>>

COMP9315 Week 02

COMP9315 25T1
DBMS Implementation

(Data structures and algorithms inside relational DBMSs)

Lecturer: **Xiaoyang Wang**

Web Site: http://www.cse.unsw.edu.au/~cs9315/

(If WebCMS unavailable, use http://www.cse.unsw.edu.au/~cs9315/25T1/)

❖ 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
- bulk storage is very large, slow, page-at-a-time

Page = fixed-size block of data; size determined by storage medium

<< ^ >>

❖ Cost Models (cont)

Since time cost is affected by many factors

- speed of i/o to/from storage devices (disk, SSD)
- load on machine

we do not consider time cost in our analyses.

For comparing methods, *page cost* is better

- identifies the workload imposed by a given method

Measures the number of page read/write requests made.

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

❖ Cost Models (cont)

Terminology:

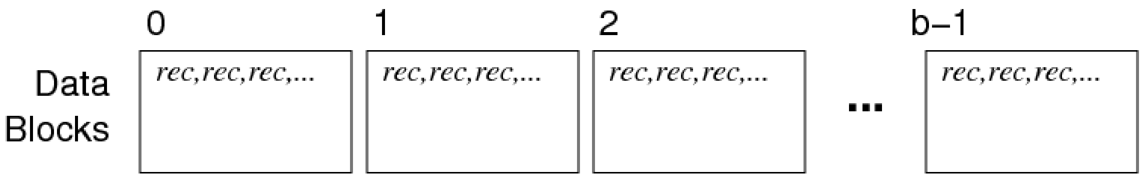
- attribute = atomic value (e.g. int, string)
- tuple = record, list of values
- relation = table, set of records
- page = fixed-size block of data
- database = collection of tables, constraints, ...

<< ∧ >>

❖ Cost Models (cont)

In developing cost models, we make assumptions on how DBMSs store data:

- a relation is a set of r tuples, with average size R bytes
- the tuples are stored in b data pages on a storage device
- 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 bulk-storage↔memory in whole pages
- cost of bulk-storage↔memory transfer $T_{r/w}$ is high



<< ^ >>

❖ Cost Models (cont)

Typical DBMS/table parameter values:

Quantity	Symbol	E.g. Value
total # tuples	r	10^6
record size	R	128 bytes
total # pages	b	10^5
page size	B	8192 bytes
# tuples per page	c	60
page read/write time	T_r, T_w	10 msec
cost to process one page in memory	-	$\cong 0$

<< ^ >>

❖ 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 tune 2/day, working 250 days per year
- Therefore 1 tuner can tune 500 pianos per year
- Therefore Sydney would need ≅ 130000/2/500 = 130 tuners

Actual number of piano tuners in Yellow Pages = 120

Example borrowed from Alan Fekete at Sydney University.

<< ^ >>

❖ Exercise: Relation Scan Cost

Consider a table *R(x,y,z)* with 10^5 tuples, implemented as

- number of tuples $r = 10{,}000$
- average size of tuples $R = 200$ bytes
- size of data pages $B = 4096$ bytes
- time to read one data page $T_r = 10msec$
- time to check one tuple *0.5 usec*
- time to form one result tuple *1 usec*
- time to write one result page $T_w = 10msec$

Calculate the total time-cost for answering the query:

```
insert into S select * from R where x > 10;
```

if 50% of the tuples satisfy the condition. Solution

<< ^ >>

❖ Storage Management

<< ^ >>

❖ Storage Technology

Persistent storage is

- large, cheap, relatively slow, accessed in blocks
- used for long-term storage of data

Computational storage is

- small, expensive, fast, accessed by byte/word
- used for all analysis of data

Access cost HDD:RAM ≅ 100000:1, e.g.

- 10ms to read block containing two tuples
- 1µs to compare fields in two tuples

❖ Storage Technology (cont)

Hard disks are well-established, cheap, high-volume, ...

Alternative bulk storage: SSD

- faster than HDDs, no latency
- can read single items
- update requires block erase then write
- over time, writes "wear out" blocks
- require controllers that spread write load

Feasible for long-term, high-update environments?

<< ^ >>

❖ Storage Technology (cont)

Comparison of HDD and SSD properties:

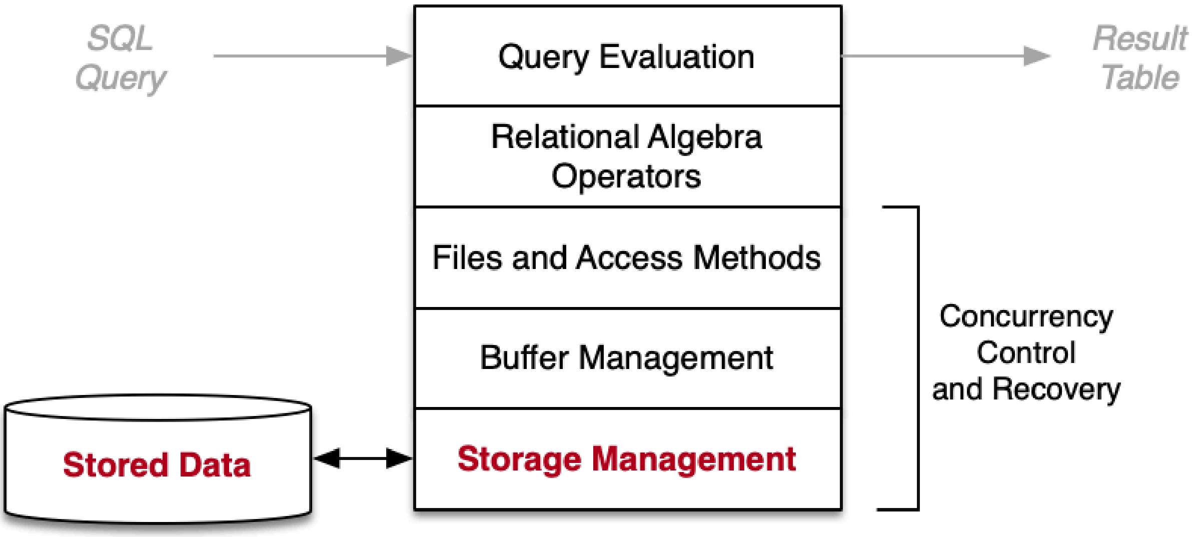
	HDD	**SSD**
Cost/byte	~ $13 / TB	~ $35 / TB
Read latency	~ 6ms	~ 50µs
Write latency	~ 6ms	~ 900µs
R/W rate	150MB/s	450MB/s
Read unit	block (e.g. 1KB)	byte
Writing	write a block	write on empty block

Will SSDs ever completely replace HDDs?

<< ^ >>

❖ Storage Management

Part of DBMS related to storage management:



<< ∧ >>

❖ Storage Management (cont)

Aims of storage management in DBMS:

- provide view of data as collection of pages/tuples
- map from database objects (e.g. tables) to disk files
- manage transfer of data to/from disk storage
- use buffers to minimise disk/memory transfers
- interpret loaded data as tuples/records
- basis for file structures used by access methods

<< ^ >>

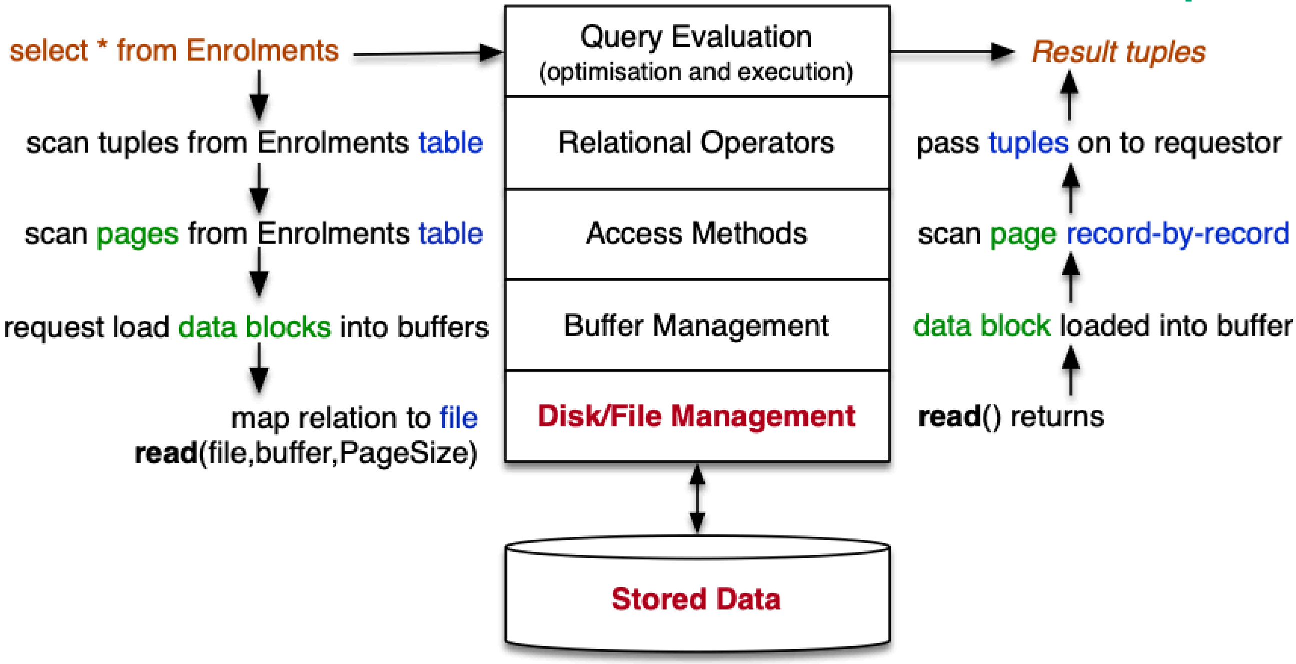
❖ Storage Management

Topics in storage management ...

- Disks and Files
  - performance issues and organisation of disk files
- Buffer Management
  - using caching to improve DBMS system throughput
- Tuple/Page Management
  - how tuples are represented within disk pages
- DB Object Management (Catalog)
  - how tables/views/functions/types, etc. are represented

<< ∧ >>

❖ Views of Data in Query Evaluation



❖ Views of Data in Query Evaluation (cont)

Representing database objects during query evaluation:

- `DB` (handle on an authorised/opened database)
- `Rel` (handle on an opened relation)
- `Page` (memory buffer to hold contents of disk block)
- `Tuple` (chunk of memory holding data values from one tuple)

Addressing in DBMSs:

- `PageID = FileID+Offset` ... identifies a block of data
  - where `Offset` gives location of block within file
- `TupleID = PageID+Index` ... identifies a single tuple
  - where `Index` gives "location" of tuple within page

❖ File Management

Aims of file management subsystem:

- organise layout of data within the filesystem
- handle mapping from database ID to file address
- transfer blocks of data between buffer pool and filesystem
- also attempts to handle file access error problems (retry)

Builds higher-level operations on top of OS file operations.

<< ^ >>

❖ File Management (cont)

Typical file operations provided by the operating system:

```
fd = open(fileName,mode)
  // open a named file for reading/writing/appending
close(fd)
  // close an open file, via its descriptor
nread = read(fd, buf, nbytes)
  // attempt to read data from file into buffer
nwritten = write(fd, buf, nbytes)
  // attempt to write data from buffer to file
lseek(fd, offset, seek_type)
  // move file pointer to relative/absolute file offset
fsync(fd)
  // flush contents of file buffers to disk
```

<< ^ >>

❖ DBMS File Organisation

How is data for DB objects arranged in the file system?

Different DBMSs make different choices, e.g.

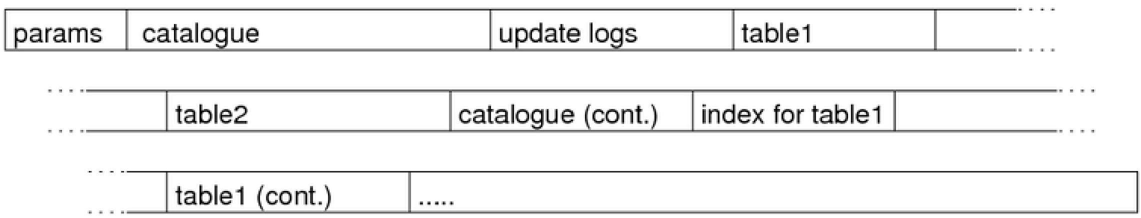
- by-pass the file system and use a raw disk partition
- have a single very large file containing all DB data
- have several large files, with tables spread across them
- have multiple data files, one for each table
- have multiple files for each table
- etc.

<< ^ >>

❖ Single-file DBMS

Consider a single file for the entire database (e.g. SQLite)

Objects are allocated to regions (segments) of the file.



If an object grows too large for allocated segment, allocate an extension.

What happens to allocated space when objects are removed?

❖ Single-file DBMS (cont)

Allocating space in Unix files is easy:

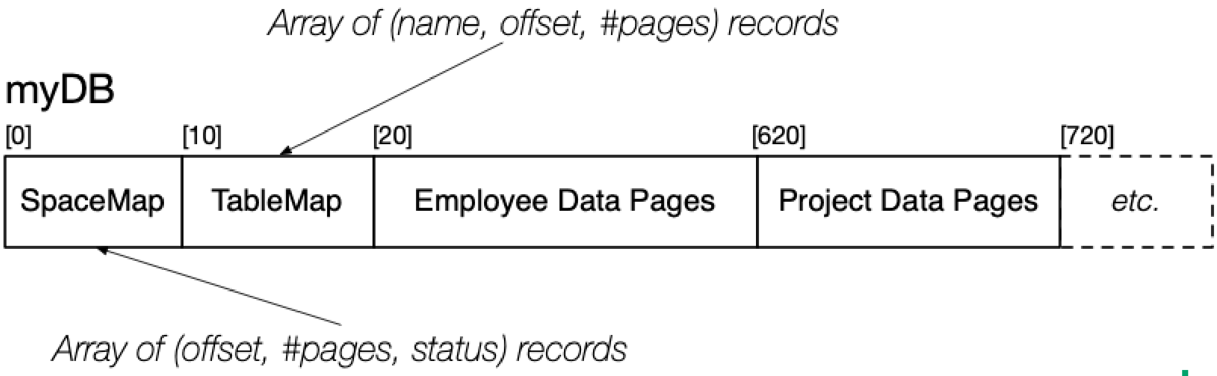
- simply seek to the place you want and write the data
- if nothing there already, data is appended to the file
- if something there already, it gets overwritten

With the above, a disk/file manager is easy to implement.

<< ∧ >>

❖ Single-file Storage Manager

Consider the following simple single-file DBMS layout:



E.g.

SpaceMap = [(0,10,U), (10,10,U), (20,600,U), (620,100,U), (720,20,F)]

TableMap = [("employee",20,500), ("project",620,40)]

<< ^ >>

❖ Single-file Storage Manager (cont)

Each file segment consists of a number fixed-size blocks

The following data/constant definitions are useful

```
#define PAGESIZE 2048       // bytes per page

typedef long PageId;        // PageId is block index
                            // pageOffset=PageId*PAGESIZE

typedef char *Page;         // pointer to page/block buffer
```

Typical `PAGESIZE` values: 1024, 2048, 4096, 8192

<< ^ >>

❖ Single-file Storage Manager (cont)

Storage Manager data structures for opened DBs & Tables

```
typedef struct DBrec {
   char *dbname;     // copy of database name
   int fd;           // the database file
   SpaceMap map;     // map of free/used areas
   NameTable names; // map names to areas + sizes
} *DB;

typedef struct Relrec {
   char *relname;    // copy of table name
   int   start;      // page index of start of table data
   int   npages;     // number of pages of table data
   ...
} *Rel;
```

<< ^ >>

❖ Example: Scanning a Relation

With the above disk manager, our example:

```
select name from Employee
```

might be implemented as something like

```
DB db = openDatabase("myDB");
Rel r = openRelation(db,"Employee");
Page buffer = malloc(PAGESIZE*sizeof(char));
for (int i = 0; i < r->npages; i++) {
   PageId pid = r->start+i;
   get_page(db, pid, buffer);
   for each tuple in buffer {
      get tuple data and extract name
      add (name) to result tuples
   }
}
```

<< ^ >>

❖ Single-File Storage Manager

```
// start using DB, buffer meta-data
DB openDatabase(char *name) {
   DB db = new(struct DBrec);
   db->dbname = strdup(name);
   db->fd = open(name,O_RDWR);
   db->map = readSpaceTable(db->fd);
   db->names = readNameTable(db->fd);
   return db;
}
// stop using DB and update all meta-data
void closeDatabase(DB db) {
   writeSpaceTable(db->fd,db->map);
   writeNameTable(db->fd,db->map);
   fsync(db->fd);
   close(db->fd);
   free(db->dbname);
   free(db);
}
```

<< ∧ >>

❖ Single-File Storage Manager (cont)

```
// set up struct describing relation
Rel openRelation(DB db, char *rname) {
   Rel r = new(struct Relrec);
   r->relname = strdup(rname);
   // get relation data from map tables
   r->start = ...;
   r->npages = ...;
   return r;
}

// stop using a relation
void closeRelation(Rel r) {
   free(r->relname);
   free(r);
}
```

<< ^ >>

❖ Single-File Storage Manager (cont)

```
// assume that Page = byte[PageSize]
// assume that PageId = block number in file

// read page from file into memory buffer
void get_page(DB db, PageId p, Page buf) {
   lseek(db->fd, p*PAGESIZE, SEEK_SET);
   read(db->fd, buf, PAGESIZE);
}

// write page from memory buffer to file
void put_page(DB db, PageId p, Page buf) {
   lseek(db->fd, p*PAGESIZE, SEEK_SET);
   write(db->fd, buf, PAGESIZE);
}
```

<< ^ >>

❖ Single-File Storage Manager (cont)

Managing contents of space mapping table can be complex:

```
// assume an array of (offset,length,status) records

// allocate n new pages
PageId allocate_pages(DB db, int n) {
   if (no existing free chunks are large enough) {
      int endfile = lseek(db->fd, 0, SEEK_END);
      addNewEntry(db->map, endfile, n);
   } else {
      grab "worst fit" chunk
      split off unused section as new chunk
   }
}
```

<< ^ >>

❖ Single-File Storage Manager (cont)

Similar complexity for freeing chunks

```
// drop n pages starting from p
void deallocate_pages(DB db, PageId p, int n) {
   if (no adjacent free chunks) {
      markUnused(db->map, p, n);
   } else {
      merge adjacent free chunks
      compress mapping table
   }
}
```

Changes take effect when `closeDatabase()` executed.

<< ^ >>

❖ Multiple-file Disk Manager

Most DBMSs don't use a single large file for all data.

They typically provide:

- multiple files partitioned physically or logically
- mapping from DB-level objects to files (e.g. via meta-data)

Precise file structure varies between individual DBMSs.

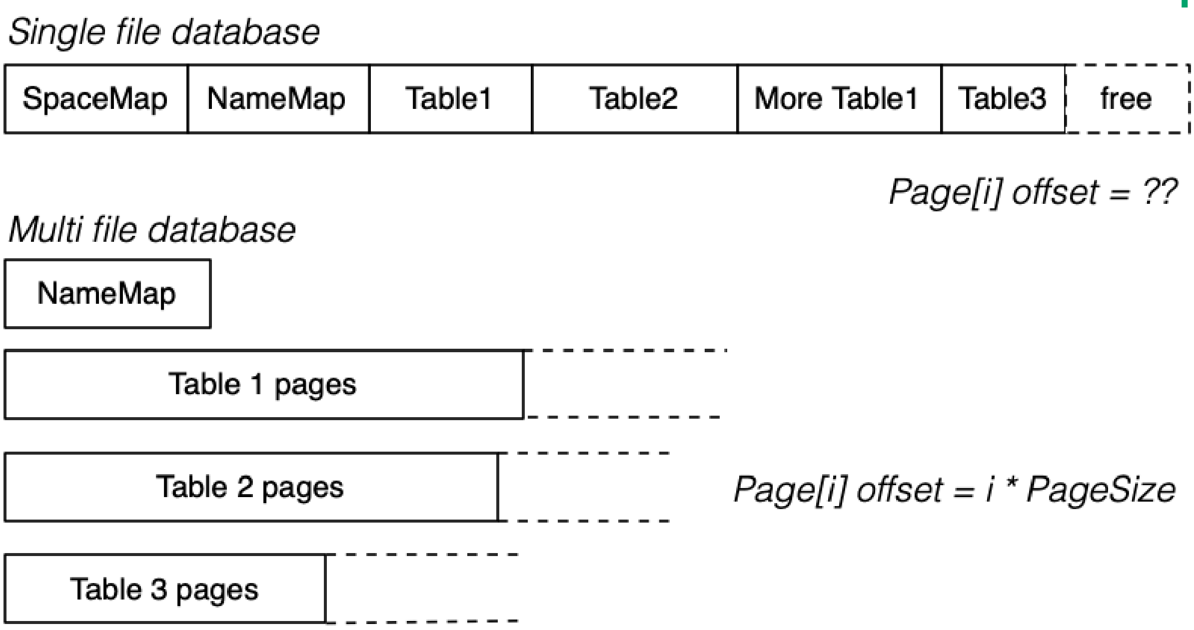
Using multiple files (one file per relation) can be easier, e.g.

- adding a new relation
- extending the size of a relation
- computing page offsets within a relation

<< ∧ >>

❖ Multiple-file Disk Manager (cont)

Example of single-file vs multiple-file:



Consider how you would compute file offset of page[i] in table[1] ...

❖ Multiple-file Disk Manager (cont)

Structure of `PageId` for data pages in such systems ...

If system uses one file per table, `PageId` contains:

- relation indentifier (which can be mapped to filename)
- page number (to identify page within the file)

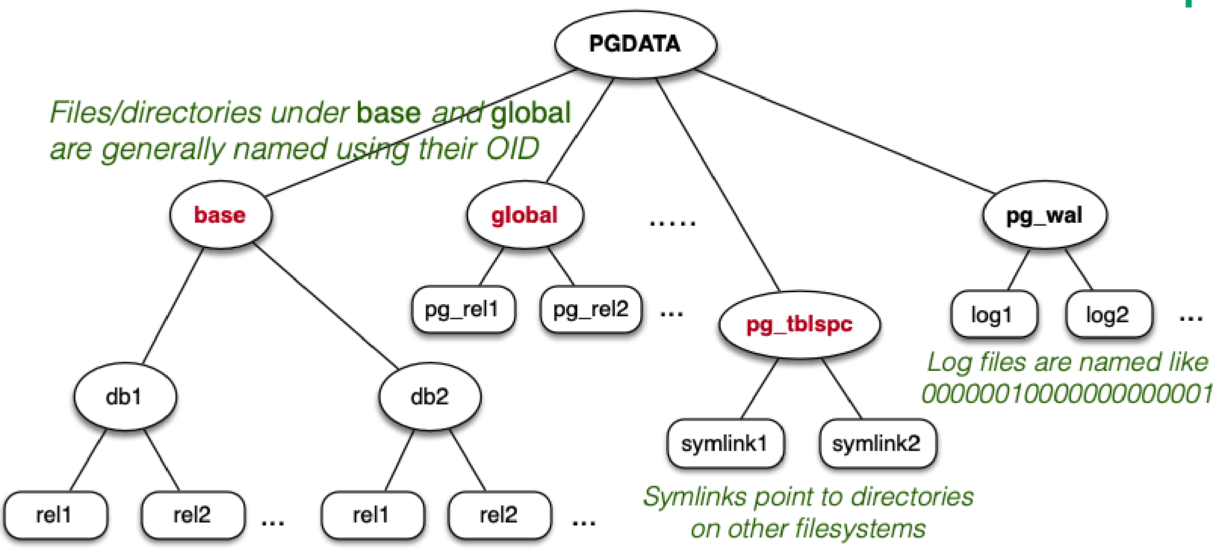
If system uses several files per table, `PageId` contains:

- relation identifier
- file identifier (combined with relid, gives filename)
- page number (to identify page within the file)

<< ^ >>

❖ PostgreSQL Storage Manager

PostgreSQL uses the following file organisation ...



<< ^ >>

❖ PostgreSQL Storage Manager (cont)

Components of storage subsystem:

- mapping from relations to files (`RelFileNode`)
- abstraction for open relation pool (`storage/smgr`)
- functions for managing files (`storage/smgr/md.c`)
- file-descriptor pool (`storage/file`)

PostgreSQL has two basic kinds of files:

- heap files containing data (tuples)
- index files containing index entries

Note: `smgr` designed for many storage devices; only disk handler provided

<< ^ >>

❖ Relations as Files

PostgreSQL identifies relation files via their OIDs.

The core data structure for this is `RelFileNode`:

```
typedef struct RelFileNode {
    Oid  spcNode;  // tablespace
    Oid  dbNode;   // database
    Oid  relNode;  // relation
} RelFileNode;
```

Global (shared) tables (e.g. `pg_database`) have

- `spcNode == GLOBALTABLESPACE_OID`
- `dbNode == 0`

<< ^ >>

❖ Relations as Files (cont)

The `relpath` function maps `RelFileNode` to file:

```
char *relpath(RelFileNode r)  // simplified
{
   char *path = malloc(ENOUGH_SPACE);

   if (r.spcNode == GLOBALTABLESPACE_OID) {
      /* Shared system relations live in PGDATA/global */
      Assert(r.dbNode == 0);
      sprintf(path, "%s/global/%u",
              DataDir, r.relNode);
   }
   else if (r.spcNode == DEFAULTTABLESPACE_OID) {
      /* The default tablespace is PGDATA/base */
      sprintf(path, "%s/base/%u/%u",
              DataDir, r.dbNode, r.relNode);
   }
   else {
      /* All other tablespaces accessed via symlinks */
      sprintf(path, "%s/pg_tblspc/%u/%u/%u", DataDir
              r.spcNode, r.dbNode, r.relNode);
   }
   return path;
}
```

<< ^ >>

❖ Exercise: PostgreSQL Files

In your PostgreSQL server

- examine the content of the `$PGDATA` directory
- find the directory containing the `pizza` database
- find the file in this directory for the `People` table
- examine the contents of the `People` file
- what are the other files in the directory?
- are there forks in any of your databases?

Solution

<< ^ >>

❖ File Descriptor Pool

Unix has limits on the number of concurrently open files.

PostgreSQL maintains a pool of open file descriptors:

- to hide this limitation from higher level functions
- to minimise expensive `open()` operations

File names are simply strings: `typedef char *FileName`

Open files are referenced via: `typedef int File`

A `File` is an index into a table of "virtual file descriptors".

<< ^ >>

❖ File Descriptor Pool (cont)

Interface to file descriptor (pool):

```
File FileNameOpenFile(FileName fileName,
                      int fileFlags, int fileMode);
     // open a file in the database directory ($PGDATA/base/...)
File OpenTemporaryFile(bool interXact);
     // open temp file; flag: close at end of transaction?
void FileClose(File file);
void FileUnlink(File file);
int  FileRead(File file, char *buffer, int amount);
int  FileWrite(File file, char *buffer, int amount);
int  FileSync(File file);
long FileSeek(File file, long offset, int whence);
int  FileTruncate(File file, long offset);
```

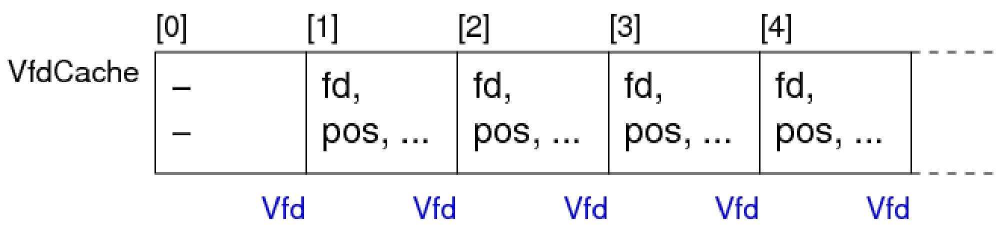
Analogous to Unix syscalls `open()`, `close()`, `read()`, `write()`, `lseek()`, ...

<< ∧ >>

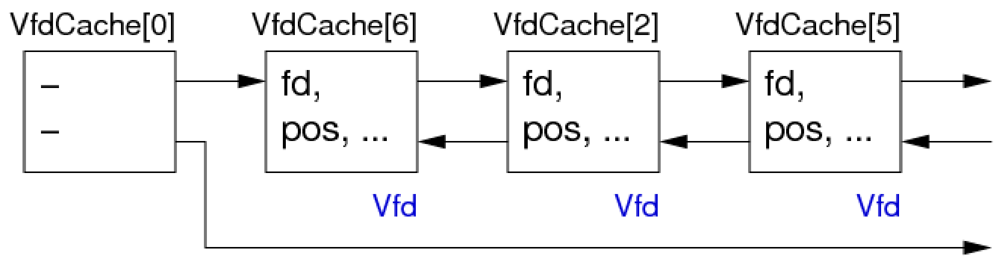
❖ File Descriptor Pool (cont)

Virtual file descriptors (`Vfd`)

- physically stored in dynamically-allocated array



- also arranged into list by recency-of-use



`VfdCache[0]` holds list head/tail pointers.

<< ^ >>

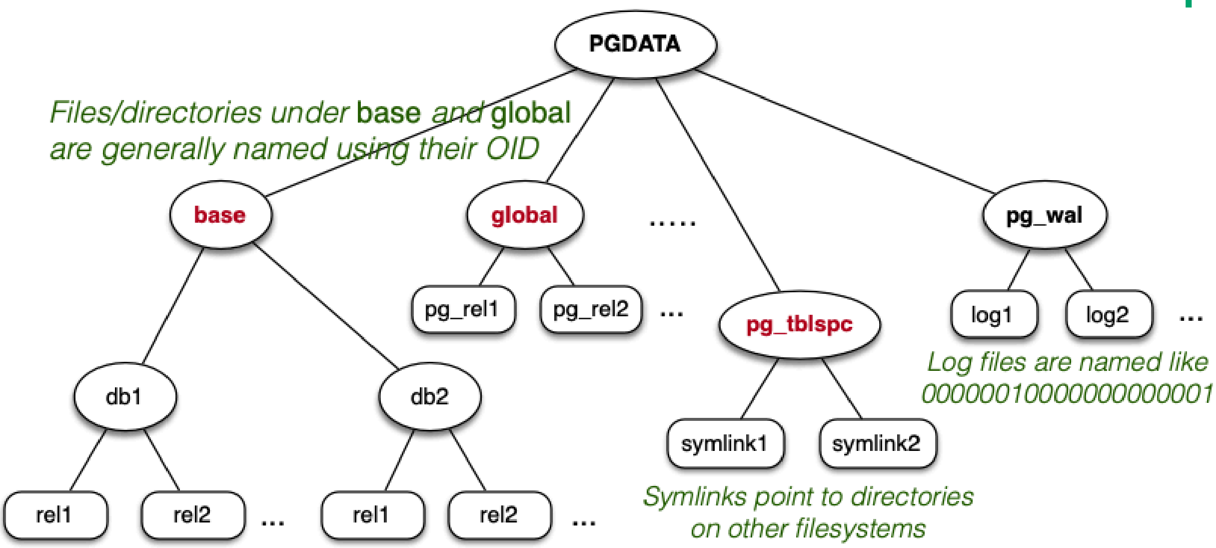
❖ File Descriptor Pool (cont)

Virtual file descriptor records (simplified):

```
typedef struct vfd
{
    s_short  fd;              // current FD, or VFD_CLOSED if none
    u_short  fdstate;         // bitflags for VFD's state
    File     nextFree;        // link to next free VFD, if in freelist
    File     lruMoreRecently; // doubly linked recency-of-use list
    File     lruLessRecently;
    long     seekPos;         // current logical file position
    char     *fileName;       // name of file, or NULL for unused VFD
    // NB: fileName is malloc'd, and must be free'd when closing the VFD
    int      fileFlags;       // open(2) flags for (re)opening the file
    int      fileMode;        // mode to pass to open(2)
} Vfd;
```

❖ File Manager

Reminder: PostgreSQL file organisation

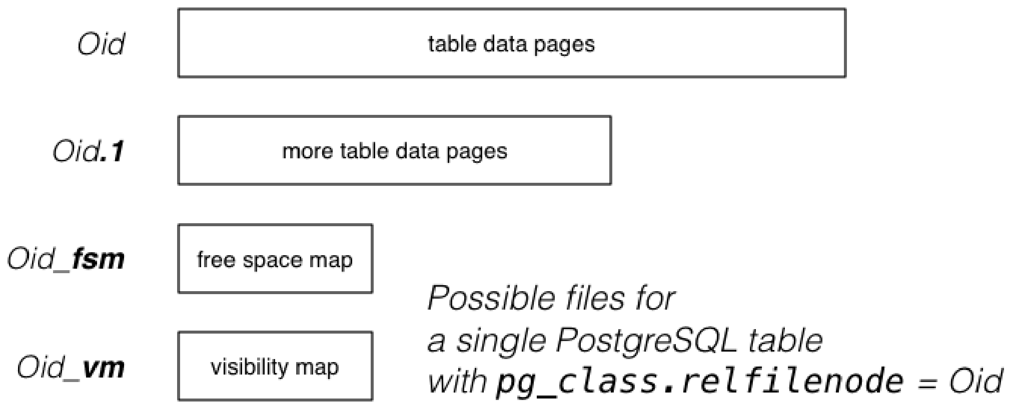


<< ∧ >>

❖ File Manager (cont)

PostgreSQL stores each table

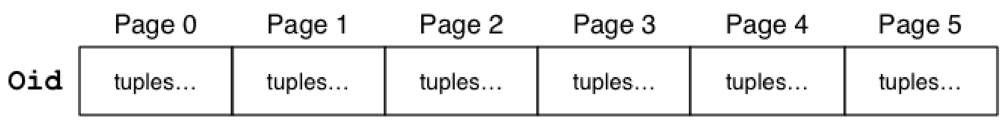
- in the directory `PGDATA/pg_database.oid`
- often in multiple data files (aka *forks*)



❖ File Manager (cont)

Data files (*Oid*, *Oid*. 1, ...):

- sequence of fixed-size blocks/pages (typically 8KB)
- each page contains tuple data and admin data (see later)
- max size of data files 1GB (Unix limitation)



PostgreSQL Data File (Heap)

<< ^ >>

❖ File Manager (cont)

Free space map (*Oid*_`fsm`):

- indicates where free space is in data pages
- "free" space is only free after `VACUUM`
  (`DELETE` simply marks tuples as no longer in use `xmax`)

Visibility map (*Oid*_`vm`):

- indicates pages where all tuples are "visible"
  (*visible* = accessible to all currently active transactions)
- such pages can be ignored by `VACUUM`

<< ^ >>

❖ File Manager (cont)

The "magnetic disk storage manager" (`storage/smgr/md.c`)

- manages its own pool of open file descriptors (Vfd's)
- may use several Vfd's to access data, if several forks
- manages mapping from `PageID` to file+offset.

PostgreSQL `PageID` values are structured:

```
typedef struct
{
    RelFileNode rnode;     // which relation/file
    ForkNumber  forkNum;   // which fork (of reln)
    BlockNumber blockNum;  // which page/block
} BufferTag;
```

<< ∧ >>

❖ File Manager (cont)

Access to a block of data proceeds (roughly) as follows:

```
// pageID set from pg_catalog tables
// buffer obtained from Buffer pool
getBlock(BufferTag pageID, Buffer buf)
{
   Vfd vf;  off_t offset;
   (vf, offset) = findBlock(pageID)
   lseek(vf.fd, offset, SEEK_SET)
   vf.seekPos = offset;
   nread = read(vf.fd, buf, BLOCKSIZE)
   if (nread < BLOCKSIZE) ... we have a problem
}
```

`BLOCKSIZE` is a global configurable constant (default: 8192)

<< ^

❖ File Manager (cont)

```
findBlock(BufferTag pageID) returns (Vfd, off_t)
{
   offset = pageID.blockNum * BLOCKSIZE
   fileName = relpath(pageID.rnode)
   if (pageID.forkNum > 0)
      fileName = fileName+"."+pageID.forkNum
   if (fileName is not in Vfd pool)
      fd = allocate new Vfd for fileName
   else
      fd = use Vfd from pool
   if (offset > fd.fileSize) {
      fd = allocate new Vfd for next fork
      offset = offset - fd.fileSize
   }
   return (fd, offset)
}
```

Produced: 24 Feb 2025