

A DATABASE SYSTEM FOR MULTIMEDIA ANALYTICS AND ANALYSIS

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Zusammenfassung

Abstract

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Good luck.

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PART I

Introduction

1

Introduction

The term *multimedia* describes the combination of different forms of content – also called *modalities* – into a single, sensory experience that carries a higher level semantic. Those modalities include but are not limited to textual, visual (e.g., images or videos) or aural (e.g., music, sound effects, speech) input. In addition, signals produced by various sensors and devices can also be seen as media modalities, even though direct experience by a human consumer may require pre-processing through specialized hard- and software.

People interact with multimedia on a daily basis when watching videos on Netflix or YouTube, when listening to music on Spotify or when browsing a private image collection on their laptop. Multimedia content makes up a large part of today's Internet and its mere omnipresence makes it a major driving force behind its growth, as both volume and variety increases steadily. A large contributing factor are social media platforms, where users act both as consumers and producers of content. Current estimates ¹ suggest, that there are roughly 4.66 billion active Internet users worldwide, of which 4.2 million can be considered active social media users. Facebook alone contributed to 144000 uploaded images per minute in 2020. And many more of these platforms, such as *Instagram* or *Twitter* serve billions of users with mixed, self-made content involving text, images, videos or a combination thereof. A similar study found ², that by 2025 we will produce a yearly amount of 175 Zettabytes (i.e., 10^{21} bytes).

Given these numbers, the need for efficient and effective tools for *managing*, *manipulating*, *searching*, *exploring* and *analysing* multimedia data corpora comes at no surprise.

¹ Source: Statista.com, "Social media usage worldwide", January 2021

² Source: Statista.com, "Big Data", January 2021

1.1 Working with Multimedia Data

On a very high level, multimedia data collections consist of individual (raw) multimedia items, such as video, image or audio files. Each item, in turn, comprises of *content*, *annotations* and *metadata*. Unlike traditional data collections that contain only text and numbers, the content of the multimedia item itself is unstructured, which gives rise to need for compact *feature representations* that can be handled by data processing systems [ZW14]. Traditionally, such feature representations are numerical vectors $f_i \in \mathbb{R}^d$ but could in theory be any mathematical object that can be processed by a computer (e.g., a tensor). Annotations, metadata and features may either have been generated upon the item's creation (e.g., for technical metadata), as a result of data-processing and analysis or by manually adding the information.

1.1.1 Multimedia Analysis & Retrieval

Multimedia analysis and multimedia retrieval are two sides of the same coin and are often used interchangeably in literature. Both areas of research have their roots in *computer vision* and *pattern recognition*, which started in the 1970s and deal with the automated, computer-aided analysis of visual information on images and videos. Classical tasks involve automatic classification of images, e.g., classifying images to either depict a dog or a cat. For the purpose of this thesis, and – one could argue – as a general definition, the distinction can be put as follows:

Multimedia analysis deals with the extraction and processing of meaningful feature representations from media items. In the early days of computer vision, a lot of effort went into the engineering of feature representations that appropriately captured certain aspects of a media item, such as the colour distribution, texture or keypoints in an image. With the advent of deep learning, the extraction of such features from, e.g., images could largely be automated through *deep learning* and neural network architectures such as the *Convolutional Neural Network (CNN)*. Once a feature has been obtained, it can be used to perform many different tasks such as classification, clustering or statistical analysis all of which fall under the umbrella of multimedia analysis.

Multimedia retrieval can be seen as a very special use cases of multimedia analysis. It's a dedicated field of research that deals with the act of searching and finding an item of interest within a large multimedia collection. Even though this may sound like the main function of a database, it is a very different

task for multimedia than it is for structured data [BVB⁺07]. On the one hand, the structure of a relational database is a given and using languages like SQL, a user can specify exactly what elements from the database should be selected using predicates that either match or don't match the items in a collection. Retrieving multimedia data, on the other hand, comes with indirections due to the feature representations used for querying. To account for the content, multimedia retrieval works with the notion of *similarity* between items in the collection and a user-specified query. In addition to working with feature representations, multimedia retrieval deals with obtaining a (dis-)similarity score from the features, a process referred to as ranking, query formulation, results presentation, data storage etc.

1.1.2 Multimedia Analytics

In simple terms, *multimedia analytics* can be seen as a combination of methods from multimedia analysis with visual analytics. While multimedia analysis deals with the different media types and how meaningful representations can be extracted from them, visual analytics deals with the user's interaction with the data [CTW⁺10]. Multimedia analytics aim at generating knowledge from the multimedia data, for example, by summarizing data or by offering means to explore it.

1.2 Research Gap and Objective

The starting point for the research described in this thesis is the current state-of-the-art for data management in multimedia retrieval and analysis as briefly touched upon in the previous sections. Starting from the models and solutions proposed in [GS16; Gia18] and motivated by the "Ten Research Questions for Scalable Multimedia Analytics" [JWZ⁺16], this thesis challenges three basic assumptions currently employed and operated upon and explores the ramifications of doing so, with the higher level goal of furthering convergence between research conducted in *multimedia retrieval*, *multimedia analysis* and *multimedia analytics* on the one hand, and classical *database systems* on the other. The assumptions that are being challenged are namely:

Assumption 1: Staticity of data collections Most multimedia retrieval systems today make a clear distinction between an *offline* phase during which media items are analysed, features are generated and derived data is ingested into

a data management system, and an *online* phase, during which queries of the database take place. Usually, no changes to the data collection are being made during the online phase. This formal model is advertised by both [Gia18] and [Ros18] and to the best of our knowledge, most existing systems explicitly or implicitly function in this manner. This simplification allows for time consuming processes related to feature extraction and indexing to take place separated from any concurrent query activities and eases requirements on transaction isolation. While this is convenient from a perspective of system design, such a mode of operation is limiting when facing data that changes frequently, as is the case, for example, when doing real-time analysis or when having an application with CRUD support.

Assumption 2: Similarity search is nearest neighbor search Multimedia retrieval relies strongly on a notion of similarity search that is usually expressed as finding the k nearest neighboring feature vectors $\vec{v}_{i \in [1,k]} \in \mathcal{C}$ to a query vector $\vec{q} \in \mathbb{R}^d$ in a collection $\mathcal{C} \subset \mathbb{R}^d$ given a certain distance function. Very often, metrics such as the Euclidean or the Manhattan distance are employed for this comparison. This is also referred to as the *vector space model*. While this model is very concise and rather simple, it merely allows for ranking of potential results and finding the relevant or desired item(s). This model is, however, limited when looking at tasks such as summarization or structuring of data, as required for multimedia analysis and analytics. Furthermore, there are cases in which features are not real-valued vectors and similarity is not directly related to proximity.

Assumption 3: User defines execution Database management systems usually evaluate and select the execution plan for an incoming query during a step that is referred to as *query planning*. The underlying assumption here is that the database system has all the information required to determine the most effective execution plan in terms of cost parameters such as required I/O, CPU and memory usage. In similarity search, this is not the case since, for example, index selection relies on a lot of different aspects that, to some extent, can be parametrized by the client issuing a query or that may be subject to change. Therefore, the index used for executing a query is usually selected manually by the user issuing the query. This limits the amount of optimization that can be applied by the multimedia database system especially in the face of non-static data collections.

1.2.1 Motivation

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1.2.2 Research Questions

Challenging the aforementioned assumptions raises very specific questions that fundamentally impact the design of a *multimedia database*. These questions are briefly summarized in Table 1.1.

Table 1.1 List of research questions resulting from challenging assumptions one, two and three.

RQ	Question	Related to
1	Which commonly used, secondary index structures for NNS (e.g., VA [WSB98], LSH [IM98], PQ [JDS11] based indexes) can cope with dynamic data collections and to what extent?	Assumption 1
2	Can we quantify and estimate how much the retrieval quality of index structures from RQ1 deterioration as changes are being made to the underlying data collections?	Assumption 1
2	How can we handle secondary index structures from RQ1 for which to expect deteriorated retrieval quality during query planning and execution?	Assumption 1
4	How can user knowledge about the the retrieval task at hand be factored into query planning without forcing the user the make explicit choices about how a query should be executed?	Assumption 1 & 3
5	88	

Obviously, the list of questions in Table 1.1 is not exhaustive and many more implications can be derived from the assumptions challenged so far. However, the questions are the one tackled by the research presented in this thesis.

1.3 Contribution

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Applications and Use Cases

2.1 Use case 1: Multimedia Retrieval System

2.2 Use case 2: Analysis of Social Media Streams

**2.3 Use case 3: Magnetic Resonance
Fingerprinting (MRF)**

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Related Work

PART II

Foundations

4

On Multimedia Analysis and Retrieval

4.1 Multimedia Data and Multimedia Collections

Formalisation of what multimedia data is and how it can look like (video, audio, images, text + metadata etc.).

4.2 Multimedia Retrieval

4.2.1 Similarity and the Vector Space Model

4.2.2 Approximate Nearest Neighbor Search

Describe techniques for approximate nearest neighbor search (ANN). Focus on a more conceptual overview of the types of algorithms rather than just enumerating concrete examples; this can be used as a build-up for discussing properties of different index structures later.

4.2.3 Beyond Similarity Search

Retrieval and analytics techniques that go beyond simple similarity search (e.g. SOM, summarization, clustering)

4.3 Online Multimedia Analysis

Introducing an online analysis pipeline (e.g., Pythia / Delphi).

4.4 Multimedia Analytics

Describe how the combination of analysis

4.4.1 Beyond Similarity Search

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On The Design of a Database Management System

Digression into design considerations of a database management system (storage, locking, query planning, execution model etc.)

5.1 The Relational Data Model

5.2 Storage, Indexes and Caching

5.3 Query Parsing, Planning and Execution

5.4 Architectural Considerations

PART III

Dynamic Multimedia Data Management

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Modelling a Database for Dynamic Multimedia Data

Is there more?

6.1 Adaptive Index Management

Describe model for index management in the face of changing data:

- Reason about properties of secondary indexes for NNS (e.g., PQ, VA, LSH) with regards to data change
- Derivation of error bounds possible (e.g., usable for planning)?! Use in query planning?
- Systems perspective: How to cope with “dirty” indexes (e.g, auxiliary data structure, offline optimization)

6.2 Generalization of Similarity Search

Describe generalized model for similarity search:

- NNS: Scan -> (Predicate) -> Distance Function -> Sort -> Limit -> (Predicate); no need for dedicated language feature aside from distance function
- Distance function is a binary function $D(q, v) \rightarrow d$ (consequence: different types of distance functions, application of weights merely an operation before executing the function etc.)

- q and v can be elements of $\mathbb{R}^d, \mathbb{C}^d$ or even matrices
- Systems perspective: How enable planner to reason about function execution

6.3 Cost Model for Retrieval Accuracy

Describe cost model with following properties:

- Cost function: $f(a_{cpu}, a_{io}, a_{memory}, a_{accuracy}) \longrightarrow C$
- Means to estimate results accuracy from execution path (e.g., when using index) based on properties of the index
- Means to specify importance of accurate results (e.g., global, per-query, context-based i.e. when doing 1NN search) in comparison to other factors
- Cost usable in query planner
- What about execution time?

6.4 Architecture Model

Putting everything together into a unified systems model (base on previous work + aforementioned aspects).

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Cottontail DB

Implementation chapter for Cottontail DB

PART IV

Discussion

8

Evaluation

8.1 Adaptive Index Management

Brute force vs. plain index vs. index with auxiliary data structure

8.2 Cost Model

Benchmark effect of cost model in different settings (e.g. based on use cases from chapter 2)

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Conclusion & Future Work

Appendix

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Declaration

I hereby declare that this doctoral dissertation "*A Database System for Multimedia Analytics and Analysis*" has been completed only with the assistance mentioned herein and that it has not been submitted for award to any other university nor to any other faculty at the University of Basel.

Basel, DD.MM.YYYY

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