DB 2

07 – Expression Evaluation

Summer 2024

Torsten Grust
Universität Tübingen, Germany

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:

```
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

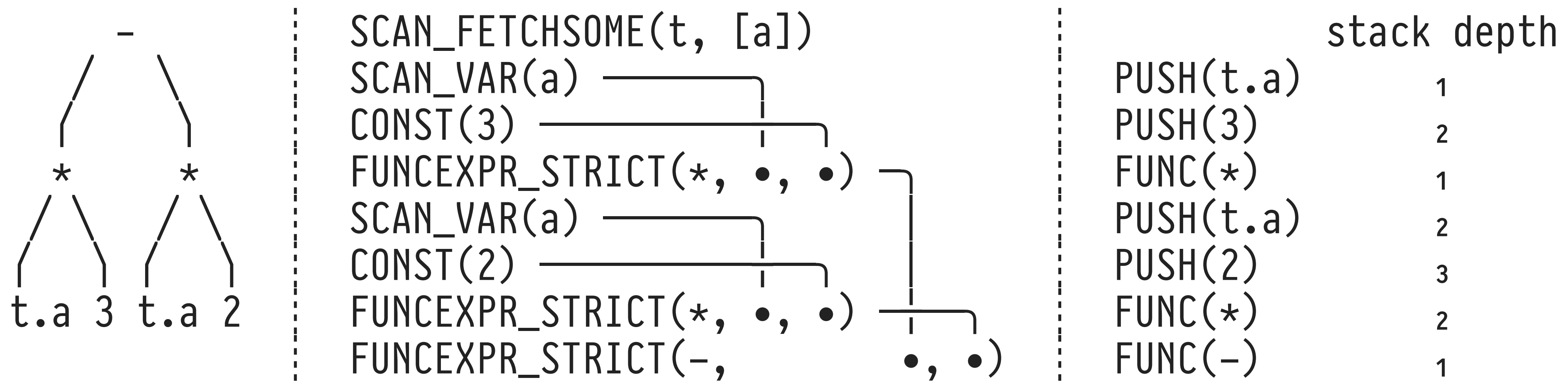
```
EXPLAIN VERBOSE
  SELECT t.a * 3 - t.a * 2    AS a,
         t.a - power(10, t.c) AS diff,
         ceil(t.c / log(2))   AS bits
  FROM   ternary AS t;
```

```
┌──────────────────────────────────────────────────────────────────────────┐
│                               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
```

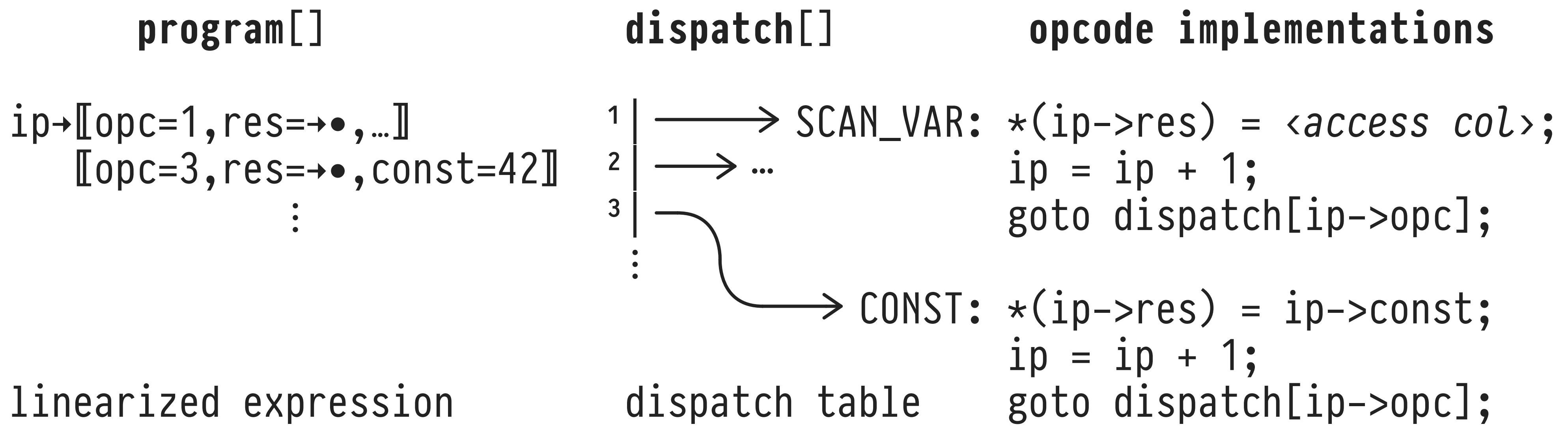
```
SCAN_FETCHSOME(t, [a])
SCAN_VAR(a)
CONST(3)
FUNCEXPR_STRICT(*, •, •)
SCAN_VAR(a)
CONST(2)
FUNCEXPR_STRICT(*, •, •)
FUNCEXPR_STRICT(-,          •, •)
```

```
                   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):



```
SCAN_VAR: *(ip->res) = ‹access col›;
          ip = ip + 1;
          goto dispatch[ip->opc];

CONST:    *(ip->res) = ip->const;
          ip = ip + 1;
          goto dispatch[ip->opc];
```

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

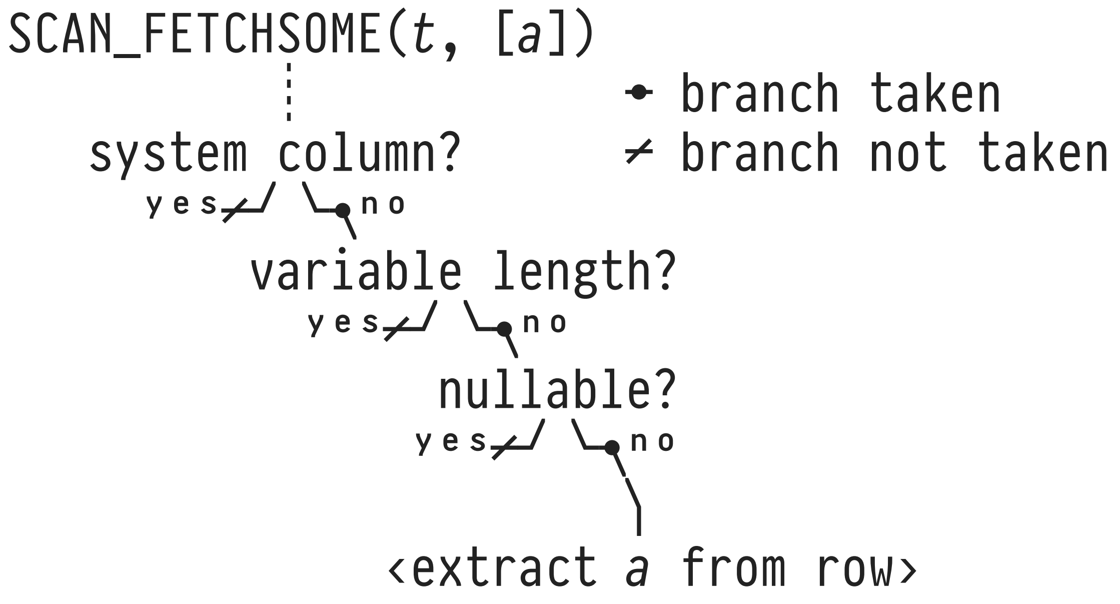
Expression Interpretation Overhead

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.
    - **NB.** LLVM-based support for JIT compilation of expressions has been added to PostgreSQL since v11.

JIT: Turn Run-time into Compile-time Decisions

- PostgreSQL's interpreter is very generic, prepared to handle corner cases, exceptions, and extensions. Leads to branch-heavy routines in the interpreter's hot code path.
- Expression compilation creates **query-specific code:**

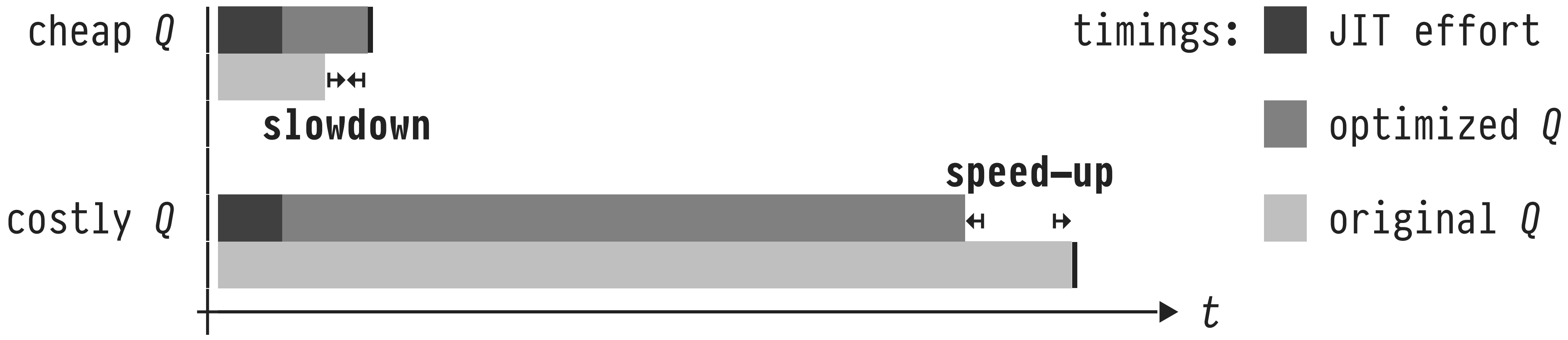


- Access field *a* of a row.
- Interpreter follows **same code path** for all rows, possibly millions of times.
- Generate specific "*a* access code" along the ╲ path.

Expression Compilation: When (Not) to JIT?

- JITing involves code generation, optimization, IR emission (LLVM bitcode), and translation to native code.
- JIT effort adds to the query planning time. Be careful not to penalize queries *Q* that are cheap to begin with:

Assume runtime of query *Q* reduced by 20% due to JIT compilation:



2 ¦ Q_6 — Column-Based Expression Evaluation

```
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.

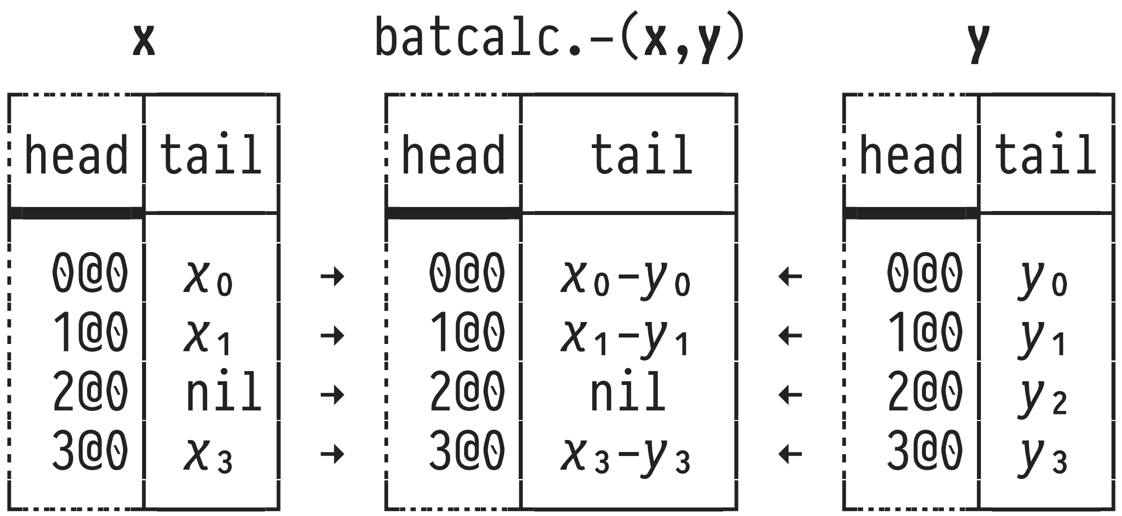
Using **EXPLAIN** on Q_6

```
sql> EXPLAIN SELECT t.a * 3 - t.a * 2 AS a,
             ceil(t.c / log10(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, 0.3010299956639812: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`, `0.301⋯:dbl` ≡ `log10(2)`).

Column-Based "Zip" Semantics

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

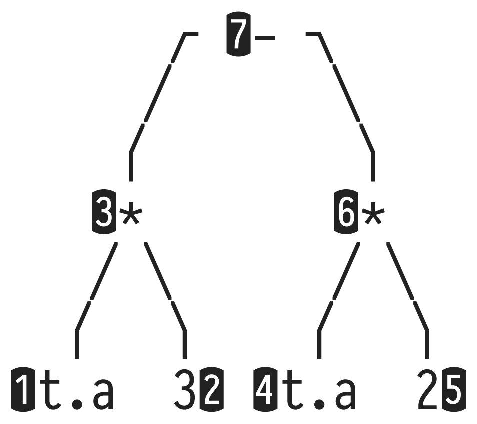


- batcalc.⊗ contains checks for arithmetic exceptions (overflow, divide by 0). Also: nil ⊗ x = x ⊗ nil = nil.

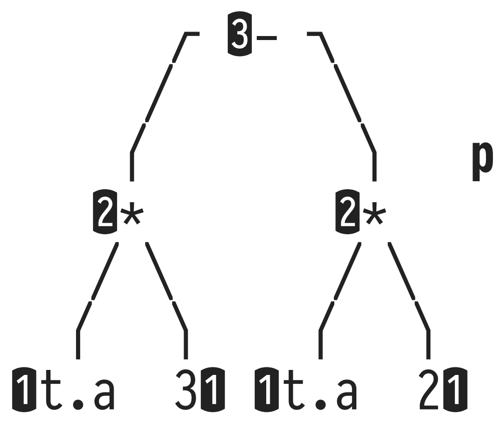
MAL: Sequential Execution vs. Data Flow

1. sequential

postorder traversal determines evaluation order



2. data flow



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:
  xorl %eax, %eax               # %rax ←32 0
loop:
  movl (%rdi,%rax,4), %ecx      # %ecx ←32 mem[%rdi + %rax]
  subl (%rsi,%rax,4), %ecx      # %ecx ←32 %ecx −32 mem[%rsi + %rax]
  movl %ecx, (%rdx,%rax,4)      # mem[%rdx + %rax] ←32 %ecx
  addq $1, %rax
  cmpq $1024, %rax              # 1024 loop iterations
  jne  loop                     # exit if %rax = 1024
  retq
```

- **NB.** 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];  ⎭
  }
}
```

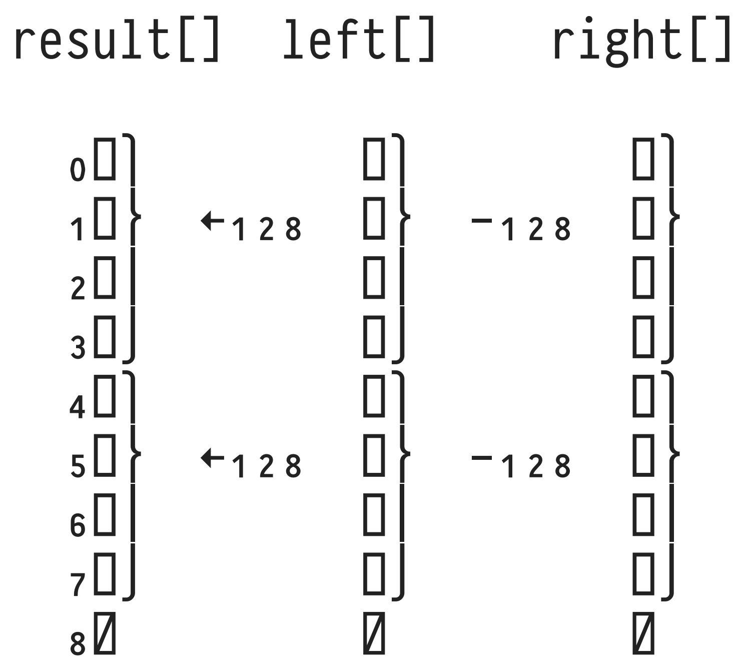
- **NB.** Needs code to handle the case $\mathrm{SIZE} \bmod 4 \neq 0$.

Loop Unrolling

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

```
BATcalcsub:
  xorl %eax, %eax                # i/j/k ←32 0
loop:
│ movl (%rdi,%rax,4), %ecx       # %ecx ←32 left[i]
│ subl (%rsi,%rax,4), %ecx       # %ecx ←32 %ecx -32 right[j]
│ movl %ecx, (%rdx,%rax,4)       # result[k] ←32 %ecx
│ movl 4(%rdi,%rax,4), %ecx      # %ecx ←32 left[i+1]
│ subl 4(%rsi,%rax,4), %ecx      # %ecx ←32 %ecx -32 right[j+1]
│ movl %ecx, 4(%rdx,%rax,4)      # result[k+1] ←32 %ecx
│ movl 8(%rdi,%rax,4), %ecx      # ⋮
│ subl 8(%rsi,%rax,4), %ecx
│ movl %ecx, 8(%rdx,%rax,4)
│ movl 12(%rdi,%rax,4), %ecx
│ subl 12(%rsi,%rax,4), %ecx
│ movl %ecx, 12(%rdx,%rax,4)
│ addq $4, %rax                  # ⎫
│ cmpq $1024, %rax               # ⎭ 1024 / 4 = 256 loop iterations
└ jne  loop                      # exit if %rax = 1024
  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 %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 (Array Overlap)

Compiler clang (options -O2 -fvectorize) uses SIMD registers and instructions.

- Extra prelude code checks for **array overlap.** If so, jumps to non-vectorized (yet unrolled) version of code.
- Declare function arguments via restrict to inform C compiler that arrays won't overlap:

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

Data-Parallelism Through SIMD (Main Loop)

Process 16 elements per iteration (SIMD + 2 loops unrolled, assumes no overlap of arrays result[] and left[]/right[]):

```
  xorl %eax, %eax                           4 × 32 bits = 128 bits wide
loop:
│ movdqu (%rdi,%rax,4), %xmm0       # %xmm0 ←128 left[i+0...i+3]
│ movdqu 16(%rdi,%rax,4), %xmm1     # %xmm1 ←128 left[i+4...i+7]
│ movdqu (%rsi,%rax,4), %xmm2       # %xmm2 ←128 right[i+0...i+3]
│ psubd %xmm2, %xmm0                # %xmm0 ←128 %xmm0 −128 %xmm2
│ movdqu 16(%rsi,%rax,4), %xmm2     # %xmm2 ←128 right[i+4...i+7]
│ psubd %xmm2, %xmm1                # %xmm1 ←128 %xmm1 −128 %xmm2
│ movdqu %xmm0, (%rdx,%rax,4)       # result[i+0...i+3] ←128 %xmm0                  loop #n
│ movdqu %xmm1, 16(%rdx,%rax,4)     # result[i+4...i+7] ←128 %xmm1   ...............................
│ movdqu 32(%rdi,%rax,4), %xmm0     # %xmm0 ←128 left[i+8 ...i+11]
│ movdqu 48(%rdi,%rax,4), %xmm1     # %xmm1 ←128 left[i+12...i+15]                   loop #n+1
│ movdqu 32(%rsi,%rax,4), %xmm2     # %xmm2 ←128 right[i+8...i+11]
│ psubd %xmm2, %xmm0                # %xmm0 ←128 %xmm0 −128 %xmm2
│ movdqu 48(%rsi,%rax,4), %xmm2     # %xmm2 ←128 right[i+12...i+15]
│ psubd %xmm2, %xmm1                # %xmm1 ←128 %xmm1 −128 %xmm2
│ movdqu %xmm0, 32(%rdx,%rax,4)     # result[i+8 ...i+11] ←128 %xmm0
│ movdqu %xmm1, 48(%rdx,%rax,4)     # result[i+12...i+15] ←128 %xmm1
│ addq $16, %rax                    # ⎫
│ cmpq $1024, %rax                  # ⎭ 1024 / 16 = 64 iterations
└ jne  loop                         # exit if %rax = 1024
  ⋮                                 # (non-vectorized code not shown)
```