Week 3

- Week 03

❖ Week 03

Things to Note ...

- Assignment 1 due before 9pm Friday 17 March
- Quiz 2 coming next week ... on Moodle
- Prac Exercise 4 released
- Theory Exercise 3 released

This Week ...

- Storage: representing tuples
- Relational Algebra Operations
- RelOps: Scan, Sort

Coming Up ...

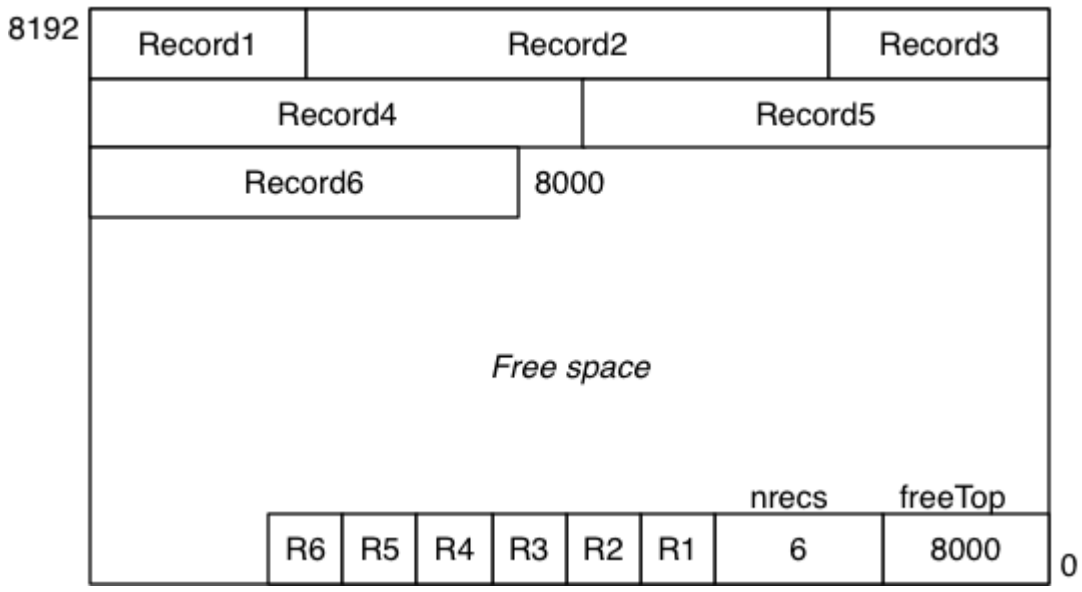
- Relops: Projection, 1d Selection, Hashing, Indexing, Nd Selection

Produced: 26 Feb 2023

Tuple Representation

❖ 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 smallint references Dept(id)
);
```

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

Reminder: schema information (meta-data) is also stored, in the DB catalog

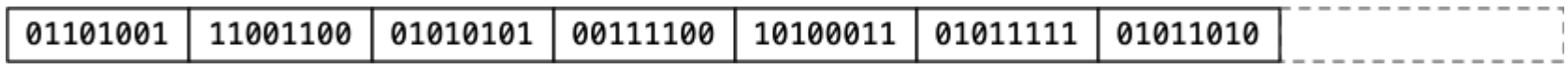
❖ Records vs Tuples (cont)

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

```
(33357462,  'Neil Young',  'Musician',  277)
```

iid:integer name:varchar(20) job:varchar(10) dept: smallint

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



Bytes need to be interpreted relative to schema to get tuple

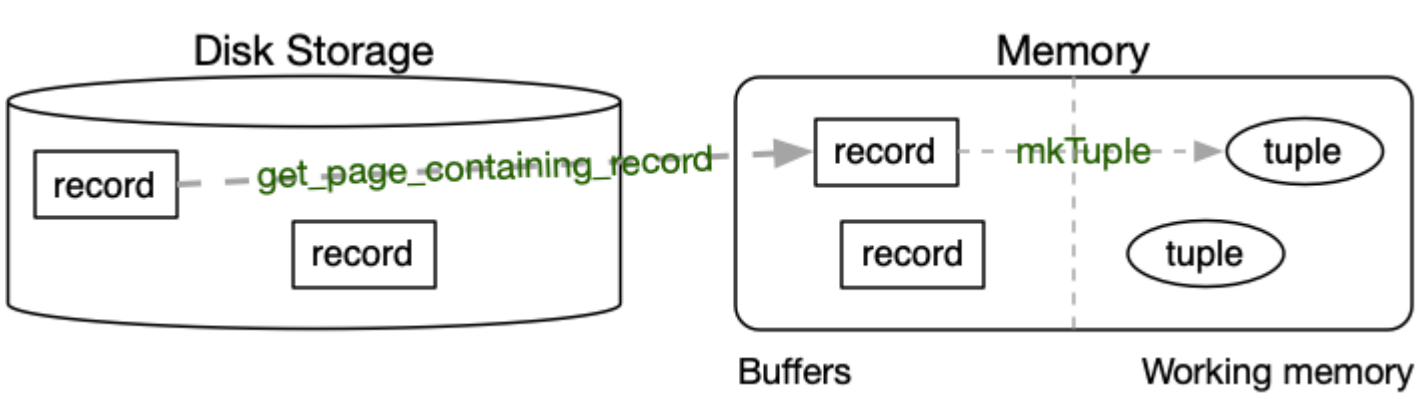
❖ Converting Records to Tuples

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 (cont)

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 varlen 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)
```

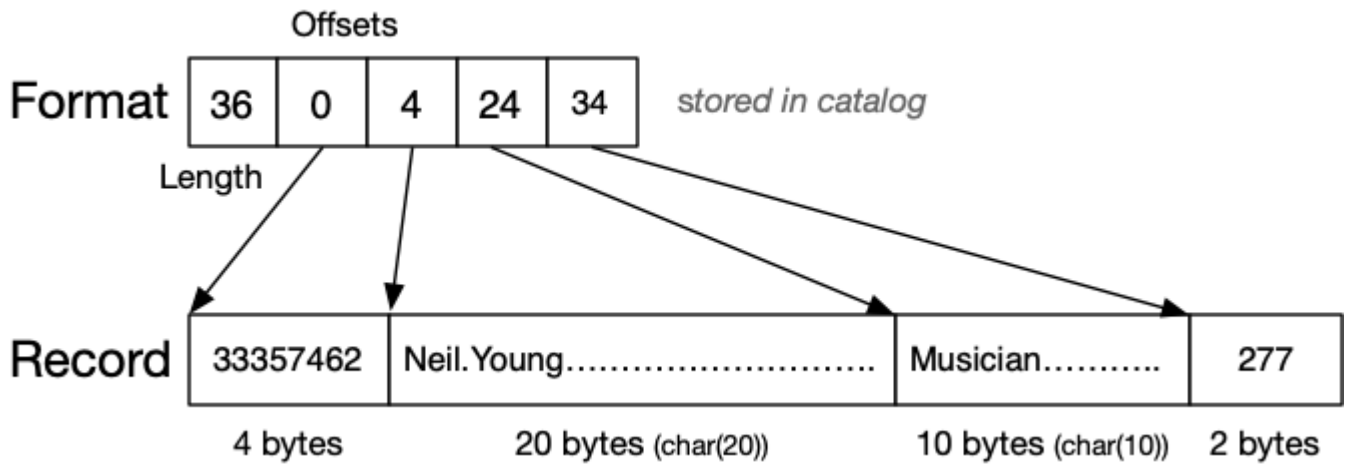
- extract the **`i`**'th field from a **`Tuple`** as a value of type *Typ*

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:

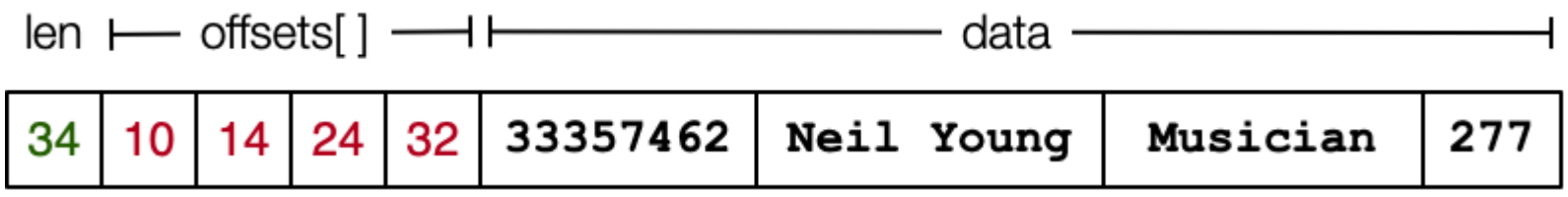
- Prefix each field by length

4	33357462	10	Neil Young	8	Musician	2	277

- Terminate fields by delimiter

33357462	X	Neil Young	X	Musician	X	277	X

- 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

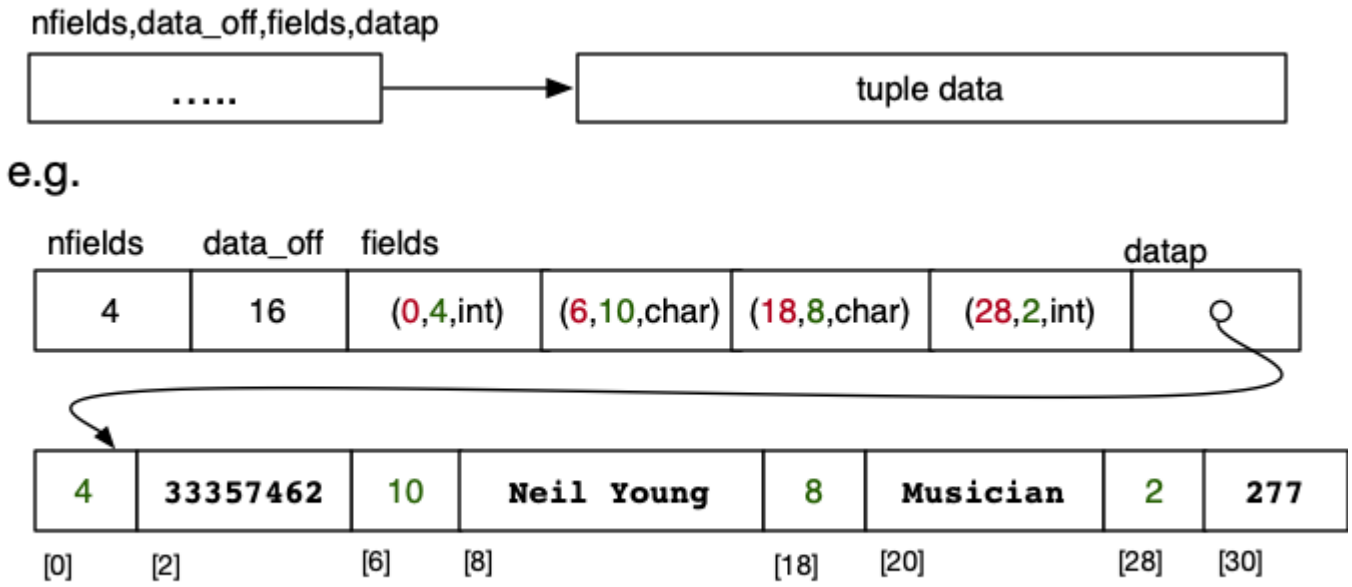
```
typedef struct {
    ushort     nfields;    // number of fields/attrs
    ushort     data_off;   // offset in struct for data
    FieldDesc  fields[];   // field descriptions
    Record     data;       // pointer to record in buffer
} Tuple;
```

Fields are derived from relation descriptor + record instance data.

❖ Field Descriptors (cont)

Tuple **`data`** could be

- a pointer to bytes stored elsewhere in memory

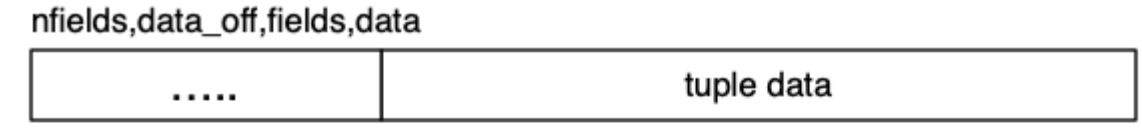


Note that the offset refers to the length field at the start of each attribute.

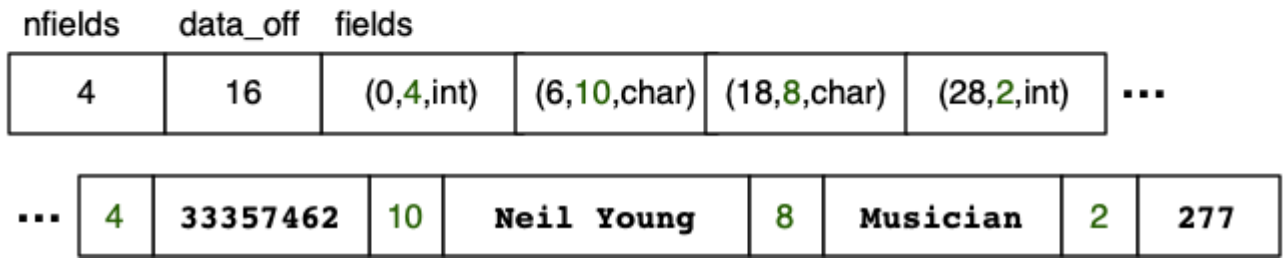
❖ Field Descriptors (cont)

Or, tuple **`data`** could be ...

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



e.g.



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PostgreSQL Tuples

❖ 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 (cont)

`HeapTupleData` contains information about a stored tuple

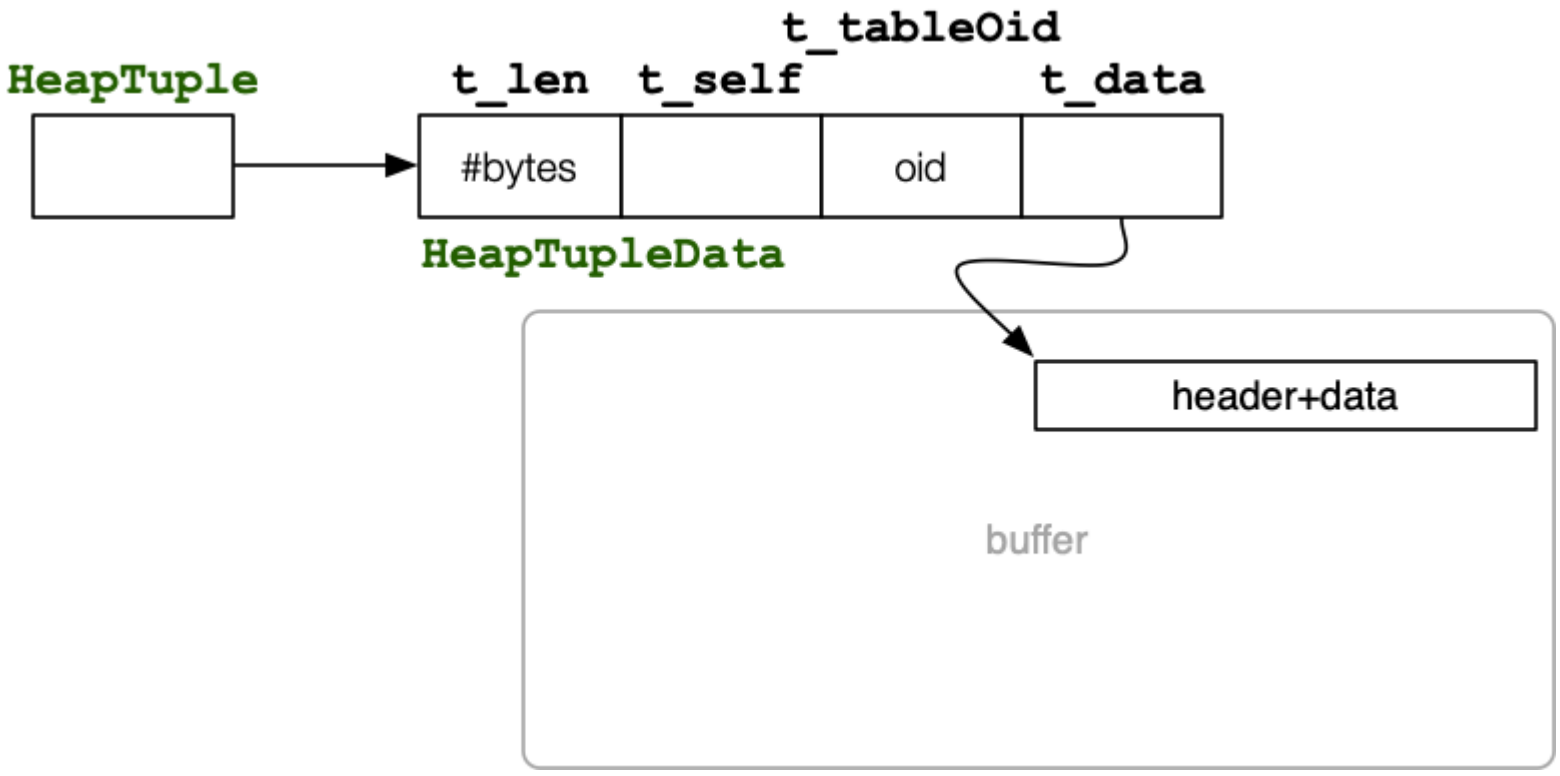
```
include/access/htup.h
typedef HeapTupleData *HeapTuple;

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 (cont)

Structure of **`HeapTuple`**:



❖ PostgreSQL Tuples (cont)

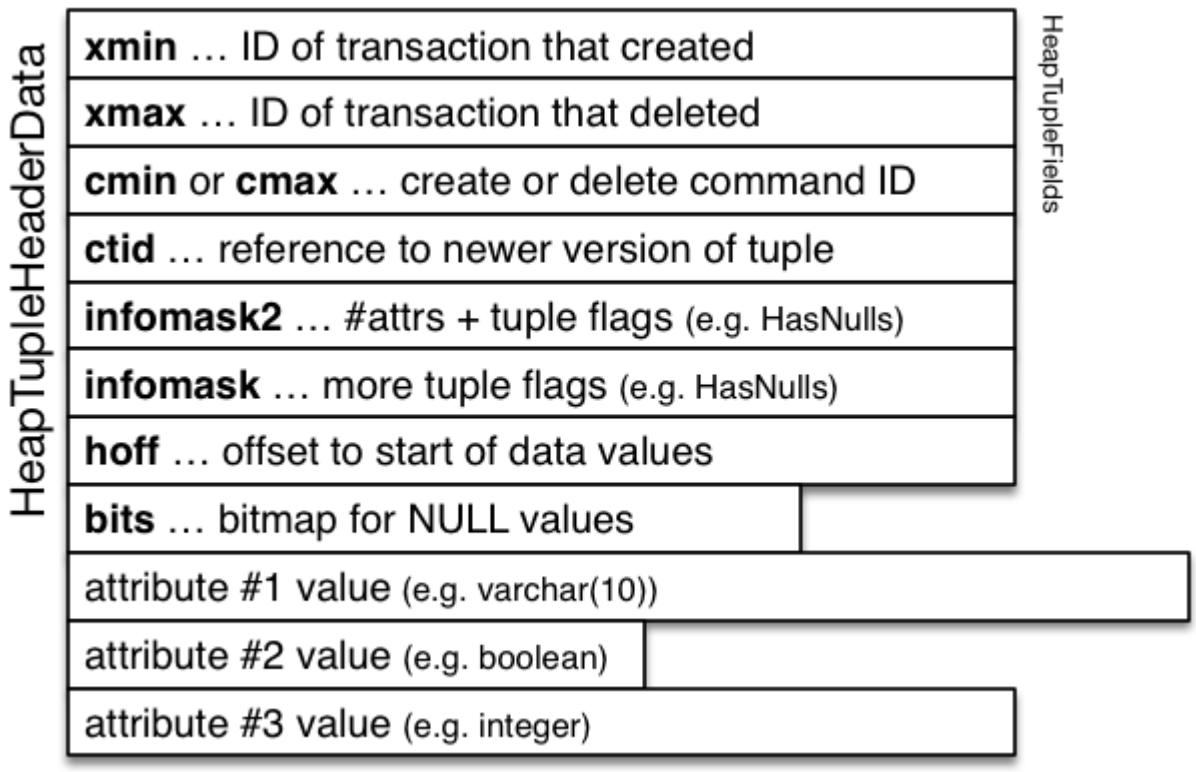
PostgreSQL stores each record as tuple header, followed by data:

```
include/access/htup_details.h
typedef HeapTupleHeaderData *HeapTupleHeader;

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 (cont)

Tuple structure:



❖ PostgreSQL Tuples (cont)

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 **`NULL`**s is stored in **`t_bits[]`** array

❖ PostgreSQL Tuples (cont)

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 Tuples (cont)

Tuple-related data types: (cont)

```
include/access/tupdesc.h
// 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 (cont)

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 Attribute Values

Attribute values in PostgreSQL tuples are packaged as **`Datum`**s

```
// 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 (cont)

Attribute values can be extracted as **`Datum`** from **`HeapTuple`**s

```
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 (cont)

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`**

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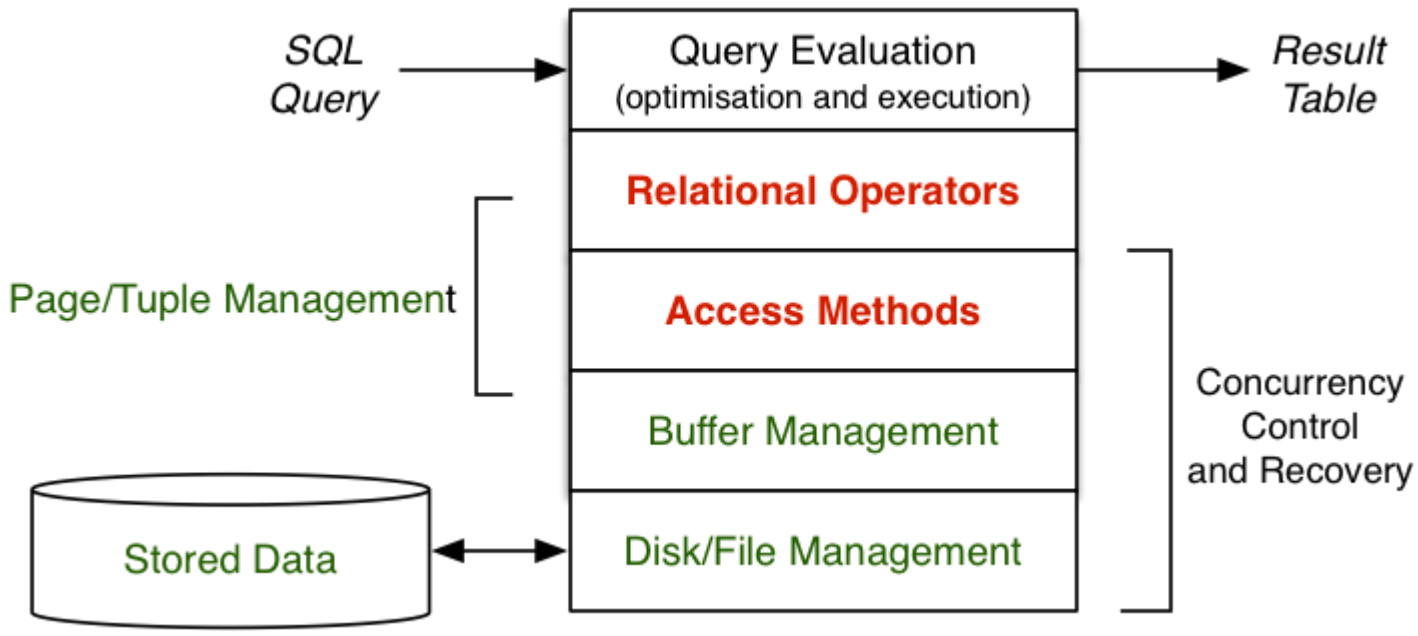
Relational Operations

- DBMS Architecture (revisited)
- Relational Operations
- Cost Models
- Query Types

❖ 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 (cont)

In order to implement relational operations the low-levels of the system provides:

- **`Relation openRel(db,name)`**
  - get handle on relation **`name`** in database **`db`**
- **`Page request_page(rel,pid)`**
  - get page **`pid`** from relation **`rel`**, return buffer containing page
- **`Record get_record(buf,tid)`**
  - return record **`tid`** from page **`buf`**
- **`Tuple mkTuple(rel,rec)`**
  - convert record **`rec`** to a tuple, based on **`rel`** schema

❖ Relational Operations (cont)

Example of using low-level functions

```
// scan a relation Emps
Page p;  // current page
Tuple t; // current tuple
Relation r = relOpen(db,"Emps");
for (int i = 0; i < nPages(r); i++) {
   p = request_page(rel,i);
   for (int j = 0; j < nRecs(p); j++)
      t = mkTuple(r, get_record(p,j));
      ... process tuple t ...
   }
}
```

❖ Relational Operations (cont)

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) which table to hash?
- e.g. two-dimensional range query on R-tree indexed file

We are interested in *cost* of query methods (and insert/delete operations)

❖ Relational Operations (cont)

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

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 (cont)

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

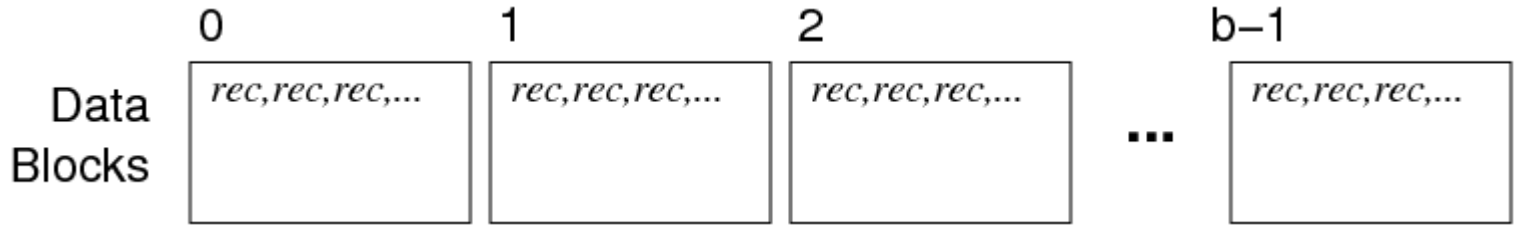
Estimating costs with multiple concurrent ops *and* buffering is difficult!!

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

❖ Cost Models (cont)

In developing cost models, we also assume:

- a relation is a set of r tuples, with average tuple 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 (cont)

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	`select * from R,S where R.id = S.r`	*R Join[id=r] S*	-

Different query classes exhibit different query processing behaviours.

Produced: 1 Mar 2023

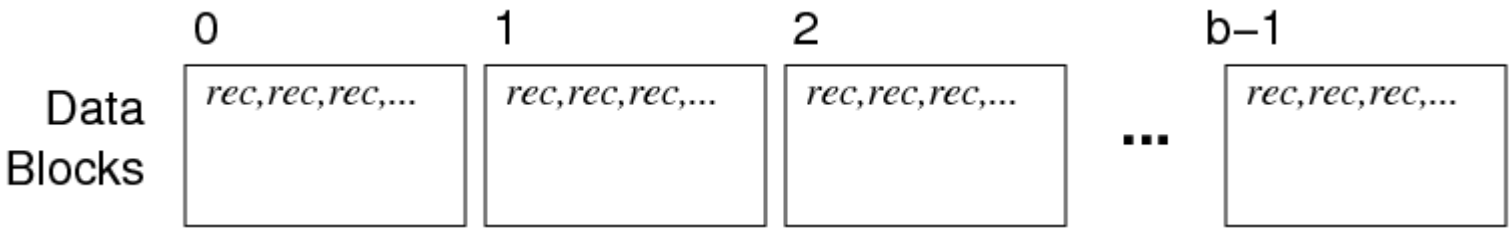
Scanning

❖ Scanning

Consider executing the query:

```
select * from Rel;
```

where the relation has a file structure like:



This would done by a simple scan of all records/tuples.

❖ Scanning (cont)

Abstract view of how the scan might be implemented:

```
for each tuple T in relation Rel {
   add tuple T to result set
}
```

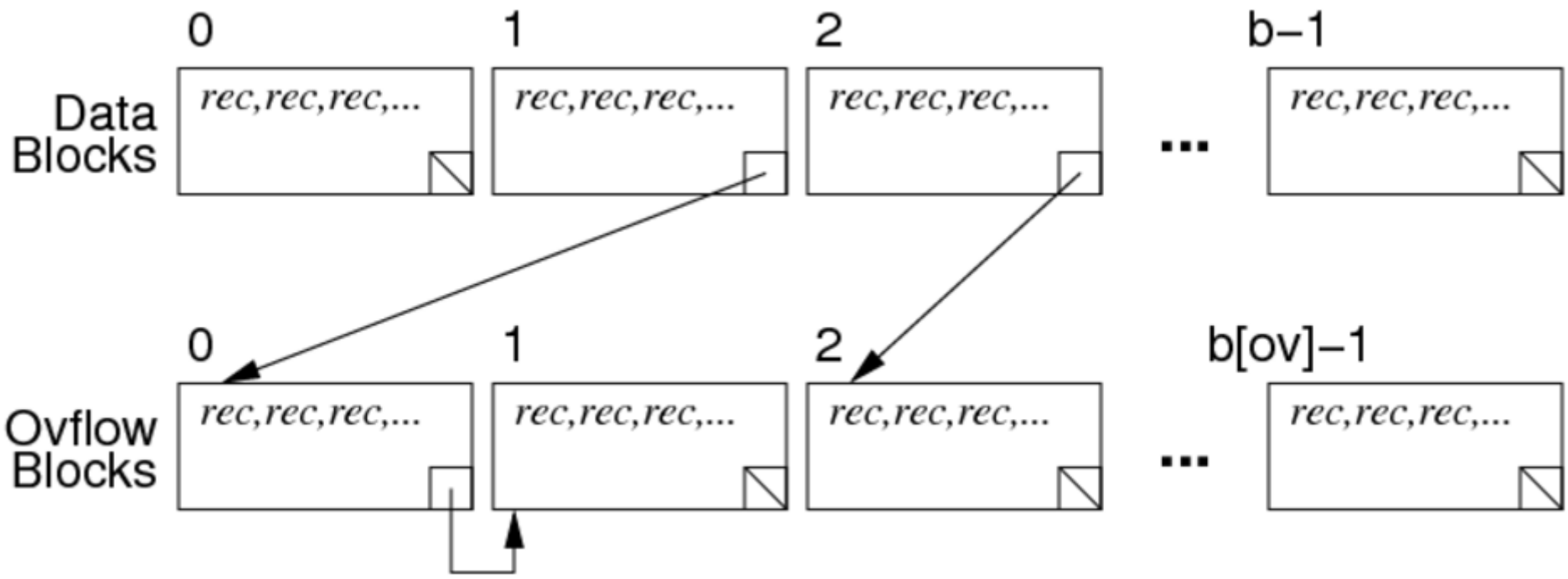
Operational view:

```
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 = *b*

❖ Scanning (cont)

Consider a file with overflow pages, e.g.



❖ Scanning (cont)

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

$Cost = b + b_{Ov}$

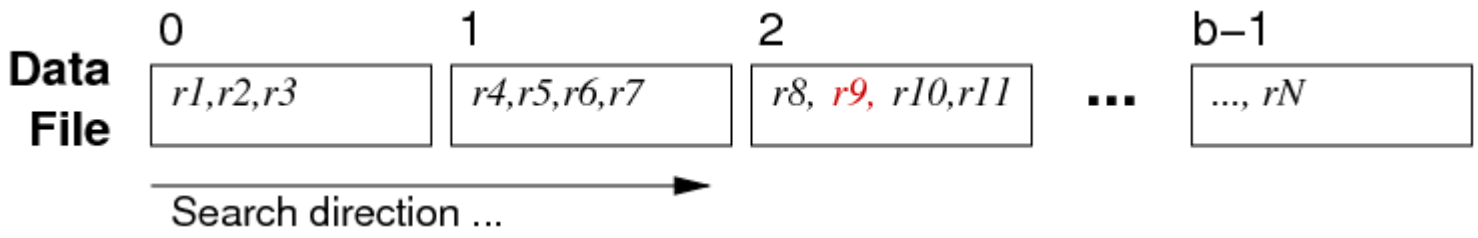
where b_{Ov} = total number of overflow pages

❖ 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 (cont)

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

❖ 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);
}
```

❖ `next_tuple()` Function

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

```
typedef ScanData *Scan;

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

Assume tuples are indexed 0..**`nTuples(p)-1`**

Assume pages are indexed 0..**`nPages(rel)-1`**

❖ `next_tuple()` Function (cont)

Implementation of **`Tuple next_tuple(Scan)`** function

```
Tuple next_tuple(Scan s)
{
    if (s->curTID >= nTuples(s->page)-1) {
        // get a new page; exhausted current page
        s->curPID++;
        if (s->curPID >= nPages(s->rel))
            return NULL;
        else {
            s->page = get_page(s->rel, s->curPID);
            s->curTID = -1;
        }
    }
    s->curTID++;
    return get_tuple(s->rel, s->page, s->curTID);
}
```

❖ Relation Copying

Consider an SQL statement like:

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

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

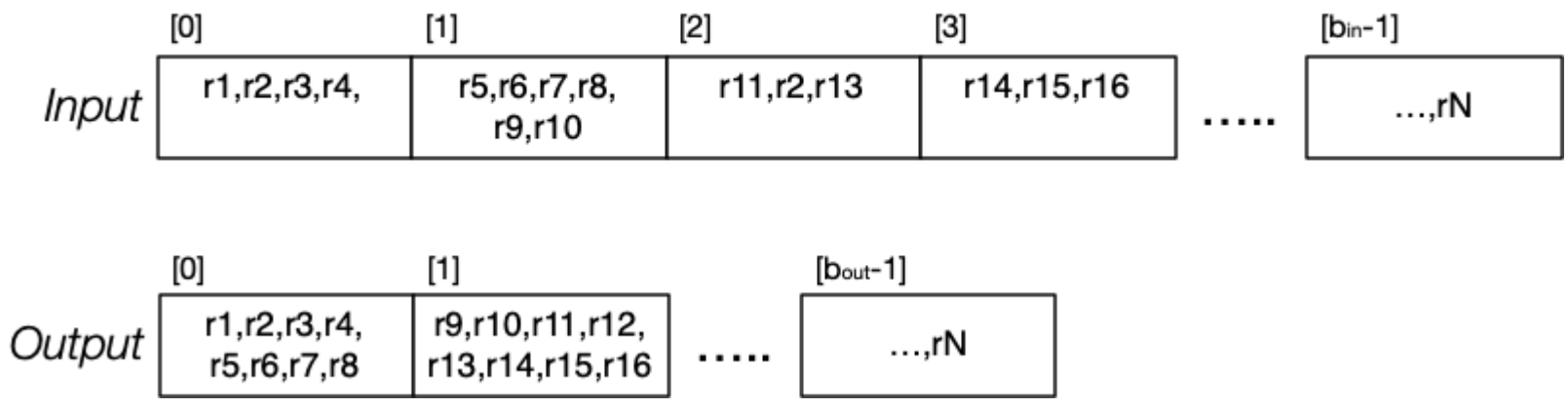
Process:

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

❖ Relation Copying (cont)

It is 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 (cont)

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);
```

❖ 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?

❖ Scanning in PostgreSQL (cont)

```
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

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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:

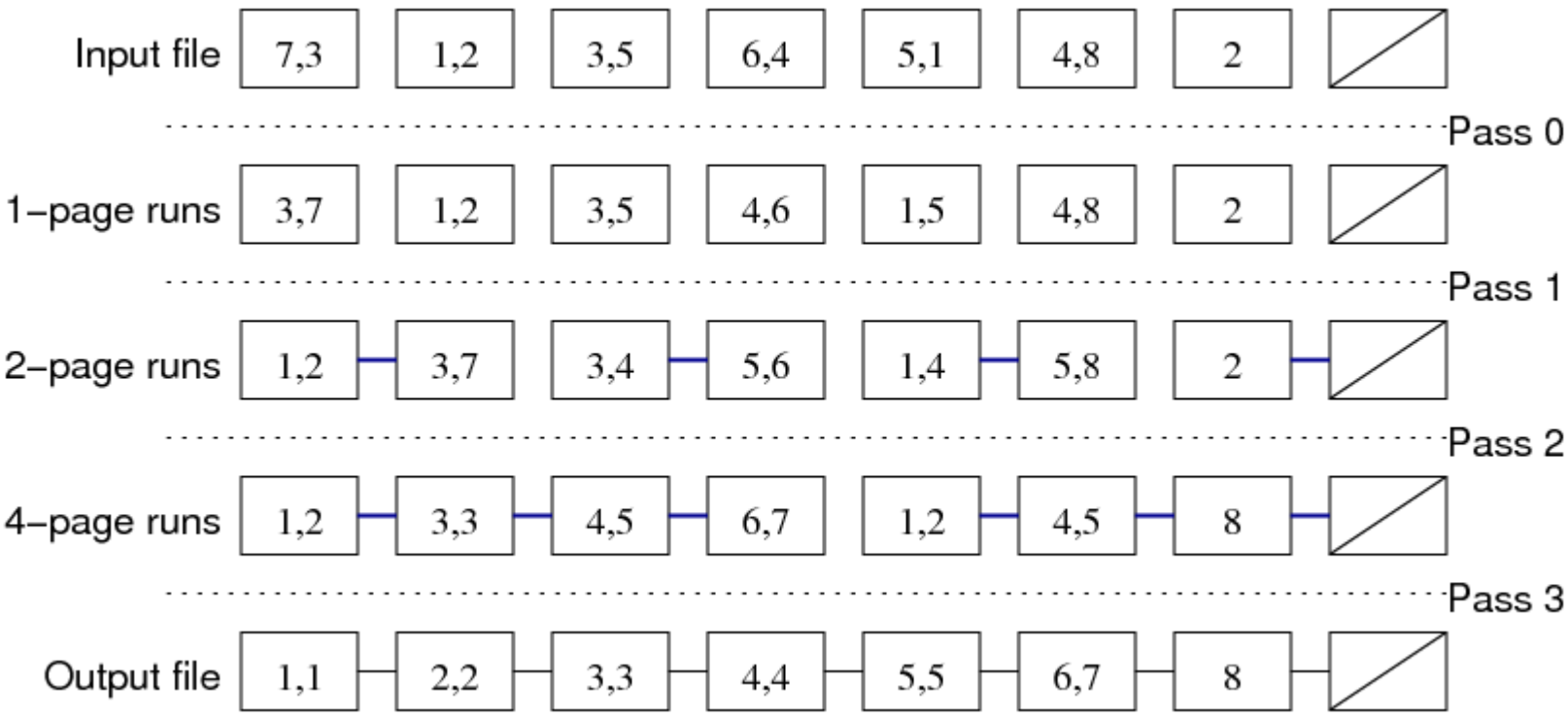
- eliminating duplicate tuples for projection
- ordering files to enhance select efficiency
- implementing various styles of join
- forming tuple groups in **`group by`**

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

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

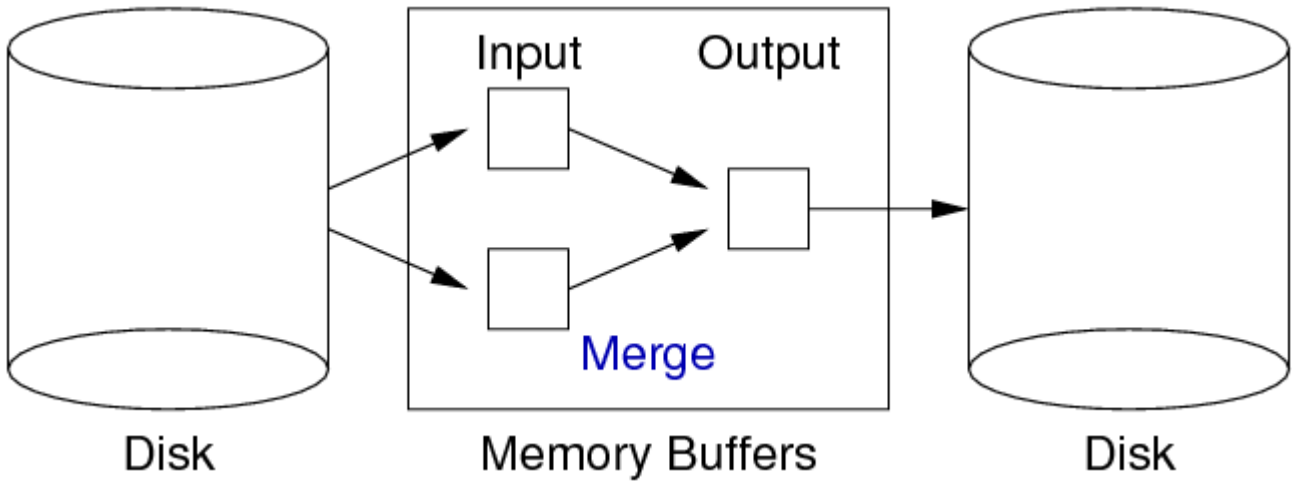
❖ Two-way Merge Sort

Example:



❖ Two-way Merge Sort (cont)

Requires at least three in-memory buffers:



Assumption: cost of Merge operation on two in-memory buffers $\cong 0$.

❖ 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 (cont)

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$_2$b)* passes to sort,
- each pass requires *b* page reads, *b* page writes

Gives total cost: *2.b.ceil(log$_2$b)*

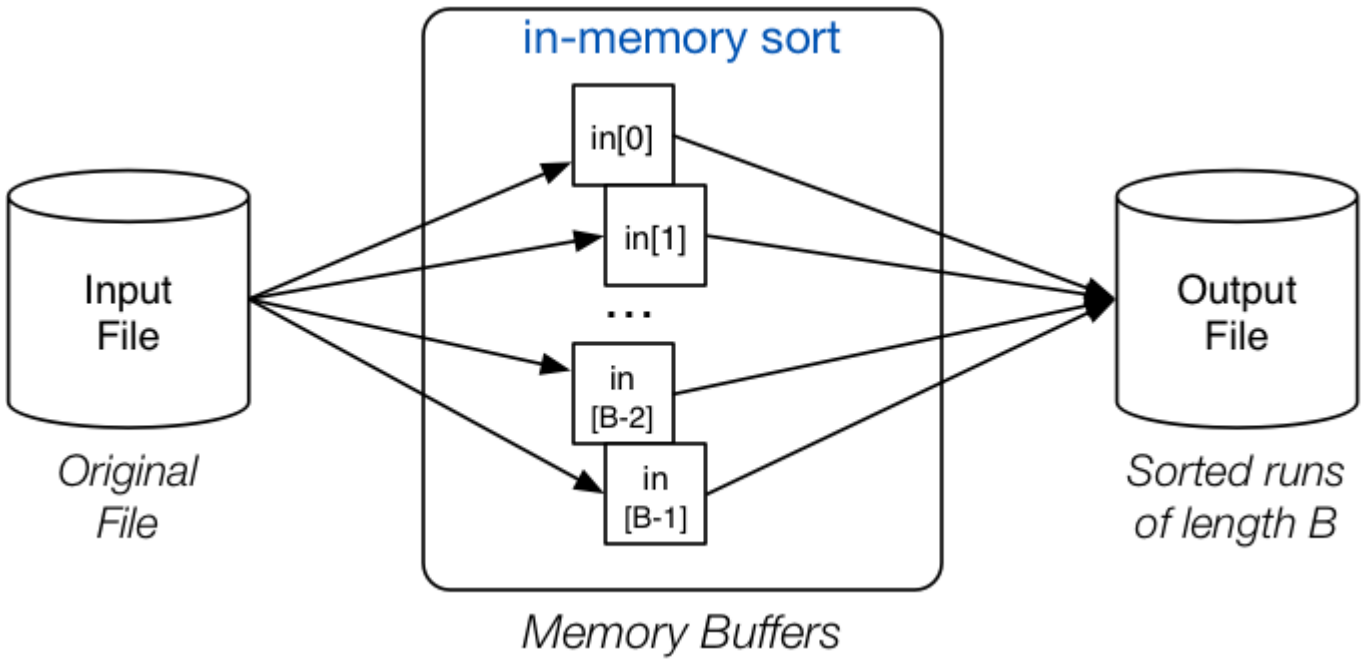
Example: Relation with *r=10^5* and *c=50* ⇒ *b=2000* pages.

Number of passes for sort: *ceil(log$_2$2000) = 11*

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

❖ n-Way Merge Sort

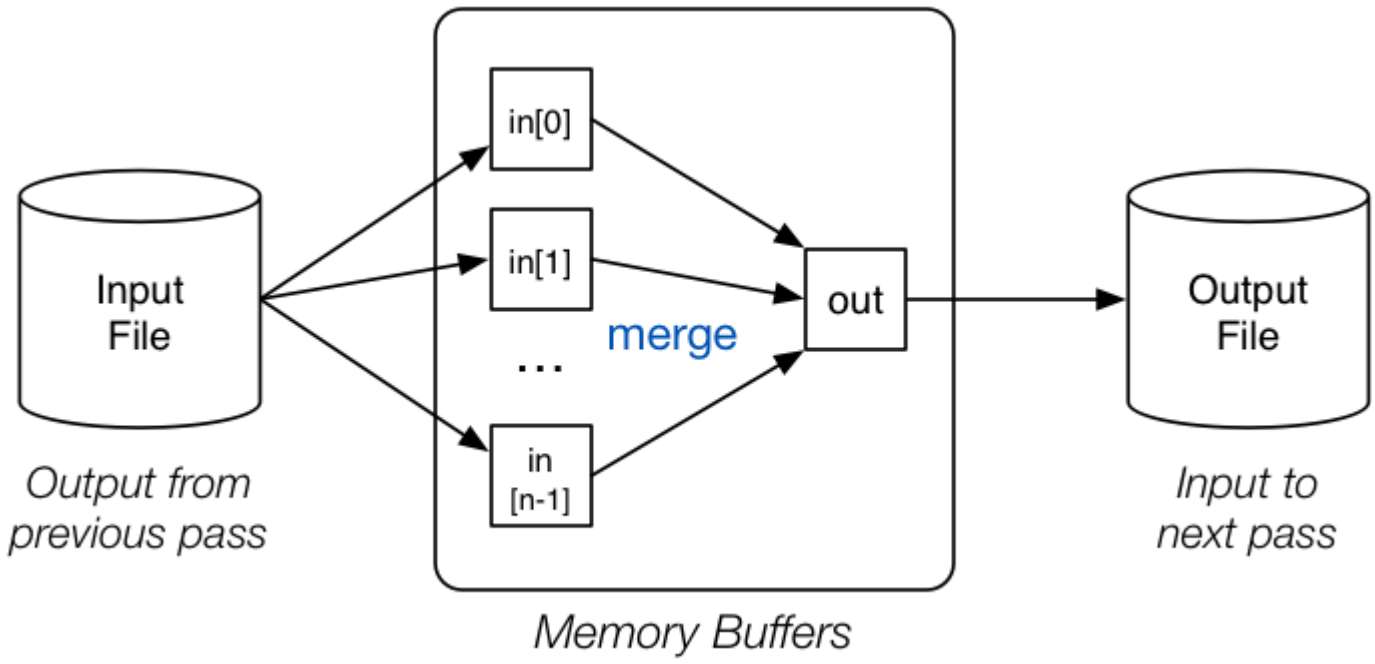
Initial pass uses: *B* total buffers



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

❖ n-Way Merge Sort (cont)

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



❖ n-Way Merge Sort (cont)

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 = ceil(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 = ceil(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 (cont)

Generalising from previous example ...

For *b* data pages and *B* buffers

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

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

❖ 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 (cont)

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 (cont)

Sorting comparison operators are obtained via catalog:

```
// backend/utils/sort/tuplesort.c
// gets pointer to function via pg_operator
struct Tuplesortstate { ... SortTupleComparator ... };

// include/utils/sortsupport.h
// 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()`**

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COMP9315 Week 3 Exercises

❖ Assignment 1

Creating a new base type requires

- telling the SQL front-end about it
- building C functions to manipulate values of the type
- setting up ordering to allow indexing

At the SQL level (**`gcoord.source`**)...

```
create type GeoCoord ( type info and function links )
```

Also useful to define comparison operators on the type (e.g. < > =)

❖ Assignment 1 (cont)

Once created, the type can be used in client SQL programs ...

```
e.g. a new base type GeoCoord in schemas ...
create table StoreInfo (id integer primary key, location GeoCoord, ...);

e.g. inserting data ...
insert into StoreInfo values (1,'Sydney,33.86°S,151.21°E');

e.g. retrieving ...
select * from StoreInfo
where location = 'Melbourne,37.84°S,144.95°E';

select * from StoreInfo
where  location > 'Sydney,33.86°S,151.21°E';
```

❖ Assignment 1 (cont)

At the C level (**`gcoord.c`**) ...

```
PG_FUNCTION_INFO_V1(gcoord_in);

Datum
gcoord_in(PG_FUNCTION_ARGS)
{
    // parse input string
    // convert to internal representation
    // return value as Datum
}
```

Link between C and SQL (**`gcoord.source`**) ...

```
CREATE FUNCTION gcoord_in(cstring)
    RETURNS GeoCoord
    AS '_OBJWD_/gcoord'
    LANGUAGE C IMMUTABLE STRICT;
```

❖ Assignment 1 (cont)

Required functions for type *T*

- **`T_in()`** ... invoked when PG receives value of type *T*
- **`T_out()`** ... convert value of type *T* to printable

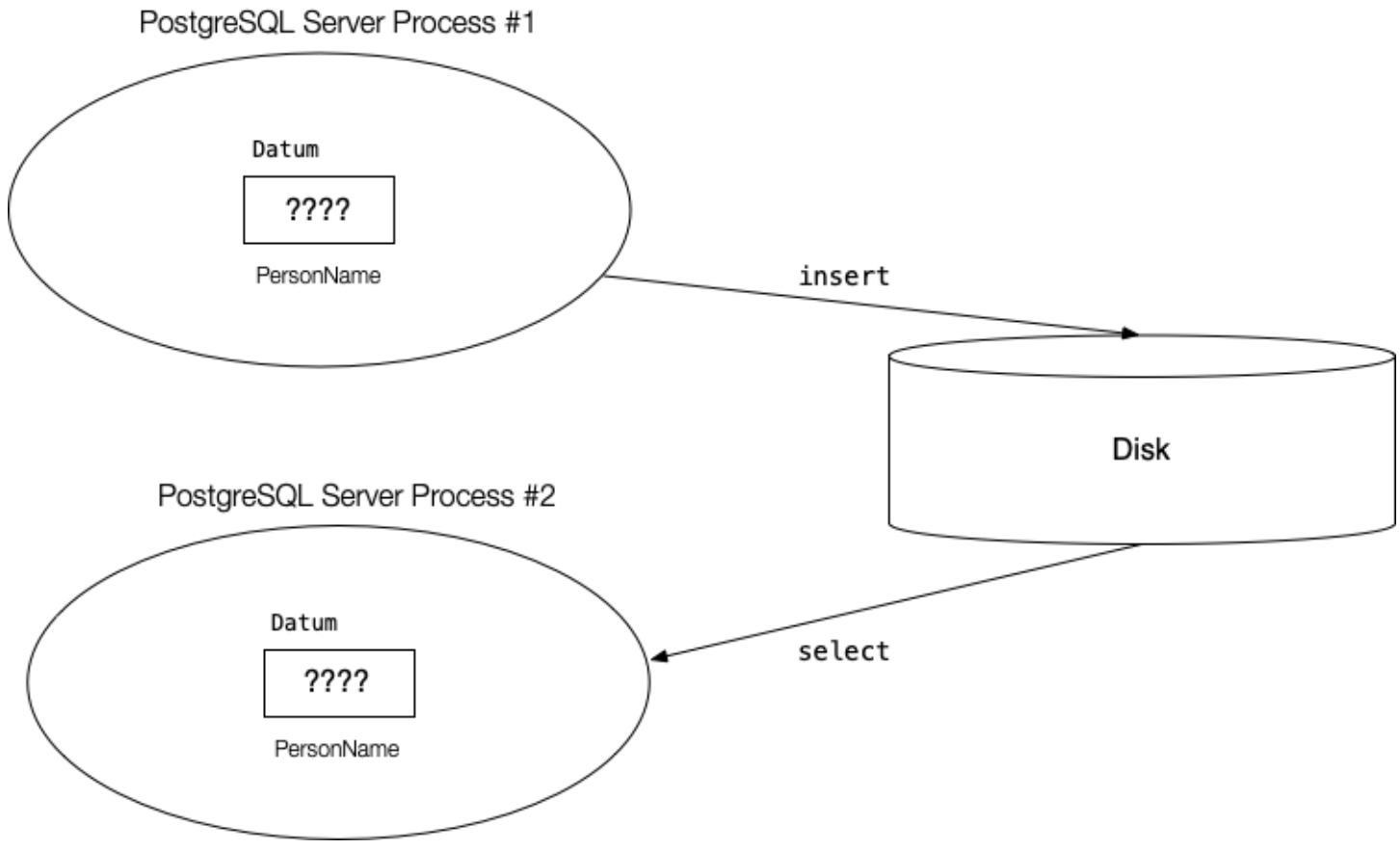
Useful options for new type

- **`INTERNALLENGTH = nbytes|VARIABLE`**
- **`ALIGNMENT = char|int2|int4|double`**

See PG Manual **`CREATE TYPE`** under SQL Commands for more details.

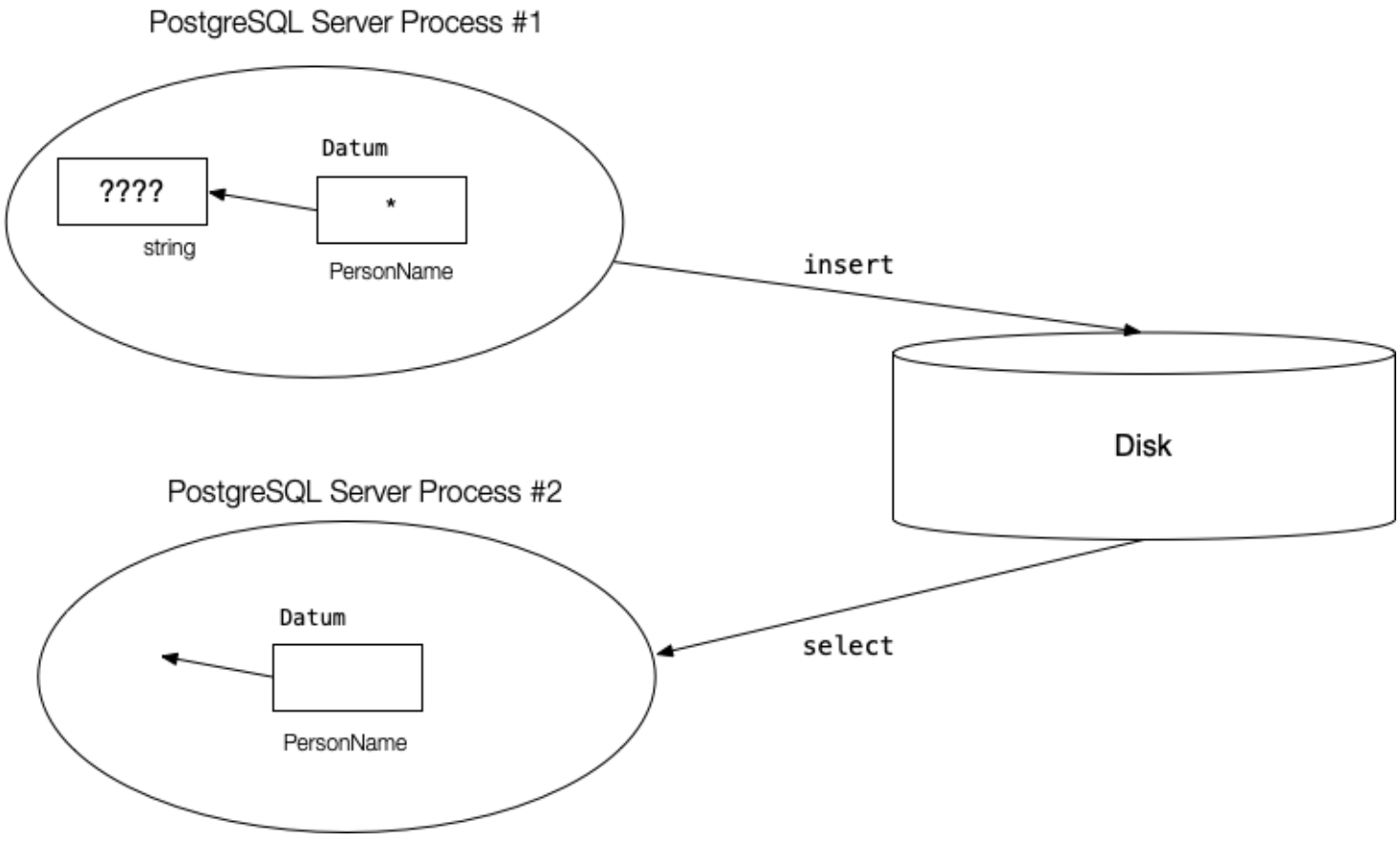
❖ Assignment 1 (cont)

Data transfers that *should* happen ...



❖ Assignment 1 (cont)

Data transfers that students sometimes implement ...



❖ Assignment 1 (cont)

Copy **`complex.c`** and **`complex.source`** ... BUT

- **`Complex`** is a fixed-length type (two **`int`**s)
- do not make **`GeoCoord`** fixed-length (how long?)
- change all references to **`Complex`** to **`GeoCoord`**
- make sure **`_OBJWD_`** references the correct directory

This assignment requires some prior reading (code + doco)

- do not leave it to the last minute

❖ Assignment 1 (cont)

Debugging the assignment ...

- can't easily use GDB or vscode; need debugging print's
- can use **`ereport()`** and **`elog()`**; see PG Docs 56.2

Implementing **`GeoCoord`** ...

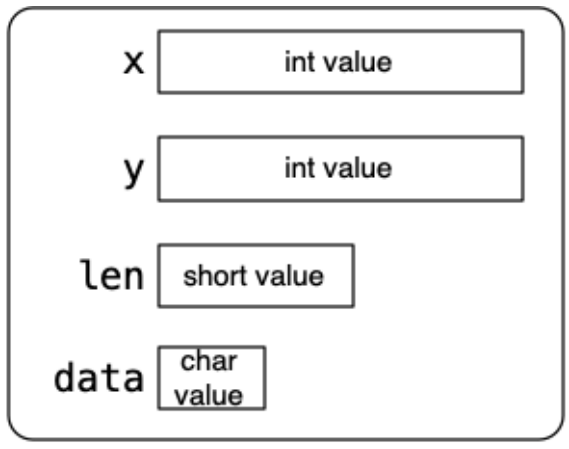
- three data usages: readable, computable, storeable
  - readable → storeable in **`gcoord_in()`**
  - storeable → readable in **`gcoord_out()`**
  - storeable → computable in e.g. **`gcoord_cmp()`**
- reminder: pointers to **`malloc`**'d memory structures are not storeable

Rebuilding PostgreSQL will *not* solve problems in **`gcoord.*`**

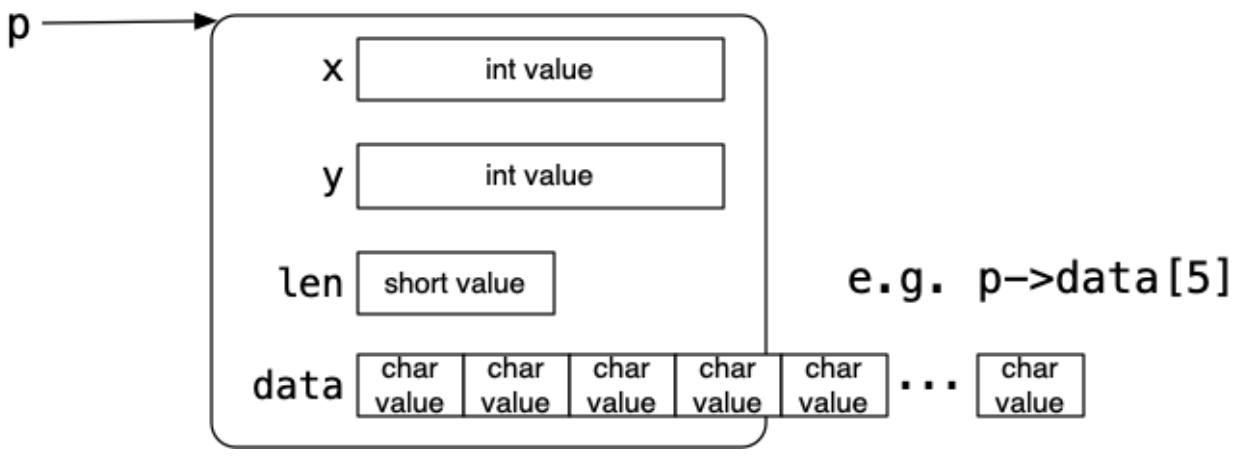
❖ Variable-length Structs

PostgreSQL uses the following trick:

```
struct vlen {
  int x;
  int y;
  short len;
  char data[1];
}
```




```
p = malloc(sizeof(struct vlen)+20)
```




```
e.g. p->data[5]
```

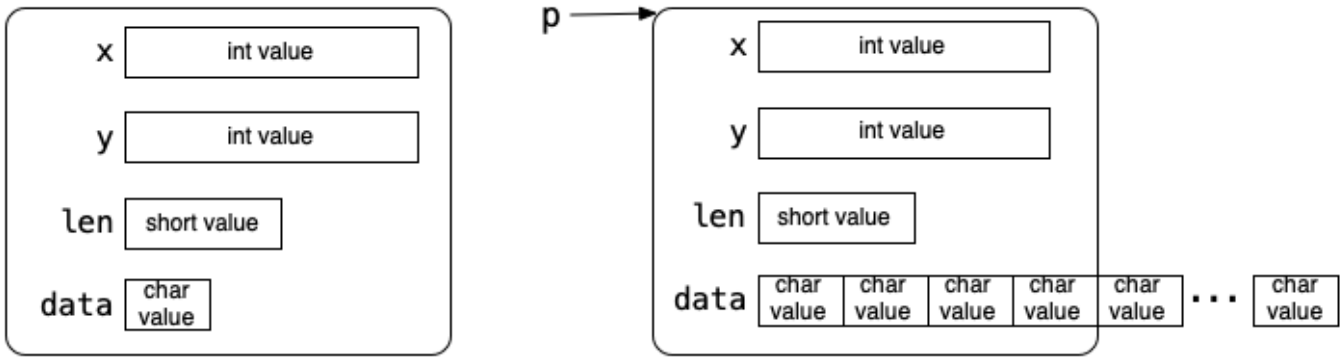
❖ Variable-length Structs (cont)

Difference between in-struct and ex-struct:

```
p = malloc(sizeof(struct vlen)+20);
```

e.g. p->data[5]

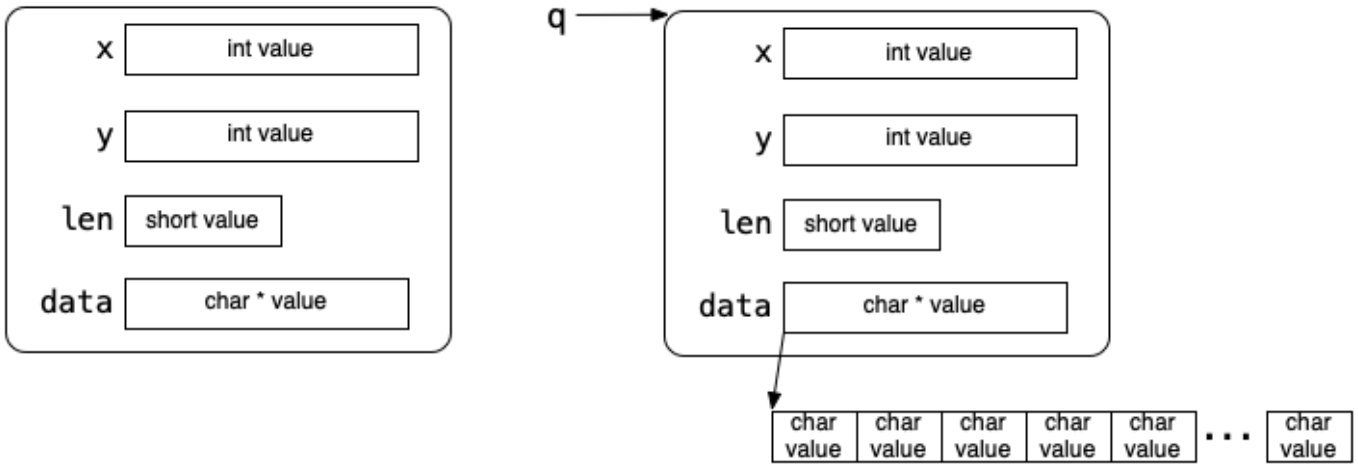
```
struct vlen {
  int x;
  int y;
  short len;
  char data[1];
}
```




```
q = malloc(sizeof(struct vlen));
q->data = malloc(strlen(...)+1)
```

e.g. p->data[5]

```
struct vlen {
  int x;
  int y;
  short len;
  char *data;
}
```



❖ Exercise 1: Building Tuples in PostgreSQL

Examine the code for

```
HeapTuple heap_form_tuple(desc,values[],isnull[])
```

and determine how a PostgreSQL tuple is built

```
HeapTuple = -> HeapTupleData
HeapTupleData =
   (t_len,t_self,t_tableOid,t_data->HeapTupleHeaderData)
HeapTupleHeaderData =
   (t_heap,t_ctid,t_infomask2,t_infomask,t_off,t_bits[],..)
HeapTupleFields =
   (t_xmin,t_xmax,(t_cid|t_xvac)
TupleDesc =
   (natts,tdtypeid,tdtypmod,tdhasoid,constraints[],atts[])
FormData_pg_attribute =
   (attrelid,attname,atttypid,attlen,attndims,attnotnull,...)
```

❖ Exercise 2: 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.

nfields	data_off	fields = FieldDesc[4]			
4	16	(0,4,int)	(6,10,char)	(18,8,char)	(28,2,int)

❖ Exercise 3: Cost of Relation Scan

How much does it cost to scan all tuples in a relation?

E.g. 10000 tuples, 100 tuples per page, 10ms to read a page

Give examples of when this might be needed?

❖ Exercise 4: Cost of Search in Sorted File

How much does it cost to find a record in a relation?

- if the file is sorted on the search field
- each page includes min/max values for each field

Example query: **`select * from R where x = 42;`**

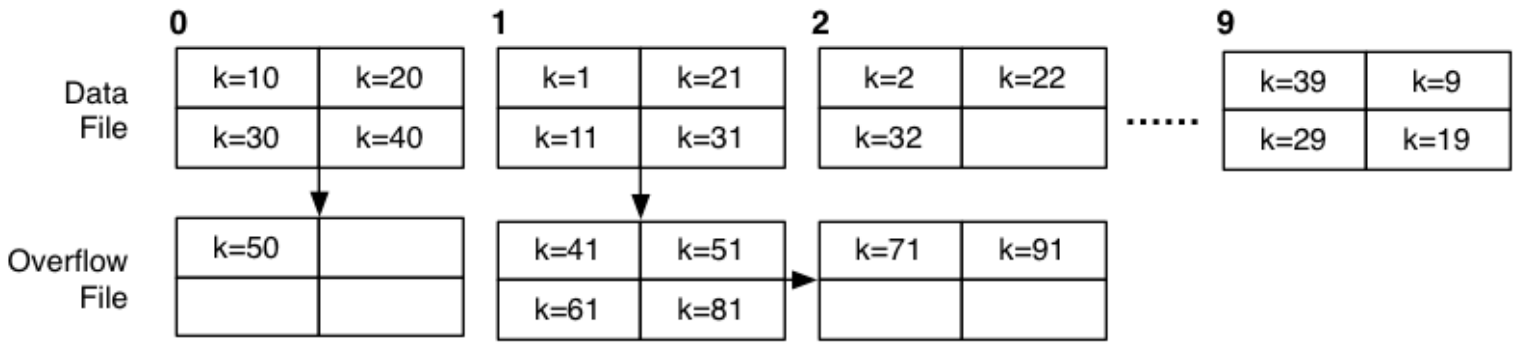
Assume: *B* = 8192, record is located in page 10

Give a pseudo-code algorithm for the search process

Give upper and lower bounds for cost.

❖ Exercise 5: 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)

❖ Exercise 6: Update 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)
- sorted and hash files use overflow pages

❖ Exercise 7: 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
- 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

❖ Exercise 8: 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

❖ Exercise 9: PostgreSQL Sort

Explore the PostgreSQL code for sorting

`src/backend/utils/sort/...`

`include/utils/sortsupport.h`

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