DB 2

07 – Expression Evaluation

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1 ┆ Q_6 — Expression Evaluation

For a large class of queries, the **CPU effort to evaluate (complex) expressions** may easily match the time spent for I/O and data access:

```sql
SELECT t.a * 3 - t.a * 2     AS a,
       t.a - power(10, t.c) AS diff,
       ceil(t.c / log(2))   AS bits
FROM   ternary AS t;
```

Iterate over rows t, access required fields (here: t.a, t.c), evaluate (multiple) expressions per row, construct resulting row.

Using EXPLAIN on Q_6: INSERT

```
EXPLAIN VERBOSE
  SELECT t.a * 3 - t.a * 2     AS a,
         t.a - power(10, t.c) AS diff,
         ceil(t.c / log(2))   AS bits
  FROM   ternary AS t;
```

QUERY PLAN

Seq Scan on public.ternary t (cost=0.00..40.00 rows=1000 width=20)
  Output: ((a * 3) - (a * 2)),
          ((a)::double precision - power('10'::double precision, c)),
          ceil((c / '0.301029995663981'::double precision))

- Expressions have been parenthesized, simplified, and annotated with type casts as required by SQL semantics.

Internal Representations of t.a * 3 - t.a * 2

- DBMSs—just like interpreters and compilers—**transform expressions into internal representations** that facilitate simplification and evaluation:

```
        -
      /   \
     *     *
    / \   / \
  t.a  3 t.a  2
```

```
SCAN_FETCHSOME(t, [a])
SCAN_VAR(a)
CONST(3)
FUNCEXPR_STRICT(*, •, •)
SCAN_VAR(a)
CONST(2)
FUNCEXPR_STRICT(*, •, •)
FUNCEXPR_STRICT(-,          •, •)
```

	stack depth
PUSH(t.a)	1
PUSH(3)	2
FUNC(*)	1
PUSH(t.a)	2
PUSH(2)	3
FUNC(*)	2
FUNC(-)	1

- Postorder traversal of expression tree to obtain a linearized “program”. Arg slots (•) or stack push/pop.

Threaded Interpretation

PostgreSQL implements a **threaded interpreter** over linearized expressions (middle column of previous slide):

```
      program[]               dispatch[]          opcode implementations

ip→⟦opc=1, res=◌⟧           1 | ──────────→ SCAN_VAR: …;
   ⟦opc=3, res=◌⟧           2 | ──→ …                 ip = ip + 1;
          ⋮                 3 | ─╮                    goto dispatch[ip->opc];
                              ⋮  │
                                 ╰──────→ CONST:      ip->res = ‹const›;
                                                      ip = ip + 1;
linearized expression    dispatch table               goto dispatch[ip->opc];
```

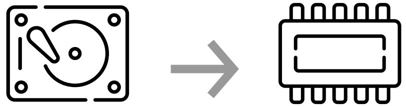
- Note: ip: instruction pointer, opc: operation code.
- Relies on support for *computed goto* (e.g., common in C).

Expression Interpretation Overhead

Overhead of expression interpretation has been found to be **massive** in DBMS (cf. the threaded interpretation vs. machine code for `t.a * 2`).

- Field access and interpretation in *hot query code path*, rediscovers same row structure and follows same opcode pointers for every row processed. Wasteful.
- 💡 Invest in **just-in-time (JIT) compilation** of expression program into machine code once, benefit for all subsequent rows.
    - **N.B.:** LLVM-based support for JIT compilation of expressions being added to PostgreSQL v11 as we speak.

2 ¦ Q_6 — Expression Evaluation



```sql
SELECT t.a * 3 - t.a * 2     AS a,
       t.a - power(10, t.c) AS diff,
       ceil(t.c / log(2))   AS bits
FROM   ternary AS t;
```

MonetDB compiles expressions into sequences of MAL operations. Like data processing, expression evaluation is column-oriented (as opposed to row-by-row).

- We will find that this vector-based evaluation mode fits modern CPU architecture particularly well.

Using EXPLAIN on Q_6: DELETE

```
sql> EXPLAIN SELECT t.a * 3 - t.a * 2 AS a,
             ceil(t.c / log(2)) AS bits
             FROM ternary AS t;
 ⋮
ternary :bat[:oid] := sql.tid(sql, "sys", "ternary");
c0      :bat[:dbl] := sql.bind(sql, "sys", "ternary", "c", 0:int);
c                  := algebra.projection(ternary, c0);
e1      :bat[:dbl] := batcalc./(c, 0.6931471805599453:dbl);
e2      :bat[:dbl] := batmath.ceil(e1);                       ◀ result column bits
a0      :bat[:int] := sql.bind(sql, "sys", "ternary", "a", 0:int);
a                  := algebra.projection(ternary, a0);
e3      :bat[:lng] := batcalc.lng(a);                           ◀ cast to type lng
e4      :bat[:lng] := batcalc.*(e3, 3:bte);
e5      :bat[:lng] := batcalc.*(e3, 2:bte);
e6      :bat[:lng] := batcalc.-(e4, e5);                         ◀ result column a
 ⋮
```

- MAL ops batcalc.⊗ accept two BATs or one BAT + one scalar (like 2:bte, 3:bte, 0.693⋯:dbl ≡ log(2)).

Column-Based “Zip” Semantics

Operators batcalc.⊗ merge the tails of two synchronized BATs using binary operator ⊗, yields a new BAT:

x

head	tail
0@0	x_0
1@0	x_1
2@0	nil
3@0	x_3

→

batcalc.-(**x**,**y**)

head	tail
0@0	$x_0 - y_0$
1@0	$x_1 - y_1$
2@0	nil
3@0	$x_3 - y_3$

←

y

head	tail
0@0	y_0
1@0	y_1
2@0	y_2
3@0	y_3

- batcalc.⊗ contains checks for arithmetic exceptions (overflow, divide by 0). Also: nil ⊗ x = x ⊗ nil = nil.

MAL: Sequential Execution vs. Data Flow

postorder traversal determines evaluation order

```
        1. sequential          |        2. data flow
                               |
             ┌ ❼- ┐            |             ┌ ❸- ┐
            /      \           |            /      \
           |        |          |           |        |
          ❸*        ❻*         |          ❷*        ❷*
         /  \      /  \        |         /  \      /  \
        |    |    |    |       |        |    |    |    |
     ❶t.a   3❷ ❹t.a   2❺       |     ❶t.a   3❶ ❶t.a   2❶
```

data dependencies hint at possible **parallel** evaluation strategy

1. Order of assignment to temporary result BATs e_i follows postorder traversal of expression tree.
2. Spawn CPU threads to evaluate data-independent subexpressions in // (see MonetDB's dataflow optimizer).

batcalc.⊗: Column-Based Operator Implementations (1)

MonetDB supplies type- and ⊗-specific implementations of MAL operations (code generation via C preprocessor macros):

```
/* batcalc.-(left:bat[:lng], right:bat[:lng]):bat[:lng] */

int i, j, k;
int nils = 0;

for (i = start, j = start*1, k = start; k < end; i += 1, j += 1, k += 1) {
  /* nil checking */
  if (is_lng_nil(left[i]) || is_lng_nil(right[j])) {
    result[k] = lng_nil;
    nils++;
  } else {
    /* omitted: overflow checking (abort on error or emit nil) */
    result[k] = left[i] - right[j];
  }
}
```

batcalc.⊗: Column-Based Operator Implementations (2)

MonetDB supplies type- and ⊗-specific implementations of MAL operations (code generation via C preprocessor macros):

```
/* batcalc.-(left:bat[:lng], right:lng):bat[:lng] */

int i, j, k;
int nils = 0;

for (i = start, j = start*0, k = start; k < end; i += 1, j += 0, k += 1) {
  /* nil checking */
  if (is_lng_nil(left[i]) || is_lng_nil(right[j])) {
    result[k] = lng_nil;
    nils++;
  } else {
    /* omitted: overflow checking (abort on error or emit nil) */
    result[k] = left[i] - right[j];
  }
}
```

Expression evaluation through column-based operator and row-wise interpretation compared:

Column-Based (MonetDB)	Row-Wise (PostgreSQL)
zero degrees of freedom	variable-width rows w/ fields of various types
instruction locality	computed goto, long code paths
optimizable tight loops	complex control flow, code in many functions
• loop pipelining	• unpredictable branches
• blocking	
• loop unrolling	
data parallelism	focus on single row
full materialization	row-by-row result generation

- Compilers **optimize tight code loops** inside MAL operators.
- CPUs offer wide registers and instructions to exploit **data //ism** (SIMD: *single instruction*, *multiple data*).

Compiling Tight Loops (cf. MAL Operators)

Inspect Intel® x86 code generated by LLVM's C compiler clang for MonetDB's routine BATcalcsub (batcalc.-), simplified:

```
#define SIZE 1024

void BATcalcsub(int *left, int *right, int *result)
{
  int i, j, k;

  for (i = j = k = 0; k < SIZE; i += 1, j += 1, k += 1) {
      result[k] = left[i] - right[j];
  }
}
```

- Arrays left,right/result represent input/output BATs.

Assembly Code for Simple Tight Loop

Uses clang (options -O2 -fno-vectorize -fno-unroll-loops).

- Register assignment:
  left: %rdi, right: %rsi, result: %rdx, i/j/k: %rax

```
BATcalcsub:
  movq $-4096, %rax              # 4096 = 1024 * 4 (≡ size of int)
loop:
  movl 4096(%rdi,%rax), %ecx     # %ecx ←32 mem[4096 + %rdi + %rax]
  subl 4096(%rsi,%rax), %ecx     # %ecx ←32 %ecx -32 mem[4096 + %rsi + %rax]
  movl %ecx, 4096(%rdx,%rax)     # mem[4096 + %rdx + %rax] ←32 %ecx
  addq $4, %rax                  # 4096 / 4 = 1024 loop iterations
  jne  loop                      # exit if %rax = 0
  retq
```

- **N.B.:** One loop exit test per array element computed.

(Explicit) Loop Unrolling

- Manually perform **loop unrolling** to
  1. improve the ratio (*useful work*) / (*loop exit test*),
  2. expose independent work that may be executed in //:

```
void BATcalcsub(int *left, int *right, int *result)
{
  int i, j, k;

  for (i = j = k = 0; k < SIZE; i += 4, j += 4, k += 4) {
      result[k  ] = left[i  ] - right[j  ];
      result[k+1] = left[i+1] - right[j+1];    independent, execute in
      result[k+2] = left[i+2] - right[j+2];    any order or even in //
      result[k+3] = left[i+3] - right[j+3];
  }
}
```

- **N.B.:** Needs code to handle the case SIZE mod 4 ≠ 0.

Loop Unrolling

Compiler clang (options -O2 -fno-vectorize -funroll-loops) unrolls four loop iterations (easy for CPU to //ize):

```
BATcalcsub:
  movq $-1024, %rax              # i/j/k
loop:
  movl 4096(%rdi,%rax,4), %ecx  # %ecx ←32 left[i]
  subl 4096(%rsi,%rax,4), %ecx  # %ecx ←32 %ecx -32 right[j]
  movl %ecx, 4096(%rdx,%rax,4)  # result[k] ←32 %ecx
  movl 4100(%rdi,%rax,4), %ecx  # %ecx ←32 left[i+1]
  subl 4100(%rsi,%rax,4), %ecx  # %ecx ←32 %ecx -32 right[j+1]
  movl %ecx, 4100(%rdx,%rax,4)  # result[k+1] ←32 %ecx
  movl 4104(%rdi,%rax,4), %ecx  # ⋮
  subl 4104(%rsi,%rax,4), %ecx
  movl %ecx, 4104(%rdx,%rax,4)
  movl 4108(%rdi,%rax,4), %ecx
  subl 4108(%rsi,%rax,4), %ecx
  movl %ecx, 4108(%rdx,%rax,4)
  addq $4, %rax                  # 1024 / 4 = 256 loop iterations
  jne  loop                      # exit if %rax = 0
  retq
```

Data-Parallelism Through SIMD

```
result[]  left[]    right[]

 0▯⎫        ▯⎫        ▯⎫
 1▯⎬ ←128   ▯⎬ −128   ▯⎬
 2▯⎪        ▯⎪        ▯⎪
 3▯⎭        ▯⎭        ▯⎭
 4▯⎫        ▯⎫        ▯⎫
 5▯⎬ ←128   ▯⎬ −128   ▯⎬
 6▯⎪        ▯⎪        ▯⎪
 7▯⎭        ▯⎭        ▯⎭
 8▯         ▯         ▯
```

- Read/compute/write four array elements (of width 4 × 32 bits = 128 bits) at a time in **data-parallel** fashion.
- Relies on SIMD register and instructions (e.g., Intel® SSE registers $\%xmm_i$ and instruction **mov**e **d**ouble **q**uad word)

- ⚠️ Requires care if
  - arrays result[] and left[]/right[] overlap in memory,
  - residual array elements (see ▯) are to be processed.

Data-Parallelism Through SIMD (Prelude)

Compiler clang (options -O2 -fvectorize) uses SIMD registers and instructions. Here: prelude, checking for array overlap:

```
BATcalcsub:
  leaq 4096(%rdi), %rax  # left:   %rdi-□□□□□□-4096+%rdi ≡ %rax
  cmpq %rdx, %rax        # result: %rdx-■■■■■■                  ⎧ □□□□□□⇢ ⇢ ⇢ ⇢
  seta %r9b              # %r9b ← true, if %rax > %rdx, i.e.  ⎩      ■■■■■■
  leaq 4096(%rdx), %rcx  # result:  %rdx-■■■■■■-4096+%rdx ≡ %rcx
  cmpq %rdi, %rcx        # left:    %rdi-□□□□□□                 ⎧      □□□□□□
  seta %r10b             # %r10b ← true, if %rcx > %rdi, i.e. ⎩ ■■■■■■⇢ ⇢ ⇢ ⇢
  leaq 4096(%rsi), %rax  # ⋮
  cmpq %rdx, %rax
  seta %al
  cmpq %rsi, %rcx
  seta %r8b
  testb %r10b, %r9b      # %r9b ∧ %r10b = true, if left[] and result[] overlap
  jne slow               # if so, choose "slow" non-SIMD unrolled code variant
  andb %r8b, %al         # %r8b ∧ %al = true, if right[] and result[] overlap
  jne slow               # if so, choose "slow" variant
  ⋮
```

Data-Parallelism Through SIMD (Main Loop)

Process 16 elements per iteration (SIMD + 2 loops unrolled):

```
  ⋮
  movq $-1024, %rax                        4 × 32 bits = 128 bits wide
loop:
  movdqu 4096(%rdi,%rax,4), %xmm0  # %xmm0 ←128 left[i+0...i+3]
  movdqu 4112(%rdi,%rax,4), %xmm1  # %xmm1 ←128 left[i+4...i+7]
  movdqu 4096(%rsi,%rax,4), %xmm2  # %xmm2 ←128 right[i+0...i+3]
  psubd %xmm2, %xmm0               # %xmm0 ←128 %xmm0 −128 %xmm2
  movdqu 4112(%rsi,%rax,4), %xmm2  # %xmm2 ←128 right[i+4...i+7]
  psubd %xmm2, %xmm1               # %xmm1 ←128 %xmm1 −128 %xmm2
  movdqu %xmm0, 4096(%rdx,%rax,4)  # result[i+0...i+3] ←128 %xmm0          loop #n
  movdqu %xmm1, 4112(%rdx,%rax,4)  # result[i+4...i+7] ←128 %xmm1
  movdqu 4128(%rdi,%rax,4), %xmm0  # %xmm0 ←128 left[i+8 ...i+11]
  movdqu 4144(%rdi,%rax,4), %xmm1  # %xmm1 ←128 left[i+12...i+15]           loop #n+1
  movdqu 4128(%rsi,%rax,4), %xmm2  # %xmm2 ←128 right[i+8...i+11]
  psubd %xmm2, %xmm0               # %xmm0 ←128 %xmm0 −128 %xmm2
  movdqu 4144(%rsi,%rax,4), %xmm2  # %xmm2 ←128 right[i+12...i+15]
  movdqu %xmm0, 4128(%rdx,%rax,4)  # %xmm1 ←128 %xmm1 −128 %xmm2
  psubd %xmm2, %xmm1               # result[i+8 ...i+11] ←128 %xmm0
  movdqu %xmm1, 4144(%rdx,%rax,4)  # result[i+12...i+15] ←128 %xmm1
  addq $16, %rax                   # 1024 / 16 = 64 iterations
  jne  loop                        # exit if %rax = 0
  ⋮
```