve emergence

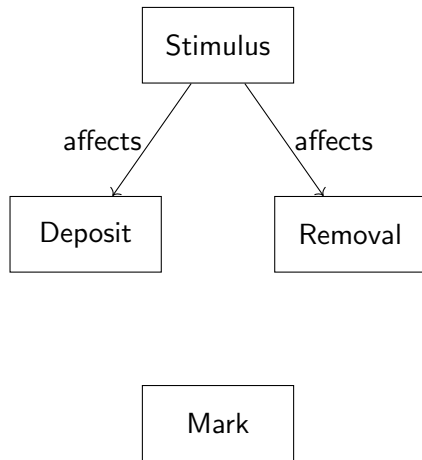Can we **emerge** a computational memory using the **stigmergy**?
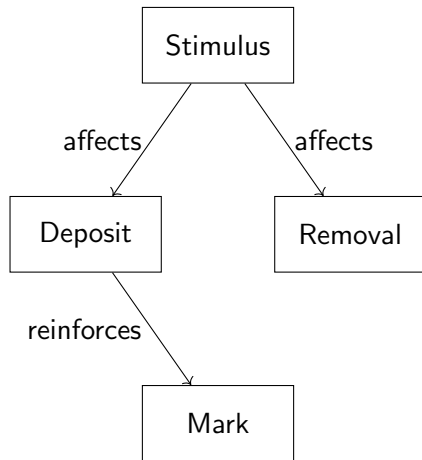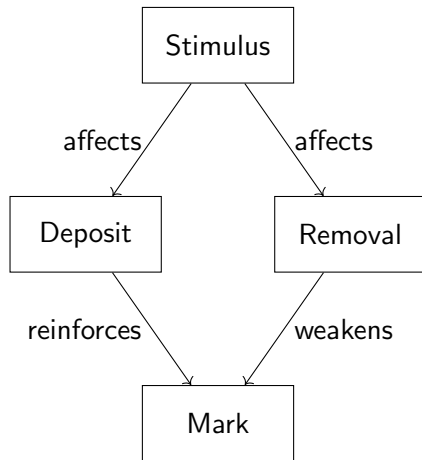
Biological Stigmergy

Implemented in nature via pheromonic marks

Biological Stigmergy

Implemented in nature via pheromonic marks

Mark

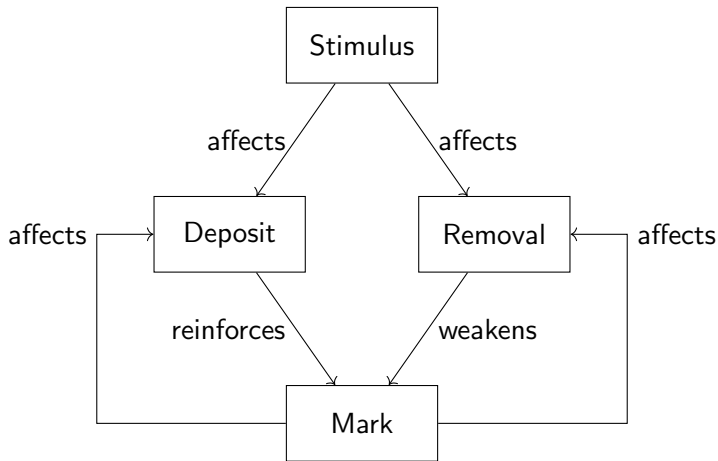# Biological Stigmergy

Implemented in nature via pheromonic marks

Stimulus

Mark

Biological Stigmergy

Implemented in nature via pheromonic marks

Stimulus

Deposit   Removal

Mark

Biological Stigmergy

Implemented in nature via pheromonic marks

Biological Stigmergy

Implemented in nature via pheromonic marks

Biological Stigmergy
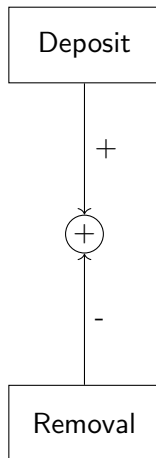
Implemented in nature via pheromonic marks

Biological Stigmergy

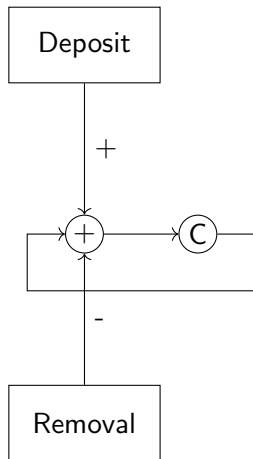Implemented in nature via pheromonic marks
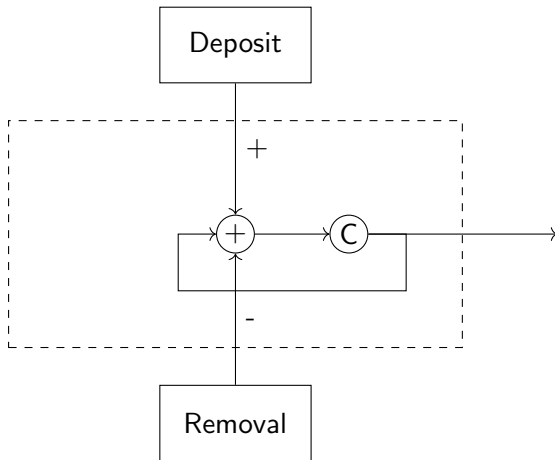
Computational Stigmergy

Deposit

Removal

Computational Stigmergy
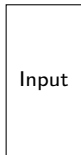
Computational Stigmergy

Computational Stigmergy

Stigmergic Memory ML Architecture

Stigmergic Memory ML Architecture

Input

Stigmergic Memory ML Architecture

Stigmergic Memory ML Architecture

Deposit ML System

Input

Stigmergic Memory
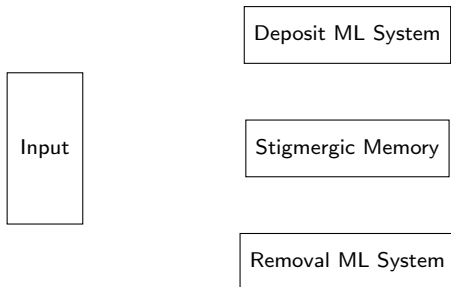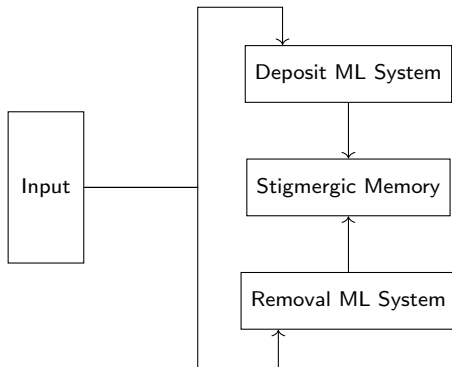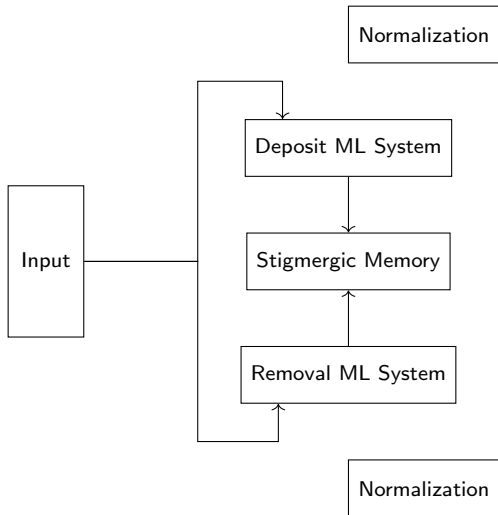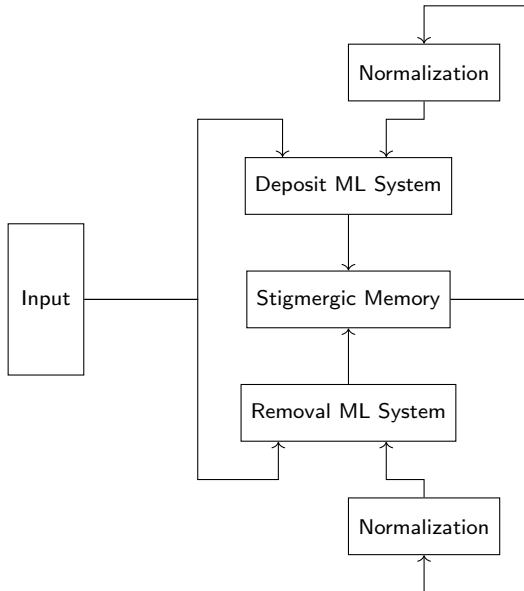
Removal ML System

Stigmergic Memory ML Architecture

Stigmergic Memory ML Architecture

Stigmergic Memory ML Architecture

Stigmergic Memory ML Architecture