A Note on Classification of Binary Signal Set in the View of Hadamard Equivalence

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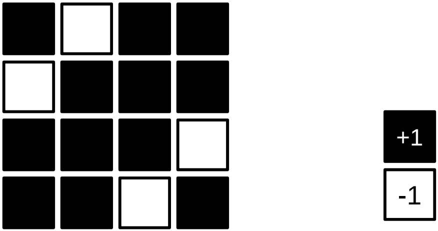
A Brief Review about the Hadamard Equivalence

Hadamard Matrix



- A Hadamard matrix of order n (or, size $n \times n$) is defined as an $n \times n$ matrix with all entries $+1$ or -1 such that

$$H \cdot H^T = nI,$$

where I is the $n \times n$ identity matrix.
- In other word, the rows of a Hadamard matrix are orthogonal

Studies on Hadamard Matrices

- Hadamard matrix is widely used in communication and signal processing:
  - Orthogonal Channelization in CDMA communication systems
  - Construction of orthogonal signals and LCZ/ZCZ signals
  - Hadamard Transform is widely used in image processing
- Theoretical/Mathematical research on Hadamard matrices:
  - Existence/Constructions
  - Classification/Equivalence/Inequivalence
- This paper is to study on how to check equivalence of two Hadamard matrices EFFICIENTLY, and generalize this idea to binary matrices in general

Hadamard Equivalence

- If H is a Hadamard matrix, then the matrix that is the result of applying following operations to H is also a Hadamard matrix:
  - Multiply -1 to all elements of some rows (row complement)
  - Multiply -1 to all elements of some columns
  - Row permutation (Exchange the position of rows)
  - Column permutation
- These operations are called as 'Hadamard-preserving operation'.
- If a Hadamard matrix B can be obtained by applying Hadamard-preserving operations to H, then we say H and B are Hadamard-equivalent

Number of Inequivalent Matrices

The size of matrices	Number of Inequivalent Hadamard Matrices
1,2,4,8,12	1
16	5
20	3
24	60
28	487
≥ 32	Unknown

Integer Representation of a Binary Matrix

Definition

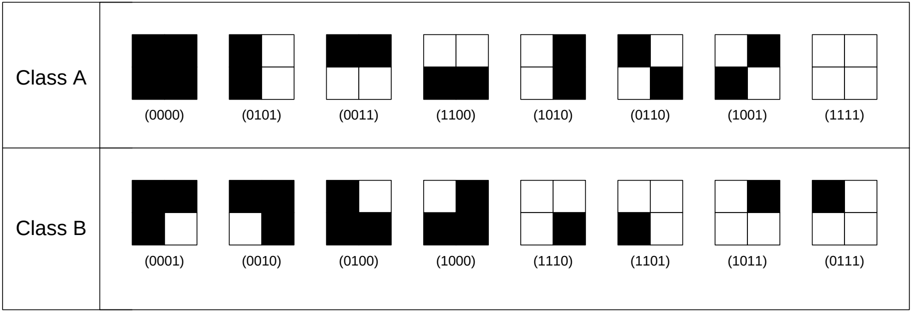
Let $A = (a_{ij})$ be an $m \times n$ binary matrix, where $i = 1, 2, ..., m$ and $j = 1, 2, ..., n$. Then,

$$\rho(A) \triangleq \sum_{i=1}^{m} \sum_{j=1}^{n} \left[a_{ij} 2^{n(m-i)+(n-j)} \right]. \qquad (1)$$

Example:

$$\rho \begin{pmatrix} 0 & 1 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{pmatrix} = 0101\ 0110\ 1001\ 1110_{(2)} = 22174$$

Minimal Matrix - Example

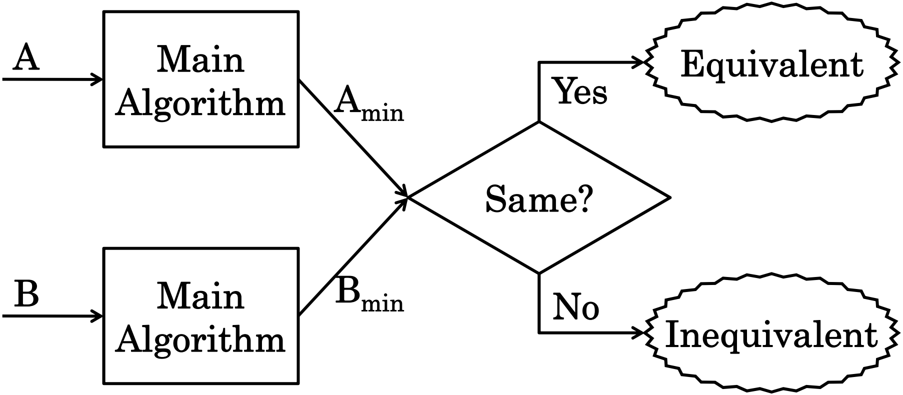


Description of the Proposed Scheme

To Check Equivalence/Inequivalence

- Two binary matrices are Hadamard-equivalent if they belong to the same class
- An equivalence class has only one minimal matrix
- Find the minimal matrices of (classes of) two binary matrices in question, and then see if they are the same or not
- How to find it?

Equivalence Check by Using Main Algorithm



Complexity of the Proposed Scheme

Theorem

1. *All elements in the first row and the first column of a minimal matrix are zero.*
2. *Given a binary matrix H and its minimal matrix L, there exist permutation matrices P_r and P_c (not necessarily unique) such that*
$$L = N(P_r H P_c). \tag{2}$$
3. *When P_r and the first column of P_c are known, the remaining columns of P_c can be determined in* (2).

- Checking whole P_r and the first column of $P_c = \mathcal{O}(m!n)$
- Determining $P_c = \mathcal{O}(nlogn)$ using Quicksort
- Overall complexity: $\mathcal{O}((m!)n^2 logn)$

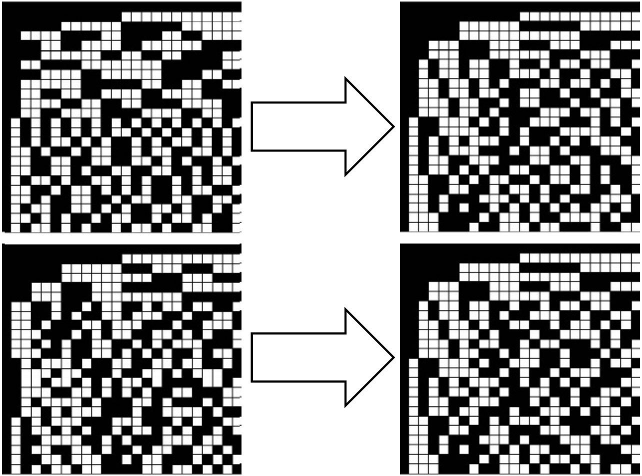
Some Applications of the Proposed Scheme

Problem	Result	CPU Time
20×20 Williamson - apply HPOs randomly	All equivalent decision	40 seconds for each
All 24×24 inequivalent Hadamard matrices	All inequivalent decision	3 to 15 minutes for each
60×60 Paley I/II	Inequivalent decision	I: 30 hours, II: 3 hours
Various size of random binary matrices	Successful decisions	Less than 1 second when size < 50

Examples of Order 24

Two Hadamard matrices of order 24

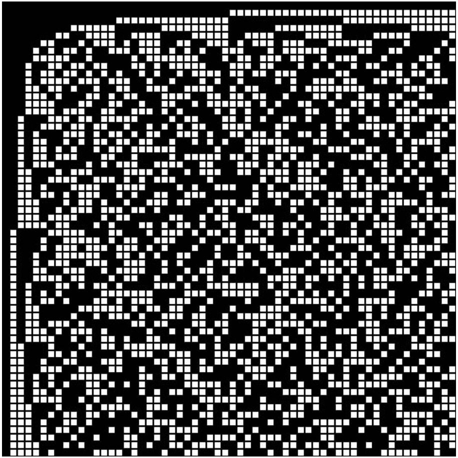
Their minimal matrices



Examples of Order 60

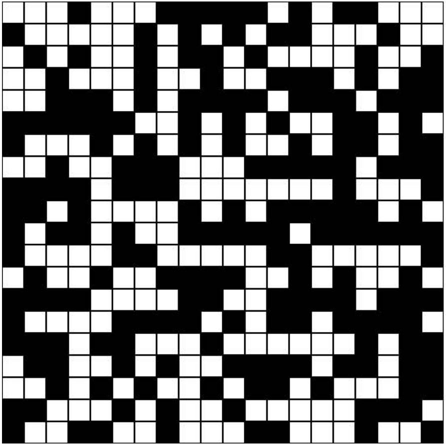
Minimal Matrices of Payley type I and II

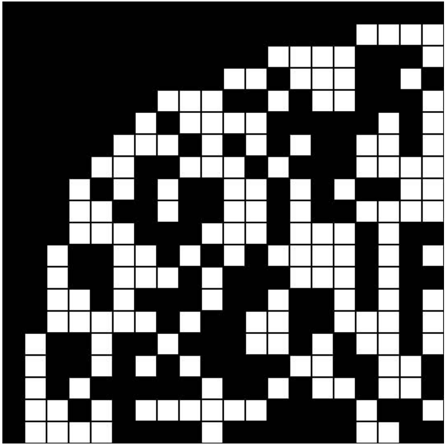
$\Longrightarrow$ This shows they are inequivalent.



Examples of General Binary Matrix

Minimal Matrix of a Random Binary Matrix of Size 20





Fast Algorithm (Not in the Paper)- Basic Idea

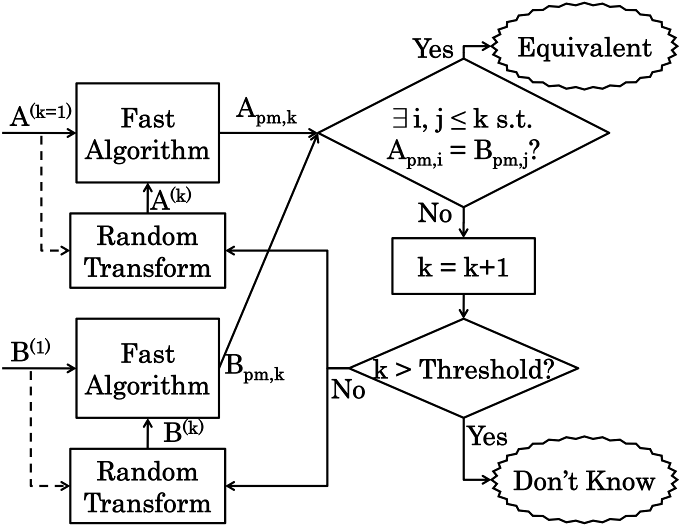
- Calculation time highly depends on the matrices, For example, 32×32 Kronecker type matrix takes too long time to get output by the main algorithm
- When progress is slower, the minimal matrix gets out faster, and almost all matrices' minimal matrix is found at very early time
  - For example, 60×60 Payley II took 3 hours to finish
  - But the time when the minimal matrix is found is about 2 minutes after the algorithm started
  - And Payley I's time, which took 30 hours, was only 15 seconds
- So if two matrices are equivalent, same minimum may be found in reasonably short time

Fast Algorithm

- Step 1. Operate the main algorithm with A
- Step 2. When certain time (threshold time) passes, stop and get the minimal matrix stored

- We can't assure the result becomes the minimal matrix if algorithm is not completed
- But it may be with high probability when the threshold time is sufficiently long
- We call the result of the Fast Algorithm as pseudo-minimal matrix

Equivalence Check by Using Fast Algorithm



Conclusion and Future Work

- We propose an efficient scheme to check Hadamard-equivalence of binary matrices
- We show the results of this scheme for some Hadamard matrices and binary matrices
- We also propose some basic theorems about the minimal matrix (in the paper)

- Generalization of the problem - numer of inequivalent Hadamard matrix - to the set of $m \times n$ binary matrices (especially all sizes) could lead to new and interesting combinatorial problems