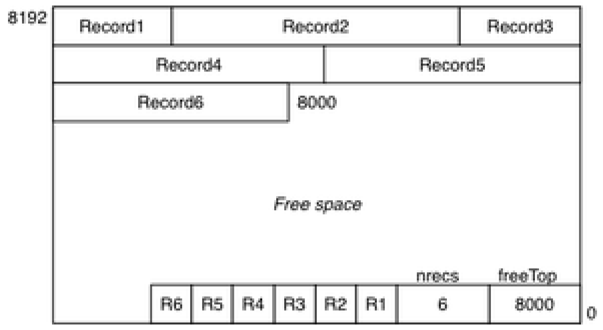
Week 04 Lectures

Tuples

Tuples

Each *page* contains a collection of *tuples*



What do tuples contain? How are they structured internally?

Records vs Tuples

A *table* is defined by a *schema*, e.g.

```
create table Employee (
   id   integer primary key,
   name varchar(20) not null,
   job  varchar(10),
   dept number(4) references Dept(id)
);
```

where a schema is a collection of attributes (name,type,constraints)

Schema information (meta-data) is stored in the DB catalog

... Records vs Tuples

Tuple = collection of attribute values based on a schema, e.g.

```
(33357462, 'Neil Young', 'Musician', 0277)
```

Record = sequence of bytes, containing data for one tuple, e.g.

01101001
11001100
01010101
00111100
10100011
01011111
01011010

Bytes need to be interpreted relative to schema to get tuple

Converting Records to Tuples

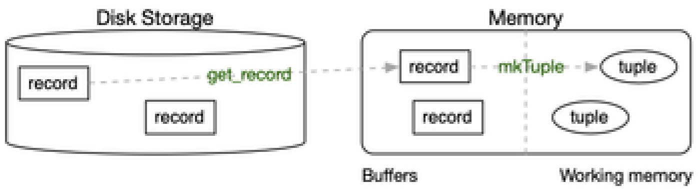
A `Record` is an array of bytes (`byte[]`)

- representing the data values from a typed `Tuple`

- stored on disk (persistent) or in a memory buffer

A `Tuple` is a collection of named,typed values (cf. C `struct`)

- to manipulate the values, need an "interpretable" structure
- stored in working memory, and temporary



... Converting Records to Tuples

Information on how to interpret bytes in a record ...

- may be contained in schema data in DBMS catalog
- may be stored in the page directory
- may be stored in the record (in a record header)
- may be stored partly in the record and partly in the schema

For variable-length records, some formatting info ...

- must be stored in the record or in the page directory
- at the least, need to know how many bytes in each value

Operations on Records

Common operation on records ... access record via `RecordId`:

```
Record get_record(Relation rel, RecordId rid) {
    (pid,tid) = rid;
    Page buf = get_page(rel, pid);
    return get_bytes(rel, buf, tid);
}
```

Cannot use a `Record` directly; need a `Tuple`:

```
Relation rel = ... // relation schema
Record rec = get_record(rel, rid)
Tuple t = mkTuple(rel, rec)
```

Once we have a `Tuple`, we can access individual attributes/fields

---

Operations on Tuples

Once we have a record, we need to interpret it as a tuple ...

`Tuple t = mkTuple(rel, rec)`

- convert record to tuple data structure for relation `rel`

Once we have a tuple, we want to examines its contents ...

`Typ` **`getTypField(Tuple t, int i)`**

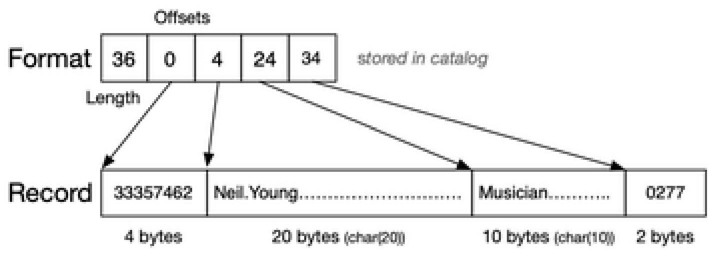
- extract the `i`'th field from a `Tuple` as a value of type *Typ*

E.g. `int x = getIntField(t,1), char *s = getStrField(t,2)`

Fixed-length Records

A possible encoding scheme for fixed-length records:

- record format (length + offsets) stored in catalog
- data values stored in fixed-size slots in data pages

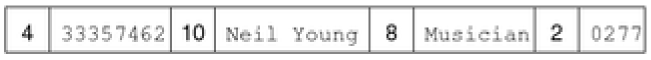


Since record format is frequently used at query time, cache in memory.

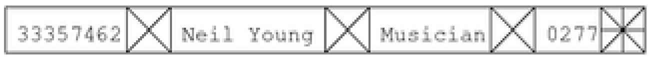
Variable-length Records

Possible encoding schemes for variable-length records:

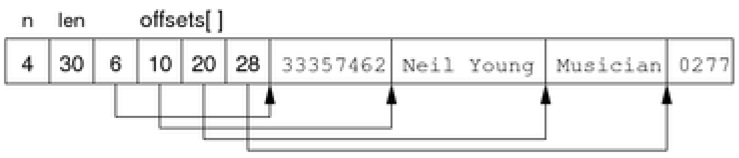
- Prefix each field by length



- Terminate fields by delimiter



- Array of offsets



Data Types

DBMSs typically define a fixed set of base types, e.g.

`DATE`, `FLOAT`, `INTEGER`, `NUMBER(`*n*`)`, `VARCHAR(`*n*`)`, ...

This determines implementation-level data types for field values:

`DATE`	`time_t`
`FLOAT`	`float,double`
`INTEGER`	`int,long`
`NUMBER(`*n*`)`	`int[]` (?)
`VARCHAR(`*n*`)`	`char[]`

PostgreSQL allows new base types to be added

Field Descriptors

A `Tuple` could be implemented as

- a list of field descriptors for a record instance
  (where a `FieldDesc` gives (offset,length,type) information)
- along with a reference to the `Record` data

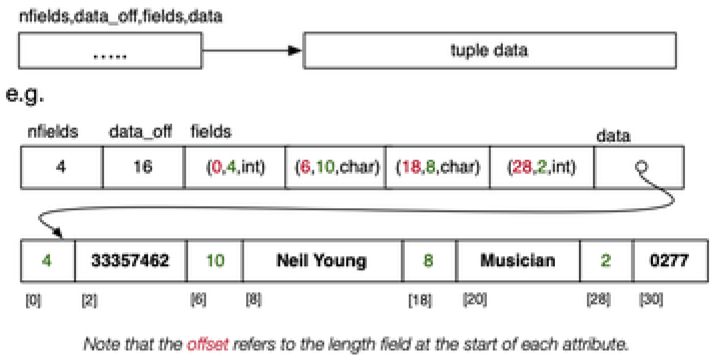
```
typedef struct {
  ushort    nfields;   // number of fields/attrs
  ushort    data_off;  // offset in struct for data
  FieldDesc fields[];  // field descriptions
  Record    data;      // pointer to record in buffer
} Tuple;
```

Fields are derived from relation descriptor + record instance data.

... Field Descriptors

Tuple `data` could be

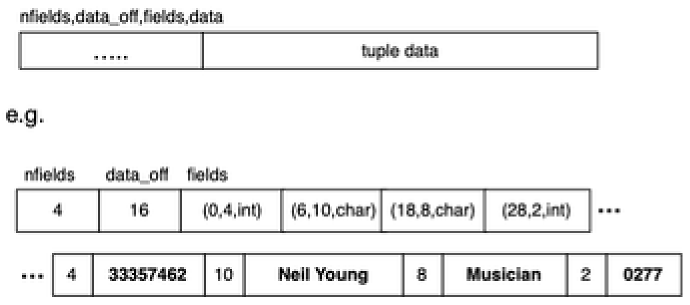
- a pointer to bytes stored elsewhere in memory



... Field Descriptors

Or, tuple `data` could be ...

- appended to `Tuple struct` (used widely in PostgreSQL)



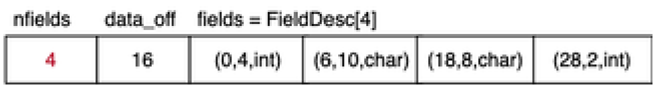
Exercise 1: How big is a `FieldDesc`?

`FieldDesc` = (offset,length,type), where

- offset = offset of field within record data
- length = length (in bytes) of field
- type = data type of field

If pages are 8KB in size, how many bits are needed for each?

E.g.



PostgreSQL Tuples

Definitions: `include/postgres.h`, `include/access/*tup*.h`

Functions: `backend/access/common/*tup*.c` e.g.

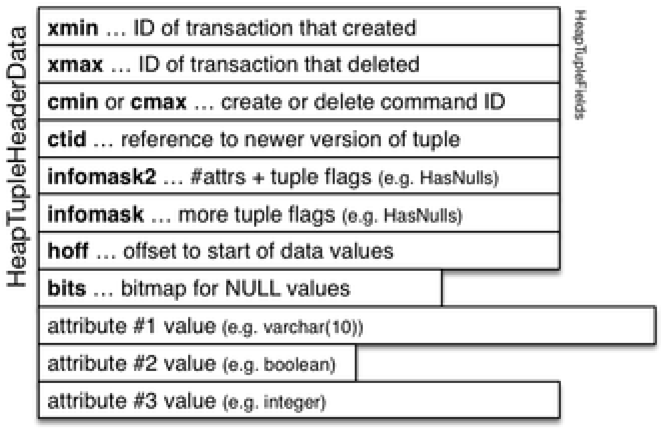
- `HeapTuple heap_form_tuple(desc,values[],isnull[])`
- `heap_deform_tuple(tuple,desc,values[],isnull[])`

PostgreSQL implements tuples via:

- a contiguous chunk of memory
- starting with a header giving e.g. #fields, nulls
- followed by data values (as a sequence of `Datum`)

... PostgreSQL Tuples

Tuple structure:


HeapTupleHeaderData
HeapTupleFields
xmin ... ID of transaction that created
xmax ... ID of transaction that deleted
cmin or cmax ... create or delete command ID
ctid ... reference to newer version of tuple
infomask2 ... #attrs + tuple flags (e.g. HasNulls)
infomask ... more tuple flags (e.g. HasNulls)
hoff ... offset to start of data values
bits ... bitmap for NULL values
attribute #1 value (e.g. varchar(10))
attribute #2 value (e.g. boolean)
attribute #3 value (e.g. integer)

... PostgreSQL Tuples

Tuple-related data types: (cont)

```
// TupleDesc: schema-related information for HeapTuples

typedef struct tupleDesc
{
  int          natts;       // # attributes in tuple
  Oid          tdtypeid;    // composite type ID for tuple type
  int32        tdtypmod;    // typmod for tuple type
  bool         tdhasoid;    // does tuple have oid attribute?
  int          tdrefcount;  // reference count (-1 if not counting)
  TupleConstr *constr;      // constraints, or NULL if none
  FormData_pg_attribute attrs[];
  // attrs[N] is a pointer to description of attribute N+1
} *TupleDesc;
```

... PostgreSQL Tuples

Tuple-related data types: (cont)

```
// FormData_pg_attribute:
// schema-related information for one attribute

typedef struct FormData_pg_attribute
{
  Oid      attrelid;    // OID of reln containing attr
  NameData attname;     // name of attribute
  Oid      atttypid;    // OID of attribute's data type
  int16    attlen;      // attribute length
  int32    attndims;    // # dimensions if array type
  bool     attnotnull;  // can attribute have NULL value
  .....                 // and many other fields
} FormData_pg_attribute;
```

For details, see `include/catalog/pg_attribute.h`

... PostgreSQL Tuples

`HeapTupleData` contains information about a stored tuple

```
typedef HeapTupleData *HeapTuple;

typedef struct HeapTupleData
{
  uint32           t_len;  // length of *t_data
  ItemPointerData t_self;  // SelfItemPointer
  Oid         t_tableOid;  // table the tuple came from
  HeapTupleHeader t_data;  // -> tuple header and data
} HeapTupleData;
```

`HeapTupleHeader` is a pointer to a location in a buffer

... PostgreSQL Tuples

PostgreSQL stores a single block of data for tuple

- containing a tuple header, followed by data `byte[]`

```
typedef struct HeapTupleHeaderData // simplified
{
  HeapTupleFields t_heap;
  ItemPointerData t_ctid;      // TID of newer version
  uint16          t_infomask2; // #attributes + flags
  uint16          t_infomask;  // flags e.g. has_null
  uint8           t_hoff;      // sizeof header incl. t_bits
  // above is fixed size (23 bytes) for all heap tuples
  bits8           t_bits[1];   // bitmap of NULLs, var.len.
  // OID goes here if HEAP_HASOID is set in t_infomask
  // actual data follows at end of struct
} HeapTupleHeaderData;
```

... PostgreSQL Tuples

Some of the bits in `t_infomask` ..

```
#define HEAP_HASNULL      0x0001
        /* has null attribute(s) */
#define HEAP_HASVARWIDTH  0x0002
        /* has variable-width attribute(s) */
#define HEAP_HASEXTERNAL  0x0004
        /* has external stored attribute(s) */
#define HEAP_HASOID_OLD   0x0008
        /* has an object-id field */
```

Location of `NULLs` is stored in t_bits[] array

... PostgreSQL Tuples

Tuple-related data types: (cont)

```
typedef struct HeapTupleFields  // simplified
{
  TransactionId t_xmin;  // inserting xact ID
  TransactionId t_xmax;  // deleting or locking xact ID
  union {
    CommandId   t_cid;   // inserting or deleting command ID
    TransactionId t_xvac;// old-style VACUUM FULL xact ID
  } t_field3;
} HeapTupleFields;
```

Note that not all system fields from stored tuple appear

- `oid` is stored after the tuple header, if used
- both `xmin/xmax` are stored, but only one of `cmin/cmax`

PostgreSQL Attribute Values

Values of attributes in PostgreSQL tuples are packaged as `Datums`

```
// representation of a data value
typedef uintptr_t Datum;
```

The actual data value:

- may be stored in the `Datum` (e.g. `int`)
- may have a header with length (for varlen attributes)
- may be stored in a TOAST file (if large value)

... PostgreSQL Attribute Values

Attribute values can be extracted as `Datum` from `HeapTuples`

```
Datum heap_getattr(
      HeapTuple tup,      // tuple (in memory)
      int attnum,         // which attribute
      TupleDesc tupDesc,  // field descriptors
      bool *isnull        // flag to record NULL
)
```

`isnull` is set to true if value of field is `NULL`

`attnum` can be negative ... to access system attributes (e.g. OID)

For details, see `include/access/htup_details.h`

... PostgreSQL Attribute Values

Values of `Datum` objects can be manipulated via e.g.

```
// DatumGetBool:
//   Returns boolean value of a Datum.

#define DatumGetBool(X) ((bool) ((X) != 0))

// BoolGetDatum:
```

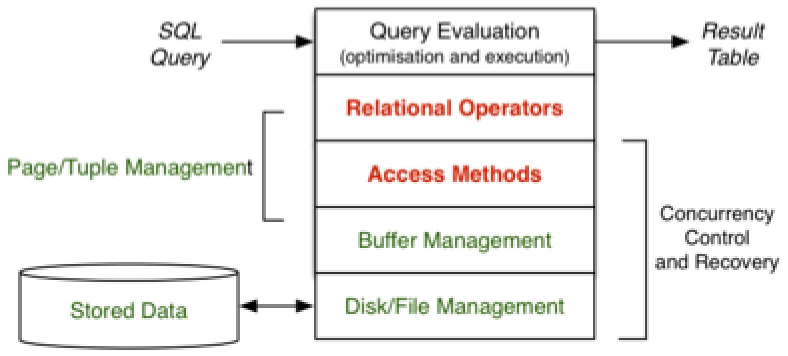
```
//   Returns Datum representation for a boolean.

#define BoolGetDatum(X) ((Datum) ((X) ? 1 : 0))
```

For details, see `include/postgres.h`

Implementing Relational Operations

DBMS Architecture (revisited)

Implementation of relational operations in DBMS:



Relational Operations

DBMS core = relational engine, with implementations of

- selection, projection, join, set operations
- scanning, sorting, grouping, aggregation, ...

In this part of the course:

- examine methods for implementing each operation
- develop cost models for each implementation
- characterise when each method is most effective

Terminology reminder:

- tuple = collection of data values under some schema ≅ record
- page = block = collection of tuples + management data = i/o unit
- relation = table ≅ file = collection of tuples

... Relational Operations

Two "dimensions of variation":

- which relational operation (e.g. Sel, Proj, Join, Sort, ...)
- which access–method (e.g. file struct: heap, indexed, hashed, ...)

Each *query method* involves an operator and a file structure:

- e.g. primary–key selection on hashed file
- e.g. primary–key selection on indexed file
- e.g. join on ordered heap files (sort–merge join)
- e.g. join on hashed files (hash join)
- e.g. two–dimensional range query on R–tree indexed file

As well as query costs, consider update costs (insert/delete).

... Relational Operations

SQL vs DBMS engine

- `select ... from R where C`
  - find relevant tuples (satisfying C) in file(s) of R
- `insert into R values(...)`
  - place new tuple in some page of a file of R
- `delete from R where C`
  - find relevant tuples and "remove" from file(s) of R
- `update R set ... where C`
  - find relevant tuples in file(s) of R and "change" them

Cost Models

Cost Models

An important aspect of this course is

- analysis of cost of various query methods

Cost can be measured in terms of

- *Time Cost*: total time taken to execute method, or
- *Page Cost*: number of pages read and/or written

Primary assumptions in our cost models:

- memory (RAM) is "small", fast, byte–at–a–time
- disk storage is very large, slow, page–at–a–time

... Cost Models

Since *time cost* is affected by many factors

- speed of i/o devices (fast/slow disk, SSD)
- load on machine

we do not consider time cost in our analyses.

For comparing methods, *page cost* is better

- identifies workload imposed by method
- BUT is clearly affected by buffering

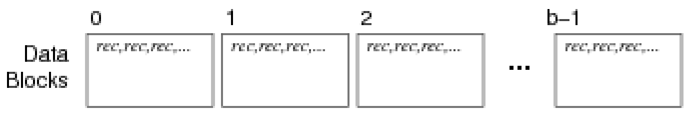
Estimating costs with multiple concurrent ops *and* buffering is difficult!!

Addtional assumption: every page request leads to some i/o

... Cost Models

In developing cost models, we also assume:

- a relation is a set of r tuples, with average size R bytes
- the tuples are stored in b data pages on disk
- each page has size B bytes and contains up to c tuples
- the tuples which answer query q are contained in b_q pages
- data is transferred disk↔memory in whole pages
- cost of disk↔memory transfer $T_{r/w}$ is very high



... Cost Models

Our cost models are "rough" (based on assumptions)

But do give an *O(x)* feel for how expensive operations are.

Example "rough" estimation: how many piano tuners in Sydney?

- Sydney has ≅ 4 000 000 people
- Average household size ≅ 3 ∴ 1 300 000 households
- Let's say that 1 in 10 households owns a piano
- Therefore there are ≅ 130 000 pianos
- Say people get their piano tuned every 2 years (on average)
- Say a tuner can do 2/day, 250 working-days/year
- Therefore 1 tuner can do 500 pianos per year
- Therefore Sydney would need ≅ 130000/2/500 = 130 tuners

Actual number of tuners in Yellow Pages = 120

Example borrowed from Alan Fekete at Sydney University.

Query Types

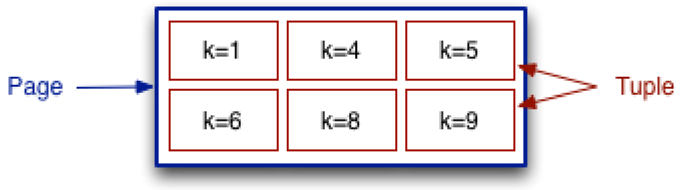
Type	SQL	RelAlg	a.k.a.
Scan	`select * from R`	*R*	–
Proj	`select` *x,y* `from R`	*Proj[x,y]R*	–
Sort	`select * from R order by` *x*	*Sort[x]R*	*ord*
Sel_1	`select * from R where id =` *k*	*Sel[id=k]R*	*one*
Sel_n	`select * from R where a =` *k*	*Sel[a=k]R*	–
Join_1	`select * from R,S where R.id = S.r`	*R Join[id=r] S*	–

Different query classes exhibit different query processing behaviours.

Example File Structures

When describing file structures

- use a large box to represent a *page*
- use either a small box or tup_i (or rec_i) to represent a *tuple*
- sometimes refer to tuples via their *key*
    - mostly, *key* corresponds to the notion of "primary key"
    - sometimes, *key* means "search key" in selection condition

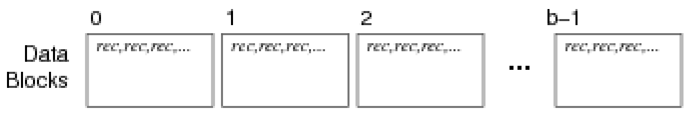


... Example File Structures

Consider three simple file structures:

- *heap file* ... tuples added to any page which has space
- *sorted file* ... tuples arranged in file in key order
- *hash file* ... tuples placed in pages using hash function

All files are composed of *b* primary blocks/pages



Some records in each page may be marked as "deleted".

Exercise 2: Operation Costs

For each of the following file structures

- heap file, sorted file, hash file

Determine #page-reads + #page-writes for insert and delete

You can assume the existence of a file header containing

- values for *r*, *R*, *b*, *B*, *c*
- index of first page with free space (and a free list)

Assume also

- each page contains a header and directory as well as tuples
- no buffering (worst case scenario)

Scanning

Scanning

Consider the query:

```
select * from Rel;
```

Operational view:

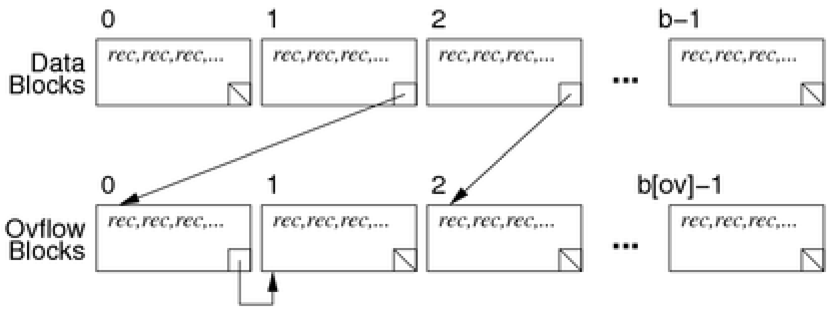
```
for each page P in file of relation Rel {
   for each tuple t in page P {
      add tuple t to result set
   }
}
```

Cost: read every data page once

Time Cost = $b.T_r$,   *Page Cost* = b

... Scanning

Scan implementation when file has overflow pages, e.g.



... Scanning

In this case, the implementation changes to:

```
for each page P in data file of relation Rel {
    for each tuple t in page P {
        add tuple t to result set
    }
    for each overflow page V of page P {
        for each tuple t in page V {
            add tuple t to result set
}   }   }
```

Cost: read each data page and each overflow page once

Cost = $b + b_{Ov}$

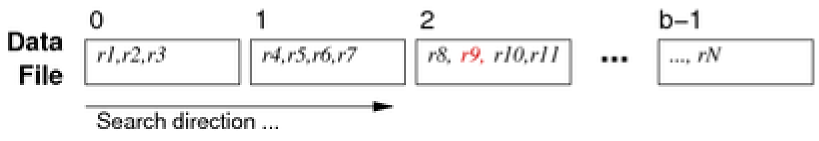
where b_{Ov} = total number of overflow pages

Selection via Scanning

Consider a *one* query like:

```
select * from Employee where id = 762288;
```

In an unordered file, search for matching tuple requires:



Guaranteed at most one answer; but could be in any page.

... Selection via Scanning

Overview of scan process:

```
for each page P in relation Employee {
    for each tuple t in page P {
        if (t.id == 762288) return t
}   }
```

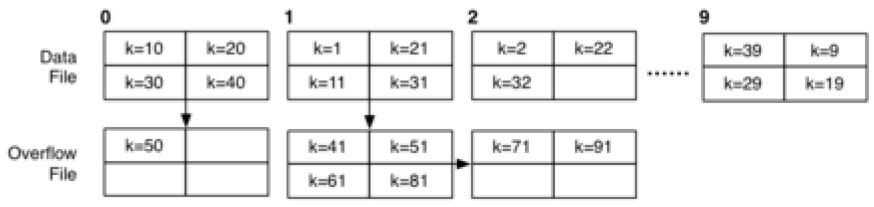
Cost analysis for *one* searching in unordered file

- best case: read one page, find tuple
- worst case: read all *b* pages, find in last (or don't find)
- average case: read half of the pages (*b/2*)

Page Costs: $Cost_{avg} = b/2$ $Cost_{min} = 1$ $Cost_{max} = b$

Exercise 3: Cost of Search in Hashed File

Consider the hashed file structure $b = 10, c = 4, h(k) = k\%10$



Describe how the following queries

```
select * from R where k = 51;
select * from R where k > 50;
```

might be solved in a file structure like the above ($h(k) = k\%b$).

Estimate the minimum and maximum cost (as #pages read)

Iterators

Access methods typically involve *iterators*, e.g.

`Scan s = start_scan(Relation r, ...)`

- commence a scan of relation `r`
- `Scan` may include condition to implement `WHERE`-clause
- `Scan` holds data on progress through file (e.g. current page)

`Tuple next_tuple(Scan s)`

- return `Tuple` immediately following last accessed one
- returns `NULL` if no more `Tuples` left in the relation

Example Query

Example: simple scan of a table ...

```
select name from Employee
```

implemented as:

```
DB db = openDatabase("myDB");
Relation r = openRelation(db,"Employee",READ);
Scan s = start_scan(r);
Tuple t;  // current tuple
while ((t = next_tuple(s)) != NULL)
{
   char *name = getStrField(t,2);
   printf("%s\n", name);
}
```

Exercise 4: Implement next_tuple()

Consider the following possible **`Scan`** data structure

```
typedef struct {
   Relation rel;
   Page     *curPage;  // Page buffer
   int      curPID;    // current pid
   int      curTID;    // current tid
} ScanData;
```

Assume tuples are indexed 0..`nTuples(p)`

Assume pages are indexed 0..`nPages(rel)`

Implement the **`Tuple next_tuple(Scan)`** function

P.S. What's in a `Relation` object?

Relation Copying

Consider an SQL statement like:

```
create table T as (select * from S);
```

Effectively, copies data from one table to a new table.

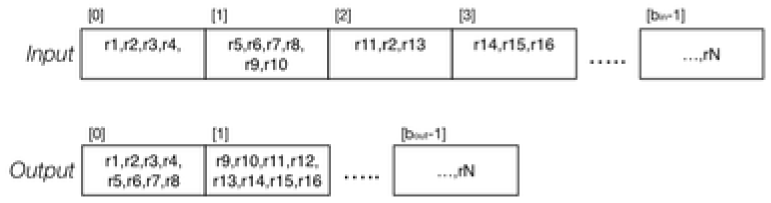
Process:

```
make empty relation T
s = start scan of S
while (t = next_tuple(s)) {
    insert tuple t into relation T
}
```

... Relation Copying

Possible that `T` is smaller than `S`

- may be unused free space in `S` where tuples were removed
- if `T` is built by simple append, will be compact



... Relation Copying

In terms of existing relation/page/tuple operations:

```
Relation in;        // relation handle (incl. files)
Relation out;       // relation handle (incl. files)
int ipid,opid,tid;  // page and record indexes
Record rec;         // current record (tuple)
Page ibuf,obuf;     // input/output file buffers

in = openRelation("S", READ);
out = openRelation("T", NEW|WRITE);
clear(obuf);  opid = 0;
for (ipid = 0; ipid < nPages(in); ipid++) {
    ibuf = get_page(in, ipid);
    for (tid = 0; tid < nTuples(ibuf); tid++) {
        rec = get_record(ibuf, tid);
        if (!hasSpace(obuf,rec)) {
            put_page(out, opid++, obuf);
            clear(obuf);
        }
        insert_record(obuf,rec);
}   }
if (nTuples(obuf) > 0) put_page(out, opid, obuf);
```

Exercise 5: Cost of Relation Copy

Analyse cost for relation copying:

1. if both input and output are heap files
2. if input is sorted and output is heap file
3. if input is heap file and output is sorted

Assume ...

- *r* records in input file, *c* records/page
- b_{in} = number of pages in input file
- some pages in input file are *not* full
- all pages in output file are full (except the last)

Give cost in terms of #pages read + #pages written

Scanning in PostgreSQL

Scanning defined in: backend/access/heap/heapam.c

Implements iterator data/operations:

- **`HeapScanDesc`** ... struct containing iteration state
- **`scan = heap_beginscan(rel,...,nkeys,keys)`**
- **`tup = heap_getnext(scan, direction)`**
- **`heap_endscan(scan)`** ... frees up `scan` struct
- **`res = HeapKeyTest(tuple,...,nkeys,keys)`**
  ... performs `ScanKeys` tests on tuple ... is it a result tuple?

```
typedef HeapScanDescData *HeapScanDesc;

typedef struct HeapScanDescData
{
  // scan parameters
  Relation      rs_rd;         // heap relation descriptor
  Snapshot      rs_snapshot;   // snapshot ... tuple visibility
  int           rs_nkeys;      // number of scan keys
  ScanKey       rs_key;        // array of scan key descriptors
  ...
  // state set up at initscan time
  PageNumber    rs_npages;     // number of pages to scan
  PageNumber    rs_startpage;  // page # to start at
  ...
  // scan current state, initally set to invalid
  HeapTupleData rs_ctup;       // current tuple in scan
  PageNumber    rs_cpage;      // current page # in scan
  Buffer        rs_cbuf;       // current buffer in scan
   ...
} HeapScanDescData;
```

Scanning in other File Structures

Above examples are for *heap* files

- simple, unordered, maybe indexed, no hashing

Other access file structures in PostgreSQL:

- **btree**, **hash**, **gist**, **gin**
- each implements:
    - startscan, getnext, endscan
    - insert, delete (update=delete+insert)
    - other file-specific operators

Sorting

The Sort Operation

Sorting is explicit in queries only in the `order by` clause

```
select * from Students order by name;
```

Sorting is used internally in other operations:

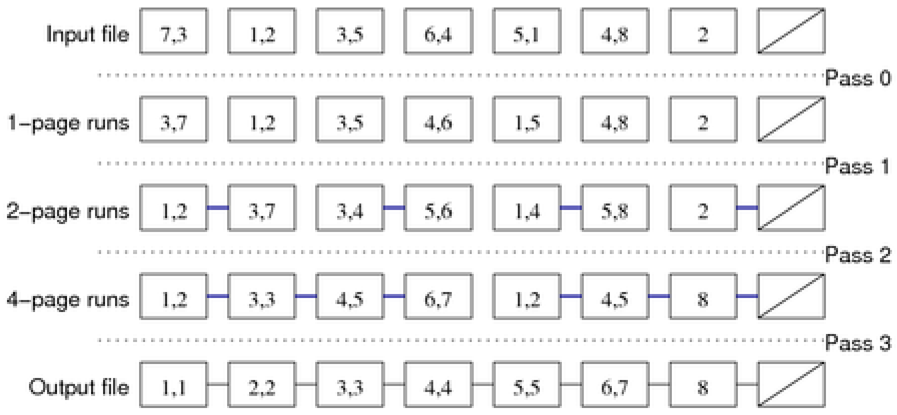
- eliminating duplicate tuples for projection
- ordering files to enhance select efficiency
- implementing various styles of join
- forming tuple groups in `group by`

Sort methods such as quicksort are designed for in-memory data.

For large data on disks, need external sorts such as *merge sort*.

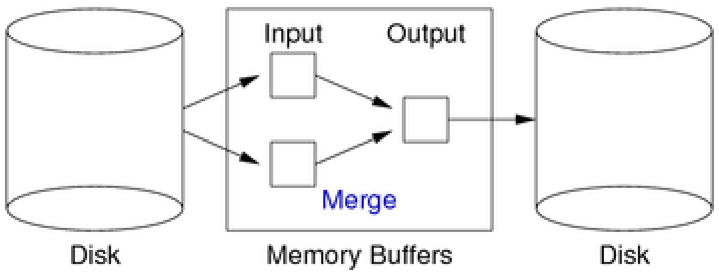
Two-way Merge Sort

Example:



... Two-way Merge Sort

Requires three in-memory buffers:



Assumption: cost of Merge operation on two in-memory buffers ≅ *0*.

Comparison for Sorting

Above assumes that we have a function to compare tuples.

Needs to understand ordering on different data types.

Need a function `tupCompare(r1,r2,f)` (cf. C's `strcmp`)

```
int tupCompare(r1,r2,f)
{
   if (r1.f < r2.f) return -1;
   if (r1.f > r2.f) return 1;
   return 0;
}
```

Assume =, <, > are available for all attribute types.

... Comparison for Sorting

In reality, need to sort on multiple attributes and ASC/DESC, e.g.

```
-- example multi-attribute sort
select * from Students
order by age desc, year_enrolled
```

Sketch of multi-attribute sorting function

```
int tupCompare(r1,r2,criteria)
{
   foreach (f,ord) in criteria {
      if (ord == ASC) {
         if (r1.f < r2.f) return -1;
         if (r1.f > r2.f) return 1;
      }
      else {
         if (r1.f > r2.f) return -1;
```

```
            if (r1.f < r2.f) return 1;
        }
    }
    return 0;
}
```

Cost of Two-way Merge Sort

For a file containing *b* data pages:

- require *ceil(log_2b)* passes to sort,
- each pass requires *b* page reads, *b* page writes

Gives total cost: *2.b.ceil(log_2b)*

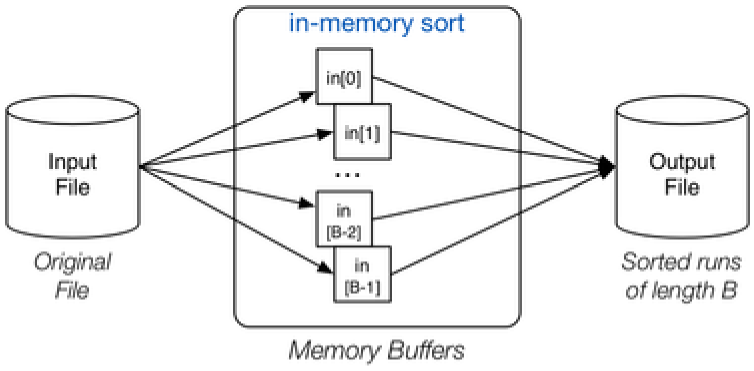
Example: Relation with $r=10^5$ and $c=50$ ⇒ $b=2000$ pages.

Number of passes for sort: *ceil($log_2 2000$)* = *11*

Reads/writes entire file 11 times! Can we do better?

n-Way Merge Sort

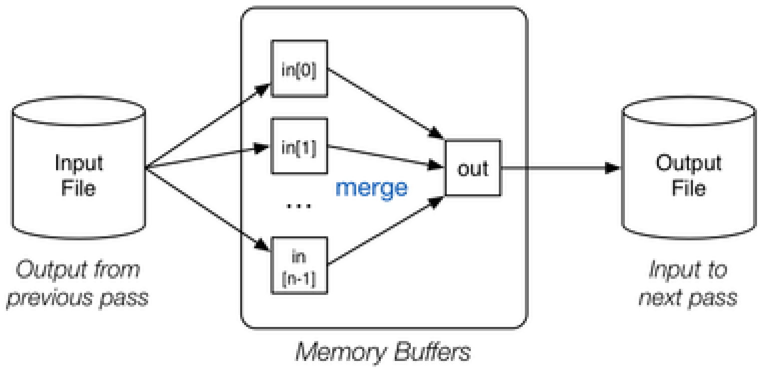
Initial pass uses: *B* total buffers



Reads *B* pages at a time, sorts in memory, writes out in order

... n-Way Merge Sort

Merge passes use: *n* input buffers, *1* output buffer



... n-Way Merge Sort

Method:

```
// Produce B-page-long runs
for each group of B pages in Rel {
    read B pages into memory buffers
    sort group in memory
    write B pages out to Temp
}
// Merge runs until everything sorted
numberOfRuns = ⌈b/B⌉
while (numberOfRuns > 1) {
    // n-way merge, where n=B-1
    for each group of n runs in Temp {
        merge into a single run via input buffers
        write run to newTemp via output buffer
    }
    numberOfRuns = ⌈numberOfRuns/n⌉
    Temp = newTemp // swap input/output files
}
```

Cost of n-Way Merge Sort

Consider file where $b = 4096$, $B = 16$ total buffers:

- pass 0 produces 256 × 16-page sorted runs
- pass 1
  - performs 15-way merge of groups of 16-page sorted runs
  - produces 18 × 240-page sorted runs   (17 full runs, 1 short run)
- pass 2
  - performs 15-way merge of groups of 240-page sorted runs
  - produces 2 × 3600-page sorted runs   (1 full run, 1 short run)
- pass 3
  - performs 15-way merge of groups of 3600-page sorted runs
  - produces 1 × 4096-page sorted runs

(cf. two-way merge sort which needs 11 passes)

... Cost of n-Way Merge Sort

Generalising from previous example ...

For b data pages and B buffers

- first pass: read/writes b pages, gives $b_0 = \lceil b/B \rceil$ runs
- then need $\lceil \log_n b_0 \rceil$ passes until sorted, where $n = B-1$
- each pass reads and writes b pages   (i.e. $2.b$ page accesses)

$Cost = 2.b.(1 + \lceil \log_n b_0 \rceil)$,   where b_0 and n are defined above

Exercise 6: Cost of n-Way Merge Sort

How many reads+writes to sort the following:

- r = 1048576 tuples (2^{20})
- R = 62 bytes per tuple (fixed-size)
- B = 4096 bytes per page
- H = 96 bytes of header data per page
- D = 1 presence bit per tuple in page directory
- all pages are full

Consider for the cases:

- 9 total buffers, 8 input buffers, 1 output buffer
- 33 total buffers, 32 input buffers, 1 output buffer
- 257 total buffers, 256 input buffers, 1 output buffer

Sorting in PostgreSQL

Sort uses a merge-sort (from Knuth) similar to above:

- backend/utils/sort/tuplesort.c
- include/utils/sortsupport.h

Tuples are mapped to **`SortTuple`** structs for sorting:

- containing pointer to tuple and sort key
- no need to reference actual Tuples during sort
- unless multiple attributes used in sort

If all data fits into memory, sort using **`qsort()`**.

If memory fills while reading, form "runs" and do disk-based sort.

... Sorting in PostgreSQL

Disk-based sort has phases:

- divide input into sorted runs using HeapSort
- merge using *N* buffers, one output buffer
- *N* = as many buffers as `workMem` allows

Described in terms of "tapes" ("tape" ≅ sorted run)

Implementation of "tapes": backend/utils/sort/logtape.c

... Sorting in PostgreSQL

Sorting comparison operators are obtained via catalog (in *`Type`*`.o`):

```
// gets pointer to function via pg_operator
struct Tuplesortstate { ... SortTupleComparator ... };

// returns negative, zero, positive
ApplySortComparator(Datum datum1, bool isnull1,
                    Datum datum2, bool isnull2,
                    SortSupport sort_helper);
```

Flags in `SortSupport` indicate: ascending/descending, nulls-first/last.

`ApplySortComparator()` is PostgreSQL's version of `tupCompare()`

Implementing Projection

The Projection Operation

Consider the query:

```
select distinct name,age from Employee;
```

If the `Employee` relation has four tuples such as:

```
(94002, John, Sales, Manager,   32)
(95212, Jane, Admin, Manager,   39)
(96341, John, Admin, Secretary, 32)
(91234, Jane, Admin, Secretary, 21)
```

then the result of the projection is:

```
(Jane, 21)   (Jane, 39)   (John, 32)
```

Note that duplicate tuples (e.g. `(John,32)`) are eliminated.

... The Projection Operation

The projection operation needs to:

1. scan the entire relation as input
    - already seen how to do scanning

2. remove unwanted attributes in output tuples
    - implementation depends on tuple internal structure
    - essentially, make a new tuple with fewer attributes
      and where the values may be computed from existing attributes

3. eliminate any duplicates produced (if `distinct`)
    - two approaches: sorting or hashing

Sort-based Projection

Requires a temporary file/relation (`Temp`)

```
for each tuple T in Rel {
    T' = mkTuple([attrs],T)
    write T' to Temp
}

sort Temp on [attrs]

for each tuple T in Temp {
    if (T == Prev) continue
    write T to Result
    Prev = T
}
```

Exercise 7: Cost of Sort-based Projection

Consider a table *R(x,y,z)* with tuples:

```
Page 0:  (1,1,'a')   (11,2,'a')  (3,3,'c')
Page 1:  (13,5,'c')  (2,6,'b')   (9,4,'a')
Page 2:  (6,2,'a')   (17,7,'a')  (7,3,'b')
Page 3:  (14,6,'a')  (8,4,'c')   (5,2,'b')
Page 4:  (10,1,'b')  (15,5,'b')  (12,6,'b')
Page 5:  (4,2,'a')   (16,9,'c')  (18,8,'c')
```

SQL: `create T as (select distinct y from R)`

Assuming:

- 3 memory buffers, 2 for input, one for output
- pages/buffers hold 3 `R` tuples (i.e. $c_R=3$), 6 `T` tuples (i.e. $c_T=6$)

Show how sort-based projection would execute this statement.

Cost of Sort-based Projection

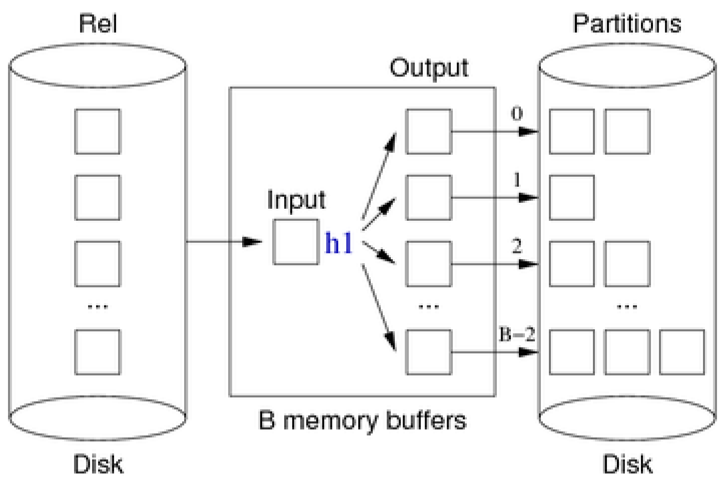
The costs involved are (assuming $B=n+1$ buffers for sort):

- scanning original relation `Rel`: b_R (with c_R)
- writing `Temp` relation: b_T (smaller tuples, $c_T > c_R$, *sorted*)
- sorting `Temp` relation:
  $2.b_T.ceil(log_n b_0)$ where $b_0 = ceil(b_T/B)$
- scanning `Temp`, removing duplicates: b_T
- writing the result relation: b_{Out} (maybe less tuples)

Cost = sum of above = $b_R + b_T + 2.b_T.ceil(log_n b_0) + b_T + b_{Out}$

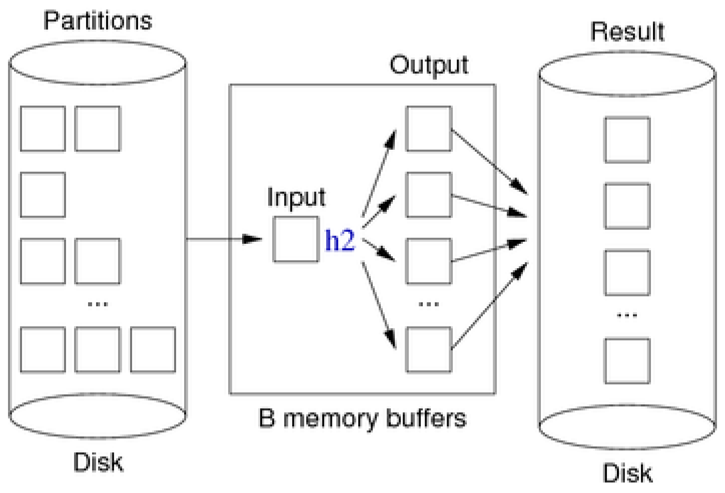
Hash-based Projection

Partitioning phase:



... Hash-based Projection

Duplicate elimination phase:



... Hash-based Projection

Algorithm for both phases:

```
for each tuple T in relation Rel {
    T' = mkTuple([attrs],T)
    H = h1(T', n)
    B = buffer for partition[H]
    if (B full) write and clear B
    insert T' into B
}
for each partition P in 0..n-1 {
    for each tuple T in partition P {
        H = h2(T, n)
        B = buffer for hash value H
        if (T not in B) insert T into B
        // assumes B never gets full
    }
    write and clear all buffers
}
```

Exercise 8: Cost of Hash-based Projection

Consider a table *R(x,y,z)* with tuples:

```
Page 0:  (1,1,'a')   (11,2,'a')  (3,3,'c')
Page 1:  (13,5,'c')  (2,6,'b')   (9,4,'a')
Page 2:  (6,2,'a')   (17,7,'a')  (7,3,'b')
Page 3:  (14,6,'a')  (8,4,'c')   (5,2,'b')
Page 4:  (10,1,'b')  (15,5,'b')  (12,6,'b')
Page 5:  (4,2,'a')   (16,9,'c')  (18,8,'c')
-- and then the same tuples repeated for pages 6-11
```

SQL: `create T as (select distinct y from R)`

Assuming:

- 4 memory buffers, one for input, 3 for partitioning
- pages/buffers hold 3 `R` tuples (i.e. $c_R=3$), 4 `T` tuples (i.e. $c_T=4$)
- hash functions: h1(x) = x%3,   h2(x) = (x%4)%3

Show how hash-based projection would execute this statement.

Cost of Hash-based Projection

The total cost is the sum of the following:

- scanning original relation `R`: b_R
- writing partitions: b_P (b_R vs b_P ?)
- re-reading partitions: b_P
- writing the result relation: b_{Out}

Cost = $b_R + 2b_P + b_{Out}$

To ensure that n is larger than the largest partition ...

- use hash functions (h1,h2) with uniform spread
- allocate at least $sqrt(b_R)+1$ buffers
- if insufficient buffers, significant re-reading overhead
