Physical Fluctuomatics
1st Review of probabilistic information processing

Kazuyuki Tanaka
Graduate School of Information Sciences
kazu@smapip.is.tohoku.ac.jp
http://www.smapip.is.tohoku.ac.jp/~kazu/

Webpage:
http://www.smapip.is.tohoku.ac.jp/~kazu/PhysicalFluctuomatics/
Textbooks


References of the present lecture

Benefit of Information & Communications Technology

- Ubiquitous Computing
- Ubiquitous Internet

→ Benefit of Information & Communications Technology

Demand for Intelligence

It cannot be satisfied only with it being only cheap and being quick.
Information processing for numerical calculations
- Definite Procedure has been given for each calculation.

Information processing according to theories
- Inference from propositions
- Realization by progress of computational processing capacity

Information processing in real world
- Diversity of reason in phenomenon
- Compete data is not necessarily obtained.
- It is difficult to extract and select some important information from a lot of data.

Uncertainty caused by the gap of knowing simply and understanding actually.
We hope to deal successfully with such uncertainty.
Computer for next generations

Required Capacity
- Capability to sympathize with a user (Knowledge)
- Capability to put failure and experience to account in the next chance (Learning)

How should we deal successfully with the uncertainty caused by the gap of knowing simply and understanding actually?

Formulation of knowledge and uncertainty

Realization of information processing data with uncertainty
Computational model for information processing in data with uncertainty

Mathematical expression of uncertainty

=> Probability and Statistics

Probabilistic Inference

Probabilistic model with graphical structure (Bayesian network)

Medical diagnosis
Failure diagnosis
Risk Management

Inference system for data with uncertainty

Node is random variable.
Arrow is conditional probability.

Graph with cycles

Probabilistic information processing can give us unexpected capacity in a system constructed from many cooperating elements with randomness.

Important aspect
Computational Model for Probabilistic Information Processing

Bayes Formula

Probabilistic Information Processing

Probabilistic Model

Algorithm

Monte Carlo Method
- Markov Chain Monte Carlo Method
- Randomized Algorithm
- Genetic Algorithm

Approximate Method
- Belief Propagation
- Mean Field Method

Randomness and Approximation
Probabilistic Image Processing


The elements of such a digital array are called pixels. At each point, the intensity of light is represented as an integer number or a real number in the digital image data.

Algorithm

Modeling of Probabilistic Image Processing based on Conventional Filters

Conventional Filter

Markov Random Field Model

Noise Reduction by Probabilistic Image Processing

Physical Fuctuomatics (Tohoku University)
Probabilistic Image Processing


Degraded Image (Gaussian Noise)  Probabilistic Image Processing

MSE: 2137
Lowpass Filter
MSE: 520
Median Filter
MSE: 860
Wiener Filter
MSE: 767

Error Correcting Code


Error Correcting Codes

Parity Check Code

Turbo Code, Low Density Parity Check (LDPC) Code

High Performance Decoding Algorithm
Error Correcting Codes and Belief Propagation

\[ X_7 = X_1 + X_2 + X_4 \pmod{2} \]
\[ X_8 = X_3 + X_4 + X_6 \pmod{2} \]
\[ X_9 = X_2 + X_3 + X_5 \pmod{2} \]

\[ (\begin{array}{c}
    x_1 \\
    x_2 \\
    x_3 \\
    x_4 \\
    x_5 \\
    x_6 \\
\end{array}) = (\begin{array}{c}
    1 \\
    1 \\
    0 \\
    0 \\
    1 \\
    1 \\
\end{array}) \]

\[ X_7 = 1 + 1 + 0 \pmod{2} = 0 \]
\[ X_8 = 0 + 0 + 1 \pmod{2} = 1 \]
\[ X_9 = 1 + 0 + 1 \pmod{2} = 0 \]

\[ (\begin{array}{c}
    x_1 \\
    x_2 \\
    x_3 \\
    x_4 \\
    x_5 \\
    x_6 \\
\end{array}) = (\begin{array}{c}
    1 \\
    1 \\
    0 \\
    0 \\
    1 \\
    1 \\
\end{array}) \]

\[ (\begin{array}{c}
    y_1 \\
    y_2 \\
    y_3 \\
    y_4 \\
    y_5 \\
    y_6 \\
\end{array}) = (\begin{array}{c}
    1 \\
    1 \\
    1 \\
    0 \\
    1 \\
    1 \\
\end{array}) \]

Binary Symmetric Channel
Error Correcting Codes and Belief Propagation

\[ X_7 = X_1 + X_2 + X_4 \pmod{2} \]
\[ X_8 = X_3 + X_4 + X_6 \pmod{2} \]
\[ X_9 = X_2 + X_3 + X_5 \pmod{2} \]

Fundamental Concept for Turbo Codes and LDPC Codes
CDMA Multiuser Detectors in Mobile Phone Communication


- Relationship between mobile phone communication and spin glass theory

Signals of User A

Coded Signals of User A

Spreading Code Sequence

Wireless Communication

Received Data

Noise

Decoded Signals of Other Users

Coded Signals of Other Users

Probabilistic model for decoding can be expressed in terms of a physical model for spin glass phenomena
Artificial Intelligence

Bayesian Network


Probabilistic inference system

Practical algorithms by means of belief propagation
Main Interests
Information Processing:
  Data
Physics:
  Material,
  Natural Phenomena

System of a lot of elements with mutual relation
Common Concept between Information Sciences and Physics

Data is constructed from many bits

A sequence is formed by deciding the arrangement of bits.

A lot of elements have mutual relation of each other

Some physical concepts in Physical models are useful for the design of computational models in probabilistic information processing.

Materials are constructed from a lot of molecules.

Molecules have interactions of each other.
Compensation of expressing uncertainty using probability and statistics

It must be calculated by taking account of both events with high probability and events with low probability.

Computational Complexity

It is expected to break throw the computational complexity by introducing approximation algorithms.
What is an important point in computational complexity?

How should we treat the calculation of the summation over $2^N$ configuration?

$$\sum_{x_1=T,F} \sum_{x_2=T,F} \cdots \sum_{x_N=T,F} f(x_1, x_2, \cdots, x_N)$$

If it takes 1 second in the case of $N=10$, it takes 17 minutes in $N=20$, 12 days in $N=30$ and 34 years in $N=40$.

```plaintext
a ← 0;
for(x_1 = T or F) {
  for(x_2 = T or F) {
    :  
    for(x_N = T or F) {
      a ← a + f(x_1, x_2, ..., x_L);
    }
  }
}
N fold loops
```
Why is a physical viewpoint effective in probabilistic information processing?

Materials are constructed from a lot of molecules. (10^{23} molecules exist in 1 mol.)

Molecules have intermolecular forces of each other

\[ \sum_{x_1} \sum_{x_2} \cdots \sum_{x_N} f(x_1, x_2, \cdots, x_N) \]

Theoretical physicists always have to treat such multiple summation.

Probabilistic information processing is also usually reduced to multiple summations or integrations.

Application of physical approximate methods to probabilistic information processing
Academic Circulation between Physics and Information Sciences

Understanding and prediction of properties of materials and natural phenomena

Common Concept

Statistical Mechanical Informatics

Academic Circulation

Statistical Sciences

Probabilistic Information Processing

Extraction and processing of information in data

Physics

Information Sciences

Physical Fuctuomatics (Tohoku University)
Summary of the present lecture

- Probabilistic information processing
- Examples of probabilistic information processing
- Common concept in physics and information sciences
- Application of physical modeling and approximations

Future Lectures

- Fundamental theory of probability and statistics
- Linear model
- Graphical model