DB 2

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07 – Expression Evaluation

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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.

Benefits of linear (vs. tree-shaped) expression representation:

- compact (data cache)
- allows jumping easily
- prepares for compilation (e.g. to LLVM bytecode)

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=→•,const=42⟧   2 │ ───→ …              ip = ip + 1;
               ⋮             3 │ ─╮                  goto dispatch[ip->opc];
                               ⋮  │
                                  ╰─────→ CONST:     ip->res = ip->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).

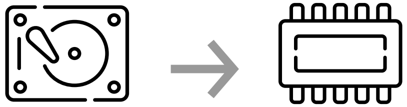
In the PostgreSQL source, see src/backend/executor/execExprpnterp.c, function ExecInterpExpr() for the threaded interpreter.

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	$x_3 - y_3$

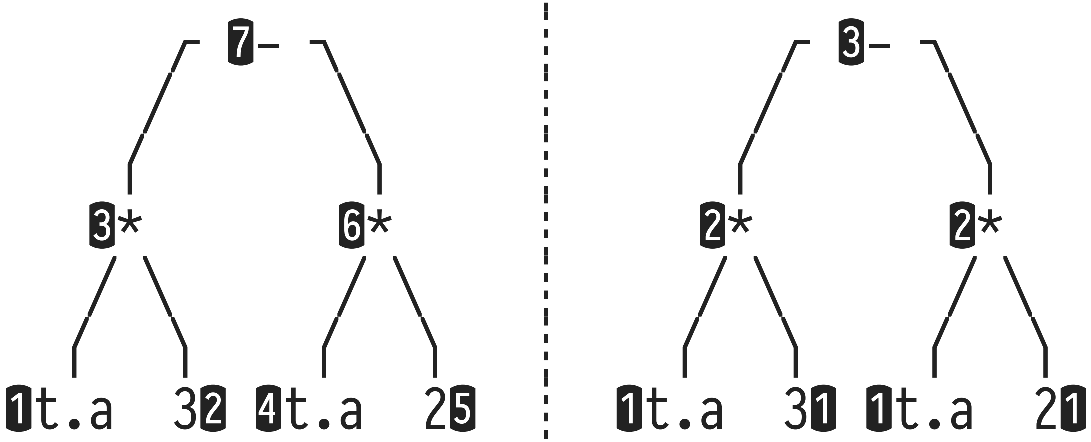
y

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.

1. sequential | **2. data flow**

postorder traversal determines evaluation order



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];
  }
}
```

MonetDB source: see gdk/gdk_calc.c:

1. functions BATcalcsub() and BATcalcsubcst()
2. function sub_typeswitchloop()
3. macro sub_##TYPE1##_##TYPE2##_##TYPE3 (instantiation sub_lng_lng_lng)

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.

These examples compile the following C code with varying compiler options on http://godbolt.org. Compiler used: x86-64 clang 6.0.0, language C:

- No loop unrolling, no vectorization: -O2 -fno-vectorize -fno-unroll-loops
- Loop unrolling, no vectorization: -O2 -fno-vectorize [-funroll-loops]
- Loop unrolling, vectorization: -O2 [-fvectorize] [-funroll-loops]

```
#include <stdio.h>

#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];
  }
}

int main()
{
  int e1[SIZE], e2[SIZE], e3[SIZE];

  for (int i = 0; i < SIZE; i += 1)
      e1[i] = e2[i] = 0;

  BATcalcsub(e1, e2, e3);
  printf("%d", e3[42]);    /* pseudo inspection of result */

  return 0;
}
```

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];
      result[k+2] = left[i+2] - right[j+2];
      result[k+3] = left[i+3] - right[j+3];
  }
}
```

independent, execute in any order or even in //

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

Demonstrate the effect of explicit loop unrolling. See C file mat/unroll.c. Uses the BATcalcsub example as shown in the above slide.

Compile and run as follows:

```
# de-activate clang's vectorizer and automatic loop unroller to
# demonstrate the effect of our own explicit unrolling:

$ cc -Wall -O2 -fno-vectorize -fno-unroll-loops unroll.c -o unroll

$ ./unroll
time (unrolled): 180186µs (e3[42] = 0)
time:            203755µs (e3[42] = 0)
```

From https://en.wikipedia.org/wiki/Duff%27s_device. Can compile these functions on http://godbolt.org using x86-64 clang 6.0.0:

1 Original loop-unrolled code (cannot handle cases where count % 8 ≠ 0):

```
void send(int *to, int *from, int count)
{
    int n = count / 8;
    do {
        *to = *from++;
        *to = *from++;
        *to = *from++;
        *to = *from++;
        *to = *from++;
        *to = *from++;
        *to = *from++;
        *to = *from++;
    } while (--n > 0);
}
```

2 Duff's device (count % 8 ≠ 0 handled properly):

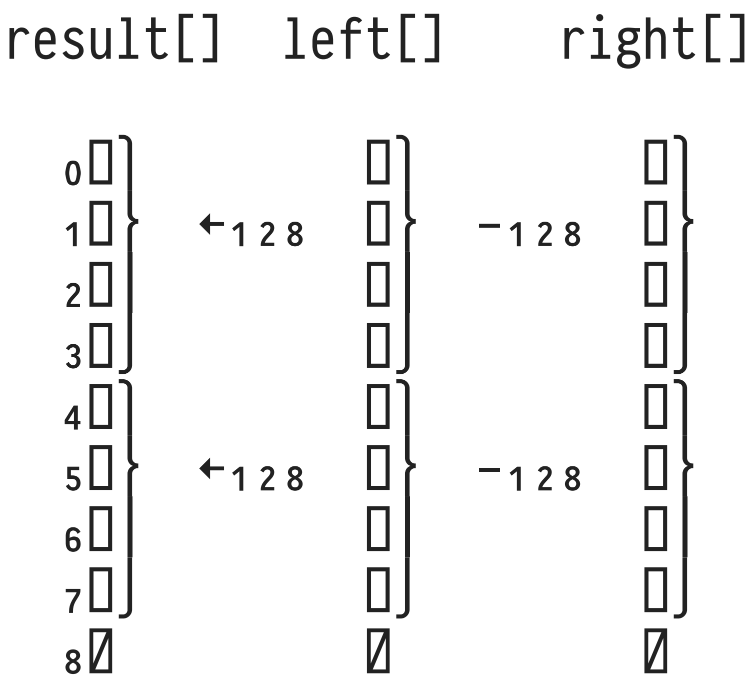
- Assume count = 42, then
  - n = (count + 7) / 8 == 6: due to --n > 0 ⇒ 5 full iterations of loop ≡ 40 elements copied)
  - count % 8 == 2: 2 elements copied

```
void send(int *to, int *from, int count)
{
    int n = (count + 7) / 8;
    switch (count % 8) {
    case 0: do { *to = *from++;
    case 7:      *to = *from++;
    case 6:      *to = *from++;
    case 5:      *to = *from++;
    case 4:      *to = *from++;
    case 3:      *to = *from++;
    case 2:      *to = *from++;
    case 1:      *to = *from++;
            } while (--n > 0);
    }
}
```

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



- 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 $\%\text{xmm}_i$ 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.

- `movdqu`: move **d**ouble **q**uad word **u**naligned: array of 32-bit int may not be located at address % 64 == 0.

- Adding the `restrict` keyword to function parameters `left`, `right`, `result` announces to the compiler that the arrays do not overlap (no aliasing). Array overlap checking (see next slide) is then removed from the code. ⚠️ Requires language `C` (not `C++`):

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

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
  ⋮
```

Notes:

- start of left[]: %rdi, end of left[] = 4096+%rdi

- Unsigned comparison:
  - cmpq %rdx, %rax
  - seta %r9b # %r9b ≡ %rax > %rdx (seta: set if above)

- %r9b = true, if end of left[] > start of result[]
- %r10b = true, if end of result[] > start of left[]
- %al = true, if end of right[] > start of result[]
- %r8b = true, if end of result[] > start of right[]

- %r9b ∧ %r10b = true, if left[] and result[] overlap
- %r8b ∧ %al = true, if right[] and result[] overlap

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
  ⋮
```