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COMP9315 Week 01

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COMP9315 25T1
DBMS Implementation

(Data structures and algorithms inside relational DBMSs)

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

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

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❖ Things To Note

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❖ PostgreSQL

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❖ 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

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❖ User View of PostgreSQL

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

```
$ psql webcms
psql (15.11)
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"] ... }
```

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❖ PostgreSQL Functionality

PostgreSQL systems deal with various kinds of objects:

- 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

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❖ PostgreSQL Functionality (cont)

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

- attributes containing arrays of atomic values

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

- table type inheritance

```
create table S ( x float, y float );
create table T inherits ( R, S );    T(id,a,x,y)
```

- table-valued functions

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

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❖ PostgreSQL Functionality (cont)

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

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❖ PostgreSQL Functionality (cont)

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');
```

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❖ PostgreSQL Functionality (cont)

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:

- need to check "existence" of each tuple in transaction
- extra storage for old versions of tuples (`vacuum` fixes this)

PostgreSQL also provides locking to enforce critical concurrency.

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❖ PostgreSQL Functionality (cont)

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

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❖ Catalogs

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❖ 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 can have OIDs).

How are the different types of objects represented?

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

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❖ 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`

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❖ Catalogs (cont)

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’;
```

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❖ Catalogs (cont)

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`)

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❖ Catalogs (cont)

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

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❖ Catalogs (cont)

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

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❖ Catalogs (cont)

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.

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❖ Representing Databases (cont)

`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
```

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❖ 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, ...`

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❖ Representing Tables (cont)

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, ...`

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❖ Exercise: 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.

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❖ Exercise: 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)
...
```

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❖ Exercise: 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?

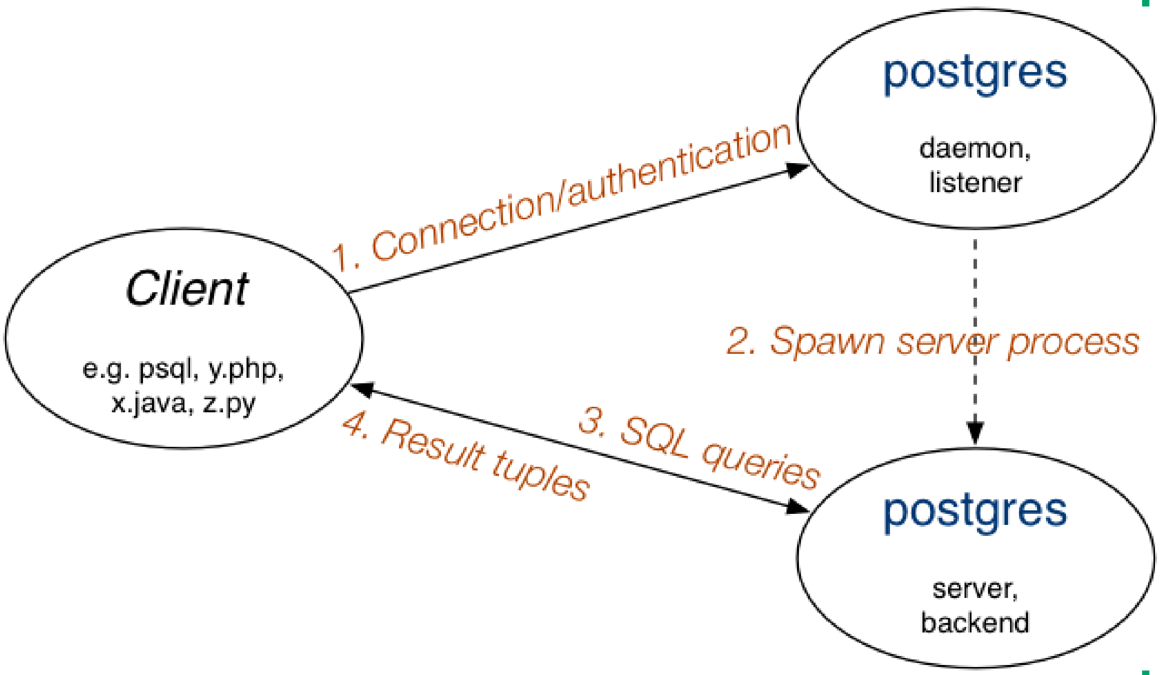
Hint:

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

❖ PostgreSQL Architecture

❖ PostgreSQL Architecture

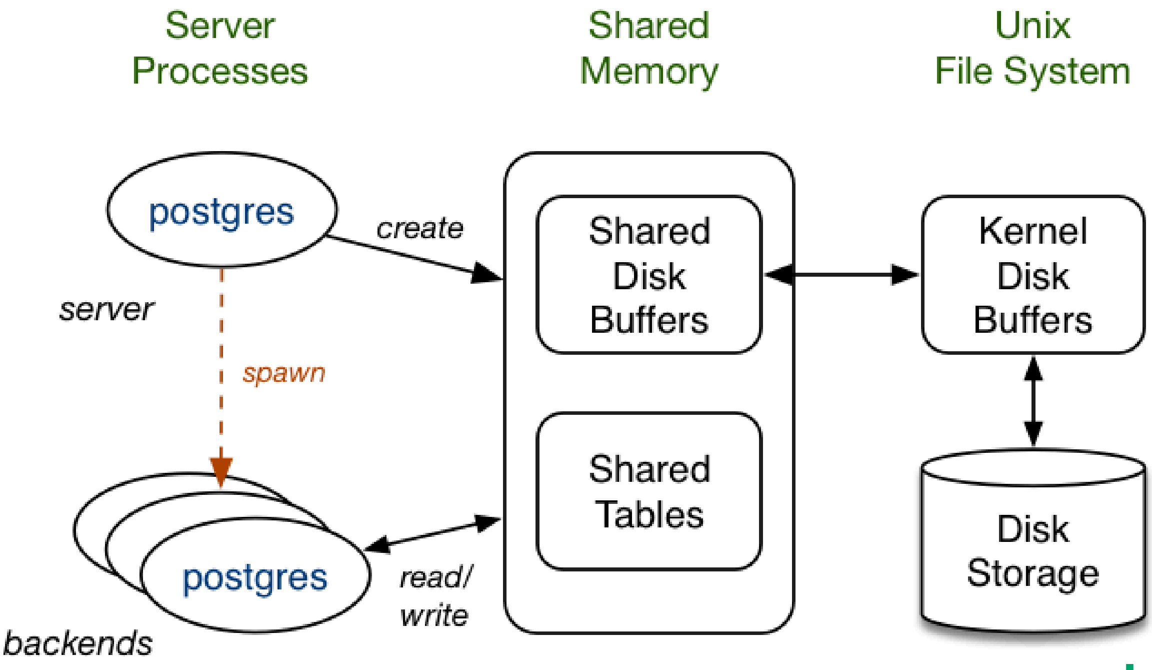
Client/server architecture:



The listener process is sometimes called `postmaster`

❖ PostgreSQL Architecture (cont)

Memory/storage architecture:



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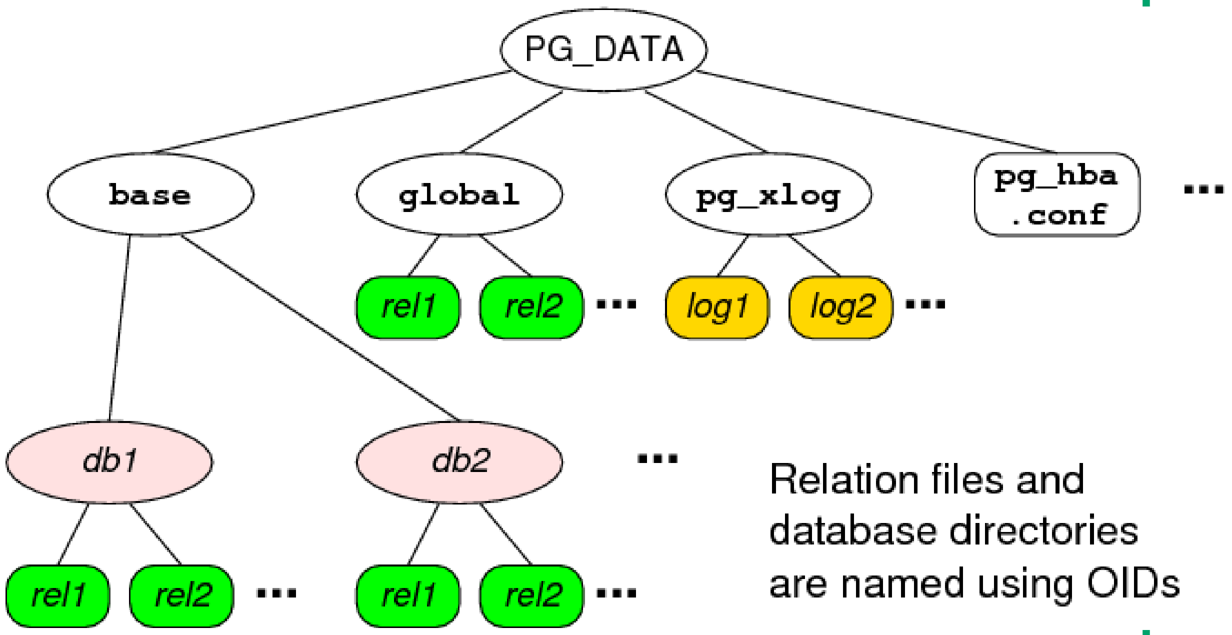
❖ PostgreSQL Architecture (cont)

File-system architecture:



Relation files and database directories are named using OIDs

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❖ Exercise: 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 `beer` database
- the data files for the `Beers` and `Breweries` tables

Relevant catalog info ...

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

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❖ 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

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❖ PostgreSQL Source Code (cont)

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)

- ~2200 files (~1200.c, ~1000.h, 9.y, 11.l), ~10^6 lines of code

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❖ PostgreSQL Source Code (cont)

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 Doco link on web site
- Readings link on web site

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❖ PostgreSQL Source Code (cont)

PostgreSQL documentation has detailed description of internals:

- Section VII, Chapters 52 - 76
- Ch.52 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`

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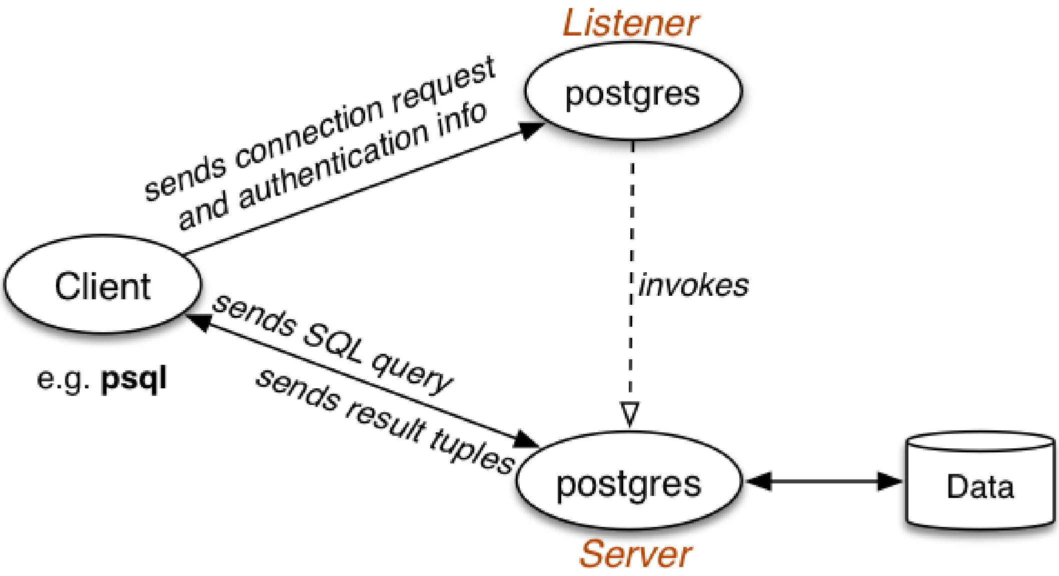
❖ Life-cycle of a PostgreSQL query

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

❖ Life-cycle of a PostgreSQL query (cont)

Data flow to get to execute a query:



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❖ 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

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❖ PostgreSQL server (cont)

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

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❖ 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`

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❖ 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

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❖ PostgreSQL Query Evaluation (cont)

```
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

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❖ PostgreSQL Query Evaluation (cont)

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

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❖ PostgreSQL Query Evaluation (cont)

`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`

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❖ PostgreSQL Query Evaluation (cont)

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 structure, 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

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❖ PostgreSQL Query Evaluation (cont)

`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

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❖ PostgreSQL Query Evaluation (cont)

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)

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❖ PostgreSQL Query Evaluation (cont)

How query evaluation happens in `exec_simple_query()`:

- parse, rewrite and plan ⇒ `PlannedStmt`s
- 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

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