Introduction to Hacking PostgreSQL

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Outline

1. Development environment
2. Architecture of PostgreSQL
3. Backend conventions and infrastructure
4. How to submit a patch
5. Example patch: adding `WHEN` qualification to triggers

Part 1: Development Environment

- Most of the Postgres developers use Unix; you probably should too
- You'll need to know C
  - Fortunately, C is easy
- Unix systems programming knowledge is helpful, depending on what you want to work on
- Learning to understand how a complex system functions is a skill in itself ("code reading")

Development Tools

- Basics: $CC, Bison, Flex, CVS, autotools, gdb
  - Configure flags: `enable-depend`, `enable-debug`, `enable-cassert`
  - Consider `CFLAGS=-O0` for easier debugging, but this suppresses some classes of warnings
- `tags` or `cscope` are essential
  - "What is the definition of this function/type?"
  - "What are all the call-sites of this function?"
  - `src/tools/make_[ce]tags`
- `ccache` and `distcc` are useful, especially on slower machines
- `valgrind` can be useful for debugging memory errors

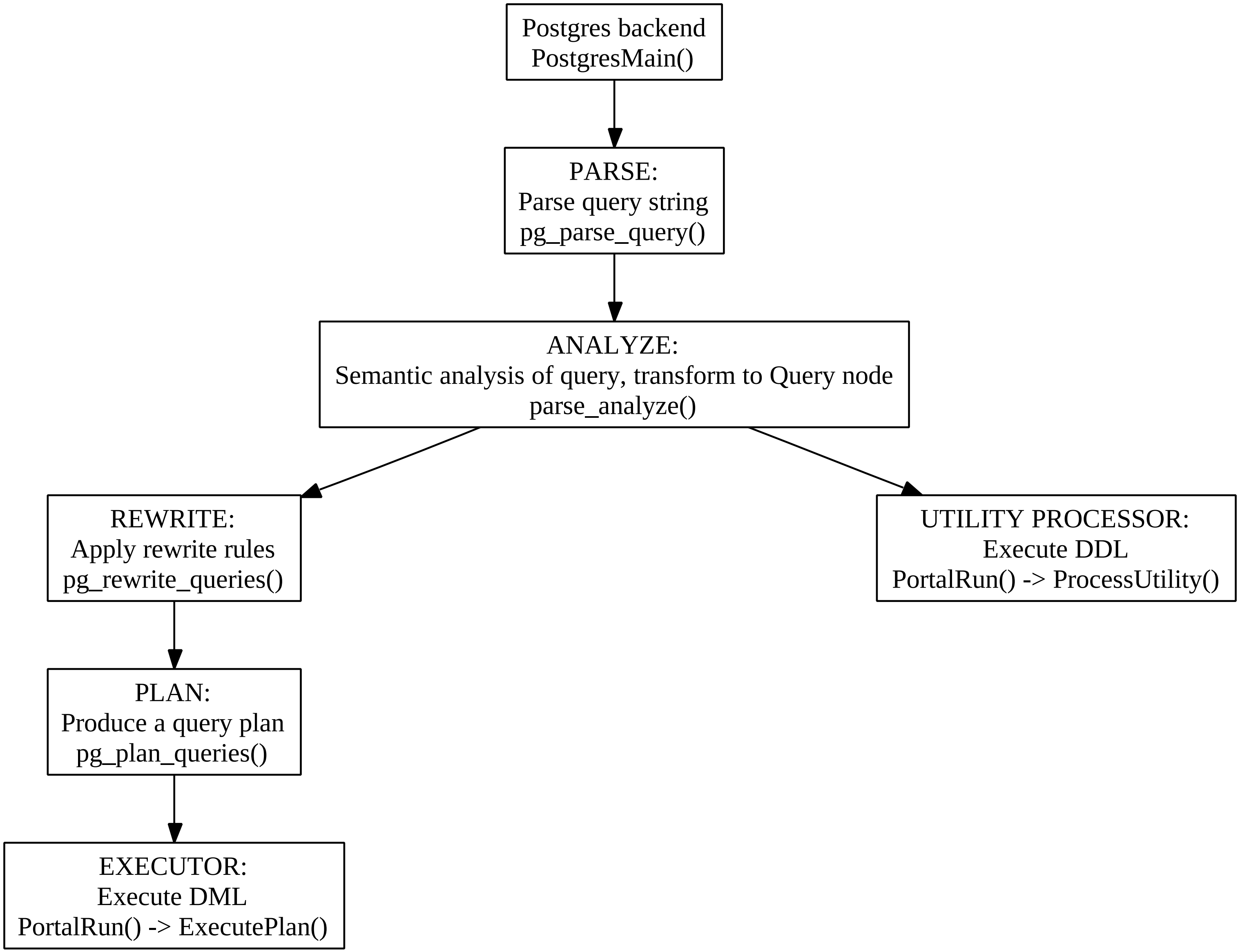
Text Editor

- If you're not using a good programmer's text editor, start
- Teach your editor to obey the Postgres coding conventions:
  - Hard tabs, with a tab width of 4 spaces
  - Similar to Allman/BSD style; just copy the surrounding code
- Using the Postgres coding conventions makes it more likely that your patch will be promptly reviewed and applied

Part 2: PostgreSQL Architecture

- Five main components:
  1. The **parser** - parse the query string
  2. The **rewriter** - apply rewrite rules
  3. The **optimizer** - determine an efficient query plan
  4. The **executor** - execute a query plan
  5. The **utility processor** - process DDL like `CREATE TABLE`

Architecture Diagram



The Parser

- Lex and parse the query string submitted by the user
  - `parser/gram.y` has the guts; entry point is `parser/parser.c`
- Produces a “raw parsetree”: a linked list of parse nodes
  - Parse nodes are defined in `include/nodes/parsenodes.h`
- There is usually a simple mapping between grammar productions and parse node structure

Semantic Analysis

- In the parser itself, only syntactic analysis is done; basic semantic checks are done in a subsequent "analysis phase"
  - `parser/analyze.c` and related code under `parser/`
- Resolve column references, considering schema path and query context
  - ```
    SELECT a, b, c FROM t1, t2, x.t3
      WHERE x IN (SELECT t1 FROM b)
    ```
- Verify that target schemas, tables and columns exist
- Check that the types used in expressions are consistent
- In general, check for errors that are impossible or difficult to detect in the parser itself
    ```

Rewriter, Planner

- The analysis phase produces a `Query`, which is the query's parse tree
- The rewriter applies rewrite rules: view definitions and ordinary rules. Input is a `Query`, output is zero or more `Querys`
- The planner takes a `Query` and produces a `Plan`, which encodes how the query ought to be executed
  - Only needed for "optimizable" statements (`INSERT`, `DELETE`, `SELECT`, `UPDATE`)

Executor, Utility Processor

- DDL statements are “executed” via the utility processor, which basically just calls the appropriate function for each different kind of DDL statement
  - `processUtility()` in `tcop/utility.c`; the implementation of the DDL statements is in `commands/`
- Optimizeable statements are processed via the Executor: given a `Plan`, it executes the plan and produces any resulting tuples
  - `executor/`; entry point is in `execMain.c`

Part 3: Common Idioms: Nodes

- Postgres uses a very simple object system with support for single inheritance. The root of the class hierarchy is `Node`:

```
typedef struct         typedef struct              typedef struct
{                      {                           {
    NodeTag type;          NodeTag   type;             Parent parent;
} Node;                    int       a_field;          int    b_field;
                       } Parent;                   } Child;
```

- This relies on a C trick: you can treat a `Child *` like a `Parent *` since their initial fields are the same
- The first field of *any* `Node` is a `NodeTag`, which can be used to determine a `Node`'s specific type at runtime

Nodes, Cont.

- Create a new `Node`: `makeNode()`
- Run-time type testing via the `IsA()` macro
- Test if two nodes are equal: `equal()`
- Deep copy a node: `copyObject()`
- Serialise a node to text: `nodeToString()`
- Deserialise a node from text: `stringToNode()`

Nodes: Hints

- *When you modify a node or add a new node, remember to update*
  - `nodes/equalfuncs.c`
  - `nodes/copyfuncs.c`
- You may have to update `nodes/outfuncs.c` if your `Node` is to be serialised/deserialised
- Grepping for references to the node's type can be helpful to make sure you don't forget to update anything

Memory Management

- Postgres uses hierarchical, region-based memory management, and it absolutely rocks
  - `backend/util/mmgr`
- Memory is allocated via `palloc()`
- All allocations occur inside a *memory context*
- Default memory context: `CurrentMemoryContext`

Memory Management, cont.

- Allocations can be freed individually via `pfree()`
- When a memory context is reset, all allocations in the context are released
  - Resetting contexts is both faster and less error-prone than releasing individual allocations
- Contexts are arranged in a tree; deleting/resetting a context deletes/resets its child contexts

Memory Management Conventions

- You should *sometimes* `pfree()` your allocations
  - If the context of allocation is known to be short-lived, don't bother with `pfree()`
  - If the code might be invoked in an arbitrary memory context (e.g. utility functions), you should `pfree()`
- The exact rules are a bit hazy
- Be aware of the memory allocation assumptions made by functions you call
- Memory leaks, *per se*, are rare in the backend
  - All memory is released eventually
  - A "leak" is when memory is allocated in a too-long-lived memory context: e.g. allocating some per-tuple resource in a per-txn context

Error Handling

- Most errors reported by `ereport()` or `elog()`
  - `ereport()` is for user-visible errors, and allows more fields to be specified (SQLSTATE, detail, hint, etc.)
- Implemented via `longjmp(3)`; conceptually similar to exceptions in other languages
  - `elog(ERROR)` walks back up the stack to the closest error handling block; that block can either handle the error or re-throw it
  - The top-level error handler aborts the current transaction and resets the transaction's memory context
    - Releases all resources held by the transaction, including files, locks, memory, and buffer pins

Error Handling, Cont.

- Custom error handlers can be defined via `PG_TRY()`
- Think about error handling!
  - *Never* ignore the return values of system calls
- Should your function return an error code, or `ereport()` on failure?
  - Probably `ereport()` to save callers the trouble of checking for failure
  - *Unless* they can provide a better (more descriptive) error message, or they might not consider the failure to be an actual error
- Use assertions (`Assert`) liberally to detect programming errors, but *never* errors the user might encounter

Part 4: Your First Patch

- *Step 1:* Research and preparation
  - Is your new feature actually useful? Does it just scratch your itch, or is it of general value?
  - Does it need to be implemented in the backend, or can it live in pgfoundry, `contrib/`, or elsewhere?
  - Does the SQL standard define similar or equivalent functionality?
    - What about Oracle, DB2, . . . ?
  - Has someone suggested this idea in the past?
    - Search the archives and TODO list
  - Most ideas are bad

Sending A Proposal

- *Step 2:* Send a proposal for your feature to `pgsql-hackers`
  - Patches that appear without prior discussion risk wasting your time
- Discuss your proposed syntax and behavior
  - Consider corner cases, and how the feature will relate to other parts of PostgreSQL (consistency is good)
  - Will any system catalog changes be needed?
  - Backward-compatibility?
- Try to reach a consensus with `-hackers` on how the feature ought to behave

Implementation

- *Step 3:* Implement the patch
  - A general strategy is to look at how similar parts of the system function
    - *Don't copy and paste* (IMHO)
      - Common source of errors
    - Instead, read through similar sections of code to try to understand how they work, and the APIs they are using
    - Implement (just) what you need, refactoring the existed APIs if required
  - Ask for implementation advice as needed (`-hackers` or IRC)
  - Consider posting work-in-progress versions of the patch

Testing, Documentation

- *Step 4:* Update tools
  - For example, if you've modified DDL syntax, update `psql`'s tab completion
  - Add `pg_dump` support if necessary
- *Step 5:* Testing
  - Make sure the existing regression tests don't fail
  - *No compiler warnings*
  - Add new regression tests for the new feature
- *Step 6:* Update documentation
  - `make check` in `doc/src/sgml` does a syntax check that is faster than building the whole SGML docs
  - Check documentation changes visually in a browser

Submitting The Patch

- *Step 7:* Submit the patch
  - Use context diff format: `diff -c`
  - Review *every* hunk of the patch
    - Is this hunk necessary?
    - Does it needlessly change whitespace or existing code?
    - Does it have any errors? Does it fail in corner cases? Is there a more elegant way to do this?
  - Work with a code reviewer to make any necessary changes
  - If your patch falls through the cracks, *be persistent*
    - The developers are busy and reviewing patches is difficult, time-consuming, and unglamorous work

Part 5: WHEN Clause

- We'll be walking you through the implementation of the `WHEN` clause for `CREATE TRIGGER`
  - You can see a patch at
    `http://neilconway.org/talks/hacking/when_clause.patch`
- Defined by SQL:2003, implemented by Oracle and others
- Optional clause; when the `WHEN` expression evaluates to `false` (or NULL), the associated trigger is not fired
- In the `WHEN` clause, `OLD` and `NEW` tuples can be referenced:
  - In `UPDATE` and `DELETE` triggers, `OLD` is the tuple being replaced
  - In `UPDATE` and `INSERT` triggers, `NEW` is the tuple being added

WHEN Clause Considerations

- Syntax is easy: defined by SQL spec

```
CREATE TRIGGER name { BEFORE | AFTER } { event [ OR ... ] }
    ON table [ FOR [ EACH ] { ROW | STATEMENT } ]
        [ WHEN ( expr ) ]
    EXECUTE PROCEDURE funcname ( arguments )
```

`WHEN` Clause Considerations, cont.

- Behavioral questions:
  - Should we allow `WHEN` clause for statement-level triggers? (SQL spec doesn't specify)
  - What subset of SQL should we allow? Aggregate functions, subqueries, . . . ?
- No backward-compat concerns
- Obviously needs to be in the backend
- Useful for at least SQL-spec compliance

Implementation Outline

1. Add support for the new syntax to the parser
2. Update the `CREATE TRIGGER` parsenode
3. Add support for `WHEN` clause to analysis phase
4. Add new field to `pg_trigger` system catalog, containing the `WHEN` clause
5. Modify implementation of `CREATE TRIGGER` to add the `WHEN` clause to the new `pg_trigger` row
6. Add support for the `WHEN` clause when firing triggers in the executor (most of the difficulty is here)
7. Update `pg_dump`/`psql` to support the `WHEN` clause

Parser Changes

- Trivial, as it turns out — see page 1

```
CreateTrigStmt:
            CREATE TRIGGER name TriggerActionTime TriggerEvents ON
            qualified_name TriggerForSpec TriggerWhen EXECUTE PROCEDURE
            func_name '(' TriggerFuncArgs ')'
{
    CreateTrigStmt *n = makeNode(CreateTrigStmt);
    /* ... */
    n->when = $10;
    $$ = (Node *) n;
}

TriggerWhen:
          WHEN '(' a_expr ')'                { $$ = $3; }
          | /*EMPTY*/                        { $$ = NULL; }
```

Parsenode Changes

- The definition of the `CreateTrigStmt` parse node is closely derived from the syntax of `CREATE TRIGGER`
- Add a new field to the struct to stash the `WHEN` clause
- Be sure to update `equalfuncs.c` and `copyfuncs.c`
- See pages 2 and 3 of handout
- *Next*: update the analysis phase. How do we parse `WHEN` clauses like `OLD.a <> NEW.a`?

Expressions In Postgres

- The `WHEN` clause is a boolean expression
- An expression is a tree of `Expr` nodes
  - There are `Expr` subclasses for the different kinds of expressions: function calls, operator invocations, constants, variables, etc.
- `ExecEvalExpr()` evaluates an expression by recursing through this tree. For example:
  - A function is evaluated by first evaluating its arguments, then calling the function itself
  - A constant value is trivial to evaluate
- See pages 4 and 5 of handout

Variable Expressions

- In an expression like $t.a > 10$, $t.a$ is a *range variable*, colloquially known as a table column
  - Represented by the `Var` expression type
- How are range variables implemented?
  - `Var.varno` identifies the variable's table (t above)
  - `Var.varattno` is the attribute number of the variable's column
- `varno` is an index into the expression's *range table*
  - The range table is the set of relations that can be referenced in expressions — each `Query` has an associated range table

Analysis Phase

- The analysis phase is where we lookup identifiers; therefore, during the analysis phase, we need to add range table entries for the `NEW` and `OLD` relations
- Other analysis phase work is straightforward:
  - Exclusive-lock the target relation
  - Disallow subqueries and aggregates in the `WHEN` clause
- See pages 4 through 6 of the handout

System Catalogs

- The format of the system catalogs is defined by header files, in the `src/include/catalog` directory
  - These files are normal C headers, with some special macros
  - These macros are pre-processed for bootstrapping (`initdb`)
- Nice effect: access to system catalog fields is the same as accessing a C `struct`
- A compiled copy of the backend depends upon the exact definition of the system catalogs
  - If you modify the system catalog format, bump the catalog version to force `initdb`
- See pages 6 and 7

System Catalog Changes

- Triggers are stored in the `pg_trigger` catalog
- To add support for `WHEN`, we add a new field to `FormData_pg_trigger` in `pg_trigger.h`
- Add `tgqual` field, which stores a serialized version of the `WHEN` expression tree
  - Review: `nodeToString()` serializes a `Node`
  - We can use `stringToNode()` to reconstruct the expression tree when needed

`CREATE TRIGGER` Changes

- `CREATE TRIGGER` needs to store the textual representation of the `WHEN` clause in the new row it inserts into `pg_trigger`
- Also reject `WHEN` clause for statement-level triggers here
- Also create a dependency between the elements of the `WHEN` expression and the trigger
  - If the `WHEN` clause references column a of the table, `DROP COLUMN a` should be disallowed (without cascade)
- See page 7

`TriggerDesc` Updates

- The `Relation` struct contains metadata about an opened relation: the relation's `pg_class` row, a description of the format of its tuples, associated indexes, associated triggers, etc.
  - Stored in the *relcache*
- See pages 3 and 4

`TriggerDesc` Updates, cont.

- Trigger information is stored in a subsidiary struct, `TriggerDesc`, which itself contains a `Trigger` struct for each trigger on the relation
  - Add a field to `Trigger` to store the `WHEN` clause
  - Fill it in when `TriggerDesc` constructed
- Remember to update support functions!
  - `FreeTriggerDesc()`, `CopyTriggerDesc()`, `equalTriggerDescs()`

Executor Changes

- The guts of the required changes are in the executor
- We need to evaluate the `WHEN` clause before we fire a row-level trigger
- To do that, we need to:
  - Preprocess the `WHEN` clause to get it ready to be evaluated
  - Teach the executor to be able to evaluate expressions referencing the `NEW` and `OLD` relations
- See pages 8 through 10

OLD and NEW in Executor

- Review: `ExecEvalExpr()` evaluates expression trees
- To do so, it uses an `ExprContext`
  - All info needed to evaluate an expression
  - To evaluate an expression, you find an appropriate `ExprContext`, setup the necessary information, then use `ExecEvalExpr()`
    - The executor keeps a “per-tuple `ExprContext`” that we can use: it is reset for each tuple that is output
- See pages 10 and 11

Evaluating Variable Expressions

`ExecEvalVar()` is called by `ExecEvalExpr()` to evaluate `Var` expressions:

```
switch (variable->varno)
{
    case INNER: /* get the tuple from the inner node */
        slot = econtext->ecxt_innertuple;
        break;

    case OUTER: /* get the tuple from the outer node */
        slot = econtext->ecxt_outertuple;
        break;

    default:    /* get the tuple from the relation being scanned */
        slot = econtext->ecxt_scantuple;
        break;
}
```

Evaluating Variables

- Note that the `varno` is ignored, except for the special `INNER` and `OUTER` varnos
  - The code assumes that the caller will insert the current tuple into the `ExprContext`'s "scan tuple" slot before calling `ExecEvalExpr`
- This won't work for us: the `WHEN` expression could reference *two* different tuples (`OLD` and `NEW`)
- How can we solve this?

Solution

- Add two more special varnos, `TRIG_OLD_VARNO` and `TRIG_NEW_VARNO`
- In the analysis phase, rewrite the varnos in the expression so that references to the special relations are assigned the right varno
  - Machinery for this exists: `ChangeVarNodes` walks an expression tree, changing varno $x \rightarrow y$ in every node of the tree
- Add two new slots to `ExprContext` to hold the `OLD` and `NEW` tuples, and setup these slots before calling `ExecEvalExpr`
- In `ExecEvalVar`, add two more special-cases for the two special varnos, fetching from the appropriate slots of the `ExprContext`

Checking The Qualification

- Before firing triggers, check the `WHEN` clause
- For `BEFORE` triggers, this is easy. Add code to invoke `ExecQual()` to:
  - `ExecBRDeleteTriggers()`
  - `ExecBRInsertTriggers()`
  - `ExecBRUpdateTriggers()`
- Use the current executor instance to get per-tuple `ExprContext`; try to avoid overhead by preparing `WHEN` expression the first time the trigger is fired for this command
- See page 10

AFTER Trigger Support

- Unfortunately, supporting `AFTER` triggers is not so easy
- `AfterTriggerSaveEvent()` enqueues a trigger to be invoked later, such as at the end of the current query
- We *can't* check the `WHEN` condition here
- Instead, we need to check the `WHEN` condition when the saved events are fired — but we won't necessarily have an executor instance to use!
    - Should just be a Small Matter of Programming

Subqueries in `WHEN` clause

- Subqueries in the `WHEN` clause would be convenient
- Unfortunately, they're hard to implement
- We'd have to run the full-fledged query planner on the expression
- Postgres has the infrastructure to do this, it's just a matter of using it
- All the other code we've written is prepared to handle subqueries

`psql` Support

- psql's `\d` command includes the definitions of the triggers on a table. How do we get it to include the `WHEN` clause?
- psql gets trigger definitions by calling the backend function `pg_get_triggerdef()`, so we need to update it
- There is already machinery for pretty-printing expressions as SQL text, so we can reuse all that
- One hurdle: `tgqual` may contain the special `TRIG_OLD_VARNO` and `TRIG_NEW_VARNO` varnos, which the expression printing code doesn't understand
  - Quick hack: use `ChangeVarNodes()` to switch back to original varnos
- See pages 11 and 12

pg_dump Support

- We need to update `pg_dump` to dump `WHEN` clause
- `pg_dump` reconstructs the `CREATE TRIGGER` command for a trigger by examining the trigger's `pg_trigger` row
- For `WHEN`, this isn't so easy:
  - `tgqual` references `TG_OLD_VARNO` and `TG_NEW_VARNO`, so there is no easy way to reconstruct `tgqual` in a client app
- Change `pg_dump` to use `pg_get_triggerdef()` to send a fully-formed `CREATE TRIGGER` to the client
- See pages 11 and 12

Regression Tests

- Invoked by `make check`
- Run out of `src/test/regress`
- Put tests in `sql/triggers.sql`
- Reflect changes in `expected/triggers.out`
- See page 12

Documentation

- Documentation is in DocBook SGML
- Located in `docs/src/sgml`
- SQL command reference in `ref/create_trigger.sgml`
- Be sure to add an example
- See page 12 and 13

TODO Items

- As implemented, the patch has some deficiencies:
  - No support for `AFTER` triggers
  - No support for subqueries in the `WHEN` clause
  - Leaks the `when` field in `FreeTriggerDesc()`
  - `setup_trigger_quals()` does some redundant work