

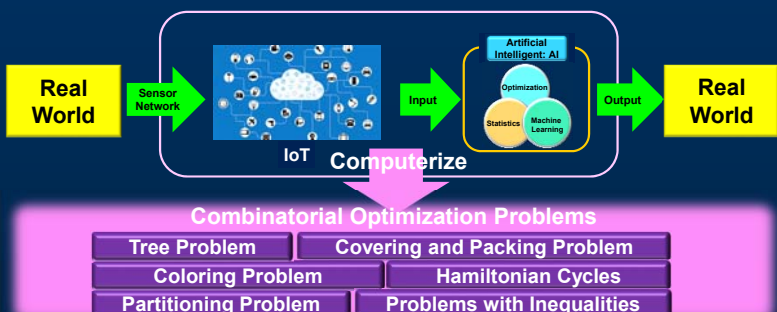
Prompt Decision Method for Ground-State Searches of Natural Computing Architecture Using 2D Ising Spin Model

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1. Natural Computing



Solving Combinatorial Optimization Problems Using Conventional Computing

No algorithms are currently available to find solutions for these problems in polynomial time.

Cuckoo Algorithm



Y. Zhou et al., Appl. Math. Inf. Sci. 7 (2013) 785.

Ant Colony Algorithm



G. Bhardwaj et al., International Journal of Computer Applications 99 (2014) 9.

Nature Based Inspired Computing Architecture to Solve Combinatorial Optimization Problems

Brain Chip



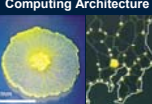
R. F. Service, Science 345 (2014) 614.

D-Wave 2X



M. W. Johnson et al., Nature 473 (2011) 194.
S. Boixo et al., Nature Phys. 10 (2014) 218.

Amoeba-Inspired Computing Architecture



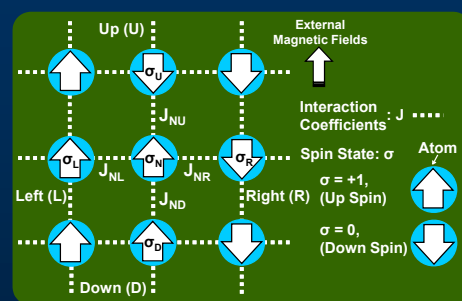
Atsushi Tero et al., Science 327 (2010) 439.

CMOS Ising Computing Chip



M. Yamaoka et al., IEEE J. Solid-St. Circ. 51 (2016) 303.

2. Ising Spin System Using Digital Logic Gates



I. XNOR gates are implemented to combine information from neighbors (product of spin state and interaction coefficient).
II. σ_N is determined by $\sigma_U, \sigma_L, \sigma_R,$ and σ_D .

Relation between Input and Output States of Spins

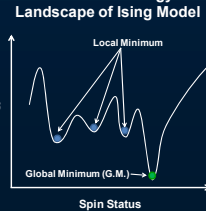
Input	Output
Adjacent Spin σ_N	Target Spin σ_N
Interaction Coefficients J_{ij}	
0	0
0	1
1	0
1	1

Hamiltonian: H

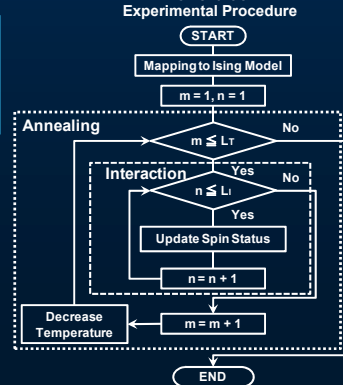
Energy function of Ising spin model is calculated using following equation.

$$H = -\sum_{i,j} J_{ij} \sigma_i \sigma_j - \sum_i h_i \sigma_i$$

Schematic Energy Landscape of Ising Model



Flowchart of Experimental Procedure



Calculation Condition

CPU: Core i7 970
OS: Windows 10
Frequency: 3.2 GHz
Number of Cores: 6

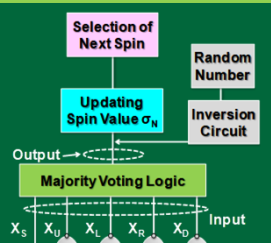
L_T: Number of Temperature Update
L_I: Number of Spin Status Update (Interaction Steps)

3. Calculation Experiments on Ground-State Searches of Maximum-Cut Problem

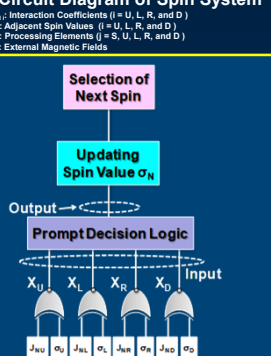
Majority Voting Logic

Relation between Input and Output States of Majority Voting and Prompt Decision Methods

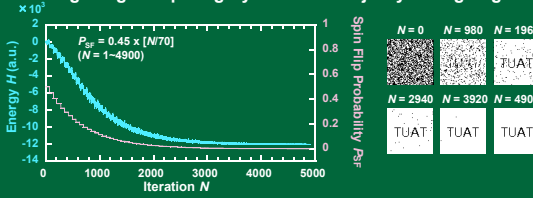
Input	Output
Processing Elements X_1, X_2, X_3, X_4, X_5	Majority Voting Method
1 0 0 0 0	0
1 0 0 0 1	0
1 0 0 1 0	0
1 0 0 1 1	1
1 0 1 0 0	0
1 0 1 0 1	1
1 0 1 1 0	1
1 0 1 1 1	1
1 1 0 0 0	0
1 1 0 0 1	1
1 1 0 1 0	1
1 1 0 1 1	1
1 1 1 0 0	1
1 1 1 0 1	1
1 1 1 1 0	1
1 1 1 1 1	1



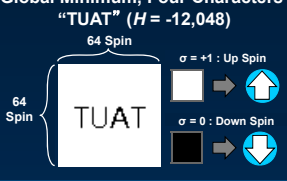
Circuit Diagram of Spin System



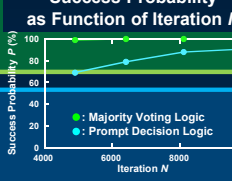
Energy Convergence Properties for Solving Max-Cut Problem Using Ising Computing System with Majority Voting Logic



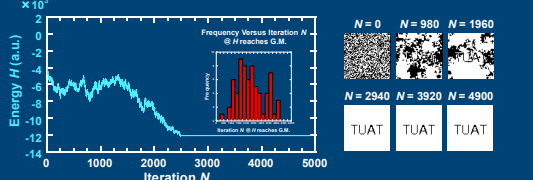
Global Minimum, Four Characters "TUAT" ($H = -12,048$)



Success Probability as Function of Iteration N

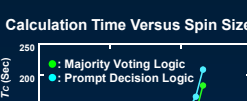


Energy Convergence Properties for Solving Max-Cut Problem Using Ising Computing System with Prompt Decision Logic



Relationship between Problem Size (Number of Spins)

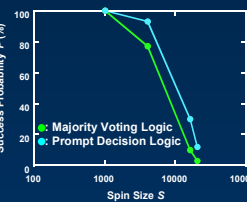
Global Minimum Solution "Chess-Board Pattern"



Calculation Time Versus Spin Size



Success Probability Versus Spin Size



Prompt Decision Logic (without Annealing Schedule)

4. Conclusions

- ◆ **Ground-State Searches of Natural Computing Architecture by Two-Dimensional Ising Spin Model**
 - Optimum solution searches of Ising spin model can be achieved by nearest-neighbor ferromagnetic exchange interactions of 2D spins.
- ◆ **Prompt Decision Method for Optimum Solution Searches of Ising Spin System**
 - Cell has no inversion circuit, and next state of spin is determined by selecting randomly one of nearest-neighbor spins.
 - Local energy of two-dimensional Ising spin model is spontaneously increased by the interaction operations of prompt decision method.

Possibilities of Ground-State Searches of 2D Ising Spin Model Using Prompt Decision Method