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A Novel Approach on De-Identification of Heterogeneous Data based on a Modified Mondrian Algorithm

Master's Thesis

Fabian Singhofer | July 7, 2023 | Data Science and Big Data Analytics (DSBDA) in cooperation with BT (UK)

Outline

Motivation

Why do we want to anonymize data?

- Data and especially sharing it has become important nowadays
- **However:** Privacy regulations like the Data Protection Act 2018 in the UK require actions to enforce privacy
- **Particular action:** Anonymizing Personally Identifiable Information (PII)

What about heterogeneous data?

- Question came up during discussions with Aygul and Mathias
- Often there is a mix between traditional relational data and textual data

➔ **How can a combined anonymization approach look like?**

Motivating Example

A^*	Relational Attributes $A_1, ..., A_5$					Textual Attribute X
id	**gender**	**age**	**topic**	**sign**	**date**	**text**
1	male	36	Education	Aries	2004-05-14	My name is Pedro, I'm a 36 years old engineer from Mexico.
1	male	36	Education	Aries	2004-05-15	A quick follow up: I will post updates about my education in more detail.
2	male	24	Student	Leo	2005-08-18	I will start working for a big tech company as an engineer.
3	male	37	Banking	Pisces	2004-05-27	During my last business trip to Canada I met my friend Ben from college.
4	female	24	Science	Aries	2004-01-13	As a scientist from the UK, you can be proud!
4	female	24	Science	Aries	2004-01-17	Four days ago, I started my blog. Stay tuned for more content.
4	female	24	Science	Aries	2004-01-19	2004 will be a great year for science and for my career as a biologist.
5	male	29	indUnk	Pisces	2004-05-15	Did you know that Pisces is the last constellation of the zodiac.
6	female	27	Science	Aries	2004-05-15	Rainy weather again here in the UK. I hope you all have a good day!

- *RX*-dataset containing traditional relational attributes as well as free text attributes

A^* direct-identifying relational attribute
A_j quasi-identifying relational attribute
X textual attribute containing sensitive terms

Motivating Example

Structured Data

A^* | Relational Attributes $A_1, ..., A_5$

id	gender	age	topic	sign	date
1	male	36	Education	Aries	2004-05-14
1	male	36	Education	Aries	2004-05-15
2	male	24	Student	Leo	2005-08-18
3	male	37	Banking	Pisces	2004-05-27
4	female	24	Science	Aries	2004-01-13
4	female	24	Science	Aries	2004-01-17
4	female	24	Science	Aries	2004-01-19
5	male	29	indUnk	Pisces	2004-05-15
6	female	27	Science	Aries	2004-05-15

- Naive approach: Separation of concerns

A^* direct-identifying relational attribute
A_i quasi-identifying relational attribute
X textual attribute containing sensitive terms

Unstructured Data

A^* | Textual Attribute X

id	text
1	My name is Pedro, I'm a 36 years old engineer from Mexico.
1	A quick follow up: I will post updates about my education in more detail.
2	I will start working for a big tech company as an engineer.
3	During my last business trip to Canada I met my friend Ben from college.
4	As a scientist from the UK, you can be proud!
4	Four days ago, I started my blog. Stay tuned for more content.
4	2004 will be a great year for science and for my career as a biologist.
5	Did you know that Pisces is the last constellation of the zodiac.
6	Rainy weather again here in the UK. I hope you all have a good day!

Motivating Example

Structured Data

A^* | Relational Attributes $A_1, ..., A_5$

id	gender	age	topic	sign	date
1	male	[36-37]	(Education, Banking)	(Aries, Pisces)	2004-05
1	male	[36-37]	(Education, Banking)	(Aries, Pisces)	2004-05
2	male	[24-29]	(Student, indUnk)	(Leo, Pisces)	[2004-2005]
3	male	[36-37]	(Education, Banking)	(Aries, Pisces)	2004-05
4	female	[24-27]	Science	Aries	2004
4	female	[24-27]	Science	Aries	2004
4	female	[24-27]	Science	Aries	2004
5	male	[24-29]	(Student, indUnk)	(Leo, Pisces)	[2004-2005]
6	female	[24-27]	Science	Aries	2004

- Apply 2-anonymity for structured part

Unstructured Data

A^* | Textual Attribute X

id	text
1	My name is Pedro, I'm a 36 years old engineer from Mexico.
1	A quick follow up: I will post updates about my education in more detail.
2	I will start working for a big tech company as an engineer.
3	During my last business trip to Canada I met my friend Ben from college.
4	As a scientist from the UK, you can be proud!
4	Four days ago, I started my blog. Stay tuned for more content.
4	2004 will be a great year for science and for my career as a biologist.
5	Did you know that Pisces is the last constellation of the zodiac.
6	Rainy weather again here in the UK. I hope you all have a good day!

A^* direct-identifying relational attribute
A_i quasi-identifying relational attribute
X textual attribute containing sensitive terms

Motivating Example

Structured Data

A^*	Relational Attributes $A_1, ..., A_5$				
id	**gender**	**age**	**topic**	**sign**	**date**
1	male	[36-37]	(Education, Banking)	(Aries, Pisces)	2004-05
1	male	[36-37]	(Education, Banking)	(Aries, Pisces)	2004-05
2	male	[24-29]	(Student, indUnk)	(Leo, Pisces)	[2004-2005]
3	male	[36-37]	(Education, Banking)	(Aries, Pisces)	2004-05
4	female	[24-27]	Science	Aries	2004
4	female	[24-27]	Science	Aries	2004
4	female	[24-27]	Science	Aries	2004
5	male	[24-29]	(Student, indUnk)	(Leo, Pisces)	[2004-2005]
6	female	[24-27]	Science	Aries	2004

- Anonymize textual part by suppressing sensitive terms

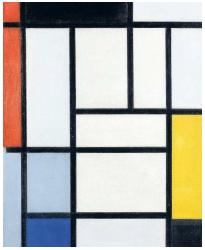
Unstructured Data

A^*	Textual Attribute X
id	**text**
1	My name is ~~Pedro~~, I'm a ~~36 years old engineer~~ from ~~Mexico~~.
1	A quick follow up: I will post updates about my education in more detail.
2	I will start working for a big tech company as an ~~engineer~~.
3	During my last business trip to ~~Canada~~ I met my friend ~~Ben~~ from college.
4	As a scientist from the ~~UK~~, you can be proud!
4	~~Four days ago~~, I started my blog. Stay tuned for more content.
4	~~2004~~ will be a great year for science and for my career as a ~~biologist~~.
5	Did you know that ~~Pisces~~ is the last constellation of the zodiac.
6	Rainy weather again here in the ~~UK~~. I hope you all have a good day!

A^* direct-identifying relational attribute
A_i quasi-identifying relational attribute
X textual attribute containing sensitive terms

Structured Data

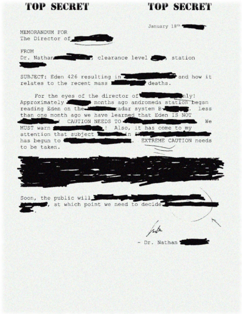
- k-anonymity as fundamental framework by Sweeney [15]
- Work on efficient implementations (e.g. Mondrian by LeFevre et. al [11])
- Work from Nergiz et. al [13] and Gong et. al [6] transferred k-anonymity to a multi-relational setting
- He and Naughton [8] adapted k-anonymity for set-valued data



Credit: https://www.tagesspiegel.de/

Textual Data

- Majority of work uses Named Entity Recognition (NER) to detect sensitive terms [3, 9, 12, 16]
- Khan et. al [10] showed that transformer-based models achieve good recall for NER tasks
- Johnson et. al [9] already used transformer models for de-identification of texts
- Liu et. al [12] emphasize a combined approach using language models and rules



TOP SECRET TOP SECRET

January 18th [redacted]

MEMORANDUM FOR
The Director of [redacted]

FROM
Dr. Nathan [redacted], clearance level [redacted], station [redacted]

SUBJECT: Eden 426 resulting in [redacted] and how it relates to the recent mass [redacted] deaths.

For the eyes of the director of [redacted]! Approximately [redacted] months ago andromeda station began reading Eden on the [redacted] system B[redacted]. Less than one month ago we have learned that Eden IS NOT [redacted] CAUTION NEEDS TO [redacted]. We MUST warn [redacted]! Also, it has come to my attention that subject [redacted] in [redacted] has begun to [redacted]. EXTREME CAUTION needs to be taken.

[redacted]

Soon, the public will [redacted], at which point we need to decide [redacted].

- Dr. Nathan [redacted]

Credit: https://media.moddb.com/

Problem Statement

Given: RX-dataset with traditional relational attributes $A_1, ..., A_n$ and textual attribute X

Ultimate Goal: Transferring sensitive terms within texts to the structured world to reduce textual information loss while making privacy guarantees

Important Definitions:

- *Redundant sensitive information*: Information with same meaning appearing in at least one relational and textual attribute of same record
- *Non-redundant sensitive information*: Poses "new" information and therefore those terms are stored in new set-valued attribute X'
- *Equivalence class*: Partition P where for any two records $r, s \in P$ $(r.A_1, ..., r.A_n) = (s.A_1, ..., s.A_n)$ and $r.X' = s.X'$
- *k-anonymity*: All equivalence classes must be at least size k [15]

Anonymization Pipeline

1. Detecting sensitive terms in textual attributes using NLP libraries
2. Linking redundant sensitive information between relational and textual attributes based on string matching
3. Building a person-centric view by aggregating data based on a direct identifier
4. Partitioning of the dataset using a pre-defined strategy
5. Recoding of relational as well as textual attributes in found partitions

Anonymization Pipeline

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4. Partitioning of the dataset using a pre-defined strategy
5. Recoding of relational as well as textual attributes in found partitions

Modified Mondrian Partitioning

- Recursive strategy by LeFevre et. al [11]
- Median-based splitting of partition in two sub-partitions
  - Non-numerical attributes: Sort and split by middle element
- Result is a set of partitions with size $|P| \geq k$
- **Addition:** Weight parameter λ to tune balance between relational and textual attributes

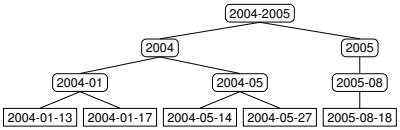
Algorithm 1: *Modified Mondrian Partitioning* - Greedy strict top-down partitioning for relational attributes adapted from [11].

Input : Partition P, relational weight λ
Output: Set of partitions with size of at least k

```
1  Function mondrian_partitioning(P, λ):
2      if |P| < 2k then
3          return P
4      end
5      else
6          A = next_attribute(λ)
7          F = frequency_set(P, A)
8          P_l = (r ∈ P | r.A < find_median(F))
9          P_r = P \ P_l
10         return mondrian_partitioning(P_l) ∪
               mondrian_partitioning(P_r)
11     end
```

Recoding - Relational Attributes

- **Recoding:** Find a single value as a replacement for multiple (probably) different values
- We use local recoding to favor utility
- For numerical and date attributes, we generate generalized values automatically
- Categorical attributes get grouped as sets



Domain Generalization Hierarchy adapted from El Emam et. al [5]

Recoding - Textual Attributes

id	gender	age	topic	sign	date	text
1	male	[24-36]	(Student,Education)	(Leo,Aries)	[2004-2005]	My name is Pedro, I'm a 36 years old engineer from Mexico.
1	male	[24-36]	(Student,Education)	(Leo,Aries)	[2004-2005]	A quick follow up: I will post updates about my education in more detail.
2	male	[24-36]	(Student,Education)	(Leo,Aries)	[2004-2005]	I will start working for a big tech company as an engineer.
3	male	[29-37]	(indUnk,Banking)	Pisces	2004-05	During my last business trip to Canada I met my friend Ben from college.
4	female	[24-27]	Science	Aries	2004	As a scientist from the UK, you can be proud!
4	female	[24-27]	Science	Aries	2004	Four days ago, I started my blog. Stay tuned for more content.
4	female	[24-27]	Science	Aries	2004	2004 will be a great year for science and for my career as a biologist.
5	male	[29-37]	(indUnk,Banking)	Pisces	2004-05	Did you know that Pisces is the last constellation of the zodiac.
6	female	[24-27]	Science	Aries	2004	Rainy weather again here in the UK. I hope you all have a good day!

1. Take recoded relational attributes as basis

Recoding - Textual Attributes

id	gender	age	topic	sign	date	text
1	male	**[24-36]**	(Student,Education)	(Leo,Aries)	[2004-2005]	My name is Pedro, I'm a **[24-36]** years old engineer from Mexico.
1	male	[24-36]	(Student,Education)	(Leo,Aries)	[2004-2005]	A quick follow up: I will post updates about my education in more detail.
2	male	[24-36]	(Student,Education)	(Leo,Aries)	[2004-2005]	I will start working for a big tech company as an engineer.
3	male	[29-37]	(indUnk,Banking)	Pisces	2004-05	During my last business trip to Canada I met my friend Ben from college.
4	female	[24-27]	Science	Aries	2004	As a scientist from the UK, you can be proud!
4	female	[24-27]	Science	Aries	2004	Four days ago, I started my blog. Stay tuned for more content.
4	female	[24-27]	**Science**	Aries	**2004**	**2004** will be a great year for **science** and for my career as a biologist.
5	male	[29-37]	(indUnk,Banking)	**Pisces**	2004-05	Did you know that **Pisces** is the last constellation of the zodiac.
6	female	[24-27]	Science	Aries	2004	Rainy weather again here in the UK. I hope you all have a good day!

1. Take recoded relational attributes as basis
2. Recode **redundant sensitive information** using replacements from linked relational attributes

Recoding - Textual Attributes

id	gender	age	topic	sign	date	text
1	male	**[24-36]**	(Student,Education)	(Leo,Aries)	[2004-2005]	My name is **person**, I'm a **[24-36]** years old **engineer** from **location**.
1	male	[24-36]	(Student,Education)	(Leo,Aries)	[2004-2005]	A quick follow up: I will post updates about my education in more detail.
2	male	[24-36]	(Student,Education)	(Leo,Aries)	[2004-2005]	I will start working for a big tech company as an **engineer**.
3	male	[29-37]	(indUnk,Banking)	Pisces	2004-05	During my last business trip to **location** I met my friend **person** from college.
4	female	[24-27]	Science	Aries	2004	As a **job** from the **UK**, you can be proud!
4	female	[24-27]	Science	Aries	2004	**Date**, I started my blog. Stay tuned for more content.
4	female	[24-27]	**Science**	Aries	**2004**	**2004** will be a great year for **science** and for my career as a **job**.
5	male	[29-37]	(indUnk,Banking)	**Pisces**	2004-05	Did you know that **Pisces** is the last constellation of the zodiac.
6	female	[24-27]	Science	Aries	2004	Rainy weather again here in the **UK**. I hope you all have a good day!

1. Take recoded relational attributes as basis
2. Recode **redundant sensitive information** using replacements from linked relational attributes
3. Recode **non-redundant sensitive information**: Sensitive terms appearing in all records of a partition can **stay**, others will be **suppressed** with their entity types

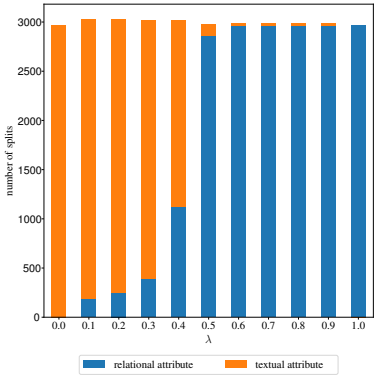
Experimental Apparatus

- Implemented anonymization pipeline in Python
- spaCy and its new transformer-based model is used to analyze textual attributes
- Run experiments on
  - *Blog Authorship Corpus*: 681,260 blog posts of 19,319 distinct bloggers [14]
  - *Hotel Reviews Dataset*: 512,126 reviews for 1,475 distinct hotels [1]
- Anonymize dataset by varying
  - k (2, 3, 4, 5, 10, 20, 50)
  - partitioning strategy and parameters (λ)
  - considered entity types (all entity types vs. only locations)
- Measure
  - statistics on split decisions and partitions
  - information loss using Normalized Certainty Penalty (NCP)

Experiment Results - Partitions

Blog Authorship Corpus, all entities

- Without modifying the partition decisions ($\lambda = 0.5$), relational attributes are favored
- λ is able to control splitting decisions for $\lambda < 0.5$
- Same partition layout for $0.6 \leq \lambda \leq 0.9$

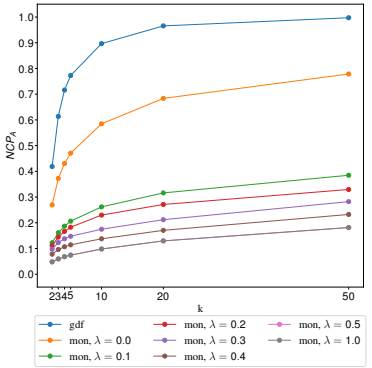


Distribution of partition splits using Mondrian for k = 5

Experiment Results - Information Loss

Blog Authorship Corpus, all entities

- Increasing k results in more information loss
- Relational information loss increases with decreasing λ

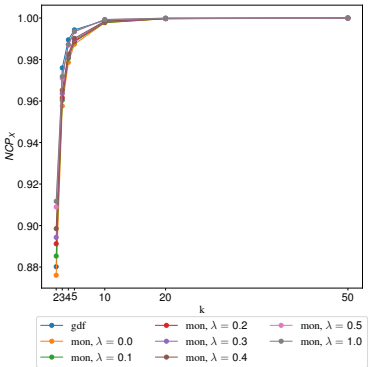


Relational Information Loss NCP_A

Experiment Results - Information Loss

Blog Authorship Corpus, all entities

- Increasing k results in more information loss
- Relational information loss increases with decreasing λ
- For small k → textual information loss less than 1
- λ can slightly control textual information loss

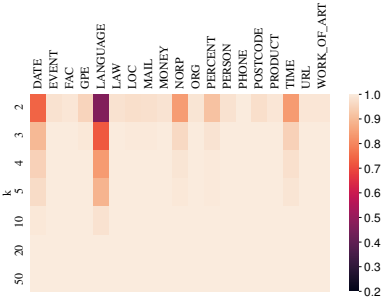


Textual Information Loss NCP_X

Experiment Results - Information Loss

Blog Authorship Corpus, all entities

- Increasing k results in more information loss
- Relational information loss increases with decreasing λ
- For small k → textual information loss less than 1
- λ can slightly control textual information loss
- LANGUAGE entities can be better preserved



Detailed textual information loss for $\lambda = 0.2$

Discussion

- k-anonymity applicable on texts by transferring the task of anonymizing sensitive terms to a structured problem
- Tuning Mondrian crucial to cope with heterogeneity of sensitive terms
- Textual information loss can be reduced under our k-anonymity model
- Over-anonymization in case of different terms with same meaning
  - "London" vs. "the capital of the UK"
- Under-anonymization if sensitive terms have different context
  - "I love London" vs. "I live in London"
- Identity disclosure might still be possible using authorship identification on texts

Conclusion and Future Work

- Combined anonymization approach achieved using k-anonymity
- Tuning and prioritization possible using λ in Mondrian partitioning
- Framework is applicable for variable datasets
- Experiments indicate that sensitive entities can be preserved

What's next?

- Abu-Khzam et. al [2]: Clustering algorithms with lower boundary on cluster size
- Hassanzadeh et. al [7]: Methods on finding non-trivial links within data
- Dwork [4]: Differential private anonymization techniques

Thank you!

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Anonymization Framework