Data Management for Dynamic Multimedia Analytics and Retrieval

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Zusammenfassung

Abstract

Acknowledgements

Good luck.

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List of Acronyms

1NF   First Normal Form
2NF   Second Normal Form
3NF   Third Normal Form

ACID   Atomicity, Consistency, Isolation, Durability
ARIES   Algorithm for Recovery and Isolation Exploiting Semantics
AST   Abstract Syntax Tree
AVX   Advanced Vector Extensions

BASE   Basically available, Soft state, Eventually consistent
BCNF   Boyce–Codd Normal Form

CLI   Call Level Interface
CNN   Convolutional Neural Network
CPU   Central Processing Unit
CRUD   Create, Read, Update, Delete
CWA   Closed-world assumption

DBMS   Database Management System
DBO   Database Object
DDL   Data Definition Language
DFC   Distance Function Class
DML   Data Manipulation Language
DQL   Data Query Language

ERM   Entity Relationship Model

FIFO   First In First Out
FK   Foreign Key
FNS   Farthest Neighbour Search

GPU   Graphics Processing Unit

HNSW   Hierarchical Navigable Small World Graph
HOG   Histogram of Oriented Gradients

JDBC   Java Database Connectivity
JVM   Java Virtual Machine

kFN   k-Farthest Neighbour Search
kNN   k-Nearest Neighbour Search

LRU   Least Recently Used
LSC   Lifelog Search Challenge
LSH   Locality Sensitive Hashing

MFCC   Mel-frequency Cepstral Coefficient
MIPS   Maximum Inner Product Search
MRF   Magnetic Resonance Fingerprinting
MRI   Magnetic Resonance Imaging
MVCC   Multi-Version Concurrency Control

NMR   Nucleic Magnetic Resonance
NNS   Nearest Neighbour Search

ODBC   Open Database Connectivity
OLTP   Online Transaction Processing

PCP   Pitch Class Profiles
PK   Primary Key
POSIX   Portable Operating System Interface
PQ   Product Quantisation

RDF   Resource Description Framework
RNNS   Reverse Nearest Neighbour Search

S2PL   Strict 2-Phase Locking
SH   Spectral Hashing
SIFT   Scale Invariant Feature Transformation
SIMD   Single Instruction Multiple Data

SOM	Self-organizing Map
SQL	Structured Query Language
SSD	Solid State Drive
SSE	Streaming SIMD Extensions
SURF	Speeded-Up Robust Features
UDF	Used Defined Function
VAF	Vector Approximation Files
VBS	Video Browser Showdown

List of Symbols

Basics

$\mathbb{N}$	Set of natural numbers.
$\mathbb{R}$	Set of real numbers.
$\wedge$	Logical conjunction.
$\vee$	Logical, inclusive disjunction.
$\neg$	Logical negation.

Relational Algebra

$\mathcal{R}$	A relation. Sometimes with subscript, e.g., $\mathcal{R}_{\texttt{name}}$ to specify name or index.
$\mathcal{R}^O$	A ranked, relation that exhibits a partial ordering of elements induced by O. Sometimes used with subscript, e.g., $\mathcal{R}^O{}_{\texttt{name}}$ to specify name or index.
$\mathcal{D}$	A data domain of a relation. Sometimes with subscript, e.g., $\mathcal{D}_{\texttt{name}}$, to specify name or index.
$\mathcal{A}$	An attribute of a relation, i.e., a tuple $(\texttt{name}, \mathcal{D})$. Sometimes with subscript to specify name or index.
$\mathcal{A}^*$	An attribute that acts as a primary key.
$\overline{\mathcal{A}}$	An attribute that acts as a foreign key.
t	A tuple $t \in \mathcal{R}$ of attribute values $a_i \in \mathcal{D}_i$. Sometimes with subscript to specify the index of the tuple in $\mathcal{R}$.
$\mathbb{D}$	The set system of all data domains $\mathcal{D}$ supported by a DBMS.
$\texttt{SCH}$	The schema of a relation $\mathcal{R}$, i.e., all attributes $\texttt{SCH}(\mathcal{R}) = (\mathcal{A}_1, \mathcal{A}_2, \ldots, \mathcal{A}_N)$ that make up $\mathcal{R}$.
σ	The unary selection operator used to filter a relation $\mathcal{R}$. Usually printed with a subscript to describe the boolean predicate, e.g. $\sigma_\mathcal{P}$.
π	The unary projection operator used to restrict the attributes $\mathcal{A}$ of a relation $\mathcal{R}$. Usually used with subscript to list the desired attributes, e.g. $\pi_{\mathcal{A}_1, \mathcal{A}_2}$.

τ The binary sort operator used to construct a ranked relation $\mathcal{R}^O$.

γ The unary group operator aggregates tuples in $\mathcal{R}$ to the first k tuples. Usually printed with a subscript to list the group attributes, e.g. σ_G.

λ The unary k-selection operator restricts $\mathcal{R}$ to the first k tuples.

Multimedia Retrieval

$\mathbb{O}$ The media collection domain $\mathbb{O} = \{o_1, o_2, \ldots, o_N\}$.

$\mathbb{F}$ The feature domain $\mathbb{F} = \{f_1, f_2, \ldots f_M\}$.

$\mathfrak{t}$ Feature transformation function $\mathfrak{t}\colon \mathbb{O} \to \mathbb{F}$

$\mathfrak{d}$ Dissimilarity or distance function $\mathfrak{d}\colon \mathbb{F} \times \mathbb{F} \to \mathbb{R}$.

$\mathfrak{s}$ Similarity function $\mathfrak{s}\colon \mathbb{F} \times \mathbb{F} \to [0, 1.]$.

$\mathfrak{c}$ A correspondence function $\mathfrak{c}\colon \mathbb{R} \to [0, 1]$.

$\hat{\delta}$ A Distance Function Class (DFC) $\hat{\delta}\colon \mathcal{D}_q \times \mathcal{D}_q \times \mathcal{D}_1 \cdot \times \mathcal{D}_n \to \mathbb{N}$

Introduction

1

Introduction

The term *multimedia* describes the combination of different forms of digital media – also called *modalities* – into a single, sensory experience that carries a higher level semantic. Those modalities include but are not limited to images and videos (visual), music, sound effects and speech (aural) or textual information. However, more exotic media types such as 3D models or signals produced by sensors can also be seen as modalities, even though experience by a human consumer may depend on pre-processing by specialized hard- and software.

Nowadays, people encounter digital media and multimedia on a daily basis when watching videos on Netflix or YouTube, when listening to music on Spotify or when browsing a private photo collection on their laptop. (Multi-)media content makes up a large part of today's Internet and constitutes a major driving force behind its growth, as both its volume and variety increases at an ever increasing pace. An important contributing factor are social media platforms, where users act both as consumers and producers of digital content (so called "prosumers" [RJ10; RDJ12]). Current estimates suggest, that there are roughly 4.66 billion active Internet users worldwide, of which 4.2 billion can be considered active social media users[1]. Facebook alone contributed to 144 thousand uploaded images per minute in 2020. And many more of these platforms, such as Instagram, Twitter or TikTok, serve millions of users with mixed, self-made content involving text, images, videos or a combination thereof. A similar study found, that by 2025 we are bound to produce an estimated, annual amount of 175 ZB (i.e, 175×10^{21} B) worth of data[2] a large part of which can be considered multimedia, which must be *managed*, *manipulated*, *searched*, *explored* and *analysed* in an efficient and effective manner.

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[1] Source: Statista.com, "Social media usage worldwide", January 2021
[2] Source: Statista.com, "Big Data", January 2021

1.1   Working with Multimedia Data

At a very high level, multimedia data collections consist of individual multimedia items, such as video, image or audio files. Each item, in turn, comprises of *content* and *metdata*. Unlike traditional data collections that contain mainly (semi-)structured information such as text or numbers, the content of the multimedia item itself is unstructured at a data level, which is why *feature representations* or *descriptors* that reflect a media item's content in some way and that can be handled by data processing systems are required [ZW14]. Traditionally, such feature representations have often been numerical vectors $f_i \in \mathbb{R}^d$. However, in theory, any mathematical object that can be processed by a computer can act as such a descriptor.

Multimedia analysis – which has its roots in *computer vision* and *pattern recognition* and started in the early 1960s – deals with the automated, computer-aided analysis of media data, i.e., the extraction and processing of feature representations. In the early days of computer vision, for example, a lot of effort went into the engineering of feature representations that captured certain aspects of an image's content, such as the colour distribution, texture or relevant keypoints [Low99; BTVG06]. Once such features have been obtained, they could be used to perform various tasks such as classification, clustering or statistical analysis. With the advent of deep learning, the extraction of features could largely be automated through deep neural network architectures such as the Convolutional Neural Network (CNN) and sometimes even be integrated with the downstream analysis [GBC16].

Obviously, such analysis is not restricted to the visual domain and can be applied to other types of media such as speech, music, video or 3D models with specific applications including speech recognition, audio fingerprinting in music (re-)identification, movement detection in videos or classification of 3D models, all of which fall into the broader category of multimedia analysis.

1.1.1   Multimedia Analytics

Multimedia analytics aims at generating new knowledge and insights from multimedia data by combining techniques from multimedia analysis and visual analytics. While multimedia analysis deals with the different media types and how meaningful representations and models can be extracted from them, visual analytics deals with the user's interaction with the data and the models themselves [CTW⁺10; KKE⁺10]. Simply put, multimedia analytics can be seen as a

back and forth between multimedia (data) analysis and visual analytics, wheras analysis is used to generate models as well as visualisations from data which are then examined and refined by the user and their input. This is an iterative process that generates new knowledge and may in and by itself lead to new information being attached to the multimedia items in a collection.
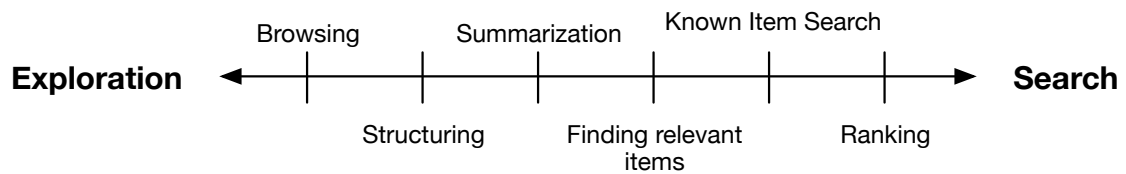
Figure 1.1   Exploration-search axis of multimedia analytics [ZW14].

For analytics on a multimedia collection, Zahalka et al. [ZW14] propose the formal model of an *exploration-search axis*, which is depicted in Figure 1.1. The model is used to characterize the different types of tasks carried out by the user. The axis specifies two ends of a spectrum, with *exploration* marking one end – in case the user knows nothing about the data collection – and *search* marking the other end – in case the user knows exactly which specific items of a collection they're interested in. During a multimedia analytics task, a user's activities often oscillate between the two ends of the spectrum until the desired knowledge has been generated. Unsurprisingly, all of the depicted activites come with distinct requirements on data transformation and processing.

1.1.2   Multimedia Retrieval

Traditionally, multimedia retrieval could be seen as a special niche within the multimedia analysis domain. It constitutes a dedicated field of research that deals with searching and finding items of interest within large (multi-)media collections based on information that may not necessarily be available in a structured manner (e.g., elements depicted in an image). Even though search and retrieval may sound like the main function offered by a database, it is a very different task for multimedia than it is for structured data [BdB⁺07]. On the one hand, given the structure of, e.g., a relational database and languages like SQL, a user can specify exactly what elements from the database should be selected using predicates that lead to a binary decision whether items in a collection match or don't. For example, when considering a product database that contains price information for individual items on sale, it is trivial to formulate a query that selects all items above a specific price threshold.

Retrieving multimedia data, on the other hand, comes with indirections due to the unstructured nature of the content, the feature representations used as a proxy for it and the *semantic gap* [BdB+07; Ros18] associated with them. A very popular model to work with the feature representation in multimedia retrieval involves calculation of (dis-)similarity scores from the features and sorting and ranking of items based on this score. This is commonly referred to as the *vector space model* of multimedia retrieval and similarity search [ZAD+06] and it is inherently non-binary in nature, i.e., an item matches a query to some degree and2 may be among the results even though the score indicates that it is a bad match. Over the years, many different combinations of features and ranking models have been proposed to facilitate content-based retrieval of different media types, such as, images, audio or video [HXL+11; DA13; MK18] as have been different types of query formulation, that complement traditional, text-based input. These models include examples such as *Query-by-Example* [KCH95], *Query-by-Sketch* [SMM99], *Query-by-Humming* [GLC+95] or *Query-by-Sculpting* [BGS+20].

It is worth noting, that when considering concrete, "real-world" multimedia retrieval system implementations today, the lines between traditional multimedia retrieval and multimedia analytics quickly start to blur. This is because traditional multimedia retrieval operates under the assumption that a specific retrieval model produces the correct result in the top ranks (e.g., the top 5) and that an item can thus be retrieved by a single query. In practice, this is often not the case due to limitations of the model itself, imprecissions in the query or simply because an information need may be very general rather than specific. Therefore, finding an item of interest often requires multiple queries and other types of interaction with the collection. This is sometimes refered to interactive multimedia retrieval and it almost always includes a human user in the loop.

Therefore, in addition to the extraction of appropriate features and the conception of effective ranking algorithms, interactive multimedia retrieval systems also concern themselves with aspects such as query (re-)formulation and refinement, results presentation and efficient exploration [LKM+19]. In addition, multimedia retrieval systems do not simply operate on features representations anymore but combine similarity and Boolean search [RGL+20]. Consequently, one could argue that interactive multimedia retrieval systems perform a specific type of multimedia analytics task, which is that of finding unknown items that satisfy a specific information need. This makes all the arguments made about data processing and data management requirements for multimedia analytics applicable to interactive multimedia retrieval as well.

1.1.3 Multimedia Data Management

As (multi-)media collections become large enough for the relevant units of information to no longer fit into main memory, multimedia retrieval and analytics quickly becomes an issue of scalable data management [JWZ$^+$16; PYC$^+$18]. Therefore, it is no longer just a problem of effective means of multimedia indexing but also of storing the original data as well as derived descriptors in a manner that allows for efficient and effective processing. This data management aspect brings about many challenges when considering the volume and variety of the multimedia data, the velocity at which new data is generated

1.2 Research Gap and Objective

It has been pointed out by Jonson et al. that "Multimedia analytics state of the art [...] has up to now [...] not explicitly considered the issue of data management, despite aiming for large-scale analytics." [JWZ$^+$16] (p. 296). Despite the development of theoretical models for multimedia database management [AN97], the conception of concrete multimedia database systems [LC08; GS16; WYG$^+$21] and multimedia retrieval systems that refactor data management into distinct components [RGT$^+$16; GRS19a], that statement, to some extent, still holds true today. While [Gia18] proposes important contributions towards a unified data-, query- and execution model required for effective search and exploration in multimedia collections, scalability aspects and the need for near real-time query performance, especially in the face of changing data, are not systematically considered. Contrarily, the proposed models – despite being seminal for data management in multimedia retrieval applications – postulate assumptions, that have considerable impact on the practical applicability of systems implementing them.

The starting point for the research described in this thesis is therefore the current state-of-the-art for data management in multimedia retrieval and analytics as briefly touched upon in the previous sections. Starting from and inspired by 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 in multimedia data management and explores the ramifications of doing so, with the higher level goal of bridging certain gaps between research conducted in multimedia retrieval, analysis and analytics on the one hand, and classical data management and databases on the other. These assumptions are namely:

Assumption 1: Nearest Neighbour Search The metric space model employed in multimedia retrieval [ZAD+06] relies on a notion of similarity search that is usually expressed as finding the k nearest neighboring feature vectors $f_{i \in [1,k]} \in \mathbb{F}$ to a query vector $q \in \mathbb{R}^d$ in a collection $\mathbb{F} \subset \mathbb{R}^d$ given a certain distance function. As a consequence, the operation is often added as a new query primitive. While this model is very concise, computationally efficient and simple to implement, it merely allows for the ranking of results and, provided that the underlying descriptor and the query is precise enough, finding the desired item(s). This limits the generalisability and does not consider operations that may involve multimedia descriptors and distance calculations in other contexts.

Assumption 2: Staticity of Data Collections Multimedia retrieval systems today often make a 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 data management system take place. Usually, no changes to the data collection are being made during the online phase. This model is proposed by both [Gia18] and [Ros18] and to the best of our knowledge, most existing multimedia retrieval and analytics systems implement this either explicitly or implicitly. 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.

Assumption 3: User Driven Query Execution Database systems usually evaluate and select the execution plan for an incoming query during a step that is refered to as *query planning*. The underlying assumption is that the database has all the information required to determine the most effective execution path in terms of cost parameters such as required I/O, CPU and memory usage. In multimedia retrieval systems, this is often not the case and instead if falls to the user to make decisions as to how a query should be executed, e.g., in terms of indexes that are being employed.

It is worth noting, that Assumption 2 and 3 both go against well-established design principles usually found it modern database systems [Pet19]. While it may be convenient from a perspective of system design, to assume a data collection to be static, this is always never the case and such a mode of operation is utterly limiting when considering data that is subject to change, as, for example, when performing online analytics or when working with an application

that offers CRUD support. A similar argument can be made for manual selection of query execution paths. While it may be simplifying the process of query planning it (falsely) assumes, that a user is always a technical expert and that all the potential query workloads are known in advance. Furthermore, it limits the amount of optimization that can be applied by the data management system.

Generally speaking, we cannot assume that we are able to anticipate all the different query workloads a multimedia database management system must handle as soon was we expect an interactive session involving a user in the loop. This was pointed out by Smeulders at al. in 2000 already, who stated that "The interacting user brings about many new challenges for the response time of the system. Content-based image retrieval is only scalable to large data sets when the database is able to anticipate what interactive queries will be made. A frequent assumption is that the image set, the features, and the similarity function are known in advance. In a truly interactive session, the assumptions are no longer valid. A change from static to dynamic indexing is required." [SWS+00] (p. 1369). This statement still holds true today and can be regarded as another argument to consider multimedia data management as a research challenge.

As for Assumption 1, one can state that the described model is only able to accommodate the search-end of the *exploration-search axis*, assuming that features are, in fact, real valued vectors. It quickly becomes too limited for tasks such as browsing, structuring and summarization, delegating the required data processing to upper-tier system components. Refering to [JWZ+16], it would however be desirable to offer such primitives at the level of the data management system.

1.3   Contribution

In this thesis, we try to address the research gaps identified in Section 1.2 and thereby try to bridge the disparity between the fields of databases and retrieval systems. The contribution of this thesis can be summarized as follows:

– We propose a *generalised model for similarity search* as an extension to the relational data model and explore implications of such a model on aspects, such as, optimisation of query execution time and query planning.

– We examine the impact of challenging the *data staticity assumption* on index structures commonly used for similarity search and describe an *adaptive index management* model by which a multimedia database system can cope with deteriorating index structures.

– We propose a *cost-model that factors-in accuracy* of generated results in addition to common performance metrics, and, based on that model, derive mechanisms for the user to express their preference for either accuracy or speed at different levels of the system.

– We introduce a working multimedia database *Cottontail DB* [GRH⁺20] that implements and employs the aforementioned models and present an evaluation thereof.

The described contributions are presented in four parts, each of which consists of several chapters:

Part I introduces the general topic and problem statement (Chapter 1) and describes motivating use cases and the requirements they bring (Chapter 2).

Part II gives a brief summary of the theoretical foundation and state of the art in database (Chapter 3) and multimedia analysis & retrieval (Chapter 4) research and tries to combine the two aspects on a systems level in a brief survey of multimedia database systems (Chapter 5). In addition to establishing a common foundation and framework for the remainder of this thesis, we also use this part to survey related work.

Part III formalises the theoretical models that make up the aforementioned contributions (Chapter 6) and describes our reference implementation Cottontail DB (Chapter 7).

Part IV presents the evaluation using Cottontail DB as an implementation (Chapter 8) and discusses the conclusions and potential future directions (Chapter 9)

2

Applications and Use Cases

An aspect that has always fascinated me about computer science and information technology is, that it has applications in every conceivable domain. It is this combination of purely technological aspects – the computational part – and the domain knowledge, that make this field challenging as well as interesting. Digital transformation – the act of improving businesses and processing using digital technology [Via19] – has been a driving force behind economic activity over the past decades, and while many non-technological factors define digital transformation, optimisation through the application of disruptive technologies remains the main incentive behind it.

It is therefore, that we do not want to detach the work presented in this Thesis from its concrete applications and instead aim to motivate it based on real-world scenarios. We do so, by introducing three use cases, for which we believe that a general-purpose multimedia database system could fulfill an important function. From these use cases, we then go on to derive a series of requirements for such a database system.

2.1 Use case 1: Interactive Multimedia Retrieval

Multimedia retrieval in a broader sense describes the act of finding items of interest in large multimedia collections, wherein "multimedia" can refer to any type of modality, such as text, images, videos or audio and any combination thereof. Consequently, a multimedia retrieval system must be able to have a user express their *information need*, which is translated to a *query* that the system can use to produce the item(s) of interest as a *result*. The process is visualized in Figure 2.1 and a formal problem definition will be provided in Chapter 4.

Figure 2.1   **The idealised multimedia retrieval problem: A user expresses an information need as a query and the multimedia retrieval system returns matching items from a collection as a resultset, ideally including the desired item.**

There are many potential applications of the multimedia retrieval problem, and to name a few, one could consider libraries of media items produced by radio or TV stations that must be made searchable [WOK+98], collections of cultural heritage data as maintained by museums, archives and archaeology departments [Tsa07] or medical image databases containing X-rays or MRIs [MMB+04].

What makes multimedia retrieval a challenging problem is the inherently unstructured nature of the data, by which we mean that the raw, (digital) information may not directly reflect the content of the item as a human consumer might perceive or describe it. Let us take, for example, the image of a rabbit the user in Figure 2.1 is looking for[1]. If our task were to describe that image so that we can retrieve it from a large database, we might use terms like "rabbit", "bunny" or "grass". We might assume, judging from the image, that the scene is taking place in a "garden" and maybe we notice that the rabbit is currently "munching" on a "leaf" or "strain of grass". We might even know the rabbit's breed or name, if we happened to be its owner.

All of this information is formed based on a series of steps ranging from perception, over interpretation to cognition as illustrated in Figure 2.2 and each of these steps is accompanied by a loss or distortion of information [JLX21; Ros18], which makes this process highly subjective, giving rise to a series of "gaps" that influence the outcome. Most importantly, however, all of the aforementioned descriptions are not explicitly contained in the raw image data, which is merely an array of colour values that constitutes the image and does neither come pre-labeled nor pre-described.

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[1] On purpose, we do not consider the aspect of reconstructing the image from memory, which makes the problem even more challenging.

Figure 2.2   A simplified model of knowledge formation from an analogue input in humans (adapted from [JLX21]) and computers.

This impedance mismatch between the content being stored and the information required to find it, is the main challenge that unstructured data brings with it, as opposed to structured data, which consists of retrievable units of information by its very nature. Bridging the gaps between the information available and the information one might use to actually search for an item of interest is therefore one of the obstacles to overcome in multimedia retrieval. Over the years, different solutions have emerged:

Manual Labeling The obvious solution is to manually embed the aforementioned labels and descriptions into the multimedia item so that we can use this information to find it at a later point in time. While as of today, this approach is still widely used, it comes with two important disadvantages. Obviously, it remains a subjective task, because as we have argued, the process of forming these labels may yield different results depending on who is assigning them (due to the perceptive, interpretative and semantic gap). Most importantly, though, the task of manual label assignment is laborious and unable to scale with the large volumes and the ever increasing velocity at which multimedia data is produced. This is related to the general challenge of working with Big Data [KUG14].

Automatic Labeling Recent advances in machine learning have provided us with the ability to automatically label [RDG+16] and describe [RKH+21] different types of multimedia through classification. So instead of annotating the content ourselves, we can leave this to pre-trained models that have, at a high level, a similar mode of operation as a human operator would have, as

is illustrated in Figure 2.2. While this solves the problem of scalability, it still remains a subjective task since the process of model training is also prone to the aforementioned gaps found in the data being trained, which can lead to biases [BK17]. Furthermore, there may be discrepancies between the (mental) model used for classification and the one employed during query formulation, which are typically caried out at different times by different people.

Content-Based Search The last approach and the one that "classical" multimedia retrieval has concerned itself with for decades is that of *content-based search*. Instead of using the higher-level concepts in the form of textual labels, content-based search works with intermediate representations called *descriptors* that are derived from the data directly using signal processing or statistical analysis. These descriptors – which are often real-valued vectors [ZAD+06] – can then be used to establish a notion of *similarity* between items in a collection and a query. Instead of a list of exact matches, this type of query returns a ranked list of items that match the query well enough. This is called similarity search [BdB+07] and in this context, the query may refer to more than simply textual input. Given the example in Figure 2.1, one could use another image of a rabbit (Query-by-Example, [KCH95]) or try to create a sketch (Query-by-Sketch, [SMM99]). One could even come-up with more sophisticated types of queries, such as, searching for poses held by people in an image or video [HAG+22] or using visual-text co-embeddings [RKH+21; SGH+22] to map textual descriptions to images and vice-versa.

Research has shown that while individual methods falling into any of the three categories may yield acceptable or even exceptional results, there is clear indication that ultimately, a combination of the three is the most powerful solution, especially, since the exact type of information need cannot always be anticipated [RGL+20]. Furthermore, and partly because different techniques may perform better or worse depending on the information need, we often find that instead of the simple "issue a query, get a result" scheme illustrated in Figure 2.1, actual multimedia retrieval applications are more interactive and require a back and forth between system and user [LBB+22] that involves query (re-)formulation potentially using different descriptors, exploration, examination, query refinement and relevance feedback [LKM+19; GSJ+19] as illustrated in Figure 2.3. These types of interactive multimedia retrieval systems are explicitly tested at evaluation campaigns such as the Video Browser Showdown (VBS) [Sch19] or the Lifelog Search Challenge (LSC) [GJS+21].
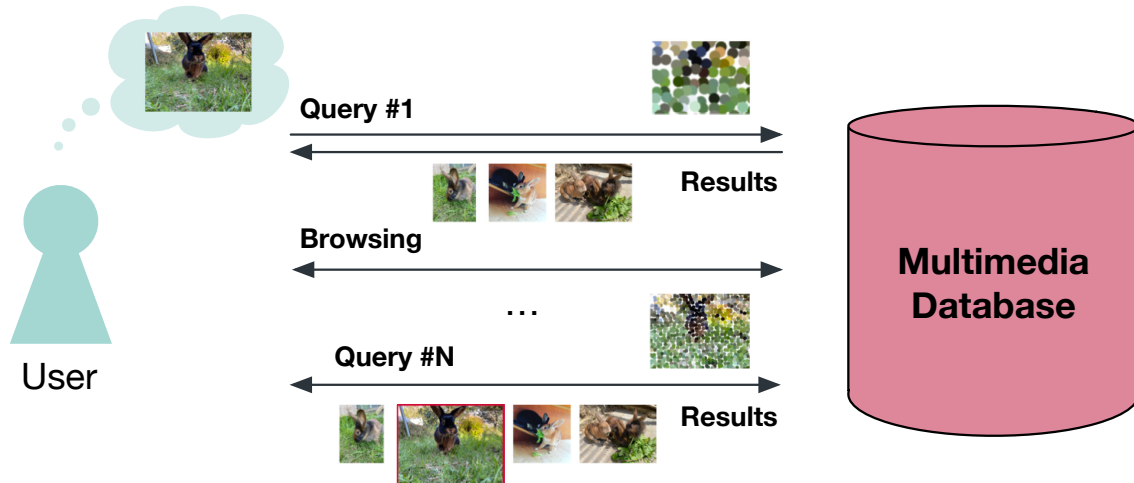
Figure 2.3 **The interactive multimedia retrieval problem: A continuous back and forth between system and user involving different types of workload as the user tries to find the item of interest through query (re-)formulation, browsing and examination.**

Both aspects have important implications for the aforementioned data management system that must support (interactive) multimedia retrieval:

Firstly, such a system must consider different data- and query models when dealing with information from the aforementioned categories as well as a wide range of query workloads. While searching for labels and textual descriptions at scale can be achieved by the well-established *Boolean retrieval* model, we require the completely different *vector space retrieval* model when dealing with descriptors derived from multimedia data and, ideally, we should have the ability to combine the two in unified queries [HSS+20]. This is a problem that has been acknowledged by other authors before [JWZ+16] and that has been partially addressed, for example, by [Gia18; GS16; WYG+21].

Secondly, any database management system supporting interactive multimedia retrieval must be able to satisfy the different types of query workloads in a reasonable amount of time, so that the user in the loop must not wait for results too long. One can even state that retrieval speed is more important than perfect accuracy, especially in timeboxed settings such as VBS or LSC, because (i) the retrieval process itself is inherently inaccurate due to the aforementioned gaps, and (ii) there is a user in the loop who examines the results and makes the final decisions.

A final aspect to consider is the staticity of the data itself. In multimedia retrieval, we often implicitly assume that data collections remain static while they are being queried but it must be emphasized that for most use cases, this is very likely not to be the case.

2.2   Use case 2: Analysis of Social Media Streams

Social media platforms such as Twitter[2], Facebook[3], Instagram[4] and TikTok[5] have gained enormous traction over that past few decades. Current estimates suggest, that there are roughly 4.66 billion active Internet users worldwide, of which 4.2 billion can be considered active social media users[6]. Facebook alone contributed to 144 thousand uploaded images per minute in 2020. And many more of these platforms, such as Instagram or Twitter, serve millions of users with self-made content consisting of text, images, videos and more.

This brave new world of interaction and interconnection on different platforms, which are the sole source of information for many people, has brought about new challenges in need of solutions. Probably the most important challenge is known under the umbrella term "fake news" [LBB+18], by which we mean information that comes disguised as authentic but contains fabricated, misleading or even wrong information. The term became highly polarised in the 2016 U.S. elections [QFB+19], when orchestrated campaigns on social media were targeted at voters and may have tipped the scales in favour of the winning party and their president.

While the problem of fake news can arguably not be solved by mere technological means, the issue has brought about many different research questions in the realm of social media analysis and analytics. One focus lies on the direct detection of misinformation on different channels [ZZ20] by different means such as content, propagation patterns or sources. Others try to tackle the detection of bots [Cre20], user-accounts that are not backed by real humans and that are often used to create or spread misinformation. And then there is the topic of sentiment analysis [YCL+19], which can yield important clues about how (fake-) news stories are received by their consumers.

While many of the aforementioned problems mainly deal with textual information, multimedia obviously plays an important role as well. Instagram and TikTok, for example, focus solely on the sharing of images and videos respectively. A very recent and preliminary analysis suggests [Ciu22], that the sharing of images and videos plays an important role in the international covering of Russia's war on Ukraine. Potential problems in need of solution could, for example, be the automatic detection of image forgeries [Far09].

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[2] See https://www.twitter.com
[3] See https://www.facebook.com
[4] See https://www.instagram.com
[5] See https://www.tiktok.com
[6] Source: Statista.com, "Social media usage worldwide", January 2021
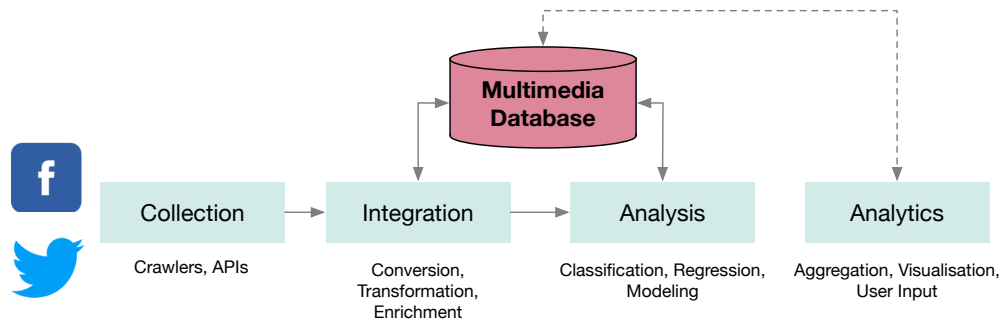
Figure 2.4   The architecture of a fictious social media analytics platform.

If we examine what a fictious and generalised pipleine for social media analysis and analytics would look like, we might arrive at something as illustrated in Figure 2.4 [CSW+19; YPM+19; BPS+20]. The many different channels in existence, require for a broad range of tools that deal with data collection using crawlers or APIs provided by the respective source. Since all these potential sources are likely to use very different types of data models, some sort of integration into a common framework is very likely. This step may also be accompanied by data enrichment using external services or data existing in the system's own collection. This is then followed by what we call analysis, which may include a wide range of machine learning and data analysis techniques that may or may not rely on existing data. A common theme for this step is that, similarly to multimedia retrieval, it probably involves generation and storage of formal descriptors of the multimedia content. Therefore, the entire pipeline is very likely to be backed by some type of persistent data store, which can store labels, descriptors and metadata and which allows queries by both the analysis and the analytics components built on top of it. From the described architecture we can, again, derive certain needs with respect to that underlying database:

Firstly, for this use case the multimedia database must be able to deal with non-static data, since the various sources potentially generate a steady flow of new information which are likely to be contributing to future inquiries.

Secondly, and similarly to the multimedia retrieval problem, the pipline is likely to deal with structured, semi-structured and unstructured information that must be stored and processed jointly and the multimedia database must be able to cope with this variety.

And finally, with social media being a very classical field for applying multimedia analytics techniques [PYC+18; JWZ+16], the different tools built upon the multimedia database are likely to rely on a wide range of query workloads, which the database should be able to accomodate.

2.3   Use case 3: Signal Analysis in MRF

Multimedia retrieval for medical applications has been an important area of research for many decades now [MU17; MMB+04] and many of the arguments that we have made in Section 2.1 can be repeated for this specialised sub-domain.

However, in this section, we focus on a very specific application, in which we do not consider media in the classical sense but in a broader sense of raw signals stemming from a Magnetic Resonance Imaging (MRI) device.

MRI is a non-invasive, non-ionizing imaging technique that has gained huge importance in various fields of modern medicine. MRI is enabled by Nucleic Magnetic Resonance (NMR), which was first described by Purcell and Bloch in 1946 [Blo46; PTP46]. The process behind it is roughly illustrated in Figure 2.5.

In simple terms, an MRI-machine operates by applying a very strong, external, magnetic field – often referred to as B_0 – which forces nuclei with a non-zero spin, e.g., a ^{1}H nucleus (proton), to align to it. That static field is disrupted by applying a second, radio-frequency pulse that interferes with the nucleus' alignment. As this pulse is switched of, the protons start to re-align with B_0 over time in what is called relaxation. This process is characterized by the relaxation times T_1 (spin-lattice relaxation) and T_2 (spin-spin relaxation), which are specific to a type of material and tissue, and it is accompanied by a measurable, oscillating magnetic field that induces a current in the detector coil. This current – also known as free induction decay – is the signal recorded by the MRI-machine and it can be used to reconstruct magnetic properties of the material. To optimise the signal to noise ratio, the procedure is repeated multiple times. Furthermore, spatial resolution is also atained by repetition while scanning the body or a specific part thereof. Both aspects contribute to a direct trade-off between acquisition time and image quality.
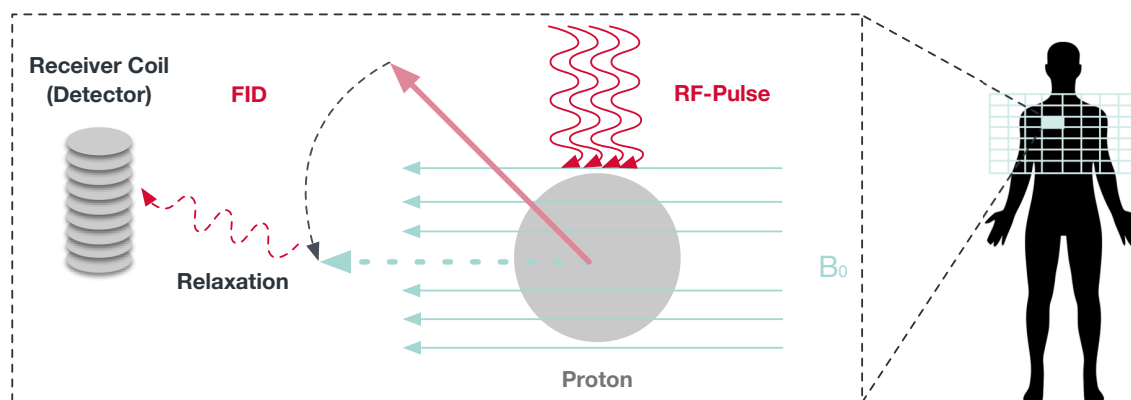
Figure 2.5   Simplified illustration of the physical processes enabling MRI.

MRI has the ability to generate fine-grained contrasts in different types of soft tissue. However, it comes with two critical disadvantages: Firstly, there is an inherently long acquisition time that can range anything from several minutes to over an hour per scan, especially when one tries to achieve quantification of magnetic properties of soft tissue. This is an issue because the patient is required to lie still for that time, which they are often unwilling or unable to do. Secondly, and due to this lack of fast, quantitative tools, MRI images have become mostly qualitative in nature. Anatomical areas are often referred to as either "hyperintense" or "hypointense" with respect to their immediate surrounding, but the difference between such areas or even the absolute values themselves are not measured directly.

Magnetic Resonance Fingerprinting (MRF) is a technique [MGS+13] that proposes a solution to this problem and allows for a quantitative mapping of multiple properties simultaneously while lowering acquisition time. The method is described in [BMCFM+19] and illustrated in Figure 2.6. In summary, MRF is based on the assumption that different types of tissue produce a distinct signal evolution – called *fingerprint* – when exposed a specific acquisition scheme. This means that during data acquisition, measurements take place under varying (pseudo-random), external magnetic field and RF-pulse configurations and signals are recorded for the different configurations resulting in the fingerprint. That fingerprint can then be matched against a database (called dictionary) of pre-calculated, discretised fingerprints that have been simulated using *Bloch*'s theorem of magnetic resonance [Blo46]. Through that matching step, values for B_0, T_1 and T_2 (and other parameters) can be obtained and subsequently used to reconstruct an image. similarly to MRI, spatial resolution is attained by scanning and the overall process is therefore repeated several times.

Most MRF setups implement the pattern matching step as an exhaustive search that looks up the simulated entry from the dictionary that maximises the inner product with the obtained signal [BMCFM+19]. This is called Maximum Inner Product Search (MIPS) and it involves evaluating the inner product between a complex signal vector and all the vectors in the database. This is a problem similar to the similarity search problem being solved in multimedia retrieval, with the difference that the vectors are complex and not real-valued, that the inner product is maximised instead of minimised and that there is interest in a single result per query only. This step constitutes one bottleneck of the entire process, since many queries must be performed in sequence. In fact, several attempts at speed up have been made over the years [MPM+14].

A few more references
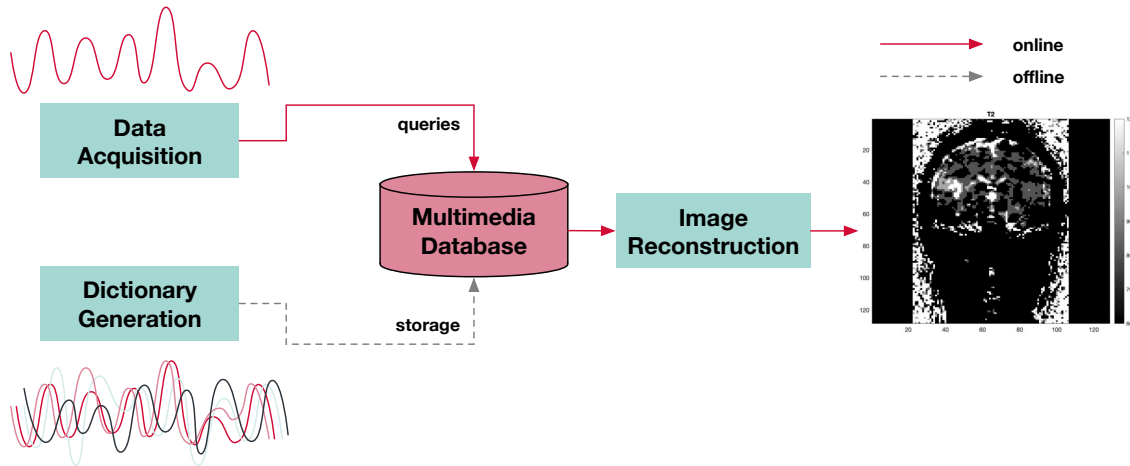
Figure 2.6   **Simplified block diagram of a MRF system (adapted from [BMCFM+19],
reconstruction of brain scan kindly provided by Manuel Hürbin).**

Again, we assume that this pattern matching process should be supported
by a dedicated multimedia database, which becomes necessary once dictionaries
become so large that they no longer fit into main memory. For a last time, we
can try to describe the requirements imposed on such a database:

Firstly, and similarly to the multimedia retrieval problem, one requires a
dedicated data- and query model to store complex vectors and perform MIPS.
This model even differs from the metric-space model applied in multimedia
retrieval (however, considering complex vectors has been discussed in previous
work, e.g., in the context of similarity search on time series [RM97]). At the same
time, the database must also be able to store and access very classical data that
fits into the Boolean retrieval model such as the individual parameters B_0, T_1 or
T_2.

Secondly, and also similarly to interactive multimedia retrieval, query time
is an important aspect and should be minimised as much as possible, especially
in a clinical setup. However, in contrast to multimedia retrieval, this optimisa-
tion cannot be bought by trading retrieval accuracy, because the MRF problem
does not have a human in the loop who might correct an error in an individual
query. Instead, the process relies on the lookup of the correct signal vector for
every single query. Preliminary work on applying multimedia retrieval tech-
niques to speeding up MRF pattern matching has shown that sacrificing accu-
racy leads to sub-optimal image reconstruction results [Hür20; Zih21] and thus
high-dimensional indexing methods known from multimedia retrieval are not
directly applicable.

2.4 Deriving Requirements

In Sections 2.1, 2.2 and 2.3 we have discussed three applications that, (i) deal with large amounts of unstructured (multimedia) data that must be stored, managed and queried, (ii) use some mathematical descriptors of that unstructured (multimedia) data to enable analysis, comparison and queries, (iii) and that combine these descriptors with data such as labels, descriptions and other information, that must be accessed and sometimes queried as well.

We acknowledge, that while the details may vary, the basic needs outlined in the aforementioned use cases are overlaping to such an extent that it raises the question whether a dedicated multimedia database management system would make sense. In fact, the argument for such a system has been made by different authors before us [AN97; SWS+00; ZW14; JWZ+16; Kha21] and steps towards such a system have been taken [Gia18; WYG+21]. However, all concrete approaches somehow narrow the scope in a way that restricts their generalisability.

In this section, we assume that a general-purpose multimedia database is desirable and based on the argument thus far we formalise the requirements imposed on such a system. We do not claim that we address all of the listed requirements in this Thesis. We merely attempt to raise and formalise them, similarly to [AN97; JWZ+16; Kha21].

2.4.1 Traditional Database Capabilities

Regardless of application, any multimedia database is very likely to rely on traditional DBMS capabilities at some point. Be it when data changes or is accessed concurrently and guarantees regarding consistency must be provided or when executing traditional Boolean queries on some aspect of the available metadata. This has been pointed out by [AN97; Kha21] already and we can therefore reiterate, that a multimedia database must bring the same, basic abilities that any traditional DBMS would w.r.t. to data modeling, data management, execution of Boolean queries and the enforcement of guarantees such as ACID or BASE.

Requirement 2.1 A Multimedia Database is a DBMS

At its core, any general-purpose multimedia database is a classical Database Management System and should provide the same functionality in terms of data modeling, data management, query execution and guarantees with regards to integrity- and concurrency control, persistence and recovery.

2.4.2   Multimedia Query Support

Multimedia queries are fundamentally different in that, as opposed to Boolean queries, they do not produce exact results but instead rely on scores and ranking to quantify similarity between a query and an object in a database. Obviously, a multimedia database system must therefore have the ability to support such queries at all levels from query formulation (i.e., query language) to query execution [AN97]. Furthermore, the combination of similarity search with Boolean queries should possible and well-defined in terms of outcome.

It is worth noting, that by "Boolean query" we merely refer to the ability to produce exact matches based on Boolean predicates without making an assumption about the underlying data model. If a multimedia database system choses to implement the graph model then traditional graph traversal queries fall under the category "Boolean query" as well.

Requirement 2.2   Multimedia Query Support

A multimedia database must be able to support multimedia queries based on similarity and scores in addition to Boolean queries and it must allow the combination of the two search paradigms in a unified framework.

2.4.3   Multimedia Data is Big Data

At its core, dealing with multimedia data equates to dealing with *Big Data* in that a system deals with large *volumes* of information, that may change at a high *velocity* and exhibit a large *variety*, ranging from highly structured metadata attributes to completely unstructured, raw data[7]. A multimedia database can, of course, favour one of the three aspects over the others (e.g., assume that velocity at which data changes is zero) but in general, all three aspects must be considered jointly, which results in interesting engineering and research problems, e.g., for high-dimensional indexing [HJB19] or distribution of data and computation.

Requirement 2.3   Multimedia Data is Big Data

A multimedia database must be able to deal with large volumes of data that exhibit a broad variety and may be subject to change at a high velocity within a single, well-defined framework.

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[7] This is known as the "3 V's of Big Data". Over time, more of these V's have been described in literature, for example in [KUG14].

2.4.4   Modelling Retrieval Accuracy

Classical databases produce results that match or don't match a given query, i.e., there is no notion of uncertainty or imprecission in the results. In contrast, the models used in multimedia retrieval are inherently inaccurate to some extent, in that the "best matching" entries are obtained, meaning that even bad results may be produced in the absence of better options. This imprecission or inaccuracy is influenced by many factors, not the least of which are the design and choice of the multimedia descriptors themselves.

While the inherent (in-)accuracy of any given descriptor is impossible to predict and thus out of scope for the database that holds it, the notion of accuracy still opens a relevant avenue, since some of that accuracy can be deliberately sacrificed in order to gain speed, which is often done in high-dimensional indexing. Since some use cases are very robust to such decisions while others are not, this aspect must be made explicit at a system level.

Requirement 2.4   Model for Retrieval Accuracy

A multimedia database must employ an internal model of accuracy of results. That model must (i) enable a user to specify the desired accuracy of the result (ii) allow the database system to derive the expected accuracy for a query execution path (iii) take both aspects into account when planning query execution.

2.4.5   Complex Data Types as First-class Citizen

Since multimedia analysis and analytics workloads rely on mathematical objects such as vectors, complex numbers or matrices, we argue, that the data model of a multimedia database must be extended to consider those types of data as *first-class citizens* in addition to well-established data types such as numbers or strings. This means, that the structure as well as the mathematical properties of those types must be considered for storage, query planning and execution.

This is not a new idea, per-se, and to some extent self-evident since new use cases obiously require additions to existing data models. Therefore, unsurprisingly, the idea of extensible data models was already discussed as early as 1988 [LKD+88] and it was also argued by [Gia18] that to support multimedia retrieval workloads in a relational database, one must extend the relational model to support those vectors as basic data types.

Requirement 2.5   Complex Data Types as First-class Citizen

A multimedia database must treat composite data types (e.g., vectors, complex numbers, matrices, tensors) as first-class citizens of the data model in addition to primitive types such as numbers or strings.

2.4.6   Functions as First-class Citizen

All multimedia retrieval problems considered so far involve the execution of functions that operate on individual, complex data atoms, e.g., to determine the similarity between items in the database. For a multimedia database to be able to operate effectively, those functions must be considered first-class citizens of the data model as well, in that the multimedia database must have the ability to reason about them and make decisions regarding their execution.

Requirement 2.6   Functions as First-class Citizen

A multimedia database must treat mathematical functions as first-class citizens and must have the ability to reason about those functions' properties during query planning and execution.

PART II

Foundations

Preface to Part II

Since the contributions of this Thesis rely on decades of research in database systems as well as multimedia retrieval and analysis, we will use this part to provide an overview over the relevant fundamentals. Furthermore, we use it to survey related work and to establish the common terminology, which we think is necessary to understand the contributions of this Thesis.

Chapter 3 discusses the theory surrounding Database Management System both at a data model and systems level. Most of the fundamentals are guided by the books *DATABASE SYSTEMS The Complete Book* [GUW09] and *Database Internals* [Pet19]. Furthermore, some information was adapted from a video lecture kindly provided by Andy Pavlo – Associate Professor at Carnegie Melon University. That lecture is freely available on YouTube[8].

Chapter 4 shifts the focus to the analysis and retrieval of multimedia data – including but not limited to images, audio and video. In addition to the basic techniques, we also discuss concrete system implementations. The two major sources used in this chapter are the books *Multimedia Retrieval* [BdB+07] and *Similarity Search – The Metric Space Approach* [ZAD+06].

Chapter 5 tries to combine the two previous chapters and briefly surveys what efforts have been made to converge the two domains, which are, to this day, still largely disjoint areas of research. This is where the transition to the next part is staged.

All the aforementioned text books and resources provide an excellent overview of their respective fields and this is as a good time as any to thank the authors for their invaluable work. While we do indicate if specific ideas were taken directly from those sources, some information that we considered to be "general knowledge", is not always cited explicitly.

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[8] https://www.youtube.com/c/CMUDatabaseGroup

3

On The Design of a Database Management System

Database Management System (DBMS), or simply "databases", power everything from small and simple websites to large data warehouses that serve millions of users in parallel. Database systems play a crucial role in banking, e-commerce, science, entertainment and practically every aspect of our socioeconomic lives, because more and more we rely on insights generated from the analysis of data [Dha13] and DBMS form the backbone of many information and data processing systems.

The first commercial DBMS were introduced in the 1960s [GUW09] and they have evolved ever since to adapt to a wide range of requirements. Even though many different flavours of Database Management System (DBMS) have emerged over the years, at their core, they still serve the same, fundamental purpose:

Management DBMS enable their users to organize data corpora that can range from a few megabytes to houndreds of terrabytes according to a defined data model. For example, data can be structured into documents [HR16], graphs [AG08] or tables that in turn can be organized into collections or schemata.

Definition DBMS provide users with the ability to alter the organization of their data within the constraints of the data model using a Data Definition Language (DDL).

Manipulation DBMS provide users with the ability to modify the data within the constraints of the data model using a Data Manipulation Language (DML). Modifications may include adding, removing or changing entries.

Querying DBMS provide users with the ability to query the data using a Data
   Query Language (DQL). Such queries can be used to answer specific "ques-
   tions" about the data and to generate the aforementioned insights.

Guarantees DBMS usually provide guarantees, such as assuring durability upon
   failure or providing access control for concurrent read and write operations.
   A well-known set of guarantees offered by many modern DBMS is known by
   its acronym ACID – which stands for **A**tomicity, **C**onsistency, **I**solation and
   Durability [HR83] – or BASE [Pri08].

3.1   Data Management and Data Models

A data model is a formal framework that describes any type of data or infor-
mation. It usually involves a formal description of the data's *structure*, the *oper-
ations* that can be performed and the *constraints* that should be imposed on the
data [GUW09]. The purpose of any data model is to formalize how data gov-
erned by it can be accessed, modified and queried and any given DBMS usually
adopts a specific type of data model (or multiple models, for that matter).

   In the context of database systems and data management, it has become
common practice to distinguish between different levels of abstraction for data
models, as can be seen in Figure 3.1. At the top, there is the *conceptual data
model*, which is often closely tied to some real-world object, fact or process. For
example, in an online shop, one can think in terms of customers that place
orders, products that are being sold and invoices that must be sent out. In
the Entity Relationship Model (ERM) [Che76] – a popular framework used to
describe conceptual data models – those "real things" would be modeled as
entities that come with *attributes* that describe them and that have *relationships*
among them as required by the concrete application.
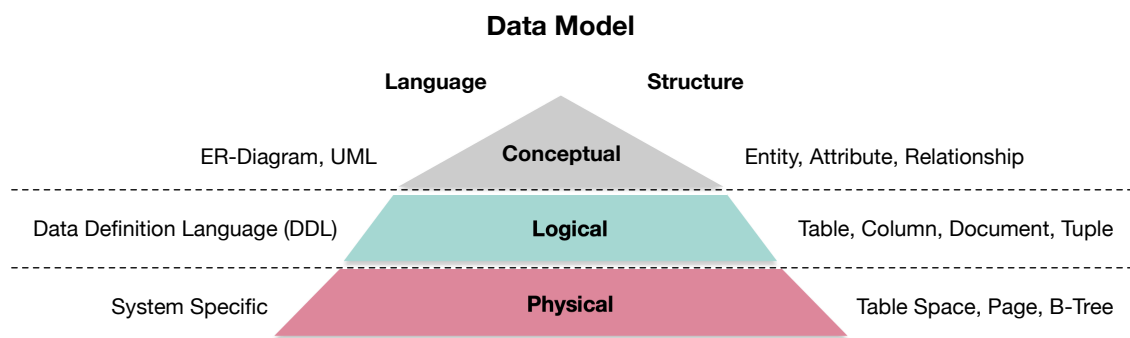
Figure 3.1   Different levels of abstraction for data modelling.

The *logical data model* is more closely tied to the type of database being used. Different data models have been conceived over the years, including, but not limited to models centered around documents [HR16], graphs [AG08], key-value pairs and tables, each bringing their own (often domain-specific) advantages and disadvantages. At this level, one can use DDL to describe and modify the data organization and DQL or DML to query and modify the data itself. As an example, one could store each entity described before in a dedicated table wherein each attribute occupies a different column. This is known as the relational data model [Cod70] and a important language for the relational model is the Structured Query Language (SQL), which became an international standard in 1987 under *ISO 9075* and has evolved ever since [Cha12].

At the very bottom, we usually find the *physical data model*, which is specific to the database implementation and describes low-level aspects such data access in terms of *read* and *write* operations to data structures such as *table spaces*, *data pages* or *trees*. An important argument in favour of separating logical from physical data model, even though they are both somewhat specific to a DBMS implementation, is that the end-users should not concern themselves with how exactly data is organized and accessed at the lowest level but should instead describe their intent in terms of the information they are trying to access. Mapping user-intent to low-level data access operations then becomes a task of the DBMS.

3.2 The Relational Data Model

In June 1970, E. F. Codd published his pivotal research article *Relational Model of Data for Large Shared Data Banks* [Cod70] in which he describes a logical data model, which he himself refers to as "relational". This model has become the fundament on which many modern database management systems have been built, with examples dating back to the 1970s [ABC⁺76] and promintent, contemporary examples including systems such as *Maria DB*, *PostgreSQL* or *Oracle*.

The relational model is structured around *relations*, which are a mathematical construct but can be visualized as two-dimensional tables. Such a table consists of columns – which are called *attributes* – and rows – which are called *tuples* and hold *attribute values*. Semantically, a relation can be seen as a knowledge-base about some fact – such as, the paintings held by a museum – under a Closed-world assumption (CWA). That is, the relation contains all the information available about the fact and can thus be used do derive conclusive answers or results given a stated question or query.

Reference

In order to formalize the structure of and the operations that can be executed on the data represented by a relation, one can use Definition 3.1.

Definition 3.1   Relation according to [Cod70]

Let $\mathcal{D}_j$ be sets we call *data domains* with $j \in [1, N]$ and $N \in \mathbb{N}_{>0}$. A *relation* $\mathcal{R}$ constructed over these data domains is a set of *M tuples* $t_i = (a_{i,1}, a_{i,2}...a_{i,N})$ with $i \in [1, M]$ and $M \in \mathbb{N}_{>0}$ such that the first attribute value of any tuple comes from $\mathcal{D}_1$, the second from $\mathcal{D}_2$ and so forth. That is, values $a_{i,1} \in \mathcal{D}_1, a_{i,2} \in \mathcal{D}_2...a_{i,N} \in \mathcal{D}_N$. Ergo, a relation can be seen as a subset of the cartesian product of all data domains over which it was constructed, i.e., $\mathcal{R} \subset \mathcal{D}_1 \times \mathcal{D}_2... \times \mathcal{D}_N$.

The number of data domains N is referred to as its *degree* and we call such a relation *N-ary*. The number of tuples M is called the *cardinality* of $\mathcal{R}$ with $M = |\mathcal{R}|$. It must be noted, that the relational model does not dictate what the data domains $\mathcal{D}$ are (apart from the constraint that its values must be atomic). However, in a relational DBMS, they usually correspond to the data types supported by the database and the programming environment it was written in, for example, integer and floating point numbers or text. In this Thesis, we therefore sometimes use *data domain* synonymous for *data type* [1].

In addition to Definition 3.1, we will use the identities 3.2 to 3.5.

Definition 3.2   Attributes of a Relation

Let $\mathcal{R}$ be a N-ary relation over the data domains $\mathcal{D}_i$, $i \in [1, N]$ with corresponding names or indexes l_i. We call the combination of a data domain with a human readable label *attribute*, that is, $\mathcal{A}_i = (\mathcal{D}_i, l_i)$. To simplify notation, we sometimes use the label of an attribute in the subscript instead of the index.

Definition 3.3   Schema of a Relation

Let $\mathcal{R}$ be a N-ary relation over the attributes $\mathcal{A}_i$, $i \in [1, N]$. We call the list of all attributes over which $\mathcal{R}$ was constructed the *heading* or *schema* $\text{SCH}(\mathcal{R})$ of $\mathcal{R}$.

$$\text{SCH}(\mathcal{R}) = (\mathcal{A}: \text{if } \mathcal{A} \text{ is an attribute of } \mathcal{R})$$

---

[1] Strictly speaking, the data domains of a given relation $\mathcal{R}$ are merely subsets of the sets that represent the respective data type which, in turn, are subsets of even more basic sets such as $\mathbb{N}$ or $\mathbb{R}$ for Int and Float respectively. The relationship between types and data domains is subject of a more categorical approach to data models and nicely layed out in [Spi09]

Definition 3.4   Accessing Attribute Values

Let $\mathcal{R}$ be a N-ary relation over attributes $\mathcal{A}_i$, $i \in [1, N]$ and let further $t \in \mathcal{R}$. To address the attribute value $a_i \in t$ that belongs to attribute $\mathcal{A}_i \in \text{SCH}(\mathcal{R})$, we use the *attribute value accessor* $t[\mathcal{A}_i]$.

$$a_i = t[\mathcal{A}_i] = \{a_j \in t : i = j\}$$

Definition 3.5   Supported Data Domains

For a given DBMS, we call $\mathbb{D}$ the set system of data domains or data types supported by the system.

$$\mathbb{D} = \{\mathcal{D} : \text{if } \mathcal{D} \text{ is supported by DBMS}\}$$

In its original form, the relational model assumes the following properties to be true for a relation $\mathcal{R}$ and its attributes [Cod70]:

Ordering of Tuples Tuples $t \in \mathcal{R}$ are inherently unordered and two relations are considered equal if they contain the same tuples, regardless of order.

Ordering of Attributes Attribute values a_i always occur in the same order within the tuple $t \in \mathcal{R}$, which corresponds to the order of the attributes $\mathcal{A}_i \in \text{SCH}(\mathcal{R})$. This order can evolve over time but remains constant in a momentary snapshot of $\mathcal{R}$. It follows from the definition that $|t| = |\text{SCH}(\mathcal{R})| \forall t \in \mathcal{R}$

Duplicates Since relations are sets, they do not allow for duplicates, i.e., every tuple $t \in \mathcal{R}$ must be unique in terms of their attribute values.

Given the idea of a relation, the sum of all data managed by a DBMS can logically be regarded as a collection of different relations $\mathcal{R}_k$, $k \in \mathbb{N}_{\geq 0}$ of assorted degrees N_k over data domains $\mathcal{D} \in \mathbb{D}_{\text{dbms}}$ (i.e., a collection of tables). The schema of a database can then be seen as the set system of all $\text{SCH}(\mathcal{R}_k)$. As [Cod70] points out, relations are subject to change over time. These changes can take place on the level of any relation's structure, i.e., $\text{SCH}(\mathcal{R}_k)$, the relations $\mathcal{R}_k$ itself, e.g., by tuples being added to (insert) or removed from (delete) a relation or the level of a tuple $t \in \mathcal{R}_k$, e.g., by altering one or multiple attribute values.

Example 3.1 features an example relation `paintings` visualized as a table. Each entry in the table represents a painting and the related attribute values.

Example 3.1   Table Representation of a Relation $\mathcal{R}_{\texttt{paintings}}$

The following table lists the content of a ternary relation ($N = 3$) $\mathcal{R}_{\texttt{paintings}}$. The attributes $\mathcal{A}_{\texttt{title}}, \mathcal{A}_{\texttt{artist}}, \mathcal{A}_{\texttt{painted}}$ correspond to the table's columns. The individual tuples t_i are "valid" combinations of painting title, artist and year of conception under CWA and constitute the rows.

$\mathcal{R}_{\texttt{paintings}}$	$\mathcal{A}_{\texttt{title}}$	$\mathcal{A}_{\texttt{artist}}$	$\mathcal{A}_{\texttt{painted}}$
t_1	Mona Lisa	Leonardo da Vinci	1506
t_2	The Starry Night	Vincent van Gogh	1889
t_3	Las Meninas	Diego Velázquez	1665

3.2.1   Keys and Normal Forms

The notion of a relation provides us with the basic tools for data modeling. In addition to Definition 3.1, Codd proposed a range of constraints to guarantee proper data definition using the relational model and the following constructs [Cod70]:

A Primary Key (PK) $\mathcal{P}$ of relation $\mathcal{R}$ is a subset of attributes $\mathcal{P} \subset \text{SCH}(\mathcal{R})$ that uniquely identify a tuple $t \in \mathcal{R}$. That is, the attributes that are not part of the PK and the associated values are functionally determined by $\mathcal{P}$. Using Example 3.2, the painting and all its attributes, i.e., the artist and the year of its creation, are functionally determined by the name of the painting, which is assumed to uniquely identify the entry.

A Foreign Key (FK) $\mathcal{F}$ of relation $\mathcal{R}$ is a subset of attributes $\mathcal{F} \subset \text{SCH}(\mathcal{R})$ that are not member of a PK, i.e., $\mathcal{F} \cap \mathcal{P} = \emptyset$, but reference the PK of $\mathcal{R}$ or some other relation R^*. FK can be used to model relationships between relations. Using Example 3.2, the artist that created a painting is referenced through a FK $\overline{\mathcal{A}}_{\texttt{artist}}$ in $\mathcal{R}_{\texttt{painting}}$ that references the PK $\mathcal{A}^*{}_{\texttt{artist}}$ in $\mathcal{R}_{\texttt{artist}}$.

An example of relations with primary and foreign key attributes is given in Example 3.2. PKs and FKs are indicated with star and overline respectively. Note, that we assume here that people (artists) and paintings are uniquely identified by their first and lastname and their title respectively, which is obviously a simplification. In reald-world applications, often artificial PKs are being generated to avoid unintended collisions. Furthermore, it is typically the task of the DBMS to guarantee entity and referential integrity as part of keeping the data consistent.

Example 3.2   Relations with Primary and Foreign Keys

The following tables lists the schema and extent of $\mathcal{R}_{\texttt{paintings}}$ and $\mathcal{R}_{\texttt{artists}}$.

$\mathcal{R}_{\texttt{painting}}$	$\mathcal{A}^*_{\texttt{title}}$	$\overline{\mathcal{A}}_{\texttt{artist}}$	$\mathcal{A}_{\texttt{painted}}$
t_1	Mona Lisa	Leonardo da Vinci	1506
t_2	The Starry Night	Vincent van Gogh	1889
t_3	Las Meninas	Diego Velázquez	1665

$\mathcal{R}_{\texttt{artist}}$	$\mathcal{A}^*_{\texttt{artist}}$	$\mathcal{A}_{\texttt{birth}}$	$\mathcal{A}_{\texttt{death}}$
t_1	Leonardo da Vinci	1452	1519
t_2	Vincent van Gogh	1853	1890
t_3	Diego Velázquez	1599	1660

Given the notion of primary and foreign keys, Codd proposed a series of *normal forms* that are an indication of the quality of a data model based on the functional dependency of the attributes on a PK. The basic idea is to avoid redundancy by normalization, i.e., by putting data that belongs together into dedicated relations and modeling relationships between them using foreign keys. The first three normal forms are as follows:

First Normal Form (1NF) requires, that no attribute in a relation has other relations as values, i.e., attributes are atomic and instead, relationships can be established by means of FKs. Given $\mathcal{R}_{\texttt{painting}}$ in Example 3.2, this means that $\mathcal{R}_{\texttt{artist}}$ cannot be stored as an attribute of $\mathcal{R}_{\texttt{painting}}$ (which would be possible according to Definition 3.1, since data domains can hold any type of element) and instead requires a dedicated relation.

Second Normal Form (2NF) requires, that every non-prime attribute is functionally determined by the whole primary key and not any subset thereof. Given $\mathcal{R}_{\texttt{artist}}$ in Example 3.2 and assuming that $\mathcal{A}^*_{\texttt{artist}}$ was split into two attributes $\mathcal{A}^*_{\texttt{firstname}}$ and $\mathcal{A}^*_{\texttt{lastname}}$ (composite key), this means that all of the non-prime attributes must be determined by $\mathcal{A}^*_{\texttt{firstname}}$ and $\mathcal{A}^*_{\texttt{lastname}}$ jointly, i.e., the full name, and not just either $\mathcal{A}^*_{\texttt{firstname}}$ or $\mathcal{A}^*_{\texttt{lastname}}$.

Third Normal Form (3NF) requires, that every non-prime attribute is functionally determined solely by the primary key and that they do not depend on any other attribute. Given $\mathcal{R}_{\texttt{artist}}$ in Example 3.2, this means that all of the non-prime attributes must be determined by $\mathcal{A}^*_{\texttt{artist}}$ alone.

All the normal forms build onto one another, i.e., for a data model to be considered 3NF is also required to satisfy 2NF and 1NF[2]. Additional normal forms up to *6NF* and the Boyce–Codd Normal Form (BCNF), a slightly stronger version of 3NF, have been defined. For the sake of brevity, we will ommit those since they are not relevant for the discussion ahead.

3.2.2 Relational Algebra

Having introduced the aspect of data representation and constraints, we can now move to that of operations that can be performed on the data upon querying. For that purpose, [Cod70] proposed the idea of a *relational algebra*, which follows a simple yet powerful idea: All query operations performed on relations are expressed by a set of *relational operators* that take one or multiple relations as input and output a new relation as expressed by Equation (3.1).

$$\text{OP} : \mathcal{R}_1, \ldots, \mathcal{R}_n \to \mathcal{R}_O \tag{3.1}$$

Those relational operators can then be composed to express a query of arbitrary complexity as indicated by Equation (3.2).

$$\text{QUERY} = \text{OP}_1 \circ \text{OP}_2, \ldots, \circ \text{OP}_m \tag{3.2}$$

In addition to this idea, Codd proposed a minimal set of relational operators listed in Table 3.1 and explained in the following sections. For the sake of completeness, it must be mentioned that notation and operators may slightly differ depending on the literature. We mainly use [GUW09] as our reference, with a few adjustments of our own for the sake of internal consistency.

3.2.2.1 Simple Set Operations

Since relations are in essence sets of tuples, all basic operations known from set theory can be applied, namely *union*, *intersection* and *difference*, with the only constraint that the two input relations $\mathcal{R}_L, \mathcal{R}_R$ must be *union compatible* and thus exhibit the same attributes, i.e., $\text{SCH}(\mathcal{R}_L) = \text{SCH}(\mathcal{R}_R)$.

The set union $\mathcal{R}_L \cup \mathcal{R}_R$ generates a new relation of all tuples contained in either $\mathcal{R}_L$ OR $\mathcal{R}_R$, as expressed by Equation (3.3). Due to relations being sets, duplicates resulting from a union operation are *implictly* eliminated.

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[2] This has led to the mnemonic *"The key, the whole key, and nothing but the key, So help me Codd."* in reference to a similarly structured oath often used in courts of law.

Table 3.1   The relational operators proposed by Codd et al. [Cod70; GUW09].

Name	Symbol	Arity	Example
Union	$\cup$	2	Set union of two input relations.
Intersection	$\cap$	2	Set intersection of two input relations.
Difference	$\setminus$	2	Set difference of two input relations.
Cartesian Product	$\times$	2	Pairs each tuple from one the left with every tuple of the right input relation and concatenates them.
Rename	$\rho_{\mathcal{A}_A \to \mathcal{A}_B}$	1	Renames attribute $\mathcal{A}_A$ in input relation to $\mathcal{A}_B$.
Selection	$\sigma_{\mathcal{P}}$	1	Removes tuples from the input relation that don't match predicate $\mathcal{P}$.
Projection	π_{χ}	1	Removes attributes from the input relation that are not included in χ.
Natural join	$\bowtie_{\mathcal{P}}$	2	Pairs each tuple from the left with every tuple of the right input relation if their shared attributes match and concatenates them.

$$\mathcal{R}_L \cup \mathcal{R}_R = \{t : t \in \mathcal{R}_L \vee t \in \mathcal{R}_R\} \tag{3.3}$$

The intersection $\mathcal{R}_L \cap \mathcal{R}_R$ generates a new relation of all tuples contained in $\mathcal{R}_L$ AND $\mathcal{R}_R$, as expressed by Equation (3.4).

$$\mathcal{R}_L \cap \mathcal{R}_R = \{t : t \in \mathcal{R}_L \wedge t \in \mathcal{R}_R\} \tag{3.4}$$

The difference $\mathcal{R}_L \setminus \mathcal{R}_R$ generates a new relation of all tuples contained in $\mathcal{R}_L$ AND NOT in $\mathcal{R}_R$, as expressed by Equation (3.5).

$$\mathcal{R}_L \setminus \mathcal{R}_R = \{t : t \in \mathcal{R}_L \wedge t \notin \mathcal{R}_R\} \tag{3.5}$$

These basic set operations simply combine two input relations without changing its structure, i.e., $\text{SCH}(R_L) = \text{SCH}(R_R) = \text{SCH}(R_O)$.

3.2.2.2   Cartesian Product

The binary, *cartesian product* or *cross product* $\mathcal{R}_L \times \mathcal{R}_R$ of two input relations $\mathcal{R}_L, \mathcal{R}_R$ concatenates every tuple $t_L \in \mathcal{R}_L$ with every tuple $t_R \in \mathcal{R}_R$ to form a new output tuple, as expressed by Equation (3.6).

$$\mathcal{R}_L \times \mathcal{R}_R = \{(t_L, t_R) : t_L \in \mathcal{R}_L \wedge t_R \in \mathcal{R}_R\} \tag{3.6}$$

The result is a relation that contains all the attributes of $\mathcal{R}_L$ and $\mathcal{R}_R$, i.e., $\text{SCH}(\mathcal{R}_L \times \mathcal{R}_R) = \text{SCH}(\mathcal{R}_L) \cup \text{SCH}(\mathcal{R}_R)$ and every possible permutation of tuples from the input relations.

3.2.2.3 Rename

The unary *rename* operator $\rho_{\mathcal{A}_A \to \mathcal{A}_B}(\mathcal{R})$ renames the attribute $\mathcal{A}_A$ to $\mathcal{A}_B$ without changing any value. This can be useful to elliminate collisions before applying the cartesian product or to enable a natural join on differently named attributes.

3.2.2.4 Selection

The unary, generalized *selection* operator $\sigma_\phi(\mathcal{R})$ applied on an input relation $\mathcal{R}$ creates an output relation that contains a subset of tuples $t \in \mathcal{R}$ such that only tuples that match the predicate ϕ are retained as expressed by Equation (3.7).

$$\sigma_\phi(\mathcal{R}) = \{t \in \mathcal{R} : \phi(t)\} \subset \mathcal{R} \tag{3.7}$$

The predicate ϕ can be any conditional statement consisting of individual atoms that involve attributes of $\mathcal{R}$ or any constant value and comparison operators $=, \neq, >, <, \geq, \leq$. Individual atoms can also be combined by logical operators $\wedge, \vee$ or $\neg$. Examples could be $\mathcal{A}_1 \geq 2$, $\mathcal{A}_2 = \mathcal{A}_3$ or $\mathcal{A}_1 \geq 2 \wedge \mathcal{A}_2 = \mathcal{A}_3$ to express that an attribute should be greater than a constant, equal to another attribute or combine the two with $A_1, A_2, A_3 \in \text{SCH}(\mathcal{R})$.

3.2.2.5 Projection

The unary *projection* operator $\pi_\chi(\mathcal{R})$ with $\chi \subset \text{SCH}(\mathcal{R})$ applied on an input relation $\mathcal{R}$ creates an output relation that only contains the attributes listed in χ, i.e., $\text{SCH}(\pi_\chi(\mathcal{R})) = \chi$, as expressed by Equation (3.8).

$$\pi_\chi(\mathcal{R}) = \{t\,[\chi] : t \in \mathcal{R}\} \text{ with } t\,[\chi] = \{t[\mathcal{A}] : \mathcal{A} \in \chi\} \tag{3.8}$$

All the tuples in $\mathcal{R}$ are retained, however, resulting duplicates are removed.

3.2.2.6 Natural Join

The binary, *natural join* operator $\mathcal{R}_L \bowtie \mathcal{R}_R$ on two input relations $\mathcal{R}_L, \mathcal{R}_R$ concatenates every tuple $t_L \in \mathcal{R}_L$ with every tuple $t_R \in \mathcal{R}_R$ to form a new output tuple, if the attribute values of t_L and t_R are the same for the shared attribues $\xi = \{\mathcal{A} : \mathcal{A} \in \text{SCH}(\mathcal{R}_L) \wedge \mathcal{A} \in \text{SCH}(\mathcal{R}_R)\}$ as expressed by Equation (3.9)

$$\mathcal{R}_L \bowtie \mathcal{R}_R = \{t_L \cup t_R : t_L \in \mathcal{R}_L \wedge t_R \in \mathcal{R}_R \wedge t_L\,[\xi] = t_R\,[\xi]\} \tag{3.9}$$

The result is a relation that contains all the attributes of $\mathcal{R}_L$ and $\mathcal{R}_R$, i.e., $\text{SCH}(\mathcal{R}_L \bowtie \mathcal{R}_R) = \text{SCH}(\mathcal{R}_L) \cup \text{SCH}(\mathcal{R}_R)$. Shared attributes are only retained once.

3.2.2.7 Expressing Queries

The following Example 3.3 illustrates how relational operators can be combined to form complex queries. Since expressing queries in such a way is quite inconvenient, in practice, queries are usually formulated in a human-readable query language, which is then translated to the relational operators. A famous example of such a language is SQL [Cha12] for relational databases.

Example 3.3   Searching for Paintings Using Relational Algebra

The following tables lists the schema and extent of $\mathcal{R}_{\texttt{paintings}}$ and $\mathcal{R}_{\texttt{artists}}$.

$\mathcal{R}_{\texttt{painting}}$	$\mathcal{A}^{*}_{\texttt{title}}$	$\overline{\mathcal{A}}_{\texttt{artist}}$	$\mathcal{A}_{\texttt{painted}}$
t_1	Mona Lisa	Leonardo da Vinci	1506
t_2	The Starry Night	Vincent van Gogh	1889
t_3	Las Meninas	Diego Velázquez	1665

$\mathcal{R}_{\texttt{artist}}$	$\mathcal{A}^{*}_{\texttt{artist}}$	$\mathcal{A}_{\texttt{birth}}$	$\mathcal{A}_{\texttt{death}}$
t_1	Leonardo da Vinci	1452	1519
t_2	Vincent van Gogh	1853	1890
t_3	Diego Velázquez	1599	1660

Using relational algebra, the query "return the names of all paintings that were painted by an artist who died after 1800" can be expressed by joining $\mathcal{R}_{\texttt{paintings}}$ and $\mathcal{R}_{\texttt{artists}}$, followed by a selection and projection:

$$\mathcal{R}_{\texttt{result}} = \pi_{\mathcal{A}_{\texttt{title}}}(\sigma_{\mathcal{A}_{\texttt{death}} \geq 1800}(\mathcal{R}_{\texttt{paintings}} \bowtie \mathcal{R}_{\texttt{artists}}))$$

This query produces the relation $\mathcal{R}_{\texttt{result}}$ that contains t_2 of $\mathcal{R}_{\texttt{paintings}}$.

3.2.3 Extensions

While the relational model and its algebra forms the foundation of many modern DBMS, the model as originally proposed by Codd has often turned out to be too limited to accomodate certain functionality as required, e.g., by the ANSI SQL standard [Lib03; Xopb]. For example, many applications require storage of duplicate data and therefore, the notion of a relation – which is a set of tuples and thus does not allow for duplicates – is inadequate. Another example could be the support for sorting or aggregation (ORDER BY and GROUP BY in SQL), which also isn't covered by the original algebra.

Over the years, this has led to a growing list of proposals for extensions, some of which have seen adoption while a majority has remained theoretical in nature. In the following sections, we will introduce a few examples. While at a first glance, these adaptions seem to be an elegant way of extending the expressiveness of the relational data model, there are important implications: Most importantly, some operators may not behave in the way specified in Section 3.2.2 or we may require additional or different operators to accomodate all the functionality needed. This adds complexity to the DBMS, especially when considering aspects such as query planning.

3.2.3.1 Relations vs. Bags vs. Sequences

The motivation for considering other mathematical structures than sets as an algebraic foundation for a data model are twofold: Firstly, relations are unable to provide functionality that may be desirable in a DBMS, such as duplicate entries or explicit ordering of tuples. Secondly, some of the mathematical convenience of the relational model, e.g., prohibiting duplicates, may be inefficient to actually implement [GUW09]. It is therefore not surprising that ANSI SQL [Xopb] formally operates on *bags* rather than sets, which allow for duplicate entries [GUW09; Cha12]. If one would want to express explicit ordering of tuples, we could even have to move to sequences, in which every tuple occupies a specific position.

We will not elaborate on all the consequences such a transition may have and refer to [GUW09], which discusses this issue in great detail. However, for illustrative purposes, we still provide the Example 3.4 inspired by [GUW09]. It demonstrates that even minor changes to the properties of the purely relational data model must be taken into account when implementing systems, e.g., during algebraic query optimisation.

Example 3.4   Searching for Paintings Using SQL

The following tables list the schema and extent of $\mathcal{R}_{p1}$ and $\mathcal{R}_{p2}$, which are union compatible and have one tuple in common (t_1).

$\mathcal{R}_{p1}$	$\mathcal{A}^*_{\texttt{title}}$	$\overline{\mathcal{A}}_{\texttt{artist}}$	$\mathcal{A}_{\texttt{painted}}$
t_1	Mona Lisa	Leonardo da Vinci	1506
t_2	The Starry Night	Vincent van Gogh	1889
t_3	Las Meninas	Diego Velázquez	1665

$\mathcal{R}_{\text{p2}}$	$\mathcal{A}^*_{\text{title}}$	$\overline{\mathcal{A}}_{\text{artist}}$	$\mathcal{A}_{\text{painted}}$
t_1	Mona Lisa	Leonardo da Vinci	1506
t_2	The Birth of Venus	Sandro Botticelli	1485
t_3	The Night Watch	Rembrandt Harmenszoon van Rijn	1642

If now consider the union operation, i.e., $\mathcal{R}_p = \mathcal{R}_{\text{p1}} \cup \mathcal{R}_{\text{p2}}$, we will see, that for ordinary relations, $|\mathcal{R}_p| = 5$, whereas for bags, $|\mathcal{R}_p| = 6$, since since the common tuple will appear twice.

Now let us further consider the set difference and the distributive law with union, i.e., $(\mathcal{R}_{\text{p1}} \cup \mathcal{R}_{\text{p2}}) \setminus \mathcal{R}_{\text{p1}} = (\mathcal{R}_{\text{p1}} \setminus \mathcal{R}_{\text{p1}}) \cup (\mathcal{R}_{\text{p2}} \setminus \mathcal{R}_{\text{p1}})$. We can easily see, that this identity holds for sets but not for bags, since $|(\mathcal{R}_{\text{p1}} \setminus \mathcal{R}_{\text{p1}}) \cup (\mathcal{R}_{\text{p2}} \setminus \mathcal{R}_{\text{p1}})| = 2$ wheras $|(\mathcal{R}_{\text{p1}} \cup \mathcal{R}_{\text{p2}}) \setminus \mathcal{R}_{\text{p1}}| = 3$, since one of the duplicates will be retained.

3.2.3.2 Extended Projection

The extended project as described by [GUW09] is an addition to the projection operator π_χ specified in the relational data model and necessitated by the ANSI SQL standard [Xopb]. It involves a more general definition of χ, that can now contain any of the following elements for a relation $\mathcal{R}$ [3]: (i) any attribute $\mathcal{A} \in \text{SCH}(\mathcal{R})$, (ii) any literal value $\mathcal{L} \in \mathcal{D}_\mathcal{L}$, with $\mathcal{D}_\mathcal{L} \in \mathbb{D}$ or, (iii) any N-ary function expression $\mathcal{E} \colon \mathcal{G}_1 \times, \ldots, \times \mathcal{G}_A \to \mathcal{A}_{\text{out}}$ with $\mathcal{G}_j$ being either an attribute $\mathcal{A}_i \in \text{SCH}(\mathcal{R})$ or a literal $\mathcal{L}_j \in \mathcal{D}_\mathcal{L}$.

Therefore, in addition to projecting on existing attributes, the extended projection can be used to project onto literal values and arbitrary function expressions, thus appending new attributes to a relation. This is a very powerful extension, because it enables the generation of new values based on existing ones. A lot of DBMS also allow users to define their own Used Defined Function (UDF).

3.2.3.3 Aggregation

Aggregation is the act of summarizing certain attribute values based on the membership of a tuple in a specific category or group, which is established based on other attribute values. An example could be a customer who would like to see the maximum price of all products per brand. The ANSI SQL standard [Xopb] defines the `GROUP BY` operator for this purpose.

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[3] We deliberately deviate from [GUW09] in that we don't limit ourselves to algebraic expressions and special functions.

[GUW09] formalises the grouping operator γ_G, which can be used to aggregate on attributes in $\mathcal{R}$. G is a list of elements, which can either be: (i) any attribute $\mathcal{A} \in \text{SCH}(\mathcal{R})$, the attribute(s) that the operator aggregates by or, (ii) any aggregation or set function $\text{AGR}: \mathcal{A} \rightarrow \mathcal{A}_{\text{out}}$

The output relation $\gamma_G(\mathcal{R})$ is then constructed as follows: First, the tuples in the input relation $\mathcal{R}$ are grouped into N groups $\mathcal{G}_1, \dots, \mathcal{G}_N \subset \mathcal{R}$ based on the values in the specified grouping attribute(s). Subsequently, the aggregation function is executed for all tuples in each group, giving rise to an output relation that contains N tuples – one per group – each bearing the grouping attributes as well as the ouput of the set functions. The ANSI SQL standard [Xopb] defines a list of supported set functions including but not limited to functions such as COUNT, MIN, MAX, SUM and MEAN.

3.2.3.4 Sorting and Ranking

Sorting is the act of arranging items in a specific order based on their attribute values. Consider, for example, a customer who wants to look at prices of products from lowest to highest. The ANSI SQL standard [Xopb] defines the ORDER BY operator for this purpose.

However, formally, the act of sorting is difficult in the context of "pure" relational algebra because neither sets nor bags exhibit any ordering. [GUW09] proposes the τ_T operator to make this operation explicit. Given a relation $\mathcal{R}$, T is simply a list of attributes to sort on, i.e., $T \subset \text{SCH}(\mathcal{R})$ and the result $\tau_T(\mathcal{R})$ is a sorted list of values. The conversion between set, bag and list takes place implicitly through application of the operator and the consequences for the algebra are not addressed.

More formal approaches to sorting were proposed, e.g., by [RDR+98] who introduced four additional operators and a *sequence algebra* that can deal with ordered queries. Similarly, [LCI+05] proposes a more systematik approach to *ranking*, which is sorting based on an external function. They introduce the idea of a *rank relation*, which carries explicit properties w.r.t to the ranking applied.
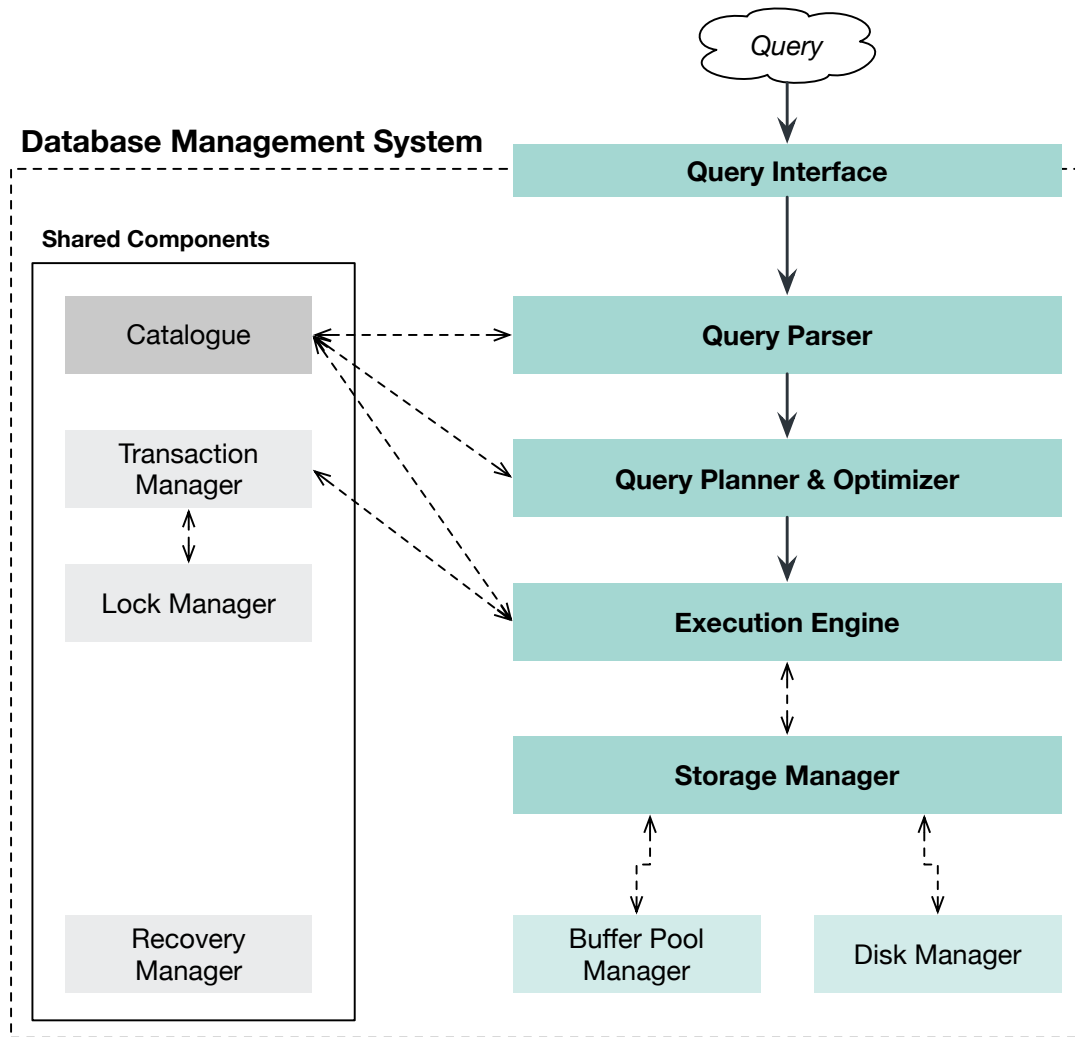
Figure 3.2   The general architecture of a DBMS and its individual components.

3.3   Database Management System (DBMS)

Irrespective of the concrete system and data model, DBMS generally exhibit an internal structure that is very similar [Pet19; HSH07] even though, specifics may vary widely between implementations. This overall structure is depicted in Figure 3.2 and in this section we use the path a query[4] takes within the system, as indicated by the directed, red arrows, to illustrate the components involved.

3.3.1   Query Interface

The query interface is the DBMS's channel to the outside world and enables its use by other systems. The query interface takes care of client connections, accepts and forwards queries for processing and returns results to the caller.

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[4] Henceforth, the term "query" refers to any DDL, DML or DQL expression.

Queries accepted by the query interface are usually expressed in a specific query language – which are often designed for human users and therefore human-readable. We have already mentioned SQL [Cha12] as the most prominent example of such a query language, which can be used to express queries using a declarative, textual syntax (see Example 3.5). In addition to SQL, there also exist other, domain-specific languages such as SPARQL [PAG09] to query Resource Description Framework (RDF) data, *Cypher* to query labeled property graphs [FGG⁺18] found in graph databases such as *Neo4j* [5] or the document-oriented query language used by *MongoDB* [6].

Example 3.5   Searching for Paintings Using SQL

Again using the relations $\mathcal{R}_{\texttt{paintings}}$ and $\mathcal{R}_{\texttt{artists}}$ from Example 3.3, the query "return the names of all paintings that were painted by an artist who died after 1800" can be expressed in SQL as follows [Gra93]:

```
1        select * from paintings natural join artists
             where artist.death > 1800
```

The `select` clause expresses the projection π to all attributes (*), the `natural join` clause expresses the natural join $\bowtie$ between `paintings` and `artist` and the `where` clause expresses the selection σ to tuples whose `artist.death` attribute is greater than 1800.

Early attempts at a client-facing standardisation of the query interface for SQL-based systems led to the inception of the Call Level Interface (CLI) standard [Xopa], which in its early version enabled embedding of SQL commands into C or Cobol programms. The CLI standard was later complemented by Open Database Connectivity (ODBC) and Java Database Connectivity (JDBC), which provide database connectivity to a wide range of SQL and NoSQL systems. In addition, most of the SQL (e.g., MySQL, PostgreSQL, MS-SQL, Oracle) and NoSQL (e.g., MongoDB, Neo4j, Redis) provide database specific and therefore un-standardised connectivity thorugh a plethora of client libraries that are maintained for different platforms and programming environments by either companies and / or open source contributors.

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[5] https://neo4j.com/
[6] https://www.mongodb.com/
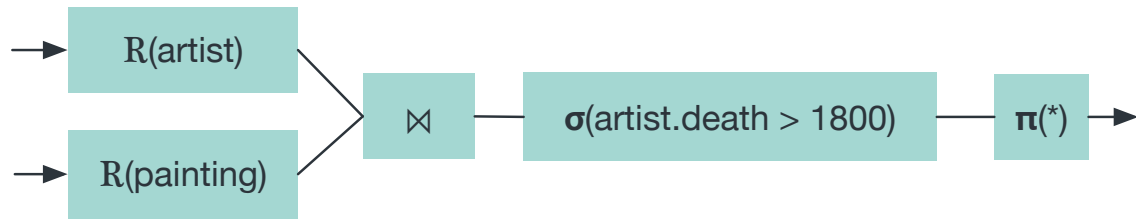
Figure 3.3 **The query from Example 3.5 represented as a tree of relational operators also called a logical query execution plan. By convention, the tree is executed and read from left to right (bottom to top) and information flows from the leafs to the root.**

3.3.2 Query Parser

The query parser's main task is to transform a query provided in a human-readable query language to a logical representation that can be processed by a DBMS. This often involves a conversion of a syntax to the operators specified by the data model, e.g., a tree of the relational operators that represent an SQL query as illustrated in Figure 3.3, for example. The result is what is generally called a *logical query (execution) plan*, since it outlines all the operations necessary to generate the desired results without, however, specifying concrete access methods or algorithms.

Practically, query parsing involves several steps [Gra93; GUW09]: First, the syntax of the textual query must be analysed and converted to a data structure that can be processed. Very often, Abstract Syntax Tree (AST)'s or *parse trees* based on formal grammars of the query language, and libraries such as *ANTLR*[7] are employed in this step. Subsequently, the leaf-nodes in the AST must be mapped to Database Object (DBO)'s contained in the DBMS in a step called preprocessig. This involves lookups in the *catalogue* – a data structure that lists a DBMS' units of data organisation. For a relational database, for example, the catalogue would contain named tables, columns and indexes. And finally, the nodes in the AST must be converted to an internal representation that matches the data model, e.g., a tree of relational operators. This conversion step may also involve basic sanity checks, e.g., for type compatibility or the existence of requested DBOs. Certain optimisations can also be employed, e.g., simplifying trivial identities such as $1 = 1$ (which is always true) or $0 \geq 1$ (which is always false). If we take the query from Example 3.5, the logical query plan would look as illustrated in Figure 3.3.

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[7] https://www.antlr.org/

3.3.3   Query Planner & Optimizer

A query planner tries to transform the logical query plan produced by the parser to a physical plan in a way that allows for efficient and effective query execution, e.g., in terms of minimal execution time or resource usage [JK84; GUW09]. Despite being a central task of every DBMS and a huge body of research, there are only very few, comprehensive surveys and overviews of established techniques [JK84; Gra93; Cha98]. This has been pointed as early as 1984 and one of the reasons identified is that query optimisation is achived "by integrating a large number of techniques and strategies, ranging from logical transformations of queries to the optimization of access paths and the storage of data on the file system level" [JK84]. Consequently, many of the techniques are very specific to a concrete DBMS implementation and the underlying data and execution model.

Example 3.6   Implementation of a `JOIN` **between two relations.**

Let $\mathcal{R}_{paintings}$ and $\mathcal{R}_{artists}$ be the two relations from Example 3.5 with $N = |\mathcal{R}_{artists}|$, $M = |\mathcal{R}_{paintings}|$ and $N < M$. The `JOIN` between the two relations, i.e., $\mathcal{R}_{artist} \bowtie \mathcal{R}_{paintings}$ can be implemented by the following algorithms [Gra93]:

Nested-Loop Join The nested loop join iterates over all elements in the smaller relation, i.e., $\mathcal{R}_{artists}$ and tries to find matching entries in the larger relation, i.e., $\mathcal{R}_{paintings}$ for every element. If $\mathcal{R}_{paintings}$ exhibited an index on the join column, that index could be used for lookup. Otherwise, a full scan of $\mathcal{R}_{paintings}$ must be performed for every element in $\mathcal{R}_{artists}$. Therefore, computational complexity ranges between $O(N \log M)$ and $O(NM)$.

Hash Join The hash join algorithm builds-up a hash-table for one side of the `JOIN` to speed-up the lookup of join keys, hence, ommitting the inner loop of the nested-loop join. If resource consumption of building and accessing the hash-table is ignored, the computational complexity becomes $O(N + M)$. However, typically building the hash-table is accompanied by a non-negligible cost, especially, if it does not fit into main memory.

Sort-Merge Join The sort-merge join can only be used if $\mathcal{R}_{artists}$ and $\mathcal{R}_{paintings}$ were sorted by the join key (i.e., the name of the artist) and if the comparison operator checks for equality between the two keys. Given this pre-condition, the join can be realised in a single loop that collects the entries for distinct values of the join keys, i.e., computational complexity is $O(N + M)$, if we assume that the relations come pre-sorted.
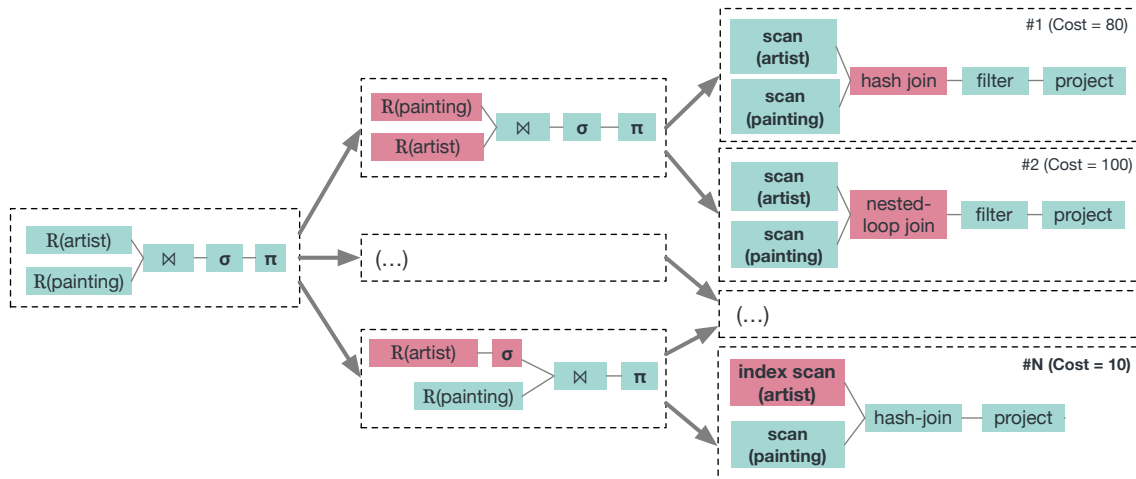
Figure 3.4 **Cost-based query planning in a DBMS based on Example 3.5. A logical input plan is transformed into different, equivalent versions and the most cost-efficient is selected.**

Over the years, two strategies at optimising a query have emerged: bottom-up and top-down [JK84]. Early research focused on bottom-up approaches wherein individual operators and special edge-cases were studied and optimised. This turned out to be important, foundational work since at the lowest level, query optimisation can obviously be achieved by employing efficient algorithms. Example 3.6 tries to demonstrate this using possible implementations of a JOIN between two relations.

However, as queries became more complex, bottom-up optimisation started to reach its limits, especially in terms of generalisability. If we turn to Example 3.6, we will realise that the optimal path of execution does not only depend on the choice of JOIN algorithm but also on the join order, the presence or absence of indexes and the estimated size of intermediate data structures and thus the size of the relations themselves. If now, in addition, we consider queries that involve multiple JOINs, we must acknowledge that these metrics may differ for every combination of relation, i.e., there may not be a single, optimal choice of algorithm. Consequently, some attention has shifted towards top-down approaches that focused on holistic optimisation of the entire query plan.

Early top-down approaches tried to focus on heuristic methods [JK84]. However, the System-R paper [SAC+79] published in 1979 established the idea of *cost-based query optimisation* as a gold standard for DBMS. A cost-based query planner enumerates physical plans that employ different strategies and selects the one that minimises the estimated cost. Those costs may involve computation (time used on a CPU), storage access (data accessed on disk) or transmission (data transfered between nodes) required by a query [JK84; GUW09]. Which of

those metrics are used is highly dependent on the system: In the not too distant past before the invention of Solid State Drive (SSD), access to secondary storage was considered to be the defining cost and thus the main focus was to minimize disk access [GUW09]. However, for distributed databases, the moving of data between nodes has become an important factor to consider as well [BJZ13].

The general approach at doing cost-based query optimisation is illustrated in Figure 3.4. It relies on an internal representation of the query, e.g., the logical plan illustrated in Figure 3.3 and can be summarised as follows [JK84; GM93] [8]:

1. Transformation of the logical input plan to either simplify it or to replace parts that can be covered by a specific edge-cases. This results in different, alternative logical query plans.

2. Mapping the transformed, logical query plans into sequences of elementary operations with known costs by selecting specific algorithms or access patterns. This results in a (potentially larger) set of physical query plans.

3. Estimate the total cost for the physical query plans and select the one that minimises those costs.

Each of the aformentioned steps involve sub-steps that apply algebraic equivalence rules [GUW09] (e.g., commutativity of operations), heuristics [GUW09; Gra93; Swa89; BGJ10; TSF+12] (e.g., predicate pushdown) or special rules to handle certain (edge-)cases [JK84; Gra93] (e.g., replace table by index scan).

A critical factor for any cost-based query optimizer is the model used for cost and cardinality estimation [JK84; YHM15]. Most existing systems rely on statistical modeling based on the data stored in the database [GTK01; Ioa03] as well as model for cost incurred by accessing system resources [MBK02]. Simple statistics involve information about the number of entries in a relation or statistical moments of columns but may also rely on more complex analysis of data distribution such as histograms. This pre-hoc modeling was later complemented by taking the atained execution speed into account, which requires post-hoc analysis of an execution plan w.r.t to the cost model and created a continuous control loop between planner and execution engine [ML86]. Recent work in the field of query planning also tries to apply machine learning techniques at different levels of the cost-estimation and planning process [WCZ+13; Vu19].

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[8] The *Volcano Optimizer Generator* [GM93] still builds the theoretical foundation for modern systems such as *Apache Calcite*.

3.3.4 Execution Engine

Once a query execution plan has been selected, the execution of that plan falls to the DBMS's execution engine. At a high level, every operator in the plan is typically mapped to an actual operator in a query execution pipeline that performs the necessary operations, e.g., executes a scan of a table or a specific `JOIN` algorithm. This is visualised in Figure 3.5. In the resulting *operator tree*, every operator functions independently, reads input, processes it and produces output that is then handed to the next operator in the tree (or to the client).

While this model is simple enough, there are a few subtle differences in how this can be implemented by a system. First, there is a distinction as to how data is being handed from operator to operator:

Iterator Model This is the model described in [GM93; Gra93] and implemented in the Cascades [Gra95] framework. In this model, every operator reads a single tuple, processes it and hands it to the next operator in the pipeline. Therefore, tuples are iterated one by one and handed from the leafs to the root of the operator tree.

Materialization Model In this model, every operator reads all tuples from the input, performs its work and then forwards the entire output to the next operator in one go. This requires potentially large buffers to store intermediate results.

Batch Model In this model, every operator reads a specific number of tuples from it inputs (a batch), processes these tuples and then forwards the batched results to the next operator. Therefore, data is processed batch by batch.

It must be mentioned, that even in the iterator model, some operators require intermediate materialisation (e.g., sort operators). In addition, we can distinguish between which operator initiates data exchange:

Pull-based Operators higher-up in the operator tree request the next item from the previous operator. This is the common model for disk-based systems and leads to the slowest operator in the pipeline determining execution speed.

Push-based Operators lower in the operator tree send their results to the next operator, which has to buffer if it is not ready to process. While potentially more efficient, this requires a buffering infrastructure.
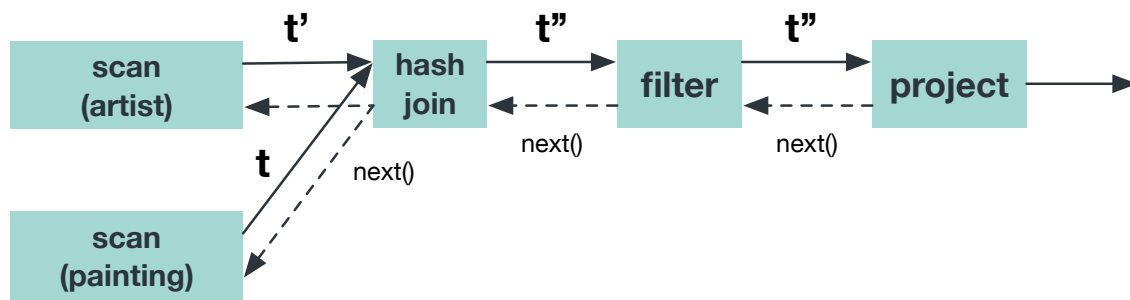
Figure 3.5 **Illustration of the iterator model for query listed in Example 3.5. Every operator calls the upstream operator with `next()` to request the next tuple for processing.**

The pull-based iterator model is very easy to implement, since basically, every operator just needs to implement a `next()` method that returns the next tuple (and `open()` and `close()` methods to signal start and end). The model is illustrated in Figure 3.5. It is probably the most common processing model found in disk-based DBMS, even though, it has downsides such a poor instruction locality and overhead due to the large number of method calls [NL14]. The materialization model can be beneficial for small datasets and OLTP queries. However, it is not a good fit for analytical workloads on large datasets, especially, if main memory is limited. The batch model is something in between the previous two and can be very when using vectorised processing and SIMD instructions such as those provided by the AVX or SSE extensions. It is thus often employed in analytical databases such as MonetDB [IGN+12].

3.3.4.1 Query Parallelism

With most computing platforms offering multiple CPUs or CPU cores, parallel execution of queries can provide a considerable speed-up in terms of execution time. [Gra93] distinguishes between three types of parallelism in a DBMS:

Inter-query parallelism refers to the parallel execution of different, independent queries (potentially from different users). At a high level, there are two approaches at achieving inter-query parallelism, namely, by mapping different queries to different system processes (e.g., PostgreSQL) or to different threads within the same process (e.g., MySQL), with the advantage of the latter being that all queries share the same memory address space.

Inter-operator parallelism refers to the parallel execution of different operators within a query, which are then synchronised by a dedicated operator that merges the results. This is a form of *intra-query parallelism*.

Intra-operator parallelism refers to the splitting-up of the work performed by a specific operator. This typically involves the ability to parallelise based on the data, e.g., by partitioning on it and letting different operators taking care of parts of the workload. This is also a form of *intra-query parallelism*.

All three aspect must be handled by the query execution engine (and other component involved) and give rise to a large number of implementation details that must be considered when building a DBMS. For example, the challenges that arise from parallel query execution and the resulting, concurrent data access – especially in the presence of parallel reads and writes – are covered by the *isolation* part of ACID and typically mitigated by a *transaction manager* and *concurrency control protocols*.

3.3.4.2   Optimising Execution Speed

Speeding-up query execution has been a large corpus of research at different levels and has given rise to many relevant solutions. We have already mentioned the use of specialised CPU instructions such as AVX or SSE, which is an active area of research [IGN+12; PR20; PR19; SXJ21] even to the extent, that workloads are executed on a GPU instead of a CPU [PLH+21].

An other approach used to minimise the overhead incurred by the iterator model is compilation as implemented by HyPer [NL14], which is also an active area of research [KVH21; FT21]. This technique tries to compile parts of the execution plan directly into machine code, i.e., merging multiple operators into one, which increases instruction locality and allows for caching and later re-use of pre-compiled elements. The method can also be combined with vectorised execution [SZB11; RBM22].

3.3.5   Storage Manager

At the lowest levels of any DBMS there is the storage manager, which orchestrates access to data on primary and secondary storage devices. Many different approaches at storage have been implemented over the years and we will simply focus on some basic concepts and refer to [Pet19] for more information on the topic. What most DBMS have in common is that they implement a two-level memory architecture wherin data resides on disk (which is typically slower) and in main memory (which is typically faster). The two aspects are handled by the two main components: the *disk manager* and the *buffer pool manager* [Pet19].

3.3.5.1 Disk Manager

The disk manager provides access to the files that reside on disk. Most databases organsise disk access in terms of fixed-size database pages that can be read and written. Typically, the size of a page is a fixed multiple of the block-size implemented by the underlying file system and ranges between 4 to 16 kB.

On top of this basic page structure, different types of storage can be implemented. The classical approach is to distinguish between data and index pages and to superimpose a B-Tree structure on top of the pages [BM70]. Data pages contain the actual data. Index pages are required for navigating in the data and looking up records, e.g., based on a tuple identifier. There are many implementation details to be considered, such as dealing with variable-length data, dealing with data that is larger than a page, checksumming and versioning and different techniques are being applied to address these issues.

Recent work has given rise to different types of data organisation, e.g., in systems like MonetDB where data is organised in fixes size arrays called binary association tables [BKM08] for databases using log-structured merge trees [OCG+96; SR12] such as JetBrains Xodus.

3.3.5.2 Buffer Pool Manager

The main objective of the buffer pool manager is to keep frequently accessed pages in memory for faster access. That is, if upper-levels of the DBMS require access to a given page, they request it from the buffer pool manager, which can either serve it from memory or read it from disk through the disk manager. Meanwhile, the buffer pool manager can keep track of page access and can evict or retain pages depending on usage. In addition to caching, buffer pool managers also implement different strategies for page replacement and eviction (e.g., FIFO or LRU), pre-fetching of pages depending on workloads (e.g., when scans are performed) as well as locking of pages for concurrency control.

Some DBMS, such as MonetDB [BKM08] or LMDB [Hen19], forego the implementation of a buffer pool manager and instead rely on the POSIX `mmap` system call [Sto81], which allows the mapping of files on disk into the address space of an application and leaves caching of pages to the operating system. While this simplifies handling of data because loading and eviction of pages must not be handled explicitly, research suggest that the use of `mmap` in a DBMS is far from optimal [CLP22], and that knowledge about the database workload (e.g., random access vs. scan) allows for much more finegrained control than `mmap`.

3.3.6   Common Components

The following components are also part of a DBMS and are briefly described for the sake of completeness:

Catalogue The catalogue is used to persistently store and lookup information used by DBMS to organise the data it contains, i.e., information about units of data organisation such as tables, columns, collections, indexes as well as metadata such as statistics, transactions or locks.

Transaction One or multiple queries processed by a DBMS are typically wrapped in transactions, i.e., a series of operations that should be executed together and either be committed or rolled back at the end. Often, the DBMS provides guarantees with respect to the execution of transactions such as ACID [HR83] or BASE [Pri08], e.g., assuring an all-or-nothing semantic (atomicity) for operations being executed within a transaction (the A ind ACID).

Transaction Managers In order to provide the aforementioned guarantees for a transaction, the query workloads must be orchestrated across different components (e.g., disk manager, buffer pool manager, execution engine, lock manager, recovery manager). This is the main task of the transaction manager in addition to keeping track of a transaction's lifecycle.

Lock Manager One approach to provide transaction isolation (the I in ACID), i.e., proper protection of the data in case different transactions access it concurrently, is the implementation Strict 2-Phase Locking (S2PL). This is typically provided by a lock manager, which keeps shared and exclusive locks on pages that are accessed and detects lock cycles.

Recovery Manager Typically, databases are required to provide some form of durability with respect to the execution of a transaction. Therefore, once a transaction commits, changes are expected to be permanent (the D in ACID). This is guaranteed by different techniques such as write-ahead logging which allow for data reconiliation in case of a system failure (e.g., power outage). This is the main task of the recovery manager and a famous algorithm employed here is known as ARIES [MHL+92].

Obviously, some databases feature additional system components depending on concrete applications, e.g., a distribution manager for DBMS that provide distribution of data and processing accross multiple nodes.

4

On Multimedia Analysis and Retrieval

Multimedia data is ubiquitous and used in different forms in every area of our daily lives, be it private or professional. Statista.com estimates, that the amount of data created, captured, copied, and consumed in 2025 will exceed 181 000 EB from an estimated 2000 EB in 2010[1]. To a large extent, that data is multimedia data, which is being uploaded and shared on social media and the Internet.

A key development in this regard was the broad adoption of the smartphone in the early 2000s, which enabled almost every person on this planet to not only consume but also produce multimedia content in the form of texts, images, videos and audio snippets and to share those on platforms such as Twitter, Instagram, Facebook or TicToc turning them effectively into prosumers [RJ10; RDJ12]. Fueled by this technological progress, the past few decades have seen a staggering development in both *volume* and *variety* of multimedia data found in the wild and in private data collections.

This extreme growth as well as the increasing *velocity* at which data is being produced, poses an enormous challenge for information processing, analysis and retrieval systems that deal with multimedia. Therefore, researchers have tried to tackle the questions surrounding the efficient and effective management, analysis and retrieval of multimedia data at large scales for many decades now, with first attempts reching back to the early 70s.

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[1] Source: Statista.com, "Volume of data/information created, captured, copied, and consumed worldwide from 2010 to 2025", February 2022

4.1 Multimedia Data and Multimedia Collections

The term *multimedia* refers to a combination of one or many different *media types*, such as but not limited to, aural or visual information. We distinguish between these types, based on the representation we use when working and interacting with them. Sound, for example, is formed by airpressure waves that are registered by our ears. In contrast, visual information, involves electormagnetic waves captured by our eyes. In both cases, the brain plays an important role in interpreting the underlying processes and forming the human perception of the phenomenon. Similarily, we rely on different techniques when converting these media types from their analogue to their digital representations.

Traditionally, we often think of media as information that somehow can be perceived directly by our human senses. However, we consider (multi-)media data in a wider sense, which may also include less apparent and sometimes even digitally native examples such as motion capture data or data streams stemming from sensors or medical devices.

Even though the various media types may exhibit very different characteristics in their original representation, we find some commonalities that are crucial for formalising the problem of processing and analysing such data in information processing systems in general and analytics and retrieval systems in particular (see Examples 4.1 and 4.2).

Relationship with Time At a high level, we can roughly classify all the different media types based on their relationship with time. *Static* media types (e.g., an image) do not exhibit a temporal development, whereas the information in *dynamic* media types (e.g., an audio signal) depends on the time point that is being examined [BdB+07].

Unstructured Data The digital representation of any media type is typically highly unstructured, thus, there is no natural data model that can be leveraged for analysis. For example, there is generally no apparent connection between the raw image data and the motives it depicts. Therefore, information processing systems rely on *derivative representations* of the original data, gained through pre-processing and data analysis.

Semantic Gap The derivative representations of the original data usually describe specific aspects thereof and conversion to/from such representations is therefore often accompanied by a loss of information. This is a problem often referred to as the *semantic gap* [BdB+07; Ros18].

Example 4.1   Digital Representation of Visual Information
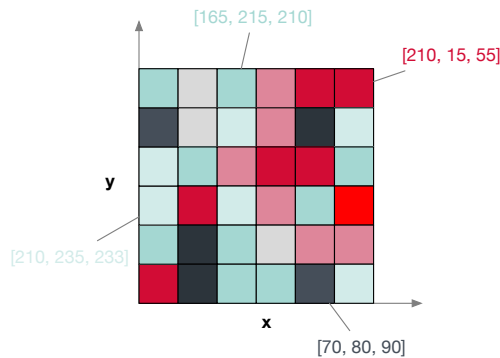
The visual information in a flat image is stored as a two dimensional array of *pixels*. The information in every pixel is typically formed by a sensor, in an array of sensors, that captures the electormagnetic signal. Each pixel holds colour values, usually one per colour channel. For example, with the RGB colour model, every pixel holds three values, one for the red, green and blue channel. The number of pixels per dimension determines the *resolution* of the image. Typically, we use a fixed number of bits per colour – the *colour depth* – which determines the number colours that can be distinguished.

If we take, for example, a coloured image of 1000×1000 pixel, we must encode 3×10^6 individual colour values. Using 8 bit per colour, we end up storing 24×10^6 bit, which amounts to 3 MB worth of uncompressed image data. Images coming from modern cameras, exhibit resolutions much higher than that.

Example 4.2   Digital Representation of Aural Information

The airpressure waves that form sound can be recorded and translated to an electrical signal by microphones. When digitizing this information, the temporal development of this signal amplitude is *sampled* at a fixed rate. Each sample point consist of a value that quantizes the amplitude's energy at a given point in time
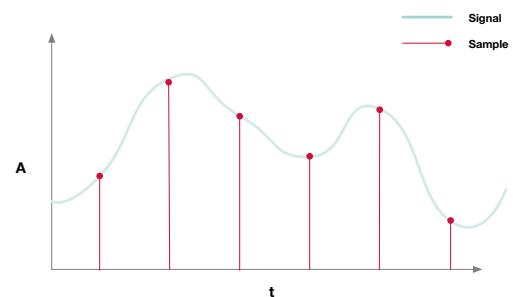
to a number on a given range. An audio stream is then a sequence of these values. The quality of the process is determined by the *sample rate*, i.e., the number of samples per time unit, and the *bit depth*, which determines quantization of the amplitude power.

If we take a 1 s audio snippet, sampled at 44 kHz, we end up storing 44 000 sample points. Using a bit depth of 16 bit per sample, this amounts to 704 000 bit or 88 kB of uncompressed audio data. In modern audio systems, we typically record multiple audio channels independently, leading to even more data.

4.1.1 A Data Model for (Multi-)Media Data

In Chapter 3, we have introduced the notion of a data model and its importance for working with any type of data. Despite being agnostic to the concrete, conceptual data model in principle, the work presented in this Thesis still relies on a formal understanding of media data that enables organisation and management thereof. Due to its tight integration into the *vitrivr* project [RGT⁺16; GRS19a; HSS⁺20], there is a particular model that we would like to introduce. Under this data model – which is illustrated in Figure 4.1 – a (multi-)media collection consists of multiple *media object*s. The media object describes the data at the level of individual documents – e.g., a video or image file – and comprises of basic attributes such its identifier, its media type or its path. The path forms the link to the raw media data in the filesystem, which we assume to be the most suited form of storage for this type of information.

To account for the temporal development found in dynamic media types, *vitrivr*'s data model has a notion of a *media segment*, which represents a clearly defined, temporal slice of the object and stands in a one-to-many relationship with it. However, the model does not make any assumption as to how segments are formed. For static media types, such as images, there is a trivial one-to-one relationship between an object and a segment. For more complex media types, such as audio or video, *media segmentation* is a dedicated area of research [KC01] and can be approached in many different ways, e.g., at a fixed rate, based on changes in the content [Foo00; TYB16] or using self-adaptive, deep neural networks [SML19]. Obiviously, different strategies for segmentation yield different degrees of summarization of information over time. Additionally, the proposed distinction also allows for very application specific media types and segmentation strategies, such as *image sequences* – introduced for LSC 2020 [HPG⁺20] – which group related images per day for the purpose of lifelog analysis.

To model the different derivative representations that are used to describe a media object and its segments, the model foresees *features*, which again stand in a one-to-many relationship with the segments. That is, every segment can have an arbitrary number of such features that describe different aspects of the segment's content. In practice, different types of features are obtained and stored in dedicated entities. Additionally, *descriptive metadata* allows for a description of the media both at the document and segment level by means of simple key-value pairs containing descriptions or labels.

While proven to be useful, the proposed model is only one possible approach to model media data and media collections and in certain aspects.
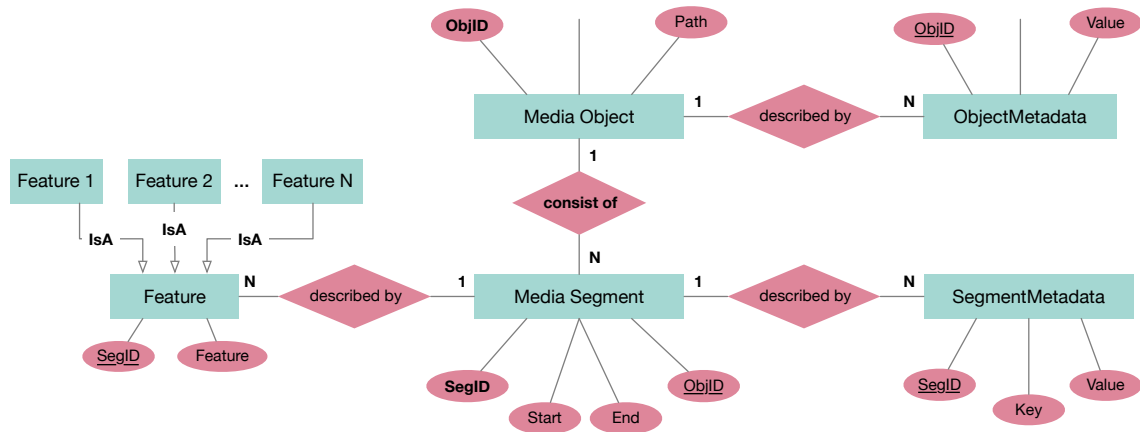
Figure 4.1 **An extended ERM of the multimedia data model used in the *vitrivr* project. The model is centered around the notion of media objects and media segments which are described by metadata and features.**

For the purpose of this Thesis, we consider a slightly altered version of the aforementioned data model, which is more in line with [BdB+07] and is illustrated in Figure 4.2. This model also considers media objects to be an abbstraction of individual files. However, this model foregoes the indirection introduced by the media segment and treats *features*, *annotations* and *descriptions* as different types of a more general *metadata* type that describes the media object directly. To model the temporal aspect in dynamic media types, the metadata itself exhibits information about the part of the object that is being described, denoted by an optional *start* and an *end* marker. In practice, this could be a frame number or a timestamp.

While the difference between the two models may seem marginal, we argue, that the latter offers several advantages over the former: Firstly, it eliminates a level of indirection introduced by the media segment and thus simplifies handling of static media types, which are simply described by different types of metadata that lack a start and end marker. Secondly, it does not assume segmentation to be statically defined and instead makes this a property of the metadata itself. This is reasonable, because the optimal segmentation strategy may depend on a particular feature, especially when multiple media types are involved, e.g., aural and visual information in a video. And finally, the model could be extended to also support spatial information as basis for segmentation, e.g., in images, which would enable description of spatio-temporal aspects of any media type. However, such ideas are beyond the scope of this Thesis.

We will use the proposed, conceptual data model from Figure 4.2 throughout this Thesis and whenever we refer to terms like collection, media object, feature or descriptive metadata, we refer to the concepts introduced in this model.
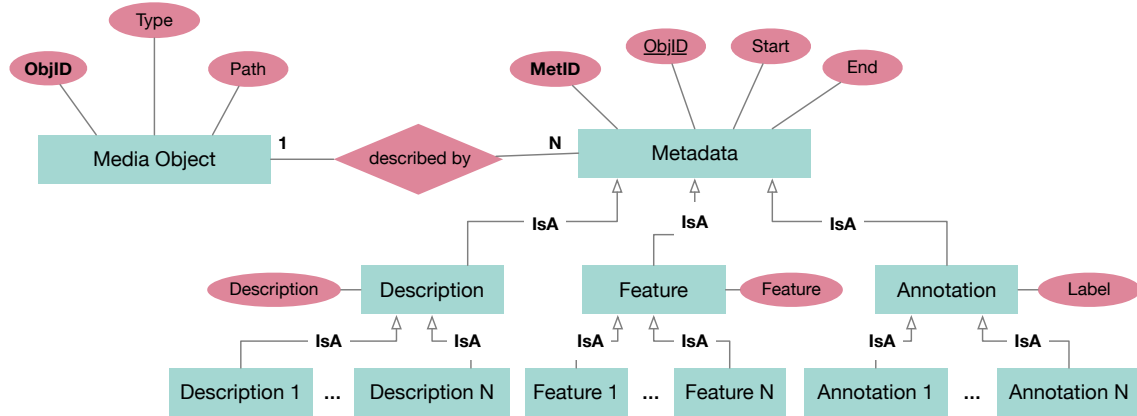
Figure 4.2 **An extended ERM of the multimedia data model used for the purpose of this Thesis. It has been derived from *vitrivr*'s data model and foregoes the explicit segment entity.**

4.1.2 Descriptive Metadata

Descriptive metadata in the sense of the proposed data model comprises of textual descriptions (e.g, title, summary), technical information (e.g., duration, location, frame rate) and annotations (e.g., category labels). Such information has always played an important role in multimedia retrieval and analysis, because it provides (indirect) access to the media's content and can be leveraged in a structured way, e.g., in database queries or for data organisation.

Over the years, many different metadata standards have emerged. For example, ID3[2] tags allow for organisation of large music libraries and classification of songs based on information about artists or albums. Similarly, the Dublin Core Metadata Element Set (DCMES or just Dublin Core)[3] comprises of 15 basic properties that can be used to describe any type of media, e.g., videos or images. And last but not least, EXIF[4] can be used to describe images and also includes technical metadata, such as the camera model, the exposure time or the f-number. These well established standards are complemented by a plethora of domain specific, standardised and non-standardised metadata frameworks.

However, while useful and important for the problem of analysis and retrieval, this type of metadata comes with important disadvantages. Firstly, and notwithstanding recent developments in machine learning, e.g., in image captioning [HSS+19], such information is traditionally assigned manually in a laborious and time-consuming annotation process. This process is barely able to keep up with the ever increasing velocity at which new content is created. Sec-

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[2] See https://id3.org/
[3] See https://www.dublincore.org/
[4] See https://www.loc.gov/preservation/digital/formats/fdd/fdd000146.shtml/

ondly, descriptions and labels – especially if not standardised – are often subjective due to language, expertise and personal experience and may therefore differ depending on the person assigning them. This is closely related to the problem of the perceptive- and interpretative gap [Ros18] and highly relevant for any search process. And finally, it is often challenging to describe the content of media in a textual manner, especially if temporal development is involved.

Regardless of these challenges, however, experience shows that annotations – be they assigned manually or automatically – play an important role, especially when it comes to information retrieval. A contributing factor here is that of query formulation, which is very low-effort and familiar for textual input and becomes more challenging for other types of queries .

> We use this often. But is there some study on this?

> Source

4.1.3 Features

Simply put, a *feature* is a mathematical object that describes "derived characteristics" [BdB+07] of a media object or a part thereof. Therefore, they are sometimes also referred to as *descriptors*. A formal definition is given in Definition 4.1.

Definition 4.1 Definition of a Feature in Multimedia Analysis

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Let $\mathbb{O} = \{o_1, o_2, \ldots, o_N\}$ be a media collection of media objects o (i.e., files). A *feature* $f_{i,\texttt{start},\texttt{end}} \in \mathbb{F}$ describes a temporal interval $[\texttt{start},\texttt{end}]$ with $\texttt{start},\texttt{end} \in \mathbb{N}_0, \texttt{start} \leq \texttt{end}$ of the media object $o_i \in C$ under the feature transformation $\mathfrak{t}$, with

$$\mathfrak{t} \colon C \times \mathbb{N}_0 \times \mathbb{N}_0 \longrightarrow \mathcal{F} \tag{4.1}$$

We call $\mathbb{O}$ the media object domain and $\mathbb{F}$ the feature domain. The structure of $\mathbb{F}$ is fully determined by $\mathfrak{t}$.

Features play a central role in many different domains, ranging from mere (multi-)media analysis to retrieval. [BdB+07] distinguishes between low-level and high-level features, which is a qualitative assesment of how far removed the derived characteristic of a particular feature is from a concept that has a semantic meaning to a human user. For example, a histogram of the colours found in an image would be considered a low-level feature, whereas a feature capturing salient keypoints or even objects in the same image would be classified as high-level. In practice, high-level features are often derived from low-level features, and again these conversions are subject to the semantic gap.

The process of generating features from media objects is called *feature extraction* [BdB+07] and there is an entire corpus of research that deals with the engineering of features that describe the relevant aspects of a given media type's content, with first attempts in computer vision and image understanding dating back to the early 60s. Various surveys, such as [MB03; DZJ+12; SJ19], cover the topic of feature extraction and we simply name and describe a few selected examples to provide an (unrepresentative) overview. Obviously, every type of media has their own analysis technqiues that can be used to generate features.

For images, one can roughly distinguish between low-level colour, texture and shape features [SJ19], as well as higher-level local keypoint-based features. An example of a colour feature could be a simple colour histogram or a statistical moment that captures colour distribution, e.g., the average colour in a defined area of the image. Prominent examples for keypoint detection features include algorithms such as Scale Invariant Feature Transformation (SIFT) [Low99], Speeded-Up Robust Features (SURF) [BTVG06] or Histogram of Oriented Gradients (HOG) [DT05]. All these features are employed in many different applications ranging from retrieval and similarity search to the detection of higher-level concepts, such as, objects or faces [DBS+11; Far16].

Similarily, there is a wide range of features applied in audio analysis and retrieval. Mel-frequency Cepstral Coefficient (MFCC) – a representation of a short-term power spectrum on the perceptual *mel scale* – play an important role in speaker recognition, sound and music classification as well as audio segmentation [KS04] and were shown to outperform audio descriptors outlined in the MPEG-7 standard [QL01], which is a collection of standardised feature descriptors for images, audio and video. Other types of features include Pitch Class Profiles (PCP) for music retrieval and classification [Lee06; DBS19] or features based on rhythm, timbre or speed.

So far, we have mostly considered features that were engineered through the careful application of signal processing and/or statistical analysis of the raw media data. However, advances in machine learning and deep neural neutwork architectures have enabled the feature extraction process to be automated to some extend, leading to a shift from engineered to learned features [HE10; GAR+16]. There is also research that deals with the comparison of the two paradigms in multimedia retrieval and analysis [BGS+17] as well as other domains, such as chemical structure analysis [GLSJ+21]. Preliminary results show, that while learned features often outperform the engineered ones, best results are attained by a combination of the two.

Given the cornucopia of features and feature extraction techniques to chose from, there are two important aspects that ought to be considered with respect to data modeling and data management: First, and despite the vast range of feature extraction techniques, the resulting features often exhibit a comparatively simple mathematical structure. We will show in Section 4.2 that in multimeda retrieval, one often deals with vectors in a high-dimensional, real-valued vector space [ZAD+06]. Second, when considering a complex enough use-case, no single feature can satisfy all the different types of applications because, as we as have pointed out, a specific feature usually focuses on a specific aspect of the content. Consequently, a combination of features often yields the best results [DKN08].

Both these aspect have important implications for the the requirements on a data management and processing system for multimedia data, especially, if such a system should be able support different use-cases that are not necessarily known in advance. We would also like to point out, that both data models introduced in Section 4.1.1 are flexible enough to handle these two aspects.

4.2 Multimedia Retrieval

Multimedia retrieval deals with algorithms, methods and systems that allow for content-based search and obtaining items of interest from large (multi-)media collections based on user-defined queries. In addition to text-based search, such queries may also involve new modes of query formulation such as *Query-by-Example* [KCH95], *Query-by-Sketch* [CWW+10], *Query-by-Humming* [GLC+95] or *Query-by-Sculpting* [BGS+20]. Many different research domains for the different types of media have emerged over the years, including but not limited to image retrieval [DA13], audio retrieval [Lu01], video retrieval [HXL+11], 3D model retrieval [YLZ07] and various, specialised subdomains [MK18].

Formally, the multimedia retrieval problem can be charactersied finding all media objects $o \in O$ that may be relevant to a given *information need* expressed by a user as query Q. This is achieved by obtaining some form of *(dis-)similarity*[5] between Q and o and ranking results based on it, which is why the method is also referred to as *similarity search*. In contrast to Boolean search, the results of similarity search are non-binary in the sense that an object o may match a query Q only to a certain degree but still be considered part of the resultset, as opposed to a strict match / no-match semantic.

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[5] Depending on the context, the similarity of an object to a query may be directly or inversely proportional to the obtained score, which is what makes the difference.

Since a direct comparison of a media object to a query is often not feasible – for reasons described in Section 4.1 – features are used as a proxy instead. This is a manifestation of the idea that derivative representations are considered in lieu of the actual object, leading to the formal Definition 4.2 of similarity search.

Definition 4.2   Definition of the General Similarity Search Problem

Let $\mathbb{O} = \{o_1, o_2, \ldots, o_N\}$ be a media collection of media objects o and let further $\mathbb{F}$ be a feature domain of $\mathbb{O}$ under the feature transformation $\mathfrak{t}$. Furthermore, we assume a query Q that can be mapped to $\mathbb{F}$, i.e., $\mathfrak{t}(Q) = q \in \mathbb{F}$ and the existence of an inverse $\mathfrak{t}'$ with $\mathfrak{t}'(f) = o$ [a].

Similarity search then is the optimisation problem of finding the object $o \in \mathbb{O}$ that given a query q and a similarity function $\mathfrak{s}\colon \mathbb{F} \times \mathbb{F} \to [0,1]$ maximises the following expression.

$$o_r = \mathfrak{t}'\left(\operatorname*{argmax}_{f \in \mathbb{F}} \mathfrak{s}(f, q)\right) \tag{4.2}$$

We call the resulting item o_r most similar w.r.t. to Q, which is indicated by the similarity score $\mathfrak{s}(f, q)$. In practice, we may be interested in the top k results rather than just a single item.

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[a] While this may seem like a wild assumption at first, this is a given since we explicitly store the relationship between o and f, according to the data model in Section 4.1.

In simple terms, a multimedia retrieval system operates upon features $f \in \mathbb{F}$ derived from the original media objects by means of a feature transformation. This transformation is applied twice: Once when indexing a media object in the collection – often a step that is thought as taking place offline – and once when deriving the same feature from the query input Q provided by the user. Subsequently, the system generates the similarity measure $\mathfrak{s}(q, f)$ which quantifies the similarity between q and f from low (0.0) to almost identical (1.0). The flow of information that results from this approach is illustrated in Figure 4.3.

In many cases, the function $\mathfrak{s}$ may not express similarity but dissimilarity between objects, in which case we can simply consider the dual problem. Furthermore, the score may not always be normalized to $[0, 1]$, which makes it difficult to combine scores of multiple features, e.g., in *score-based late fusion* [DM10; Ros18]. However, a normalised similarity score can always be derived by applying an additional correspondence function $\mathfrak{c}\colon \mathbb{R} \to [0, 1]$. Both aspects are of high practical relevance but do not change the fundamental problem definition.
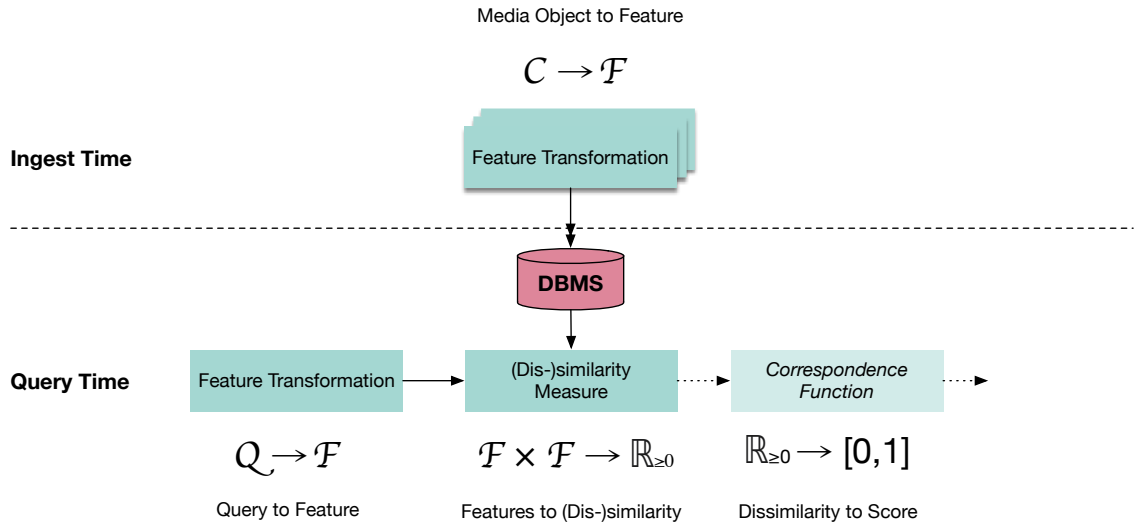
Figure 4.3 Flow of information in similarity search at ingest- and query time.

4.2.1 Similarity Search and the Vector Space Model

The *vector space model* of similarity search assumes that the domain of the feature vectors $\mathbb{F}$ is a subset of a mathematical vector space – that is, a set whose elements may be added and multiplied by a scalar. In practice, we often consider that vector space to be real-valued and high-dimensional, i.e., $\mathbb{F} \subset \mathbb{R}^d$ wherein d is the dimension and an inherent property of the feature and the underlying transformation $\mathfrak{t}$. Consequently, every feature $f \in \mathbb{R}^d$ is simply a point in that high-dimensional vector space.

Under this premise, we consider the dissimilarity function $\mathfrak{d}(f, q)$ to be a function that calculates the distance between a feature and a query $f, q \in \mathbb{F}$, as defined by Equation (4.3). Typically, the farther two vectors lie apart under the distance measure, the more dissimilar they are, which is why we also call this proximity based search. A list of important distance functions used in similarity search is given in Table 4.1.

$$\mathfrak{d} \colon \mathbb{F} \times \mathbb{F} \to \mathbb{R} \tag{4.3}$$

At a high level, one can distinguish between *continuous* and *discrete* distance functions [ZAD+06]. Continuous functions typically exhibit a very large, potentially infinite co-domain wheras discrete functions map to a limited, often pre-defined set of values. For example, the *Euclidean distance* is a continuous distance function, whereas the *Levenshtein distance* [Lev65] is discrete.

Furthermore, we can distinguish between metric distance functions that induce a topology on the underlying vector space – often denoted as $(\mathbb{F}, \mathfrak{d})$ – as

opposed to functions that do not. A metric distance function satisfies the *non-negativity*, *symmetry*, *identity of indiscernables* and *triangle inequality* constraints and $(\mathbb{F}, \mathfrak{d})$ is called a *metric space*.

$$\mathfrak{d}(f, q) \geq 0 \qquad \text{(non-negativity)}$$
$$\mathfrak{d}(f, q) = \mathfrak{d}(q, f) \qquad \text{(symmetry)}$$
$$\mathfrak{d}(f, q) = 0 \iff f = q \qquad \text{(identity of indiscernables)}$$
$$\mathfrak{d}(f, q) \leq \mathfrak{d}(f, g) + \mathfrak{d}(g, q) \qquad \text{(triange inequality)}$$
$$\forall f, g, q \in \mathbb{F} \wedge (\mathbb{F}, \mathfrak{d})$$

The constraints imposed on a metric space give rise to mathematical properties that can be exploited for efficient execution of similarity search and specialised indexing techniques [ZAD+06]. However, despite their mathematical convenience, some applications involve distances that do not exhibit all the aforementioned properties of a metric, e.g., quasi-metrics (lack symmetry), semi-metrics (lack triangle inequality), meta-metrics (lack identity) [ZAD+06] or even necessitate the use of non-metric functions [SB11].

The choice of (dis-)similarity measure mainly depends on the application. All the Minkowski distances, (i.e., L^1, L^2, L^p) can be used for any type of real-valued vector and in practice, it often makes little difference which one is employed [Ros18]. Of all the Minkowski distances, the Euclidean distance (L^2) is the most common. The Chi-squared distance is well suited, if the feature vectors represent histgrams [PW10]. The Hamming- and Levenshtein distances belong to the class of *edit distances* and can be used to compare strings.

Name	Symbol	$\mathfrak{d}(\mathbf{f}, \mathbf{q})$	Domain	Co-Domain	Metric
Manhattan	L^1	$\sum_{i=1}^{d} |f_i - q_i|$	$\mathbb{R}^d$	$\mathbb{R}$	metric
Euclidean	L^2	$\sqrt{\sum_{i=1}^{d} (f_i - q_i)^2}$	$\mathbb{R}^d$	$\mathbb{R}$	metric
Minkowski	L^p	$\sqrt[p]{\sum_{i=1}^{d} (f_i - q_i)^p}$	$\mathbb{R}^d$	$\mathbb{R}$	metric if $p \in \mathbb{N}_{\geq 1}$
Chi-Square	χ^2	$\sum_{i=1}^{d} \frac{(f_i - q_i)^2}{f_i + q_i}$	$\mathbb{R}^d$	$\mathbb{R}$	metric
Kullback-Leibler	-	$\sum_{i=1}^{d} q_i \log(\frac{q_i}{f_i})$	$\mathbb{R}^d$	$\mathbb{R}$	non-metric
Cosine	-	$1 - \frac{\sum_{i=1}^{d} f_i q_i}{\sqrt{\sum_{i=1}^{d} f_i^2} \sqrt{\sum_{i=1}^{d} q_i^2}}$	$\mathbb{R}^d$	$[-1, 1]$	semi-metric
Jacccard	-	$1 - \frac{A \cap B}{A \cup B}$	$\mathbb{F}$	$[0, 1]$	metric
Levenshtein	-	-	S	$\mathbb{N}$	metric
Hamming	-	-	S	$\mathbb{N}$	quasi-metric
LCS [Hir77]	-	-	S	$\mathbb{N}$	non-metric

Table 4.1   List of distance functions often used in similarity search.

Regardless of what (dis-)similarity measure is selected, the similarity search problem always looks as defined in Definition 4.2: Given a query $q \in \mathbb{F}$, the search algorithm should return all features $o \in \mathbb{O}$ whose features $f = \mathfrak{t}(o)$ lie within a given proximity or distance to the query object q and that further satisfy the selection condition. Depending on this selection condition, we distinguish between different types of similarity search problems [ZAD$^+$06]. Those are illustrated in Figure 4.4 and Example 4.3

4.2.1.1 Nearest Neighbour Search (NNS)

NNS is probably one of the most prominent types of queries used in multimedia retrieval and certainly the one employed most often in the context of the *vitrivr* [RGT$^+$16; GRS19a] stack. Given the query object q and an arbitrary limit $k \in \mathbb{N}$ the task is to find the k features $f \in \mathbb{F}$ that are closest to q as illustrated in Figure 4.4(a). This is also referred to as k-Nearest Neighbour Search (kNN). Formally, the resultset R is given by Equation (4.4).

$$\{R \subset \mathbb{F} : \forall f_r \in R, f \in \mathbb{F} \setminus R, \mathfrak{d}(q, f_r) \leq \mathfrak{d}(q, f) \wedge |R| = k\} \tag{4.4}$$

Algorithmically, the distance between all $f \in \mathbb{F}$ and q must be evaluated exhaustively and the top k results must be retained by ranking and ordering the results, e.g., in a *bound priority queue*. This is sometimes referred to as *brute-force* approach to NNS. For $\mathbb{F} \subset \mathbb{R}^d$, its runtime complexity is $O(dN)$ and thus depends linearly on the cardinaltiy $N = |\mathbb{F}|$ and the dimension d.

A variant of kNN is k-Farthest Neighbour Search (kFN) wherein instead of the nearest, the farthest neighbours are obtained. This can be useful, for example, to obtain negative examples to train recommender systems [PSS$^+$15]. However, the underlying algorithm remains the same.

4.2.1.2 Range Search

The range query or ϵNN is useful for finding objects that lie within a given range, typically expressed by a value $\epsilon \in \mathbb{R}$. Given the query object q, the task is to find all features $f \in \mathbb{F}$ that lie within ϵ of q as illustrated in Figure 4.4(b). Formally, the resultset R is given by Equation (4.5).

$$\{R \subset \mathbb{F} : \forall f_r \in R, \mathfrak{d}(q, f_r) \leq \epsilon\} \tag{4.5}$$

Algorithmically, this search strategy is similar to NNS in that all features must be evaluated exhaustively and in that its complexity for $\mathbb{F} \subset \mathbb{R}^d$ is $O(dN)$.

However, in contrast to NNS, there is no need for intermediate sorting, since the selection is based on a simple, numerical comparison to the constant ϵ.

Variants of ϵNN include instances, where f must be larger than ϵ or where f must fall into an interval $[\epsilon_{lower}, \epsilon_{upper}]$. However, these variants are equivalent to the base-case since only the selection predicate changes.

4.2.1.3 Reverse Nearest Neighbour Search (RNNS)

In RNNS we try to find all $f \in \mathbb{F}$ that given a limit $k \in \mathbb{N}$ consider the query $q \in \mathbb{F}$ to be part of their kNN resultset as illustrated in Figure 4.4(c). Formally, the resultset R is given by Equation (4.6)

$$\{R \subset \mathbb{F} \colon \forall f_r \in R, q \in \mathtt{kNN}(f_r) \land f \in \mathbb{F} \setminus R \colon q \in \mathtt{kNN}(f)\} \tag{4.6}$$

Algorithmically, this type of search is more complex than kNN or ϵNN, because basically, a NNS problem must be solved for every element $f \in \mathbb{F}$. Therefore, the runtime complexity is $O(dN^2)$ and scales with the square of $N = |\mathbb{F}|$.

Example 4.3   Comparing different types of similarity search algorithms

For this example, we consider $\mathbb{F} \subset \mathbb{R}^2$ and $f \in \mathbb{F}$ to be points of interest (e.g., museums, hotels, parks) on a two-dimensonal city map. Furthermore, we consider $q \in \mathbb{F}$ to be another position on the same map, e.g., given by our current position or a selected point of interest. The different types of similarity queries can now be thought of as follows:

Nearest Neighbour Search is the equivalent of finding the k points of interest that are closest to q (e.g., the three museums closest to my location).

Range Search is the equivalent of finding all points of interest that are within ϵ distance from q (e.g., all museums within 3 km from my location).

Reverse Nearest Neighbour Search is the equivalent of finding all points of interest that consider q to be among their closest points of interest (e.g., finding all hotels that have a specific museum in the set of their three closest sites that must be seen when visiting the city).

((a)) kNN   **((b)) ϵNN**   **((c)) RkNN**
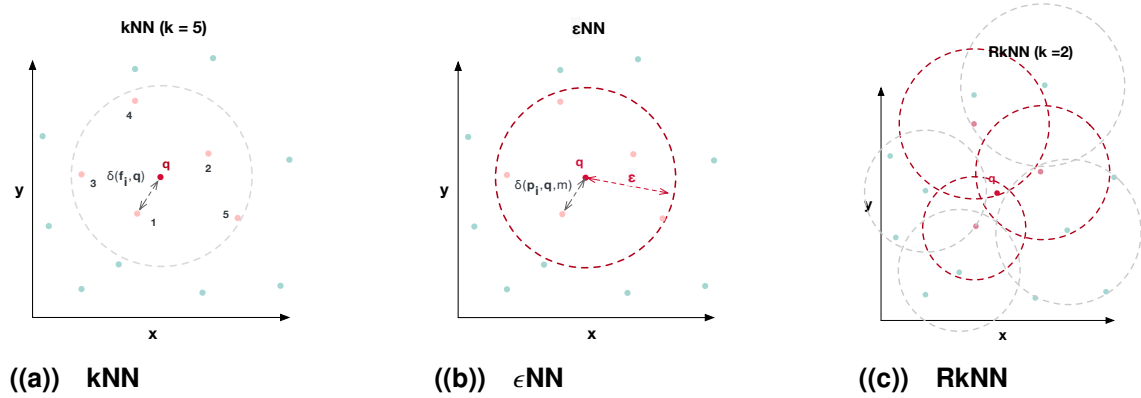
Figure 4.4   Illustration of the different similarity search algorithms in $\mathbb{F} \subset \mathbb{R}^2$ using the Euclidean distance (L^2). Matches are highlighted in red.

4.2.2   NNS and High-Dimensional Index Structures

As we have argued in Section 4.2, even the simple NNS problem in $\mathbb{R}^d$ exhibits a non-negligible runtime complexity of $O(dN)$ for a linear, brute-force scan – thus being proportional to the cardinality of $N = |\mathbb{F}|$ and the dimension d. Experience from database research shows that linear scans are too slow in terms of time required for query execution if N becomes large enough, especially when interactive query workloads are involved. This necessitates the use of index structures that allow for sub-linear data access.

For search in high-dimensional vector spaces, the dependency on d has a huge impact on execution performance of any NNS algorithm, due to what is known as the *curse of dimensionality* [IM98; ZAD+06]. The impact of this "curse" is twofold: First, the execution time of a brute-force algorithm is directly proportional to the size of the feature vector. With a tendency towards more complex and thus higher-dimensional vectors, there is a direct, negative effect on runtime. Second, and more importantly, research has shown that the task of indexing high-dimensional vectors for more efficient access is not trivial and that traditional approaches, e.g., based on partitioning or classical tree structures, degenerate as dimensionality increases [IM98; WSB98] with the consequence, that they only yield marginal or no improvement over executing a linear scan. In fact, it was formally proven by [SR06] in their *Theory of Nearest Neighbor Indexability* that the performance of almost all known index structures at that time deteriorate to that of a linear scan if d becomes large enough.

Nevertheless, the issue of index structures that allow for more efficient and thus sub-linear NNS has been taken on by various researchers over the past few decades with results of high practical relevance. At a high-level, indexing algorithms can be classified along three dimensions: First, based on whether they

Name	Guarantees	Structure	Method
KDB-Tree [Rob81]	exact	tree	space partitioning
R^*-Tree [BKS$^+$90]	exact	tree	data partitioning
VAF [WSB98]	exact	list	quantization
VA+ [FTA$^+$00]	exact	list	quantization
LSH [IM98; WZs$^+$18]	approximate, probabilistic	hash table i.a.	hashing
PQ [JDS10]	approximate	inverted file	quantization
NV-tree [LÁJ$^+$09]	approximate	tree	quantization
MRNG [LÁJ$^+$09]	approximate	graph	proximity graph
HSNW [MY18]	approximate	graph	proximity graph

Table 4.2 **Non-representative and non-exhaustive list of high-dimensional index structures employed in similarity search and retrieval.**

provide any guarantees w.r.t. to the accuracy of the results, wherein "accuracy" is often measured in terms of precission and recall of a result produced by an index as compared to the the result produced by a linear scan [EZP21]. Second, based on their *structure* [SR06], e.g., *list, tree, graph, hash table* and *inverted file.* And finally, by the method that is employed, e.g., *quantization, hashing* or *partitioning.* An overview of different, prominent algorithms is provided in Table 4.2.

Early examples of high-dimensional indexes used to rely on space or data partitioning methods. Both have in common, that they assign features in the vector space to buckets or data files based on some partitioning of either the vector space or the data. Space partitioning methods include but the KD-Trees [Ben75], KDB-Trees [Rob81] or Quadtrees [FB74]. The data partitioning methods involve R-Trees [Gut84], R^*-Trees [BKS$^+$90] or M-Trees [CPZ97]. All of these methods were shown to perform well as long as dimensionality remains small (i.e., 4 to 12 dimensions) but they tend to deteriorate as d increases.

In the next few sections, we will highlight a few more recent examples of high-dimensional indexing methods to provide a non-representative overview.

4.2.2.1 Vector Approximation Files (VAF)

VA-files were first proposed by Weber et al. [WSB98] to address the problem of the dimensionality curse and were later refined by [FTA$^+$00]. The basic idea of a VAF is the division of the data space into 2^b cells, as illustrated in Figure 4.5, where b denotes a fixed number of bits. Typically, one choses a specific number of bits per dimension b_d and uniformly partitions the vector space along each dimension, i.e., $b = b_d d$. A feature vector's position in the grid is concatenated into a compact *signature* of size b and the VA-file is a list of those signatures.
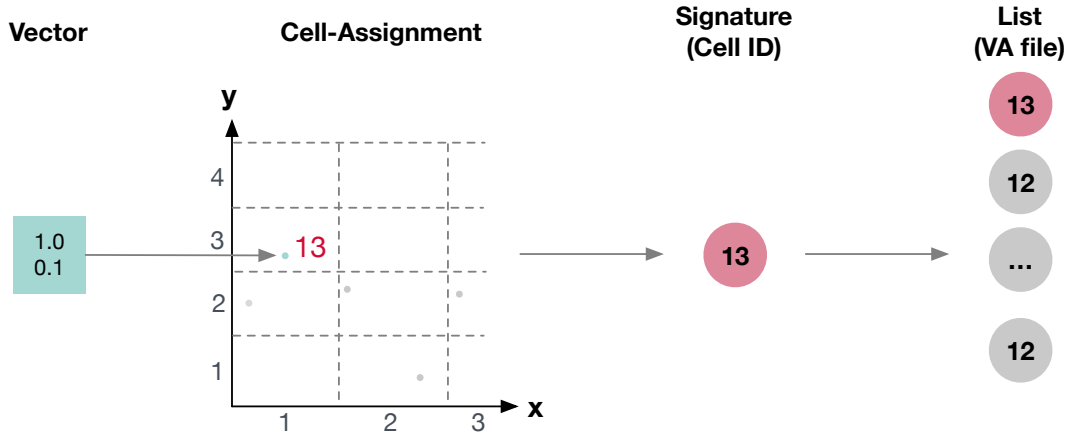
Figure 4.5 **Simplified illustration of basic VAF indexing scheme in for $\mathbb{F} \subset \mathbb{R}^2$. A vector is assigned to a cell which gives rise to a signature that is stored in a linear list.**

NNS is then realised as a linear scan of the file. Speed-up over a linear scan of the original vectors is achieved in two ways: Firstly, the signatures are more compact than the original representation, which reduces IO cost through compression. Secondly, the signatures can be used to obtain approximate bounds that are computationally less expensive than the actual distance calculation. These bounds can be used to filter out a majority of the points in the file, further reducing IO and CPU costs. Experimental results presented in [WSB98] demonstrate that 90% of all features can be skipped thus a distance must only be obtained for the remaining 10%. However, [EZP21] determine theoretically that for VAF degeneration is to be expected nevertheless for high dimensions, depending on how the data is distributed.

The VA+-files proposed by [FTA⁺00] introduce a few optimisations to the original algorithm. They suggest a prior decorellation of the individual dimensions by applying a *Karhunen-Loève Transform* and a dynamic assignment of bit per dimension based on data distribution as opposed to a uniform distribution proposed in the original paper.

4.2.2.2 Locality Sensitive Hashing (LSH)

LSH refers to a family of algorithms [EZP21; WZs⁺18] that all share the same, basic idea of *locality preserving hashing* as first proposed by [IM98]. The idea is centered around a hash function $h : \mathbb{F} \to B$ that maps any two points $f, q \in \mathbb{F}$ to a bucket $b \in B$ such that Equations 4.7 and 4.8 hold, wherein $(\mathbb{F}, \eth)$ must
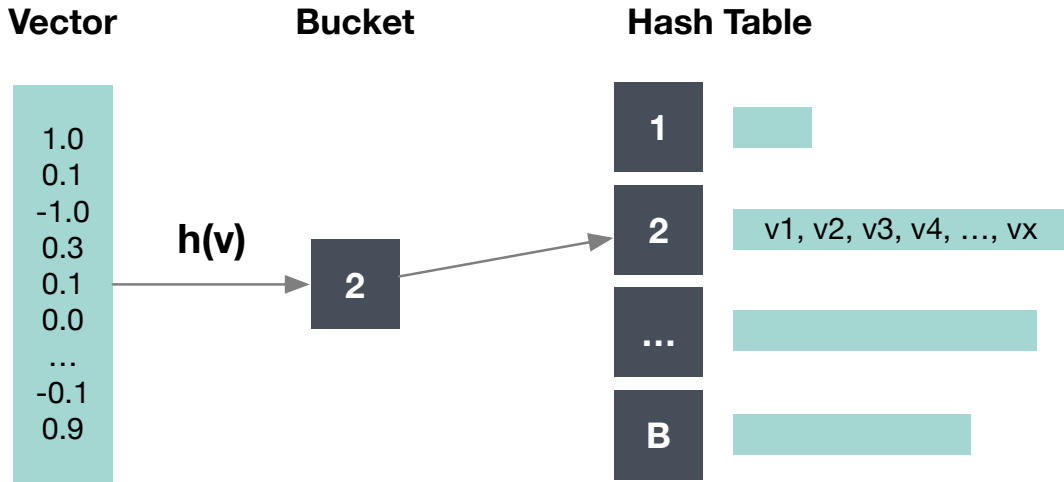
Figure 4.6 **A simplified illustration of the basic LSH indexing scheme. A vector is hashed to a bucket by a locality preserving hash function h. The vector is then stored in the assigned bucket in a hash table.**

constitute a metric space, $P_1, P_2 \in [0,1], P_1 > P_2$ denote probabilities, $R > 0$ denotes an arbitrary threshold and $c > 1$ denotes an approximation factor.

$$\eth(p,q) \leq R \Rightarrow h(f) = h(q) \text{ with a probability of at least } P_1 \qquad (4.7)$$

$$\eth(p,q) \geq cR \Rightarrow h(f) = h(q) \text{ with a probability of at most } P_2 \qquad (4.8)$$

In simple terms, a locality preserving hash function has a high probability for collision (i.e., mapping to the same bucket) if two features $f, q \in \mathbb{F}$ lie close to one another, i.e., $\eth(q,f) \leq R$, but exhibits a low probability for collision if $\eth(q,f) \geq cR$. Given such a hash function, a feature $f \in \mathbb{F}$ can be hashed to a bucket and stored in a hash table with other vectors that lie close to it. This is illustrated in Figure 4.6.

Speedup for NNS can be achieved by limiting distance calculation to the vectors in the bucket a query q falls into. This is referred to as non-exhaustive search. However, due to the probabilistc nature of the hash function, this type of search strategy may exhibit errors due to vectors that were hashed into the "wrong" bucket. More refined strategies can be employed including hash-code ranking as well as single- and multi-table lookup [WZs+18] to further minimize that error. Nevertheless, LSH remains an approximate search strategy. A survey of different LSH algorithms can be found in [WZs+18].
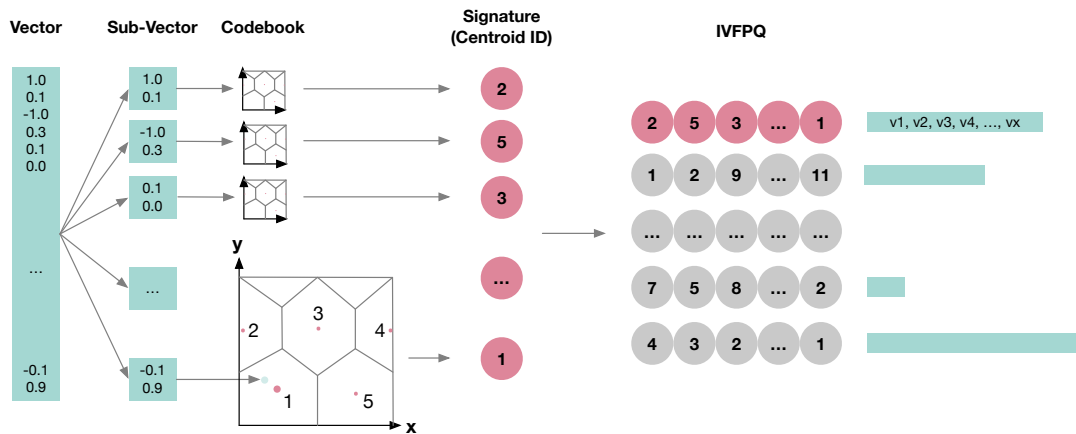
Figure 4.7 **A simplified illustration of the basic PQ indexing scheme. A vector is divided into smaller subvectors and each subvector is assigned to the nearest centroid in the codebook of the respective subspace. Concatenating the resulting centroid index per subspace gives rise to the signature, which can be stored in an inverted file index.**

4.2.2.3 Product Quantisation (PQ)

The idea for PQ was proposed by [JDS10] and it describes a technique for quantizing vectors. The main idea involves decomposition of the original vector space $\mathbb{R}^d$ into smaller subspaces $\mathbb{R}^s$ with $s < d$ and separate quantization of each subspace. The quantization is achieved by learning a codebook for every subspace through k-means clustering on a representative sample of the data. Upon indexing, all subvectors of each feature vector $f \in \mathbb{F}$ are assigned to the nearest centroid in the codebook for the respective subspace. Concatenation of the centroid indexes gives rise to a compact signature that can be stored in an inverted file index, as illustrated in Figure 4.7.

Speedup of NNS is achieved in two ways: First, the resulting signature is a highly compressed representation of the original vector, which reduces IO by a large margin as is demonstrated in Example 4.4. Secondly, the signature can be used directly to approximate the distance between a query q and a feature f using a pre-calculated lookup-table and inexpensive operations, which reduces CPU costs. However, this speedup must be bought by a distortion of the approximated distance, which may lead to errors if features lie very close to one another and makes PQ a suboptimal fit if exact distance values are required.

[JDS10] also discusses several optimisations that can be employed, e.g., encoding the residuals instead of the actual feature vectors to increase accuracy or to use multiple levels of coarse quantizers to introduce an additional partitioning of the data in very large data collections.

Example 4.4   Size of PQ-Signature vs. original feature

Let us assume $\mathbb{F} \subset \mathbb{R}^{256}$, i.e., a 256-dimensional vector space ($d = 256$). Assuming a `float` data type, we require 4 B per vector component, i.e., 1024 B to store a single vector.

Using PQ, this space could now be divided into 16 subspaces with a dimensionality of 16 each, i.e., $s = 16 < d$. If now we assume, that we create a codebook consisting of 128 clusters for each subspace, then every subvector will be assigned to one of 128 centroids, which will result in 16 numbers (one per subspace) between 0 and 127. Each of these numbers can be stored in a single `byte`, that is, we only need 16 B per vector to store an index entry.

4.2.3 Beyond Similarity Search

In real-world multimedia retrieval systems, the query workloads are far more diverse than what we have described so far. In addition to "simple", one-shot queries, users find themselves searching, refining, browsing and exploring datasets with the aim to find a particular item [LKM+19; RGL+20]. This is exemplified by interactive retrieval competitions such as Video Browser Showdown (VBS) [Sch19; LBS+18] or Lifelog Search Challenge (LSC) [GJS+21], where participants are required to find items of interest in large, standardised data collections [BRS+19; RSB21] within a limited amount of time.

The various participants have demonstrated interesting techniques that complement and replace mere similarity search. While the 2022 iteration was won by a system combining search using the CLIP model [RKH+21] and sophisticated browsing [HSJ+22], the team behind [KVM+20] has won the 2020 iteration of VBS with a system that relies on Self-organizing Map (SOM) [Koh90] to generate a clustered visualisation of the high-dimensonal data collection initialised by search input. Similarily, the system that won in 2016 used [BHM16] hierarchical graphs and visually sorted image maps to facilitate exploration without providing any classical search functionality. Generally, it was found that efficient browsing is as important for effective retrieval as an effective similarity search model [LKM+19]. Another comparison of systems at the LSC 2018 has shown, that a combination of functionality that complements similarity search is very common, including functions such as Boolean search on biometric data, facet filters and visual clustering. [GSJ+19]. Hence, as argued in Section 2.1, multimedia retrieval goes way beyond mere similarity search but always relies on it to some extent.

5

Multimedia Database Systems

The insight that special requirements are needed to accomodate multimieda in traditional databases can be traced back to the 1990s [MS96; AN97]

5.1 Multimedia Database Sytems

Over the years, different systems have been conceived with the aim to bring data management and multimedia applications closer together. Using the relationship between (diss-)similarity and distance, it has been shown by Giangreco et al., that for a database system to be able to support similarity search given the relational model for databases as described in Section 3.2, one can extend the set system of allowed data domains $\mathbb{D}$ by $\mathcal{D} \subset \mathbb{R}^{dim}, dim \in \mathbb{N}_{>1}$ and postulate the existence of a relational similarity operator $\tau_{\delta(\cdot,\cdot),a,q}(R)$ that *"performs a similarity query under a distance $\delta(\cdot,\cdot)$ applied on an attribute a of relation R and compared to a query vector q."* ([Gia18], p. 138). Such an operation introduces an implicit attribute in the underlying relation $\mathcal{R}$, which in turn induces an ascending ordering of the tuples. Using this operation, one can go on to define two concrete implementations, namely $\tau_{\delta(\cdot,\cdot),a,q}^{kNN}(\mathcal{R})$, and $\tau_{\delta(\cdot,\cdot),a,q}^{\epsilon NN}(\mathcal{R})$, which limit the number of retrieved results by their cardinality k or a maximum cut-off distance ϵ respectively.

While postulating two new, relational operation $\tau_{\delta(\cdot,\cdot),a,q}^{kNN}(\mathcal{R})$ or $\tau_{\delta(\cdot,\cdot),a,q}^{\epsilon NN}(\mathcal{R})$ as proposed by [Gia18] is well in tradition with how relational algebra has been extended over the years, it comes with limitations that become apparent upon disection of its structure. In its postulated form, τ addresses several functions at once:

1. It specifies the distance function that should be evaluated.

2. It generates an implicit distance attribute on the underlying relation $\mathcal{R}$.

3. It imposes an ascending ordering and limits the cardinality of $\mathcal{R}$ based on a predicate or a specified limit.

While being very specific and thus straightforward to implement, the amalgamation of all this functionality into a single operation is very specifically tailored to the use-case NNS and range search for a very specific case and only of limited value when considering more general proximity-based query operations. If one would, for example, want to obtain the k farthest neighbours rather than the k nearest neighbours, as necessary when doing MIPS or obtaining negative examples, we would have to either change the distance function or extend the definition of τ.

Another important issue with the definition of τ in its current form is that despite the two operations $\tau^{kNN}_{\delta(\cdot,\cdot),a,q}(\mathcal{R})$ and $\tau^{\epsilon NN}_{\delta(\cdot,\cdot),a,q}(\mathcal{R})$ serving a very similar purpose, they behave very differently with respect to other operations. Generally, $\tau^{kNN}_{\delta(\cdot,\cdot),a,q}(\mathcal{R})$ does not commute with any selection σ due to the inherent limiting of the cardinality to a constant value, hence:

$$\sigma(\tau^{kNN}_{\delta(\cdot,\cdot),a,q}(\mathcal{R})) \neq \tau^{kNN}_{\delta(\cdot,\cdot),a,q}(\sigma(\mathcal{R})) \tag{5.1}$$

The left-hand side of Equation (5.1) filters the results of a kNN-search on $\mathcal{R}$, thus returning $n \leq k$ results, wherein $n = k$ only if σ matches all tuples. The right-hand side of Equation (5.1) performs a kNN-search on a pre-filtered relation $\mathcal{R}$, also returning $n \leq k$ entries. However, n will only be smaller than k if σ selects fewer than k tuples.

Another database system that considers itself a "vector database built for scalable similarity search" [1] is called Milvus [WYG+21]. While the theoretical foundation behind it is not quite transparent, it claims to support hybrid queries involving both similarity search and predicates on scalar data types such as strings, booleans, integer and floating-point numbers as well as index support for both types of queries.

Most importantly, however, Milvus provides efficient NNS through state-of-the-art libraries and approaches namely FAISS [JDJ19], ScANN [GSL+20] and Spotify's Annoy [2], offers SIMD and GPU support and sports various indexes such as HNSW or PQ. Dynamic data is supported by partitioning the data into segments and (re-)building of indexes on a segment per segment basis.

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[1] See https://milvus.io/, accessed in June 2022
[2] See https://github.com/spotify/annoy/, accessed in June 2022

PART III

Dynamic Multimedia Data Management

6

Modelling a Database for Dynamic Multimedia Data

As we have described in Chapter 2, multimedia retrieval and analytics workloads pose specific requirements on any data management system. These requirements can be summarised as follows:

Support for non-atomic data Multimedia workloads process features, which are usually real-valued, high-dimensional vectors but can theoretically be any mathematical object (e.g., complex numbers, matrices etc.). A DBMS with multimedia support must support these objects as first-class citizens.

Support for distance computation The notion of distance or proximity between features plays a crucial role in all types of multimedia workloads, be it for simple nearest neighbor search or clustering. While certain workloads rely on raw speed for simple computations and data structures that allow for this type of lookup, other workloads may require the ability to compose more complex computations and execute them efficiently without the use of an index. Both aspects must be covered by a DBMS with multimedia support.

Dynamically changing data Data today is subject to constant change, and a DBMS for multimedia data must be able to cope with and propagate these changes to all the relevant data structures that are required to satisfy the aforementioned requirements efficiently.

Accuracy vs. Time Multimedia queries often trade retrieval accuracy against speed or vice-versa, e.g., when using a high-dimensional index for lookup. The DBMS must allow the user to express their perference, which is often highly use-case dependent, at different levels of the system.

To address these requirements, we propose and formalize a set of functionality, which will be specified in the next sections. First, we define a notion of *generalized, proximity based queries* and their relationship to the high-dimensional index structures currently in existence. Second, we introduce a general-purpose mechanism to enable high-dimensional indexes to cope with changing data regardless of how they work internally. And finally, we describe a *cost-model* that takes the notion of accuracy of results into acount. All these contributions can be seen as extensions to the functionality provided by a classical DBMS.

6.1   Generalized Proximity Based Operations

Starting with the metric space model for similarity search [ZAD+06] presented in Chapter 4, we propose to extend the notion of distance-based similarity search to that of a more general *proximity based query* following Definition 6.1.

Definition 6.1   Proximity Based Query

Let $\mathcal{R}$ be a relation. Any database query that relies on the evaluation of a distance function $\delta : \mathcal{D}_q \times \mathcal{D}_q \rightarrow \mathbb{R}_{\geq 0}$ that calculates the distance between an attribute $\mathcal{A}_p \in \text{SCH}(\mathcal{R})$ and some query $q \in \mathcal{D}_q$, is called a *proximity based query*. We call q the *query* and $\mathcal{A}_p$ the *probing argument*, which both share the same *query data domain* $\mathcal{D}_q$.

It is important to note, that Definition 6.1 simply requires a notion of proximity between some attribute and a query to be obtained by evaluating some distance function. The definition does not make any assumption as to what data domains $\mathcal{D}_q$ query and probing attribute belong to nor how the distance is being used within the query, once it has been obtained.

It is obvious, that similarity search falls into the broader category of a proximity based query, wherein the distance is used to rank a relation and subsequently limit its cardinality. In addition to this common application, the definition of proximity based queries also includes operations such as evaluating a distance function followed by some filtering or aggregation based on the computed value. That is, we are not limited to mere NNS, since we consider obtaining the distance as one step, which can be freely combined with all other operations supported by the underlying algebra.

6.1.1 Revisiting Distance Computation

Since the choice of the distance function δ is a crucial part of any proximity based query, it is worth revisiting its definition. Again, starting with the metric space modell [ZAD+06], we identify the following (implicit) constraints with respect to the distance function:

1. The domain (i.e., the input) of the distance function δ is assumed to be $\mathbb{R}^{dim} \times \mathbb{R}^{dim}$, that is, the distance function is assumed to be a binary function and arguments are restricted to real-valued vectors.

2. The codomain (i.e., the output) of the distance function δ is assumed to be $\mathbb{R}_{\geq 0}$, hence, the generated distance value is a positive, real number.

3. The pair $(\mathcal{D}_q, \delta)$ usually constitutes a metric, thus satisfying the non-negativity, identity of indiscernibles, symmetry and subadditivity properties.

Upon closer examination and if we consider the use cases presented in Chapter 2, one must come to challenge some of these constraints. If, for example, we turn to Example 6.1, we realise that it is not reasonable to impose a general restriction of the domain of the distance function to $\mathbb{R}^{dim}$ with $dim \in \mathbb{N}^+$

Example 6.1   Maximum Inner Product Search for MRF

In MRF (see Section 2.3), we try to obtain the signal vector $a_{i \in \mathbb{N}} \in \mathcal{D}_q \subset \mathbb{C}^{dim}$ so that it maximizes the inner product to a signal (query) vector $q \in \mathbb{C}^{dim}$. In this case, the distance function δ has the form $\delta : \mathbb{C}^{dim} \times \mathbb{C}^{dim} \to \mathbb{R}_{\geq 0}$. Hence, the domain of δ is a complex vector space.

Obviously, this limitation of the definition of δ can be easily remediated simply by extending the set of supported data domains $\mathbb{D}$ by $\mathbb{C}^{dim}$ similarily to how we did for $\mathbb{R}^{dim}$ as proposed by [Gia18]. Nevertheless, we have to acknowledge, that the text-book definition of a distance function is obviously too limited for some real-world applications, and that the query and probing arguments of a distance function could be any type of value supported by the DBMS. Another, similar example could be the *Levenshtein distance* [Lev65] – often used in computer linguistics – which is a distance metric on string values.

If now in addition, we consider Example 6.2, we see that restricting oneself to binary functions with $\mathbb{R}_{\geq 0}$ is also too limiting when facing certain practical scenarios.

Example 6.2   Distance Between a Vector and a Hyperplane

To find positive and negative examples $a_i \in \mathcal{D}_q \subset \mathbb{R}^{dim}$ given a linear classifier, e.g., provided by a SVM, we evaluate the distances between the attributes and a (query-)hyperplane described as $\mathbf{q}^T \mathbf{x} - b = 0$ with $\mathbf{q}, \mathbf{x} \in \mathbb{R}^{dim}$ and $b \in \mathbb{R}$. The distance function is then given by:

$$\delta(\mathbf{a}_i, \mathbf{q}, b) = \frac{\left\| \mathbf{q}^T \mathbf{a_i} + b \right\|}{\left\| \mathbf{q} \right\|} \tag{6.1}$$

δ now has the form $\delta \colon \mathbb{R}^{dim} \times \mathbb{R}^{dim} \times \mathbb{R} \to \mathbb{R}$. Hence, δ is no longer a binary but a ternay function with arguments $\mathbf{a_i}$, $\mathbf{q}$ and b. Furthermore, the distance may take negative values depending on whether a result is considered a positive or negative example.

Again, we are confronted with an example that violates the text-book definition of a distance function. While the idealized idea that distance functions used in proximity based queries must always constitute a metric on some real-valued vector space may be very common [ZAD+06], we see in practice that this assumption is often violated [BS19] and that many functions used to calculate proximity between objects, are not actual metrics. Even though, this can be a disadvantage when considering high-dimensional index structures that exploit the geometric properties of metric spaces, it is obvious that such functions exist and must thus be considered in any generalized database application supporting proximity based queries.

In contrast, there is actually good reason to assume the codomain of a distance function δ to lie in $\mathbb{R}$. On the one hand, it is obviously convenient both for the underlying mathematics as well as from an implementation prespective. More importantly, however, real numbers – unlike, for example, complex numbers or vectors – come with a natural, total ordering, which is required for a lot of downstream operations such as sorting or clustering.

To summarize, we now find ourselves in the position where, on the one hand, we require a proper definition of what is considered to be a valid distance function so as to be able to efficiently plan and execute queries that use them, while on the other hand keeping that definition open enough to accomodate the many different, applications.

To address the aforementioned limitations while still accomodating classical, metric distances, we propose the extension of a the distance function to the more general notion of a Distance Function Class (DFC) following Definition 6.2.

More examples

Definition 6.2   Distance Function Class

A DFC $\hat{\delta} \colon \mathcal{D}_q \times \mathcal{D}_q \times \mathcal{D}_1 \ldots \times \mathcal{D}_N \to \mathbb{R}$ is an N-ary but at least binary function $\hat{\delta}(p, q, s_1, \ldots, s_n)$ that outputs a distance $d \in \mathbb{R}$ between a probing argument $p \in \mathcal{D}_q$ and a query argument $q \in \mathcal{D}_q$ using a defined number of *support arguments* $s_{k \in \mathbb{N}}$ from any of the data domains in $\mathbb{D}$.

A DFC (and any function for that matter) is uniquely defined by its *signature*, a $(N + 1)$-tuple specifying the name of the DFC and the data domains $\mathcal{D}_i$ of the arguments it can accept as defined in Equation (6.2). As a convention for notation, the probing argument p of a DFC $\hat{\delta}(p, q, s_1, ..., s_n)$ will always come first, followed by the query argument q, again followed by its support arguments s_k in no particular order.

$$\mathrm{SIG}(\hat{\delta}) = (\mathrm{NAME}, \mathcal{D}_p, \mathcal{D}_q, \mathcal{D}_1, ...\mathcal{D}_{N-2}) \tag{6.2}$$

In the context a concrete execution plan for a proximity based query, we observe that most of the time, the query argument effectively remains constant, while the support arguments may or may not be subject to change. For example, for simple NNS, there is a single, constant query vector that is compared against all the vectors in the DBMS, i.e., the probing argument. Hence, irrespective of the arity of the DFC, its (partial-) *implementation* δ used during execution, comes with an arity of at most $N - 1$. This is denoted by Equation (6.3).

$$\delta = \mathrm{IMP}(\hat{\delta}) \ni \mathrm{SIG}(\delta) \subset \mathrm{SIG}(\hat{\delta}) \tag{6.3}$$

With this idea of a DFC and its implementation in mind, we can start to reason about their properties in the broader context of database operations in general and proximity based queries in particular:

DFC and Proximity Based Queries In extension to Definition 6.1, we realise that any query execution plan that involves the evaluation of a (partial) implementation of a DFC, falls into the category of a proximity based query.

Purity of Domain Since the purpose of a DFC is to quantify proximity between a probing argument p and a query argument q, we can assume that $p, q \in \mathcal{D}_q$.

Scalarity of Codomain A DFC and its implementations always produce a single, scalar output $d \in \mathbb{R}$ to quantify the distance.

Minkowski Distance   **Hyperplane Distance**
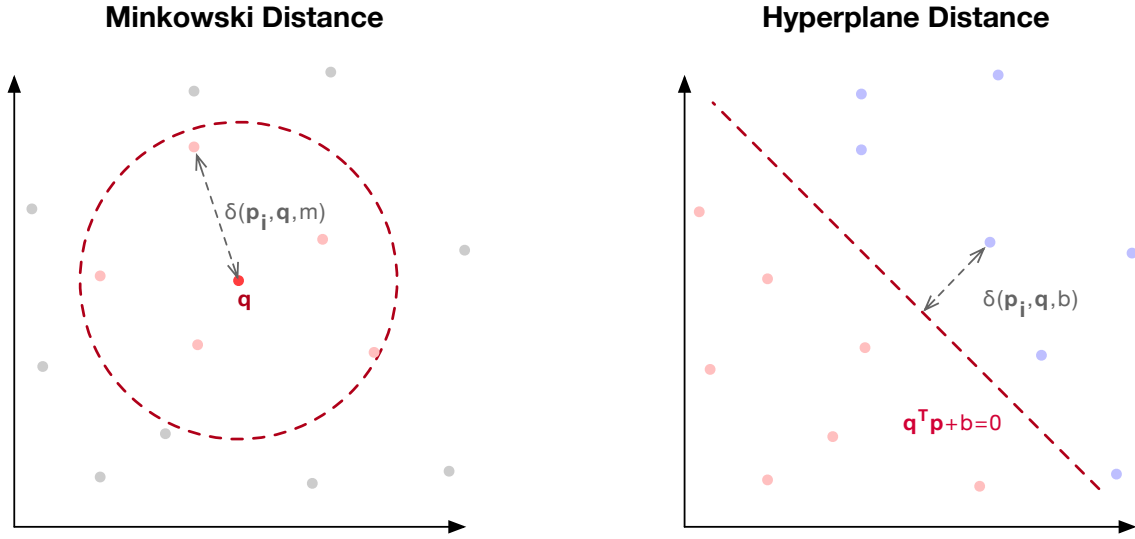
Figure 6.1 **Two examples of distance functions that fall into the broader category of a DFC. On the left, the point-distance between** q **and** p_i **and on the right, the distance between a hyperplane** $q^T x + b = 0$ **and points** p_i**.**

From the perspective of the DBMS, DFCs often represent a family of higher-order functions, which parametrize lower-order functions using the query q and support arguments s_k. Implementing a DFC in essence means fixing values for q and s_k in the context of a query, where this is possible given its general structure. This implementation requirement enshrines that for a proximity based query, altering q and (sometimes) even s_k constitutes a different query.

An illustrative and widely used example of a DFC would be the family of *Minkowski Distances* $\hat{\delta}_M \colon \mathbb{R}^{dim} \times \mathbb{R}^{dim} \times \mathbb{R} \to \mathbb{R}_{\geq 0}$ with its two, partial implementations, the Manhattan (L1) and the Euclidean (L2) distance:

$$\hat{\delta}_M(\mathbf{a}, \mathbf{q}, p) = \left(\sum_{i=1}^{n} | q_i - a_i |^p \right)^{\frac{1}{p}} \tag{6.4}$$

$$\hat{\delta_{L1}}(\mathbf{a}, \mathbf{q}) = \text{IMP}_{p=1}(\hat{\delta}_M) = \sum_{i=1}^{n} | q_i - a_i | \tag{6.5}$$

$$\hat{\delta_{L2}}(\mathbf{a}, \mathbf{q}) = \text{IMP}_{p=2}(\hat{\delta}_M) = \sqrt{\sum_{i=1}^{n} | q_i - a_i |^2} \tag{6.6}$$

However, using the idea of a DFC, we can express many different types of much more complex distance functions in a simple yet powerful framework. Two examples are illustrated in Figure 6.1 and it is easy to see that both the functions used in Example 6.1 (complex domain) and Example 6.2 (ternay function with scalar support argument) fall into the category of a DFC.

As an aside, we must address the role of dimensionality *dim* in the case of data domains that are subsets of vector spaces, i.e., $\mathcal{D}_q \subset \mathbb{R}^{dim}$ or $\mathcal{D}_q \subset \mathbb{C}^{dim}$. One could argue, that the dimensionality of such a vector space can also be seen as a parameter of the DFC. Irrespective of the merits such an argument might have, we consider the dimensionality of the vector space to be a strictly structural property of the underlying data domain $\mathcal{D}_q$ and thus thightly coupled to the data type. This means, that the data types and by extension the dimensionality of all of the attributes involved are well-defined and remain constant for a query.

6.1.2   Extending the Relational Model

Using Definition 6.2, one can now start to integrate DFCs into the relational data model. In line with [Gia18], we first assume $\mathbb{D}$ – the set system of data domains supported by the database – to be extended by whatever data domain $\mathcal{D}_q$ is required, such as but not limited to $\mathbb{R}^{dim}$ or $\mathbb{C}^{dim}$.

Extended Projection and DFCs   We use the idea of an extended projection $\pi_{\mathcal{E}}$ – as proposed by [GHQ95; GUW09] and introduced in Section 3.2 – wherein $\mathcal{E}$ denotes a list of projection expressions e that involve attributes $\mathcal{A}_i \in \mathcal{R}$. That is, in addition to the simple projection onto attributes $\mathcal{A}_i$, an extended projection may also include the evaluation of literals or functions as expressed in Definition 6.3.

Definition 6.3   Extended Projection $\pi_{\mathcal{E}}$

Let $\mathcal{R}$ be a N-ary relation over attributes $\mathcal{A} \in \text{SCH}(\mathcal{R})$ with tuples $t \in \mathcal{R}$. We call $\pi_{\mathcal{E}}$ the *extended projection* with K projection elements $e_i \in \mathcal{E}$, i.e.,

$$\mathcal{E} = \{e_1, e_2, \ldots e_K\}, \text{with } e_i \in \text{SCH}(\mathcal{R}) \vee e_i \in \mathcal{D}_i \vee e_i \in \mathbb{F}$$

where $\mathbb{F}$ is a set of all functions $f_i \colon \mathcal{D}_1 \times \mathcal{D}_2 \ldots \mathcal{D}_M \to \mathcal{D}_{out}$ known to the DBMS and $\mathcal{D}_i \in \mathbb{D}$. The extended projection is then defined as follows:

$$\pi_{\mathcal{E}}(\mathcal{R}) = \{t\,[\mathcal{E}] : t \in \mathcal{R}\} \text{ with } t\,[\mathcal{E}] = \bigcup_{e_i \in \mathcal{E}} \begin{cases} t\,[e_i] & \text{if } e_i \in \text{SCH}(\mathcal{R}) \\ e_i & \text{if } e_i \in \mathcal{D}_i \\ e_i(t\,[\mathcal{E}']) & \text{if } e_i \in \mathbb{F} \end{cases}$$

It is to be noted, that the domain of every function $f_i \in \mathbb{F}$ is again, an implicit, extended projection $t\,[\mathcal{E}']$, where $\mathcal{E}'$ contains all projection elements required as function arguments. Hence, function invocations can be nested arbitrarily.

If now we assume any DFC supported by the DBMS to be member of $\mathbb{F}$, the evaluation of a DFC as part of a query is given by Definition 6.4.

Definition 6.4   Distance Function Class in Extended Projection $\pi_{\mathcal{E}}$

Let $\hat{\delta}\colon \mathcal{D}_q \times \mathcal{D}_q \times \mathcal{D}_1 \ldots \times \mathcal{D}_{N-2} \to \mathbb{R}$ be a N-ary DFC. The *extended projection* $\pi_{\hat{\delta}(a_1,a_2,\ldots a_N)}(\mathcal{R})$ with $a_i \in \mathtt{SCH}(\mathcal{R}) \vee a_i \in \mathcal{D}_i \vee a_i \in \mathbb{F}$ denotes the evaluation of $\hat{\delta}$ using any number of argument. Applying $\pi_{\delta(\cdot)}$ on a M-ary relation $\mathcal{R}$ introduces a new distance attribute $\mathcal{A}_\delta$, i.e., $\mathtt{SCH}(\pi_{\hat{\delta}(\cdot),\mathcal{A}_1,\ldots\mathcal{A}_M}(\mathcal{R})) = \mathtt{SCH}(\mathcal{R}) \cup \{\mathcal{A}_\delta\}$

Obviously, the evaluation of multiple DFCs in a single, extended projection or the combination of simple attribute projections with the evaluation of DFCs are also allowed. In fact, all of the following expressions are valid examples of the extended projection on relation $\mathcal{R}$ with $\mathtt{SCH}(\mathcal{R}) = \{\mathcal{A}_1,\mathcal{A}_2,\mathcal{A}_3,\mathcal{A}_4\}$ and $\delta_i = \mathtt{IMP}(\hat{\delta}_i)$: (i) Evaluation of multiple DFCs with same or different probing arguments (e.g., $\pi_{\delta_1(\mathcal{A}_1),\delta_2(\mathcal{A}_1)}(\mathcal{R})$), (ii) evaluation of same DFC using same or different probing arguments (e.g., $\pi_{\delta_1(\mathcal{A}_1),\delta_1(\mathcal{A}_2)}(\mathcal{R})$), (iii) combination of DFCs with any attribute projection and/or algebraic expression evaluation (e.g., $\pi_{\delta(\mathcal{A}_1),\mathcal{A}_2,\mathcal{A}_4}(\mathcal{R})$).

With the proposed, extended projection, the obtained distance value becomes an explicit attribute in the relation $\pi_{\hat{\delta}(\cdot)}(\mathcal{R}) = \mathcal{R}'$, which can then be used by downstream, relational operators and/or be returned by the query to any calling system. This makes sense, for example in NNS, because the distance is usually converted to a similarity score by some correspondence function.

Ranked Relations   To support sorting by the obtained distance (or any other attribute for that matter), which is an essential part of many types of proximity based queries, we use a variant of the *ranked relation* as proposed by [LCI+05] and described in Section 3.2.3. A ranked relation $\mathcal{R}^O$ exhibits an ordering of tuples $t \in \mathcal{R}^O$, which is induced by O. As opposed to [LCI+05] and more in line with [GUW09], we assume $O \subset \mathtt{SCH}(\mathcal{R})$ to be a sequence of *attributes* by which the relation should be sorted,[1] as is specified in Definition 6.5.

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[1] We argue that formally, the evaluation of a *scoring function*, as proposed by [LCI+05], can be expressed within the scope of the extended projection and does not need to be part of the order operation.

Definition 6.5   Ranked relation $\mathcal{R}^O$

Let $\mathcal{R}$ be a N-ary relation over attributes $\mathcal{A} \in \text{SCH}(\mathcal{R})$ with M tuples $t_m \in \mathcal{R}$. We call $\mathcal{R}^O$ a *ranked relation* with ranking attributes $O \subset \text{SCH}(\mathcal{R})$. O induces a non-strict, total ordering using the binary, lexicographic ranking relation $\leq$, such that:

$$t_i \leq t_k = \bigvee_{a \in O} t_i \leq_a t_k, \text{with}$$

$$t_i \leq_a t_k \leftrightarrow t_i[a] \leq t_k[a]$$

The position of a tuple $t_m \in \mathcal{R}^O$ w.r.t. $\leq$ is signified by the ranking function

$$\text{RANK} : \mathcal{R} \to [1, M]$$

which assigns a rank $m \in [1, M]$ depending on the tuple's position within $\mathcal{R}^O$, i.e., the first tuple t_1 gets rank 1, second tuple t_2 rank 2 etc.

It is to be noted, that the ranking O is an inherent property of a ranked relation $\mathcal{R}^O$ as is, for example, its schema $\text{SCH}(\mathcal{R})$. That property is retained or induced as operators are being applied. Furthermore, if a relation does not exhibit a specific ordering, then O is empty and $\mathcal{R}^O = \mathcal{R}^\emptyset = \mathcal{R}$. Importantly, though, we expect an unordered relation to still exhibit some interal ordering of tuples, which we call the *natural ordering* of $\mathcal{R}$ and which is not related to any observable property. Consequently, RANK is also defined for such relations, even though the returned values may appear arbitrary.

To explicitly order a relation, we introduce the *relational order operator* τ_O, which simply imposes order O on relation $\mathcal{R}$, overriding any previous ordering, as denoted by Equation (6.7).

$$\tau_O(\mathcal{R}) = \mathcal{R}^O \tag{6.7}$$

For example, using the relation $\mathcal{R}$ with $\text{SCH}(\mathcal{R}) = \{\mathcal{A}_1, \mathcal{A}_2, \mathcal{A}_3, \mathcal{A}_4\}$, the application of $\tau_{\mathcal{A}_1, \mathcal{A}_2}$ on relation $\mathcal{R}$ sorts the tuples $t_i \in \mathcal{R}$ based on $\mathcal{A}_1$ and breaks ties sorting by $\mathcal{A}_2$. Tuples that are equal in both attributes appear in natural, i.e., arbitrary order. To support ascending ($\uparrow$) and descending ($\downarrow$) sort direction, we can use the duality property of the individual ranking relations in an actual implementation.

k-selection   To be able to execute a specific type of proximity based query –
namely, kNN or kFN – we require one last extension to the relational algebra in
the form of the *k-selection* operator $\lambda(\mathcal{R})$, which simply limits the cardinality of
a relation $\mathcal{R}$ to the first k tuples. It is trivial to see that for a ranked relation $\mathcal{R}^O$,
$\lambda_k(\mathcal{R}^O)$ limits the tuples to the top k results w.r.t. to the ordering induced by O.

$$\lambda_k(\mathcal{R}^O) = \{t \in \mathcal{R}^O : \text{RANK}(t) \le k\} \tag{6.8}$$

We can now use Example 6.3 to demonstrate the flexibility of the proposed
algebra and the different types of queries that can be expressed through it.

Example 6.3   Relation listing paintings with feature vectors

$\mathcal{R}_p$ lists paintings with their title $\mathcal{A}_t$, the year of their creation $\mathcal{A}_y$ and some
arbitrary feature vector $\mathcal{A}_f$. Note that $\mathcal{D}_f \subset \mathbb{R}^3$.

$\mathcal{R}_p$	$\mathcal{A}_t$	$\mathcal{A}_y$	$\mathcal{A}_f$
t_1	Mona Lisa	1506	$[0.0, 0.2, -1.3]$
t_2	The Starry Night	1889	$[1.0, 0.9, 2.6]$
...	...	...	...
t_N	Las Meninas	1665	$[-0.5, 3.0, 0.8]$

Using DFCs and the proposed, relational algebra extensions, we can now ex-
press:

Name	Result	Algebraic Form
NNS / kNN	$\mathcal{R}^{\mathcal{A}_d\uparrow}$	$\lambda_k(\tau_{\mathcal{A}_d\uparrow}(\pi_{\mathcal{A}_y,\delta(\mathcal{A}_f)}(\mathcal{R}_p)))$
FNS / kFN	$\mathcal{R}^{\mathcal{A}_d\downarrow}$	$\lambda_k(\tau_{\mathcal{A}_d\downarrow}(\pi_{\mathcal{A}_y,\delta(\mathcal{A}_f)}(\mathcal{R}_p)))$
ϵNN [Gia18]	$\mathcal{R}^{\mathcal{A}_d\uparrow}$	$\tau_{\mathcal{A}_d\uparrow}(\sigma_{\mathcal{A}_d\le\epsilon}(\pi_{\mathcal{A}_y,\delta(\mathcal{A}_f)}(\mathcal{R}_p)))$
NNS w. selection	$\mathcal{R}^{\mathcal{A}_d\uparrow}$	$\tau_{\mathcal{A}_d\uparrow}(\pi_{\mathcal{A}_{year},\delta(\mathcal{A}_f)}(\sigma_{\mathcal{A}_y=1889}(\mathcal{R}_p)))$
Multi order	$\mathcal{R}^{\mathcal{A}_{d1}\uparrow,\mathcal{A}_{d2}\uparrow}$	$\tau_{(\mathcal{A}_{d1}\uparrow,\mathcal{A}_{d2}\uparrow}(\pi_{\delta_1(\mathcal{A}_f),\delta_2(\mathcal{A}_f)}(\mathcal{R}_p))$
Aggregation by distance	$\mathcal{R}$	

6.1.2.1   Algebraic Properties of $\pi_{\mathcal{E}}, \tau_O, \lambda_k$

Since a query planner of a DBMS must be able to manipulate the operators that
were introduced before, there is a series of algebraic properties that must be
specified. For unary operators, we must consider *commutativity*, i.e., whether
changing the order of application leads to the same result or not. Two unary
operators OP_1, OP_2 commute if, and only if, $\text{OP}_1(\text{OP}_2(\mathcal{R})) = \text{OP}_2(\text{OP}_1(\mathcal{R}))$.

Table 6.1 The relational operators and their properties w.r.t to the proposed extensions.

Name	Symbol	Arity	Order	Commutativity	Distributivity
Union	$\mathcal{R}_L^{O_1} \cup \mathcal{R}_R^{O_2}$	2	$\emptyset$	✓	-
Intersection	$\mathcal{R}_L^{O_1} \cap \mathcal{R}_R^{O_2}$	2	O_1	✗	-
Difference	$\mathcal{R}_L^{O_1} \setminus \mathcal{R}_R^{O_2}$	2	O_1	✗	-
Cartesian Product	$\mathcal{R}_L^{O_1} \times \mathcal{R}_R^{O_2}$	2	$\emptyset$	✗	-
Natural Join	$\mathcal{R}_L^{O_1} \bowtie_{\mathcal{P}} \mathcal{R}_R^{O_2}$	2	O_1	✗	-
Rename	$\rho_{\mathcal{A}_A \rightarrow \mathcal{A}_B}(\mathcal{R}^O)$	1	O	$\pi, \sigma, \rho, \lambda, \tau$	$\cup, \cap, \setminus, \times, \bowtie$
Selection	$\sigma_{\mathcal{P}}(\mathcal{R}^O)$	1	O	π, σ, ρ, τ	$\cup, \cap, \setminus, \times, \bowtie$
Extended Projection	$\pi_{\mathcal{E}}(\mathcal{R}^O)$	1	O	$\pi, \sigma, \rho, \lambda, \tau$	$\cup$
Limit	$\lambda(\mathcal{R}^O)$	1	O	π, ρ	✗
Order	$\tau_O(\mathcal{R}^{O'})$	1	O	π, σ, ρ	$\cap, \setminus, \bowtie$

For binary operators, we must consider the *commutativity of operands*, i.e., whether $\mathrm{OP}(\mathcal{R}_L, \mathcal{R}_R) = \mathrm{OP}(\mathcal{R}_R, \mathcal{R}_L)$. Furthermore, w.r.t. to unary operation, there is *distributivity* to consider, i.e., whether $\mathrm{OP}_1(\mathrm{OP}_2(\mathcal{R}_L, \mathcal{R}_R)) = \mathrm{OP}_2(\mathrm{OP}_1(\mathcal{R}_L), \mathrm{OP}_1(\mathcal{R}_R))$.

In addition, to support ranked relations, we must require all existing, relational operators to be either *order retaining* or *order inducing*. A summary of these properties can be found in Table 6.1.

It follows directly from its definition, that τ_O is an order inducing operator. Furthermore, σ, π, ρ and λ are order retaining, since they do not alter the input relation w.r.t ordering.

It is a bit more complicated for the binary operators, which do not behave consistently: On the one hand, the set difference ($\setminus$), the set intersection ($\cap$) and the natural join ($\bowtie_{\mathcal{P}}$) retain the order of the left operand $\mathcal{R}_L$, since the operators retain or remove elements from $\mathcal{R}_L$ based on their presence in $\mathcal{R}_R$, without taking ordering into account. As a consequence, the operands no longer commute, since it is always the left operand that defines the output ordering.

The set union ($\cup$) and the cross product ($\times$), on the other hand, combine two relations $\mathcal{R}_L$ and $\mathcal{R}_R$. The resulting relation does not have an order that can be expressed in the proposed framework and must thus be considered unordered, i.e., the operators are order inducing in that they induce a new, natural ordering.

When turning to the individual operators, the extended projection $\pi_{\mathcal{E}}$ inherits all its properties from the normal projection π if we require $f \in \mathbb{F}$ to be stateless and side-effect free, i.e., it must not influence the state of the DBMS in any other way than producing the desired output and it must not maintain an internal state itself. Irrespective of $\pi_{\mathcal{E}}$, this is a reasonable assumption also from a implementation perspective.

Double-check properties in table.

The order operator τ_O is idempotent and commutes with other unary operators if they are neither *rank sensitive* nor *rank inducing*, namely, π, σ and ρ. Importantly, τ_O does not commute with itself.

$$\tau_{O'}(\tau_O(\mathcal{R})) \neq \tau_O(\tau_{O'}(\mathcal{R}))$$

In addition, distributivity with all the order retaining binary operations is given, e.g., when taking set intersection as an example.

$$\tau_O(\mathcal{R}_L^{O_L} \cap \mathcal{R}_R^{O_R}) = \tau_O(\mathcal{R}_L^{O_L}) \cap \tau_O(\mathcal{R}_R^{O_R})) = (\mathcal{R}_L \cap \mathcal{R}_R)^O$$

However, the order operator does not distribute with the order inducing, binary operators $\cup$ and $\times$, for example, taking set union as an example.

$$\tau_O(\mathcal{R}_L^{O_L} \cup \mathcal{R}_R^{O_R}) = (\mathcal{R}_L^{O_L} \cup \mathcal{R}_R^{O_R})^O \overset{!}{\neq} \tau_O(\mathcal{R}_L^{O_L}) \cup \tau_O(\mathcal{R}_R^{O_R})) = (\mathcal{R}_L \cup \mathcal{R}_R)^\emptyset$$

Finally, the k-selection operator λ is also idempotent but does neither commute with the selection operator σ nor the order operator τ.

$$\lambda(\tau(\mathcal{R})) \neq \tau(\lambda(\mathcal{R}))$$
$$\lambda(\sigma(\mathcal{R})) \neq \sigma(\lambda(\mathcal{R}))$$

Lack of commutativity of λ with τ follows directly from its definition: λ is sensitive to the ranking of $\mathcal{R}^O$ and τ influences that ranking. Consequently, executing λ before or after imposing a certain order will yield different results. For commutativity with σ, one can turn to Proof 6.1.

Proof 6.1   Non-commutativity of σ and λ

Let $\mathcal{R}$ be a relation with M rows and $\text{SCH}(\mathcal{R}) = \{\mathcal{A}_R\}$ and let further be $t\,[\mathcal{A}_R] = \text{RANK}(t) \forall t \in \mathcal{R}$. If σ and λ_k were to commute, then

$$\sigma_{\mathcal{A}_R > M-2}(\lambda_{M-1}(\mathcal{R})) = \lambda_{M-1}(\sigma_{\mathcal{A}_R > M-2}(\mathcal{R}))$$

However, we can proof by contradiction that this does not hold since:

$$\sigma_{\mathcal{A}_R > M-2}(\lambda_{M-1}(\mathcal{R})) = \{t_M\} \overset{!}{\neq} \lambda_{M-1}(\sigma_{\mathcal{A}_R > M-2}(\mathcal{R})) = \{t_{M-1}, t_M\}$$

That is, whenever λ_k removes tuples that match the predicate of σ, the order of execution influences the result and the two operators do not commute.

Figure 6.2 **Function hierarchy of all** $f \in \mathbb{F}$. **As we go down the hierarchy, the DBMS gains knowledge about a function's structure.**

6.1.3 DFCs and Query Planning

In addition to the algebraic properties of the extended relational algebra, we can also leverage the requirements imposed on the structure of a function $f \in \mathbb{F}$ to enable a DBMS to plan and optimize the execution of a proximity based query by altering the execution plan in terms of DFC implementations that should be employed. To do so, we must first assume that a DBMS maintains the collection of functions $\mathbb{F}$. Since every function can be identified by its signature SIG, $\mathbb{F}$ can be used for obtaining the correct function implementation given the specification of the query. We refer to this data structure as *function registry*, which can also be used to store additional properties and metadata.

In addition, we propose the notion of a *function hierarchy* depicted in Figure 6.2. As we move down that hierarchy, more information about the structure of a DFC and the concrete implementation employed in a query plan becomes available to the DBMS. That information can be leveraged when deciding about the best execution path for a query, wherein every level offers certain properties that can be leveraged:

General Function Every function $f \in \mathbb{F}$ is known with information about its name and domain (i.e., its signature SIG(f)). This enables the DBMS to provide optimised implementationsor to provide replacements for composit operations.

Distance Function Class Since DFCs constitute a specific type of function, we
can embedd equivalences between a DFC and different types of high-dimensional
index structures directly within the function registry. Those equivalences al-
low a query planner to select one over the other, for a particular plan.

Logical Implementation As an implementation of a query manifests, the struc-
ture of a DFC may change through implementation $\delta = \texttt{IMP}(\hat{\delta})$. For example,
certain attributes may turn-out to remain constant, which can be leveraged
by the planner to optimise execution.

Physical Implementation As the physical execution plan emerges, a plan can
make decisions as to what type of implementation for a DFC should be se-
lected. For example, it may select a vectorised version of a DFC, which
leverages Single Instruction Multiple Data (SIMD) instructions of the CPU,
over a scalar implementation that calculates the distance in a tight loop.

6.1.3.1 Functions and Optimised Implementations

Optimising implementations of DFCs and general function invocations can be
achieved in multiple ways. First, it is reasonable to provide and select imple-
mentations that are specific for the data type of the function arguments, so as to
avoid type conversion in a tight loop over a large amount of data. From the per-
spective of execution performance, it is desirable to make this selection during
planning rather than at query execution time.

Another aspect that can be optimised is the use of vectorized implementa-
tions for computations that involve vectors or matrices, i.e., exchanging a scalar
implementation of a DFC by an implementation that uses SIMD instructions.
However, it is to expected that one challenge lies in finding the threshold af-
ter which usage of such an optimised version pays off. If we take real-valued
vectors as an example, it is likely that vectorised execution will not benefit low-
dimensional vectors (e.g., $dim = 3$) while it will greatly benefit high-dimensional
vectors (e.g., $dim = 2048$). Finding this threshold poses challenge in and by itself,
which could be subject for future research.

Finally, one can also try to match constellations of nested functions and re-
place them with optimised version. An example could be the expression $a * b + c$,
i.e., $\texttt{add}(\texttt{mul}(a, b), c)$, which can be replaced by a single *fused multiply-add* func-
tion $\texttt{fma}(a, b, c)$ to avoid loss of precission. In a manner of speaking, trading-in
a high-dimensional index for the execution of a DFC also falls into this category.

6.1.3.2 DFCs and High-dimensional Index Structures

One identity that is particularly relevant for the execution of proximity based queries is the relationship between the execution of a DFC and a high-dimensional index. While there are many different types of HD-indexes, we distinguish between three broader categories proposed by [LÁJ+18] and introduced and discussed in Chapter 4, namely *quantization based* (e.g., PQ or VAF), *hash based* (e.g., LSH or SH) and *tree based* (e.g., NV-tree [LJA11]) indexes. We postulate the relationship between a high-dimensional index and a DFC given in Definition 6.6.

Definition 6.6   DFCs and high-dimensional index structures (exact case).

Let $\hat{\delta} \colon \mathcal{D}_q \times \mathcal{D}_q \times \mathcal{D}_1 \ldots \times \mathcal{D}_n \to \mathbb{R}$ be a DFC and $\pi_{\mathcal{E}}$ be the extended projection involving execution of that DFC, i.e., $\hat{\delta} \in \mathcal{E}$. A high-dimensional index INDEX is a pre-computed database object such that $\pi_{\hat{\delta}(\cdot)}(\mathcal{R}) = \text{INDEX}(\mathcal{R})$ and therefore, the following equation holds:

$$\pi_{\mathcal{E}}(\mathcal{R}) = \pi_{\mathcal{E} \setminus \hat{\delta}}(\mathcal{R}) \bowtie \text{INDEX}(\mathcal{R})$$

We call such an index *exact* and we can use it as a replacement for the DFC.

In addition to Definition 6.6, the following restrictions apply (in addition to implementation specific restrictions for a specific index):

- Indexes are always derived from a materialized relation $\mathcal{R}$ and a feature attribute $\mathcal{A}_f \in \text{SCH}(\mathcal{R})$. Therefore, an index can only replace a DFC if they operate on an unaltered version of $\mathcal{A}_f$. Changes to $\mathcal{A}_f$, e.g., through application of a nested function, will render the index unusable unless the same alteration was applied when creating the index.

- Indexes are usually trained for a specific distance function (e.g., Euclidean) or class of distance functions (e.g., Minkowski). Therefore, an index can only replace a DFC if that DFC coincides with the original function (-class).

With Definition 6.6 and the aforementioned, we have defined the basic relationship and rule that can be applied by a DBMS, when deciding whether or not to use a particular high-dimensional index structure. We will provide more insights into the nature of *approximate* index structures in Section 6.2.

6.2   Cost Model for Retrieval Accuracy

As we have explained in Chapter 3, most DBMS rely on a cost-model for planning and selecting the execution and access path of a user-specified query. In fact, ever since the System R paper [SAC+79], cost-based query planning and optimisation is considered a gold standard for database systems.

Must traditional DBMS exhibit comparatively simple cost-models that mainly rely on the cost incurred by accessing (reading / writing) pages from or to disk. Based on what has been discussed thus far, we argue that such a model has several shortcomings and that a cost model from multimedia databases should take the following aspects into account when chosing an execution path:

Disk Access (IO) Persistent storage and the access to information residing on disk is still the factor that contributes the most to long query execution times and is thus something, that a system should try to minimise [SAC+79].

CPU Due to the computational complexity of proximity based operations, especially when high-dimensional vectors are involved, the processing time on CPU is a factor that can no longer be ignored and must thus be taken into account as well. For example, several index structures achieve speed-up by reducing the computational complexity of the operations involved [WSB98; JDS10]

Memory Some algorithms, e.g., for sorting, can benefit greatly from pure in-memory processing as opposed to writing intermediate results to disk. While memory used to be a scarce resource, some environments allow for complete in-memory process even for very large datasets.

Inaccuracy The inaccuracy of a result incurred, e.g., by the choice of a certain high-dimensional index structure [IM98; JDS10], is a price that can be paid to attain speed-up but should be transparent to the system.

These factors can be used to characterise query workloads in a purely local setup consisting of a single node. For distributed databases, obviously, the cost incurred by data and message exchange must be considered as well. However, this is not in scope for the work presented in this Thesis. The aforementioned factors lead us to Definition 6.7 for the cost incurred by a query execution plan P.

Definition 6.7 Cost of a Query Exection Plan.

Let P be an execution plan. The we call the 4-tuple $C = (c_{CPU}, c_{IO}, c_{MEM}, c_{ACC})$ the *cost* of P, which captures the atomic costs in terms of disk access (IO), CPU usage (CPU), memory usage (MEM) and accuracy (ACC).

As we have argued in chapter Chapter 2, the requirements to a database system, especially in terms of robustness against inaccuracy is highly use-case dependent. Some use-cases can accept inaccuracy in the results while others cannot. Furthermore, there may be

Describe cost model for execution plans with following properties:

– Cost as a function of atomic costs: $f(a_{cpu}, a_{io}, a_{memory}, a_{accuracy}) \longrightarrow C$

– Means to estimate results accuracy and associated considerations 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

– Systems perspective 1: How can such a cost model be applied during query planning and optimization?

6.3 Adaptive Index Management
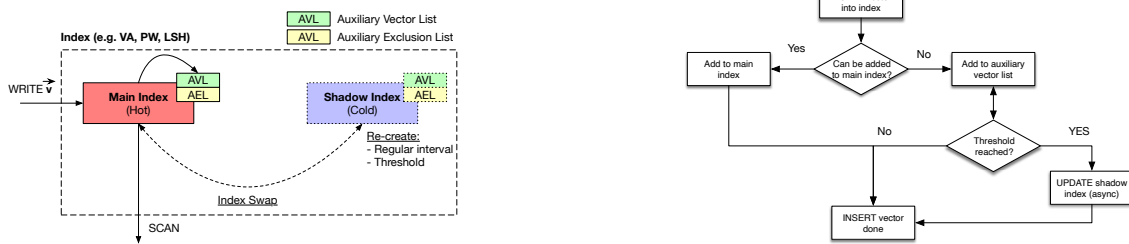
Figure 6.3 Adaptive index structures overview.

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

– Reason about properties of secondary indexes for NNS (e.q., PQ, VA, LSH) with regards to data change

- Derivation of error bounds possible (e.g., usable for planning)?! Use in query planning?

- Systems perspective 1: How to cope with "dirty" indexes? Proposal: hot vs. cold index, auxilary data structure, offline optimization, see Figure 6.3

- Systems perspective 2: On-demand index based on query workload?

6.4 Architecture Model

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

7

Cottontail DB

Cottontail DB [GRH+20] is our reference implementation for the query, cost and index-models described in Chapter 6. Starting out as a drop-in replacement for ADAMpro [GS16], it has grown to be a full fledged DBMS with support for both classical boolean retrieval as well as proximity based search used in multimedia retrieval and analytics applications. Both aspects are combined in a unified query and execution model and many explicit and implicit decisions, which are described in this chapter, went into its conception and design.

Cottontail DB is written in Kotlin[1] and runs on the Java Virtual Machine (JVM). *Cottontail DB*'s source code can be downloaded from GitHub[2]. It is freely available under a permissive open source license and can be used as standalone application, Docker container or in an embedded mode.

7.1   Data Model and Nomenclature

Cottontail DB uses a data model very similar to that of other relational DBMS': All data is organized into *entities* – which correspond to tables or relations. Every entity consists of individual, strongly typed *columns*. The different data types currently supported are listed in Table 7.1. Columns can hold values of the declared type or NULL to indicate the absence of information (if the column has been declared as being nullable). To support the features used in multimedia retrieval applications, vector types are first-class members the type system.

An entity can host multiple *records*, which correspond to tuples in the relation. Since *Cottontail DB* is a column store, records are only logical constructs in memory and do not reflect the physical data representation on disk. Conse-

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[1]   See: https://kotlinlang.org/
[2]   See: https://github.com/vitrivr/cottontaildb

Table 7.1　**Data types supported by *Cottontail DB*. Types in the numeric, vector and complex class allow for domain specific arithmetics.**

Name	Scalar	Numeric	Vector	Complex	JDBC / SQL
String	✓	✗	✗	✗	`VARCHAR`
Date	✓	✗	✗	✗	`TIMESTAMP`
Boolean	✓	✓	✗	✗	`BOOLEAN`
Byte	✓	✓	✗	✗	`TINYINT`
Short	✓	✓	✗	✗	`SMALLINT`
Int	✓	✓	✗	✗	`INT`
Long	✓	✓	✗	✗	`BIGINT`
Float	✓	✓	✗	✗	`REAL`
Double	✓	✓	✗	✗	`DOUBLE`
Complex 32	✓	✗	✗	✓	-
Complex 64	✓	✗	✗	✓	-
Boolean Vector	✗	✗	✓	✗	`ARRAY[BOOLEAN](1, d)`
Integer Vector	✗	✗	✓	✗	`ARRAY[INT](1, d)`
Long Vector	✗	✗	✓	✗	`ARRAY[BIGINT](1, d)`
Float Vector	✗	✗	✓	✗	`ARRAY[REAL](1, d)`
Double Vector	✗	✗	✓	✗	`ARRAY[DOUBLE](1, d)`
Complex32 Vector	✗	✗	✓	✗	-
Complex32 Vector	✗	✗	✓	✗	-

quently, records are assembled on-the-fly as queries are being executed. Similarily to columns, every record is also strongly typed, wherein a record is a tuple type of its strongly typed elements. Internally, every record is uniquely identified by a *tuple ID* (`TID`), which is a `long` value that can be used to address the record within an entity or an (in-memory) *recordset*. This `TID` is not exposed to the outside because it remains at the discretion of the storage and execution engine to generate, assign, change and (re-)use them as data gets (re-)organized.

Furthermore, *Cottontail DB* allows for multiple entities to be grouped into *schemata*, which currently serves an organisational purpose only. Every entity can also host one or multiple secondary *indexes* that index a single or multiple *columns* for more efficient data access. In addition to indexes for Boolean and Fulltext search, *Cottontail DB* also hosts different types of high-dimensional index structures used for proximity based queries, for example, PQ [JDS10], VAF [WSB98] and LSH-based [IM98] indexes.

To address database objects, *Cottontail DB* uses a hierarchical namespace, i.e., every schema, entity, column and index must be uniquely named by a *fully qualified name*. All the information about the database objects is tracked in an internal *catalogue*, which is backed by the main storage engine.
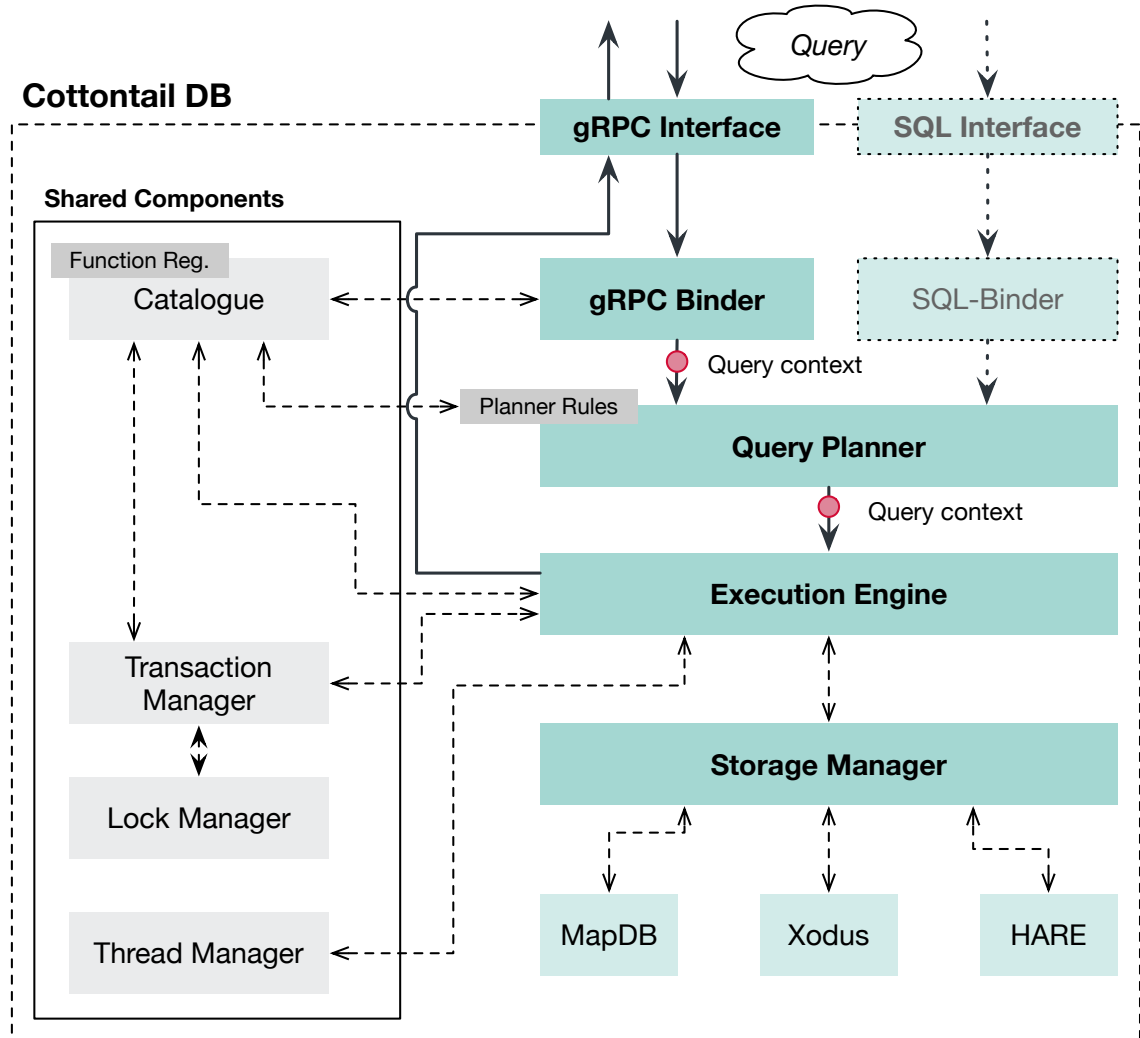
Figure 7.1   **Architecture diagram of *Cottontail DB*'s main components. The directed arrows indicate the path a query takes within the system. The dashed, double arrows indicate interactions between components.**

7.2   Architecture

The main components of *Cottontail DB* are depicted in Figure 7.1. We use the path a query takes within the system, as indicated by the directed arrows, to illustrate the components involved in its implementation.

At a high level, every query must undergo *parsing*, *binding*, *planning* and *execution* in that order, even though, planning may be skipped for certain types of queries (e.g. DDL statements). Starting with the binding step, all the information required for query processing is accumulated in a *query context* object, which is passed between the steps. In the following sections, we will describe the aforementioned steps in reverse order, since important concepts can be introduced more naturally that way.

Table 7.2 **Main types of operators implemented by *Cottontail DB* alongside with their arity, their correspondence to relational operators and whether or not they require materialization.**

Type	Arity	Rel. Op.	Mat.	Description
Scan	0	$\pi_\mathcal{E}$ $\sigma_\mathcal{P}$ $\rho_{\mathcal{A}_A \to \mathcal{A}_B}$		Act as data sources. Usually scan an *entity* or an *index* and thus interact directly with the storage manager to do so.
Fetch	1	$\pi_\mathcal{E}$		Extend every incoming record by fetching values for one or multiple columns and appending them to the record. Usually interact directly with the storage manager to perform random reads.
Function	1	$\pi_\mathcal{E}$		Extend every incoming record by evaluating a specific function and appending the result as a new column to the record.
Filter	1	$\sigma_\mathcal{P}$		Filter incoming records by evaluating a given predicate. Records that don't match the predicate are not handed down the pipeline.
Sort	1	τ_O	✓	Sort the incoming records based on the specified columns in the specified direction.
Limit	1	λ_k		Skip and drop incoming records according to specification and thus limit the number of outbound records to a specified number
Project	1	π_χ $\rho_{\mathcal{A}_A \to \mathcal{A}_B}$		A terminal operator that actively removes and/or renames columns in the incoming records. This is sometimes necessary because columns that are fetched for processing may not be desired in the final result.

7.2.1 Query Implementation and Execution

Cottontail DB implements an *iterator model* for query execution. This means that an implemented query is a pipeline of operators, wherein each operator processes single records it receives from its upstream (input) operator(s) and passes single records to the next operator in the pipeline. Most operators have a direct correspondence to the relational operators (Chapter 3) and extensions (Chapter 6) introduced thus far. However, not all operators behave exactly as required by the model due to implementation details.

Conceptually, *Cottontail DB* distinguishes between *Nullary*, *Unary*, *Binary* and *N-Ary* operators, which differ in the number of inputs they can accept (0, 1, 2 or N). Furthermore, some operators require materialization of intermediate result-sets and therefore act as pipeline breakers since they must collect all inbound records before they can start handing them down (e.g., sort operator). The most important types of operators implemented by *Cottontail DB* along with their correspondence to the relational operators are listed in Table 7.2.
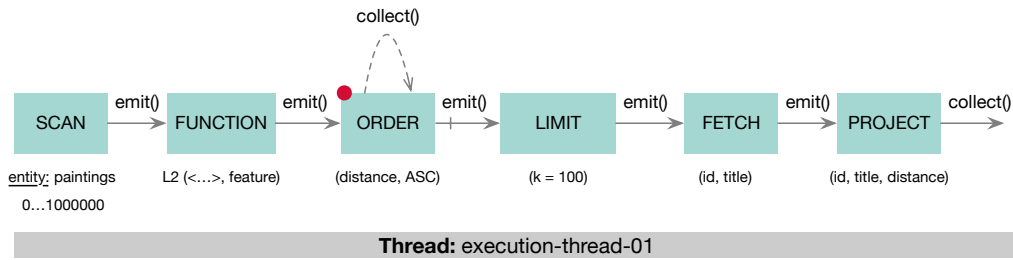
Figure 7.2 **Operator pipeline for a proximity based query that scans the entity *paintings*, caluates the L2 distance between a *feature* column and a query, orders by the obtained distance and limits the number of outputs (kNN). Pipeline breaking operators are indicated by the red dot.**

Every operator is implemented in Kotlin and pre-compiled to byte code. Ergo, there is no on-the-fly code generation at runtime. The operator implementations are derived from the plan that is selected in the planning stage.

7.2.1.1 Execution Model

Operators in *Cottontail DB* are implemented as *coroutines*, i.e., every operator is a suspendable function that yields to the next operator in the pipeline upon emission of a value. Each operator collects a single record from its input operator(s), performs processing and forwards the resulting record by calling `emit()`, thus yielding to the next operator in the pipeline. Source operators usually iterate some data collection through a cursor and thus only `emit()` values, whereas sink operators `collect()` values without emiting anything (practically, the collected values are usually sent to the client that issued the query). Pipeline breaking operators are required to `collect()` all inbound values before they can start to `emit()`, i.e., they materialize a recordset. The suspension and continuation of operator calls is orchestrated by Kotlin's coroutines "Flow" framework[3]. A very simple example of a naive operator pipeline is provided in Figure 7.2.

Inter-query parallelism is achieved, by collecting different operator pipelines on different threads. The assignment of operator pipeline to thread is delegated to a *dispatcher*, which has a defined thread pool at its disposal and which is part of Kotlin's coroutines framework. Transaction isolation is guaranteed at all time by the *transaction manager*.

In addition, this execution model also allows for intra-query parallelism, which is used for queries that incur high CPU cost. This is realised in a *data parallel* fashion by partitioning on the input. The decision whether or not to allow for parallelism is made upon implementation of a query – i.e., the last step

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[3] See: https://kotlinlang.org/docs/coroutines-overview.html
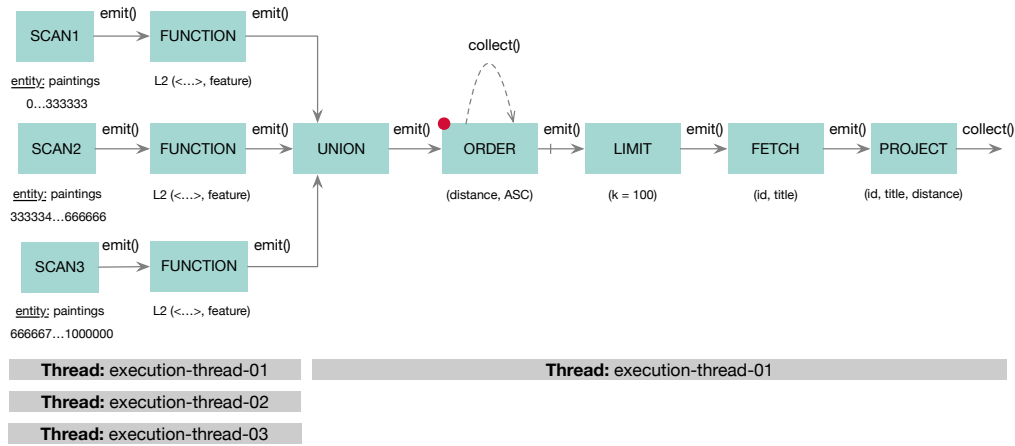
Figure 7.3   Operator pipeline that performs kNN on the entity *paintings*. The *scan* and distance *function* steps are partitioned and unioned before order, limit and projection is applied, which allows for parallel execution.

after the final plan has been selected – since it requires structural changes to the operator pipeline. The degree of parallelism depends on the expected CPU cost of the plan and the available CPUs on the machine *Cottontail DB* is running on.

To prepare for intra-query parallelism, part of the operator pipeline is partitioned wherein every partition operates on a fraction of the input data. Since not all steps in a pipeline can be parallelised effectively, usually only parts of the pipeline are partitioned. Whether partitioning is possible at a given point in the pipeline depends on whether the operator itself as well as all upstream operators allow for partitioning, which is queried upon implementation. An additional concurrency aware *union* operator is introduced after such an operator, which synchronizes and merges all the incoming strands using a FIFO scheme. Since union operators do not retain ordering, sort operations must take place afterwards. An example for this is given in Figure 7.3.

With an operator pipeline prepared in this fashion, it again remains up to the dispatcher to allocate parts of the pipeline to concrete threads. *Cottontail DB* only declares how allocation should take place by chosing the appropriate type of dispatcher. Scheduling then depends on available hardware and system load. Consequently, the number of partitions is merely an upper bound on parallelism without guarantee, that every strand will be processed in its own thread.

7.2.2   Query Planner

The goal of *query planning* is to find a cost-optimal execution plan for a query given any *policy* valid for the current query context and *Cottontail DB*'s cost model. The input into the query planner is a logical representation of the oper-

ators that should be executed as part of the operator pipeline, which we call the *canonical operator node tree*. It results directly from the *query binding* stage.

Query planning in *Cottontail DB* then takes place in three steps: First, and optionally, the canonical operator node tree is compared to the *plan cache*. If the cache contains a hit for that tree, the already optimized plan in the cache can be re-used and all the subsequent steps can be skipped. Second, if there is no hit in the cache or the cache is bypassed, the canonical operator node tree undergoes *optimization*. The optimization step generates different versions of the input plan by applying optimization rules that act on and manipulate the tree to generate new, equivalent plans. Finally, once optimization has concluded, the plan that minimizes the expected cost is selected and *implemented*, that is, converted to a concrete sequence of executable operators.

7.2.2.1   Basic Optimization Algorithm

The query planner used by *Cottontail DB* is rather naive and can be categorized as a rule-based query planner. It is losely inspired by the Cascades Framework that was built as part of the Volcano project [GM93]. The planner generates new plans by enumerating and applying a set of rules to the input plan(s) in a recursive fashion. These rules are transformations that recognize patterns in the structure of the operator node tree and try to re-arange and/or replace nodes in the tree to generate a more optimal but equivalent version of the plan.

The optimization follows the same, basic algorithm: The available list of rules is enumerated and every rule is applied to every node starting from the base of the tree. The application of rules takes place recursively, i.e., every node propagates a rule up the tree to its inputs. At every node, the rule first checks if it can be applied to the current node. This check usually incurs little cost and simply considers the type of node and other, available properties. If the check is successful, the actual application of the rule follows. This application may or may not yield a new version of the query plan, depending on more complex and more costly factors, such as the availability of an index, which requires a catalogue lookup. If a new plan results from the application of a rule, that new query plan is stored in a *memoization table* for future reference.

Every planning stage involves a defined number of passes, and the sum of all plans generated by one pass act as the input for the next. All the intermediate plans are therefore run through the same algorithm and all the rules are applied again. Consequently, the search space grows exponentially with the complexity of the input plan, the number of rules to apply and the number of passes. To

address this issue, *Cottontail DB*'s query planner employs certain heuristics to keep the search space manageable:

- Very large, complex plans (e.g., stemming from sub-selects or JOINs) are broken into groups and every group is optimized and treated as an isolated plan. The assumption being that the combination of smaller, near-optimal plans must be close to optimal as well.

- The planning of every group is done in two stages – a *logical* and *physical* stage – with distinct and disjoint sets of rules. The results of the logical stage act as an input for the physical stage.

- Logical and physical query plans are uniquely identified by a hash. Memoization in combination with the aforementioned hash is used to track trees that have already been optimized and skip them.

- Physical execution plans generated in the second stage are actively pruned by the planner between the different passes based on the cost estimate.

Between the logical and the physical planning, there is a step that maps every logical operator node to its naive, physical counterpart. The number of passes per stage and active pruning of plans during the physical phase are used to steer the high-level behaviour of the query planner. During the logical phase, the goal is to generate as many, equivalent, logical query representations as possible to have a corpus of plans to optimize on (expansion phase). In contrast, during the physical phase, the planner tries to limit the number of intermediate plans to prevent the search space from exploding.

7.2.2.2 Plan Caching

The plan cache is an optimization mechanism that amortizes the cost of the potentially expensive query planning if a certain type of query is encountered multiple times. At its core, the cache maps the hash code of every incoming canonical operator tree to the resulting, optimized physical plan. If the same query is encountered again, that plan can be looked-up and re-used directly, hence, avoiding another round of planning.

Currently, there are certain limitations to the plan cache mechanism in *Cottontail DB*, which is why it is disabled by default. Firstly, the actual execution performance of a plan is not being evaluated against the cost model, i.e., the level of optimality of an execution plan is not assessed. And secondly, there is no mechanism that invalidates cached entries as changes to the data occur.

7.2.2.3 Logical Optimization

The logical optimization step acts on structural properties of the operator node tree and aims at expanding the list of query plans in a way that increases the likelihood of finding the optimal plan during the physical phase. It basically leverages the algebraic properties of the operators involved. The logical optimization stage in *Cottontail DB* currently involves the following type of rules:

Defer Fetch On Scan Rewrite Rule This rules tries to defer access to columns upon scanning the data. It makes sure, that only columns are accessed during a table scan, that are required by the first operator following the scan that requires the presence of specific columns. All remaining columns are pushed down in the tree into a dedicated *fetch* operation following that node.

Defer Fetch On Fetch Rewrite Rule This rule tries to defer access to columns upon fetching data. Similarly to the *Defer Fetch on Scan Rewrite Rule,* it pushes the fetching of columns not required by any of the downstream operators that express a specific requirement, into a dedicated fetch operation following such an operator.

Conjunction Rewrite Rule This rule refactors a filter operator evaluating a conjunctive predicate into two consecutive *filter* operators, one for each side of the conjunction. There are two versions of this rule, one that applies the left side first and one that applies the right side first.

The first two rules make sure, that columns are accessed only if they are needed and as close to the site of processing as possible. Furthermore, and since these rules are applied multiple times, columns that are not accessed at all will eventually be pushed out and eliminated from the tree completely. This is illustrated in the example given in Figure 7.4. Since *Cottontail DB* is a column store, deferral of column access can drastically reduce I/O, especially in the presence of filtering predicates or if a column is not needed.

The conjunction rewrite rule decomposes filtering predicates that contain conjuctions. This is illustrated in the example given in Figure 7.5. The applicaton of this rule can be seen as a preparation for the physical optimization phase, where specific predicates may be pushed down to a secondary index.

7.2.2.4 Physical Optimization

The physical optimization step tries different implementations of operators to arrive at a more cost-effective plan. While structural changes to the operator

Pass 1   **Pass 2**
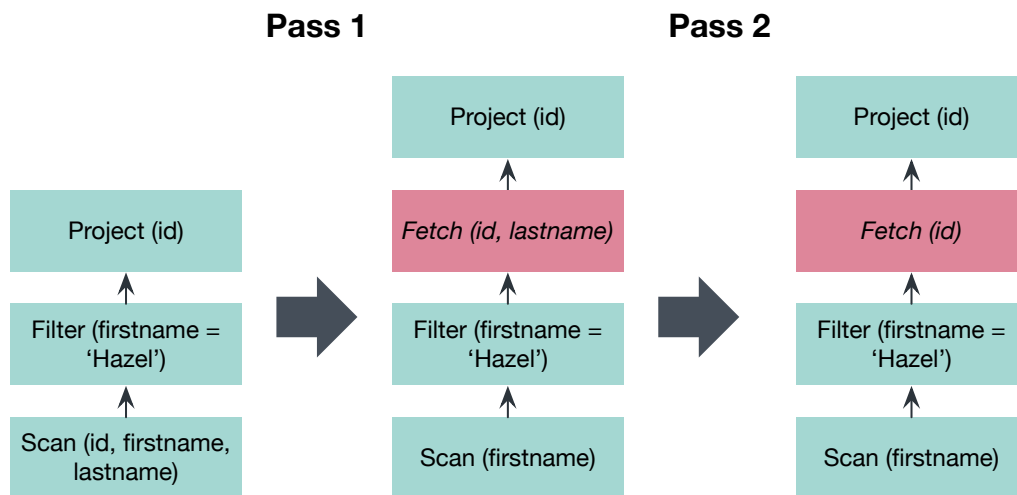
**Figure 7.4   Illustration of deferal of column access. In the first pass, access to
columns *id* and *lastname* is defered until after the filter operation, be-
cause the filter only requires *firstname*. In the second pass, access to
lastname is eliminated completely.**

Pass 1
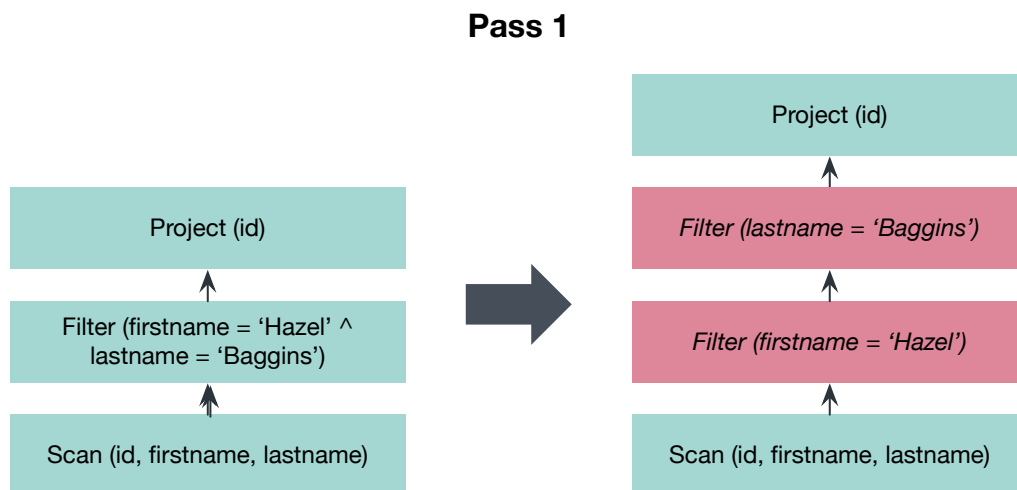
**Figure 7.5   Illustration of decomposing conjunctive predicates. In this example,
the filter on the column *firstname* may be pushed down to an index
during physical optimization, if such an index is available.**

tree may be possible, the focus lies on implementation aspects. At a high level,
we distinguish between the following three types of rules:

Pushdown Rules These rules try to push down *filter* predicates or *function* in-
vocations to the *scan* operation, usually by leveraging a secondary index or
existing statistics (e.g., for counting). For example, an entity scan followed by
a filter can be replaced by a more efficient scan of a B^+-tree index followed
by a *fetch* operation or proximity based operations can be delegated to an
available, high-dimensional index using Definition 6.6.

Summarization Rules These rules try to merge operations to arrive at a more efficient execution. For example, a *sort* operation followed by a *limit* operation can be replaced by a single, *limiting heap sort* operation, which applies sorting and limiting in a single step. Combining these two operations and the use of the heap-sort algorithm allows for more effective sorting in terms of CPU and memory cost, as compared to naively sorting all records first and then limiting to the top k records thereafter.

Implementation Rules These rules simply replace different implementations of a operation one-to-one, e.g., hash-join vs. nested-loop join for a theoretical JOIN operation.

After each pass in the physical optimization step, the list of resulting plans is pruned to the n best performing plans before handing them to the next pass. By this, we limit the size of the search space that is being explored. Once all passes have concluded, the best plan in terms of cost is selected and implemented. We directly apply the cost model introduced and described in Chapter 6.

7.2.3   Query Parsing and Binding

As every DBMS, *Cottontail DB* uses a query language that allows for interaction with other systems. These interactions include data definition, data management, transaction management and the formulation of queries. In its current version, *Cottontail DB*'s query language is based on *gRPC*[4], hence, all queries are expressed as *Protocol Buffer*[5] messages. Internally, the gRPC endpoint is a collection of four services for handling DDL, DML, DQL and transaction management messages. The parsing of incoming messages, the mapping of messages to the correct service and endpoint and low-level handling of communication with clients is delegated to the gRPC Kotlin library.

The reason for the choice of gRPC is threefold: Firstly, *Cottontail DB*'s predecessor – ADAMpro [GS16] – already used and introduced gRPC into the *vitrivr* ecosystem. Consequently, building on this work greatly simplified the task of integrating *Cottontail DB*. Secondly, gRPC – being a platform independent remote procedure call framework – introduces out-of-the-box support for a large range of programming environments[6]. And finally, the gRPC Kotlin library

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[4] See: https://grpc.io/
[5] See: https://developers.google.com/protocol-buffers/
[6] Furthermore, there are specialized client libraries for Java, Kotlin and Python

greatly simplified the task of structuring query endpoints, parsing incoming query messages and handling the query responses.

Irrespective of the use of gRPC, *Cottontail DB* is compatible with the SQL standard insofar as it supports a specific feature. This was demonstrated by be the successful integration of *Cottontail DB* as a storage engine for *Polypheny-DB*. Consequently, it is possible to add additional endpoints that can accept, for example, SQL queries. However, for complete SQL compliance, one would have to add language features that are currently not supported by *Cottontaild DB* (e.g., JOINS). Furthermore, handling the technical details of parsing the incoming query and communication with the client must be handled as well, which would lead to the implementation of many different standards such as JDBC or ODBC.

Irrespective of its source, any incoming query message undergoes a *binding* step in *Cottontail DB*. Query binding includes three aspects:

1. Names that reference database objects such as entities, columns and indexes are resolved using *Cottontail DB*'s catalogue and replaced by concrete pointers to the respective object.

2. Literal values, function calls and column references, e.g., in predicates, are extracted and replaced by *bindings* and attached to a *binding context*.

3. The parsed message is converted into a *canonical operator node tree* that logically represents the query.

The result of the parsing and binding step is the canonical operator node tree, which acts as a logical and unoptimized query representation. Every node in the tree represents an operator that acts on a *record* or *tuple* and that must be executed in order to generate the result specified by the query. The conversion of a message to a tree is performed in a naive manner and only syntactic checks and optimization are performed at this stage (e.g., type checks, removal of trivial predicates such as "1 = 1").

7.2.3.1   Binding Context

The binding context is a data structure that is member of the query context and a very important piece of functionality for query planning and execution. At their core, bindings are proxies for values used in a query. *Cottontail DB* distinguishes between *literal*, *column* and *function* bindings. At any point during query execution, the binding context holds the current values for all the bindings associated with it, so that these can be accessed as the query is being evaluated.

(margin note) Ref: Polypheny-DB + Cottontail DB, joint publication

The layer of indirection introduced by bindings enables many of *Cottontail DB*'s functionalities, e.g., in the evaluation of complex expressions for predicates or functions. Most importantly, however, it allows for re-use of query plans, as bindings can be simply rebound to another binding context. Plan re-use then simply comes down to copying a plan with all its bindings and assigning it a new binding context afterwards.

With regards to intra-query parallelism, it is important to note that binding contexts are not thread-safe, which is why they are copied upon partitioning of a query plan. Consequently, every branch of an operator tree acts on its own child of the same, root binding context.

7.2.4 Functions and Function Generators

In compliance with the model proposed in Chapter 6, *Cottontail DB* implements a *function registry*, which is part of the catalogue and can be used to obtain function implementations during query binding and planning. The function registry comprises of three parts: The registry itself, *function generator*s and *functions*.

The registry is a singleton object that is kept in memory for an instance of *Cottontail DB*. It provides the interface to register function generators and resolve function implementations given a *closed signature*. Function resolution then is facilitated by the function generators, which are again singleton objects per type of function – e.g., Euclidean distance or scalar multiplication – and act as factories for concrete function implementations. A function generator is always associated with an *open signature*, which comprises of a function's name and potentially *open* arguments, which only specify the class (e.g., number, vector) but not the concrete type (e.g., float number, double vector) of arguments. It is then up to the generator to return an implementation based on a closed signature, if such an implementation exists.

Given this facility, function resolution takes place in two steps: First, a closed signature is converted to an open signature to lookup the responsible function generator in a hash map. That generator then produces the concrete implementation, based on the closed signature. This two-step process allows for easy extension, since adding new functions comes down to adding a generator and the type-specific implementations. Furthermore, the mechanism could be adapted to generate code at runtime, which *Cottontail DB* doesn't support.

Equivalences between DFCs and high-dimensional indexes, as required by Definition 6.6, are currently implemented at the index-level, i.e., an index is aware of the type of DFC it can replace.

Table 7.3 **Primitive operations offered by the storage engines's `Tx` abstractions to interact with DBOs including the argument and return types (`arg → ret`).**

Type	Schema	Entity	Index	Column
`create()`	✓	✓	✓	✗
`drop()`	✓	✓	✓	✗
`read()`	✗	TID → Record	✗	TID → Value
`update()`	✗	Record	✗	TID, Value → Value
`insert()`	✗	Record → TID	✗	Value → TID
`delete()`	✗	TID → Record	✗	TID → Value
`scan()`	✗	Cursor < Record >	Cursor < Record >	Cursor < Value >
`filter()`	✗	✗	Cursor < Record >	✗
`count()`	✗	✗	✓	✓
`maxTupleId()`	✗	✗	✓	✓
`commit()`	✓	✓	✓	✓
`rollback()`	✓	✓	✓	✓

7.2.5 Storage

Over time, *Cottontail DB* has seen multiple different layers for low-level data organisation and storage. Each of these layers addressed certain requirements that were valid at the time of conception. To accomodate these different engines, the *storage manager* offers a unified interface to interact with underlying *storage engines*, regardless of the concrete implementation.

The storage manager offers abstractions for Database Object (DBO), namely, `Schema`, `Entity`, `Index` and `Column`, in the form of interfaces. A instance of a `Tx` can be obtained through the respective DBO to initiate transactional interaction (i.e., `Schema.Tx`, `Entity.Tx`, `Index.Tx` and `Column.Tx`). For that, each `Tx` implementation provides low-level primitives, e.g., `Column.Tx` offers `read()`, `update()`, `insert()` and `delete()` for individual `Values`. A complete list of primitives can be found in Table 7.3.

Even though the storage manager abstraction layer could be used to combine different storage engines within a single instance, this is currently not implemented. This is mainly because replacement of a storage engine was often triggered by a very specific requirement the other engines could not fullfil. On an implementation side, however, *Cottontail DB* also relies on low-level aspects of the engines to ensure atomicity and (sometimes) transaction isolation. It would take some additional engineering to maintain these guarantees accross different storage engines.

7.2.5.1 Storage engine: MapDB

The *MapDB* storage engine is based on version 3.0.8 of a library with the same name[7] and was the first storage engine for *Cottontail DB*. The main requirement at that time was speed and ease of integration.

At its core, *MapDB* offers persistent versions of the `Map` interface in Java backed by segmented hash trees. It can thus be regarded as a simple key-value store. *MapDB* uses memory mapped files, which allow for fast I/O, and a generic and extendible serialization engine to read and write arbitrary types from and to disk. Atomicity and durability of transactions is guaranteed by write-ahead logging and in-memory latches mediate concurrent access to the underlying tree structure.

Cottontail DB integrates with *MapDB* by storing every column in a dedicated page-file that maps `TID` to record value. To do so, it bypasses the official high-level APIs offered by *MapDB* and instead uses internal, lower-level storage mechanism to write records to pages directly. This has proven to be significantly faster than using the higher level, abstractions, especially for linear scans. However, the catalogue and all information about schemata, entities etc. are stored in persistent maps as are some of the data structures required for secondary indexes.

While easy to use in practice and reasonably fast by default, *MapDB* has several disadvantages. Firstly, the use of memory-mapped files, while tempting, is highly discouraged for DBMS as shown by [CLP22]. Secondly, the implementation of memory mapped files provided by the JVM is far from optimal and plagued by issues with resource retention on certain platforms. And finally, *MapDB* does not offer any MVCC, which is why isolation is provided by S2PL.

7.2.5.2 Storage engine: Xodus

The *Xodus* storage engine is based on version 1.3.238 of the open source, transactional and schema less, embedded database for Java and Kotlin with the same name, developed and maintained by JetBrains[8]. As opposed to *MapDB*, *Xodus* does not rely on the use of memory mapped files. Atomicity and durability in *Xodus* is guaranteed through write-ahead logging. A property that is very desirable in the context of dynamic index management described in Chapter 6, is *Xodus'* support for non-blocking reads through the use of MVCC and snapshot isolation, which was one of the reasons to experiment with this engine.

Xodus offers three different levels of abstraction over the same core IO facility:

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[7] See: https://mapdb.org/
[8] See https://github.com/JetBrains/xodus()

Environments encapsulate multiple, named key-value stores that can hold arbitrary keys and values. They allow for transactional reading and modification of data accross stores. The interface for stores provides simple primitives such as `read()`, `put()` and `delete()` based on the key as well as `scan()` operations using `Cursors`.

Entity Stores use environments to store more complex entities with attributes and links to other entities. This higher level abstraction allows for more advanced data modelling as well as the formulation of complex queries.

Virtual File Systems use the envoronments to provide a transactional file system within *Xodus*.

Cottontail DB integrates directly with *Xodus*'s environment API, by having dedicated store for each column within a single environment. In a store, the `TID` is mapped to the respective value. Furthermore, *Cottontail DB* maintains dedicated stores for all the necessary catalogue information as well as data structures required for indexes.

While *Xodus* offers many advantages for Boolean retrieval and transactional workloads, it is slightly slower than *MapDB* for linear scans of columns containing large values in a read-only setting. This is due to the tree traversal that is involved, which incurs more overhead than scanning *MapDB*'s page files. However, we were able to compensate for this drawback by the application *Snappy*[9] compression for high-dimensional vectors, leading to even higher throughput for full table scans.

7.2.5.3 Storage engine: HARE

HARE is an experimental storage engine for *Cottontail DB* that so far has not made it to a final version and has thus never been used in a productive setting. The idea of *HARE* was to build the storage engine end-to-end to have more fine-grained control over data access patterns.

HARE sports all components required for persitent data management, including a dedicated *disk manager* and a *buffer pool manager*. Atomicity and durability are provided by maintaining an undo and redo logs on a page level, which is reasonably straightforward to implement, but too slow for write-heavy workloads.

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[9] See https://github.com/google/snappy/

Structurally, *HARE* is built around page files, which hold the values for an entry. In interfaces with *Cottontail DB*'s type system through a serialization subsystem not unline that of *MapDB*. Internal data organisation in *HARE* comes in two forms: Fixed-length columns essentially organise data in a persistent array, which enables addressing of values based on the *TID* by simple arithmetics. This allows for very fast random reads as well as extraordinary scan performance, but comes with many of challenges for transactional workloads, for which solutions have only emerged in highly experimental form.

Variable-length records use a skip-list structure with *index-* and *slotted data pages* for lookup, which is slower for random reads but still reasonably fast for full table scans, since index pages can simply be skipped.

In summary, *HARE* can be seen as a proof-of-concept of building a dedicated storage engine for *Cottontail DB*, which certainly offers a very interesting foundation for future research but falls short of existing engines, in its current form.

> Question: Should HARE be mentioned at all?

7.2.6 Transactional Guarantees

The *transaction manager* provides transactional semantics and guarantees in *Cottontail DB*. A transaction formally starts with the creation of a *transaction context* and ends with either a call to `commit()`, `rollback()` or `kill()`, which is a rollback for deadlocked transactions. The transaction context is always attached to the query context. However, unlike the query context, the transaction context may live beyond the scope of a single query. This depends on whether a transaction was *explicitly* started through the respecitve endpoints, or whether it is an *implicit* transaction, spawned by the issuing of a single query. Transactions of the first type must be explicitly terminated by the caller by calling `commit()` or `rollback()` whereas transactions of the second type end with the execution or abortion of the query that created them.

The transaction context provides access to the DBO's `TX` instances used for query execution. Since all these accesses are routed through the transaction context, it can take necessary steps to ensure transaction isolation. Irrespective of the guarantees provided by the storage engine, isolation can always be guaranteed through *Cottontail DB*'s *lock manager*, which provides DBO-level locking through the S2PL algorithm. While this is not the most efficient solution, it is applicable even for storage engines that do not provide any means of transaction isolation. In case they do, though, the lock manager can be bypassed.

To guarantee atomicity and durability of transactions, *Cottontail DB* relies on the capabilities of the underlying storage engine. The transaction manager simply assures, that calls to `commit()` or `rollback()` are propagated accordingly. As was mentioned, both properties are assured by some form of write-ahead logging for all storage engines, which is state-of-the-art for current DBMS.

There are only few guarantees w.r.t. to consistency, since *Cottontail DB* currently does not support any advanced constraints on columns. What *Cottontail DB* enforces, though, is that non-null columns are not nulled and that changes to indexes are propagated to the underlying index structures as described in Chapter 6. Failure to fullfil this, will raise errors, which inevitably lead to a rollback of a transaction.

Discussion

8

Evaluation

8.1 Interactive Multimedia Retrieval

vitrivr's participation to VBS, LSC etc, DRES.

8.2 Adaptive Index Management

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

8.3 Cost Model

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

9

Conclusion & Future Work

Appendix

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Curriculum Vitae

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Education

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Sep. 2007 – Jul. 2014	B. Sc. in Nanoscience, University of Basel, Switzerland
Sep. 2002 – Dec. 2006	Matura, Gymnasium Liestal, Liestal, Switzerland

Employment

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Publications

2021

– Luca Rossetto, Ralph Gasser, Loris Sauter, et al. A System for Interactive Multimedia Retrieval Evaluations. In *Proceedings of the 27th International Conference on Multimedia Modeling*, MMM 2021, pages 385–390, Cham. Springer International Publishing, 2021. ISBN: 978-3-030-67835-7

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2020

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2018

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Advised Theses

– Renato Farrugio. *Scene Text Recognition in Images and Video with Cineast*. Bachelor's Thesis, University of Basel

– Florian Mohler. *Online Image Analysis to Identify Politicians in Twitter Images*. Bachelor's Thesis, University of Basel

– Gabriel Zihlmann. *Magnetic Resonance Fingerprinting Reconstruction using Methods from Multimedia Retrieval*. Master's Thesis, University of Basel

– Yan Wang. *Detecting Visual Motives Using Online Clustering of Similar Images*. Bachelor's Thesis, University of Basel

– Samuel Börlin. *3D Model Retrieval using Constructive Solid Geometry in Virtual Reality*. Master's Thesis, University of Basel

– Manuel Hürbin. *Retrieval Optimization in Magnetic Resonance Fingerprinting*. Bachelor's Thesis, University of Basel

– Loris Sauter. *Fighting Misinformation: Image forgery detection in social media streams*. Master's Thesis, University of Basel

Honors and Awards

Best VBS System Award for the winning system of the Video Browser Showdown (VBS) and paper titled *Towards Explainable Interactive Multi-Modal Video Retrieval with vitrivr* at the *27th International Conference on Multimedia Modeling (MMM 2021)*

Best Demo Award for the best demo paper titled *A System for Interactive Multimedia Retrieval Evaluations* at the *27th International Conference on Multimedia Modelling (MMM 2021)*

Best Open Source Award for the best open source system paper titled *Cottontail DB: An Open Source Database System for Multimedia Retrieval and Analysis* at the *28th ACM International Conference on Multimedia (ACM MM 2020)*

Best Demo Award for the best demo paper titled *Multimodal Multimedia Retrieval with vitrivr* at the *ACM International Conference on Multimedia Retrieval (ICMR 2019)*

Best VBS System Award for the winning system of the Video Browser Showdown (VBS) and paper titled *Deep Learning-based Concept Detection in vitrivr* at the *25th International Conference on Multimedia Modeling (MMM 2019)*

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Declaration on Scientific Integrity

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Declaration
I hereby declare that this doctoral dissertation *"Data Management for Dynamic Multimedia Analytics and Retrieval"* 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.

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