Week 01 Lectures

Some Revision

Exercise 1: SQL (revision)

Given the following schema:

```
Students(sid, name, degree, ...)
e.g. Students(3322111, 'John Smith', 'MEngSc', ...)
Courses(cid, code, term, title, ...)
e.g. Courses(1732, 'COMP9311', '12s1', 'Databases', ...)
Enrolments(sid, cid, mark, grade)
e.g. Enrolments(3322111, 1732, 50, 'PS')
```

Write an SQL query to solve the problem

- find all students who passed COMP9315 in 18s2
- for each student, give (student ID, name, mark)

Exercise 2: Unix File I/O (revision)

Write a C program that reads a file, block-by-block.

Command-line parameters:

- block size in bytes
- name of input file

Use low-level C operations: `open, read`.

Count and display how many blocks/bytes read.

Exercise 3: Relational Algebra

Using the same student/course/enrolment schema as above:

```
Students(sid, name, degree, ...)
Courses(cid, code, term, title, ...)
Enrolments(sid, cid, mark, grade)
```

Write relational algebra expressions to solve the problem

- find all students who passed COMP9315 in 18s2
- for each student, give (student ID, name, mark)

Express it as a sequence of steps, where each step uses one RA operation.

PostgreSQL

PostgreSQL

PostgreSQL is a full-featured open-source (O)RDBMS.

- provides a relational engine with:
  - efficient implementation of relational operations
  - transaction processing (concurrent access)
  - backup/recovery (from application/system failure)
  - novel query optimisation (genetic algorithm-based)
  - replication, JSON, extensible indexing, etc. etc.
- already supports several non-standard data types
- allows users to define their own data types
- supports most of the SQL3 standard

PostgreSQL Online

Web site: www.postgresql.org

Key developers: Bruce Momjian, Tom Lane, Marc Fournier, ...

Full list of developers: www.postgresql.org/developer/

Local copy of source code:

http://www.cse.unsw.edu.au/~cs9315/20T1/postgresql/src.tar.bz2

Documentation is available via WebCMS menu.

User View of PostgreSQL

Users interact via SQL in a *client* process, e.g.

```
$ psql webcms
psql (12.1)
Type "help" for help.
webcms2=# select * from calendar;
 id | course |   evdate   |      event
----+--------+------------+--------------------------
  1 |      4 | 2001-08-09 | Project Proposals due
 10 |      3 | 2001-08-01 | Tute/Lab Enrolments Close
 12 |      3 | 2001-09-07 | Assignment #1 Due (10pm)
 ...
```

or

```
$dbconn = pg_connect("dbname=webcms");
$result = pg_query($dbconn,"select * from calendar");
while ($tuple = pg_fetch_array($result))
   { ... $tuple["event"] ... }
```

PostgreSQL Functionality

PostgreSQL systems deal with various kinds of entities:

- *users* ... who can access the system
- *groups* ... groups of users, for role-based privileges
- *databases* ... collections of schemas/tables/views/...
- *namespaces* ... to uniquely identify objects (schema.table.attr)
- *tables* ... collection of tuples (standard relational notion)
- *views* ... "virtual" tables (can be made updatable)
- *functions* ... operations on values from/in tables
- *triggers* ... operations invoked in response to events
- *operators* ... functions with infix syntax
- *aggregates* ... operations over whole table columns
- *types* ... user-defined data types (with own operations)

- *rules* ... for query rewriting (used e.g. to implement views)
- *access methods* ... efficient access to tuples in tables

... PostgreSQL Functionality

PostgreSQL's dialect of SQL is mostly standard (but with extensions).

- attributes containing arrays of atomic values

```
create table R ( id integer, values integer[] );
insert into R values ( 123, '{5,4,3,2,1}' );
```

- table-valued functions

```
create function f(integer) returns setof TupleType;
```

- multiple langauges available for functions
  - PLpgSQL, Python, Perl, Java, R, Tcl, ...
  - function bodies are strings in whatever language

... PostgreSQL Functionality

Other variations in PostgreSQL's `CREATE TABLE`

- `TEMPORARY` tables
- `PARTITION`'d tables
- `GENERATED` attribute values (derived attributes)
- `FOREIGN TABLE` (data stored outside PostgreSQL)
- table type inheritance

```
create table R ( a integer, b text);
create table S ( x float, y float);
create table T inherits ( R, S );
```

... PostgreSQL Functionality

PostgreSQL stored procedures differ from SQL standard:

- only provides functions, not procedures
  (but functions can return `void`, effectively a procedure)
- allows function overloading
  (same function name, different argument types)
- defined at different "lexical level" to SQL
- provides own PL/SQL-like language for functions

```
create function ( Args ) returns ResultType
as $$
... body of function definition ...
$$ language FunctionBodyLanguage;
```

- where each *Arg* has a *Name* and *Type*

... PostgreSQL Functionality

Example:

```
create or replace function
    barsIn(suburb text) returns setof Bars
as $$
declare
    r record;
begin
```

```
    for r in
        select * from Bars where location = suburb
    loop
       return next r;
    end loop;
end;
$$ language plpgsql;
used as e.g.
select * from barsIn('Randwick');
```

Do the previous example more simply using an SQL function

Could we use a view?

... PostgreSQL Functionality

Uses *multi-version concurrency control* (MVCC)

- multiple "versions" of the database exist together
- a transaction sees the version that was valid at its start-time
- readers don't block writers; writers don't block readers
- this significantly reduces the need for locking

Disadvantages of this approach:

- extra storage for old versions of tuples (`vacuum` fixes this)
- need to check "visibility" of every tuple fetched

PostgreSQL also provides locking to enforce critical concurrency.

... PostgreSQL Functionality

PostgreSQL has a well-defined and open extensibility model:

- stored procedures are held in database as strings
  - allows a variety of languages to be used
  - language interpreters can be integrated into engine
- can add new data types, operators, aggregates, indexes
  - typically requires code written in C, following defined API
  - for new data types, need to write input/output functions, ...
  - for new indexes, need to implement file structures

Installing/Using PostgreSQL

Installing PostgreSQL

PostgreSQL is available via the COMP9315 web site.

Provided as tar-file in `~cs9315/web/20T1/postgresql/`

File: `src.tar.bz2` is ~20MB **

Unpacked, source code + binaries is ~130MB **

If using on CSE, do not put it under your home directory

Place it under `/srvr/`*`YOU`*`/` which has 500MB quota

Most efficient to run server on `grieg`

Before Installing ...

If you have databases from previous DB courses

- the databases will no longer work under v12.1
- to preserve them, use dump/restore

E.g.

```
... login to grieg ...
... run your old server for the last time ...
$ pg_dump -O -x myFavDB > /srvr/YOU/myFavDB.dump
... stop your old server for the last time ...
... remove data from your old server ...
$ rm -fr /srvr/YOU/pgsql
... install and run your new PostgreSQL 12.1 server ...
$ createdb myFavDB
$ psql myFavDB -f /srvr/YOU/myFavDB.dump
... your old database is restored under 12.1 ...
```

Installing/Using PostgreSQL

Environment setup for running PostgreSQL in COMP9315:

```
# Must be "source"d from sh, bash, ksh, ...

# can be any directory
PGHOME=/home/jas/srvr/pgsql
# data does not need to be under $PGHOME
export PGDATA=$PGHOME/data
export PGHOST=$PGDATA
export PGPORT=5432
export PATH=$PGHOME/bin:/home/cs9315/bin:$PATH

# /home/cs9315/bin/pgs simplifies managing server
```

Will probably work (with tweaks) on home laptop if Linux or MacOS

... Installing/Using PostgreSQL

Brief summary of installation:

```
$ tar xfj ..../postgresql/src.tar.bz2
  # create a directory postgresql-12.1
$ source ~/your/environment/file
  # set up environment variables
$ configure --prefix=$PGHOME
$ make
$ make install
$ initdb
  # set up postgresql configuration ... done once?
$ edit postgresql.conf
$ pg_ctl start -l $PGDATA/log
  # do some work with PostgreSQL databases
$ pg_ctl stop
```

On CSE machines, `~cs9315/bin/pgs` can simplify some things

Using PostgreSQL for Assignments

If changes don't modify storage structures ...

```
$ edit source code
$ pg_ctl stop
$ make
$ make install
$ pg_ctl start -l $PGDATA/log
  # run tests, analyse results, ...
$ pg_ctl stop
```

In this case, existing databases will continue to work ok.

... Using PostgreSQL for Assignments

If changes modify storage structures ...

```
$ edit source code
$ save a copy of postgresql.conf
$ pg_dump testdb > testdb.dump
$ pg_ctl stop
$ make
$ make install
$ rm -fr $PGDATA
$ initdb
$ restore postgresql.conf
$ pg_ctl start -l $PGDATA/log
$ createdb testdb
$ psql testdb -f testdb.dump
  # run tests and analyse results
```

Old databases will not work with the new server.

... Using PostgreSQL for Assignments

Troubleshooting ...

- read the `$PGDATA/log` file
- which socket file are you trying to connect to?
- check the `$PGDATA` directory for socket files
- remove `postmster.pid` if sure no server running
- ...

Prac Exercise P01 has useful tips down the bottom

Catalogs

Database Objects

RDBMSs manage different kinds of objects

- databases, schemas, tablespaces
- relations/tables, attributes, tuples/records
- constraints, assertions
- views, stored procedures, triggers, rules

Many objects have names (and, in PostgreSQL, all have OIDs).

How are the different types of objects represented?

How do we go from a name (or OID) to bytes stored on disk?

Catalogs

Consider what information the RDBMS needs about relations:

- name, owner, primary key of each relation
- name, data type, constraints for each attribute
- authorisation for operations on each relation

Similarly for other DBMS objects (e.g. views, functions, triggers, ...)

This information is stored in the *system catalog* tables

Standard for catalogs in SQL:2003: `INFORMATION_SCHEMA`

... Catalogs

The catalog is affected by several types of SQL operations:

- `create` *Object* `as` *Definition*
- `drop` *Object* ...
- `alter` *Object* *Changes*
- `grant` *Privilege* `on` *Object*

where *Object* is one of table, view, function, trigger, schema, ...

E.g. `drop table Groups;` produces something like

```
delete from Tables
where  schema = 'public' and name = 'groups';
```

... Catalogs

In PostgreSQL, the system catalog is available to users via:

- special commands in the `psql` shell (e.g. `\d`)
- SQL standard `information_schema`

  e.g. `select * from information_schema.tables;`

The low-level representation is available to sysadmins via:

- a global schema called `pg_catalog`
- a set of tables/views in that schema (e.g. `pg_tables`)

... Catalogs

You can explore the PostgreSQL catalog via `psql` commands

- **`\d`** gives a list of all tables and views
- **`\d`** ***`Table`*** gives a schema for *`Table`*
- **`\df`** gives a list of user-defined functions
- **`\df+`** ***`Function`*** gives details of *`Function`*
- **`\ef`** ***`Function`*** allows you to edit *`Function`*
- **`\dv`** gives a list of user-defined views
- **`\d+`** ***`View`*** gives definition of *`View`*

You can also explore via SQL on the catalog tables

... Catalogs

A PostgreSQL installation (cluster) typically has many DBs

Some catalog information is global, e.g.

- catalog tables defining: databases, users, ...
- one copy of each such table for the whole PostgreSQL installation
- shared by all databases in the cluster (in `PGDATA/pg_global`)

Other catalog information is local to each database, e.g

- schemas, tables, attributes, functions, types, ...
- separate copy of each "local" table in each database
- a copy of many "global" tables is made on database creation

---

... Catalogs

Side-note: PostgreSQL tuples contain

- owner-specified attributes (from `create table`)
- system-defined attributes

`oid`	unique identifying number for tuple (optional)
`tableoid`	which table this tuple belongs to
`xmin/xmax`	which transaction created/deleted tuple (for MVCC)

OIDs are used as primary keys in many of the catalog tables.

Representing Databases

Above the level of individual DB schemata, we have:

- *databases* ... represented by `pg_database`
- *schemas* ... represented by `pg_namespace`
- *table spaces* ... represented by `pg_tablespace`

These tables are global to each PostgreSQL cluster.

Keys are names (strings) and must be unique within cluster.

... Representing Databases

`pg_database` contains information about databases:

- `oid, datname, datdba, datacl[], encoding, ...`

`pg_namespace` contains information about schemata:

- `oid, nspname, nspowner, nspacl[]`

`pg_tablespace` contains information about tablespaces:

- `oid, spcname, spcowner, spcacl[]`

PostgreSQL represents access via array of access items:

Role=Privileges/Grantor

where *Privileges* is a string enumerating privileges, e.g.

```
jas=arwdRxt/jas,fred=r/jas,joe=rwad/jas
```

Representing Tables

Representing one table needs tuples in several catalog tables.

Due to O-O heritage, base table for tables is called `pg_class`.

The `pg_class` table also handles other "table-like" objects:

- views ... represents attributes/domains of view
- composite (tuple) types ... from `CREATE TYPE AS`
- sequences, indexes (top-level defn), other "special" objects

All tuples in `pg_class` have an OID, used as primary key.

Some fields from the `pg_class` table:

- `oid, relname, relnamespace, reltype, relowner`
- `relkind, reltuples, relnatts, relhaspkey, relacl, ...`

... Representing Tables

Details of catalog tables representing database tables

`pg_class` holds core information about tables

- `relname, relnamespace, reltype, relowner, ...`
- `relkind, relnatts, relhaspkey, relacl[], ...`

`pg_attribute` contains information about attributes

- `attrelid, attname, atttypid, attnum, ...`

`pg_type` contains information about types

- `typname, typnamespace, typowner, typlen, ...`
- `typtype, typrelid, typinput, typoutput, ...`

Exercise 4: Table Statistics

Using the PostgreSQL catalog, write a PLpgSQL function

- to return table name and #tuples in table
- for all tables in the `public` schema

```
create type TableInfo as (table text, ntuples int);
create function pop() returns setof TableInfo ...
```

Hints:

- `table` is a reserved word
- you will need to use dynamically-generated queries.

Exercise 5: Extracting a Schema

Write a PLpgSQL function:

- `function schema() returns setof text`
- giving a list of table schemas in the `public` schema

It should behave as follows:

```
db=# select * from schema();
            tables
---------------------------
 table1(x, y, z)
 table2(a, b)
 table3(id, name, address)
...
```

Exercise 6: Enumerated Types

PostgreSQL allows you to define enumerated types, e.g.

```
create type Mood as enum ('sad', 'happy');
```

Creates a type with two ordered values `'sad' < 'happy'`

What is created in the catalog for the above definition?

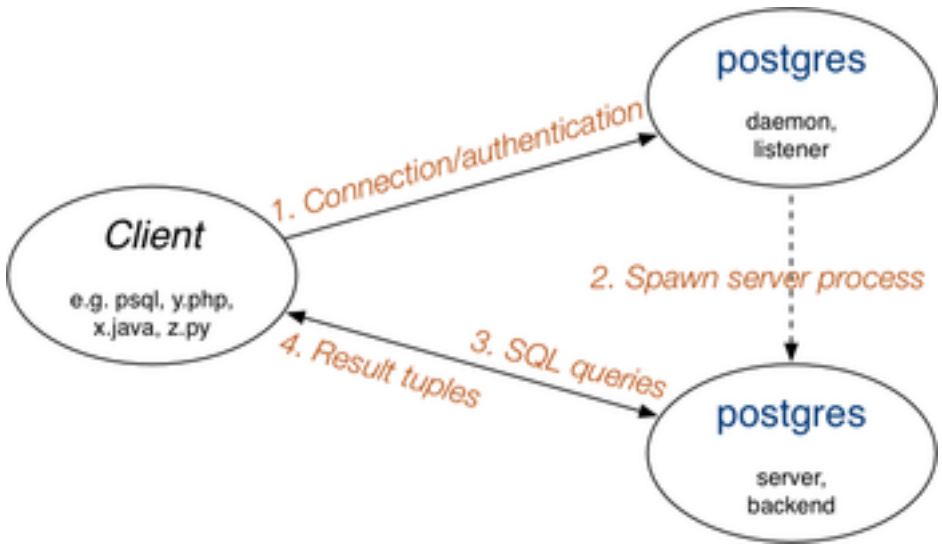
Hint:

```
pg_type(oid, typname, typelen, typetype, ...)
pg_enum(oid, enumtypid, enumlabel)
```

PostgreSQL Architecture

PostgreSQL Architecture

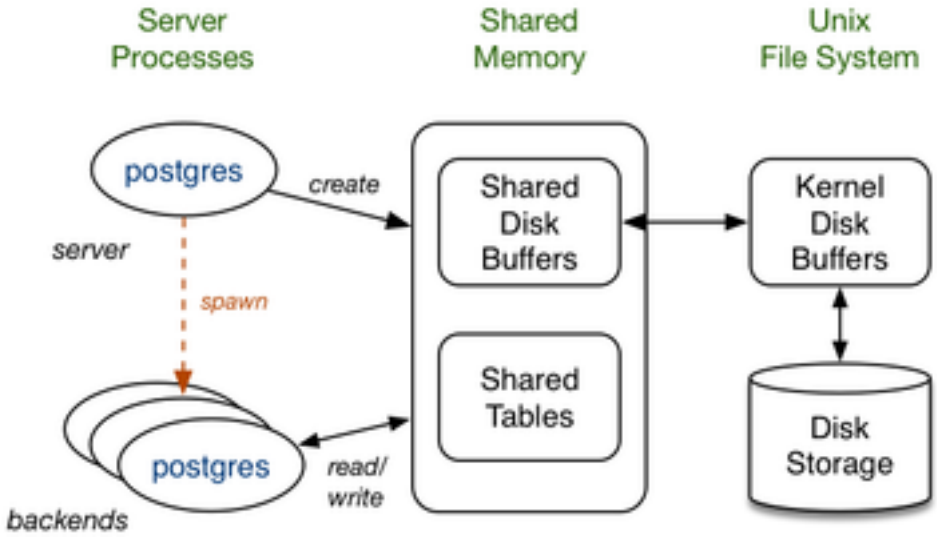
Client/server architecture:



The listener process is sometimes called `postmaster`

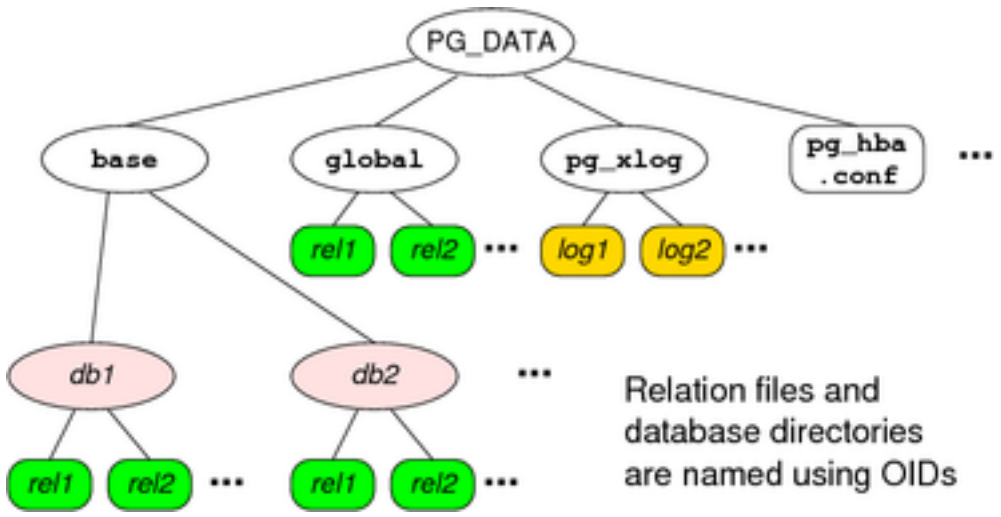
... PostgreSQL Architecture

Memory/storage architecture:



... PostgreSQL Architecture

File-system architecture:



Exercise 7: PostgreSQL Data Files

PostgreSQL uses OIDs as

- the name of the directory for each database
- the name of the files for each table

Using the `pg_catalog` tables, find ..

- the directory for the database
- the data files for the `Pizzas` and `People` tables

Relevant catalog info ...

```
pg_database(oid,datname,...)
pg_class(oid,relname,...)
```

PostgreSQL Source Code

Top-level of PostgreSQL distribution contains:

- *README,INSTALL*: overview and installation instructions
- *config**: scripts to build localised Makefiles
- *Makefile*: top-level script to control system build
- *src*: sub-directories containing system source code
- *doc*: FAQs and documentation
- *contrib*: source code for contributed extensions

The source code directory (*src*) contains:

- *include*: ***.h** files with global definitions (constants, types, ...)
- *backend*: code for PostgreSQL database engine
- *bin*: code for clients (e.g. psql, pg_ctl, pg_dump, ...)
- *pl*: stored procedure language interpreters (e.g. plpgsql)
- *interfaces* code for low-level C interfaces (e.g. libpq)

along with Makefiles to build system and other directories ...

Code for backend (DBMS engine)

- ~2000 files (~1100.c, ~900.h, 8.y, 10.l), 1.5×10^6 lines of code

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How to get started understanding the workings of PostgreSQL:

- become familiar with the user-level interface
  - psql, pg_dump, pg_ctl
- start with the ***.h** files, then move to ***.c** files
  - ***.c** files live under src/backend/*
  - ***.h** files live under src/include
- start globally, then work one subsystem-at-a-time

Some helpful information is available via:

- PostgreSQL Doc link on web site
- Readings link on web site

PostgreSQL documentation has detailed description of internals:

- Section VII, Chapters 50 - 70
- Ch.50 is an overview; a good place to start
- other chapters discuss specific components

See also "How PostgreSQL Processes a Query"

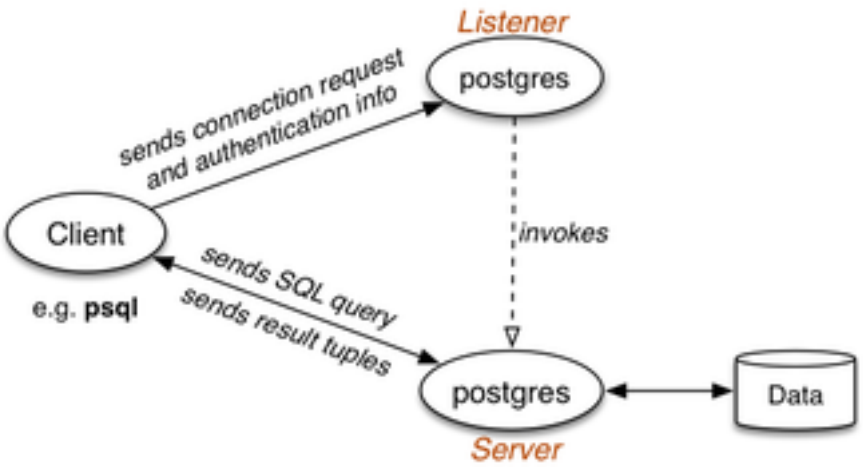
- `src/tools/backend/index.html`

Life-cycle of a PostgreSQL query

How a PostgreSQL query is executed:

- SQL query string is produced in client
- client establishes connection to PostgreSQL
- dedicated server process attached to client
- SQL query string sent to server process
- *server parses/plans/optimises query*
- server executes query to produce result tuples
- tuples are transmitted back to client
- client disconnects from server

Data flow to get to execute a query:



PostgreSQL server

`PostgresMain(int argc, char *argv[], ...)`

- defined in `src/backend/tcop/postgres.c`
- PostgreSQL server (`postgres`) main loop
- performs much setting up/initialisation
- reads and executes requests from client
- using the frontend/backend protocol (Ch.46)
- on `Q` request, evaluates supplied query
- on `X` request, exits the server process

... PostgreSQL server

As well as handling SQL queries, `PostgresqlMain` also

- handles "utility" commands e.g. `CREATE TABLE`
  - most utility commands modify catalog (e.g. `CREATE` *X*)
  - other commands affect server (e.g. `vacuum`)
- handles `COPY` command
  - special `COPY` mode; context is one table
  - reads line-by-line, treats each line as tuple
  - inserts tuples into table; at end, checks constraints

PostgreSQL Data Types

Data types defined in `*.h` files under `src/include/`

Two important data types: **`Node`** and **`List`**

- `Node` provides generic structure for nodes
  - defined in `src/include/nodes/nodes.h`
  - specific node types defined in `src/include/nodes/*.h`
  - functions on nodes defined in `src/backend/nodes/*.c`
  - `Node` types: parse trees, plan trees, execution trees, ...
- `List` provides generic singly-linked list
  - defined in `src/include/nodes/pg_list.h`
  - functions on lists defined in `src/backend/nodes/list.c`

PostgreSQL Query Evaluation

`exec_simple_query(const char *query_string)`

- defined in `src/backend/tcop/postgres.c`
- entry point for evaluating SQL queries
- assumes `query_string` is one or more SQL statements

- performs much setting up/initialisation
- parses the SQL string (into one or more parse trees)
- for each parsed query ...
  - perform any rule-based rewriting
  - produces an evaluation plan (optimisation)
  - execute the plan, sending tuples to client

... PostgreSQL Query Evaluation

`pg_parse_query(char *sqlStatements)`

- defined in `src/backend/tcop/postgres.c`
- returns list of parse trees, one for each SQL statement

`pg_analyze_and_rewrite(Node *parsetree, ...)`

- defined in `src/backend/tcop/postgres.c`
- converts parsed queries into form suitable for planning

... PostgreSQL Query Evaluation

Each query is represented by a **`Query`** structure

- defined in `src/include/nodes/parsenodes.h`
- holds all components of the SQL query, including
  - required columns as list of `TargetEntry`s
  - referenced tables as list of `RangeTblEntry`s
  - `where` clause as node in `FromExpr` struct
  - sorting requirements as list of `SortGroupClause`s
- queries may be nested, so forms a tree structure

... PostgreSQL Query Evaluation

`pg_plan_queries(querytree_list, ...)`

- defined in `src/backend/tcop/postgres.c`
- converts analyzed queries into executable "statements"
- uses `pg_plan_query()` to plan each `Query`
  - defined in `src/backend/tcop/postgres.c`
- uses `planner()` to actually do the planning
  - defined in `optimizer/plan/planner.c`

... PostgreSQL Query Evaluation

Each executable query is represented by a **`PlannedStmt`** node

- defined in `src/include/nodes/plannodes.h`
- contains information for execution of query, e.g.
  - which relations are involved, output tuple struecture, etc.
- most important component is a tree of **`Plan`** nodes

Each `Plan` node represents one relational operation

- types: `SeqScan`, `IndexScan`, `HashJoin`, `Sort`, ...
- each `Plan` node also contains cost estimates for operation

... PostgreSQL Query Evaluation

`PlannedStmt *planner(Query *parse, ...)`

- defined in `optimizer/plan/planner.c`
- `subquery_planner()` performs standard transformations
  - e.g. push selection and projection down the tree
- then invokes a cost-based optimiser:
  - choose possible plan (execution order for operations)
  - choose physical operations for this plan
  - estimate cost of this plan (using DB statistics)
  - do this for *sufficient* cases and pick cheapest

... PostgreSQL Query Evaluation

Queries run in a **`Portal`** environment containing

- the planned statement(s) (trees of `Plan` nodes)
- run-time versions of `Plan` nodes (under `QueryDesc`)
- description of result tuples (under `TupleDesc`)
- overall state of scan through result tuples (e.g. `atStart`)
- other context information (transaction, memory, ...)

`Portal` defined in `src/include/utils/portal.h`

`PortalRun()` function also requires

- destination for query results (e.g. connection to client)
- scan direction (forward or backward)

... PostgreSQL Query Evaluation

How query evaluation happens in `exec_simple_query()`:

- parse, rewrite and plan ⇒ `PlannedStmts`
- for each `PlannedStmt` ...
- create `Portal` structure
- then insert `PlannedStmt` into `portal`
- then set up `CommandDest` to receive results
- then invoke `PortalRun(portal,...,dest,...)`
- `PortalRun...()` invokes `ProcessQuery(plan,...)`
- `ProcessQuery()` makes `QueryDesc` from `plan`
- then invoke `ExecutorRun(qdesc,...)`
- `ExecutorRun()` invokes `ExecutePlan()` to generate result
