JITing PostgreSQL using LLVM

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anarazel.de/talks/fosdem-2018-02-03/jit.pdf

TPC-H Q01

```
SELECT
    l_returnflag,
    l_linestatus,
    sum(l_quantity) AS sum_qty,
    sum(l_extendedprice) AS sum_base_price,
    sum(l_extendedprice * (1 - l_discount)) AS sum_disc_price,
    sum(l_extendedprice * (1 - l_discount) * (1 + l_tax)) AS sum_charge,
    avg(l_quantity) AS avg_qty,
    avg(l_extendedprice) AS avg_price,
    avg(l_discount) AS avg_disc,
    count(*) AS count_order
FROM lineitem
WHERE l_shipdate <= date '1998-12-01' - interval '74 days'
GROUP BY l_returnflag, l_linestatus
ORDER BY l_returnflag, l_linestatus;
```

```
Samples: 87K of event 'cycles:ppp', cnt (approx.): 71706618234
  Overhead  Command   Shared Object      Symbol
-   35.96%  postgres  postgres           [.] ExecInterpExpr
      + 72.86% ExecAgg
      - 18.33% tuplehash_insert
           LookupTupleHashEntry
           ExecAgg
           ExecSort
      + 8.81% ExecScan
-   10.79%  postgres  postgres           [.] slot_deform_tuple
        slot_getsomeattrs
      - ExecInterpExpr
         + 77.31% ExecScan
         + 22.69% tuplehash_insert
+   10.66%  postgres  postgres           [.] slot_getsomeattrs
+    4.96%  postgres  postgres           [.] tuplehash_insert
+    4.53%  postgres  postgres           [.] float8_accum
+    3.21%  postgres  postgres           [.] float8pl
+    2.61%  postgres  postgres           [.] bpchareq
+    2.40%  postgres  postgres           [.] hashbpchar
```

What is “Just In Time” compilation

- Convert forms of “interpreted” code into native code
- Specialize code for specific constant arguments
- Achieve speedups via:
  - reduced total number of instructions
  - reduced number of branches
  - reduced number of indirect jumps / calls
- Well known from browsers for javascripts, java VMs and the like

Methods of JITing considered

- Emit C code, invoke compiler, generate shared object, dlopen()
  - requires a lot of forking
  - requires C compiler
  - doesn’t easily allow inlining
- Directly emit machine language, remap memory executable
  - fastest to emit
  - no optimization (including inlining)
  - lots of per-architecture work
  - very few people want / able to maintain
  - fun
- Use compiler / optimizer framework with JIT support
  - issues around licensing, portability, maturity
  - JIT often not most common user
- => LLVM

LLVM

- Compiler Framework
- Intermediate Representation
  - can be generated for C code using clang!
- Optimizations
- JIT Support
- https://llvm.org/
- Used among my others by
  - clang C, C++ compiler
  - swift
  - rust
  - ...

Postgres LLVM usage

- C vs. C++
- LLVM usage in shared library
  - can be installed separate from main postgres package
  - C++ usage encapsulated
- Error handling
- Emissions of JITed functions batched
- Type syncing
- Inlining Support

LLVM and errors

- LLVM is not exception safe (with some exceptions)
- Many errors returned to callers
- Out of memory is **not** reported to callers
- Postgres treats out of memory as a transient condition
- LLVM has OOM / error handler callbacks – which cannot abort in non-fatal manner
  - `llvm::install_fatal_error_handler`
  - `llvm::install_bad_alloc_error_handler`
- Lots of allocation errors outside above callbacks (via c++ NEW)
  - std::set_new_handler
- PostgreSQL API

```
extern void llvm_enter_fatal_on_oom(void);
extern void llvm_leave_fatal_on_oom(void);

extern void llvm_assert_in_fatal_section(void);
extern void llvm_reset_fatal_on_oom(void);
```

- IOW out of memory in LLVM results in a FATAL error (cancelled connection)
- Memory usage usually not that high, especially comparing to typical analytics queries
- Need better solution medium-long term

LLVM and Errors #2

- Most errors are non-FATAL
- generated functions need to be free'd

Emission of functions, batching & deallocation

- Emitting objects has near-constant overhead
- Objects need to be freed at query end
- API:

```
LLVMJitContext *llvm_create_context(int jitFlags);
LLVMModuleRef llvm_mutable_module(LLVMJitContext*);
void *llvm_get_function(ctx, const char *funcname);
```

- Emission of code delayed until `llvm_get_function`
- Context automatically deallocated via ResourceOwner mechanism / query end

v10+ Expression Evaluation Engine

- WHERE a.col < 10 AND a.another = 3
  - EEOP_SCAN_FETCHSOME (deform necessary cols)
  - EEOP_SCAN_VAR (a.col)
  - EEOP_CONST (10)
  - EEOP_FUNCEXPR_STRICT (int4lt)
  - EEOP_BOOL_AND_STEP_FIRST
  - EEOP_SCAN_VAR (a.another)
  - EEOP_CONST (3)
  - EEOP_FUNCEXPR_STRICT (int4eq)
  - EEOP_BOOL_AND_STEP_LAST (AND)
- direct threaded
- lots of indirect jumps

Postgres Function Call Interface

```
typedef struct FunctionCallInfoData
{
    FmgrInfo  *flinfo;          /* ptr to lookup info used for this call */
    fmNodePtr  context;         /* pass info about context of call */
    fmNodePtr  resultinfo;      /* pass or return extra info about result */
    Oid     fncollation;        /* collation for function to use */
    bool        isnull;         /* function must set true if result is NULL
                                  */
    short       nargs;          /* # arguments actually passed */
    Datum       arg[FUNC_MAX_ARGS]; /* Arguments passed to function */
    bool        argnull[FUNC_MAX_ARGS]; /* T if arg[i] is actually NULL */
} FunctionCallInfoData;

#define FunctionCallInvoke(fcinfo) \
    ((* (fcinfo)->flinfo->fn_addr) (fcinfo))
```

```
    EEO_CASE(EEOP_FUNCEXPR_STRICT)
    {
        FunctionCallInfo fcinfo = op->d.func.fcinfo_data;
        bool    *argnull = fcinfo->argnull;
        int             argno;
        Datum           d;

        /* strict function, so check for NULL args */
        for (argno = 0; argno < op->d.func.nargs; argno++) // unnecessary
        {
            if (argnull[argno])
            {
                *op->resnull = true;
                goto strictfail;
            }
        }
        fcinfo->isnull = false; // optimized away
        d = op→d.func.fn_addr(fcinfo); // indirect
        *op->resvalue = d;  // moved to register
        *op->resnull = fcinfo->isnull;

strictfail:
        EEO_NEXT();  // indirect
    }
```

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JITed expressions

- directly emit LLVM IR for common opcodes
- emit calls to functions implementing less common opcodes
  - can be inlined
- indirect opcode → opcode jumps become direct
- indirect funcexpr calls become direct
  - can be inlined
- TPCH Q01 non-jitted vs jitted:
  - 28759 ms vs 22309 ms
  - branch misses: 0.38% vs 0.07%
  - iTLB load misses: 58,903,279 vs 48,986 (yes, really)

```
block.op.2.start:                                 ; preds = %block.op.1.start
  %v_argnullp = getelementptr inbounds %struct.FunctionCallInfoData,
%struct.FunctionCallInfoData* %v_fcinfo, i32 0, i32 7
  store i8 1, i8* %resnullp
  br label %check-null-arg

check-null-arg:                                   ; preds = %block.op.2.start
  %25 = getelementptr inbounds [100 x i8], [100 x i8]* %v_argnullp, i32 0, i32 0
  %26 = load i8, i8* %25
  %27 = icmp eq i8 %26, 1
  br i1 %27, label %block.op.3.start, label %check-null-arg1

check-null-arg1:                                  ; preds = %check-null-arg
  %28 = getelementptr inbounds [100 x i8], [100 x i8]* %v_argnullp, i32 0, i32 1
  %29 = load i8, i8* %28
  %30 = icmp eq i8 %29, 1
  br i1 %30, label %block.op.3.start, label %no-null-args

no-null-args:                                     ; preds = %check-null-arg1
  %v_fcinfo_isnull = getelementptr inbounds %struct.FunctionCallInfoData,
%struct.FunctionCallInfoData* %v_fcinfo, i32 0, i32 4
  store i8 0, i8* %v_fcinfo_isnull
  %funccall = call i64 @date_le_timestamp(%struct.FunctionCallInfoData* %v_fcinfo) #13
  %31 = load i8, i8* %v_fcinfo_isnull
  store i64 %funccall, i64* %resvaluep
  store i8 %31, i8* %resnullp
  br label %block.op.3.start
```

Type Synchronization

- Types like `%struct.FunctionCallInfoData` need to be available to IR / LLVM
- Manual syncing possible – but work intensive, failure prone, unmaintainable
- llvmjit_types.c:

```
…
ExprState StructExprState;
FunctionCallInfoData StructFunctionCallInfoData;
HeapTupleData StructHeapTupleData;
…
```

- clang converts llvmjit_types.c to llvmjit_types.bc at build time
- llvmjit infrastructure loads all known types from llvmjit_types.bc by name
- LLVM's IR doesn't have field names:

```
typedef struct FunctionCallInfoData
{
    …
    #define FIELDNO_FUNCTIONCALLINFODATA_ISNULL 4
    bool   isnull;/* function must set true if result is NULL */
    …
} FunctionCallInfoData;
```

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```
LLVMTypeRef members[8];

members[0] = LLVMPointerType(StructFmgrInfo, 0); /* flinfo */
members[1] = LLVMPointerType(StructPGFinfoRecord, 0); /* context */
members[2] = LLVMPointerType(StructPGFinfoRecord, 0); /* resultinfo */
members[3] = LLVMInt32Type(); /* fncollation */
members[4] = LLVMInt8Type(); /* isnull */
members[5] = LLVMInt16Type(); /* nargs */
members[6] = LLVMArrayType(TypeSizeT, FUNC_MAX_ARGS);
members[7] = LLVMArrayType(LLVMInt8Type(), FUNC_MAX_ARGS);

StructFunctionCallInfoData = LLVMStructCreateNamed(
    LLVMGetGlobalContext(),
    "struct.FunctionCallInfoData");
LLVMStructSetBody(StructFunctionCallInfoData, members,
                  lengthof(members), false);
```

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Tuple Deforming

- Often most significant bottleneck
- TupleDesc (“tuple format”) can be made known at JIT time in many cases
- Optimizable:
  - Number of columns to deform - constant
  - Number of columns in tuple – if to-deform below last NOT NULL
  - column type - constant
  - column width – known for fixed width types
  - Variable alignment requirements – known for fixed width (depending on NULLness)
  - NULL bitmap – no need to check if NOT NULL
- Resulting code often very pipelineable, previously lots of stalls
- Access to tuple’s `t_hoff` / `HeapTupleHeaderGetNatts()` still major source of stalls
- TPC-H Q01: unjitted deform vs jitted
  - time: 22277 ms vs 19580 ms
  - branches: 1396.318 M/sec vs 1161.628M/sec (despite higher throughput)

Inlining

- All operators in postgres are functions! Lots of external function calls
- Postgres function calls are expensive, lots of memory indirection
- Convert sourcecode to bitcode at buildtime, install into

```
$pkglibdir/bitcode/<module>.index.bc
$pkglibdir/bitcode/<module>/path/to/file.bc
```

- LLVM’s cross-module inlining not suitable
  - requires exporting of symbols at compile time, unknown which needed
- Postgres specific inlining logic:
  - build combined summary (via LLVM’s LTO infrastructure)
  - inlining safety check (no mutable static variables referenced)
  - cost analysis
  - inline function, referenced static functions, referenced constant static variables (mainly strings)
  - use `llvm::IRMover` to move relevant globals
  - can’t cache modules in memory, cloning expensive and incomplete
- Allows need to implement direct JIT emission for lots of semi critical code
- Function call interface significantly limits benefits

Planner

- Naive!
- Perform JIT if `query_cost > jit_above_cost`
- Optimize if `query_cost > jit_optimize_above_cost`
- Optimize if `query_cost > jit_above_cost`
- Whole query decision
- *NOT* a tracing JIT:
  - costing makes tracing somewhat superflous
  - tracing decreases overall gains

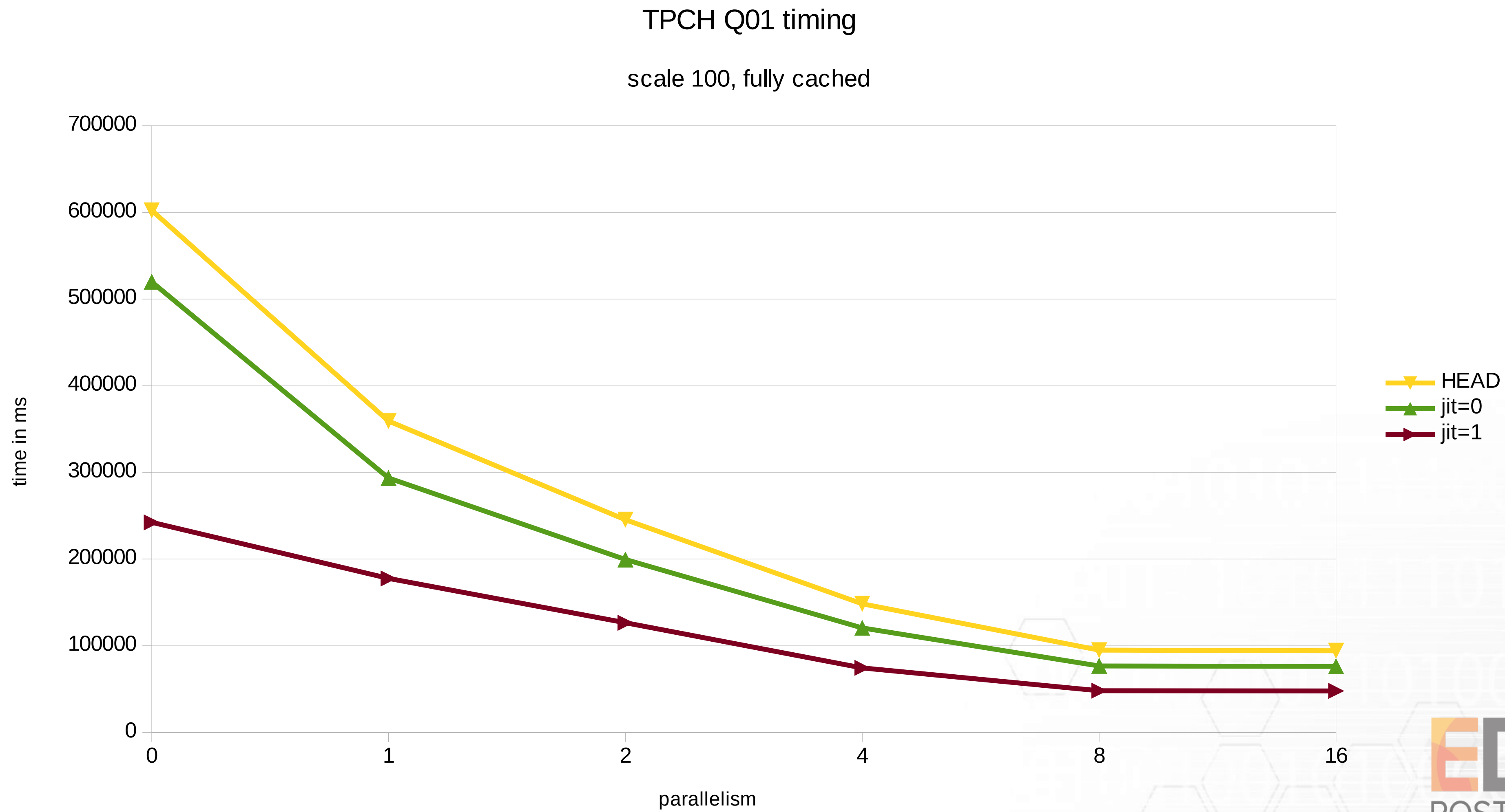
Profiling

- Requires patches to LLVM
- To-be-submitted upstream
- perf record -k 1 -p $pid
- perf inject --jit -i /tmp/perf.data -o /tmp/perf.jit.data
- Issues:
  - function names not great
  - requires session to end to flush profiling data

```
+   10.88%  postgres  perf-6402.map                                   [.] 0x00007f4f7d4c702e
+    7.53%  postgres  postgres                                        [.] tuplehash_insert
...
+    1.10%  postgres  perf-6402.map                                   [.] 0x00007f4f7d4c7053
...
+    0.70%  postgres  perf-6402.map                                   [.] 0x00007f4f7d4c718d
..
+    0.47%  postgres  perf-6402.map                                   [.] 0x00007f4f7d4c90c3
```

```
-   24.75%  postgres  jitted-6402-7.so                   [.] evalexpr.1.7
   - 99.99% evalexpr.1.7
        ExecAgg
-   20.28%  postgres  jitted-6402-4.so                   [.] evalexpr.1.0
     evalexpr.1.0
     ExecScan
     ExecAgg
-   12.73%  postgres  jitted-6402-6.so                   [.] evalexpr.1.4
   - 98.16% evalexpr.1.4
        tuplehash_insert
        LookupTupleHashEntry
        lookup_hash_entries
        ExecAgg
+    7.53%  postgres  postgres                           [.] tuplehash_insert
+    4.93%  postgres  postgres                           [.] heap_getnext
+    3.28%  postgres  postgres                           [.] lookup_hash_entries
+    2.93%  postgres  postgres                           [.] hash_any
```

Faster Execution:
JIT Compilation



JIT Issues – Code Generation

- Expressions refer to permanently allocated memory
  - generated code references memory locations
  - optimizer can't optimize away memory lots of memory references
  - FIX: separate permanent and per eval memory
- Function Call Interface requires persistence
  - **lots** of superflous memory reads/writes for arguments, optimizer can't eliminate in most cases
    - massively reduces benefits of inlining
  - FIX: pass FunctionCallInfoData and FmgrInfo separately to functions
    - remove FunctionCallInfoData->flinfo
    - move context, resultinfo, fncollation to FmgrInfo
    - move isnull field to separate argument? Return struct?
- Expression step results refer to persistent memory
  - move to temporary memory

JIT Issues - Caching

- Optimizer overhead significant
  - TPCH Q01: unopt, noinline: time to optimize: 0.002s, emit: 0.036s
  - TPCH Q01: time to inline: 0.080s, optimize: 0.163s, emit 0.082s
- references to memory locations prevent caching (prev slide)
- Introduce per-backend LRU cache of functions keyed by hash of emitted LRU (plus comparator)
  - relatively easy task
- Allow expressions to be generated at plan time, and tied to a prepared statement
  - medium – hard

JIT Issues – Planning

- Whole Query decision too coarse
  - use estimates about total number of each function evaluation?
- Some expressions guaranteed to only be evaluated once
  - VALUES()
  - SQL functions

Future things to JIT

- Aggregate & Hashjoin hash computation
  - easy
- entire in-memory tuplesort
  - easy
- on-disk tuplesort comparator
  - easy
- COPY input
  - medium
- Whole of Executor
  - wheeee

Future JIT Infastructure

- Perform JIT without optimization in foreground
- Have background worker perform incrementally better optimization in background
- Replace JITed function once finished
- Relocations still need to be performed in backend
- Better error handling
- EXPLAIN (ANALYZE, JIT)?

LLVM Issues

- Error Handling
- C-API isn’t large enough, C++ API changes
- Medium-High level API documentation bad to nonexistent
- Some optimization passes (primarily dead store elimination) not aggressive enough
- Parts of API pointlessly complicated (welcome Error.h)
- My notebook’s battery doesn’t like it

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