Evaluation of flow of information between skyrmions in cellular automaton-type device

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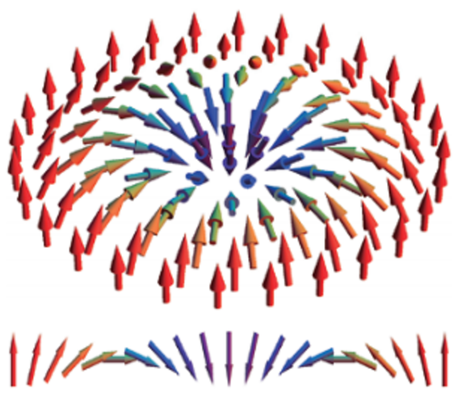
1. Introduction

1.1 Skyrmion

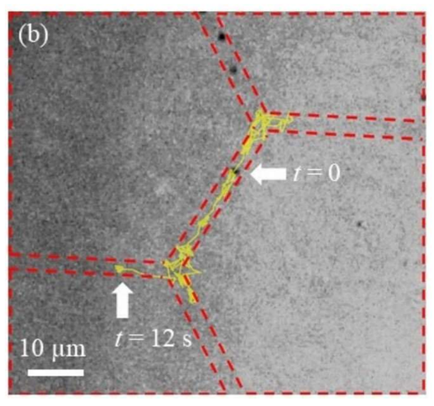


A quasiparticle that exhibits a vortex-like spin orientation in a magnetic material.

L. Kezsmarki *et al.*, Nat. Mater., **14**, 1116 (2015)

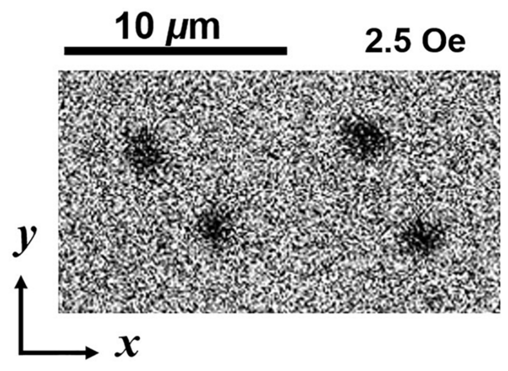
・Features

・ Brownian motion in a magnetic film



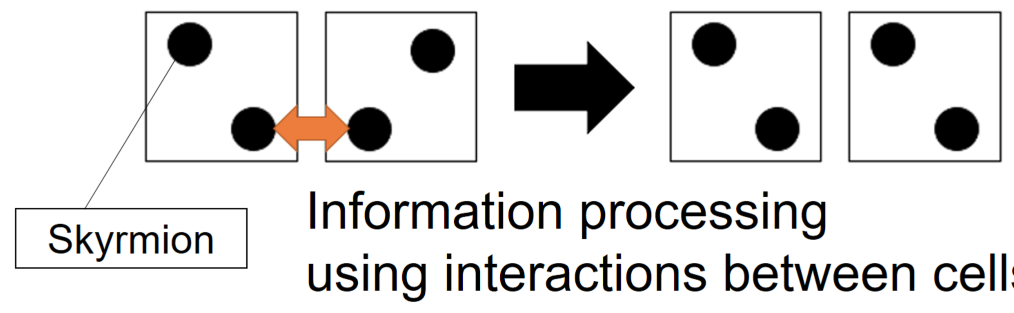
Y. Jibiki et al., Appl. Phys. Lett. **117**, 082402 (2020)

・ Repulsive interactions between skyrmions

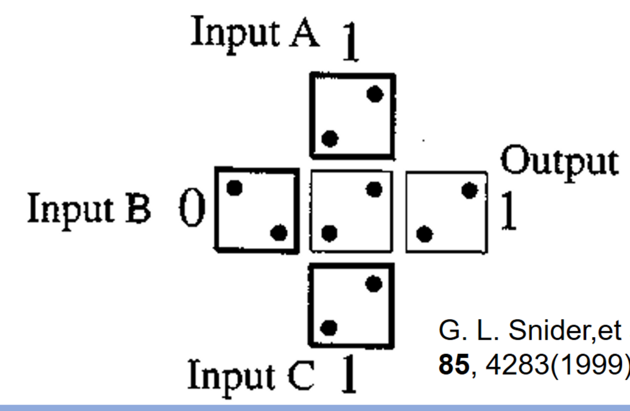


R. Ishikawa *et al.*, Appl. Phys. Lett., **119**, 072402 (2021)

1.2 Skyrmion cellular automaton



Information processing using interactions between cells



G. L. Snider,et al., J. Appl. Phys., **85**, 4283(1999).

Reversible logic operations that can transfer information with ultra-low energy consumption

Flow of information is critical to device performance

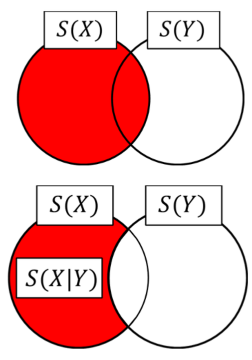
1.3 Flow of Information

T. Sagawa, M. Ueda, Phys. Rev. Lett. **100**, 080403(2008)

Shannon entropy : Randomness of random variable a_n

$$S(a_n) = -k_B \sum_{a_n} p(a_n) \ln p(a_n)$$

$p(x)$: Probability of event x occurring



Conditional Shannon entropy :
Randomness of random variable a_{n+j} when a_n is known

$$S(a_{n+j}|a_n) = -k_B \sum_{a_{n+j},a_n} p(a_{n+j}, a_n) \ln p(a_{n+j}|a_n)$$

Mutual information : Correlation of two random variables

$$I(a_n: b_n) = S(a_n) - S(a_n|b_n) = S(b_n) - S(b_n|a_n)$$

The flow of information : Partial differentiation of mutual information

$$\dot{I_{b_n}}(t) = \frac{I(b_{n+dt}: a_n) - I(b_n: a_n)}{dt}$$

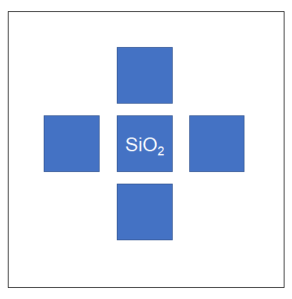
Transfer entropy :
Causal information flow for two probabilistic time series data

$$I^{tr}(a_n \to b_{n+j}|b_n) = S(b_{n+j}|b_n) - S(b_{n+j}|a_n, b_n)$$

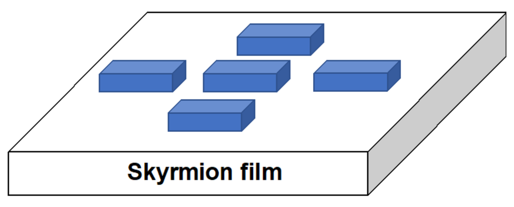
Purpose : Analyzing information current between skyrmions by the observation of their Brownian motions for the establishment of an evaluation method for device performance

2. Experiment

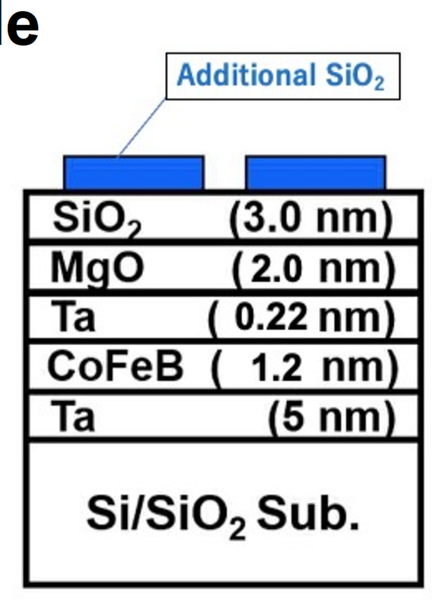
2.1 Structure of Sample



・Top View



・Perspective view



Skyrmion film

・Cross Sectional View

Skyrmions can be confined to the additional SiO_2 deposition area.
→ **Skyrmions can be confined to five squares by additional deposition on design**

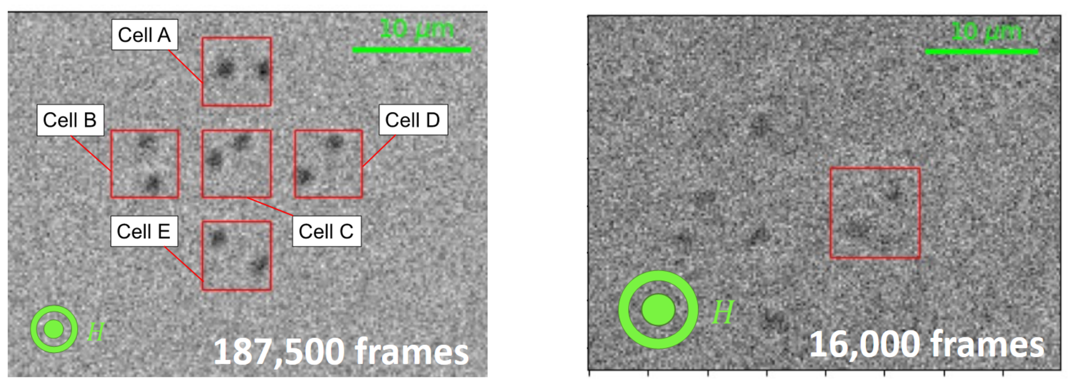
2.2 Analysis

① Obtaining the trajectory by observation of their Brownian motions

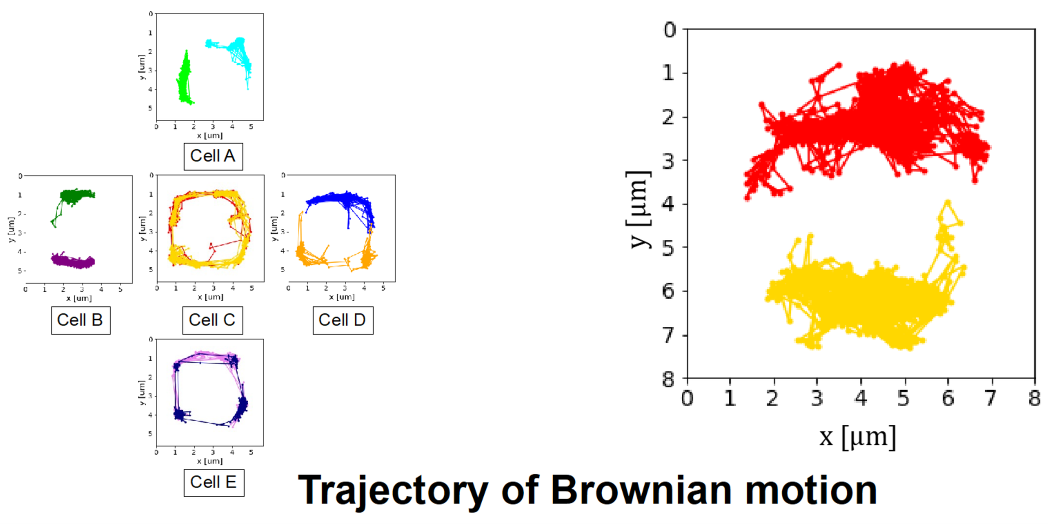
② Binarizing the position by treating the median of it as a threshold value

Skyrmion A : $a_n = [0, 0, 1, \ldots,]$
Skyrmion B : $b_n = [1, 1, 1, \ldots,]$

③ Calculation
Mutual information : $I(a_n: b_n)$
The flow of information : $\dot{I_{b_n}}(t)$
Transfer entropy : $I^{tr}(a_n \to b_{n+j}|b_n)$



Skyrmions confined in squares array

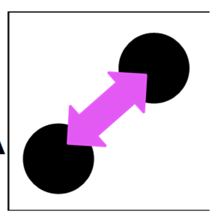


Trajectory of Brownian motion

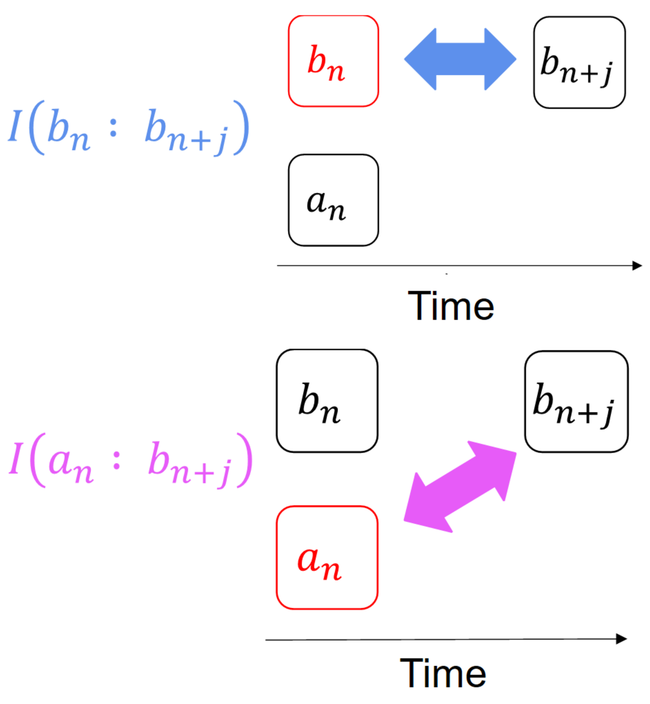
3. Result

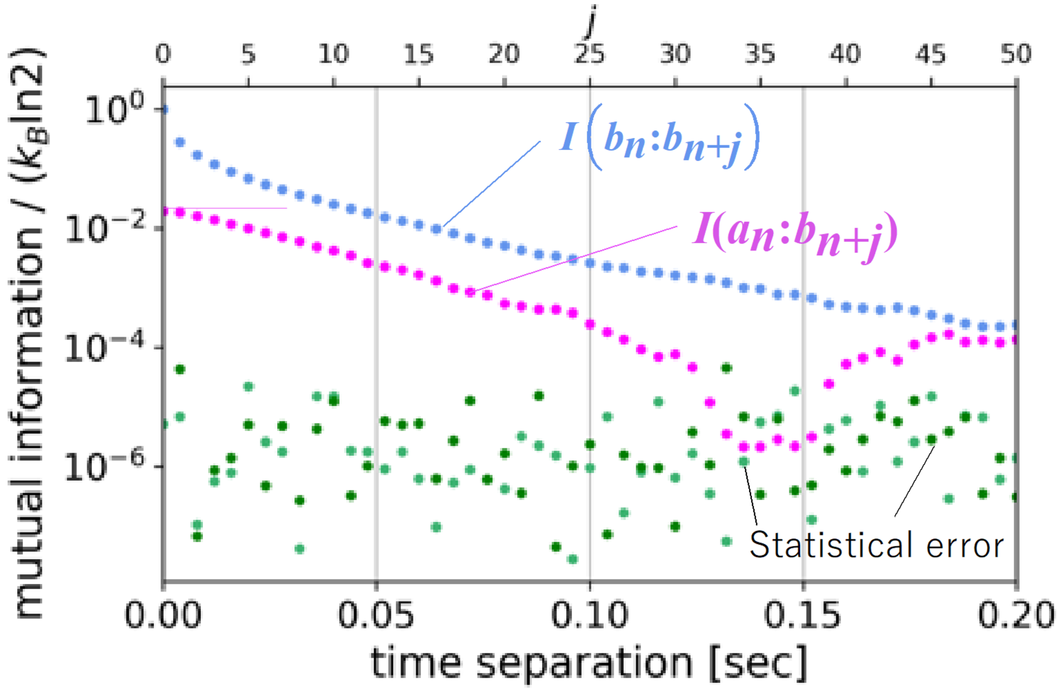
Correlation in single Cell

Skyrmion A : $a_n = [0, 0, 1, \ldots,]$
Skyrmion B : $b_n = [1, 1, 1, \ldots,]$

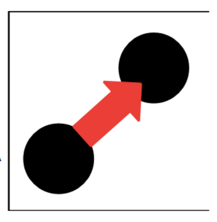


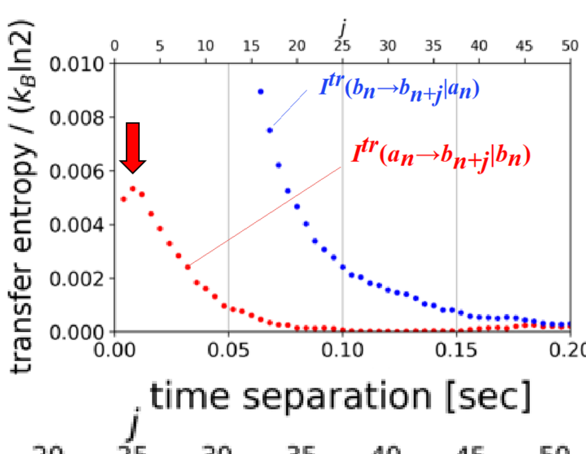
・**Mutual information**



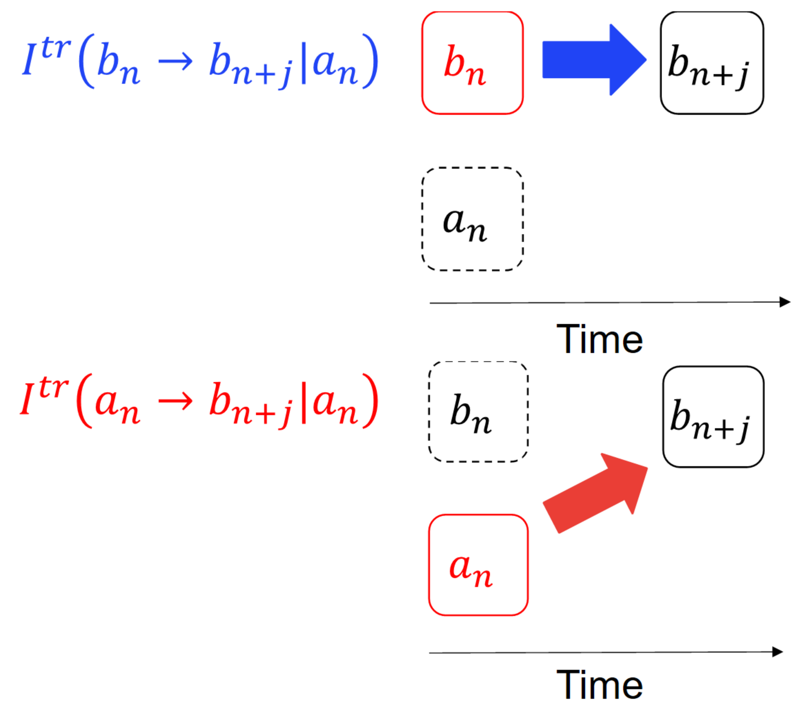


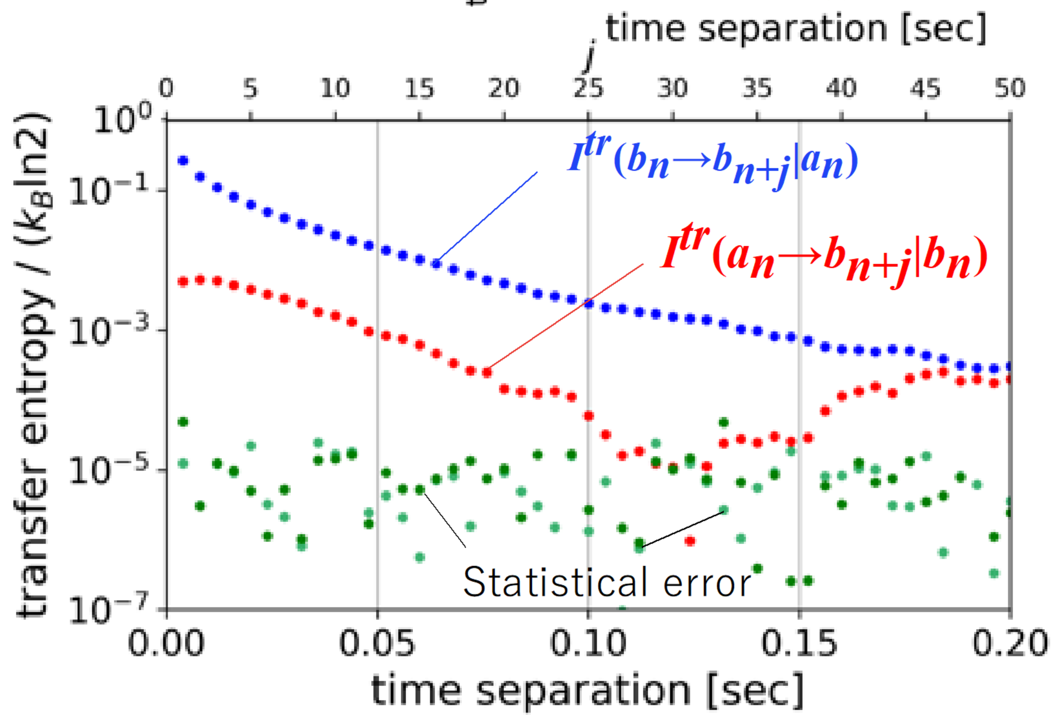
Skyrmion A : $a_n = [0, 0, 1, \ldots,]$
Skyrmion B : $b_n = [1, 1, 1, \ldots,]$





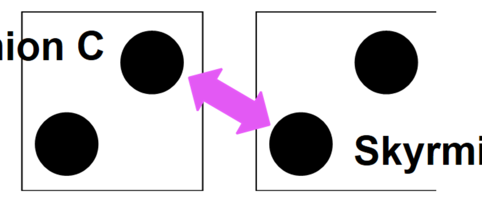
・**Transfer entropy**

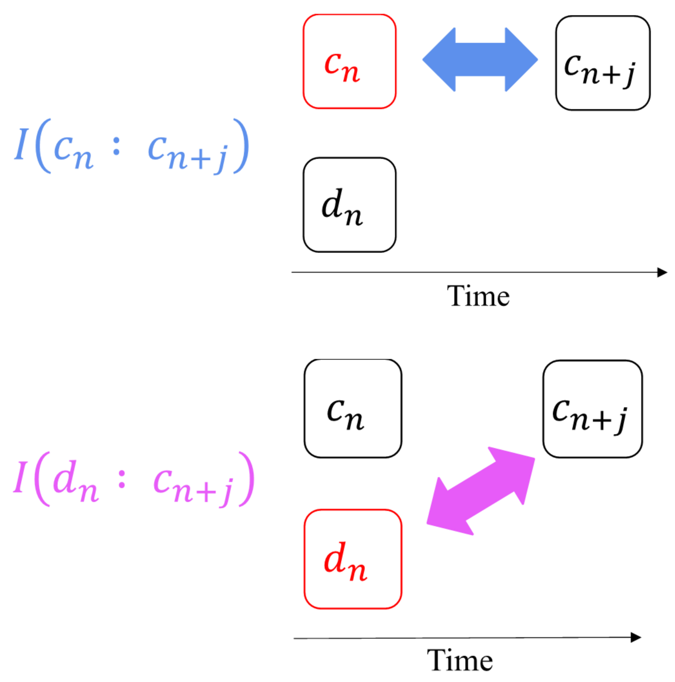


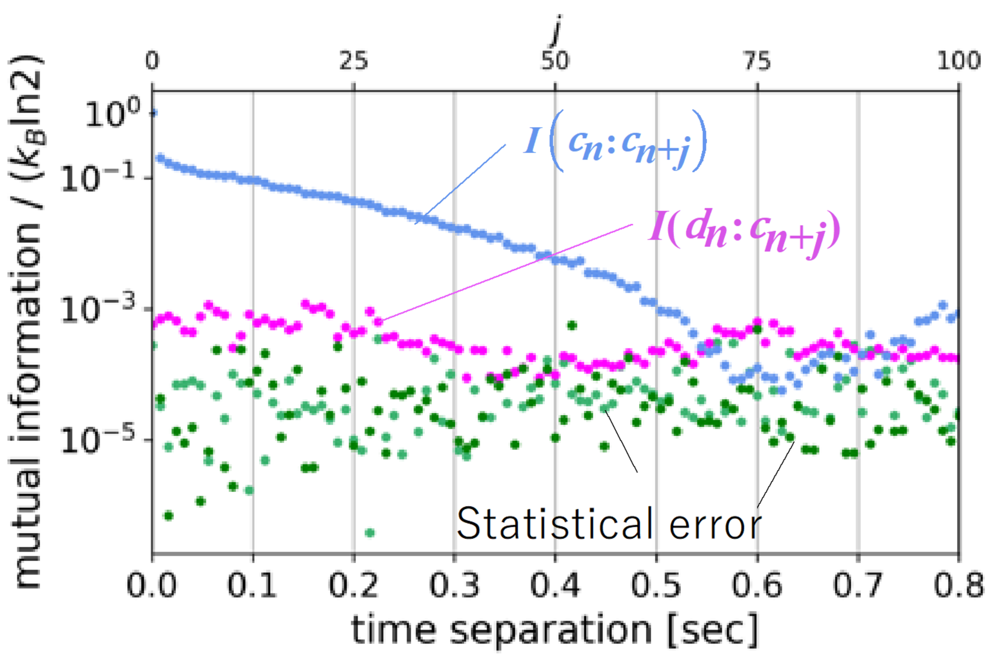


Correlation between Cell D and Cell E

Skyrmion in Cell C : $c_n = [1, 0, 1, \ldots,]$
Skyrmion in Cell D : $d_n = [0, 1, 1, \ldots,]$

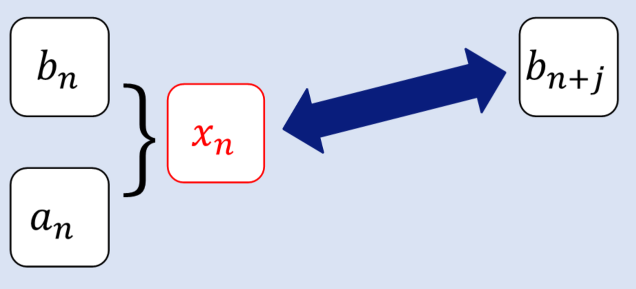






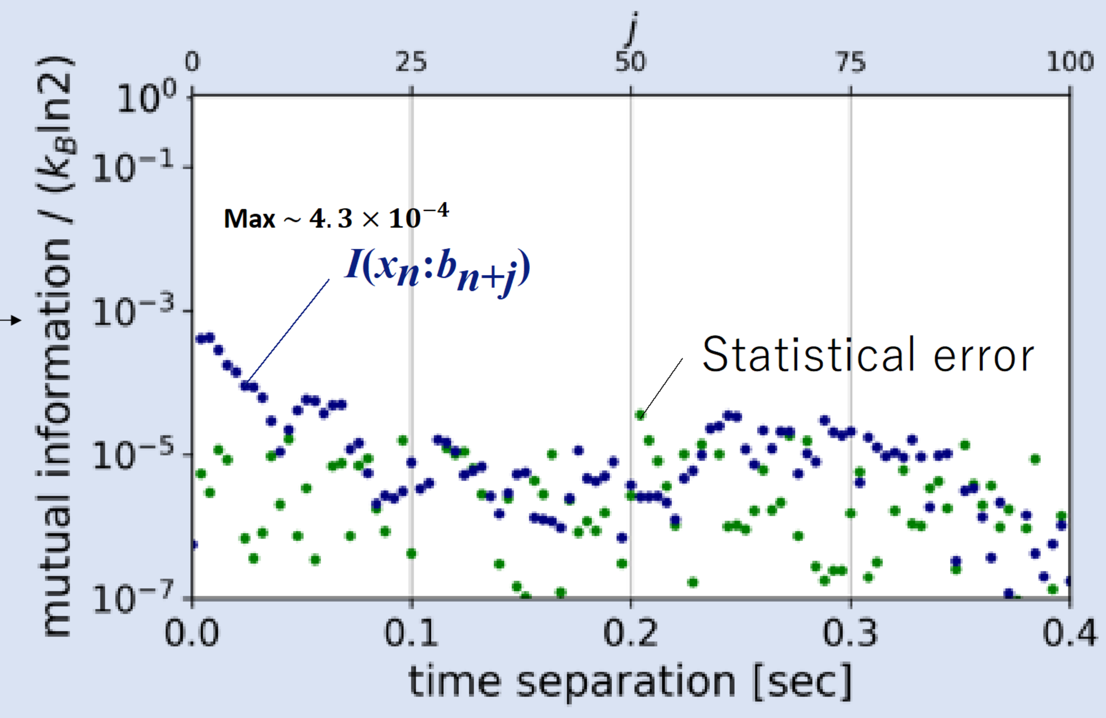
Evaluation of arithmetic functions -XOR operation-

・**Mutual information**



Input 1	Input 2	Output
0	0	0
0	1	1
1	0	1
1	1	0

XOR operation



The analytical system is partially performing natural computation.
The computing power of the system could be evaluated in detail.

4. Conclusion

- **Flow of information between skyrmions in a single cell takes about 0.01 second.**
- **There is no unidirectional flow of information in steady state.**
- **The computing power of the system could be evaluated in detail by taking a large number of pictures at a higher speed.**

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