Design and Implementation of DuckDB Internals

⑦

Vectorized Query Execution

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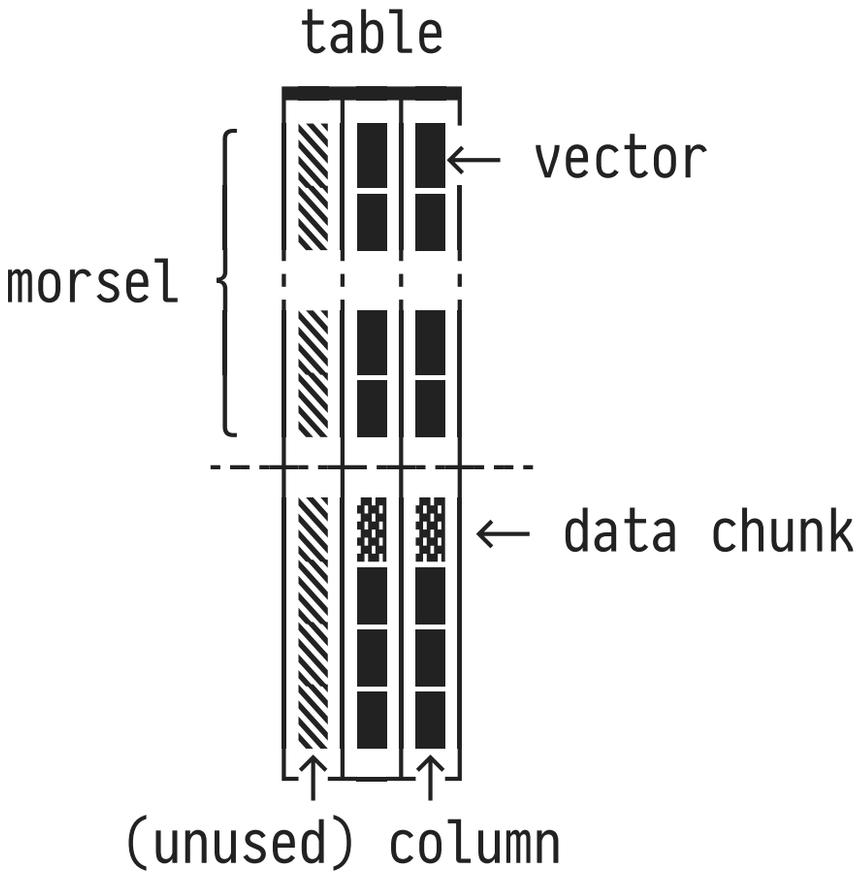
1 DuckDB Terminology Recap

Before we proceed, let us make sure that we agree on the data items processed by DuckDB's query engine:



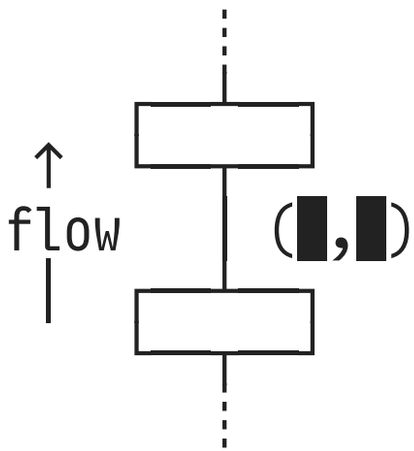
- **Tables** are organized in **columns** some of which may be unused ▒ in any given plan operator.
- Columns are split into **vectors** ▉, each containing 2048 values.[1]
- A **data chunk** (▒,▒) groups vectors of multiple columns, representing a horizontal slice of a table.
- Threads consume input data **morsel**-by-morsel, each consisting of 60 data chunks (= 122,880 rows).

[1] DuckDB's vector size can be configured at compile time (STANDARD_VECTOR_SIZE).

2 ┆ Passing Data Chunks Between Operators

During plan execution, operators process **one data chunk at a time**, then pass that chunk downstream:

Memory Location	Latency ⧖	Size (M2 Max)	… Can Hold
CPU Registers		n × 64 bits	cell value(s)
L1 Cache	< 1 ns	(per) 192 KB	vector
L2 Cache	2.8 ns	(shared) 32 MB	data chunk
RAM	≈ 100 ns	16–96 GB	column(s)



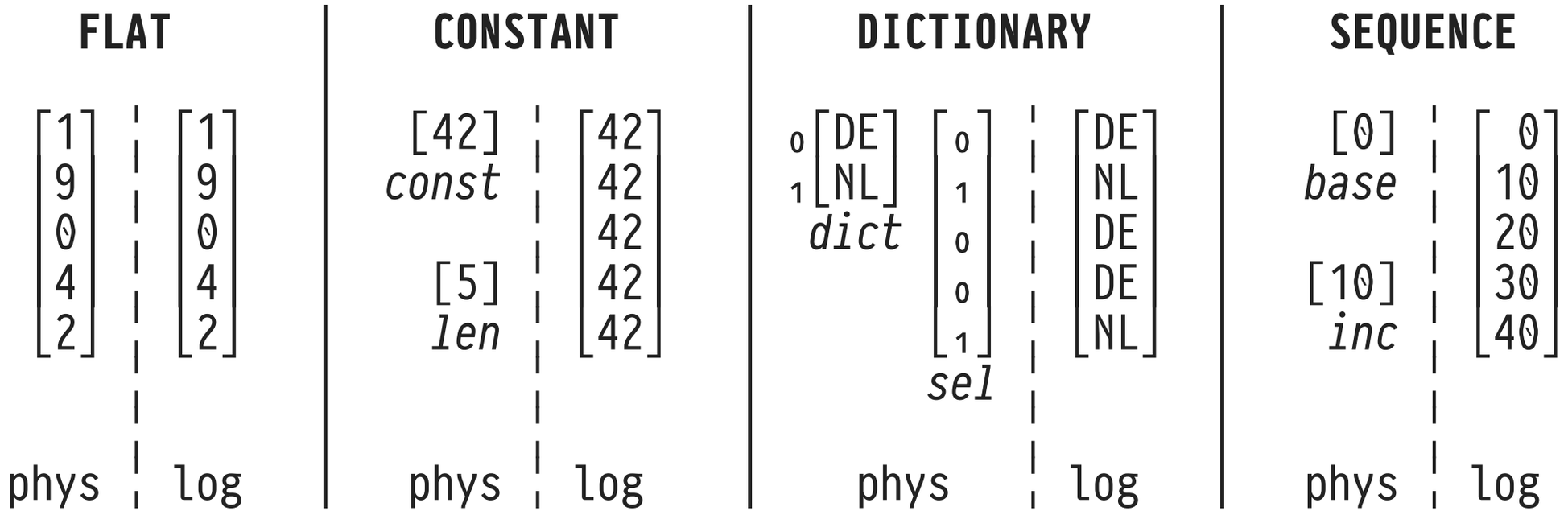
- The passed **data chunks** will fit in the L2 cache. Operators can access intermediate results with low latency.
- Passing **entire columns:** many intermediates will only fit into RAM. High latency.
- Passing **single rows:** frequent context switches between operators. CPU overhead.

#023

3 ¦ DuckDB Vectors: Logical vs. Physical

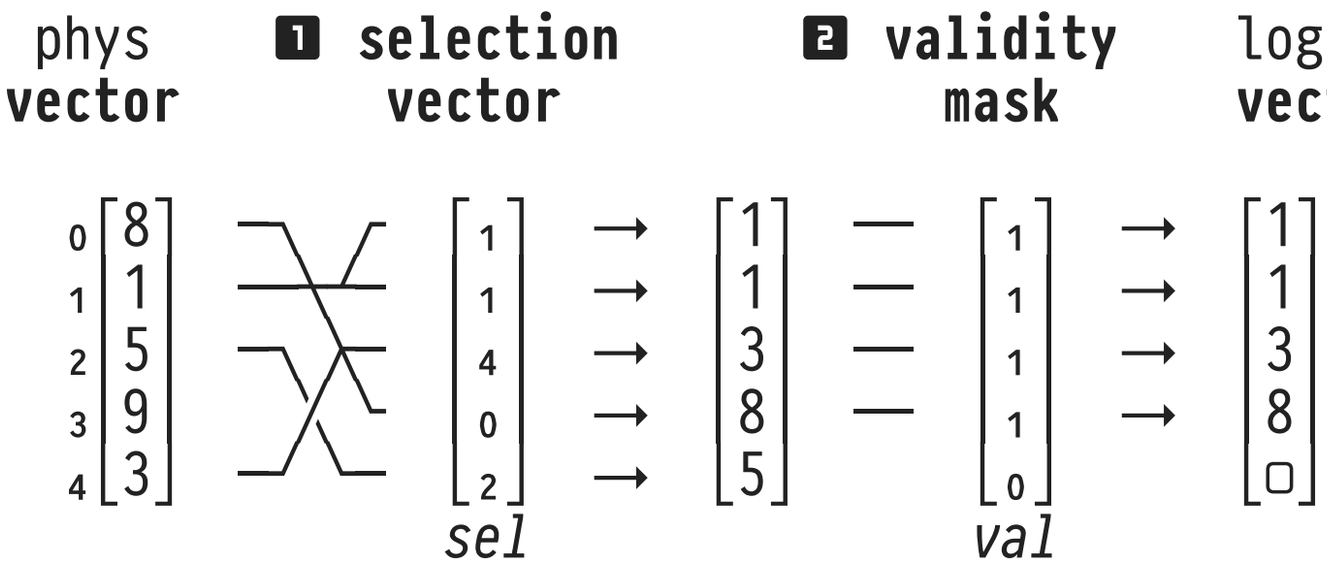
To form a horizontal table slice, data chunks (▉,...,▉) contain a **vector** for each relevant column.

- Vector ▉ (**logical**): sequence of 2048 values of a *single type*.
- DuckDB exploits regularity in value sequences to implement a family of compressed **physical vector representations:**



DuckDB Vectors: Selection Vectors and Validity Masks

Any vector is associated with a **selection vector** and **validity mask** used to permute/filter its value sequence and encode NULLs (▢):



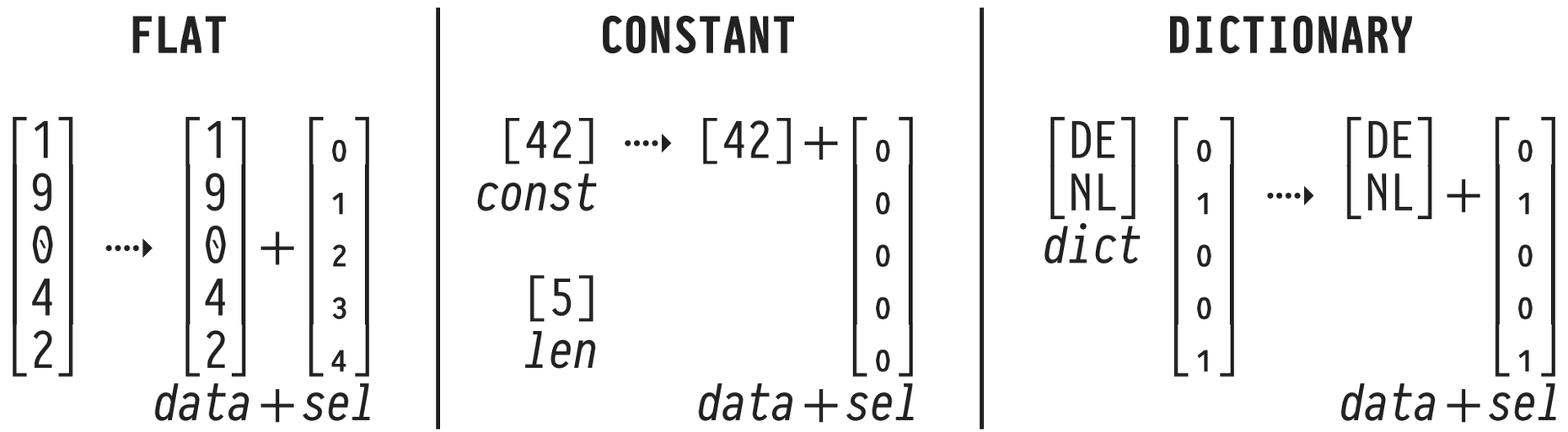
- Selection vectors contain vector indices ∈ {0,...,2047}. Can help to avoid copying—potentially sizable—values after a sorting or filtering operation.
- Validity masks contain Booleans (0/1).

DuckDB Vectors: Unified Representation

DuckDB aims to push vectors in compressed physical representation from operator to operator. However, *handling all representations everywhere* would lead to combinatorial code explosion. 👎

- 💡 Convert to (⇢) and then process a **unified representation** comprising a *data vector*+*selection vector* pair.

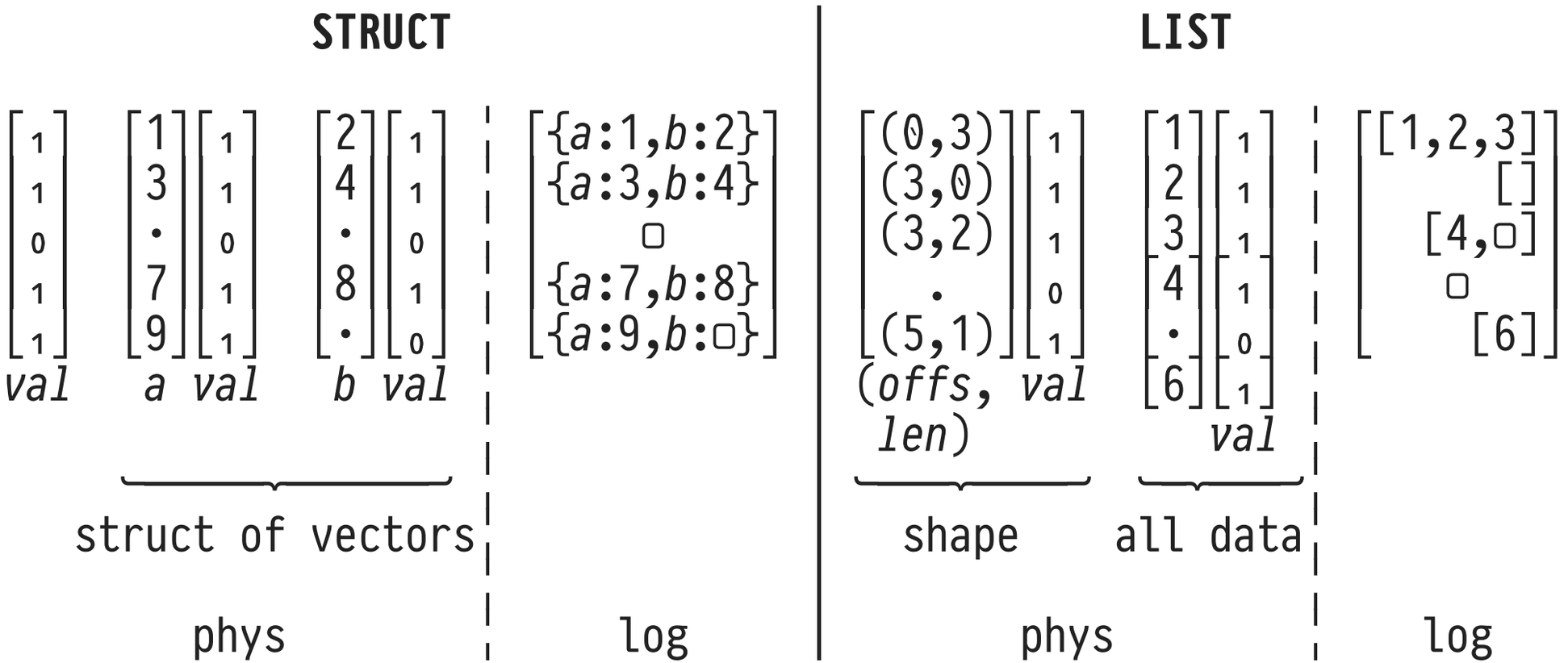
  NB. This conversion does *not* involve value copying:[2]



[2] SEQUENCE vectors are first expanded into FLAT vectors, then converted into the unified representation.

DuckDB Vectors of Complex Values (Structs {…}, Lists […])

- **Vectors of structs** are represented as structs of vectors.
- **Vectors of lists** store list shapes and data values separately, combine data of all lists into a single data vector.



- Nested types: apply representation schemes recursively.

#025

4 ¦ Super-Specific Vector Code

Q: How does DuckDB perform a binary operation on vectors `l` and `r`?

That depends on

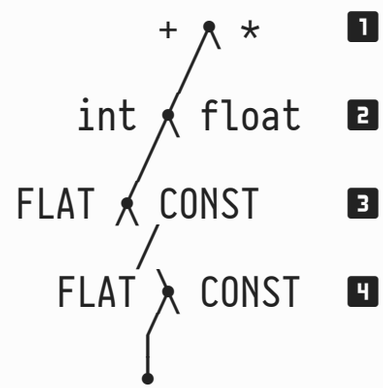
- 1️⃣ the kind of operation (e.g., arithmetics: `+`, `*`, …),
- 2️⃣ value types (`int`, `float`, …),
- vector representations of 3️⃣ `l` and 4️⃣ `r` (`FLAT`, `CONST`, …).

💡 Branch on 1️⃣…4️⃣ *before* we enter the tight loop that scans the values in `l` and `r`:

- Avoids repeated tests (with identical outcome),
- leads to *tight inner loops* that feature less branches.

Super-Specific Vector Code

```
switch (❶ op)
  case +: switch (❷ type)
  ⎪ case int: switch (❸ l.repr)
  ⎪ ⎪ case FLAT:     switch (❹ r.repr)
  ⎪ ⎪ ⎪ case FLAT:     res.repr = FLAT;
  ⎪ ⎪ ⎪ ⎪             for (i = 0; i < count; i++)
  ⎪ ⎪ ⎪ ⎪             ⎣ res.data[i] = l.data[i] + r.data[i];
  ⎪ ⎪ ⎪ ⎣             break;
  ⎪ ⎪ ⎪ case CONSTANT: res.repr = FLAT;
  ⎪ ⎪ ⎪ ⎪             for (i = 0; i < count; i++)
  ⎪ ⎪ ⎪ ⎪             ⎣ res.data[i] = l.data[i] + r.const;
  ⎪ ⎪ ⎪ ⎣             break;
  ⎪ ⎪ ⎣ ⋮
  ⎪ ⎪ case CONSTANT: switch (❹ r.repr)
  ⎪ ⎪ ⎪ case FLAT:     res.repr = FLAT;                    ⎫ Super-specific code section:
  ⎪ ⎪ ⎪ ⎪             for (i = 0; i < count; i++)         ⎬ Add the constant vector l of
  ⎪ ⎪ ⎪ ⎪             ⎣ res.data[i] = l.const + r.data[i]; ⎭ integers to flat vector r
  ⎪ ⎪ ⎪ ⎣             break;
  ⎪ ⎪ ⎪ case CONSTANT: res.repr = CONSTANT;
  ⎪ ⎪ ⎪ ⎪             res.const = l.const + r.const;
  ⎪ ⎪ ⎪ ⎣             break;
  ⎪ ⎪ ⎣ ⋮
  ⎪ ⎣ ⋮
  ⎪ case float: ...
  ⎣ ⋮
  case *: ...
  ⋮
```



Super-Specific Vector Code

Previous slide does not handle **sel**ection vector/**val**idity mask (each leaf of the decision tree 🚶 requires code much like this):

```
for (i = 0; i < count; i++)      /* code for leaf 1: +, 2: int, 3: FLAT, 4: FLAT */
| lindex = l.sel[i];
| rindex = r.sel[i];
| if (l.val[lindex] && r.val[rindex])
| | res.data[i] = l.data[lindex] + r.data[rindex];
| | res.val[i]  = 1;
| else
| | res.val[i]  = 0;
```

DuckDB aims to control the resulting C++ code volume:

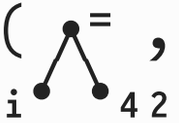
1. Convert vectors `l`, `r` to **unified representation**, process these by generic loops (cuts lower levels of 🚶).
2. Use **C++ templates** to generate code at *DBMS compile time*.[3]

[3] A different breed of DBMS—for example Umbra —generates and compiles C++/IR/machine code at *query translation time*. These query-specific code fragments are then linked with the DBMS and invoked at runtime.

Deep Dive Into DuckDB C++ Code: Vector Operations ❶

```
SELECT i = 42              -- i: SEQUENCE (base=1, inc=1), 42: CONST
FROM   generate_series(1, 100) AS _(i)
```

Trace how DuckDB vectorizes the evaluation of expression `i = 42`:

ExpressionExecutor::Execute(

, ..., count, result)

```
void ExpressionExecutor::Execute(
  const BoundComparisonExpression &expr, ..., idx_t count, Vector &result) {
  ⋮
  Execute(*expr.left,  ..., count, left);   ⇝ left  ≡ [1|1]ˢ    (SEQUENCE)
  Execute(*expr.right, ..., count, right);  ⇝ right ≡ [42]ᶜ     (CONSTANT)

  switch (expr.GetExpressionType() ❶) {
  case ExpressionType::COMPARE_EQUAL:
    VectorOperations::Equals(left, right, result, count);
    break;
  case ExpressionType::COMPARE_NOTEQUAL:
    VectorOperations::NotEquals(left, right, result, count);
    break;
  ⋮
  }
}
```

DuckDB 1.4 source: src/execution/expression_executor/execute_comparison.cpp

Deep Dive Into DuckDB C++ Code: Vector Operations ❷

VectorOperations::Equals([1|1]ˢ, [42]ᶜ, result, count)

```
void VectorOperations::Equals(
  Vector &left, Vector &right, Vector &result, idx_t count) {
    ComparisonExecutor::Execute<duckdb::Equals>(left, right, result, count); ⓐ
}
```

```
struct ComparisonExecutor {
private:
  template <class T, class OP>
  static inline void TemplatedExecute(
    Vector &left, Vector &right, Vector &result, idx_t count) {
      BinaryExecutor::ExecuteSwitch<T, T, bool, OP>(left, right, result, count); ©
  }
public:
  template <class OP>
  static inline void Execute(
    Vector &left, Vector &right, Vector &result, idx_t count) {
    ⋮
    switch (left.GetType().InternalType() ❷) {
    ⋮
    case PhysicalType::INT64:
      TemplatedExecute<int64_t, OP>(left, right, result, count); ⓑ
      break;
    ⋮
    }
  }
}
```

DuckDB 1.4 source: src/common/vector_operations/comparison_operators.cpp

Deep Dive Into DuckDB C++ Code: Vector Operations ❸

```
BinaryExecutor::ExecuteSwitch<int64_t, int64_t, bool, ..., duckdb::Equals, ...> (
  [1|1]ˢ, [42]ᶜ, result, count, ...)
```

```
struct BinaryExecutor {
⋮
  template <class LEFT_TYPE, class RIGHT_TYPE, class RESULT_TYPE, ..., class OP, ...>
  static void ExecuteSwitch(
    Vector &left, Vector &right, Vector &result, idx_t count, ...) {
      auto left_vector_type = left.GetVectorType();              ⇝ SEQUENCE_VECTOR
      auto right_vector_type = right.GetVectorType();            ⇝ CONSTANT_VECTOR
      if (left_vector_type  == VectorType::CONSTANT_VECTOR ❸ &&
          right_vector_type == VectorType::CONSTANT_VECTOR ❹) {
        ExecuteConstant<LEFT_TYPE, RIGHT_TYPE, RESULT_TYPE, ..., OP, ...>(
          left, right, result, ...);
      }
      ⋮
      else {
        ExecuteGeneric<LEFT_TYPE, RIGHT_TYPE, RESULT_TYPE, ..., OP, ...>(
          left, right, result, count, ...);
      }
  }
⋮
}
```

DuckDB 1.4 source: src/include/duckdb/common/vector_operations/binary_executor.hpp

Deep Dive Into DuckDB C++ Code: Vector Operations ❹

No specific code section for vector operation SEQUENCE = CONSTANT:
first transform left and right into **unified representation.**

```
BinaryExecutor::ExeuteGeneric<int64_t, int64_t, bool, ..., duckdb::Equals, ...> (
  [1|1]ˢ, [42]ᶜ, result, count, ...)
```

```
struct BinaryExecutor {
⋮
  template <class LEFT_TYPE, class RIGHT_TYPE, class RESULT_TYPE, ..., class OP, ...>
  static void ExecuteGeneric(
    Vector &left, Vector &right, Vector &result, idx_t count, ...) {
      UnifiedVectorFormat ldata, rdata;

      left.ToUnifiedFormat(count, ldata);   ⇝ ldata ≡ [1,2,3,...,100]ᵘ (UnifiedVector)
      right.ToUnifiedFormat(count, rdata);  ⇝ rdata ≡ [42,42,...,42]ᵘ  (UnifiedVector)

      result.SetVectorType(VectorType::FLAT_VECTOR);
      auto result_data = FlatVector::GetData<RESULT_TYPE>(result);
      ExecuteGenericLoop<LEFT_TYPE, RIGHT_TYPE, RESULT_TYPE, ..., OP, ...> (
        UnifiedVectorFormat::GetData<LEFT_TYPE>(ldata),
        UnifiedVectorFormat::GetData<RIGHT_TYPE>(rdata),
        result_data, ..., count, ...);
  }
⋮
}
```

DuckDB 1.4 source: src/include/duckdb/common/vector_operations/binary_executor.hpp

Deep Dive Into DuckDB C++ Code: Vector Operations ❺

Both argument vectors [...]ᵘ are now in unified representation:

```
BinaryExecutor::ExeuteGenericLoop<int64_t, int64_t, bool, ..., duckdb::Equals, ...> (
  [1,2,3,...,100]ᵘ, [42,42,...,42]ᵘ, result, ..., count, ...)
```

```
struct BinaryExecutor {
⋮
  template <class LEFT_TYPE, class RIGHT_TYPE, class RESULT_TYPE, ..., class OP, ...>
  static void ExecuteGenericLoop(
    const LEFT_TYPE *__restrict ldata, const RIGHT_TYPE *__restrict rdata,
    RESULT_TYPE *__restrict result_data, ..., idx_t count, ...) {
      ⋮
      for (idx_t i = 0; i < count; i++) {
        auto lentry = ldata[i];
        auto rentry = rdata[i];
        result_data[i] = Operation<..., OP, LEFT_TYPE, RIGHT_TYPE, RESULT_TYPE> (
            ..., lentry, rentry, ...);
      }
  }
⋮
}
```

DuckDB 1.4 source: src/include/duckdb/common/vector_operations/binary_executor.hpp

Deep Dive Into DuckDB C++ Code: Vector Operations ❻

```
BinaryExecutor::ExeuteGenericLoop<int64_t, int64_t, bool, ..., duckdb::Equals, ...> (
  [1,2,3,...,100]ᵘ, [42,42,...,42]ᵘ, result, ..., count, ...)
```

```
struct BinaryExecutor {
⋮
  template <class LEFT_TYPE, class RIGHT_TYPE, class RESULT_TYPE, ..., class OP, ...>
  static void ExecuteGenericLoop(
    const LEFT_TYPE *__restrict ldata, const RIGHT_TYPE *__restrict rdata,
    RESULT_TYPE *__restrict result_data, ..., idx_t count, ...) {
      ⋮
      for (idx_t i = 0; i < count; i++) {
        auto lentry = ldata[i];
        auto rentry = rdata[i];
        result_data[i] = lentry == rentry;
      }
  }
⋮
}
```

DuckDB 1.4 source: src/include/duckdb/common/vector_operations/binary_executor.hpp

- ldata/rdata: plain C++ arrays of LEFT_TYPE/RIGHT_TYPE elements.
- const ... *__restrict: *Hey C++, we never write to these arrays and they do not overlap in memory. Go on, optimize!*

5 Compiling Tight Loops

Tight loops over vectors form the core of DuckDB's query engine.

- Routine to subtract two flat integer vectors (⚠ simplified):

#023

```
#define STANDARD_VECTOR_SIZE 2048

void PROJECT_sub_int_col_int_col(
  int* col1, int* col2, int *res, int* sel)
{
    int i;

    if (sel) {
        // skip discussion of selection vector for now
    }

    for (i = 0; i < STANDARD_VECTOR_SIZE; i += 1) {
        res[i] = col1[i] - col2[i];
    }
}
```

Assembly Code for Tight Loops

Use clang (options -O2 -fno-vectorize -fno-unroll-loops) to generate code for x86-64 CPUs.[4]

- Register assignment:
  col1: %rdi, col2: %rsi, res: %rdx, i: %rax

```
PROJECT_sub_int_col_int_col:
  xorl %eax, %eax              # %rax ←₃₂ 0
loop:
  movl (%rdi,%rax,4), %ecx     # %ecx ←₃₂ mem[%rdi + %rax × 4]
  subl (%rsi,%rax,4), %ecx     # %ecx ←₃₂ %ecx -₃₂ mem[%rsi + %rax × 4]
  movl %ecx, (%rdx,%rax,4)     # mem[%rdx + %rax × 4] ←₃₂ %ecx
  incq %rax
  cmpq $2048, %rax             # 2048 loop iterations
  jne  loop                    # exit if %rax = 2048
  retq
```

- **NB.** One loop exit test per vector element computed.

[4] Use Matt Godbolt's Compiler Explorer to inspect assembly code generated by contemporary compilers.

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 $\parallel$:

#026

```
void PROJECT_sub_int_col_int_col(int* col1, int* col2, int* res)
{
  int i;

  for (i = 0; i + 3 < STANDARD_VECTOR_SIZE; i += 4) {
      res[i  ] = col1[i  ] - col2[i  ];  ┐
      res[i+1] = col1[i+1] - col2[i+1];  } independent, execute in
      res[i+2] = col1[i+2] - col2[i+2];  │ any order or even in ∥
      res[i+3] = col1[i+3] - col2[i+3];  ┘
  }
}
```

- **NB.** This code does not handle the case of `STANDARD_VECTOR_SIZE mod 4 ≠ 0`.

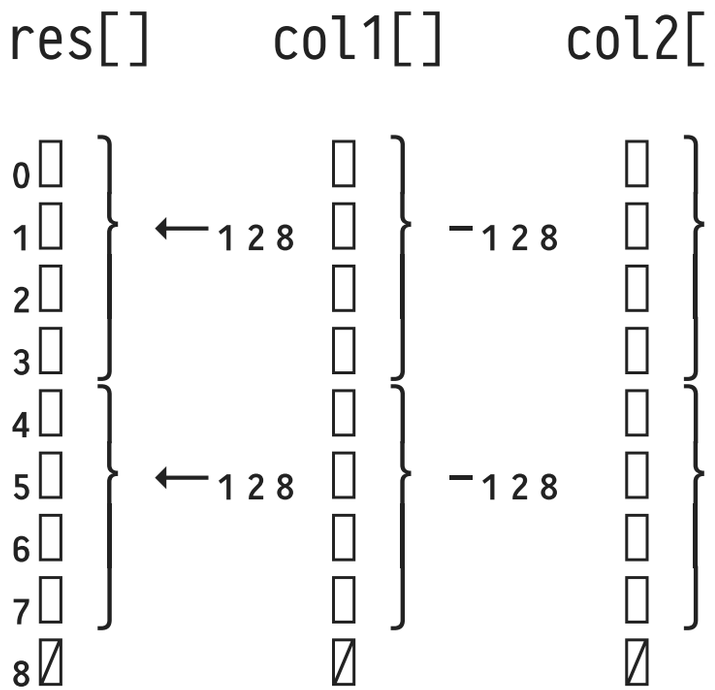
#027

Loop Unrolling by the Compiler

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

```
PROJECT_sub_int_col_int_col:
  xorl %eax, %eax               # i ←₃₂ 0
loop:
⎛ movl (%rdi,%rax,4), %ecx      # %ecx ←₃₂ col1[i]                    ⎫
⎜ subl (%rsi,%rax,4), %ecx      # %ecx ←₃₂ %ecx -₃₂ col2[i]           ⎬ no control or
⎜ movl %ecx, (%rdx,%rax,4)      # res[i] ←₃₂ %ecx                     ⎭ data dependencies
⎜ movl 4(%rdi,%rax,4), %ecx     # %ecx ←₃₂ col1[i+1]                  ⎫ between these
⎜ subl 4(%rsi,%rax,4), %ecx     # %ecx ←₃₂ %ecx -₃₂ col2[i+1]         ⎬ code blocks
⎜ movl %ecx, 4(%rdx,%rax,4)     # res[i+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                 # ⎫ i ←₃₂ i+4
⎜ cmpq $2048, %rax              # ⎬ 2048 / 4 = 512 loop iterations
⎝ jne  loop                     # exit if %rax = 2048
  retq
```

Data-Parallelism Through SIMD[5] Instructions



- Read/compute/write 4 vector elements (of width 4 × 32 bits = 128 bits) at a time in **data-parallel** fashion.
- Relies on CPU's SIMD support (e.g., Intel® SSE registers %xmm$_i$ and instruction **mov**e **d**ouble **q**uad word).

- **NB.** Requires care if
  - vectors res[] and col1[]/col2[] overlap in memory,
  - residual vector elements (see ∅) are to be processed.

[5] SIMD: **S**ingle-**I**nstruction, **M**ultiple **D**ata. Support is vendor-specific, rapidly evolving in contemporary CPUs. Intel's *AVX2* registers: 512 bits, ARM *NEON* registers: 128 bits. Compilers implement CPU architecture flags.

Data-Parallelism Through SIMD Instructions (Vector Overlap)

C compiler clang (options -O2 -fvectorize) uses SIMD registers and instruction set.

- Extra prelude code checks for **vector overlap** on function entry. If so, jumps to non-vectorized (yet unrolled) version of code.
- Declare function arguments with modifier __restrict__ to inform C compiler that vectors do not overlap (⚠ omits all checks):

```
void PROJECT_sub_int_col_int_col(
  int *__restrict__ col1, int *__restrict__ col2, int *__restrict__ res)
{
  int i;
  ⋮
}
```

Data-Parallelism Through SIMD Instructions (Core Loop)

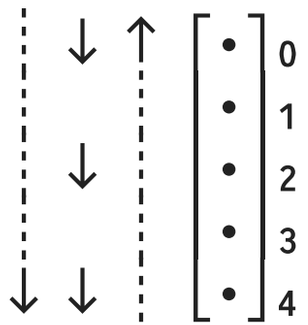
Process 16 vector elements per iteration (SIMD + 2 loops unrolled; assumes no overlap of vectors res[] and col1[]/col2[]):

```
PROJECT_sub_int_col_int_col:
  ⋮
  overlap check omitted
  ⋮
  xorl %eax, %eax                          4 × 32 bits = 128 bits wide
loop:                                      ╰──────┴──────╯
┌ movdqu (%rdi,%rax,4), %xmm0      # %xmm0 ←128 col1[i+0...i+3]
│ movdqu 16(%rdi,%rax,4), %xmm1    # %xmm1 ←128 col1[i+4...i+7]
│ movdqu (%rsi,%rax,4), %xmm2      # %xmm2 ←128 col2[i+0...i+3]
│ psubd %xmm2, %xmm0               # %xmm0 ←128 %xmm0 -128 %xmm2
│ movdqu 16(%rsi,%rax,4), %xmm2    # %xmm2 ←128 col2[i+4...i+7]
│ psubd %xmm2, %xmm1               # %xmm1 ←128 %xmm1 -128 %xmm2
│ movdqu %xmm0, (%rdx,%rax,4)      # res[i+0...i+3] ←128 %xmm0                        loop #n
│ movdqu %xmm1, 16(%rdx,%rax,4)    # res[i+4...i+7] ←128 %xmm1  ..........................................
│ movdqu 32(%rdi,%rax,4), %xmm0    # %xmm0 ←128 col1[i+8 ...i+11]
│ movdqu 48(%rdi,%rax,4), %xmm1    # %xmm1 ←128 col1[i+12...i+15]                     loop #n+1
│ movdqu 32(%rsi,%rax,4), %xmm2    # %xmm2 ←128 col2[i+8...i+11]
│ psubd %xmm2, %xmm0               # %xmm0 ←128 %xmm0 -128 %xmm2
│ movdqu 48(%rsi,%rax,4), %xmm2    # %xmm2 ←128 col2[i+12...i+15]
│ psubd %xmm2, %xmm1               # %xmm1 ←128 %xmm1 -128 %xmm2
│ movdqu %xmm0, 32(%rdx,%rax,4)    # res[i+8 ...i+11] ←128 %xmm0
│ movdqu %xmm1, 48(%rdx,%rax,4)    # res[i+12...i+15] ←128 %xmm1
│ addq $16, %rax                   # ⎫
│ cmpq $2048, %rax                 # ⎬ 2048 / 16 = 128 iterations
└ jne  loop                        # ⎭ exit if %rax = 2048
  ⋮                                # (non-vectorized code not shown)
```

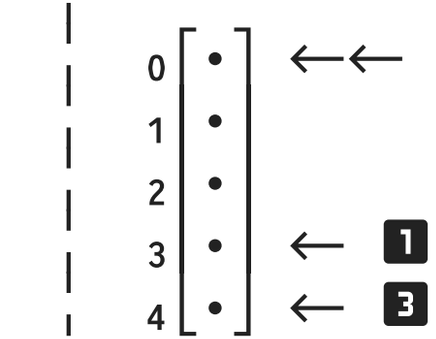
6 Predictable Memory Access and Prefetching

Predictable
Access Patterns

- forward scans (possibly with skips)
- backward scans



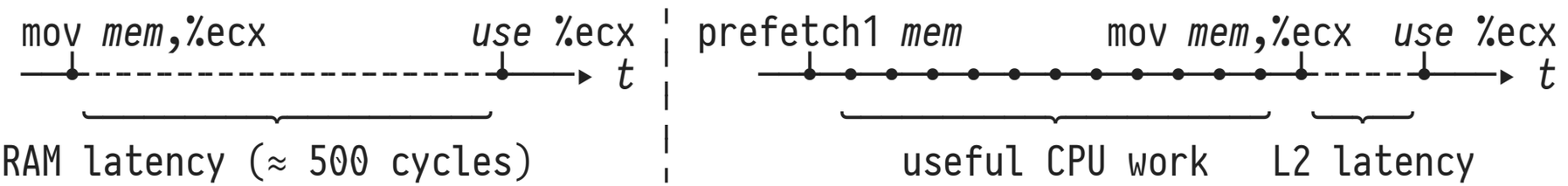
Unpredictable
Access Patterns



- “jumps”, revisits
- irregular skips

- **Predictable:** CPU automatically issues **asynchronous memory prefetch** operations to preload caches and hide memory latency.
- **Unpredictable:** DBMS code adds explicit **software prefetch**[6] **instructions** for memory addresses needed in the future:

#028



[6] No-ops with side effect on the data cache. Example: prefetcht1 loads into the L2 cache on Intel® Core i7.

7 Implementing Selection in Tight Loops

The core of the FILTER operator is a **conditional statement** that is evaluated for each input vector element (⚠ simplified again):

#023

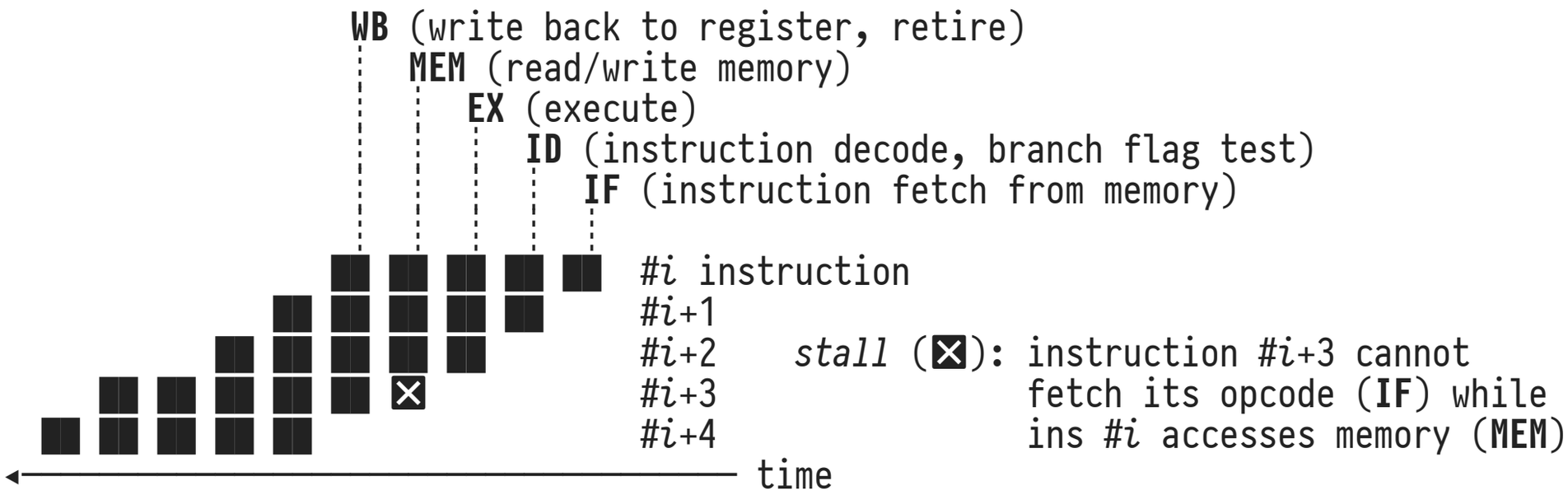
```
int FILTER_lt_date_col_date_val(int* res, int* col, int val)
{
  int i, o = 0;

  for (i = 0; i < STANDARD_VECTOR_SIZE; i += 1) {
    if (col[i] < val) {                 // test filter condition (col < val)
      res[o] = i;                       // build selection vector
      o += 1;
    }
  }

  return o;                             // output cardinality
}
```

- Conditionals (and loops) lead to **branches** in generated machine code that disrupt the CPU's processing of straight-line instruction sequences. 👎

Instruction Pipelining in Modern CPUs

Contemporary CPUs process instructions in a pipeline of execution stages that compete for CPU resources (*e.g.*, the arithmetic logic unit or the memory bus).

- A simple five-stage pipeline:

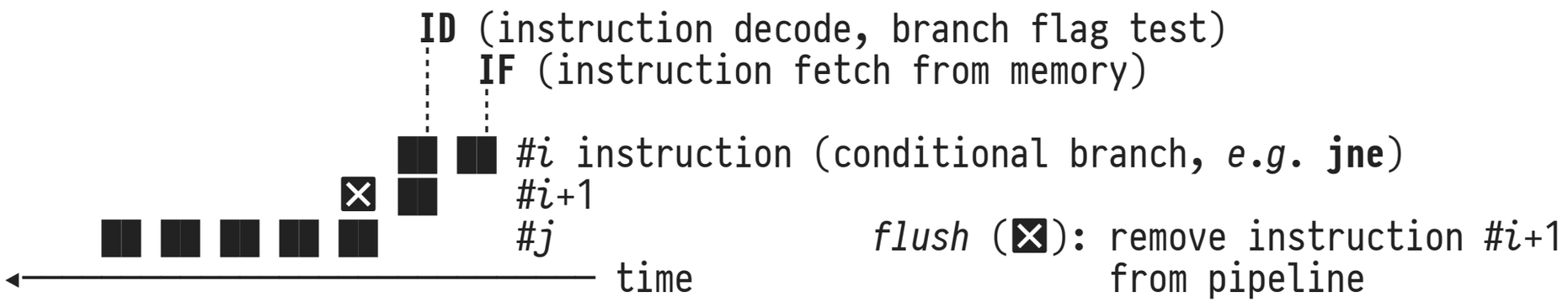


Branch Taken? Yes, Flush Pipeline

Control flow branches (for, but particularly if) are a challenge for modern pipelining CPUs.

The simple pipeline decides the outcome of branch #*i* (at end of **ID**) only *after* instruction #*i*+1 has already been fetched (**IF**).

- If the branch is taken, **flush** instruction #*i*+1 from the pipeline 👎, instead fetch instruction #*j* at jump target:



Branch Predictions: History and Heuristics

CPUs thus try to **predict the outcome of a branch** *#i* based on **earlier recorded outcomes** of the same branch:

Branch prediction	Fetch instruction
taken	*#j*
not taken	*#i*+1

- Also: **heuristics** based on typical control flow patterns (instruction ***jcc***: conditonal branch on ***c***ondition ***c***ode):

Branch to lower address, predicted *taken*

```
loop:
        ⋮
        ⋮
        jcc loop
        ⋮
```

Branch to higher address, predicted *not taken*

```
        loop:
                ⋮
                jcc break
                ⋮
                jmp loop
        break:
                ⋮
```

Avoiding Branch Mispredictions

A **mispredicted branch** leads to

1. pipeline flushes—effectively a stall ☒—and
2. (possibly) CPU instruction cache misses.

The resulting runtime penalty is significant (≈15 cycles).

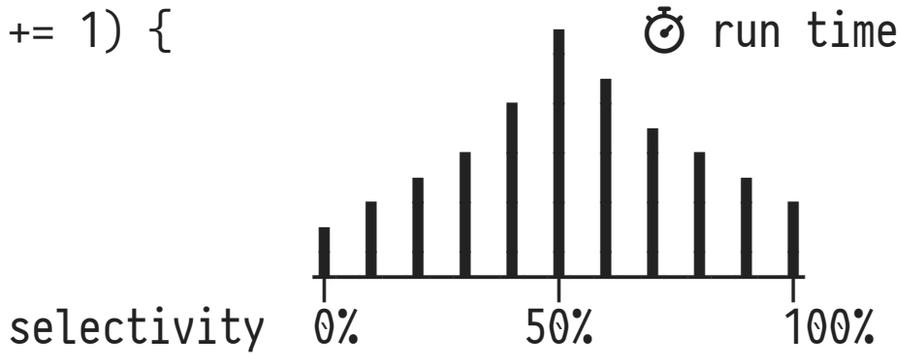
💡 DBMS code aims to avoid branch mispredictions in tight loops:

- Prefer **branch-less** implementations of operator logic,
  or at least
- reduce the number of random/hard-to-predict branches.

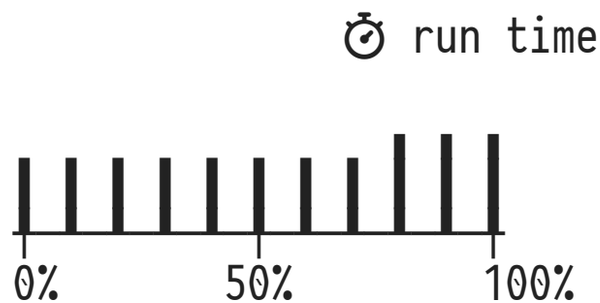
Branch-Less Filtering

Measure wall-clock run time of core FILTER loop for different **selectivities** of predicate col < val:

❶
```
for (i = 0; i < STANDARD_VECTOR_SIZE; i += 1) {
    if (col[i] < val) {
        res[o] = i;
        o += 1;
    }
}
```



❷
```
for (i = 0; i < STANDARD_VECTOR_SIZE; i += 1) {
    res[o] = i;
    o += (col[i] < v);
}
```
≡ 1 if predicate satisfied, else 0



❷: Only well-predictable loop control flow (**for**) remains. 👍

Mixed-Mode Selection

There is an entire space of possibilities to implement composite predicates (e.g., the conjunction p_1 AND p_2):

- Use branch-less selection via `o += p1 & p2` (NB. uses of C's bit-wise *and* operator `&`).
- Identify the *more selective*[7] (and thus more predictable) conjunct p_1, say, then use

```
if (p1) {
   res[o] = i;
   o += (p2);
}
```

#030

(This approach particularly fits DBMSs that generate code from SQL queries—which DuckDB does *not* do.)

[7] ⚠ **This is important.** If p_2 is unpredictable then the mixed-mode selection `if (p2) { … o += (p1) }` will suffer from branch misprediction.