

A Comparative Study of Duplicate Record Detection Techniques

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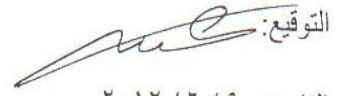
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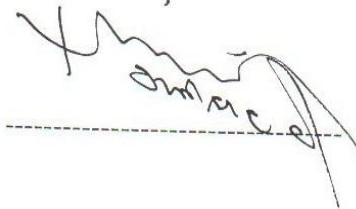
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DEDICATION

This thesis is dedicated to my parents, my brothers and sisters, for their patience, understanding and support during the time of this research.

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I am highly indebted to my supervisor Prof. Musbah M. Aqel, Faculty of Information Technology, Middle East University, for his eminent guidance, constant supervision, and overwhelming encouragement throughout my thesis work.

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Abstract

A Comparative Study of Duplicate Record Detection Techniques

**By
Osama Helmi Akel**

Duplicate record detection process is known as the process of identifying pairs of records in one or more datasets that correspond to the same real world entity (e.g. patient or customer). Despite the many techniques that have been proposed over the years for detecting approximate duplicate records in a database, there are a very few studies that compare the effectiveness of the various duplicate record detection techniques. The purpose of this study is to compare two of the proposed decision models, the Rule-based technique, and the Probabilistic-based technique, that were proposed to detect the duplicate records in a given dataset, and evaluate their advantages and disadvantages. Another aim is to design a generic framework to solve the problem of duplicate record detection. Finally, the performance of the major decision models used in record matching stage is evaluated in this study.

Recently, there exist two main techniques for duplicate record detection, categorized into techniques that rely on domain knowledge or distance metrics, and techniques that rely on training data. This study concentrates on comparison between Rule-based technique from the first category, and the Probabilistic-based technique from the second category. For the Probabilistic-based technique, instead of relying on training data, we employed the Expectation Maximization (EM) algorithm to find maximum likelihood estimates of parameters in the probabilistic models.

Experimental results on the synthetic datasets are called FEBRL, which contains patients' data of different sizes and error characteristics. These results show that the

Probabilistic-based technique employing the EM algorithm yields better results than the Rule-based technique.

الملخص

دراسة مقارنة لطرق اكتشاف السجلات المكررة

أسامة حلمي عقل

عملية اكتشاف السجلات المكررة تعرف بأنها عملية التعرف على أزواج السجلات في واحدة أو أكثر من قواعد البيانات التي تتطابق مع نفس الكيان في العالم الحقيقي (مثل: المريض أو العميل). على الرغم من الطرق العديدة التي تم اقتراحها على مر السنين لاكتشاف السجلات المكررة في قاعدة بيانات ما، دراسات قليلة جداً قامت بمقارنة فعالية طرق اكتشاف السجلات المكررة المختلفة. الهدف من هذه الدراسة هو مقارنة اثنتين من نماذج القرار المقترحة، الطريقة القائمة على القاعدة، و الطريقة القائمة على الإحتمالية، واللذين تم اقتراحهما لاكتشاف السجلات المكررة في قاعدة بيانات ما، وتقييم مزاياهما و عيوبهما. وهدف آخر هو تصميم نظام عام لحل مشكلة اكتشاف السجلات المكررة. وأخيراً، تقييم الأداء لنماذج القرار الرئيسية التي استخدمت في مرحلة اكتشاف السجلات المكررة في هذه الدراسة

مؤخراً يوجد طريقتين رئيسيتين لاكتشاف السجلات المكررة تصنف إلى طرق تعتمد على معرفة النطاق أو مقاييس الاختلاف، و طرق تعتمد على تدريب البيانات. هذه الدراسة تركز على المقارنة بين الطريقة القائمة على القاعدة من الصنف الأول، والطريقة القائمة على الإحتمالية من الصنف الثاني. بالنسبة للطريقة القائمة على الإحتمالية بدلاً من الاعتماد على تدريب البيانات قمنا بتوظيف خوارزمية توسيع التوقعات لإيجاد تقديرات الإحتمالات القصوى للمعلمات في نموذج الاحتمالية. نتائج التجارب على مجموعات البيانات التجريبية (FEBRL) التي تحتوي على بيانات لمرضى المختلفة الأحجام و خصائص الأخطاء تبين أن الطريقة القائمة على الإحتمالية والتي توظف خوارزمية توسيع التوقعات تعطي نتائج أفضل من الطريقة القائمة على القاعدة.

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Chapter 1

Introduction

1.1 Introduction

Duplicate record detection problem has occurred from decades, and it has got its importance from the very large volume of data that store in the database systems every day around the globe, and the need to make these database systems more accurate and dependable to carry out business issues. In database community this problem also known as record matching, merge-purge, data deduplication and instance identification. Duplicate record detection is the problem of identifying records in database that represent the same real-world entity. Duplicate records do not share a common key and that makes detecting the duplicates a difficult problem. In order to solve this problem, different decision models have been used to clean the erroneous data that caused by many factors, such as data entry errors (*e.g., jon instead of john*), missing integrity constraints (*e.g., age = 432*), multiple conventions of information (*e.g., 44 W. 4th St. versus 44 West Fourth Street*), and the worst problem is the structural difference between database sources (Elmagarmid et al., 2007).

Often, in integrating data from different sources data heterogeneity problem appears which has two types structural and lexical. Structural heterogeneity appears when matching two databases with different fields structure, address might be stored in one field, like *address*, while in another database might be stored in three fields, like *street*, *city*, and *state*. Lexical heterogeneity occurs when the databases have the same structure and different representation of data such as 'J. Smith' and 'Smith John'.

In this thesis, we are concerned with the lexical heterogeneity considering that the structural heterogeneity has been already solved.

1.2 Record Duplication and Data Quality

Data quality of a system is essential and important when integrated from different datasets, so it highly depends on the quality of these resources. Accordingly a false decision should be avoided. So we need to preprocess datasets to create a complete, clean, and consistent dataset before any integration tasks (Bleiholder & Naumann, 2008).

Data quality is a very complex concept. The complexity results from its composition of various characteristics or dimensions, but most researchers have traditionally agreed on it to be defined as fitness for use. Another definition for data quality is "the distance between the data views presented by an information system and the same data in the real world". Such a definition can be seen as an "operational definition", although evaluating data quality on the basis of comparison with the real world is a very difficult task (Bertolazzi et al., 2003).

Although, a standard set of dimensions has not been defined yet, researchers agree on commonly dimensions such as accuracy, completeness, currency, and consistency. The system which satisfies these dimensions of quality is said to be of high quality (Scannapieco et al., 2005).

1.3 Detecting Duplicate Records

Currently, duplicate record detection techniques can be classified into two categories: (Elmagarmid et al., 2007)

- Approaches that depend on training data to “learn” how to find the duplicate records. This category includes (some) probabilistic approaches and supervised machine learning techniques.

- Approaches that depend on domain knowledge or on generic distance metrics to find the duplicate records. This category includes approaches such as Rule-based and approaches that use declarative languages for matching and approaches that devise distance metrics appropriate for the duplication detection task.

In this study, two techniques are selected, each from the two approaches. The two techniques are the Probabilistic-based techniques and the Rule-based technique.

The Probabilistic-based technique is a popular solution that has been used in some of duplication detection softwares such as FEBRL, TAILOR, and Link King.

Mainly, the Probabilistic-based technique depends on training data to find a maximum likelihood which helps to determine if a record pair is matching or non-matching. Moreover, Probabilistic-based method can be used without training data by gaining benefits of using unsupervised Expectation Maximization (EM) algorithm, in cases of unavailability of training data, and having a clear structure of datasets.

The EM algorithm makes use of this information to supply the maximum likelihood estimate.

Winkler (2002) claims that unsupervised EM algorithm works well under these five conditions:

1. Relatively large percentage of duplicates in the dataset (more than 5%).
2. The class of matching record pairs is well separated from the other classes.
3. The rate of typographical error is low.
4. Sufficient fields to overcome errors in other fields of the record.
5. The conditional independence assumption results in good classification performance.

On the other hand, the Rule-based technique which also has been used in the Link King software, has gained much attention because of its potential to result in systems with

high accuracy (Elmagarmid et al., 2007). However, the high accuracy could be obtained basically by the effort and time of an expert to precisely devise good rules. And also it needs much analysis of the dataset to give the expert a good vision to improve the rules. Duplicates detection system should include a technique to increase the efficiency of the system beside of the duplicates detection techniques, particularly when dealing with large datasets. Such techniques reduce the number of candidate records pairs whilst maintaining the accuracy of the system. Standard blocking (Baxter et al., 2003), and sorted neighborhood (Hernández & Stolfo, 1998) techniques apply subspaces creation using a candidate key created from combination of the dataset attributes to sort the dataset before applying a block or windows. Choosing the candidate key well is important in order not to miss detecting a duplicate record.

1.4 Motivation

The important role of database systems and computer networks in various domains of life has created the need to access and manage information in many distributed systems. Therefore, there is a need for tools to support systems integration to have an error-free system with perfect clean data.

The main motivation of this study is the need of finding the best and optimal methods for detecting the duplicates in systems and to help the users of such systems to automate the process of duplicate detection so that they don't need to directly interact and manually deal with the underlying data.

1.5 Problem Definition

Duplicate record detection is an important process in data integration and data cleaning process. One of the most important stages in this process is the pre-processing stage where the detection and removal of duplicate records related to the same entity within one database. Linking or matching records relating to the same entity from several databases is often required as information from multiple sources which needs to be integrated, combined or linked in order to enrich data and allow more detailed data mining analysis. In an error-free system with perfectly clean data, the construction of a unified view of the data consists of linking or joining two or more records on their key fields. Unfortunately, data often lack a unique, global identifier that would permit such an operation.

Accordingly, a large variety of methods have been proposed for detecting approximate data matching.

Although, researchers try to solve duplicate records problem, it is uncertain which is the current state-of-the-art, an issue raised by Elmagarmid et. al. (Elmagarmid et al., 2007). Therefore there is a need to compare the effectiveness of the various methods.

1.6 Contribution

This study contributes in comparing between different decision models that are used for detecting duplicates in a given dataset. The approach which was suggested for determining the adequate models for detecting duplicates is used. A framework is proposed for duplicate record detection that takes its roots from generic designs suggested and used in solving record linkage and duplicate detection problems. Also, the performance of the major models used in record matching stage which is the main part of any duplicate record detection process is evaluated.

The contributions we make in this study are:

- The researcher introduces some of the most popular techniques that are used in duplication detection; the major steps in the duplicate detection process are discussed in brief. The researcher presents the major methods used for matching records attributes and the strings similarity functions used. The decision models used in identifying duplicates records are presented and classified.
- This study compares between the two main techniques for duplicate record detection, Rule-based technique and Probabilistic-based technique, and evaluates their advantages and disadvantages by conducting an experimental study on synthetic and large-scale benchmarking datasets.

1.7 Thesis Outline

The remainder of this thesis is organized as follows. Chapter 2 reviews the most important literature related to the duplicate record detection. Chapter 3 describes the main elements of our framework design and the implementation details for duplicate record detection problem. Chapter 4 presents the conducted experiments with their used settings and their results. Finally, the conclusions and future work are presented in chapter 5.

Chapter 2

Literature Review and Related Studies

In this chapter, we present a comprehensive review of the literature on duplicate record detection.

2.1 Comparison Subspace

Duplicate record detection depends initially on comparing all records in a database with each other to find the duplicate records which leads to inefficient duplicate detection process. For two data sets, A and B, are to be linked, potentially each record from A has to be compared with all records from B. The total number of potential record pair comparisons thus equals the product of the size of the two databases, $|A| \times |B|$. With $|A|$, $|B|$ denoting the number of records in the data set. For example, linking two databases with 100,000 records each would result in nearly 10^{10} record pair comparisons. With the expensive detailed comparing of the fields, and the fact that the number of duplicate record is small, this will consume much time and resources. In addition, there is no unique key in the database to be linked. Meanwhile, the efficiency is a major challenge to hold especially in large database. So the convenient solution is to reduce the number of comparisons by using techniques that group dataset into blocks or clusters using Blocking Key Value (BKV) with respect to a defined criterion or some threshold values (Christen & Churches, 2005) (Christen, 2007).

With having the unique key and splitting dataset into blocks, candidate pairs could be generated from the same block. That will certainly improve the efficiency with attention to reducing the quality of duplicate record detection (Tamilselvi & Saravanan, 2009).

The blocking process can be split into the following two steps: (Christen, 2007)

- 1- Build: All records from the data set are read, the blocking key values are created from record attributes, and the records are inserted into an index data structure. For most blocking methods, a basic inverted index can be used. The blocking key values will become the keys of the inverted index, and the record identifiers of all records that have the same blocking key value will be inserted into the same inverted index list.
- 2- Retrieve: Record identifiers are retrieved from the index data structure block by block, and candidate record pairs are generated. Each record in a block will be paired with all other records in the same block. The generated candidate record pairs are then compared and the resulting vectors containing the numerical comparison values are given to a classifier.

We should note that the choice of blocking keys is usually done manually by domain and duplication detection experts and are usually chosen to be very general in order to produce a high quality result, while also producing a reasonable reduction in the amount of data required to compare against for each record to be matched.

A blocking key can be defined as either the values taken from a single record attribute (or parts of values, like the first two initial letters only), or the concatenation of values (or parts of them) from several attributes. (Christen, 2007)

Next we present some of the major blocking methods that are used to improve the efficiency and scalability of duplicate detection process.

2.1.1 Standard Blocking Technique

The Standard Blocking technique groups records into disjoint blocks where they have the same BKV, and then compares all pairs of records only within the same block. A blocking key is defined to be composed from the record attributes of the data set. Assuming duplicate detection applied on a data set with N records, and the blocking technique given B number of blocks (all of the same size containing N/B records), the resulting number of record pair comparisons is $O(N^2/B)$. Thus, the overall number of comparisons is greatly reduced. (Baxter et al., 2003)

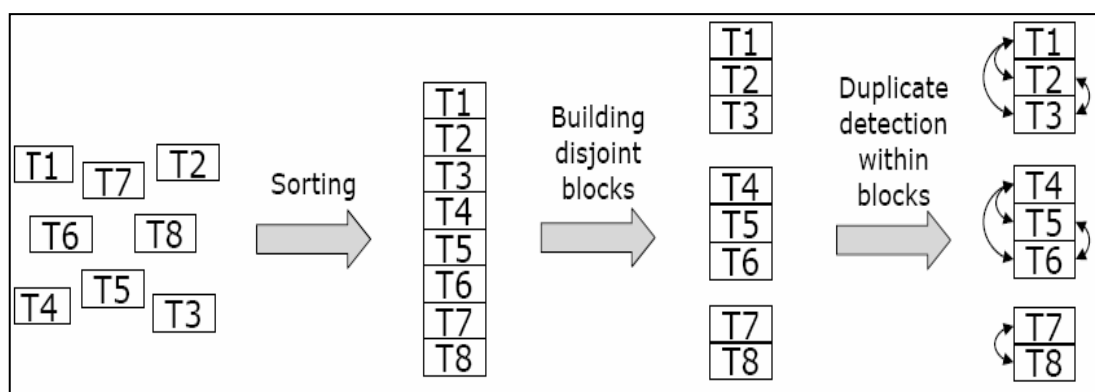


Figure 2.1: Standard blocking technique (Draisbach & Naumann, 2009)

The blocking technique depends heavily on the blocking key choosing, which determines the number and size of the blocks. The key should be chosen to gather the potential duplicates in the same block. For example, if the blocking key is the states in the United States, the dataset will be sorted and partitioned into blocks where the first block contains records with state 'AR', the second block contains records with state 'AK', and so on. As shown in Figure 2.1 only records in the same block are considered for comparison. (Draisbach & Naumann, 2009)

As blocking can increase the speed of the comparison process, it can also increase the number of false mismatches by the failure of comparing records that do not belong to the same block.

2.1.2 Sorted Neighborhood Technique

Hernández and Stolfo proposed a technique called Sorted Neighborhood (SN) or Windowing to reduce the number of comparisons by limiting the similarity measures on a small portion of the dataset. The SN technique consists of the following three steps: (Hernández & Stolfo, 1998)

- 1- Create key: A blocking key for each record in the data set is computed by extracting relevant attributes, or a sequence of substrings within the attributes, chosen from the record in an ad hoc manner. Attributes that appear first in the key have a higher priority than those that appear subsequently. For example, the key may be composed from the first three constant characters of a person's surname concatenated by the first three constant characters of a person's given name and the first three digits of the social security ID as shown in Table 2.1.
- 2- Sort data: The records in the data set are sorted by using the blocking key value created in the first step.
- 3- Merge: A window of fixed size $w > 1$ is moved through the sequential list of records in order to limit the comparisons for matching records to those records in the window. If the size of the window is w records, then every new record that enters that window is compared with the previous $w - 1$ records to find "matching" records. The first record in the window slides out of it as shown in Figure 2.2.

Table 2.1: Sorting keys generated for the SN method

First Name	Last Name	ID	Key
Sal	Stolfo	45678987	STOSAL456
Sal	Stolpho	45688987	STOSAL456
Stolfo	Sal	45688987	SALSTO456

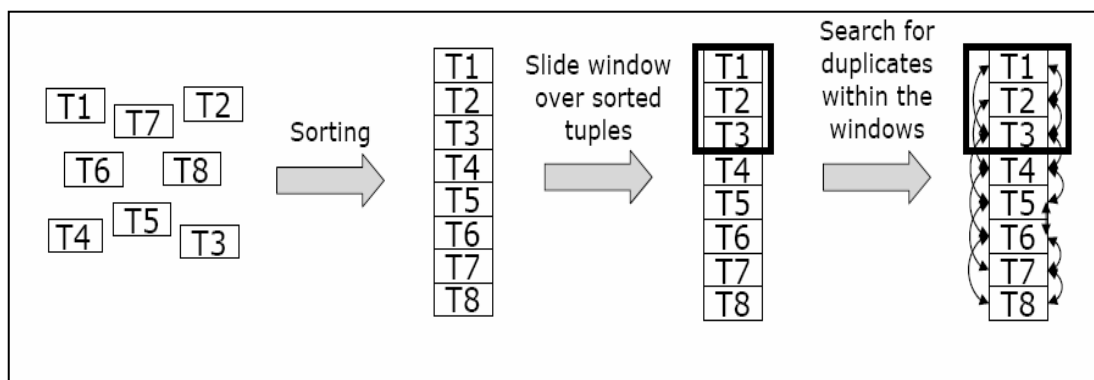


Figure 2.2: Sorted neighborhood technique (Draisbach & Naumann, 2009)

For example using zip-codes as blocking key in the SN technique, data is sorted according to the zip-code, then a window of fixed sized slides across the sorted data and compare pairs only within the window. The use of the window limits the number of candidate record pair comparisons for each record to $w - 1$. The resulting total number of record pair comparisons for a dataset with n records using the sorted neighborhood method is $O(wn)$.

We can see that the accuracy of the SN technique depends on the quality of the keys chosen. A poorly chosen key will filter out a lot of true duplicates. Also, the size of the window is very important. For records with a large number of duplicates, a small window size will result in the same result as that of a poorly-chosen key, and a large window size will bring in too much unnecessary comparisons. The size of the window (typically between 10 and 20 records) represents the trade-off between efficiency and effectiveness; larger windows yield longer run times but detect more duplicates (Draisbach & Naumann, 2009).

To solve this problem, Hernández and Stolfo (1998) introduced a multi-pass SN technique which Execute the SN technique independently several times and each time the records are sorted using a different key and a small window size. Finally the result is computed by merging the results from the multi-pass.

2.2 Attribute Matching Techniques

Duplicate record detection depends substantially on string comparison techniques to determine if two records are matching or non-matching. It is axiomatic to find the similarity between two strings instead of equality because it is common that mismatches happen due to typographical error. Various string similarity techniques have been created. In this study one of them is used, we briefly discuss it.

2.2.1 Q-Gram Similarity Function

A Q-gram could be defined as short substrings of length q from a given string. The substrings could be phonemes, syllables, letters, or words according to the usage of Q-gram function. Q-gram has many types according to the length of the substrings such as unigram with size of one, bigram with size of two, trigram with size of three, and size four or more is simply called a Q-gram. Letter Q-grams, including trigrams, bigrams, and/or unigrams, have been used in a variety of ways in text recognition and spelling correction (Innerhofer-Oberperfler, 2004).

The notion of Q-grams for a given string σ , its Q-grams are obtained by “sliding” a window of length q over the characters of σ . Since Q-grams at the beginning and the end of the string can have fewer than q characters from σ we introduce new Σ characters “#” and “%” not in σ , and conceptually extend the string σ by prefixing or padding it with $q - 1$ occurrences of “#” and suffixing it with $q - 1$ occurrences of “%”. Thus, each Q-gram contains exactly q characters, though some of these may not be from the alphabet Σ .

The intuition behind the use of Q-grams as a foundation for approximate string processing is that when two strings σ_1 and σ_2 are within a small edit distance of each other, they share a large number of Q-grams in common (Ukkonen, 1992).

For example consider the Q-grams of length $q=3$ for string “john smith” are { (##j), (#jo), (joh), (ohn), (hn_), (n_s), (_sm), (smi), (mit), (ith), (th%), (h%%) }.

Similarly, the Qgrams of length $q=3$ for “john a smith”, which is at an edit distance of two from “john smith”, are { (##j), (#jo), (joh), (ohn), (hn_), (n_a), (_a_), (a_s), (_sm), (smi), (mit), (ith), (th%), (h%%) }.

If we ignore the position information, the two Q-gram sets have 11 Q-grams in common. Interestingly, only the first five Q-grams of the first string are also Q-grams of the second string.

The Q-grams similarity metric between two strings is constructed ranging from 0 to 1.0 using a normalized formula,

$$\mathbf{Sim}_{q\text{-gram}(s_1,s_2)} = \frac{1}{2} \left(\frac{|G_{s_1} \cap G_{s_2}|}{|G_{s_1}|} + \frac{|G_{s_1} \cap G_{s_2}|}{|G_{s_2}|} \right) \quad (2.1)$$

Where $|G_{s_1} \cap G_{s_2}|$ is the number of common Q-grams between S_1 & S_2 , $|G_{s_1}|$ and $|G_{s_2}|$ is the number of Q-grams of s_1 and s_2 respectively.

For the above example, we have $|G_{s_1}|=12$, $|G_{s_2}|=14$, $|G_{s_1} \cap G_{s_2}|=11$, so the similarity between them is 0.8511 according to the above formula.

Also consider a Q-grams of length $q = 3$ for $S_1 =$ 'Street' can be constructed as $G_{s_1} = \{##S, \#St, Str, tre, ree, eet, et\#, t##\}$, and $S_2 =$ 'Steret', are $G_{s_2} = \{##S, \#St, Ste, ter, ere, ret, et\#, t##\}$. The two strings have four Q-grams in common. We have $|G_{s_1}|=8$, $|G_{s_2}|=8$, $|G_{s_1} \cap G_{s_2}|=4$, so the similarity between them is 0.5 according to the above formula.

Figure 2.3 shows the calculation of the similarity metric between two different strings S_1 and S_2 (Innerhofer-Oberperfler, 2004).

```

Algorithm Q-gram (S1, S2)
// Input: two strings S1 and S2
// Output: matching-quota between S1 and S2 in %
match = 0, i = 0, j = 0
Generate the list GS1 from S1 and the list GS2 from S2
Sort GS1 and GS2
While (i < |GS1| and j < |GS2|)
    if GS1 (i) = GS2 (j) then
        Match ++
        i ++
        j ++
    Else
    if GS1 (i) < GS2 (j) then
        i ++
    else
        j ++
    endif
endwhile
Return ((match / |GS1| + match / |GS2|) / 2)
End

```

Figure 2.3: Calculating Q-grams similarity metric. (Innerhofer-Oberperfler, 2004)

For the Q-grams complexity when sorting the lists Gs with the appropriate use of hash-based indexes, it takes $O(n \log n)$, with $n = \max(|G_{S1}|, |G_{S2}|)$. But the average time required for computing the Q-gram overlap between two strings $O(\max\{|S_1|, |S_2|\})$ (Elmagarmid et al., 2007).

It's worth indicating that an extension to Q-grams is being adapted to add positional information (location of a Q-gram within a string) and to match only common Q-grams that are within a maximum distance from each other. For example, 'peter' contains the positional bigrams ('pe', 0), ('et', 1), ('te', 2) and ('er', 3). If a maximum distance of comparison is set to 1, then bigram ('et', 1) will only be matched to bigrams in the second string with positions 0 to 2. Positional Q-grams can be padded with start and end characters similar to non-positional Q-grams, and similarity measures can be calculated in the same three ways as with non-positional Q-grams (Christen, 2006).

2.3 Duplicate Records Detection

So far, we have described techniques that can be used to match individual fields of a record. In most real-life situations, however, the records consist of multiple fields; making the duplicate detection problem much more complicated and a decision must be made as to whether consider these records as matching, or non-matching (Wang, 2008). Many techniques may be used for matching records with multiple fields. The presented methods can be broadly divided into two categories: (Elmagarmid et al., 2007)

- Approaches that rely on training the data to “learn” how to match the records. This category includes (some) probabilistic approaches and supervised machine learning models.
- Approaches that rely on domain knowledge or on generic distance metrics to match records. This category includes approaches that use declarative languages for matching and approaches that devise distance metrics.

2.3.1 Probabilistic-Based Technique

In this study we implement the Probabilistic-based technique using the Fellegi-Sunter model of record linkage without training data instead we use the Expectation Maximization (EM) algorithm to compute the maximum likelihood estimates.

2.3.1.1 Fellegi-Sunter Model of Record Linkage

Newcombe et al. (1959) ideas in duplicate detection were formalized as a mathematical model by Fellegi and Sunter (1969). Given record pair as input to the decision model, record pair is classified as matching or non-matching whose density function is different for each of the two classes. We used the same notation provided by Fellegi and Sunter. We represent the set of ordered record pairs (with a record drawn from each file A and B for each pair) as

$$A \times B = \{(a, b); a \in A, b \in B\} \quad (2.2)$$

Each record pair is assigned to either class M or U . Record pairs belonging to the M class are identified as matching whilst record pairs belonging to the U class are identified as non-matching. Therefore, the set of pairs in (2.2) is the union of two disjoint sets

$$M = \{(a, b); a = b, a \in A, b \in B\} \quad (2.3)$$

And

$$U = \{(a, b); a \neq b, a \in A, b \in B\} \quad (2.4)$$

This is called the matched and unmatched sets respectively. The records corresponding to members of A and B are denoted by $\alpha(a)$ and $\beta(b)$ respectively. We represent the record pairs as comparison vectors

$$\gamma[\alpha(a), \beta(b)] = \{\gamma^1[\alpha(a), \beta(b)], \dots, \gamma^k[\alpha(a), \beta(b)]\} \quad (2.5)$$

Where each of the $\gamma^i, i = 1 \dots K$ represents a specific comparison between the same i th attribute of A and B . For example, γ^1 could denote the agreement or disagreement between the names of two persons. The degree of agreement/disagreement varies and could be such that the name must be exactly the same and contain the word 'Brown', the name is almost similar, or the name disagrees. Taking Γ as the comparison space that represents the set of all possible realizations of γ , a linkage rule L is defined as a mapping from Γ onto a set of random decision functions $D = \{d(\gamma)\}$ where

$$d(\gamma) = \{P(A_1|\gamma), P(A_2|\gamma), P(A_3|\gamma)\}; \gamma \in \Gamma \quad (2.6)$$

And

$$\sum_{i=1}^3 P(A_i|\gamma) = 1$$

The three decisions are denoted as *link* (A_1), *non-link* (A_3), and *possible link* (A_2). The possible link class is introduced for ambiguous cases such as insufficient information.

Rather than falsely classifying the record pair that falls under these cases as not linked, it is safer to classify it as a possible match for further examination. A record pair is considered linked if the probability that it is a link, $P(M|\gamma[\alpha(a),\beta(b)])$ is greater than the probability that it is a non-link, $P(U|\gamma[\alpha(a),\beta(b)])$. To solve this, we follow the Bayes decision rule for minimum error which introduces a likelihood ratio based on conditional probabilities of the record pair when it is known to be a link or non-link. These values can be computed using a training set of pre-labeled record pairs or using the EM algorithm.

The likelihood ratio is defined as

$$R = R[\gamma(a, b)] = m(\gamma)/u(\gamma) \quad (2.7)$$

Where the conditional probability of $\gamma(a,b)$ if $(a,b) \in M$ is given by

$$m(\gamma) = P\{\gamma[\alpha(a),\beta(b)]|(a,b) \in M\} = \sum_{(a,b) \in M} P\{\gamma[\alpha(a),\beta(b)]\} \cdot P[(a,b)|M] \quad (2.8)$$

And the conditional probability of $\gamma(a,b)$ if $(a,b) \in U$ is given by

$$u(\gamma) = P\{\gamma[\alpha(a),\beta(b)]|(a,b) \in U\} = \sum_{(a,b) \in U} P\{\gamma[\alpha(a),\beta(b)]\} \cdot P[(a,b)|U] \quad (2.9)$$

The model by Fellegi and Sunter also includes errors associated with the linkage rule.

The first type of error occurs when an unmatched pair of records is classified as a link, which is also the error of making decision A_1 . This error has the probability of

$$\mu = P(A_1|U) = \sum_{\gamma \in \Gamma} u(\gamma) \cdot P(A_1|\gamma) \quad (2.10)$$

The second type of error is the error of decision A_3 that occurs when a matched pair of records is classified as a non-link. This error has the probability of

$$\lambda = P(A_3|M) = \sum_{\gamma \in \Gamma} m(\gamma) \cdot P(A_3|\gamma) \quad (2.11)$$

Fellegi and Sunter defined an optimal linkage rule L_0 with A_1 , A_2 , and A_3 according to the theorem:

Theorem: Let L' be a linkage rule associated with decisions A'_1 , A'_2 , and A'_3 such that $P(A'_3|M) = P(A_3|M)$ and $P(A'_1|U) = P(A_1|U)$. Then L_0 is optimal in that $P(A_2|U) \leq P(A'_2|U)$ and $P(A_2|M) \leq P(A'_2|M)$ (Winkler & Thibaudeau, 1991).

This property is desirable to minimize the probability of making non-conclusive decision, A_2 . In other words, the rule minimizes the probability of failing to make a conclusive decision subject to the fixed levels of error in (2.10) and (2.11).

From (2.7), the upper bound and lower bound thresholds are defined as

$$T_\mu = m(\gamma_n)/u(\gamma_n) \quad (2.12)$$

And

$$T_\lambda = m(\gamma_{n'})/u(\gamma_{n'}) \quad (2.13)$$

With this, the pairs of error levels (μ, λ) corresponding to T_μ and T_λ are given by

$$\mu = \sum_{\gamma \in \Gamma_\mu} u(\gamma) \quad (2.14)$$

$$\lambda = \sum_{\gamma \in \Gamma_\lambda} u(\gamma) \quad (2.15)$$

Where

$$\Gamma_\mu = \{\gamma: \Gamma_\mu \leq m(\gamma)/u(\gamma)\} \quad (2.16)$$

$$\Gamma_\lambda = \{\gamma: m(\gamma)/u(\gamma) \leq \Gamma_\lambda\} \quad (2.17)$$

2.3.1.2 EM Algorithm

Jaro (1989) suggested using an EM algorithm to compute the probabilities $P(x_i=I/M)$. While the probabilities $P(x_i=I/U)$ can be estimated by taking random pairs of records which are with high probabilities of U. The EM algorithm is a means of obtaining maximum likelihood estimates for incomplete data. It is a good alternative in situations

where we cannot get hold of a subset of training data to compute the conditional probabilities as given in (2.8) and (2.9). Also, the dataset itself holds plenty of information that we can harness from (Dempster, Laird, & Rubin, 1977).

The EM algorithm generates the parameter set $\Phi = (m, u, p)$ via iterative computation of the E-step (Expectation) and M-step (Minimization) on an incomplete data set. The steps are:

1. Give initial estimated values of Φ . These values can be simply guessed as the algorithm is not particularly sensitive to the starting values.
2. Compute the E-step using the values of Φ .
3. Compute the M-step to re-estimate the values of Φ based on the values from Step 2.
4. Repeat Step 2 and Step 3 until the convergence of the values of Φ .

To estimate m_i , the EM algorithm needs to consider matching record pairs. One way that is often used is by using the blocking technique to group similar records into their respective blocks. Records pairs formed from within the same block are used to compute the comparison vector γ .

Jaro used a binary model for the comparison vector γ such that $\gamma_i^j = 1$ if attribute i agrees for record pair j , and $\gamma_i^j = 0$ if attribute i disagrees for record pair j , for $i = 1 \dots N$ attributes and $j = 1 \dots N$ record pairs. Hence, the m_i and u_i probabilities can be defined as

$$m_i = P\{\gamma_i^j = 1 | r_j \in M\} \quad (2.18)$$

And

$$u_i = P\{\gamma_i^j = 1 | r_j \in U\} \quad (2.19)$$

The notation p is defined as the proportion of matched pairs where

$$p = |M| / |M \cup U| \quad (2.20)$$

Assuming an independence model, the conditional probabilities given in (2.8) and (2.9) are computed as

$$P(\gamma^j|M) = \prod_{i=1}^n m_i^{\gamma_i^j} (1 - m_i)^{1-\gamma_i^j} \quad (2.21)$$

$$P(\gamma^j|U) = \prod_{i=1}^n u_i^{\gamma_i^j} (1 - u_i)^{1-\gamma_i^j} \quad (2.22)$$

To compute the E-Step, let x be the complete data vector equal to $\langle \gamma, g \rangle$, where $g_j = (1, 0)$

iff $r_j \in M$ and $g_j = (0, 1)$ iff $r_j \in U$. The complete data log-likelihood is: (Winkler, 1993)

$$\ln f(x|\Phi) = \sum_{j=1}^N g_j \cdot (\ln P\{\gamma^j|M\}, \ln P\{\gamma^j|U\})^T + \sum_{j=1}^N g_j \cdot (\ln p, \ln(1-p))^T \quad (2.23)$$

Now, replace g_j with $(g_m(\gamma^j), g_u(\gamma^j))$ where

$$g_m(\gamma^j) = \frac{p \prod_{i=1}^n m_i^{\gamma_i^j} (1-m_i)^{1-\gamma_i^j}}{p \prod_{i=1}^n m_i^{\gamma_i^j} (1-m_i)^{1-\gamma_i^j} + (1-p) \prod_{i=1}^n u_i^{\gamma_i^j} (1-u_i)^{1-\gamma_i^j}} \quad (2.24)$$

$$g_u(\gamma^j) = \frac{(1-p) \prod_{i=1}^n u_i^{\gamma_i^j} (1-u_i)^{1-\gamma_i^j}}{p \prod_{i=1}^n m_i^{\gamma_i^j} (1-m_i)^{1-\gamma_i^j} + (1-p) \prod_{i=1}^n u_i^{\gamma_i^j} (1-u_i)^{1-\gamma_i^j}} \quad (2.25)$$

The values of $(g_m(\gamma^j), g_u(\gamma^j))$ are used in the following M-Step, which yields the following equations for the parameter set Φ after setting the partial derivatives for each of the three maximization problems to zero.

$$m_i = \frac{\sum_{j=1}^N \gamma_i^j \cdot g_m(\gamma^j)}{\sum_{j=1}^N g_m(\gamma^j)} \quad (2.26)$$

$$u_i = \frac{\sum_{j=1}^N \gamma_i^j \cdot g_u(\gamma^j)}{\sum_{j=1}^N g_u(\gamma^j)} \quad (2.27)$$

$$p = \frac{\sum_{j=1}^N g_m(\gamma^j)}{N} \quad (2.28)$$

2.3.1.3 Alternative Computation of u_i

Although the EM algorithm can derive both the values of m_i and u_i , the latter may not be accurate due to the biased situation in which it is derived from. Jaro (1989) suggested

that an alternative method can be used to estimate u_i . Estimation of u_i is simplified by the fact that the cardinality of non-matching record pairs in a dataset is much greater than that of matching record pairs. Therefore, u_i can be obtained by considering the probability of chance agreement of the attribute i . usually; this is done by considering a sample rather than all the record pairs in the dataset.

2.3.1.4 Composite Weights

The weight of each attribute of a record pair is computed based on the values in (2.26) and (2.27). If attribute i of the record pair matches, the weight of that attribute is given by:

$$w_i = \log_2 \left(\frac{m_i}{u_i} \right) \quad (2.29)$$

If attribute i disagrees, then the weight is

$$w_i = \log_2 \left(\frac{1-m_i}{1-u_i} \right) \quad (2.30)$$

We obtain the score of each record pair by summing up all the weights of attribute i . Attributes that agree make a positive contribution to this sum whilst attributes that disagree make a negative contribution to this sum. Hence, based on the optimal decision rule for record linkage by Fellegi and Sunter, if the composite weight of a record pair is above threshold value T_μ (2.12), the record pair is classified as a match. If the composite weight is below threshold value T_λ (2.13), the record pair is classified as a non-match. If the composite weight falls between these two values, the record pair is regarded as non-conclusive.

2.3.2 Rule-Based Technique

Rule-based technique proposed by Wang and Madnick (1989) determine if two records are matching or non-matching using a predefined heuristic rules developed by experts to infer additional information about the data instances to be matched. Probabilistic-based

technique assign a weight for each attribute whilst Rule-based technique each attribute is given a weight of one or zero. For example, an expert might define rules such as:

IF age < 22

THEN status = undergraduate

ELSE status = graduate

IF course_id = 564 AND course_id = 579

THEN student_major = MIS

Such rules are used to cluster records that represent the same real-world entity. However, since the rules are heuristically derived, the output from these rules may not be correct (Wang & Madnick, 1989).

Lim et al. (1993) used ILFD (instance Level Functional Dependency) which relies on functional dependencies instead of heuristic rules. The ILFDs are used to derive an extended key, which is a union of keys or attributes from the dataset. As an example, consider the two tables in Figure 2.4. Both Table R and Table S do not share any common keys because "TwinCities" in Table S can refer to either one of the records in Table R.

Table R		
name	cuisine	street
TwinCities	Chinese	Wash.Ave.
TwinCities	Indian	Univ.Ave.

Table S		
name	speciality	city
TwinCities	Mughalai	St.Paul

Figure 2.4: ILFD example (Lim et al., 1993)

To solve this, we can assert in the following IFLD that the values of attribute *speciality* can infer the values of attribute *cuisine*. Hence, Table R and Table S can be matched using the extended key (*name, cuisine*) and the corresponding extended key equivalence rule, which states that two records are similar when their *name* and *cuisine* values are the same.

ILFD:

$(e2.speciality = Mughalai) \rightarrow (e2.cuisine = Indian)$

Extended Key Equivalence Rule:

$(e1.name = e2.name) \text{ AND } (e1.cuisine = e2.cuisine) \rightarrow (e1 \text{ and } e2 \text{ are the same})$

Hernández and Stolfo suggest the use of an equational theory that dictates the logic of domain equivalence. For example, the following is a rule that exemplifies one axiom of the equational theory developed for an employee database: (Hernández & Stolfo, 1998)

Given two records, r1 and r2

IF the last name of r1 equals the last name of r2,

AND the first names differ slightly,

AND the address of r1 equals the address of r2

THEN

r1 is equivalent to r2

The implementation of *differ slightly* of the first names based upon the distance-based technique to determine the typographical gap. The gap is then compared with a predefined threshold which is normally obtained through experimental evaluation to decide if the two records are matching or non-matching. A poor choice of threshold value would result in false positives or false negatives. For instance, if the threshold value is high, we would have missed a number of duplicates. On the other hand, relaxing the value of threshold also means that non-duplicates would be misclassified as

matching records. Therefore, a good matching declarative rule very much depends on the selection of distance functions and a proper threshold.

2.4 Related Studies

Lots of work and researches in the field of duplicate record detection have been proposed and many systems have been implemented with different approaches to detect duplicate record. In this section we are going to introduce some of the most important related studies in this field which provides us a good guidance to our work.

- (Hernández & Stolfo, 1998): The authors introduced a system for accomplishing data cleansing tasks and demonstrate its use for cleansing lists of names of potential customers in a direct marketing-type application. The system provides a rule programming module using an intelligent equational theory in addition to the sorted neighborhood method as a blocking method.
- (Gu et al., 2003): The authors presented the current standard practices in record linkage methodology. The definition of the record linkage problem, the formal probabilistic model and an outline of the standard practice algorithms and its recent proposals. And it concludes with a summary of the current methods and the most worthwhile research directions.
- (Christen 2007): The author evaluated the traditional, as well as several recently developed, blocking methods within a common framework with regard to the quality of the candidate record pairs generated by them. Also proposed modifications to existing blocking methods that replace the traditional global thresholds with nearest-neighbor based parameters.
- (Elmagarmid et al., 2007): The authors presented a thorough analysis of the literature on duplicate record detection covering similarity metrics that are

commonly used to detect similar field entries. They also present an extensive set of duplicate detection techniques that can detect approximately duplicate records in a database. They also cover multiple methods for improving the efficiency and scalability of approximate duplicate detection algorithms. In addition to coverage of existing software tools with a brief discussion of the big open problems in this field.

- (Draisbach & Naumann, 2009): The authors in this paper briefly introduced and analyzed two popular families of methods for duplicate detection. Blocking methods and Windowing methods. Also the authors proposed a generalized algorithm, the Sorted Blocks method and compared the approaches qualitatively and experimentally.
- (Tamilselvi & Saravanan, 2009): The authors present a general sequential framework for duplicate detection and elimination using a rule-based approach to identify exact and inexact duplicates and to eliminate duplicates. The proposed framework uses six steps to improve the process of duplicate detection and elimination. Also the authors compare this new framework with previous approaches using the token concept in order to speed up the data cleaning process and reduce its complexity. Analysis of several blocking key is made to select best blocking key to bring similar records together through extensive experiments to avoid comparing all pairs of records.

Chapter 3

Duplicate Detection Framework Design and Implementation

3.1 Framework Design

Our framework design for duplicate record detection is derived from the generic record linkage framework suggested by (Gu et al., 2003). Figure 3.1, clarifies the framework that has developed for our duplicate record detection system. The stages on this framework are as following:

Database: the MySQL database contains dataset A and dataset B. For each dataset that is evaluated; the entire dataset is queried and loaded into memory after the preparation stage.

Data preparation: this stage refers to the process in which our datasets would be processed and stored in a uniform manner in the database.

User interaction: in this stage, user would interact with the system through the user interface for the selection of dataset, and selection of the attributes to be used as a key for the SN technique for each pass of the three passes that we use with the SN technique. And supply the parameters required for the duplicate detection techniques. Such as, dataset size, window size, and threshold value for the Rule-based technique. Then user chooses the decision model.

Blocking keys generator: the blocking keys are generated from the selected attributes of each record, and then the data are sorted according to these keys. For the

SN technique we use three passes so there are three keys (one for each pass). And for the standard blocking technique one key is generated.

Records blocking: to reduce the comparison space, a blocking technique is used to group the data into blocks. Two blocking techniques are used in this system.

Standard blocking technique: dataset is divided into non-overlapping blocks; all the records in the same block have the same key value, and then records are passed to the pairing stage. We use this technique just to compute the EM algorithm.

Sorted-Neighborhood technique: after sorting the dataset according the key it is divided into overlapping windows with window size defined by the user, then records are passed to the pairing stage to be used by the selected decision model.

Records pairing: in this stage, records from each block are paired together and sent to the EM algorithm to computes the threshold value. Meanwhile, records from each window are paired together and sent to be tested by the chosen decision model pair by pair. Of course the pairing in the blocks is different from the paring in the windows.

Threshold generator for Probabilistic-based technique: using the EM algorithm the threshold value is computed to be used by the Probabilistic-based technique. Estimating the threshold value could be done by computes the comparison vector for each record pair that received from the standard block technique. All comparison vectors and there frequency counts are sent to the EM algorithm to estimate m_i and u_i . These two values used to compute the threshold value.

Decision models matcher: the matching stage consists of a Rule-based matcher that employs the Rule-based technique, and the Probabilistic-based matcher that employs the Probabilistic-based technique. In this stage the decision is made if the record pair is matched or non-matched.

Rule-based matcher: after receiving a record pairs paired up from sliding window, the Rule-based matcher computes the similarity scores for each attribute in the record pair. The scores are sent to the Equational Theory rules to check if they satisfy the threshold. If they do, the record pair is considered matching and is sent to be classified.

Probabilistic-based matcher: to determine if a record pair is matching or non-matching, we used the sliding window to obtain record pairs that passed to the Probabilistic-based matcher to compute the composite weight of the record pair. The composite weight is compared with the threshold value that generated by the EM algorithm. If the composite weight is above the threshold value, the record pair is considered matched and sent to the classifier.

Classifier: the classifier does the following:

1. Determine the record pairs that should grouped together on the fact that all records in the same group are duplicates for each other.
2. Make sure not to overlap between the groups after next matching process.
3. Compute transitive closure over several independent runs (multi-passes).

Evaluator: the successful measuring of the duplication detection is an important but hard task, because of the lack of the gold standard for the dataset. Privacy and confidentiality are the main difficulties preventing having a benchmark dataset. We described the duplication detection measures that have been used to evaluate the performance of our duplication detection techniques such as Recall, Precision, F-Score, and Time complexity (Naumann & Herschel, 2010).

- Recall (true positive rate)

Recall also known as sensitivity, measures the ratio of correctly identified duplicates compared to all true duplicates. And it used commonly in epidemiological studies.

Recall estimated using the formula:

$$Recall = \frac{|true\ positive|}{|true\ positive| + |false\ negative|} = \frac{|true\ positive|}{|true\ duplicates|} \quad (4.1)$$

- Precision

It is also called a positive predictor value that measures the ratio of correctly identified duplicates compared to all declared duplicates. In the information retrieval field precision is widely used in combination with the recall measure for visualization in precision-recall graph. Precision estimated using the formula:

$$Precision = \frac{|true\ positive|}{|true\ positive| + |false\ positive|} = \frac{|true\ positive|}{|declared\ duplicates|} \quad (4.2)$$

- F-Score

Both recall and precision measures should be maximized, but there is a tradeoff between them. F-score measure captures this tradeoff by combining recall and precision via a harmonic mean. So it's a measure of accuracy of the experiment (Yan et al., 2007). The F-score is given by:

$$F-Score = \frac{2 * recall * precision}{recall + precision} \quad (4.3)$$

- Time complexity, which measures how well the system scales in terms of time.

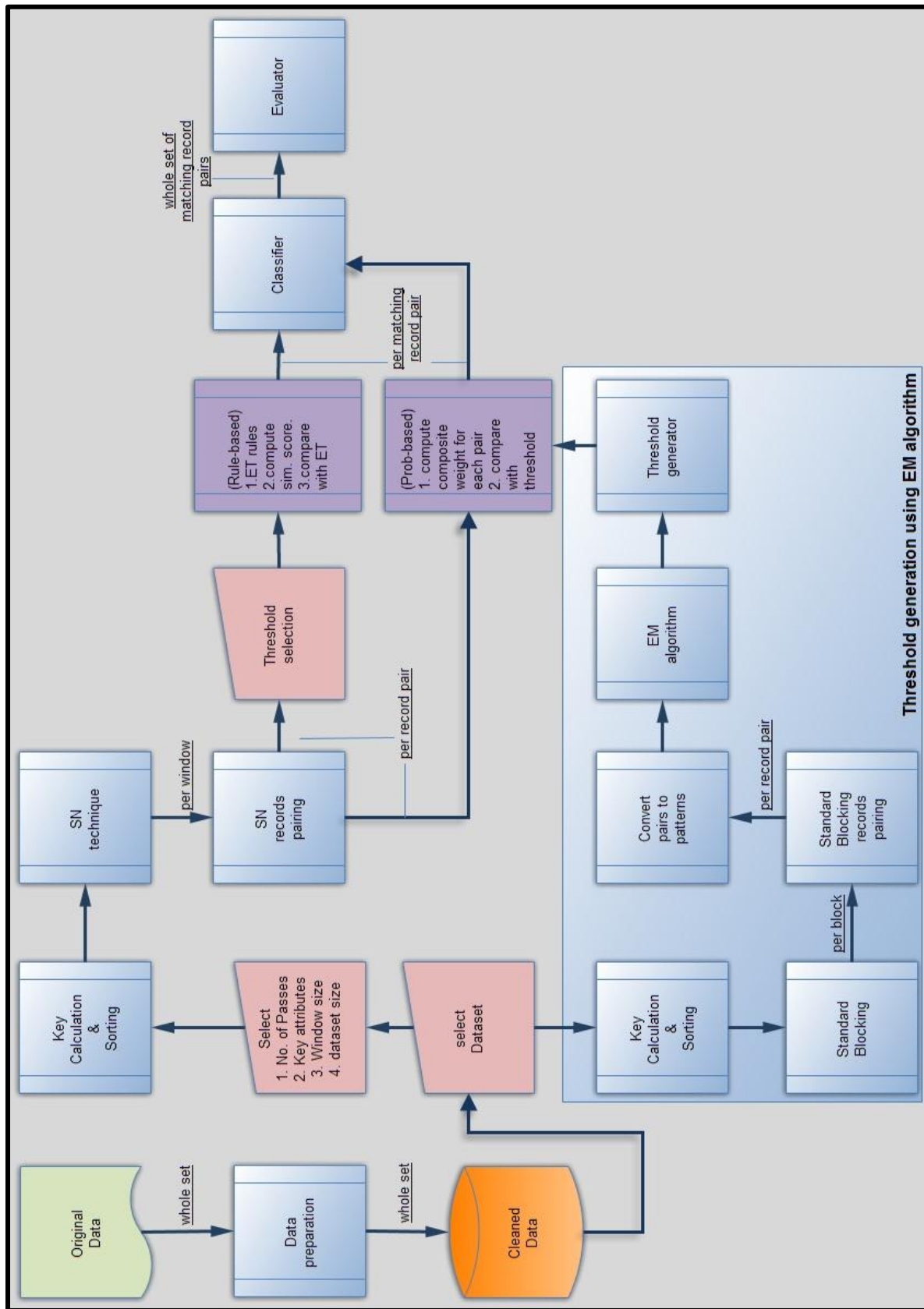


Figure 3.1: Duplicate Record Detection Framework.

3.2 Technologies

In evaluating and comparing the two duplication detection techniques, it has been used the following technologies:

Java Development Kit (JDK): the core of the system is built using the Java Platform (Standard Edition 6). Java is chosen because of its cross-platform capabilities.

MySQL server 6.0 database environment: MySQL is the world's most popular open source database, as quoted from its website Due to its free usage and fast performance; it is favored as the relational database management system (RDBMS) of choice for this project.

Netbeans: the development environment used was Netbeans IDE 7.0.1 for compiling and executions.

MySQL connector Java: the MySQL Connector Java provides the functionality to access the database system from within the Java program. It provides functionalities to access and retrieves data from the database. The MySQL Connector Java driver is downloadable from the MySQL website. The version of the connector used for this project is 5.1.18.

SimMetrics: SimMetrics is an open source Java library of distance metrics. It contains programs for a variety of edit distance and token-based metrics such as Smith-Waterman, Jaro, Needleman-Wunsch, Jaccard, TFIDF, Levenstein, and Q-Gram distance. It takes in a pair of string data and return the distance result in the form of floating-point based number (0.0 - 1.0).

3.3 Implementation Details

In this section, we describe in detail the system implementation stages. We have only implemented the needed stages required for basic functionality. Figure 3.2 clarifies the calling flow chart for the implemented algorithms.

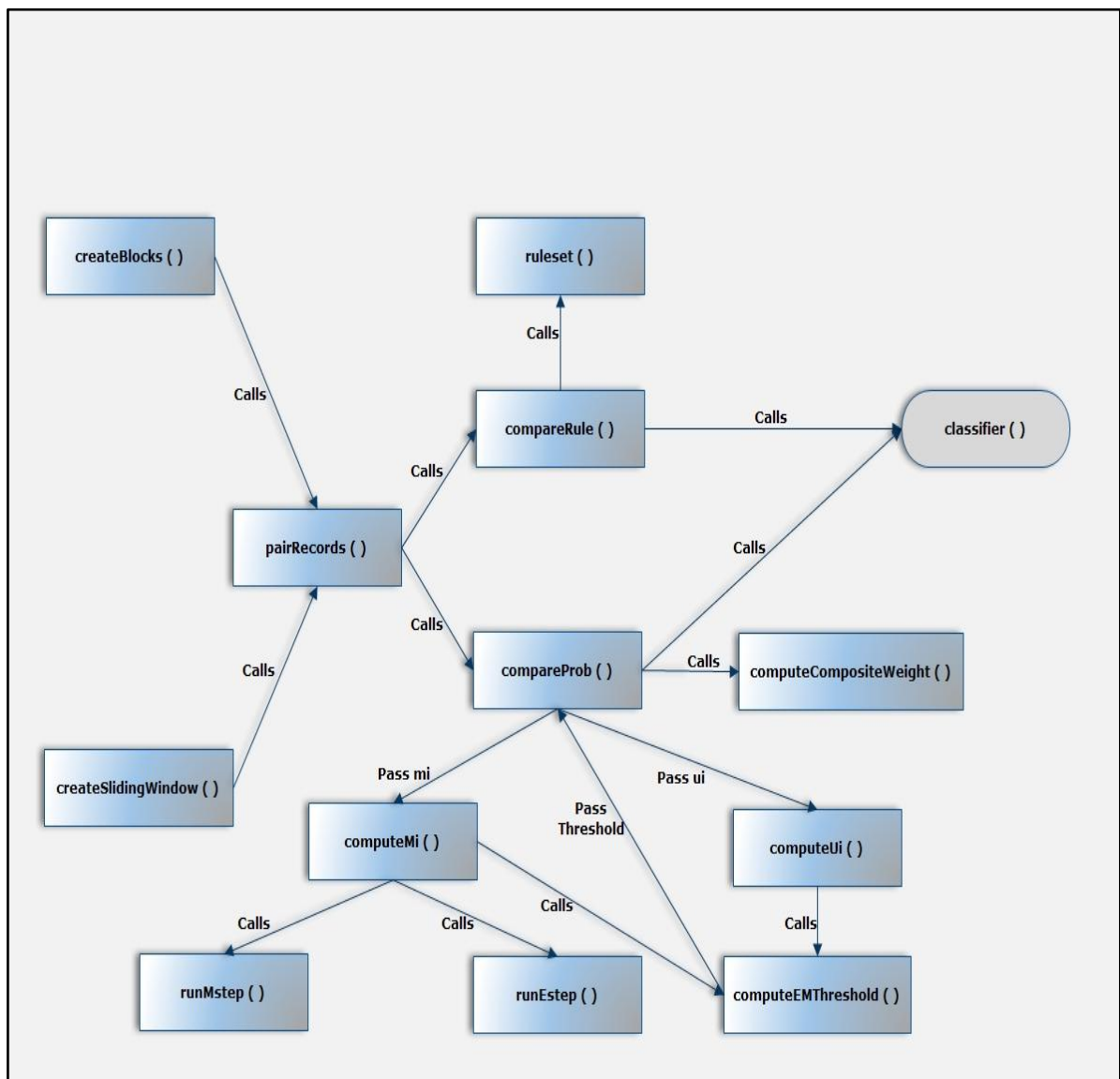


Figure 3.2: Algorithms calling flowchart.

Data preparation: we get the data in CSV files, all the data have the same entities as the database we have create for the project, let us take the (dataset_B.csv) as an example here. The file placed on accessible location on the machine, and then we access and read the file content and post all the data to the database using the access function (insert_data). We repeat this function on all the data lines in the file. Note that the function (insert_data) runs on each database sample to fill it in our database. Refer to appendix1.

Blocking keys generator: for each record in the database, we create a candidate key which is a concatenation of values (or part of them) from several attributes. Then the records sorted ascendingly according the key generated. In this stage we mainly depend on our Database Management System for some of the background activities needed such as navigating, retrieving of related records during blocking key value generation, also provides us with some helpful built-in tools such as sorting and indexing functionalities that is required after the key generation. The following SQL statements show an example of generating the blocking key.

```
UPDATE Dataset_A SET candKey=UPPER (CONCAT (SUBSTRING (gname, 1, 3),
SUBSTRING (sname, 1, 3), SUBSTRING (Stno, 1, 3)))
SELECT * FROM tablename WHERE candKey!='' ORDER BY candKey ASC
```

Standard blocking key: standard blocking use a fixed key which is the concatenation of the first three characters of "Given name", first three characters of "Surname", and first three characters of "street number". Then the records are sorted asendingly according to the key to close up the similar records.

Sorted neighborhood keys: the key for the sliding window is selected by the user by choosing any three attributes from the database, and then the system will take the first three characters from the selected attributes, and concatenate them together to generate

the key. Then the records are sorted ascendingly according to the key to close up the similar records. This key generated three times for applying the multi-pass technique with the SN each key has different selected attributes.

Records blocking: after the blocking key is generated, the records sorted ascendingly according to the blocking key. Then we apply either the blocking technique or the SN technique

Standard blocking technique: blocking technique doesn't include all the records from the database in the created blocks, which means that there are records that don't belong to any blocks. In this case these records are ignored. Also, all the blocks are non-overlapping windows. As shown in Figure 3.3.

To create the blocks, first we retrieve the first record and the second record from the database. Then, we compare the candidate key of first record with the candidate key of the second record and compute the similarity score between the two keys using the Q-Gram metric. If the similarity score is equal to one, the two records are put into the same block. After that we repeat the comparison with the third record and so on. If no records satisfy the similarity with candidate key of the first record, we used the next record to create a new block. Once a new block is found, we retrieve the identifiers of all records in the block and sent them to be paired.

Sorted-Neighborhood technique: unlike the standard blocking technique, the sliding window has a fixed size, each time the window slides down first record is removed from the window, and the next record is added to the window, and to the list of identifiers. These identifiers passed to the record pairing stage. As shown in Figure 3.4.


```

createBlocks ( )
Input: All sorted records from database (data)
Output: Identifiers of all records in a block (ids)
quitSearch ← false;
threshold ← 1;
while not end of data and !quitSearch do
    A ← candidate key for the next record;
    blockSize ← 1;
    while not end of data do
        B ← candidate key for the next record;
        score ← similarity score between A and B based on Q-Gram similarity
        metric;
        if score ≥ threshold then
            blockSize ← blockSize + 1;
        else
            go back to the previous record;
            quit inner while loop;
    if block size > 1 then
        go back to blockSize previous records;
        ids ← identifiers of all records in block;
        quitSearch ← pairRecords(ids);
    else skip;

```

Figure 3.3: Algorithm createBlocks()

```

createSlidingWindow ( )
Input: All sorted records from database (data), database size (dbSize), sliding window
size (winSize)
Output: Identifiers of all records in a sliding window (ids)
totalSlides ← dbSize - winSize;
for i ← 0 to totalSlides do
    if i is 0 then
        ids ← identifiers of all records in block from 0 to winSize - 1;
    else
        remove first record from sliding window;
        add the next record to sliding window;
        ids ← identifiers of all records in sliding window;
    pairRecords(ids);

```

Figure 3.4: Algorithm createSlidingWindow()

Records pairing: after dividing the whole dataset to blocks or windows we paired up the records within the same block or window then pairs are sent to the matcher pair by pair to determine if they are matching or non-matching. As shown in Figure 3.5.

Records pairing in blocks: here we use the identifiers of the records in the same block. The first record in the block is taken and paired up with the rest of records in the block. Then we take the second record and pair it up with the rest of records that has a position higher than the second record and so on to the rest of records. Then we continue with all blocks.

Records pairing in sliding window: pairing in sliding windows differs, except the first window in the dataset which is paired like the blocks pairing. Pairing starts with the last record in the window by pairing it with all records in the same window except itself.

pairRecords ()

Input: Identifiers of all records in a sliding window (*ids*), limit of record pairs in block (*limit*)

Output: Record pair (*t1*, *t2*), *quitSearch*

if evaluating a block then

for *id1* \in *ids* **do**

t1 \leftarrow *id1*;

for *id2* \in *ids* where position of *id2* > position of *t1* in *ids* **do**

t2 \leftarrow *id2*;

compareProb(*t1*, *t2*);

increase *totalPairs* by 1;

if *totalPairs* > *limit* **then**

quitId2 \leftarrow true;

quit inner loop;

if *quitId2* **then**

quitSearch \leftarrow true;

quit outer loop;

else if evaluating a sliding window then

t1 \leftarrow last identifier in *ids*;

for *id* \in *ids* except *t1* **do**

t2 \leftarrow *id*;

if *dicisionmodel*=*Rule* **Then**

compareRule(*t1*, *t2*);

Else

compareProb(*t1*, *t2*);

Figure 3.5: Algorithm pairRecords()

Threshold generator for Probabilistic-based technique: the Probabilistic-based technique needs to compute the threshold value, this done using the EM algorithm which use the standard blocking to pair up the records. The threshold value computes by these steps:

1. Compute the vector pattern of each record pairs that we get from the blocks by comparing the similarity score of each attribute of the record pair with a threshold value. If the score of the attribute above the threshold the value of this attribute is set to 1. Otherwise, it's set to 0. So we get from the record pair a vector pattern consists of binary values. Then we store all the vector patterns and their frequency counts.
2. Estimate the value of m_i and the value of u_i from the vector patterns and their frequency counts. As shown in Figure 3.6.
3. Compute the threshold value using the values of m_i and u_i . As shown in Figure 3.9.

The values of m_i and u_i could be estimated by converting the record pairs from the blocks to vector patterns. We store the vector patterns as a binary model and the frequency counts. If record pair generates a comparison vector in the binary model a count of one is added to the frequency count of that particular pattern. Otherwise, we add the pattern and a frequency count of one.

EM algorithm makes use of patterns and their frequency counts, by applying these equations to estimate m_i and u_i after initialize m_i , u_i , and p were 0.9, 0.1, and 0.5 respectively using the E-step and M-step (Jaro, 1989). As shown in Figures 3.7, and 3.8.

$$m_i = \frac{\sum_{j=1}^{2^n} \gamma_i^j \cdot g_m(\gamma^j) f(\gamma^j)}{\sum_{j=1}^{2^n} g_m(\gamma^j) f(\gamma^j)} \quad (3.1)$$

$$u_i = \frac{\sum_{j=1}^{2^n} \gamma_i^j \cdot g_u(\gamma^j) f(\gamma^j)}{\sum_{j=1}^{2^n} g_u(\gamma^j) f(\gamma^j)} \quad (3.2)$$

$$p = \frac{\sum_{j=1}^{2^n} g_m(\gamma^j) f(\gamma^j)}{\sum_{j=1}^{2^n} f(\gamma^j)} \quad (3.3)$$

Threshold value could be calculated according to the following steps (Jaro, 1989) which are shown in Figures 3.10, and 3.11:

Compute the composite weight for each comparison vectors. Then sort the comparison vectors ascendingly in order to their composite weights. Continue with calculation of the estimated true-positive and true-negative probabilities of each comparison vector. Finally, we used the naive way by choosing a middle index of ascendingly sorted composite weights and setting it as threshold value. Table 3.1 shows a sample of the vector patterns and its frequency counts.

Table3.1: Sample of vector patterns and frequency counts.

Vector Patterns	Frequency counts
111101111111	45
111101110111	29
111101101111	25

```

computeMi ( )
Input: total attributes of dataset ( $n$ )
Output:  $m_i, u_i$ 
 $m \leftarrow 0.9;$ 
 $u \leftarrow 0.1;$ 
 $p \leftarrow 0.5;$ 
 $convergeValue \leftarrow 0.00001;$ 
for  $i \leftarrow 1$  to  $n$  do
     $m_i \leftarrow m;$ 
     $u_i \leftarrow u;$ 
while  $m_i, u_i$  and  $p$  are not converged to  $convergeValue$  do
     $runEStep(m_i, u_i, p);$ 
     $runMStep(g_m(\gamma^j), g_u(\gamma^j));$ 

```

Figure 3.6: Algorithm computeMi()

```

runEStep ( )
Input: A collection of vector patterns  $\gamma^j$  and their respective frequency counts  $f(\gamma^j)$ 
(collectionVecPattern), total attributes of dataset ( $n$ ),  $m_i, u_i, p$ 
Output:  $g_m(\gamma^j)$ , and  $g_u(\gamma^j)$ 
for  $\gamma^j \in collectionVecPattern$  for  $j \leftarrow 1$  to size of collectionVecPattern do
    for  $i \leftarrow 1$  to  $n$  do
         $\gamma_i^j \leftarrow$  the  $i$ -th component in  $\gamma^j$ ;
         $probMatching \leftarrow probMatching * m_i^{\gamma_i^j} * (1 - m_i)^{(1 - \gamma_i^j)};$ 
         $probNotMatching \leftarrow probNotMatching * u_i^{\gamma_i^j} * (1 - u_i)^{(1 - \gamma_i^j)};$ 
     $g_m(\gamma^j) \leftarrow P * probMatching / (P * probMatching + (1.0 - P) * probNotMatching);$ 
     $g_u(\gamma^j) \leftarrow$ 
     $((1.0 - P) * probNotMatching) / (P * probMatching + (1.0 - P) * probNotMatching)$ 

```

Figure 3.7: Algorithm runEStep()

runMStep ()

Input: A collection of vector patterns γ^j and their respective frequency counts $f(\gamma^j)$ (*collectionVecPattern*), total attributes of dataset (n), total number of record pairs (N), $g_m(\gamma^j)$, $g_u(\gamma^j)$

Output: m_i , u_i , p

for i from 1 to n **do**

for γ^j and $f(\gamma^j) \in$ *collectionVecPattern* **for** $j \leftarrow 1$ **to** size of *collectionVecPattern* **do**

$\gamma_i^j \leftarrow$ the i -th component in γ^j ;

$m_{i_numerator} \leftarrow m_{i_numerator} + (\gamma_i^j * g_m(\gamma^j) * f(\gamma^j))$;

$u_{i_numerator} \leftarrow u_{i_numerator} + (\gamma_i^j * g_u(\gamma^j) * f(\gamma^j))$;

$m_{i_denominator} \leftarrow m_{i_denominator} + (g_m(\gamma^j) * f(\gamma^j))$;

$u_{i_denominator} \leftarrow u_{i_denominator} + (g_u(\gamma^j) * f(\gamma^j))$;

$m_i \leftarrow m_{i_numerator} / m_{i_denominator}$;

$u_i \leftarrow u_{i_numerator} / u_{i_denominator}$;

$p_{numerator} \leftarrow m_{i_denominator}$;

$p \leftarrow p_{numerator} / N$;

Figure 3.8: Algorithm runMStep()

```

computeUi ( )
Input: A collection of vector patterns  $g_j$  and their respective frequency counts
 $f(\gamma^j)$ (collectionVecPattern), total attributes of dataset ( $n$ ), number of records ( $N$ ),
database (tableName)
Output:  $u_i$ 
 $c \leftarrow$  collection of vector patterns  $\gamma^j$  and their respective frequency counts  $f(\gamma^j)$ ;
 $w \leftarrow$  randomly selected  $N$  records from database tableName using SQL;
totalPairs  $\leftarrow N$ ;
for  $x \leftarrow 1$  to totalPairs do
     $t1 \leftarrow$  record randomly retrieved from  $w$ ;
     $t2 \leftarrow$  record randomly retrieved from  $w$ ;
     $\gamma^j \leftarrow$  computed pattern for record pair ( $t1, t2$ );
    if  $\gamma^j$  exists in  $c$  then
        add 1 to the frequency counts  $f(\gamma^j)$  of  $\gamma^j$ ;
    else insert  $\gamma^j$  and its frequency count of 1 to  $c$ ;
for  $i \leftarrow 1$  to  $n$  do
    for  $\gamma^j$  and  $f(\gamma^j) \in$  collectionVecPattern for  $j \leftarrow 1$  to size of collectionVecPattern
    do
         $\gamma_i^j \leftarrow$  the  $i$ -th component in  $\gamma^j$ ;
        if  $\gamma_i^j$  is 1 then
            add  $f(\gamma^j)$  to counter;
         $u_i \leftarrow$  counter/totalPairs;

```

Figure 3.9: Algorithm computeUi()

computeEMThreshold ()

Input: A collection of vector patterns γ^j and their respective frequency counts $f(\gamma^j)$ (collectionVecPattern), total attributes of dataset (n), m_i , u_i

Output: threshold

```

for  $\gamma^j \in$  collectionVecPattern for  $j \leftarrow 1$  to size of collectionVecPattern do
    for  $i \leftarrow 1$  to  $n$  do
         $\gamma_i^j \leftarrow$  the  $i$ -th component in  $\gamma^j$ ;
        probMatching $_i \leftarrow$  probMatching $_i * m_i^{\gamma_i^j} * (1 - m_i)^{(1 - \gamma_i^j)}$ ;
        probNotMatching $_i \leftarrow$  probNotMatching $_i * u_i^{\gamma_i^j} * (1 - u_i)^{(1 - \gamma_i^j)}$ ;
        if  $\gamma_i^j$  is 1 then
            score $_i \leftarrow$  score $_i + \log_2(m_i/u_i)$ ;
        else
            score $_i \leftarrow$  score $_i + \log_2((1 - m_i)/(1 - u_i))$ ;
    sort score $_i$  ascendingly;
    get the middle index  $i$  of sorted score;
    while probMatching $_i >$  probNotMatching $_i$  at middle index  $i$  do
        decrease  $i$  by 1;
        middleScore  $\leftarrow$  sorted score at middle index  $i$ ;
    while probMatching $_i <$  probNotMatching $_i$  at middle index  $i$  do
        increase  $i$  by 1;
        middleScore  $\leftarrow$  sorted score at middle index  $i$ ;
    threshold  $\leftarrow$  middleScore;

```

Figure 3.10: Algorithm compute EMThreshold ().

```

computeCompositeWeight ( )
Input: total attributes of dataset ( $n$ ), vector pattern of a record pair ( $pattern$ ),  $m_i$ ,  $u_i$ ,
record pair ( $t1$ ,  $t2$ )
Output: composite score of record pair ( $score$ )
for  $i \leftarrow 1$  to  $n$  do
     $pattern_i \leftarrow$  the  $i$ -th component in  $pattern$ ;
    if  $pattern_i$  is 1 then
         $score_i \leftarrow score_i + \log_2(m_i/u_i)$ ;
    else
         $score_i \leftarrow score_i + \log_2((1-m_i)/(1-u_i))$ ;
return  $score$ ;

```

Figure 3.11: Algorithm computeCompositeWeight ().

Decision models matcher: in this stage the user selects the decision model that decides if the record pair concedes to be matched or non-matched.

Rule-Based matcher: the Rule-based matcher works as following: (as shown in Figure 3.12)

1. Create the Equational Theory rules. According to our datasets the rules focus on names similarity (Given name, Surname), addresses similarity (Street number, Address 1, Suburb, Postcode, State), and social security number similarity.
2. Set the threshold value.
3. Receiving the pairs of records paired up from the SN technique.
4. Calculate the similarity score for each attribute of each record pair.
5. Compare the attribute score which is used in the rules with the (ET) rules and the threshold value. As shown in Figure 3.13.
6. If the pair is matched then pass it to the classification stage.

For multi-pass SN technique repeat steps 3 to 6.

CompareRule ()**Input:** record pair (t1, t2)**Output:** matching record pair (t1, t2)

compute similarity scores of each attribute in (t1, t2);

pass similarity scores to **Ruleset ()**;**if** (t1, t2) is found to be matching **then**

classifier(t1, t2);

Figure 3.12: Algorithm compareRule().**Ruleset ()****Input:** Similarity score for each attributes in record pair A and B**Output:** Record pair A and B is matching or non-matching**If** similar Given_name AND similar Surname **then**

Similar name;

If similar Address_1 AND similar state **then**

Very similar address 1;

If (similar state AND !similar address_1) OR (similar address_1 AND similar postcode) **then**

Very similar address 2;

If similar ssn AND similar name **then**

Match = true;

Else if (similar ssn OR similar name) AND (very similar address 1 OR very similar address 2) **then**

Match = true;

Else if similar ssn AND similar address_1 AND !similar name **then**

Match = true;

Else if similar ssn AND very similar address 2 AND similar surname AND similar postcode **then**

Match = true;

else

Match = false;

Figure 3.13: Algorithm ruleset()

Probabilistic-Based matcher: after computing the threshold value by the EM algorithm, the real detection operation applied. The following steps show how to decide if the pairs are matched or not: (as shown in Figure 3.14)

1. Receiving the record pairs from the SN method.
2. Calculate the composite weight of each record pair. As shown in Figure 3.11.
3. Compare the composite weight with the threshold value to determine if the record pair is matching or non-matching
4. Record pairs that are found to be matched send to the classification stage.
5. For the multi-pass SN technique repeat step 1 to 5.

To compute the composite weight of record pair that used to be compared with the threshold value to determine if the pair is matched or not, we use the same way of computing the composite weight of vector patterns.

CompareProb ()

Input: record pair (t1, t2), threshold

Output: -

if compute EM algorithm **then**

compute pattern for (t1, t2); // using EM algorithm

else

weight ← computeCompositeWeight(t1, t2);

if weight ≥ threshold **then**

classifier(t1, t2);

Figure 3.14: Algorithm compareProb().

Classifier: after the record pair is decided to be matched by the Rule-based technique or Probabilistic-based technique, the pair is passed to the classification stage where stored in a class, if the pair doesn't exist in one of classes then new class created and the pair stored in it. If one of the two records in the pair exists in some class, then we add the other record to the same class. For example, suppose the pair (4, 3) is caught by the

Matcher. Next, the pair (5, 2) is caught. At this point, the two pairs are stored in two different classes. In the next matching process, the pair (5, 4) is caught. Since record 4 points to class A whilst record 5 points to the class B, we join both Sets together. What we get in the end is Set A consisting of records {2, 3, 4, 5}. As shown in Figure 3.15.

classifier ()

Input: Record pair (t1, t2)

Output: A collection of records and the set that they belong to respectively (c) $c \leftarrow$ a collection of records and the set that they belong to respectively

if both t1 and t2 exist in c then

if both t1 and t2 do not belong to the same set then

add the set of t2 to the set of t1;

change all the records in the set of t2 to point to the set of t1;

empty the set of t2 from c;

else if t1 exists in c but not t2 then

add t2 to the set of t1;

let t2 points to the set of t1 in c;

else if t2 exists in c but not t1 then

add t1 to the set of t2;

let t1 points to the set of t2 in c;

else

create a new set in c;

add t1 and t2 to the new set;

let t1 and t2 point to the new set;

Figure 3.15: Algorithm classifier().

Evaluator: the performance measures can be estimated using these possible types of errors which are: (as shown in Figure 3.16)

1. False positive (FP) which means the candidate pairs that are declared to be duplicate in fact may not be duplicates.
2. False negative (FN) which means the candidate pairs were not declared to be duplicates while in fact they are.
3. True positive (TP) which means pairs that are correctly declared to be duplicates.
4. True negative (TN) which means pairs that are correctly recognized as not being duplicates.

These four possible types of error can be estimated by comparing our results with the real duplicates in the dataset which must be known previously.

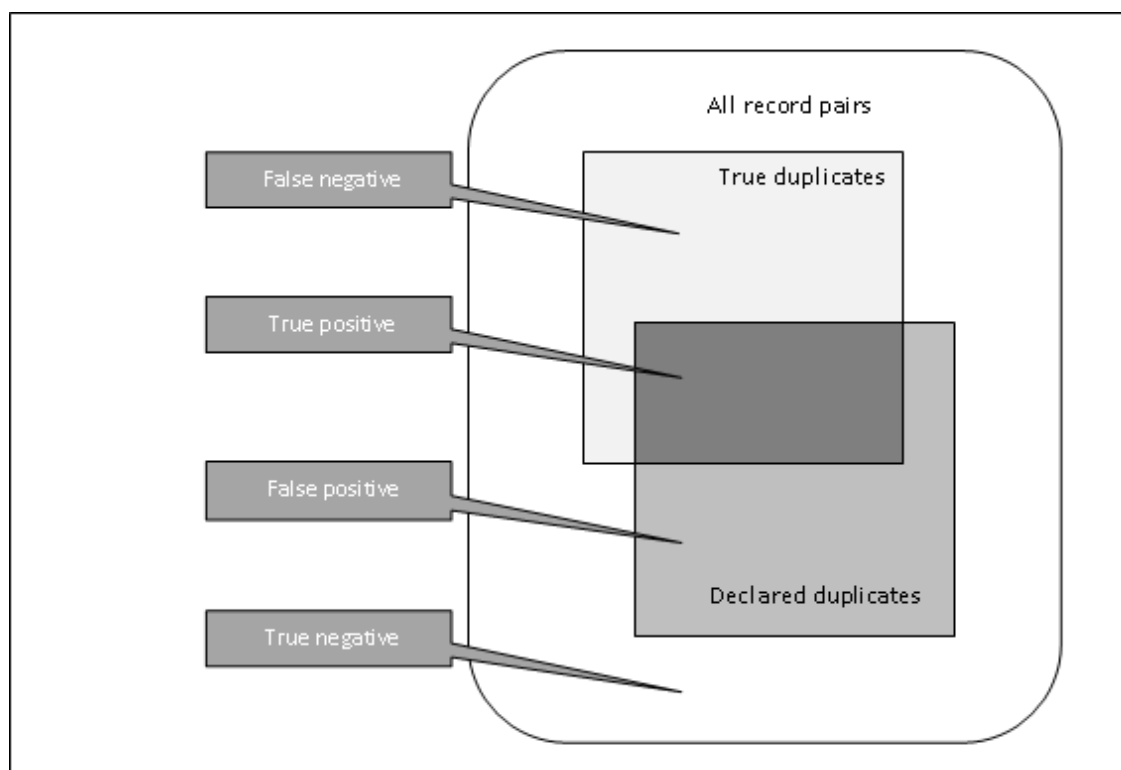


Figure 3.16: Error types in duplicate detection (Naumann & Herschel, 2010)

Chapter 4

Experimental Evaluation

In this chapter, we present the conducted experiments with their used settings and their results. We have used a synthetic dataset that was previously used as a benchmark in some of related work. In Section 4.1, dataset is presented in detail. In Section 4.2, the development environment is presented. The experiments in Section 4.3 evaluate the performance of the two duplication detection techniques, the Rule-based, and Probabilistic-based, on two different datasets using standard measures of accuracy, efficiency, and quality.

4.1 Data Set

There are a few datasets used by previous researchers are available to download on the Internet. One of these limited datasets is FEBRL (Freely Extensible Biomedical Record Linkage). This dataset is a synthetic one it contains patients' data such as given name, surname, street number, adresse1, address2, suburb, postcode, state name, date of birth, age, phone number, and social security number.

In this study two datasets of FEBRL have been used; the first (DATASET_A) contains 10000 records with 5000 original records and 5000 duplicated records. There is one duplicate per original record, maximum one modification per duplicate record and maximum one modification per attribute. The second (DATASET_B) contains 10000 records with 6000 original records and 4000 duplicated records. There is up to nine duplicates for an original record, maximum three modifications per attribute, and maximum 10 modifications per record. Table 4.1 shows a sample of duplicate records from this dataset.

Table 4.1 Sample duplicate records from the FEBRL dataset (datamining.anu.edu.au)

Given_name	Surname	Addresses	Age	Phone_num	SSN
Hannah	urquhart	Florin place	-	03 50770094	1614610
hann ah	urquzart	florihaplace	-	03 50770094	1614510
Teagan	Upton	Wilkins street	18	07 45868407	1198233
Teagan	Uptiny	Wilkins street	18	07 45867407	1198233
Teatan	Upton	Wilkins street	-	07 45886407	1198233
Brooke	Uren	barrett street	31	03 38165026	5411400
Broole	Umrh	barrettaareet	31	03 38165026	5421400
Brooke	Urpn	barrettistreet	31	03 38170526	5411050

4.2 Environment

The experiments were carried out on hp Notebook PC equipped with an Intel Core i3 of 2.27 GHz and 4GB RAM, running MS Windows 7 (64-bit) operating system. With using the technologies were mentioned in section 3.2.

4.3 Experiments

We have conducted two sets of experiments, where in the first set of experiments we have compared the two duplication detection techniques: the Rule-based and the Probabilistic-based on dataset (dataset_A) with size of 10,000 records and 5000 duplicates, one duplicate per original record, maximum one modification per duplicate record and maximum one modification per attribute.

In the second set of experiments, we have taken another dataset (dataset_B) with size of 10,000 records and 4000 duplicates, up to 9 duplicates for an original record, maximum 3 modifications per attribute, maximum 10 modifications per record to compare the Rule-based and the Probabilistic-based techniques on it.

Our experiments are designed to compare the two duplication detection techniques, using the standard performance measures defined in section 4.3 the techniques are:

1. Rule-based technique.
2. Probabilistic-based technique.

For each technique we have used the sorted neighborhood blocking technique with window size chosen by the user from 5 to 50 records.

The two techniques have been tested under the same conditions such as the sorting key, similarity function, blocking technique, and number of passes. For the blocking key value we used a key composed of the first three letters of three attributes, these attributes were chosen by the user. In the case of missing or null attribute in a record or the number of characters less than the required, we used a special characters padding at the end of each part. After key generation all the records are being sorted using the built-in feature of MySQL DBMS since it's highly optimized for performance. We used for our experiments these keys for the three runs (passes):

1. Pass 1: Given_name, Surname, and street_number.
2. Pass 2: Address_1, Suburb, and Postcode.
3. Pass 3: SSN, Phone_number, and State.

The similarity function used for comparison was Q-grams since it can give us a good result in detecting similarity between records, and it can handle insertion, deletion, and substitution in string or token for matching of two attributes (Alnoory, 2011).

There are a few threshold values for experiments on the two techniques. These values were set based on empirical results.

For the Rule-based technique, the threshold we need to set is the similarity threshold, used to compare a record pair with the Equational Theory rules. This threshold value

can be selected by the user from 0.1 to 1.0. For this experiment we set the threshold value to 0.8.

For the Probabilistic-based technique, the similarity threshold is also required to compute the vector pattern of record pair. We also set this threshold to 0.8 as a fixed value. Therefore, the binary value of the i -th attribute of a record pair is set to one if the attribute has similarity score greater than 0.8, otherwise, it's set to zero. The Probabilistic-based technique also has a blocking key similarity threshold to compare between two candidate keys. This comparison is required to create blocks using standard blocking technique for the EM algorithm. This threshold was set to 1.0. Meanwhile, the value of m_i was estimated from the vector patterns and their frequency counts over a sample of record pairs to reduce the time complexity, we decided to set a limit of 1,000 record pairs to estimate both m_i and u_i .

4.3.1 Experiment Set 1

In this section we compare both two duplication detection techniques on dataset (dataset_A) on the same circumstances. This dataset has 50% duplicates but the modifications by the record are so limited.

We have chosen threshold value for the Rule-based technique as 0.8 after several runs to get the best results. Because of the high threshold such as 0.9 can effect on the number of declared duplicates caught by the Rule-based and that will increase the false positive which effect on the precision values. And the lower threshold such as 0.5 well decrease the declared duplicates caught by the Rule-based and that well effect on the true positive and thus the precision and recall. Meanwhile, the threshold value for the Probabilistic-based technique estimate using the EM algorithm.

We should note that a similarity threshold of 0.78 used in other related work for getting good results for both recall and precision. (Draisbach & Naumann, 2009).

Experiment 1-A

Duplication detection techniques used blocking techniques to avoid comparing all records with each other to increase the efficiency of the duplication detection technique.

As shown in table 4.2.

In Figure 4.1, we clarify the effect of varying the window size from 5 records per the window to 50 records per the window on both recall, and precision. Increasing the window size will increase the pairs numbers that will compared together to find the duplicates records. And that will give us surely better results depending on the dataset size and the percentage of duplicates records in this dataset. But it will affect the runtime of the duplicate detection.

Table 4.2: Total number of detected duplicates with varying window size for Dataset_A.

Window size	5	10	15	20	25	30	35	40	45	50
Rule true duplicates	3541	3562	3566	3570	3577	3585	3594	3607	3624	3628
Prob true duplicates	3834	4019	4169	4224	4302	4316	4342	4360	4381	4394

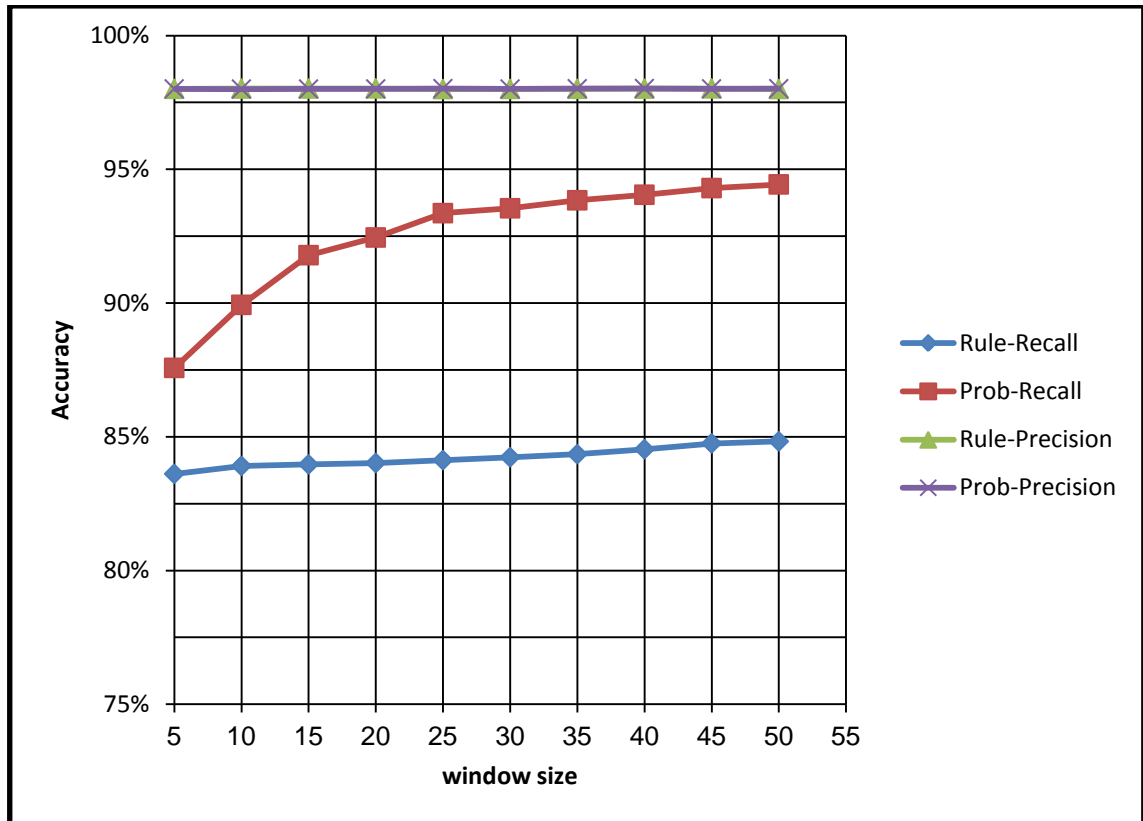


Figure 4.1: Accuracy comparison between Rule-based and Probabilistic-based with varying window size for dataset_A.

Experiment 1-B

To measure the effect of dataset size on the two techniques we conduct another experiment by increasing the number of records from 1000 records to 10,000 records. Figure 4.2 clarifies the accuracy for both duplication detection techniques according to dataset size. Probabilistic-based techniques use the frequency of matched (m_i) and unmatched (u_i) for each attribute to estimate the weight of every attribute in the record and make use of these values to compute the threshold value. Therefore, the size of dataset well effect distributing of errors within the attributes. Meanwhile, the Rule-based depends on the quality of the pairs to compare with the rules, so it's slightly affected by changing the size of dataset.

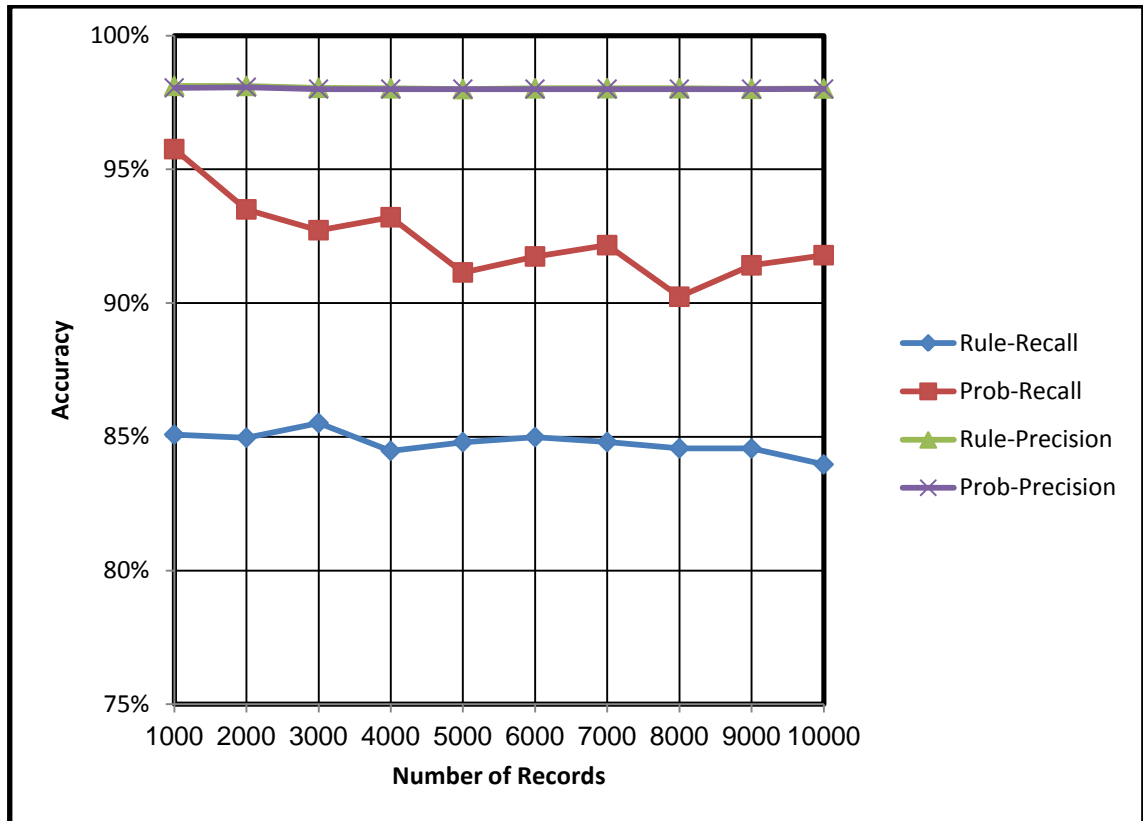


Figure 4.2: Accuracy comparison between Rule-based and Probabilistic-based with varying number of records for dataset_A.

Experiment 1-C

The previous experiments show the accuracy of each duplication detection technique, but what about the time consuming? In this experiment we estimate the runtime for each technique with the increasing size of the dataset from 1000 records to 10,000 records. Window size is set to 15 records per window and threshold value for the Rule-based is set to 0.8. Figure 4.3 shows the comparison according to the runtime. Rule-based consuming most of its runtime in blocking the records and pairing them to decide after that which of these pairs are matched or unmatched. Probabilistic-based need an extra step which is computing the threshold value and this take a lot of time.

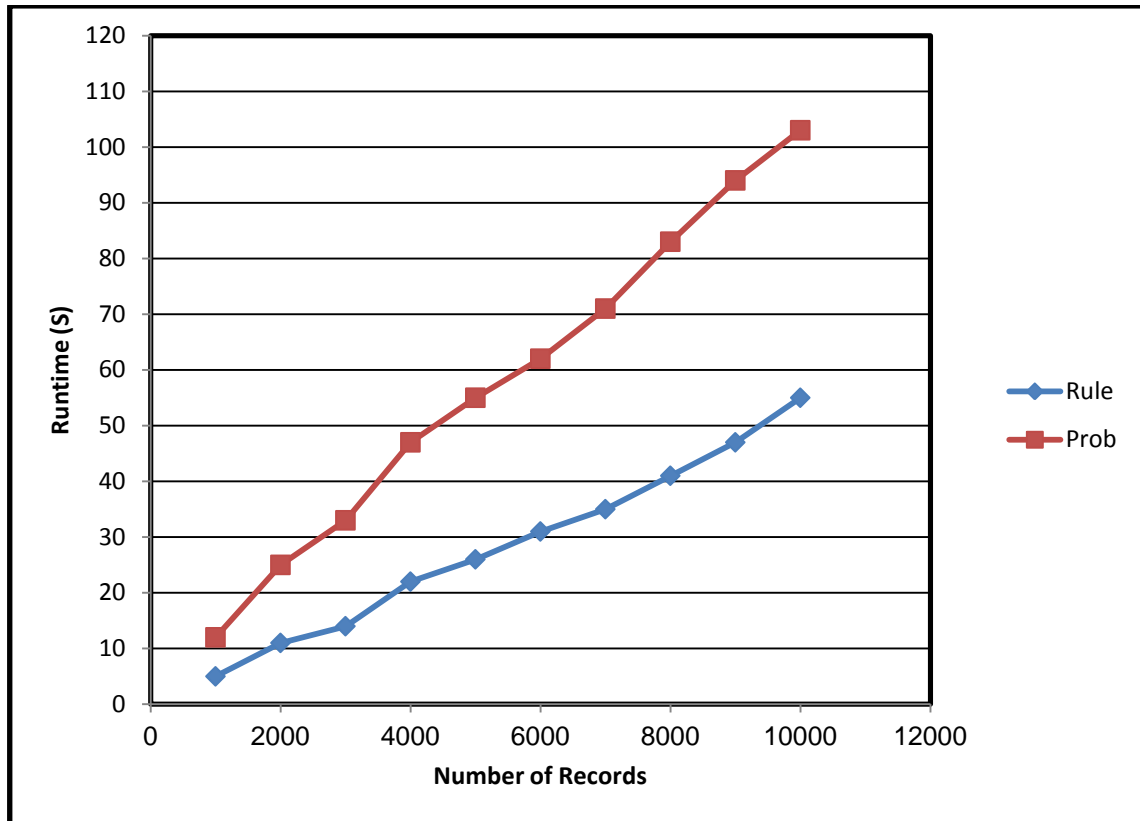


Figure 4.3: Runtime comparison between Rule-based and Probabilistic-based with varying number of records for dataset_A.

Experiment 1-D

in this experiment we compare both techniques using recall, precision, and F-score measures with dataset size 10,000 and window size 50 records per window and Rule-based threshold value is set to 0.8 showing that in Figure 4.4.

Adding the F-Score measure could provide us a better understanding for both techniques which of them is the best technique over these experiments on this particular dataset.

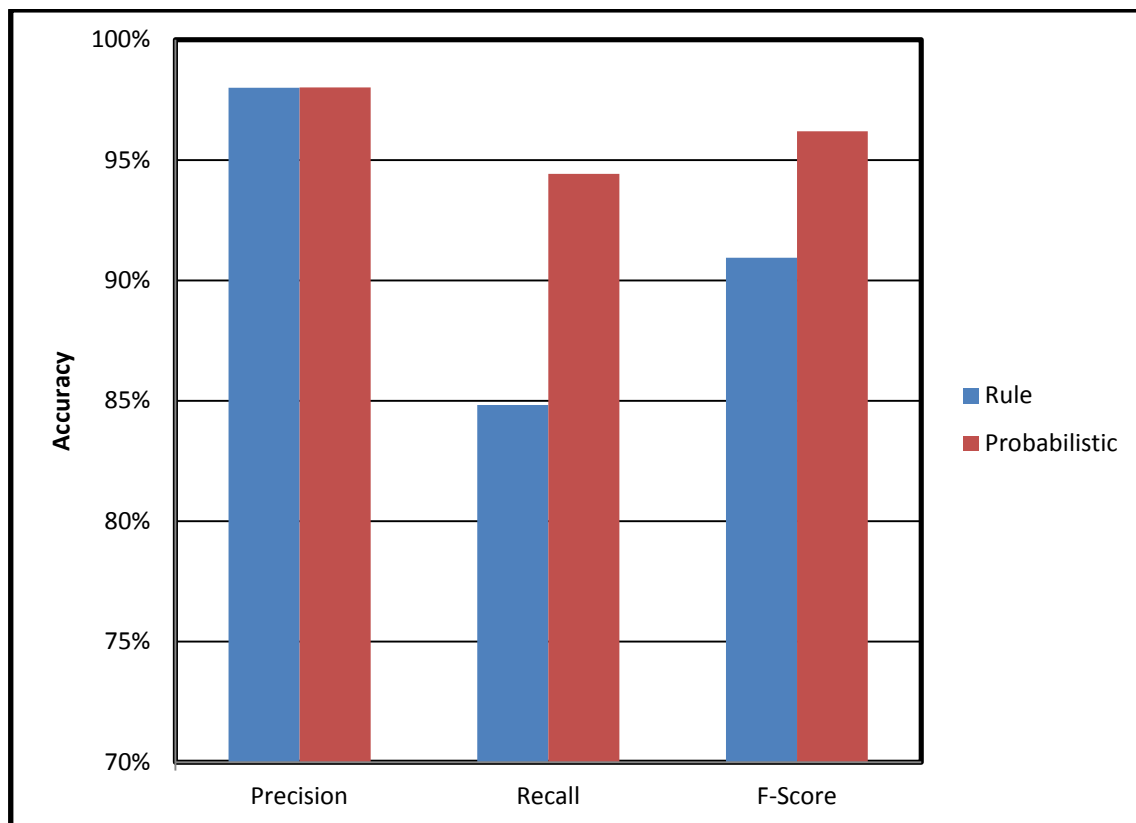


Figure 4.4: Accuracy comparison between Rule-based and Probabilistic-based technique with window size=50 and number of records=10,000 for dataset_A.

Experiment 1-E

In this experiment we study the effect of using the SN technique with Multi-pass. The dataset size is set to 10,000 records. The window size is set to 50. And the threshold for the Rule-based is 0.8. Three keys were generated to apply three passes. For one pass we select the same attribute in all three keys so they act as one key as follows:

Key1: givenname, surname, streetnumber.

Key2: givenname, surname, streetnumber.

Key3: givenname, surname, streetnumber.

For the two passes we repeat the same key in the first key and in the second key but the third key will be different as follows:

Key1: givenname, surname, streetaddress.

Key2: givenname, surname, streetaddress.

Key3: address1, suburb, postcode.

Finally, for the three passes the three keys selected are:

Key1: givenname, surname, streetaddress.

Key2: address1, suburb, postcode.

Key3: SSN, phonenumber, state.

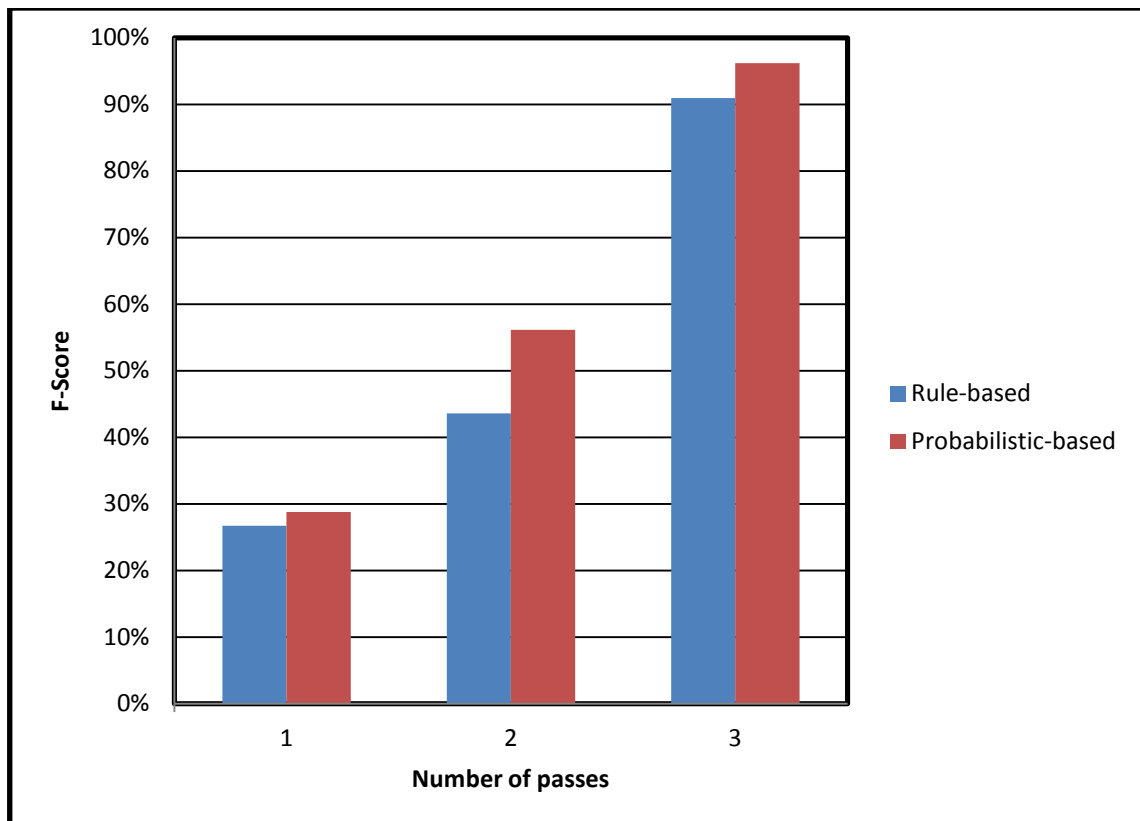


Figure 4.5: Accuracy comparison between Rule-based and Probabilistic-based technique with variation number of passes for dataset_A.

Results Analysis

From the experiments we have noted that the recall is increasing whenever we increase the window size and this is mainly due to the increasing number of pairs to be compared and the decreasing number of the false negative detected by the both duplication detection techniques. The increasing ratio for the recall of Probabilistic-based technique is more than the Rule-based technique when increasing the window size, exactly from window size 5 to 25 after that the recall grows slowly from 30 to 50.

Comparing the results for the precision, we have noted that precision stays stable when increasing the window size with insignificant change (± 0.01) because of the stability of the number of false positive.

The increasing of dataset size shows that the overall values of recall slightly decreased for both techniques, but the decreasing of Probabilistic-based technique is not a linear and that refers to the number of pairs (sample of all pairs) that used to estimate the threshold value by the EM algorithm using standard blocking technique. Number of pairs that used to compute the threshold value for dataset size 1000 records is 427 pair from 427 total pairs so this sample will give us result better than dataset with size 10,000 records which has 4123 pairs with sample 1000 pairs. Therefore, the recall decreased when increasing dataset size but in irregular shape. Table 4.3 views the pairs for the dataset with varying size.

Table 4.3: Sample of pairs for the EM algorithm for dataset_A.

Number of records	Number of pairs	Sample of pairs
1000	427	427
2500	1067	1000
5000	2088	1000
10,000	4123	1000

For the Rule-based technique the decreasing is almost linear. The precision for both techniques is almost fixed among the increasing size of the dataset.

We also measure the time efficiency for the both techniques; processing time collected during the tests shows clearly that Probabilistic-based technique is having the higher processing time. This can be reasoned by the estimation of threshold value using the EM algorithm, noted that we compute the time complexity for the classification of matched pairs and that will reflect in the overall time because we used the sorted neighborhood technique which causes redundancy in the candidates pairs.

The F-Score computed from the Recall and Precision to get a good view of the two techniques. This shows that the Probabilistic-based technique has higher F-Score with 96.19% than Rule-based technique with 90.94%.

At last, we notice that increasing the number of passes will effect positively on the accuracy of the system. The good selection of the pass key will affect the F-Score value. The experiments show that Probabilistic-based technique outperforms the Rule-based technique on dataset_A.

4.3.2 Experiment Set 2

In these set of experiments we compare both two duplication detection techniques on another dataset (dataset_B) on the same circumstances. Dataset_B has 40% duplicates with a higher number of modifications per the record than dataset_A. So it's more complex which indicates to effect on the results of our second set of experiments. It has been used the same window size and threshold value for Rule-based as mentioned in Section 4.4.1.

Our set of experiments according to:

1. Window size versus accuracy.
2. Number of records (dataset size) versus accuracy.

3. F-score measure with recall and precision.
4. Number of records versus runtime.

Experiment 2-A

Table 4.4 shows the number of true detected duplicates discovered by the Rule-based and Probabilistic-based which used to compute recall and precision, and that leads us to Figure 4.6 which clarifies the effect of varying window size from 5 to 50 on recall and precision for dataset_B.

Table 4.4: Total number of detected duplicates with varying window size for Dataset_B

Window size	5	10	15	20	25	30	35	40	45	50
Rule true duplicates	2200	2204	2209	2213	2215	2212	2222	2231	2241	2251
Prob true duplicates	2733	2931	3040	3062	3065	3068	3073	3084	3096	3110

It can be noticed the changing in recall and precision values and that refers to the data complexity of dataset_B. Of course, the number of duplicates in this dataset is small (9 or less). That leads to increasing the window size more than 15 records per window which will not affect seriously in recall and precision.

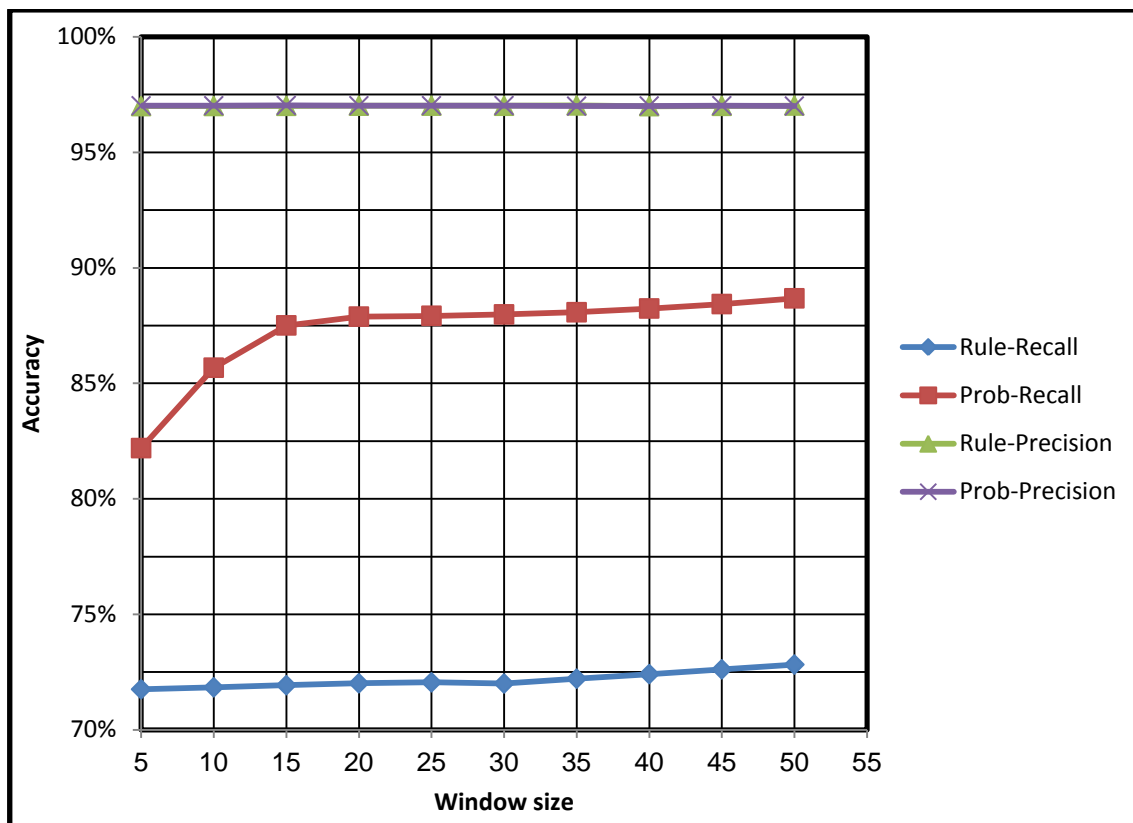


Figure 4.6: Accuracy comparison between Rule-based and Probabilistic-based techniques with varying window size for dataset_B.

Experiment 2-B

Once again, we use the size of dataset to evaluate the two techniques by increasing the size from 1000 records to 10,000 records. Figure 4.7 clarifies the accuracy for both duplication detection techniques according the dataset size.

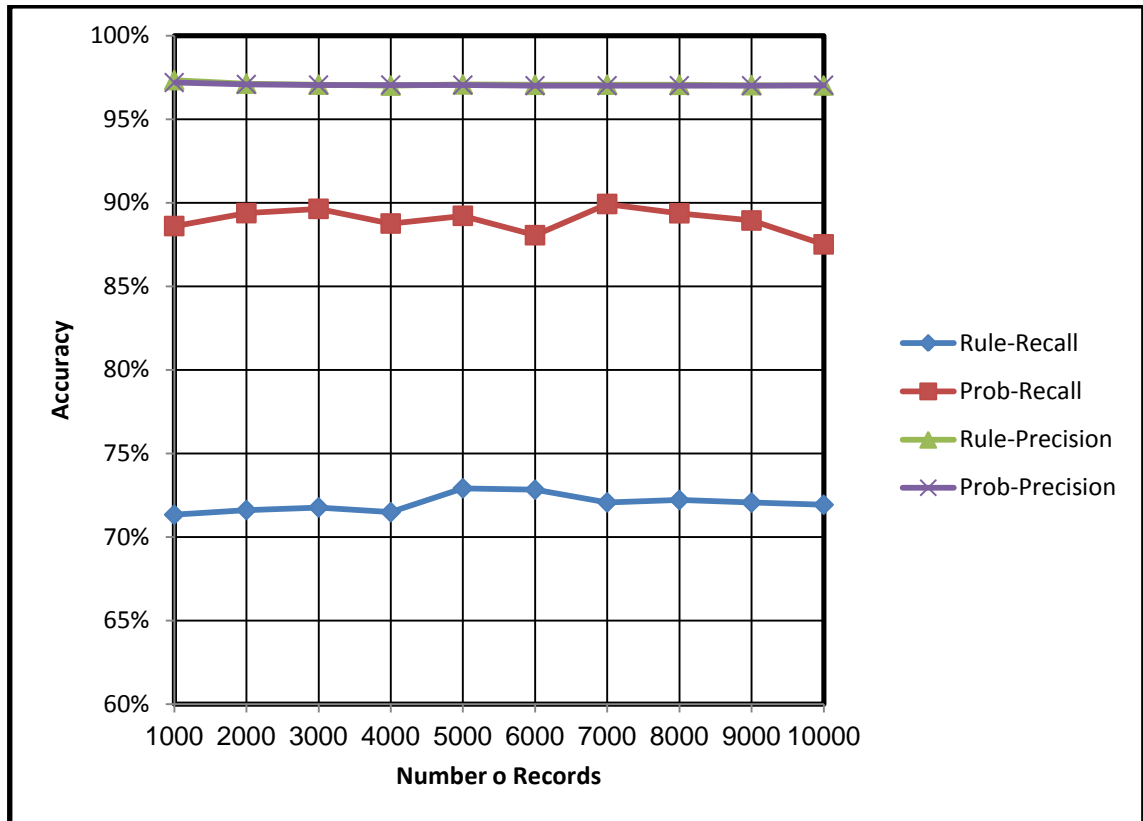


Figure 4.7: Accuracy comparison between Rule-based and Probabilistic-based techniques with varying number of records for dataset_B.

Experiment 2-C

And finally, the pervious experiments show the accuracy of each duplication detection technique, but what about the time consuming?

In this experiment, we estimate the runtime for each technique with the increasing size of the dataset from 1000 records to 10,000 records. Figure 4.8 shows the comparison according to the runtime.

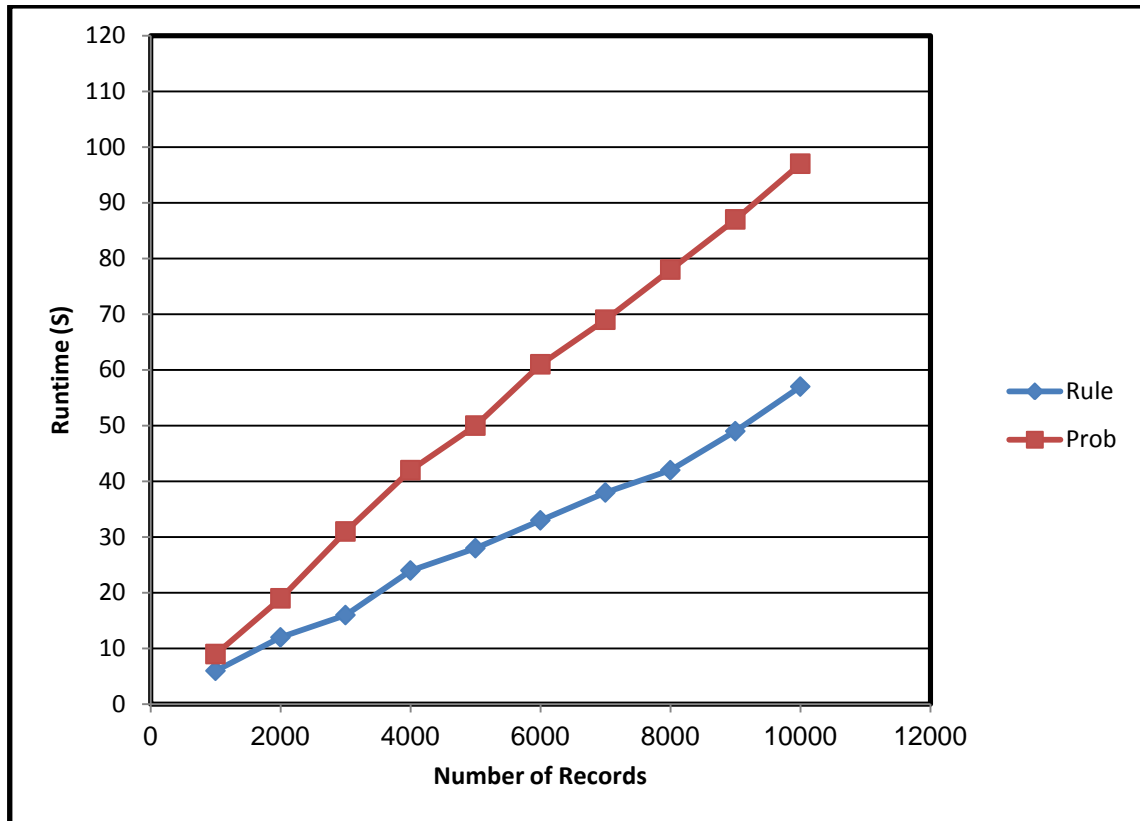


Figure 4.8: Runtime comparison between Rule-based and Probabilistic-based techniques with varying number of records for dataset_B.

Experiment 2-D

The last in this set of experiments is comparing both techniques using recall, precision, and F-score measures with dataset size=10,000 and window size=15 showing that in Figure 4.9.

Experiment 2-E

In this experiment, we study the effect of using the SN technique with Multi-pass. the dataset size is set to 10,000 records. The window size is set to 50. And the threshold for the Rule-based is 0.8. Three keys were generated to apply three passes. For one pass we select the same attribute in all three keys so they act as one key as follows:

Key1: givenname, surname, streetnumber.

Key2: givenname, surname, streetnumber.

Key3: givenname, surname, streetnumber.

For the two passes we repeat the same key in the first key and in the second key but the third key will be different as follows:

Key1: givenname, surname, streetaddress.

Key2: givenname, surname, streetaddress.

Key3: address1, suburb, postcode.

Finally, for the three passes the three keys selected are:

Key1: givenname, surname, streetaddress.

Key2: address1, suburb, postcode.

Key3: SSN, phonenumber, state.

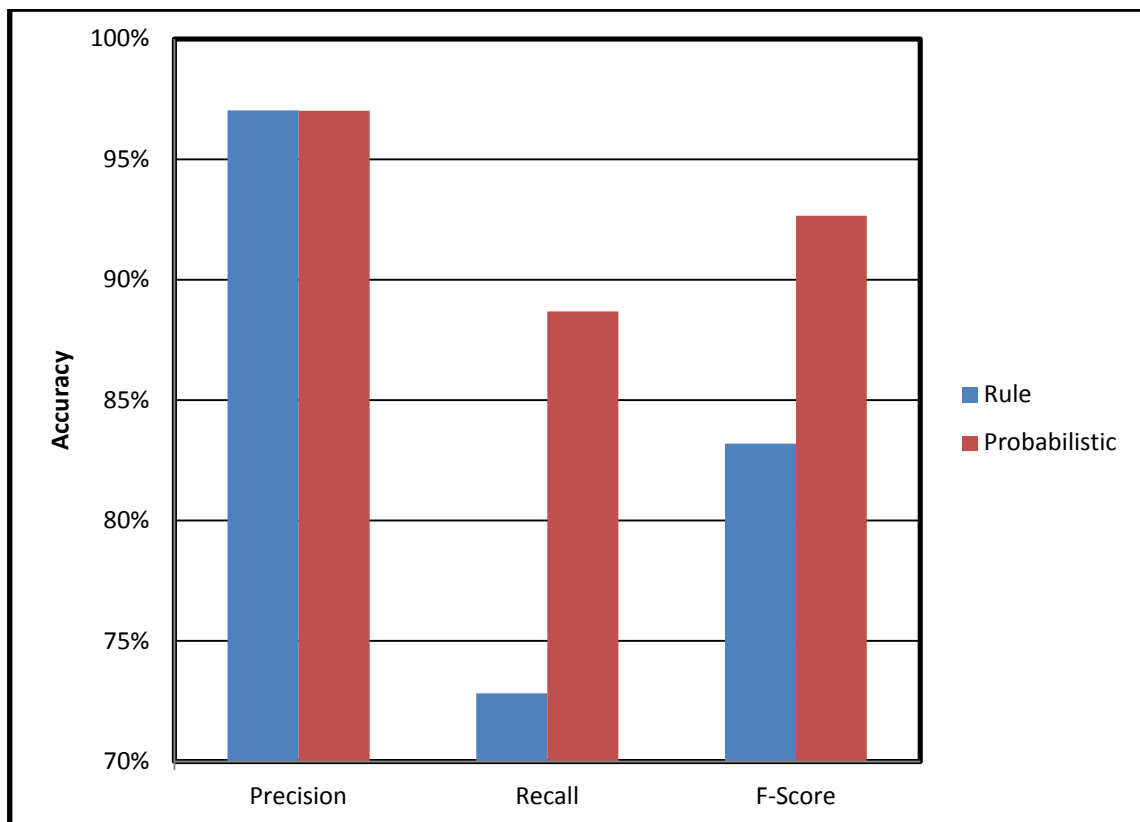


Figure 4.9: Accuracy comparison between Rule-based and Probabilistic-based technique with window size=50 and number of records=10,000 for dataset_B.

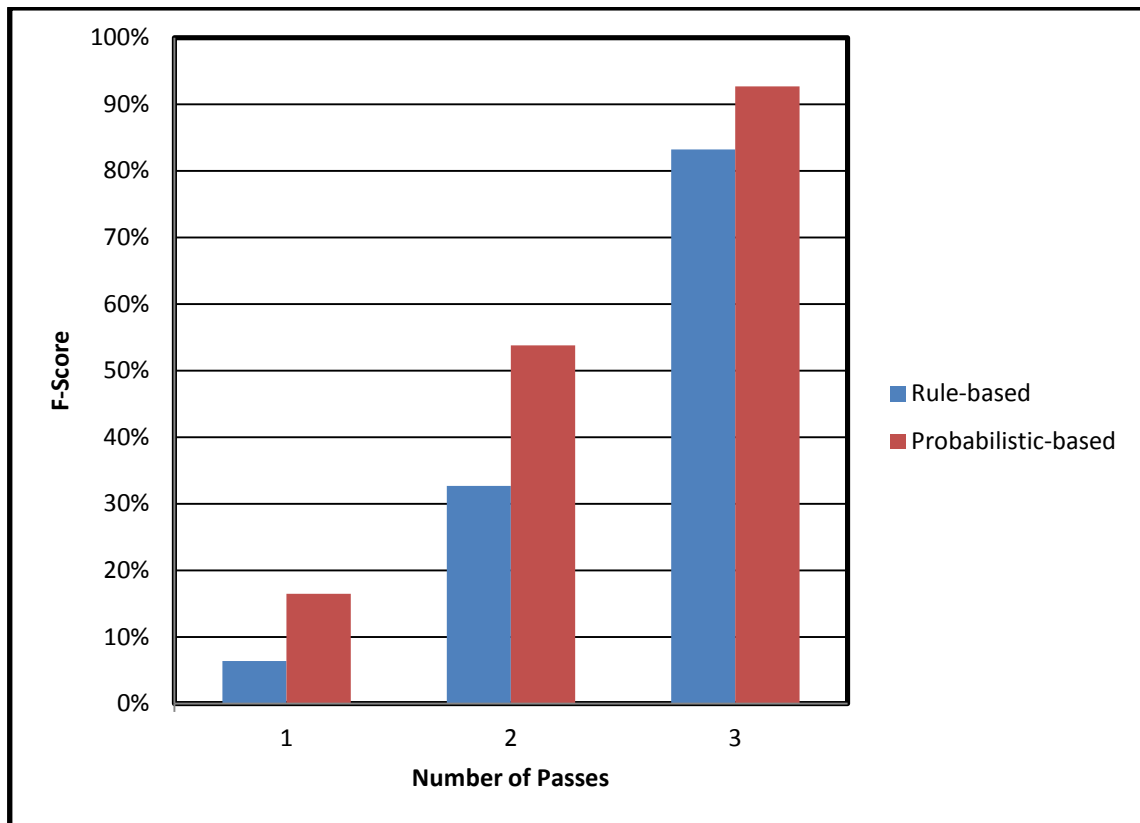


Figure 4.10: Accuracy comparison between Rule-based and Probabilistic-based technique with variation number of passes for dataset_B.

Results Analysis

From the experiments, we have noted that the recall is increasing whenever we increase the window size. The increasing ratio for the recall of Probabilistic-based technique is more than the Rule-based technique, exactly from window size 5 to 15 after that the recall grows slowly from 15 to 50.

We notice that the accuracy of the probabilistic-based is much better than Rule-based in all window sizes. That refers to the adaptation ability of probabilistic-based technique with most of datasets types because it's used the EM algorithm to compute the threshold value. In the other hand, Rule-based technique has fixed rules to detect the duplicates records which must change when dataset is changed.

Comparing the results for the precision, we have noted that precision stays stable when increasing the window size with insignificant change (± 0.01) because of the stability of the number of false positive.

In general recall decreased whenever dataset size increases for both techniques with better results for Probabilistic-based

For the Rule-based technique, the decreasing is almost linear because it's not involved with dataset size as the duplication percentage in the dataset. The precision for both techniques is almost fixed among the increasing size of the dataset.

We measure the time efficiency for both techniques; processing time collected during the tests shows clearly that Probabilistic-based technique is having the higher processing time.

The F-Score is computed from the Recall and Precision to get a good view of the two techniques. This shows that the Probabilistic-based technique has higher F-Score with 92.66% than Rule-based technique with 83.20%.

At last, we notice that increasing the number of passes will affect positively the accuracy of the system. The good selection of the pass key will effect on the F-Score value. The experiments show that Probabilistic-based technique outperforms the Rule-based technique on dataset_B.

Chapter 5

Conclusion and Future Work

This chapter summarizes the conclusions we have achieved in this thesis and discussing of the possible future works that can further extend or improve our work.

5.1 Conclusion

The purpose of duplicate record detection is finding multiple representations of the same real world object. This problem is compromised of two difficult problems: First finding an adequate similarity measure to decide upon duplicity, and second finding an efficient algorithm to detect as many duplicates as possible.

In this study we have presented a generic framework for detecting the duplicate records in a database. Our framework consists of two decision models; Rule-based model that uses domain-knowledge to define rules to identify duplicate and non-duplicates, and Probabilistic-based model that employs the EM algorithm to find likelihood ratio and determine according to it the duplicates or non-duplicates. We have clarified the variation between them with using the same blocking technique (Sorted-neighborhood) and similarity function (Q-gram), and we have experimentally compared their performance and efficiency.

We have conducted various experiments on a synthetic dataset to evaluate our implementation of both Rule-based and Probabilistic-based technique. The experiments confirmed that Probabilistic-based technique outperformed the Rule-based techniques when changing the window size of the sorted neighborhood technique, increasing dataset size, and changing the sorting keys. Rule-based technique acts better than Probabilistic-based technique when comparing them in term of time efficiency.

In our study we used high threshold values to decrease the false positives, meanwhile choosing appropriate threshold value refer to the dataset that is evaluated. For example, if the database contains patient's information like our datasets it is recommended to use high threshold to avoid matching two different persons. On the other hand, credit-rating agencies database concern with detecting duplicates even if they not so in this case low threshold values are needed.

5.2 Future Work

As the database systems become more and more common place, and with the accumulating vast amounts of errors on a daily basis, we believe that there is still room for substantial improvement in the current state-of-the-art. There are a number of key challenges that are important to address in future.

The experiment was done using synthetic data set and needed to be confirmed with different data sets, with real-world datasets and with large-scale datasets (millions of records) in order to verify the effectiveness and efficiency of the proposed decision models.

Minimizing the manual insertion of parameters used by the system, and experts interference by design the appropriate rules. That can be done by using the EM algorithm with the Rule-based to determine the significant attributes which could be used in the rules designing.

Improve the selection of blocking key value which is used to sort the dataset using different techniques such as phonetic coding.

Our work in this thesis in terms of performance measurements has focused on processing time as a major measurement where in the future we can address other needed criteria such as the effect on systems resources such as memory and disk usage.

Finally, we need to have a comprehensive framework that can determine which decision model is better with specific dataset, and that requires evaluating and comparing other decision models that we did not mention in this study such as supervised learning and semi-supervised learning techniques.

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APPENDICES

Appendix 1 Preparation Stage Implementation

```

insert_data
try {

    FileInputStream fstream = new FileInputStream("/Users/user/Desktop/fff/data/dedup-
dsgen/dataset_C_1000.csv");
    DataInputStream in = new DataInputStream(fstream);
    BufferedReader br = new BufferedReader(new InputStreamReader(in));
    String strLine;
    while ((strLine = br.readLine()) != null) {
        window_blocking.window_blocking obj = new window_blocking.window_blocking();
        obj.insert_data(strLine, "main_data_5");
    }
    in.close();
} catch (Exception e) { //Catch exception if any
    System.err.println("Error: " + e.getMessage());
}

```

The insert_data function read the line of data that came from the file and post it to the database like the following.

```

public void insert_data(String data, String table_name) throws SQLException {
    String Results = "";
    Statement stmt = null;
    String query = "";
    String[] insert_data = data.split(",");
    String GIVEN_NAME = "";
    if (!"".equals(insert_data[1].replace("","").trim())) {
        GIVEN_NAME = insert_data[1].replace("","");
    }
    String SURNAME = "";
    if (!"".equals(insert_data[2].replace("","").trim())) {
        SURNAME = insert_data[2].replace("","");
    }
    String STREET_NUMBER = "0";
    if (!"".equals(insert_data[3].replace("","").trim())) {
        STREET_NUMBER = insert_data[3].replace("","");
    }
    String ADDRESS_1 = "";
    if (!"".equals(insert_data[4].replace("","").trim())) {
        ADDRESS_1 = insert_data[4].replace("","");
    }
    String ADDRESS_2 = "";
    if (!"".equals(insert_data[5].replace("","").trim())) {
        ADDRESS_2 = insert_data[5].replace("","");
    }
    String SUBURB = "";
    if (!"".equals(insert_data[6].replace("","").trim())) {
        SUBURB = insert_data[6].replace("","");
    }
    String POSTCODE = "";
    if (!"".equals(insert_data[7].replace("","").trim())) {
        POSTCODE = insert_data[7].replace("","");
    }
}

```

```

String STATE = "";
if (!"".equals(insert_data[8].replace("","").trim())) {
    STATE = insert_data[8].replace("","");
}
String DATE_OF_BIRTH = "";
if (!"".equals(insert_data[9].replace("","").trim())) {
    DATE_OF_BIRTH = insert_data[9].replace("","");
}
String AGE = "0";
if (!"".equals(insert_data[10].replace("","").trim())) {
    AGE = insert_data[10].replace("","");
}
String PHONE_NUMBER = insert_data[11].replace("","");
String SOC_SEC_ID = insert_data[12].replace("","");
String BLOCKING = "0";
if (!"".equals(insert_data[13].replace("","").trim())) {
    BLOCKING = insert_data[13].replace("","");
}
if ("blocking_number".equals(insert_data[13].replace("","").trim())) {
    BLOCKING = "0";
}
try {
    int ddd = Integer.parseInt(BLOCKING);
} catch (Exception e) {
    BLOCKING = "0";
}
try {
    drdDataBase.DB db = new drdDataBase.DB();
    Connection conn = db.dbConnect();
    stmt = conn.createStatement(java.sql.ResultSet.TYPE_FORWARD_ONLY,
java.sql.ResultSet.CONCUR_UPDATABLE);
    query = "insert into " + table_name + " (GIVEN_NAME, SURNAME, STREET_NUMBER,
ADDRESS_1, ADDRESS_2, SUBURB, POSTCODE, STATE, DATE_OF_BIRTH, AGE,
PHONE_NUMBER, SOC_SEC_ID, BLOCKING) values (";
    query = query.concat(" ").concat(GIVEN_NAME).concat(",");
    query = query.concat(" ").concat(SURNAME).concat(",");
    query = query.concat(" ").concat(STREET_NUMBER).concat(",");
    query = query.concat(" ").concat(ADDRESS_1).concat(",");
    query = query.concat(" ").concat(ADDRESS_2).concat(",");
    query = query.concat(" ").concat(SUBURB).concat(",");
    query = query.concat(" ").concat(POSTCODE).concat(",");
    query = query.concat(" ").concat(STATE).concat(",");
    query = query.concat(" ").concat(DATE_OF_BIRTH).concat(",");
    query = query.concat(" ").concat(AGE).concat(",");
    query = query.concat(" ").concat(PHONE_NUMBER).concat(",");
    query = query.concat(" ").concat(SOC_SEC_ID).concat(",");
    query = query.concat(" ").concat(BLOCKING).concat(",");
    stmt.execute(query, Statement.RETURN_GENERATED_KEYS);
    ResultSet rs = stmt.getGeneratedKeys();
    if (rs.next()) {
        Results = Integer.toString(rs.getInt(1));
    }
} catch (SQLException e) {
    Results = e.getMessage().concat(",,").concat(query);
} finally {
    if (stmt != null) {
        stmt.close();
    }
}
}

```


Appendix 2 Performance Measures Values Used for Experiments

1. Dataset (A)

a. Varying window size.

Window size	5	10	15	20	25	30	35	40	45	50
Rule-Recall	0.836	0.839	0.840	0.840	0.841	0.842	0.843	0.845	0.848	0.848
Prob-Recall	0.876	0.899	0.918	0.924	0.934	0.935	0.938	0.940	0.943	0.944
Rule-Precision	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980
Prob-Precision	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980

b. Increasing dataset size

Number of records	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
Rule-Recall	0.851	0.850	0.855	0.845	0.848	0.850	0.848	0.846	0.846	0.840
Prob-Recall	0.958	0.935	0.927	0.932	0.911	0.917	0.922	0.902	0.914	0.918
Rule-Precision	0.981	0.981	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980
Prob-Precision	0.980	0.981	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980

c. Recall, Precision, and F-Score.

	Precision	Recall	F-Score
Rule-based	98.00%	84.83%	90.94%
Prob-based	98.01%	94.43%	96.19%

d. Runtime Complexity.

Number of records	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
Rule-based	5	11	14	22	26	31	35	41	47	55
Prob-based	12	25	33	47	55	62	71	83	94	103

e. Varying Number of Passes.

Number of passes	1	2	3
Rule-based (F-Score)	0.267	0.436	0.909
Prob-based (F-Score)	0.288	0.562	0.962

2. Dataset (B)

a. Varying window size.

Window size	5	10	15	20	25	30	35	40	45	50
Rule-Recall	0.718	0.718	0.719	0.720	0.721	0.720	0.722	0.724	0.726	0.728
Prob-Recall	0.822	0.857	0.875	0.879	0.879	0.880	0.881	0.882	0.884	0.887
Rule-Precision	0.970	0.970	0.970	0.970	0.970	0.970	0.970	0.970	0.970	0.970
Prob-Precision	0.970	0.970	0.970	0.970	0.970	0.970	0.970	0.970	0.970	0.970

b. Increasing dataset size.

Number of records	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
Rule-Recall	0.713	0.716	0.718	0.715	0.729	0.728	0.721	0.722	0.721	0.719
Prob-Recall	0.886	0.894	0.896	0.888	0.892	0.881	0.899	0.894	0.889	0.875
Rule-Precision	0.973	0.971	0.971	0.970	0.971	0.971	0.971	0.971	0.970	0.970
Prob-Precision	0.972	0.971	0.970	0.970	0.970	0.970	0.970	0.970	0.970	0.970

c. Recall, Precision, and F-Score.

	Precision	Recall	F-Score
Rule-based	0.970	0.728	0.832
Prob-based	0.970	0.887	0.927

d. Runtime Complexity.

No. of records	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
Rule-based	6	12	16	24	28	33	38	42	49	57
Prob-based	9	19	31	42	50	61	69	78	87	97

e. Varying Number of Passes.

Number of passes	1	2	3
Rule-based (F-Score)	0.064	0.327	0.832
Probabilistic-based (F-Score)	0.165	0.538	0.927