

Searching Algorithm for Match Mapping in Kidney Exchange Program

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Abstract—Before kidney transplant is performed, the kidney donor and the kidney recipient must be a compatible pair. In reality, it's not uncommon that incompatibility occurs between the donor-recipient pair. To solve this problem, Kidney Exchange Program was created so that an incompatible pair can exchange the kidney to another incompatible pair, making cross donation easier. But to search for the optimal match map from incompatible pairs pool is not an easy task. Match map searching algorithm is an algorithm created for this task. Edmond's Algorithm, the existing algorithm, is suboptimal because it closes the possibility of three or more-way exchanges. Therefore, in this paper, by modifying existing two-way match map searching algorithms, N -way match map searching algorithm is implemented. Based on the test results, using 3000 incompatible pairs data, it is proven that N -way match map searching algorithm is superior in terms of matching efficiency compared to the two-way match map searching algorithm. The increase in matching efficiency obtained on average reaches 7.75% in comparison to the matching efficiency obtained by Edmond's Algorithm.

Index Terms—kidney transplantation, kidney exchange, match map searching algorithm

I. INTRODUCTION

Kidney transplantation is the most recommended treatment method for serious kidney diseases [1]. Every year, in Indonesia alone, there are more than 100,000 patients with kidney transplantation needs. But among those patients, only about 20% can get a kidney transplantation [2]. There are many types of problems that leads to this condition, for example financial problems, public opinions, and the most common, kidney availability. Even though live donor numbers are steadily increasing [3], availability problem arises because many criteria must be met before kidney transplant can be performed [2]. The donor needs to have a healthy kidney, matching blood type, and no blood-borne diseases. Also, the patient's immune system must be able to accept the donor's kidney without killing it.

A. Kidney Transplant Prerequisites

There are few tests that have to be performed before kidney transplant can be done [4]. The blood type test is performed to both the donor and the recipient. Donors can only make a donation if one's blood type is compatible with the recipient's blood type. In Table I, number 1 indicates compatibility and 0 indicates incompatibility. Donors with blood type O are considered Universal Donors because they can give donors to every patients regardless of the blood type. Recipients with blood type AB are considered a Universal Recipients because

TABLE I
BLOOD TYPE COMPATIBILITY BETWEEN PATIENT AND DONOR [8]

Donor \ Recipient	O	A	B	AB
O	1	0	0	0
A	1	1	0	0
B	1	0	1	0
AB	1	1	1	1

they can accept kidney donation from every donors regardless of the blood type [5]. The immune test is performed after the donor-recipient pair passes the blood type test [4]. The tests are cross match test and Human Leucocyte Antigen (HLA) test. In cross match test, donor's blood are met with recipient's blood to see whether there is a resistance reaction from recipient's immune system. The resistance reaction happens when the donor kidney is considered a foreign object that must be killed by recipient's immune system [6]. HLA test tests the same reaction as cross match test, but donor's and recipient's tissue cells are being used instead of blood [7]. Finally, to test whether the donor has any blood-borne diseases, serology is performed [6].

B. Kidney Exchange Program

Because of kidney transplant prerequisites, Kidney Exchange program named Kidney Paired Donation (KPD) was created so that an incompatible donor-recipient pair can exchange their incompatible kidney to another incompatible pair, making cross-donation possible [8]. The kidney exchange can be done two-way, three-way, and can go up to N -way.

Unfortunately, because of the large number of incompatible pairs, hospitals cannot find the optimal matching solution for the pool of incompatible pairs. An algorithm that perform a mapping search is needed to address this issue. One of the most known algorithm to tackle this problem is Edmond's Algorithm [8]. In Edmond's Algorithm, the pool of incompatible pairs are represented as a graph with each node representing an incompatible pair and each edge representing a match between two incompatible pairs. The algorithm focuses on high priority pairs so that pairs who need a transplantation more can get an exchange first. Another algorithm regarding this problem is

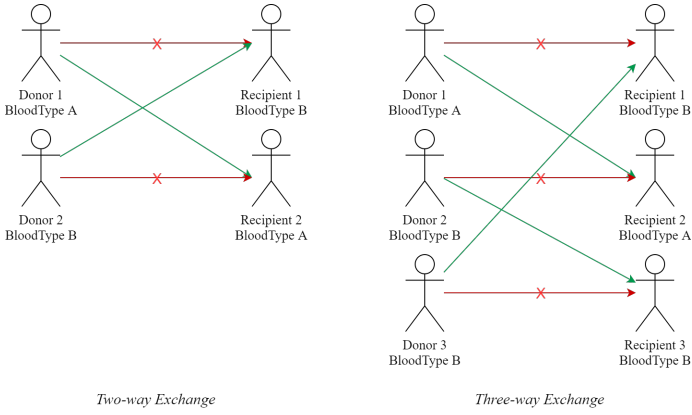


Fig. 1. Two-way(left) and Three-way(right) Exchange in KPD program

First Accept Heuristic Match [8] which focuses more on the heuristic if one registers first, then one gets an exchange first.

These algorithms are called Match Map Searching Algorithms. To evaluate and measure the performance of an algorithm, a few specific performance metrics are use [9]. There are two performance metrics to evaluate these algorithms. The first one is Matching Efficiency, which measures the number of donor-patient pairs that matched another pair and were able to exchange divided by the total number of donor-patient pairs, represented in a percentage. The second metric is execution time, which measures how long does the algorithm run to get the optimal match map, usually measured in millisecond. The best match map searching algorithm is the algorithm that can produce high matching efficiency with low execution time. Meaning that many patients can be saved as fast as possible.

As good as it looks, Edmond's Algorithm and First Accept Heuristic Match can only find two-way exchanges from the incompatible pairs pool. Meaning these algorithms are not able find a solution with three-way exchanges or more, closing the possibility.

II. METHODOLOGY

From the existing algorithms problems addressed in the previous section, match map searching algorithms that can find N -way exchanges from incompatible pairs pool are needed. By modifying existing algorithms and the used data structure, new algorithms can be created.

A. Compatibility Graph

Before creating new algorithms, incompatibility pairs pool data structure needs to be redefined. Compatibility Graph used in Edmond's Algorithm is an undirected graph [8], meaning that every edge connecting two vertices represent a back-and-forth relationship between the aforementioned two vertices, making the returned exchanges to be edges, closing up possibility of three-way exchanges or more. If the algorithm is modified to use cycle detection instead of edge detection, Edmond's Algorithm can already be used to return N -way exchanges. As seen in Fig. 2, using cycle detection yields a result with three-way exchange instead of the two-way

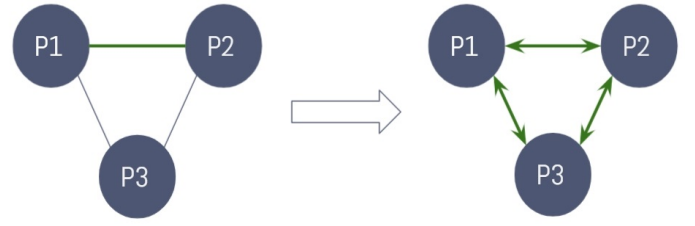


Fig. 2. Edge Detection(left) vs. Cycle Detection(right) in Compatibility Graph

exchange result returned by edge detection, resulting in a higher matching efficiency using the same compatibility graph.

B. Cycle Detection for Directed Graph

As stated in the previous subsection, edge detection used in existing algorithms needs to be converted to cycle detection. However, changing edge detection to cycle detection is not enough. The cycles returned from the graph are all back-and-forth cycles. If the compatibility graph is converted into a directed graph instead of undirected, one-way cycles can also be returned, further increasing the number of cycles, therefore increasing the matching efficiency. Directed graph is a data structure consisting a set of vertices that are connected via edges, where each edge has a one-way direction that shows the direction of movement from one vertex to another [10]. Cycle detection for directed graph is used to find the existence of a one-way path in a graph that starts and finishes at the same vertex [11].

The cycle detection algorithm being used here is a little bit different from the usual cycle detection algorithm that detects whether a graph has a cycle or not, instead this algorithm collects and returns all possible cycle in a graph in a list. Each cycle in this list is a possible exchange that can be executed. The length of the cycle represents the N in N -way exchange (e.g., a cycle with the length of 3 represents a three-way exchange). These modification is performed with the hope that the amount of cycles being detected will increase and therefore increasing matching efficiency and saving more patients.

C. N -way Match Map Searching Algorithms

With directed graph as compatibility graph and using cycle detection algorithm, N -way match map searching algorithms can be created. This algorithms receive the list of cycles returned from cycle detection and returned a reduced list of cycles called match mapping. The reduction mentioned is done because each pairs in compatibility graph can exist in more than one cycles in list of cycle, creating a many-to-many relationship among the pairs. This is obviously impossible as every pair can only donate and receive exactly one kidney. The reduction is done to change this many-to-many relationship to be a one-to-one relationship. This reduction usually leaves some pairs to be not matched at all, therefore matching efficiency is used as a performance metric to measure how many pairs can get matched out of the full incompatible pairs pool.

1) *First Accept Searching Algorithm*: The first N -way match map searching algorithm is first accept searching algorithm which is inspired by first accept heuristic match algorithm. The first-accept approach being used in this algorithm is to use the first cycles in cycles list returned from cycle detection algorithm. This algorithm ensures that no pair gets matched twice or more by deleting cycles that contains pairs that have been matched earlier.

This algorithm uses two parameters. The first parameter is the number of N , knowing that this algorithm is an N -way algorithm. The second parameter is the method to use N . The number of N can be used as a maximum or exact way of exchanges. When the maximum method is used, the algorithm will search for cycles that represents two-to- N -way exchanges. Meanwhile when exact method is used, the algorithm will search for cycles that have an exact length of N .

2) *Priority-based Searching Algorithm*: The second N -way match map searching algorithm is priority-based searching algorithm which is inspired by Edmond's algorithm. This algorithm works similarly with First Accept Searching Algorithm, but each cycle is given a priority value so that exchanges with highest priority can be returned first compared to the others.

This algorithm uses three parameters. The first two are the same parameter used in First Accept Searching Algorithm, number of N and the method to use N . The third parameter is priority assignment method. There are two methods to measure priority of every cycles. The first assignment method is the greedy method. This method assigns higher priority for longer cycles, indirectly affecting the algorithm to return more of the longer cycles with the hope that it can increase the matching efficiency. The second assignment method is the infrequent method. This method assigns higher priority for cycles with infrequent pairs. In implementation, infrequent pairs are indicated as vertices that are connected with a low number of edges, meaning that the pairs can only be matched with a low number of other incompatible pairs.

III. EXPERIMENT AND ANALYSIS

Before experiment is performed, Edmond's Algorithm is also implemented as a baseline algorithm so comparisons can be made against an existing algorithm. The data being used in this experiment can be found in this link: <https://rdm.inesctec.pt/dataset/ii-2020-001> while the source code of the implementation and the experiment can be found in this link: <https://github.com/Mingtaros/Kidney-Exchange-Match-Mapping-System>. The purpose of these experiments and evaluations are to find the algorithm and parameter combinations which can produce the best performance results based on pre-defined metrics. In addition, through the experiments, it can be concluded which N -way algorithm and parameter combinations are able to outperform the baseline, Edmond's Algorithm. Based on the pre-defined metrics, there will be comparison for Execution Time and Matching Efficiency for each algorithm.

A. Execution Time Comparison

1) *Execution Time Comparison for Different Algorithm Combinations*: For this experiment, each algorithm is used for 3000 incompatible pairs divided into 30 groups of 100. A group is called a seed. Each algorithm will be fitted with the same dataset group 50 times for every group. As seen in Figure 3, each data point in the boxplot is used to show the average execution time from the 50 executions for every dataset group, in one Y coordinate, there are 30 data points, each one for one data group.

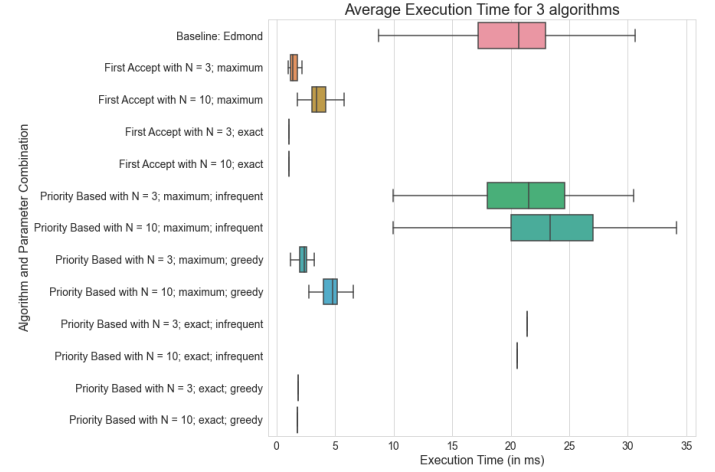


Fig. 3. Average Execution Time for 3 Algorithms

As seen from the boxplot, Edmond's Algorithm and Priority-based with infrequent method of priority assignment are the slowest algorithms. However, given that each and every algorithm does not have a significant difference in execution time, the execution time difference can be ignored.

2) *Execution Time Comparison for Different Data Sizes*: This experiment is conducted to show the effect of data size to execution time of the match map searching algorithms. For this experiment, the recorded execution time is the average execution time for each algorithm using data size of 100, 200, 300, 400, 500, 1000, 2000, as well as 3000 incompatible pairs. Each data point is the average of algorithm execution time that has been executed 10 times for each algorithm for each data size.

As seen in Figure 4, there are two plots, each one representing a group of fast algorithms and a group of slow algorithms. From the upper figure, even with 3000 incompatible pairs, the maximum algorithm runtime is around 3000 milliseconds. Meanwhile, from the lower figure, both of the algorithms can reach 600000 milliseconds (10 minutes) to process 3000 pairs. From the overall line plot, we can conclude that the relation of data size and execution time is a form of polynomial function, not linear.

B. Overall Matching Efficiency Comparison for Different Algorithms

The final experiment is conducted to show which algorithm-parameter combination is the best one in producing high

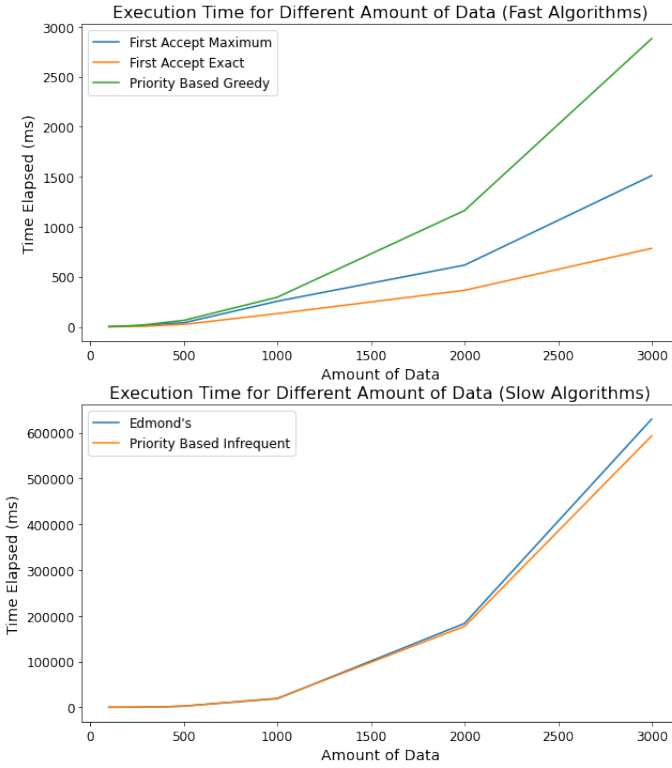


Fig. 4. Execution Time for Different Amount of Data

matching efficiency. In this experiment, each combination is used for every data seed. To ease up the comparison, in Figure 5, we use ratio of improvement in comparison to Edmond's Algorithm as a baseline shown as a horizontal line in the figure. Every data point is a matching efficiency multiplier of the matching efficiency obtained when Edmond's Algorithm is used.

To simplify the figure, Table II is used to store average matching efficiency improvement ratio in compared to baseline. The average used in the table is the average improvement ratio of an algorithm in comparison to baseline for all data seeds.

As we can see from Table II, most of N -way match map searching algorithm produces higher matching efficiency in comparison to the baseline, Edmond's Algorithm. However, some algorithms, using the exact method of using N parameter, have worse results compared to baseline. The average matching efficiency of the N -way match map searching algorithms is 7.75% higher than the baseline algorithm. The higher matching efficiency improvement is obtained when First Accept Searching algorithm is used when N is 10, maximum method of using N , with data seed 21, where the improvement against baseline is 47.06%.

IV. CONCLUSION

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V. RELATED WORK

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TABLE II
AVERAGE MATCHING EFFICIENCY RATIO OF N -WAY ALGORITHMS
COMPARED TO BASELINE

Algorithm	Average Improvement Ratio
Baseline: Edmond's Algorithm	1.0
First Accept($N=3$, Method=Max)	1.18
First Accept($N=10$, Method=Max)	1.22
First Accept($N=3$, Method=Exact)	0.94
First Accept($N=10$, Method=Exact)	1.04
Priority Based($N=3$, Method=Max, Priority=Greedy)	1.17
Priority Based($N=10$, Method=Max, Priority=Greedy)	1.26
Priority Based($N=3$, Method=Max, Priority=Infrequent)	1.14
Priority Based($N=10$, Method=Max, Priority=Infrequent)	1.16
Priority Based($N=3$, Method=Exact, Priority=Greedy)	0.94
Priority Based($N=10$, Method=Exact, Priority=Greedy)	1.04
Priority Based($N=3$, Method=Exact, Priority=Infrequent)	0.95
Priority Based($N=10$, Method=Exact, Priority=Infrequent)	0.91

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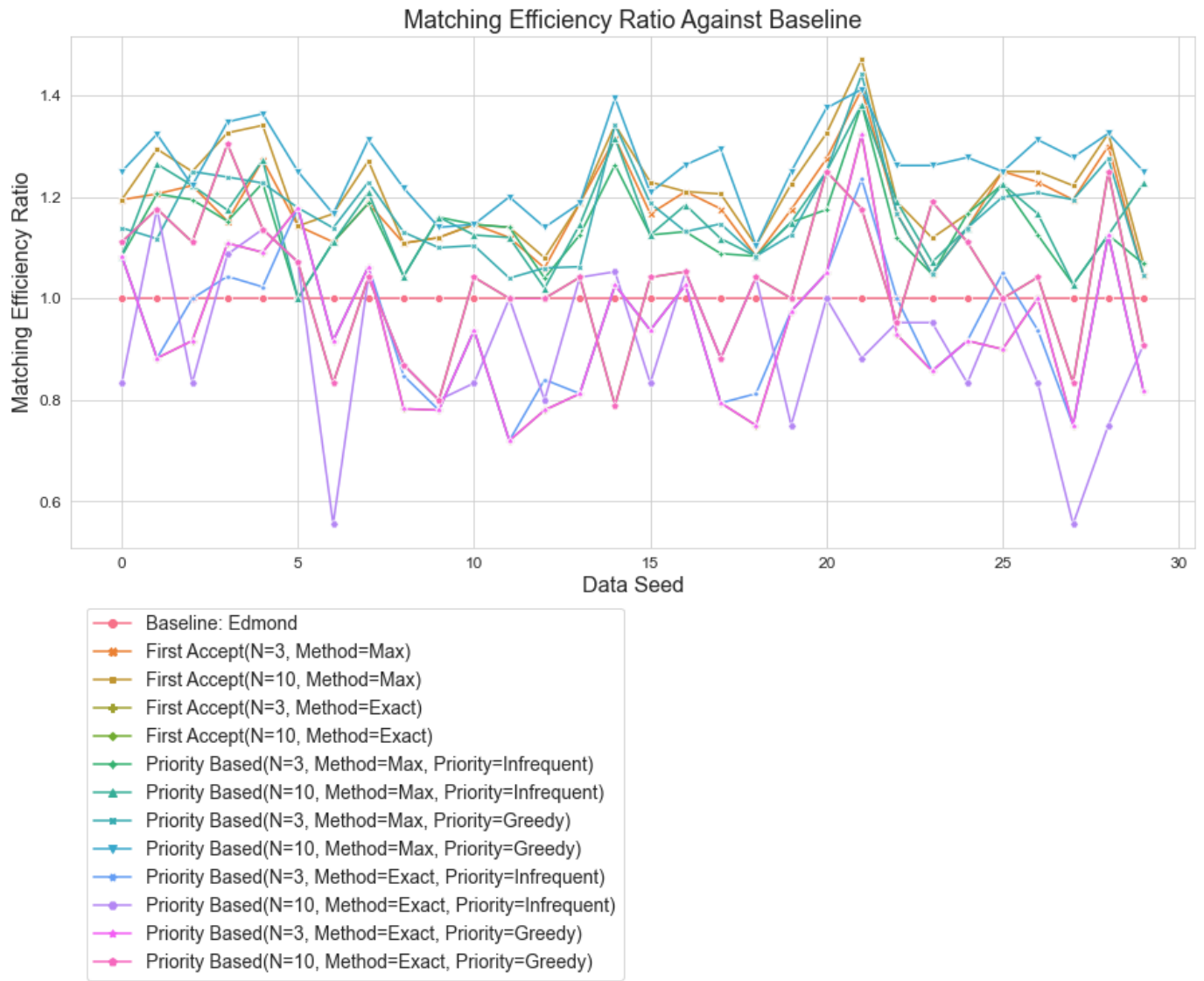


Fig. 5. Matching Efficiency Ratio of N -way Algorithms against Baseline

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