



School of Computer Science
University College Dublin

A Theoretical Framework for Modern Machine Learning

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degree of Doctor of Philosophy*

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ACRONYMS

DRY	Don't Repeat Yourself
RS	recommender system
CF	collaborative filtering

ABSTRACT

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DECLARATION

I hereby certify that the submitted work is my own work, was completed while registered as a candidate for the degree stated on the Title Page, and I have not obtained a degree elsewhere on the basis of the research presented in this submitted work.

Eolas MacDalta,
November 19, 2024

COLLABORATIONS

This work was conducted in collaboration with the following:

- Dr. A. N. Other The work in [Chapter 3](#) was conducted while visting the laboratory of Dr. A. N. Other.

PUBLICATIONS

Swap these out for your own publication list (FrontBackmatter/MyPublications.bib).

- [1] Xiangnan He, Lizi Liao, Hanwang Zhang, Liqiang Nie, Xia Hu, and Tat-Seng Chua. “Neural collaborative filtering”. In: *Proceedings of the 26th international conference on world wide web*. 2017, pp. 173–182.
- [2] Yehuda Koren, Robert Bell, and Chris Volinsky. “Matrix factorization techniques for recommender systems”. In: *Computer*. Vol. 42. 8. IEEE. 2009, pp. 30–37.
- [3] Steffen Rendle. “Factorization machines”. In: *2010 IEEE International Conference on Data Mining*. IEEE. 2010, pp. 995–1000.
- [4] Francesco Ricci, Lior Rokach, and Bracha Shapira. “Introduction to recommender systems handbook”. In: *Recommender systems handbook* (2011), pp. 1–35.
- [5] Badrul Sarwar, George Karypis, Joseph Konstan, and John Riedl. “Item-based collaborative filtering recommendation algorithms”. In: *Proceedings of the 10th international conference on World Wide Web*. 2001, pp. 285–295.
- [6] J Ben Schafer, Dan Frankowski, Jon Herlocker, and Shilad Sen. “Collaborative filtering recommender systems”. In: *The adaptive web* (2007), pp. 291–324.
- [7] Yunhong Zhou, Dennis Wilkinson, Robert Schreiber, and Rong Pan. “Large-scale parallel collaborative filtering for the netflix prize”. In: *Proceedings of the 4th international conference on Algorithmic Aspects in Information and Management (AAIM)*. Springer. 2008, pp. 337–348.

*We have seen that computer programming is an art,
because it applies accumulated knowledge to the world,
because it requires skill and ingenuity, and especially
because it produces objects of beauty.*

— Donald E. Knuth [3]

ACKNOWLEDGMENTS

Put your acknowledgments here.

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Ohana means family.

Family means nobody gets left behind, or forgotten.

— Lilo & Stitch

Dedicated to the loving memory of Rudolf Miede.

1939 – 2005

INTRODUCTION

In an era marked by an exponential growth of information and digital content, recommender system (RS) have emerged as pivotal tools in helping users navigate through the vast sea of choices. These systems are integral to numerous applications, from online shopping and streaming services to social media and personalized news feeds. By leveraging advanced algorithms and data-driven techniques, recommender systems aim to predict user preferences and deliver highly relevant content, thereby enhancing user experience and engagement [4].

The inception of recommender systems can be traced back to the early days of collaborative filtering (CF), which relied on user and item similarities to generate recommendations. Since then, the field has witnessed substantial advancements, incorporating sophisticated models such as matrix factorization, neural networks, and hybrid approaches that blend multiple recommendation strategies. These developments have significantly improved the accuracy and efficiency of recommendations, catering to diverse user needs and preferences [5].

The original matrix factorisation algorithm proposed by Simon Funk in his blog post factorized the user-item rating matrix as the product of two lower dimensional matrices, the first one has a row for each user, while the second has a column for each item. The row or column associated to a specific user or item is referred to as latent factors. The predicted ratings can be computed as $\tilde{R} = HW$, $\tilde{R} \in \mathbb{R}^{\text{users} \times \text{items}}$ is the user-item rating matrix, $H \in \mathbb{R}^{\text{users} \times \text{latent factors}}$ contains the user's latent factors and $W \in \mathbb{R}^{\text{latent factors} \times \text{items}}$ the item's latent factors. Specifically, the predicted rating user u will give to item i is computed as:

$$\tilde{r}_{ui} = \sum_{f=0}^{\text{n factors}} H_{u,f} W_{f,i} \quad (1.1)$$

Despite the remarkable progress, several challenges remain in the design and implementation of recommender systems. Issues such as scalability, cold-start problems, diversity, and fairness continue to pose significant hurdles. Furthermore, the rapid evolution of user behaviors

and the dynamic nature of content necessitate continuous adaptation and innovation in recommendation methodologies [1].

This thesis aims to contribute to the ongoing discourse in the field of recommender systems by addressing key challenges and proposing novel solutions that enhance recommendation quality and user satisfaction. Through a comprehensive exploration of state-of-the-art techniques and rigorous empirical evaluations, this research endeavors to advance our understanding of effective recommendation strategies and their practical applications.

The structure of this thesis is as follows: [Chapter 2](#) provides a detailed overview of the historical development and foundational concepts of recommender systems. [Chapter 2](#) delves into the various algorithmic approaches [2], highlighting their strengths and limitations [3]. [Chapter 3](#) addresses the pressing challenges in the field and reviews contemporary solutions proposed in the literature. [Chapter 4](#) presents the proposed methodologies and experimental setups, followed by a thorough analysis of results in [Chapter 5](#). Finally, [Chapter 6](#) concludes the thesis with a summary of findings, implications, and directions for future research.

By systematically investigating and addressing the complexities of recommender systems, this thesis aspires to contribute valuable insights and practical advancements to the field, ultimately fostering more personalized and effective user experiences across digital platforms.

1.0.1 *Testing Code*

Let's try some code listings:

```

1  def spark(request):
    """
    Creates a spark context

    Parameters
    -----
    request: pytest.FixtureRequest object
        provides access to testing context
    """
    spark = (
```

```

SparkSession
    .builder
    .appName('pytest-pyspark-local-testing')
    .master('local[2]')
16    .getOrCreate()
    )

request.addfinalizer(lambda: spark.stop())

21    return spark

```

1.0.2 Algorithm Testing

Let's try an algorithm:

```

1: function MERGESORT( $A, i, j$ )
2:   Input array  $A$ , positive integers  $i, j$  between 0 and  $n - 1$ 
3:   if  $j - i \leq 1$  then                                     ▷ length 0 or 1, so already sorted
4:     return
5:   end if
6:    $mid = (i + j) / 2$ 
7:    $mergeSort(A, i, mid)$                                      ▷ first recursive call on left side
8:    $mergeSort(A, mid, j)$                                      ▷ second recursive call on right side
9:    $merge(A, i, mid, j)$ 
10: end function

```

INTRODUCTION

BACKGROUND

2.1 SECTION A

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quaestio philosophia	facto	demonstrated

Table 2.1: Autem usu id.

2.1.1 Subsection B

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Part I

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TOPIC A

3.1 SECTION A

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3.1.1 Subsection B

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256 Lo sed apprende instruite. Que altere responder su, pan ma, i. e., signo studio. [Figure 3.1b](#) In-
 257 struite preparation le duo, asia altere tentation web su. Via unic facto rapide de, iste questiones
 258 methodicamente o uno, nos al.

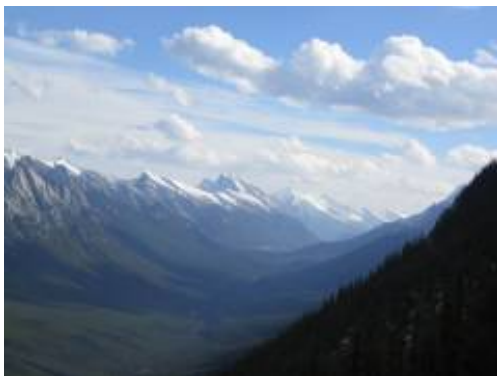
$$\mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{R} \\ \mathbf{R}^T & \mathbf{0} \end{bmatrix} \quad (3.1)$$



(a) Asia personas duo.



(b) Pan ma signo.



(c) Methodicamente o uno.



(d) Titulo debitas.

Figure 3.1: Tu duo titulo debitas latente. Don't Repeat Yourself ([DRY](#))

TOPIC A

TOPIC B

4.1 SECTION A

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. $\sin^2(\alpha) + \cos^2(\beta) = 1$. If you read this text, you will get no information $E = mc^2$. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. $\sqrt[n]{a} \cdot \sqrt[n]{b} = \sqrt[n]{ab}$. This text should contain all letters of the alphabet and it should be written in of the original language. $\frac{\sqrt[n]{a}}{\sqrt[n]{b}} = \sqrt[n]{\frac{a}{b}}$. There is no need for special content, but the length of words should match the language. $a\sqrt[n]{b} = \sqrt[n]{a^n b}$.

This is the second paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. $\sin^2(\alpha) + \cos^2(\beta) = 1$. If you read this text, you will get no information $E = mc^2$. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. $\sqrt[n]{a} \cdot \sqrt[n]{b} = \sqrt[n]{ab}$. This text should contain all letters of the alphabet and it should be written in of the original language. $\frac{\sqrt[n]{a}}{\sqrt[n]{b}} = \sqrt[n]{\frac{a}{b}}$. There is no need for special content, but the length of words should match the language. $a\sqrt[n]{b} = \sqrt[n]{a^n b}$.

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There is no need for special content, but the length of words should match the language.

$$a\sqrt[n]{b} = \sqrt[n]{a^n b}.$$

After this fourth paragraph, we start a new paragraph sequence. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place.

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This text should contain all letters of the alphabet and it should be written in of the original

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the language. $a\sqrt[n]{b} = \sqrt[n]{a^n b}$.

- First item in a list
- Second item in a list
- Third item in a list

4.1.1 Subsection B

This is the second paragraph. Hello, here is some text without a meaning. This text should

show what a printed text will look like at this place. $\sin^2(\alpha) + \cos^2(\beta) = 1$. If you read this

text, you will get no information $E = mc^2$. Really? Is there no information? Is there a difference

between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text

like this gives you information about the selected font, how the letters are written and an

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And after the second paragraph follows the third paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. $\sin^2(\alpha) + \cos^2(\beta) = 1$. If you read this text, you will get no information $E = mc^2$. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. $\sqrt[n]{a} \cdot \sqrt[n]{b} = \sqrt[n]{ab}$. This text should contain all letters of the alphabet and it should be written in of the original language. $\frac{\sqrt[n]{a}}{\sqrt[n]{b}} = \sqrt[n]{\frac{a}{b}}$. There is no need for special content, but the length of words should match the language. $a\sqrt[n]{b} = \sqrt[n]{a^n b}$.

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This is the second paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. $\sin^2(\alpha) + \cos^2(\beta) = 1$. If you read this

TOPIC B

344 text, you will get no information $E = mc^2$. Really? Is there no information? Is there a difference
345 between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text
346 like this gives you information about the selected font, how the letters are written and an
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348 should be written in of the original language. $\frac{\sqrt[n]{a}}{\sqrt[n]{b}} = \sqrt[n]{\frac{a}{b}}$. There is no need for special content,
349 but the length of words should match the language. $a\sqrt[n]{b} = \sqrt[n]{a^n b}$.

Part II

350

PART II

351

352

TOPIC C

5.1 SECTION A

And after the second paragraph follows the third paragraph. Hello, here is some text without
 a meaning. This text should show what a printed text will look like at this place. $\sin^2(\alpha) +$
 $\cos^2(\beta) = 1$. If you read this text, you will get no information $E = mc^2$. Really? Is there
 no information? Is there a difference between this text and some nonsense like “Huardest
 gefburn”? Kjift – not at all! A blind text like this gives you information about the selected
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 There is no need for special content, but the length of words should match the language.
 $a\sqrt[n]{b} = \sqrt[n]{a^n b}$.

After this fourth paragraph, we start a new paragraph sequence. Hello, here is some text
 without a meaning. This text should show what a printed text will look like at this place.
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 380 language. $\frac{\sqrt[n]{a}}{\sqrt[n]{b}} = \sqrt[n]{\frac{a}{b}}$. There is no need for special content, but the length of words should match
 381 the language. $a\sqrt[n]{b} = \sqrt[n]{a^n b}$.

382 This is the second paragraph. Hello, here is some text without a meaning. This text should
 383 show what a printed text will look like at this place. $\sin^2(\alpha) + \cos^2(\beta) = 1$. If you read this
 384 text, you will get no information $E = mc^2$. Really? Is there no information? Is there a difference
 385 between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text
 386 like this gives you information about the selected font, how the letters are written and an
 387 impression of the look. $\sqrt[n]{a} \cdot \sqrt[n]{b} = \sqrt[n]{ab}$. This text should contain all letters of the alphabet and it
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390 And after the second paragraph follows the third paragraph. Hello, here is some text without
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 398 $a\sqrt[n]{b} = \sqrt[n]{a^n b}$.

- 399 • First item in a list
- 400 • Second item in a list
- 401 • Third item in a list

402 5.1.1 Subsection B

403 After this fourth paragraph, we start a new paragraph sequence. Hello, here is some text
 404 without a meaning. This text should show what a printed text will look like at this place.
 405 $\sin^2(\alpha) + \cos^2(\beta) = 1$. If you read this text, you will get no information $E = mc^2$. Really? Is
 406 there no information? Is there a difference between this text and some nonsense like “Huardest

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 444 There is no need for special content, but the length of words should match the language.
 445 $a\sqrt[n]{b} = \sqrt[n]{a^n b}$.

CONCLUSION

6.1 SECTION A

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. $\sin^2(\alpha) + \cos^2(\beta) = 1$. If you read this text, you will get no information $E = mc^2$. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. $\sqrt[n]{a} \cdot \sqrt[n]{b} = \sqrt[n]{ab}$. This text should contain all letters of the alphabet and it should be written in of the original language. $\frac{\sqrt[n]{a}}{\sqrt[n]{b}} = \sqrt[n]{\frac{a}{b}}$. There is no need for special content, but the length of words should match the language. $a\sqrt[n]{b} = \sqrt[n]{a^n b}$.

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CONCLUSION

There is no need for special content, but the length of words should match the language.
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- First item in a list
- Second item in a list
- Third item in a list

6.1.1 Subsection B

This is the second paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. $\sin^2(\alpha) + \cos^2(\beta) = 1$. If you read this text, you will get no information $E = mc^2$. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an

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This is the second paragraph. Hello, here is some text without a meaning. This text should
 show what a printed text will look like at this place. $\sin^2(\alpha) + \cos^2(\beta) = 1$. If you read this

CONCLUSION

531 text, you will get no information $E = mc^2$. Really? Is there no information? Is there a difference
532 between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text
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536 but the length of words should match the language. $a\sqrt[n]{b} = \sqrt[n]{a^n b}$.

Part III

537

APPENDIX

538

539

APPENDIX

A.1 SECTION A

And after the second paragraph follows the third paragraph. Hello, here is some text without
 a meaning. This text should show what a printed text will look like at this place. $\sin^2(\alpha) +$
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 contain all letters of the alphabet and it should be written in of the original language. $\frac{\sqrt[n]{a}}{\sqrt[n]{b}} = \sqrt[n]{\frac{a}{b}}$.
 There is no need for special content, but the length of words should match the language.
 $a\sqrt[n]{b} = \sqrt[n]{a^n b}$.

After this fourth paragraph, we start a new paragraph sequence. Hello, here is some text
 without a meaning. This text should show what a printed text will look like at this place.
 $\sin^2(\alpha) + \cos^2(\beta) = 1$. If you read this text, you will get no information $E = mc^2$. Really? Is
 there no information? Is there a difference between this text and some nonsense like “Huardest
 gefburn”? Kjift – not at all! A blind text like this gives you information about the selected
 font, how the letters are written and an impression of the look. $\sqrt[n]{a} \cdot \sqrt[n]{b} = \sqrt[n]{ab}$. This text should
 contain all letters of the alphabet and it should be written in of the original language. $\frac{\sqrt[n]{a}}{\sqrt[n]{b}} = \sqrt[n]{\frac{a}{b}}$.
 There is no need for special content, but the length of words should match the language.
 $a\sqrt[n]{b} = \sqrt[n]{a^n b}$.

Hello, here is some text without a meaning. This text should show what a printed text will
 look like at this place. $\sin^2(\alpha) + \cos^2(\beta) = 1$. If you read this text, you will get no information
 $E = mc^2$. Really? Is there no information? Is there a difference between this text and some
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 about the selected font, how the letters are written and an impression of the look. $\sqrt[n]{a} \cdot \sqrt[n]{b} = \sqrt[n]{ab}$.

566 This text should contain all letters of the alphabet and it should be written in of the original
 567 language. $\frac{\sqrt[n]{a}}{\sqrt[n]{b}} = \sqrt[n]{\frac{a}{b}}$. There is no need for special content, but the length of words should match
 568 the language. $a\sqrt[n]{b} = \sqrt[n]{a^n b}$.

569 This is the second paragraph. Hello, here is some text without a meaning. This text should
 570 show what a printed text will look like at this place. $\sin^2(\alpha) + \cos^2(\beta) = 1$. If you read this
 571 text, you will get no information $E = mc^2$. Really? Is there no information? Is there a difference
 572 between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text
 573 like this gives you information about the selected font, how the letters are written and an
 574 impression of the look. $\sqrt[n]{a} \cdot \sqrt[n]{b} = \sqrt[n]{ab}$. This text should contain all letters of the alphabet and it
 575 should be written in of the original language. $\frac{\sqrt[n]{a}}{\sqrt[n]{b}} = \sqrt[n]{\frac{a}{b}}$. There is no need for special content,
 576 but the length of words should match the language. $a\sqrt[n]{b} = \sqrt[n]{a^n b}$.

577 And after the second paragraph follows the third paragraph. Hello, here is some text without
 578 a meaning. This text should show what a printed text will look like at this place. $\sin^2(\alpha) +$
 579 $\cos^2(\beta) = 1$. If you read this text, you will get no information $E = mc^2$. Really? Is there
 580 no information? Is there a difference between this text and some nonsense like “Huardest
 581 gefburn”? Kjift – not at all! A blind text like this gives you information about the selected
 582 font, how the letters are written and an impression of the look. $\sqrt[n]{a} \cdot \sqrt[n]{b} = \sqrt[n]{ab}$. This text should
 583 contain all letters of the alphabet and it should be written in of the original language. $\frac{\sqrt[n]{a}}{\sqrt[n]{b}} = \sqrt[n]{\frac{a}{b}}$.
 584 There is no need for special content, but the length of words should match the language.
 585 $a\sqrt[n]{b} = \sqrt[n]{a^n b}$.

- 586 • First item in a list
- 587 • Second item in a list
- 588 • Third item in a list

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COLOPHON

601

This document is typeset using the *UCD Thesis* style developed by Aonghus Lawlor¹.

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