15445

wu

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Contents

1 Introduction and the relational model

Data model:

relational	most dbms
key/value	
graph	NoSQL
document	
column family	
Array/Matrix	Machine Learning
Hierarchical	
Network	Obsolete/Legacy
Multi-value	

The special value `NULL` is a member of every domain

A relation's **primary key** uniquely identifies a single tuple. Some DBMSs automatically create an internal primary key if a table does not define one.

A **foreign key** specifies that an attribute from one relation has to map to a tuple in another relation.

Method to store and retrieve information from a database:

- Procedural - Relational Algebra
  - the query specifies the (high-level) strategy the DBMS should use to find the desired result
- Non-Procedural (Declarative) - Relational Calculus
  - The query specifies only what data is wanted and not how to find it

1.1 Relational Algebra

Select: $\sigma_{\text{predicate}}(R)$

Consider R($a_{\text{id,bid}}$)

a_{id}	b_{id}
a1	101
a2	102
a2	103
a3	104

By $\sigma_{\text{a\_id='a2'}}(R)$ we get

a_{id}	b_{id}
a2	102
a3	103

By $\sigma_{\text{a\_id='a2'} \wedge \text{b\_id>102}}(R)$ we get

a_{id}	b_{id}
a2	103

```
SELECT * FROM R
  WHERE a_id='a2' AND b_id>102;
```

Projection: $\Pi_{A1,\ldots,A_n}(R)$

By $\Pi_{\text{b\_id-100,a\_id}}(\sigma_{\text{a\_id='a2'}}(R))$ we get

b_{id}-100	a_{id}
2	a2
3	a2

```
SELECT b_id-100, a_id
    FROM R WHERE a_id='a2';
```

Union: $(R \cup S)$
Given R($a_{id,bid}$)

a_{id}	b_{id}
a1	101
a2	102
a3	103

and S($a_{id,bid}$)

a_{id}	b_{id}
a3	103
a4	104
a5	105

By $(R \cup S)$ we get

a_{id}	b_{id}
a1	101
a2	102
a3	103
a3	103
a4	104
a5	105

```
(SELECT * FROM R)
    UNION ALL
(SELECT * FROM S);
```

Intersection: $(R \cap S)$
By $(R \cap S)$ we get

a_{id}	b_{id}
a3	103

```
(SELECT * FROM R)
    INTERSECT
(SELECT * FROM S);
```

Difference: $(R - S)$ By $(R - S)$ we get

a_{id}	b_{id}
a1	101
a2	102

```
(SELECT * FROM R)
    EXCEPT
(SELECT * FROM S);
```

Product: $(R \times S)$
By $(R \times S)$ we get

R.a_{id}	R.b_{id}	S.a_{id}	S.b_{id}
a1	101	a3	103
a1	101	a4	104
a1	101	a5	105
a2	102	a3	103
a2	102	a4	104
a2	102	a5	105
a3	103	a3	103
a3	103	a4	104
a3	103	a5	105

```
SELECT * FROM R CROSS JOIN S;

SELECT * FROM R,S;
```

Join: $(R \bowtie S)$, generate a relation that contains all tuples that are a combination of two tuples with a common values for one or more attributes
By $(R \bowtie S)$ we get

a_{id}	b_{id}
a3	103

```
SELECT * FROM R NATURAL JOIN S;
```

Extra operators:

rename	ρ
assignment	$R \leftarrow S$
duplicate elimination	δ
aggregation	γ
sorting	τ
division	$R \div S$

1.2 Queries

The relational model is independent of any query language implementation
SQL is the standard

2 Intermediate SQL

Data Manipulation Language (DML)
Data Definition Language (DDL)
Data Control Language (DCL)
SQL is based on bags (duplicates) not sets (no duplicates)
Example database
student($_{\text{sid}\_}$, name, login, gpa)

sid	name	login	age	gpa
53666	Kanye	kanye@cs	44	4.0
53688	Bieber	jbieber@cs	27	3.9
53655	Tupac	shakur@cs	25	3.5

course($_{\text{cid,name}}$)

cid	name
15-445	Database Systems
15-721	Advanced Database Systems
15-826	Data Mining
15-823	Advanced Topics in Databases

enrolled($_{\text{sid}\_}$, $\underline{\text{cid}}$, grade)

sid	cid	grade
53666	15-445	C
53688	15-721	A
53688	15-826	B
53655	15-445	B
63666	15-721	C

The basic syntax for a query is

```
SELECT column1, column2, ...
FROM table
WHERE predicate1, predicate2, ...
```

which students got an A in 15-721?

```
SELECT s.name
FROM enrolled AS e, student AS s
WHERE e.grade = 'A' AND e.cid = '15-721'
AND e.sid = s.sid
```

2.1 Aggregates

Functions that return a single value from a bag of tuples

- `AVG(col)` return the average col value
- `MIN(col)` return minimum col value
- `MAX(col)` return maximum col value
- `SUM(col)` return sum of values in col
- `COUNT(col)` return # of values for col

Aggregate functions can (almost) only be used in the `SELECT` output list
Get # of students with a "@cs" login:

```
SELECT COUNT(login) AS cnt
FROM student WHERE login LIKE '%@cs'
```

Get the number of students and their average GPA that have a "@cs" login

```
SELECT AVG(gpa), COUNT(sid)
FROM student WHERE login LIKE '%@cs'
```

`COUNT`, `SUM`, `AVG` support `DISTINCT`
Get the number of unique students that have an "@cs" login

```
SELECT COUNT(DISTINCT login)
FROM student WHERE login LIKE '%@cs'
```

Output of other columns outside of an aggregate is undefined

```
SELECT AVG(s.gpa), e.cid
FROM enrolled AS e, student AS s
WHERE e.sid = s.sid
```

Group by: Project tuples into subsets and calculate aggregates against each subset

```
SELECT AVG(s.gpa), e.cid
FROM enrolled AS e, student AS s
WHERE e.sid = s.sid
GROUP BY e.cid
```

From

e.sid	s.sid	s.gpa	e.cid
53435	53435	2.25	15-721
53439	53439	2.70	15-721
56023	56023	2.75	15-826
59439	59439	3.90	15-826
53961	53961	3.50	15-826
58345	58345	1.89	15-445

we get

AVG(s.gpa)	e.cid
2.46	15-721
3.39	15-826
1.89	15-445

Non-aggregated values in `SELECT` output clause **must appear** in `GROUP BY` clause.

```
SELECT AVG(s.gpa) AS avg_gpa, e.cid
FROM enrolled AS e, student AS s
WHERE e.sid = s.sid
GROUP BY e.cid
HAVING avg_gpa > 3.9;
```

2.2 Operations

2.2.1 String operations

	String Case	String Quotes
SQL-92	Sensitive	Single Only
Postgres	Sensitive	Single Only
MySQL	Insensitive	Single/Double
SQLite	Sensitive	Single/Double
DB2	Sensitive	Single Only
Oracle	Sensitive	Single Only

```
WHERE UPPER(name) = UPPER('KaNyE') /*SQL-92*/

WHERE name = "KaNyE"               /*MySQL*/
```

`LIKE` is used for string matching
`'%'` matches any substring, `'_'` matches any one character

```
SELECT SUBSTRING(name, 1, 5) AS abbrv_name
FROM student WHERE sid = 53688

SELECT * FROM student AS s
WHERE UPPER(s.name) LIKE 'KAN%'
```

SQL standard says to use || operator to concatenate two or more strings together, MySQL uses +

DATE/TIME

```
SELECT NOW();

SELECT CURRENT_TIMESTAMP;

SELECT EXTRACT(DAY FROM DATE('2021-09-01'));

SELECT DATE('2021-09-01') - DATE('2021-01-01') AS days;

SELECT ROUND((UNIX_TIMESTAMP(DATE('2021-09-01')) - UNIX_TIMESTAMP(DATE('2021-01-01'))

SELECT DATADIFF(DATE('2021-09-01'), DATE('2021-01-01')) AS days;

SELECT juliaday(CURRENT_TIMESTAMP) - julianday('2021-01-01');

SELECT CAST((julianday(CURRENT_TIMESTAMP) - julianday('2021-01-01')) AS INT) AS days;
```

2.3 Output

Store query results in another table

- table must not already be defined
- table will have the same # of columns with the same types as the input

```
SELECT DISTINCT cid INTO CourseIds
FROM enrolled;                    /*SQL-92*/

CREATE TABLE CourseIds (
SELECT DISTINCT cid FROM enrolled);/*MySQL*/
```

Insert tuples from query into another table

- Inner `SELECT` must generate the same columns as the target table
- DBMSs have the different options/syntax on what to do with integrity violations

```
INSERT INTO CourseIds
(SELECT DISTINCT cid FROM enrolled); /*SQL-92*/
```

`ORDER BY <column*> [ASC|DESC]`

- Order the output tuples by the vgalues in one or more of their columns

```
SELECT sid, grade FROM enrolled
WHERE cid = '15-721'
ORDER BY grade
```

`LIMIT <count> [offset]`

- limit the # of tuples returned in output
- Can set an offset to return a "range"

```
SELECT sid, name FROM student
WHERE login LIKE '%@cs'
LIMIT 20 OFFSET 10
```

2.4 Nested Queries

```
SELECT name FROM student
WHERE sid IN (SELECT sid FROM enrolled)
```

Get the names of students in '15-445'

```
SELECT name FROM student
WHERE sid IN (
  SELECT sid FROM enrolled
  WHERE cid = '15-445'
)
```

- `ALL`: must satisfy expression for all rows in the sub-query
- `ANY`: must satisfy expression for at least one row in the sub-query

- IN: equivalent to '=ANY()'
- EXISTS: at least one row is returned

Get the names of students in '15-445'

```
SELECT name FROM student
WHERE sid = ANY(
  SELECT sid FROM enrolled
  WHERE cid = '15-445'
)
```

Find student record with the highest id that is enrolled in at least one course

```
SELECT MAX(e.sid), s.name
FROM enrolled AS e, student AS s
WHERE e.sid = s.sid;

SELECT sid,name FROM student
WHERE sid IN (
  SELECT MAX(sid) FROM enrolled
  ORDER BY sid DESC LIMIT 1
);
```

Find all courses that have no students enrolled in it

```
SELECT * FROM course
WHERE NOT EXISTS (
  SELECT * FROM enrolled
  WHERE course.cid = enrolled.cid
)
```

PROBLEM

2.5 Window Functions

Performs a "sliding" calculation across a set of tuples that are related. Like an aggregation but tuples are not grouped into a single output tuples

Special windows functions

- ROW_NUMBER() - # of the current window
- RANK() - Order positions of the curfrent row

```
SELECT *, ROW_NUMBER() OVER() AS row_num
FROM enrolled
```

sid	cid	grade	row_{num}
53666	15-445	C	1
53688	15-721	A	2
53688	15-826	B	3
53655	15-445	B	4
53666	15-721	C	5

The `OVER` keyword specifies how to group together tuples when computing the window function. Use `PARTITION BY` to specify group

```
SELECT cid, sid,
  ROW_NUMBER() OVER (PARTITION BY cid)
FROM enrolled
ORDER BY cid
```

cid	sid	$\text{row}_{\text{number}}$
15-445	53666	1
15-445	53655	2
15-721	53688	1
15-721	53666	2
15-826	53688	1

You can also include an `ORDER BY` in the window grouping to sort entries in each group.

Find the student with the second highest grade for each course

```
SELECT * FROM (
  SELECT *, RANK() OVER (PARTITION BY cid ORDER BY grade ASC) AS rank
  FROM enrolled
) AS ranking
WHERE ranking.rank = 2
```

2.6 Common table expressions

Provides a way to write auxiliary statements for use in a larger query

```
WITH cteSource(maxID) AS (
  SELECT MAX(sid) FROM enrolled
)
SELECT name FROM student, cteSource
WHERE student.sid = cteSource.maxId
```

Print the sequence of numbers from 1 to 10

```
WITH RECURSIVE cteSource(counter) AS (
  (SELECT 1)
  UNION ALL
  (SELECT counter + 1 FROM cteSource
    WHERE counter < 10)
)
SELECT * FROM cteSource
```

3 Database Storage

- `madvice`: tell the os how you expect to read certain pages
- `mlock`: tell the os that memory ranges cannot be paged out
- `msync`: tell the os to flush memory ranges out to disk

DBMS (almost) always wants to control things itself and can do a better job than the OS

Problem 1: How the DBMS represents the database in files on disk

Problem 2: How the DBMS manages its memory and moves data back-and-forth from disk

3.1 File Storage

The **storage manager** is responsible for maintaining a database's files

It organizes the files as a collection of **pages**

- tracks data read/written to pages
- tracks the available space

A **page** is a fixed-size block of data

Each page is given a unique identifier

- The DBMS uses an indirection layer to map page IDs to physical locations

There are three different notions of "pages" in a DBMS:

- Hardware Page (4KB)
- OS Page (4KB)

- Database Page (512B-16KB)

A hardware page is the largest block of data that the storage device can guarantee failsafe writes
A **heap file** is an unordered collection of pages with tuples that are stored in random order

- create/get/write/delete page
-

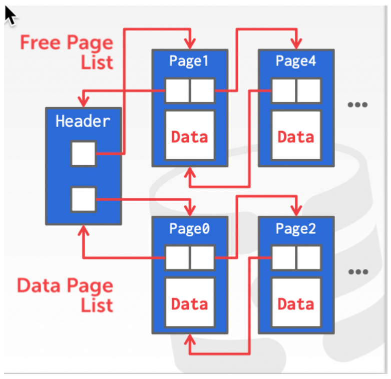
Two ways to represent a heap file

- linked list
- page directory

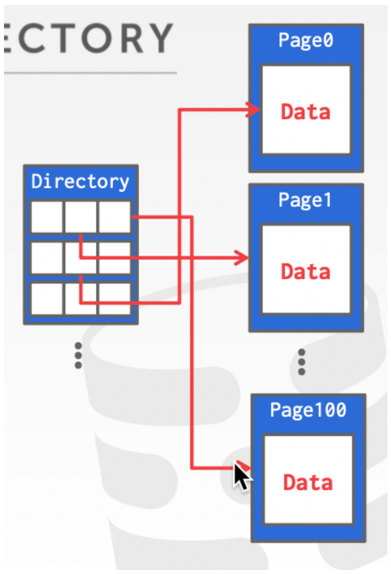
Linked List: maintain a **header page** at the beginning of the file that stores two pointers

- HEAD of the **free page list**
- HEAD of the **data page list**

Each page keeps track of how many free slots they currently have



The DBMS maintains special pages that tracks the location of data pages in the database files
The directory also records the number of free slots per page
must make sure that the directory pages are in sync with the data pages



3.2 Page Layout

Every page contains a **header** of metadata about the page's content

- page size
- checksum
- DBMS version
- transaction visibility
- compression information

Some systems require pages to be self-contained

For any page storage architecture, we need to decide how to organize the data inside of the page

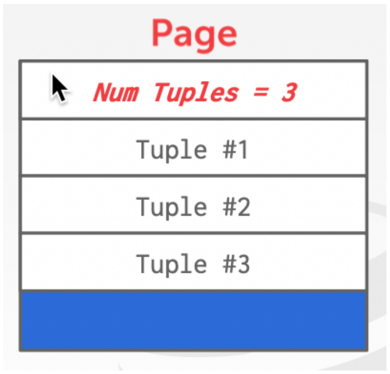
Two approaches

- tuple-oriented
- log-structured

Tuple-oriented:

Strawman Idea: keep track of the number of tuples in a page and then just append a new tuple to the end

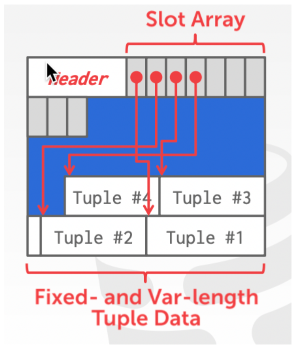
- What happens if we delete a tuple
- what happens if we have a variable-length attribute



The most common layout scheme is called **slotted pages**, the slot array maps “slots” to the tuples’ starting position offsets

The header keeps track of

- the # of used slots
- The offset of the starting location of the last slot used



The DBMS needs a way to keep track of individual tuples, each tuple is assigned a unique **record identifier**

- most common: `page_id` + `offset/slot`

An application cannot rely on these IDs to mean anything

3.3 Tuple layout

A tuple is essentially a sequence of bytes

It's the job of the DBMS to interpret those bytes into attribute types and values

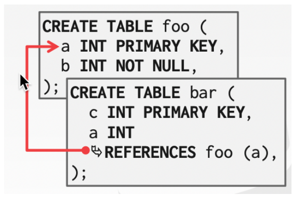
Each tuple is prefixed with a **header** that contains meta-data about it

- visibility info
- bit map for `NULL` values

We do **not** need to store meta-data about the schema

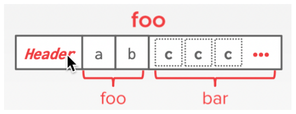
Attributes are typically stored in the order that you specify them when you create the table.

DBMS can physically **denormalize** (pre join) related tuples and store them together in the same page



```
CREATE TABLE foo (
  a INT PRIMARY KEY,
  b INT NOT NULL,
);
```

```
CREATE TABLE bar (
  c INT PRIMARY KEY,
  a INT
    REFERENCES foo (a),
);
```



Instead of storing tuples in pages, the DBMS only stores **log records**

The system appends log records to the file of how the database was modified

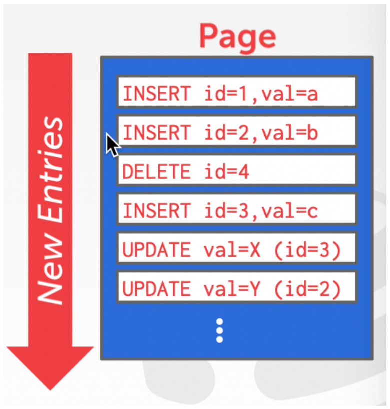
- inserts store the entire tuple
- deletes mark the tuple as deleted
- updates contain the delta of just the attributes that were modified

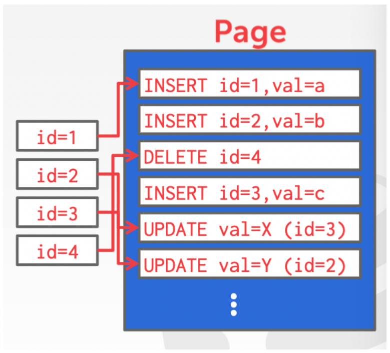
To read as records, the DBMS scans the log backwards and "recreates" the tuple to find what it needs

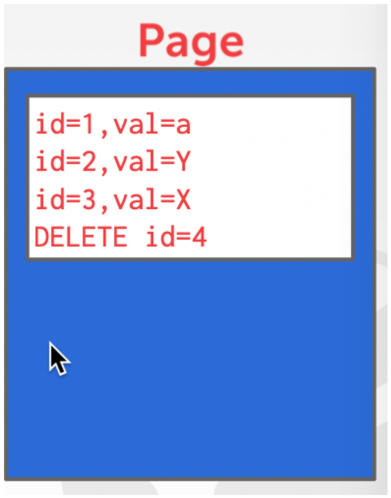
Build indexes to allow it to jump to locations in the log

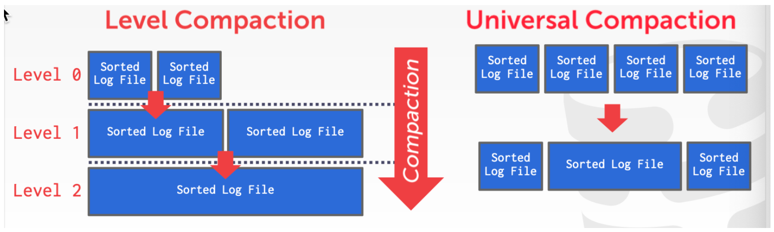
Periodically compact the log

Compaction coalesces larger log files into smaller files by removing unnecessary records


Page
New Entries
INSERT id=1,val=a
INSERT id=2,val=b
DELETE id=4
INSERT id=3,val=c
UPDATE val=X (id=3)
UPDATE val=Y (id=2)
⋮


Page
id=1
id=2
id=3
id=4
INSERT id=1,val=a
INSERT id=2,val=b
DELETE id=4
INSERT id=3,val=c
UPDATE val=X (id=3)
UPDATE val=Y (id=2)
⋮


Page
id=1,val=a
id=2,val=Y
id=3,val=X
DELETE id=4



3.4 Data representation

- `INTEGER` / `BIGINT` / `SMALLINT` / `TINYINT` C/C++ Representation
- `FLOAT` / `REAL` vs. `NUMERIC` / `DECIMAL`

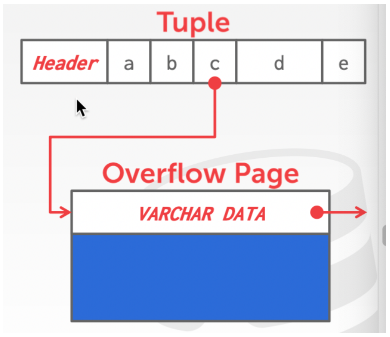
  IEEE-754 Standard / Fixed-point Decimals

  numerical/decimal is accurate without rounding errors
- `VARCHAR` / `VARBINARY` / `TEXT` / `BLOB`

  Header with length, followed by data bytes.
- `TIME` / `DATE` / `TIMESTAMP`

  32/64-bit integer of (micro)seconds since Unix epoch

To store values that are larger than a page, the DBMS uses separate **overflow** storage pages



Some systems allow you to store a really large value in an external file, treated as a `BLOB` type

The DBMS **cannot** manipulate the contents of an external file

3.5 system catalogs

A DBMS stores meta-data about databases in its internal catalogs

- tables, columns, indexes, views
- users, permissions
- internal statistics

Almost every DBMS stores the database's catalog inside itself
You can query the DBMS's internal `INFORMATION_SCHEMA` catalog to get info about the database
List all the tables in the current database:

```
/*SQL-92*/
SELECT *
FROM INFORMATION_SCHEMA.TABLES
WHERE table_catalog = '<db_name>';

/*Postgres*/
\d;

/*MySQL*/
SHOW TABLES;

/*SQLite*/
.tables
```

List all the tables in the student table

```
/*SQL-92*/
SELECT *
FROM INFORMATION_SCHEMA.TABLES
WHERE table_catalog = 'student';

/*Postgres*/
\dstudent;

/*MySQL*/
DESCRIBE student;

/*SQLite*/
.schema student
```

Database workloads:

- On-line transaction processing (OLTP)

  fast operations that only read/update a small amount of data each time

- On-line analytical processing (OLAP)

  complex queries that read a lot of data to compute aggregates

- Hybrid transaction + analytical processing (HTAP)

  OLTP+OLAP together on the same database instancew

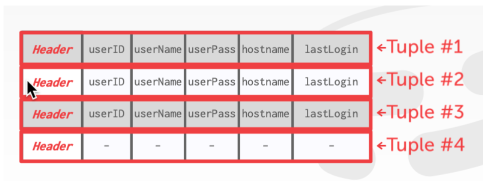
3.6 storage models

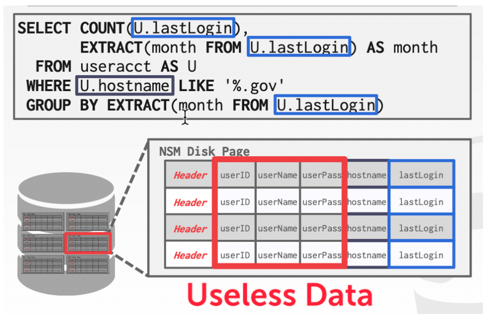
The DBMS cna store tuples in different ways that are better for either OLTP or OLAP workloads

We haven been assuming the n-ary storage model so fart this semester

n-ary storage model (NSM): the DBMS stores all attributes for a single tuple contiguously in a page

Ideal for OLTP workloads where queries tend to operate only on an individual entity and insert-heavy workloads





```
SELECT COUNT(U.lastLogin),
       EXTRACT(month FROM U.lastLogin) AS month
  FROM useracct AS U
 WHERE U.hostname LIKE '%.gov'
 GROUP BY EXTRACT(month FROM U.lastLogin)
```

Advantages

- fast insertions, updates and deletes

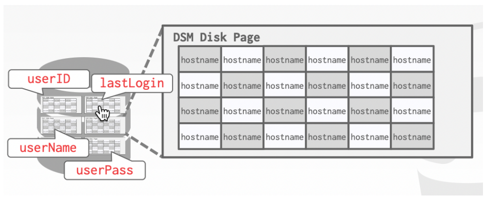
- Good for querries that need the entire tuple

Disadvantages

- not good for scanning large portions of the table and/or a subset of the attributes

decomposition storage model (**DSM**): the DBMS stores the values of a single attribute for all tupoles contiguously in a page

- also known as a "column store"



Tuple identification:

- fixed-length offsets

  each value is the same length for an atrribute

- embedded tuple Ids

  each value is stored with its tuple id in a column

4 Buffer Pools

How the DBMS manages its memory and move data back-and-forth from disk

- spatial control
  - where to write pages on disk
  - the goal is to keep pages that are used together often as physically close together as possible on disk
- temporal control
  - when to read pages into memory, and when to write them to disk
  - the goal is to minimize the number of stalls from having to read data from disk

4.1 Buffer Pool Manager

Memory region organized as an array of fixed-size pages. An array entry is called a **frame**

When the DBMS requests a page, an exact copy is places into one of these frames

The **page table** keeps track of pages that are currently in memory

Also maintains additional meta-data per page

- dirty flag
- pin/reference counter

Locks

- protects the database's logical contents from other transactions
- held for transaction duration
- need to be able to rollback changes

Latches

- protects the critical sections of the DBMS's internal data structure from other threads
- held for operation duration
- do not need to be able to rollback changes

The **page directory** is the mapping from page ids to page locations in the database files

- all changes must be recorded on disk to allow the DBMS to find on restart

The **page table** is the mapping from page ids to a copy of the page in buffer pool frames

- this is an in-memory data structure that does not need to be stored on disk

Buffer pool optimizations

- multiple buffer pools
- pre-fetching
- scan sharing
- buffer pool bypass

4.1.1 Multiple Buffer Pools

The DBMS does not always have a single buffer pool for the entire system

- multiple buffer pool instances
- per-database buffer pool
- per-page type buffer pool

Helps reduce latch contention and improve locality
Approach 1: Object Id

- Embed an object identifier in record ids and then maintain a mapping from objects to specific buffer pools

Approach 2: Hashing

- Hash the page id to select which buffer pool to access

4.1.2 Pre-fetching

The DBMS can also prefetch pages based on query plan

4.1.3 Scan Sharing

Queries can reuse data retrieved from storage or operator computations

- Also called **synchronized scans**

Allow multiple queries to attach to a single cursor that scans a table

- queries don't have to be the same
- can also share intermediate results

4.1.4 Buffer Pool Bypass

The sequential scan operator won't store fetched pages in the buffer pool to avoid overhead

4.2 Replacement Policies

Least-recently used

Approximation of LRU that does not need a separate timestamp per page

- each page has a reference bit
- when a page is accessed, set to 1

Organize the pages in a circular buffer with a clock hand

- upon sweeping, check if a page's bit is set to 1
- if yes, set to zero. If no, then evict

Better policies:

- LRU-K

  Track the history of last K references to each page as timestamps and compute the interval between subsequent accesses

  The DBMS then uses this history to estimate the next time that page is going to be accessed
- The DBMS chooses which pages to evict on a per txn/query basis.

4.3 Other Memory Pools

- sorting + join buffers
- query caches
- maintenance buffers
- log buffers
- dictionary caches

5 Hashtables

We are now going to talk about how to support the DBMS's execution engine to read/write data from pages

5.1 Hash functions

- crc-64 (1975)
- murmurhash (2008)
- google cityhash (2011)
- facebook xxhash (2012)
- google farmhash (2014)

5.2 static hashing schemes

5.2.1 linear probe hashing

single giant table of slots

resolve collisions by linearly searching for the next free slot in the table

- to determine whether an element is present, hash to a location in the index and scan for it
- must store the key in the index to know when to stop scanning
- insertions and deletions are generalizations of lookups

delete: support A and B are hashed into the same location and then B is the next element of A, now if we delete A, how do we find the B

- tombstone
- movement

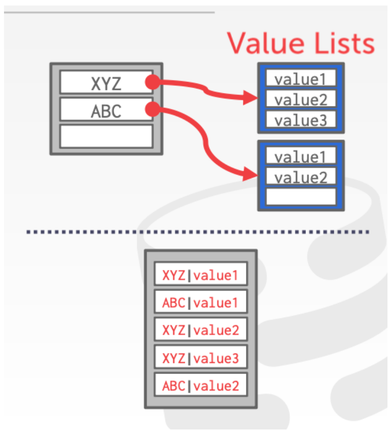
For non-unique keys,

1. separated linked list
2. redundant keys

5.2.2 robin hood hashing

Variant of linear probe hashing that steals slots from "rich" keys and give them to "poor" keys.

- Each key tracks the number of positions they are from where its optimal position in the table.
- On insert, a key takes the slot of another key if the first key is farther away from its optimal position than the second key.



5.2.3 cuckoo hashing

Use multiple hash tables with different hash functions seeds

- on insert, check every table and pick anyone that has a free slot
- if no table has a free slot, evict the element from one of them and then re-hash it find a new location

Look-ups and deletions are always O(1) because only one location per hash table is checked

5.3 dynamic hashing schemes

5.3.1 Chained hashing

maintain a linked list of **buckets** for each slot in the hash table

resolve collisions by replacing all elements with the same hash key into the same bucket

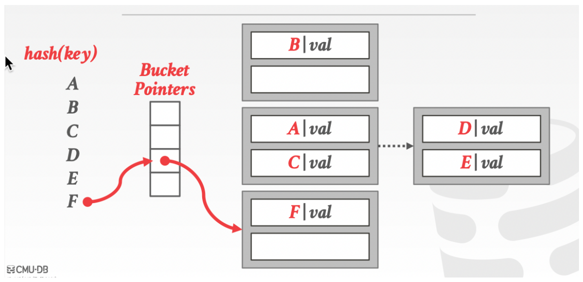
- to determine whether an element is present, hash to its buckets and scan for it

5.3.2 extendible hashing

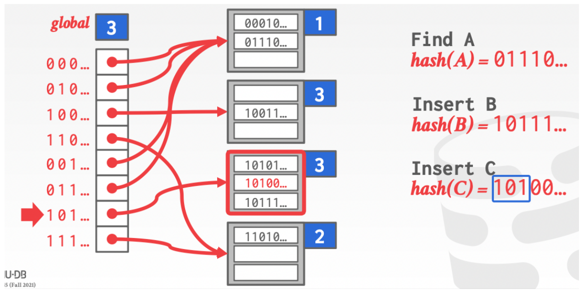
better source

chained-hashing approach where we split buckets instead of letting the linked list grow forever

multiple slot locations can point to the same bucket chain



reshuffle bucket entires on split and increase the number of bits to examine



5.3.3 linear hashing

The hash table maintains a **pointer** that tracks the next bucket to split

- when any bucket overflows, split the bucket at the pointer location

use multiple hashes to find the right bucket for a given key
can use different overflow criterion

6 Tree Indexes

A **table index** is a replica of a subset of a table's attributes that are organized and/or sorted for efficient using those attributes

6.1 B+ Tree overview

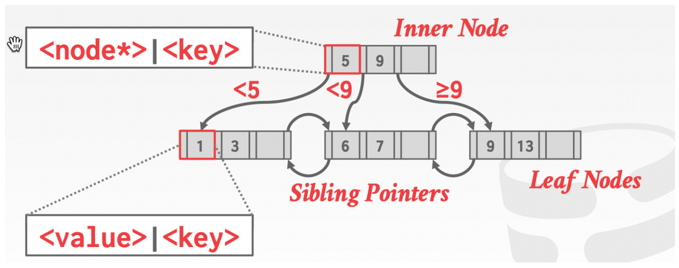
B-tree, B+tree, B*tree, Blink-tree

A B+Tree is a self-balancing tree data structure that keeps data sorted and allows searches, sequential access, insertions and deletions in $O(\log n)$

- optimized for systems that read and write large blocks of data

A B+Tree is an M-way search tree with the following properties

- it is perfectly balanced (i.e., every leaf node is at the same depth in the tree)
- every node other than the root is at least half-full $M/2 - 1 \leq$ #keys $\leq M - 1$
- every inner node with k keys has $k + 1$ non-null children



Every B+Tree node is comprised of an array of key/value pairs

- the keys are derived from the attributes that the index is based on
- the values will differ based on whether the node is classified as an **inner node** or a **leaf node**

The arrays are (usually) kept in sorted key order
Leaf node values approach

1. record IDs

   A pointer to the location of the tuple to which the index corresponds

2. tuple data

   the leaf nodes store the actual contents of the tuple

   secondary indexes must store the record ID as their values

Insert

1. find correct leaf node L
2. put data entry into L in sorted order

3. if L has enough space, done

4. otherwise, split L keys into L and a new node L2

    - redistribute entries evenly, copy up middle key
    - insert index entry pointing to L2 into parent of L

Delete

1. find leaf L where entry belongs. remove the entry

2. if L is at least half-full, done

3. if L has only M/2-1 entries

    - try to re-distribute, borrowing from sibling
    - if re-distribution fails, merge L and sibling

If merge occured, must delete entry from parent of L
Duplicate keys

1. append record ID

    - add the tuple's unique record ID as part of the key to ensure that all keys are unique
    - the DBMS can still use partial keys to find the tuples

2. Overflow leaf nodes

    - allow leaf nodes to spill into overflow nodes that contain the duplicate keys

clustered indexes The table is stored in the sort order specified by the primary key

- can be either heap- or index-organized storage

some DBMS always use a clustered index

- if a table does not contain a primary key, the DBMS will automaticall y make a hidden primary key

6.2 use in a DBMS

6.3 Design choices

6.3.1 node size

the slower the storage device, the larger the optimal node size for a B+ Tree

- HDD: 1MB
- SSD: 10KB
- In-Memory: 512B

optimal sizes can vary depending on the workload

6.3.2 merge threshold

some DBMSs do not always merge nodes when they are half full
delaying a merge operation may reduce the amount of reorganization
it may also be better to just let smaller nodes exist and then periodically rebuild entire tree

6.3.3 variable-length keys

1. pointers
2. variable-length nodes
3. padding
4. key map / indirection

6.3.4 intra-node search

1. linear
2. binary
3. interpolation

6.4 optimizations

6.4.1 prefix compression

sorted keys in the smae leaf node are likely to have the same prefix

robbed   robbing   robot

Instead of storing the entire key each time, extract common prefix and store only unique suffix for each key

6.4.2 deduplication

non-unique indexes can end up storing multiple copies of the same key in leaf nodes

the leaf node can store the key once and then maintain a list of tuples with that key

6.4.3 bulk insert

The fastest way to build a new B+Tree for an existing table is to first sort the keys and then rebuild the index from the bottom up

7 Index Concurrency

7.1 Latches Overview

Locks

- protect the database's logical contents from other txns
- held for txn duration
- need to be able to rollback changes

Latches

- Protect the critical sections of the DBMS's internal data structure from other threads
- held for operation duration
- do not need to be able to rollback changes

	Locks	Latches
Separate	User Txns	Threads
Protect	Database Contents	In-Memory Data Structures
During	Entire Txns	Critical Sections
Modes	Shared, Exclusive, Update, Intention	Read, Write
Deadlock	Detection & Resolution	Avoidance
by	Waits-for, Timeout, Aborts	Coding Discipline
Kept in	Lock Manager	Protected Data Structure

7.1.1 Latch Modes

Read Mode

- Multiple threads can read the same object at the same time
- A thread can acquire the read latch if another thread has it in read mode

Write Mode

- Only one thread an access the object
- A thread cannot acquire a write latch if another thread has it in any mode

7.1.2 Latch Implementations

1. Blocking OS Mutex non-scalable (about 25ns per lock/unlock invocation)

   ```
   std::mutex m;

   m.lock();

   m.unlock();
   ```

   But `std::mutex` -> `pthread_mutex_t` -> `futex`

2. Test-and-Set Spin Latch (TAS)

   - very efficient (single instruction to latch/unlatch)
   - non-scalable, not cache-friendly, not OS-friendly

- `std::atomic<T>`

```
std::atomic_flag latch;

while (latch.test_and_set(...)) {

}
```

Do not use spinlocks in user space, unless you actually know what you're doing. And be aware that the likelihood that you know what you are doing is basically nil.

3. Read-Writer Latches

   - Allows for concurrent readers
   - Must manage read/write queues to avoid starvation
   - can be implemented on top of spin latches

7.2 Hash table latching

easy to support concurrent access due to the limited ways threads access the data structure

- all threads move in the same direction and only access a single page/slot at a time
- deadlocks are not possible

To resize the table, take a global write latch on the entire table

1. Page latches

   - each page has its own reader-writer latch that protects its entire contents
   - threads acquire either a read or write latch before they access a page

2. Slot latches

   - each slot has its own latch
   - can use a single-mode latch to reduce meta-data and computational overhead

Atomic instruction that compares contents of a memory location M to a given value V `__sync_bool_compare_and_swap(&M,20,30)`

- if values are equal, installs new given value V′ in M
- otherwise operation fails

7.3 B+Tree Latching

We want to allow multiple threads to read and update a B+ Tree at the same time

We need to protect against two types of problems

- threads trying to modify the contents of a node at the same time
- one thread traversing the tree while another thread splits/merge nodes

7.3.1 Latch crabbing/coupling

Protocol to allow multiple threads to access/modify B+ Tree at the same time

Basic idea:

- get latch for parent
- get latch for child
- release latch for parent if "safe"

A **safe node** is one that will not split or merge when updated

- not full
- more than half-full

Find: start at root and go down

- acquire R latch on child
- then unlatch parent

Insert/Delete: Start at root and go down, obtaining W latches as needed. Once child is latched, check if it is safe:

- if child is safe, release all latches on ancestors

But taking a write latch on the root every time becomes a bottleneck with higher concurrency

7.3.2 Better latching algorithm

Most modifications to a B+Tree will <u>not</u> require a split or merge

Instead of assuming that there will be a split/merge, optimistically traverse the tree using read latches

If you guess wrong, repeat traversal with the pessimistic algorithm

Search: same as before

Insert/Delete:

- set latches as if for search, get to leaf, and set W latch on leaf
- if leaf is not safe, release all latches, and restart thread using previous insert/delete protocol with write latches

This approach optimistically assumes that only leaf node will be modified; if not, R latches set on the first pass to leaf are wasteful

7.4 Leaf Node Scans

The threads in all the examples so far have acquired latches in a "top-down" manner

But what if we want to move from one leaf node to another leaf node?

Latches do not support deadlock detection or avoidance. The only way we can deal with this problem is through coding discipline

The leaf node sibling latch acquisition protocol must support a "no-wait" mode

The DBMS's data structures must cope with failed latch acquisitions

8 Sorting & Aggregations

8.1 External Mergre Sort

What do we need to sort

- relational model/SQL is unsorted
- queries may request that tuples are sorted in a specific way
- But even if a query does not specify an order, we may still want to sort to do other things
  - trivial to support duplicate elimination
  - bulk loading sorted tuples into a B+ tree index is faster
  - aggregations

8.1.1 2-way external merge sort

2 is the number of runs that we are going to merge into a new run for each pass

data is broken up into N pages

the DBMS has a finite number of B buffer pool pages to hold input and output data

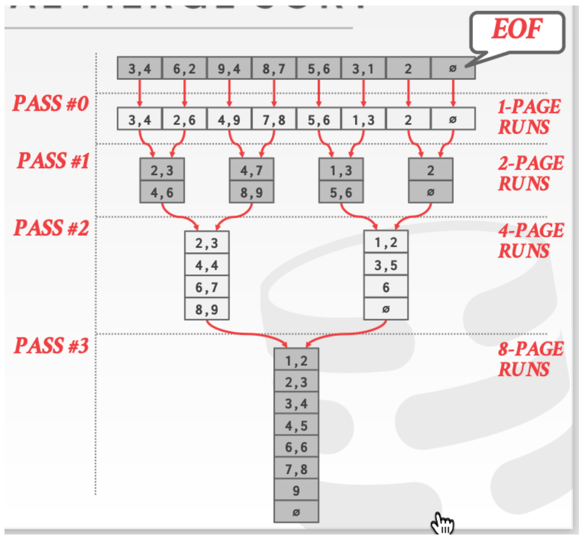
Pass 0

- read all B pages of the table into memory
- sort pages into runs and write them back to disk

Pass 1,2,3,..

- recursively merge pairs of runs into runs twice as long
- uses three buffer pages (2 for input pages, 1 for output)

Number of pass: $1 + \lceil \log_2 N \rceil$
Total I/O cost: $2N \cdot (\#\text{ of passes})$


EOF
PASS #0
PASS #1
PASS #2
PASS #3
1-PAGE RUNS
2-PAGE RUNS
4-PAGE RUNS
8-PAGE RUNS
3,4 6,2 9,4 8,7 5,6 3,1 2 ø
3,4 2,6 4,9 7,8 5,6 1,3 2 ø
2,3 4,6 | 4,7 8,9 | 1,3 5,6 | 2 ø
2,3 4,4 6,7 8,9 | 1,2 3,5 6 ø
1,2 2,3 3,4 4,5 6,6 7,8 9 ø

This algorithm only requires three buffer pool pages to perform the sorting

Double buffering optimization Prefetch the next run in the background and store it in a second buffer while system is processing the current run

- reduces the wait time for I/O requests at each step

8.1.2 General external merge sort

Pass 0

- use B buffer pages
- produce $\lceil N/B \rceil$ sorted runs of size B

Pass 1

- merge $B-1$ runs

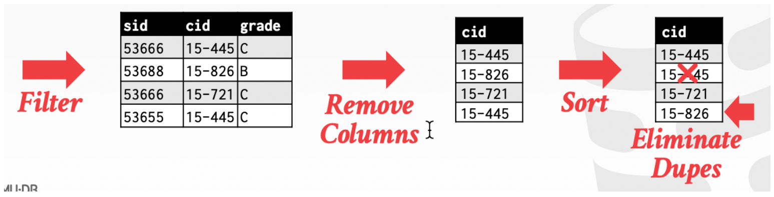
Number of pass: $1 + \lceil \log_{B-1} \lceil N/B \rceil \rceil$
Total I/O cost: $2N \cdot (\#\text{ of passes})$

8.1.3 Using B+Trees for sorting

8.2 Aggregations

Two implementation choices

- sorting
- hashing



sid	cid	grade
53666	15-445	C
53688	15-826	B
53666	15-721	C
53655	15-445	C

cid
15-445
15-826
15-721
15-445

cid
15-445
~~15-445~~
15-721
15-826

Hashing aggregate: Populate an ephemeral hash table as the DBMS scans the table. For each record, check whether there is already an entry in the hash table:

- `DISTINCT`: discard duplicate
- `GROUP BY`: perform aggregate computation

If everything fits in memory, then this is easy

8.2.1 External hashing aggregate

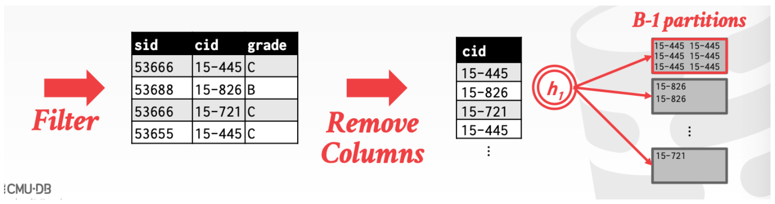
1. Phase 1: Partition

    - divide tuples into buckets based on hash key
    - write them out to disk when they get full

    use a hash function h_1 to split tuples into **partitions** on disk

    - a partition is one or more pages that contain the set of keys with the same hash value
    - partitions are "spilled" to disk via output buffers

    Assume that we have B buffers, we will use B-1 buffers for the partitions and 1 buffer for the input data



sid	cid	grade
53666	15-445	C
53688	15-826	B
53666	15-721	C
53655	15-445	C

cid
15-445
15-826
15-721
15-445
⋮

2. Phase 2: ReHash

    - build in-memory hash table for each partition and compute the aggregation

    For each partition on disk

    - read it into memory and build an in-memory hash table based on a second hash function h_2
    - then go through each bucket of this hash table to bring together matching tuples

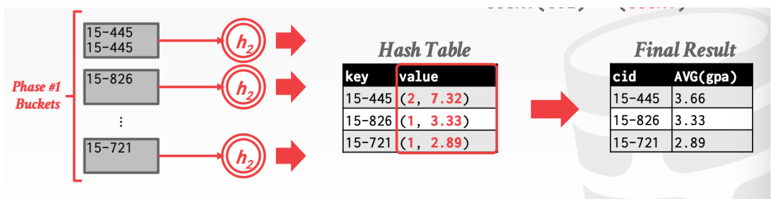
    This assumes that each partition fits in memory

8.2.2 Hashing summarization

During the rehash phase, store pairs of the form `GroupKey->RunningVal` when we want to insert a new tuple into the hash table

- if we find a matching `GroupKey`, just update the `RunningVal` appropriately

- else insert a new `GroupKey->RunningVal`



key	value
15-445	(2, 7.32)
15-826	(1, 3.33)
15-721	(1, 2.89)

cid	AVG(gpa)
15-445	3.66
15-826	3.33
15-721	2.89

9 Joins

We will focus on performing binary joins (two tables) using **inner equijoin** algorithms

- these algorithms can be tweaked to support other joins
- multi-way joins exist primarily in research literature

In general, we want the smaller table to always be the left table ("outer table") in the query plan

Decision 1: output

- what data does the join operator emit to its parent operator in the query plan tree

Decision 2: cost analysis criteria

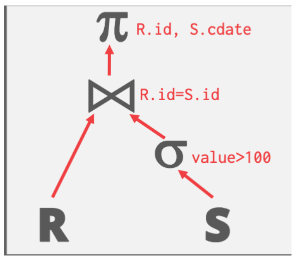
- how do we determine whether one join algorithm is better than another

```sql
SELECT R.id, S.cdate
  FROM R JOIN S
    ON R.id = S.id
 WHERE S.value > 100
```

For tuple $r \in R$ and tuple $s \in S$ that match on join attributes, concatenate r and s together into a new tuple

output contents can vary:

- depends on processing model
- depends on storage model



- depends on data requirements in query

Early Materialization:

- copy the values for the attributes in outer and inner tuples into a new output tuple
- subsequent operators in the query plan never need to go back to the base tables to get more data

Late Materialization:

- only copy the joins keys along with the Record IDs of the matching tuples
- ideal for column stores because the DBMS does not copy data that is not needed for the query

Cost Analysis Criteria
Assume

- M pages in table R, m tuples in R
- N pages in table S, n tuples in S

Cost Metric: # of IOs to compute join

$R \bowtie S$ is the most common operation and thus must be carefully optimized

$R \times S$ followed by a selection is inefficient because the cross-product is large

9.1 Join algorithms

9.1.1 Nested Loop Join

1. Simple/Stupid foreach tuple $r \in R$: foreach tuple $s \in S$: emit, if r and s match

Cost: $M + m \cdot N$

2. Block foreach block $B_R \in R$ foreach block $B_S \in S$ foreach tuple $r \in B_r$ foreach tuple $s \in B_s$ emit, if r and s match

   cost: $M + M \cdot N$

   What if we have B buffers available?

   - use $B - 2$ buffers for scanning the outer table
   - use one buffer for the inner table, one buffer for storing output

   foreach $B - 2$ blocks $b_R \in R$ foreach block $b_S \in S$ foreach tuple $r \in B - 2$ blocks foreach tuple $s \in b_S$ emit, if r and s match

   Cost: $M + \lceil M/(B-2) \rceil \cdot N$

3. Index Why is the basic nested loop join so bad?

   - for each tuple in the outer table, we must do a sequential scan to check for a match in the inner table

   We can avoid sequential scans by using an index to find inner table matches

   - use an existing index for the join

   foreach tuple $r \in R$ for each tuple $s \in$ Index$(r_i = s_j)$ emit, if r and s match

9.1.2 Sort-Merge Join

Phase 1: sort

- sort both tables on the join keys

Phase 2: merge

- step through the two sorted tables with cursors and emit matching tuples
- may need to backtrack depending on the join type

sort R, S on join keys cursor$_S \leftarrow R_{\text{sorted}}$, cursor$_S \leftarrow S_{\text{sorted}}$ while cursor$_R$ and cursor$_S$: if cursor$_R >$ cursor$_S$ increment cursor$_S$ if cursor$_R <$ cursor$_S$ increment cursor$_R$ elif cursor$_R$ and cursor$_S$ match: emit increment cursor$_S$

Sort Cost(R): $2M \cdot (1 + \lceil \log_{B-1} \lceil M/B \rceil \rceil)$ Sort Cost(S): $2N \cdot (1 + \lceil \log_{B-1} \lceil N/B \rceil \rceil)$
Merge Cost: $M + N$

When is sort-merge join useful?

- one or both tables are already sorted on join key
- output must be sorted on join key
- the input relations may be sorted either by an explicit sort operator, or by scanning the relation using an index on the join key

9.1.3 Hash Join

if tuple $r \in R$ and a tuple $s \in S$ satisfy the join condition, then they have the same value for the join attributes

if that value is hashed to some partition i, the R tuple must be in r_i and the S tuple in s_i

Therefore R tuples in r_i need only to be compared with S tuples in s_i

Phase 1: build

- scan the outer relation and populate a hash table using the hash function h_1 on the join attributes

Phase 2: probe

- scan the inner relation and use h_1 on each tuple to jump to a location in the hash table and find a matching tuple

Hash table contents
key: the attributes
value: varies per implementation

- depends on what the operators above the join in the query plan expect as its input

Approach 1: full tuple
Approach 2: tuple identifier

- could be to either the base tables or the intermediate output from child operators in the query plan
- ideal for column stores because the DBMS does not fetch data from disk that it does not need
- also better if join selectivity is low

Probe phase optimization: create a **Bloom Filter** during the build phase when the key is likely to not exist in the hash table

- threads check the filter before probing the hash table. This will be faster since the filter will fit in CPU caches
- sometimes called **sideways information passing**

Bloom filters is a probalistic data structure (bitmap) that answers set membership queries

- false negatives will never occur
- false positives can sometimes occur

`Insert(x)`: use k hash functions to set bits in the filter to 1
`Lookup(x)`: check whether the bits are 1 for each hash function
how big of a table can we hash using this approach?

- $B - 1$ "spill partitions" in phase 1
- each should be no more than B blocks big

Answer: $B \cdot (B - 1)$

- a table of N pages needs about $\sqrt{N}$ buffers
- assume hash distributes records evenly. Use a "fudge factor" $f > 1$ for that: we need $B \cdot \sqrt{fN}$

What happens if we do not have enough memory to fit the entire hash table?
we do not want to let the buffer pool manager swap out the hash table pages at random
Hash join when tables do not fit in memory

- Build Phase: Hash both tables on the join attribute into partitions
- Probe Phase: Compares tuples in corresponding partitions for each table

Cost: $3(M + N)$
partition: $2(M + N)$
probing $M + N$

algorithm	IO cost
simple nested loop join	$M + (m \cdot N)$
block nested loop join	$M + (M \cdot N)$
index nested loop join	$M + (M \cdot C)$
Sort-Merge join	$M + N$+sort cost
hash join	$3(M + N)$

10 Query execution 1

10.1 Processing Models

A DBMS's **processing model** defines how the system executes a query plan

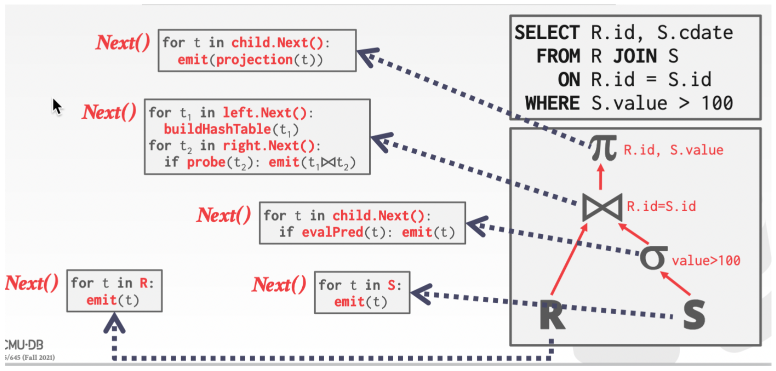
- different trade-offs for different workloads

10.1.1 Iterator Model

Each query plan operator implements a `next()` function

- on each invocation, the operator returns either a single tuple or a `null` marker if there are no more tuples
- the operator implements a loop that call `next()` on its children to retrieve their tuples and then process them

Also called **volcano** or **pipeline** model



```
SELECT R.id, S.cdate
  FROM R JOIN S
    ON R.id = S.id
 WHERE S.value > 100
```

```
Next()
for t in child.Next():
  emit(projection(t))
```

```
Next()
for t₁ in left.Next():
  buildHashTable(t₁)
for t₂ in right.Next():
  if probe(t₂): emit(t₁⋈t₂)
```

```
Next()
for t in child.Next():
  if evalPred(t): emit(t)
```

```
Next()
for t in R:
  emit(t)
```

```
Next()
for t in S:
  emit(t)
```

This is used in almost every DBMS. Allows for tuple **pipelining**
some operators must block until their children emit all their tuples

- joins, subqueries, order by

output control works easily with this approach

10.1.2 Materialization Model

Each operator processes its input all at once and then emits its output all at once

- the operator "materializes" its output as a single result
- the BDMS can push down hints (e.g. `LIMIT`) to avoid scaning too many tuples

10.1.3 Vectorized/Batch Model

10.2 Access Methods

10.3 Modification Queries

10.4 Expression Evaluation