RustFest Global 2020

Architect a High-performance SQL Query Engine in Rust

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Outline

- Introduction
- Related works
- Engineering in Rust
- System and Language
- Execution
- Evaluation
- Future insights

Introduction

- **Jin Mingjian**
- Ph.D., Data nerd
- Fields: bigdata engineering, high performance infrastructure, language and system
    - Cassandra, Spark, Impala, Kudu, ClickHouse...
    - jinmingjian.xyz/resume

Introduction

- For this talk
  - **Works and practices** in my recent open-source project TensorBase which is building a modern big data warehouse with Rust and its friend C
  - So, all working codes which covered or not covered in this talk are available in the site: **tensorbase.io**

Introduction

- For audiences of this talk
    - Keep content **as simple as possible**
        - Indeed both high performance and bigdata system are hard
    - Implementation details are ignored intentionally
        - All are available on the project sites
    - Ask questions, re-read this presentation or join the community

Related works

- Related projects in Rust
    - [DataFusion](https://github.com/apache/arrow/tree/master/rust/datafusion)
        - Use (but not control) Apache Arrow
        - Far-from-performance-oriented architecture: Mixed Arrow and Rust operator impls (in AOT) (traditional design)
        - (opensource) Spark is a bottom baseline from the view of performance
            - The state-of-the-art speed is 100x faster than that of Spark

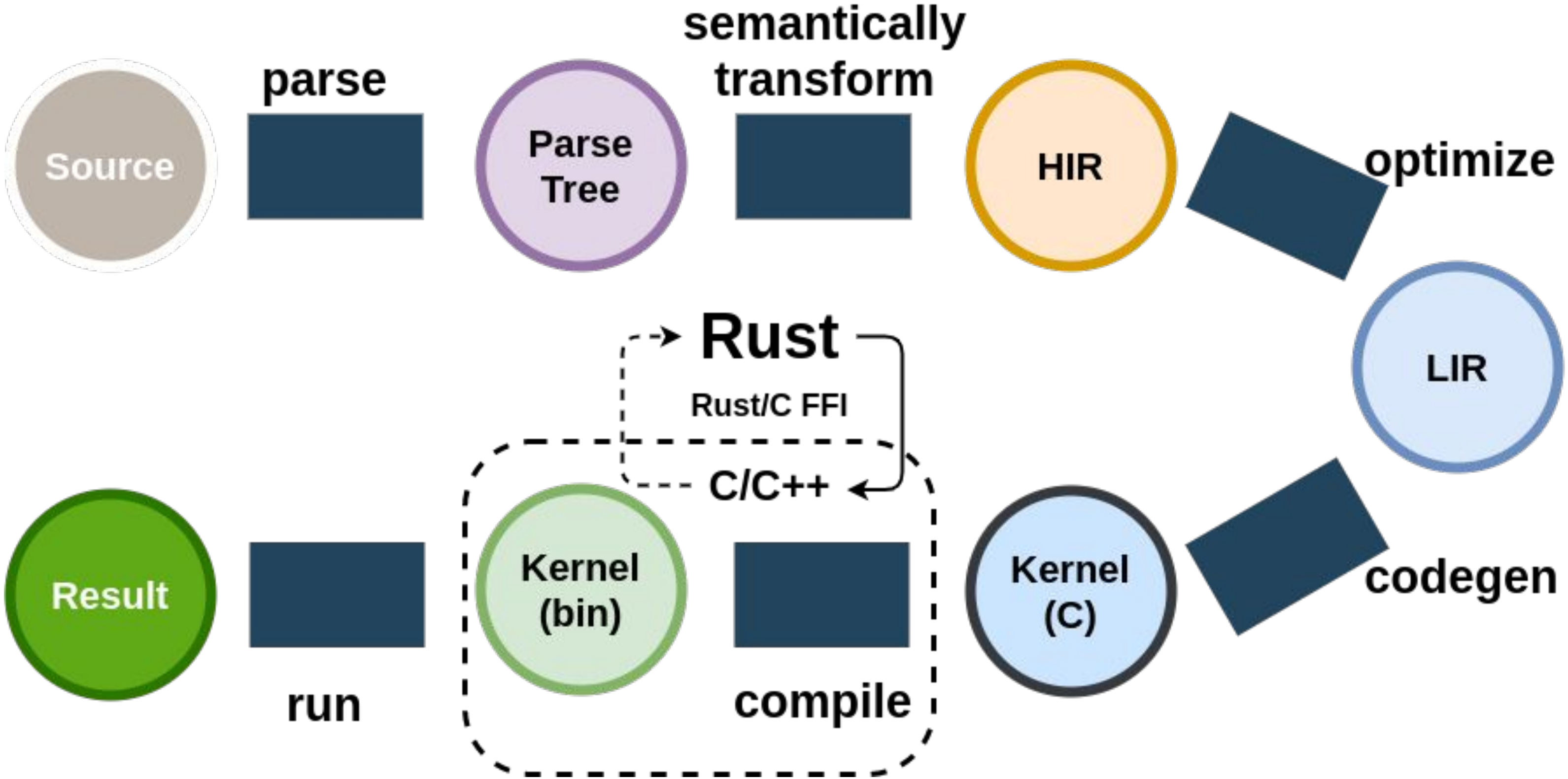
Related works

- Ruby Y. Tahboub et. al., "How to Architect a Query Compiler, Revisited"
    - Paper only but inspires TensorBase
    - Generative programming v.s. TensorBase's pipeline based IR and literal codegen
    - Generative representations on op-level are verbose and slow to compile
    - (generative) Style is **orthogonal to performance**

Related works

- Shoumik Palkar et. al., "Weld: A Common Runtime for High Performance Data Analytics"
  - Dedicated Weld IR for data vs TenosrBase's in-language IR
    - Abstract overhead
  - Deep binding to LLVM apis which is hard to upgrade without LLVM experts
- Problem of academic papers
  - Less engineering oriented
  - Hard to be validated by the public

Engineering in Rust



Engineering in Rust

- Engineering
    - **Engineering oriented language** design makes development agile and comfortable
    - TensorBase benefits from
        - Crates ecosystem, cargo, tooling/IDE, modules, macros, language(memory safe), language(zero-overhead C interop), language(ADT)
        - TensorBase: **one-person project** in several months (hope more to join in:)

Engineering in Rust

- General aspects of TensorBase in engineering
  - Performance designed in core
  - Modernization
    - Bleeding edge nightly
    - Good practices
  - KISS
    - Minimization of Dependencies
    - Highly hackable

Engineering in Rust

- Cargo
    - Highly extensible
    - Useful commands (except that most commonly used):
        - ***add***: for add latest version of deps
        - ***expand***: for proc macro debugging
        - ***tree***: for transitive deps checking

Engineering in Rust

- Proc macro
    - Problems
        - Learning curve is high
        - Too many out-of-date materials but less practices
        - Tooling is in primary stage
        - Hard to debug

Engineering in Rust

- Proc macro (cont.)
  - Suggestions
    - use **nightly** as possible
    - enable feature nightly ***proc_macro_diagnostic***, ***proc_macro_span*** for better debugging output
    - Proc_macro2 should improve the testability

Engineering in Rust

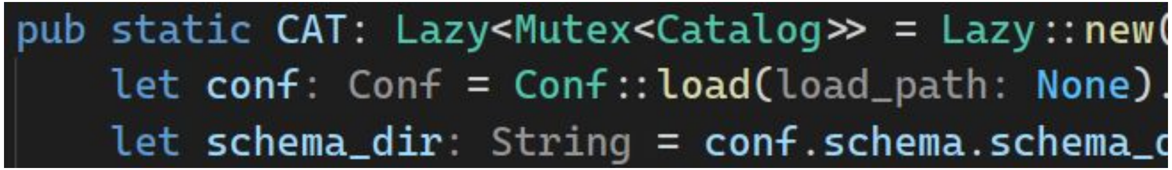
- C interoperability
  - Zero overhead
  - Resource management
    - Objects in C is managed manually but not in safe Rust
  - Error handling
  - Too many “unsafe”s and “as”
    - Nice watch PR: [RFC - Safer Transmute](/rfcs/pull/2981)

Engineering in Rust

- Concurrency
  - Nice for share-nothing thread safety
  - Awkward when memory sharing needed
    - Memory sharing - cornerstone of modern multicores
    - High frequency copy is a performance disaster
    - “Channel” is behind on sharing
  - Lack memory model like in Java/C++

Engineering in Rust

- Concurrency (cont.)
  - E.g. Global (Safe) Sharing/Singleton



```
pub static CAT: Lazy<Mutex<Catalog>> = Lazy::new
    let conf: Conf = Conf::load(load_path: None)
    let schema_dir: String = conf.schema.schema_
```

Question: Oneshot change to the global but not at the declaration point?

Safe Rust: Lazy lock

Comment: Locks are heavy. It could be safe if have change(write) “happens before” use(read) (common high-perf pattern in Java)

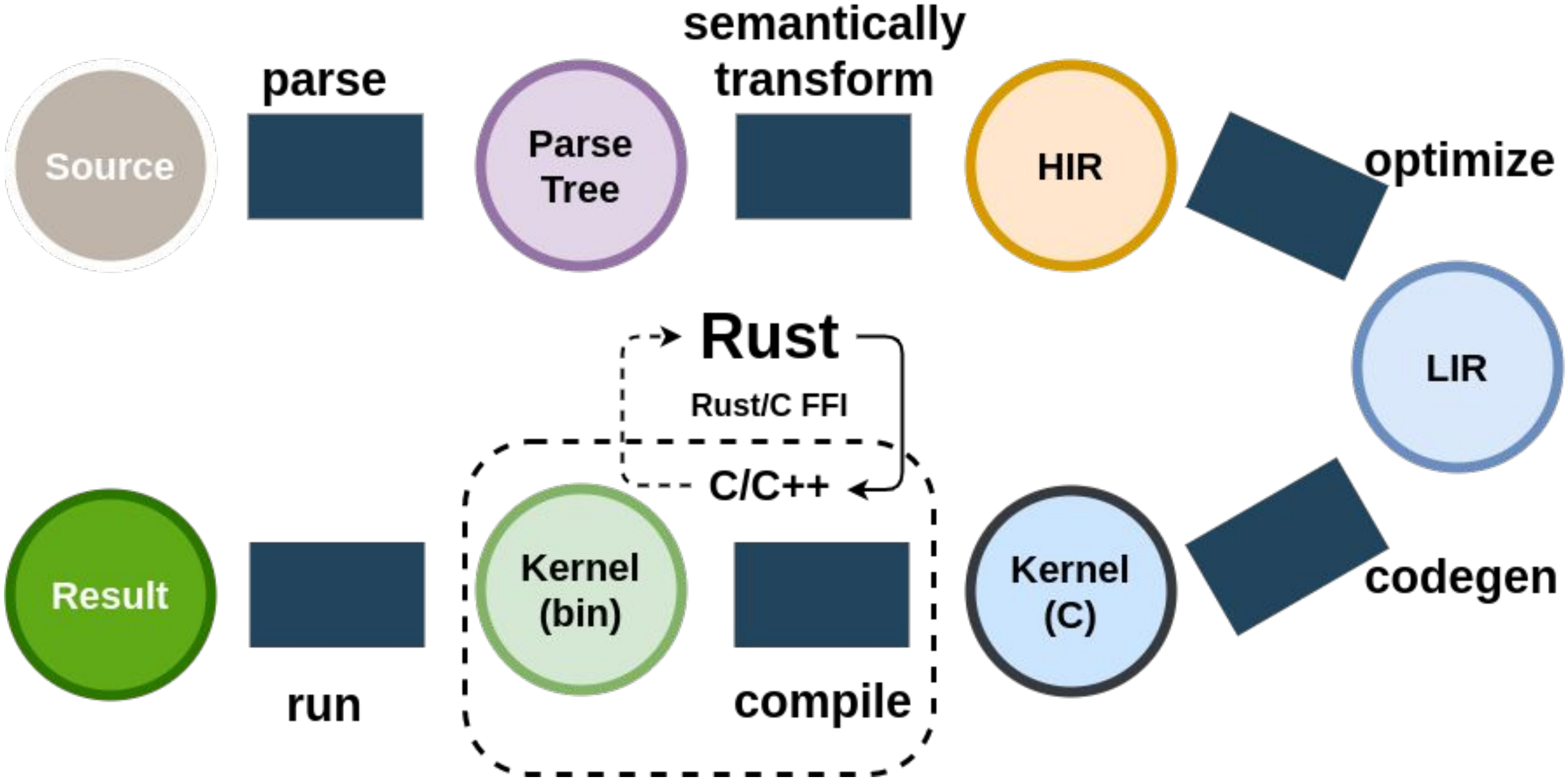
Engineering in Rust

- Concurrency (cont.)
    - Async-await
        - Style is **orthogonal to performance**
        - Great concept but too deep boxing in kinds of implementations
            - Hard to debug when something wrong
        - Not used in TensorBase now

Engineering in Rust

- Lifetime
  - Engineering excellence but make codes complex
    - Always recommends: to dance with, rather than to evade
    - Compiler enforces more than that needed when not smart
  - Alternatives
    - Arena allocator: TensorBase IR
    - Unsafe into C: TensorBase kernel algorithms in C

System


Source
parse
Parse Tree
semantically transform
HIR
optimize
LIR
codegen
Kernel (C)
compile
Kernel (bin)
C/C++
Rust
Rust/C FFI
run
Result

Language

- Input
    - Query: Plain SQL
        - Not necessarily SQL
- Parse Tree
    - PEG, based on [Pest](https://github.com/pest-parser)
    - Lexical validation
    - (free-style) AST

Language

- IR (Intermediate Representation)
  - Layered
  - No reinventing
    - Reuse modern low-level compilation infra as possible
    - Many optimizations in popular engines not needed any more
    - e.g. CSE(Common Subexpression Elimination)
    - select (a+123) as c1, (a+123)*2 as c2 from …

Language

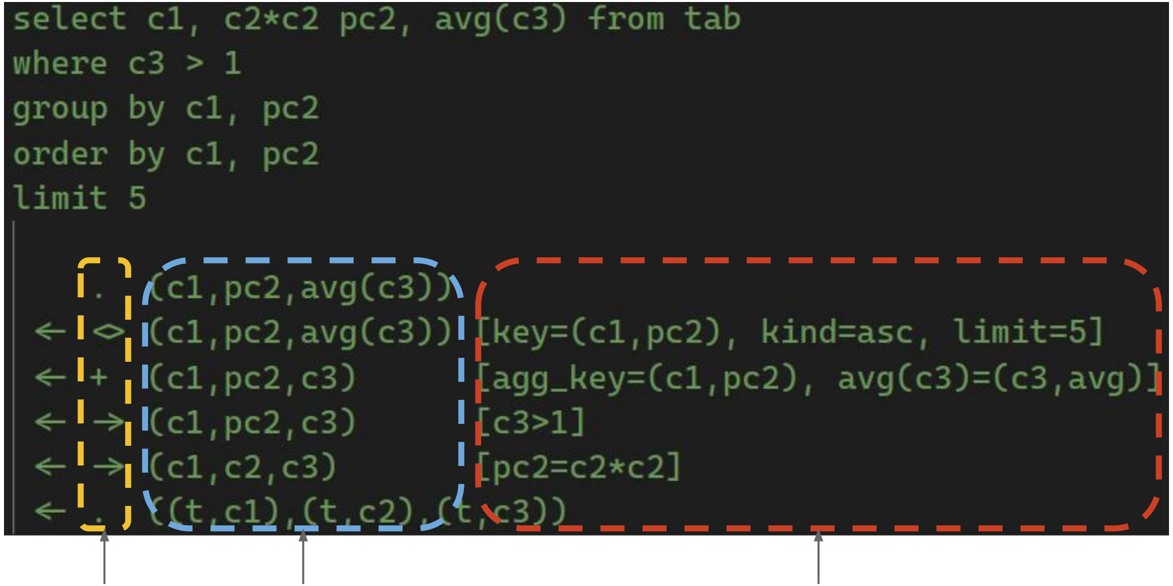
- HIR (High-level IR)
    - Data related optimizations which can be not handled by low levels compilers
        - Semantic validation
        - Relational Algebra
            - e.g. predicate pushdown
        - Some RAs can be optimized by low-level compiler

Language

- HIR (High-level IR) (cont.)
    - Unified RA operators
        - Core: 4 ops
        - ->(map), +(union/agg), *(join), <>(sort/top)
        - Inspired by J. Kepner's associative array
        - In Rust...

Language

Prettyprinted Dump of HIR



```
select c1, c2*c2 pc2, avg(c3) from tab
where c3 > 1
group by c1, pc2
order by c1, pc2
limit 5

     . (c1,pc2,avg(c3))
  ←  <> (c1,pc2,avg(c3)) [key=(c1,pc2), kind=asc, limit=5]
  ←  +  (c1,pc2,c3)      [agg_key=(c1,pc2), avg(c3)=(c3,avg)]
  ←  →  (c1,pc2,c3)      [c3>1]
  ←  →  (c1,c2,c3)       [pc2=c2*c2]
  ←  .  ((t,c1),(t,c2),(t,c3))
```

op

data

op attributes

Language

- “Sea of pipes”
    - Unify data and control-flow dependencies in graph of "pipes"
- Pipe (a.k.a. Pipeline) (note: back to the dump)
    - Operator-fused computing/data unit (being extended to more)
    - Operator-level volcano model is systematically low inefficient
    - Unified dual view - Data and Op
    - No more pull or push style, no more data center or control center

Language

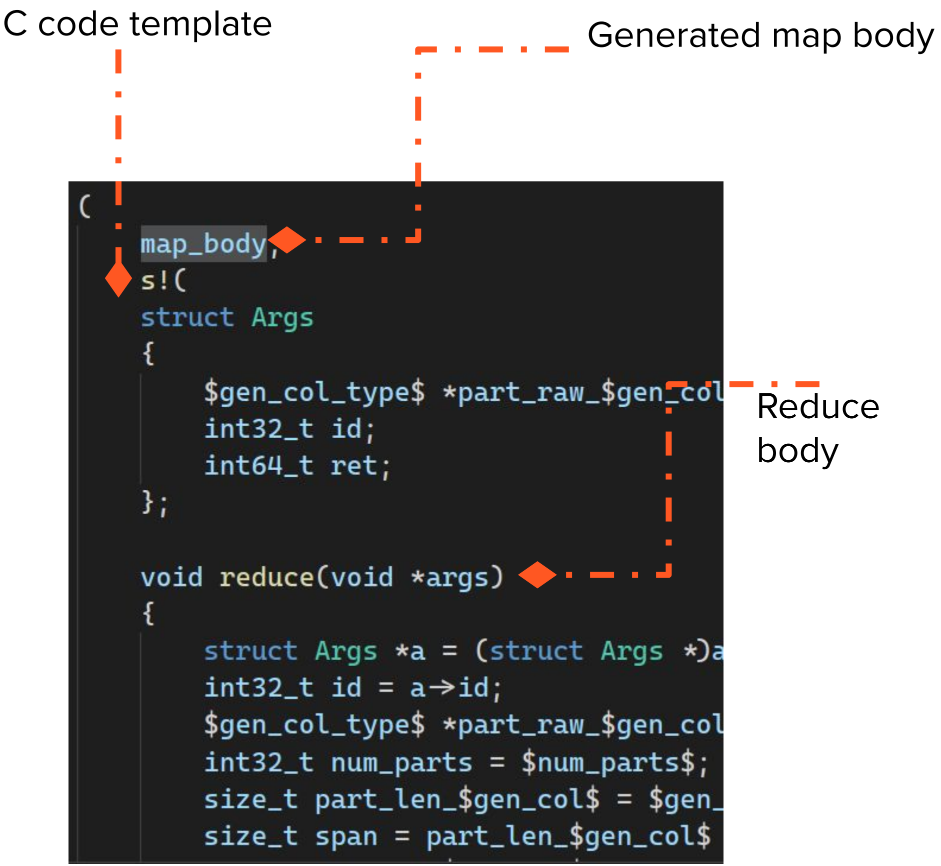
- LIR (Low-level IR)
    - Low level optimizations which can be not handled by low level compilers and not conveniently handled by high level logics
    - Platform related semantics
        - e.g. multi-cores + codegen
        - Boundaries between the high and low are not fixed
        - Scheduling will join later

Language

- LIR (Low-level IR) (cont.)
  - Parallelization representation for multi-cores
    - Generic DAG scheduling has abstract overhead
    - TensorBase: enable parallelism patterns
      - Map/reduce, fork-join...
  - Linearization representation for codegen
    - Proc macro template: provide human readable linear mapping from LIR to C primitives

Language

- LIR (Low-level IR) (cont.)
    - Right C template enables a simple map reduce pattern
    - Free style human oriented string interpolation
    - Runnable and debuggable in IDE with some setups



C code template

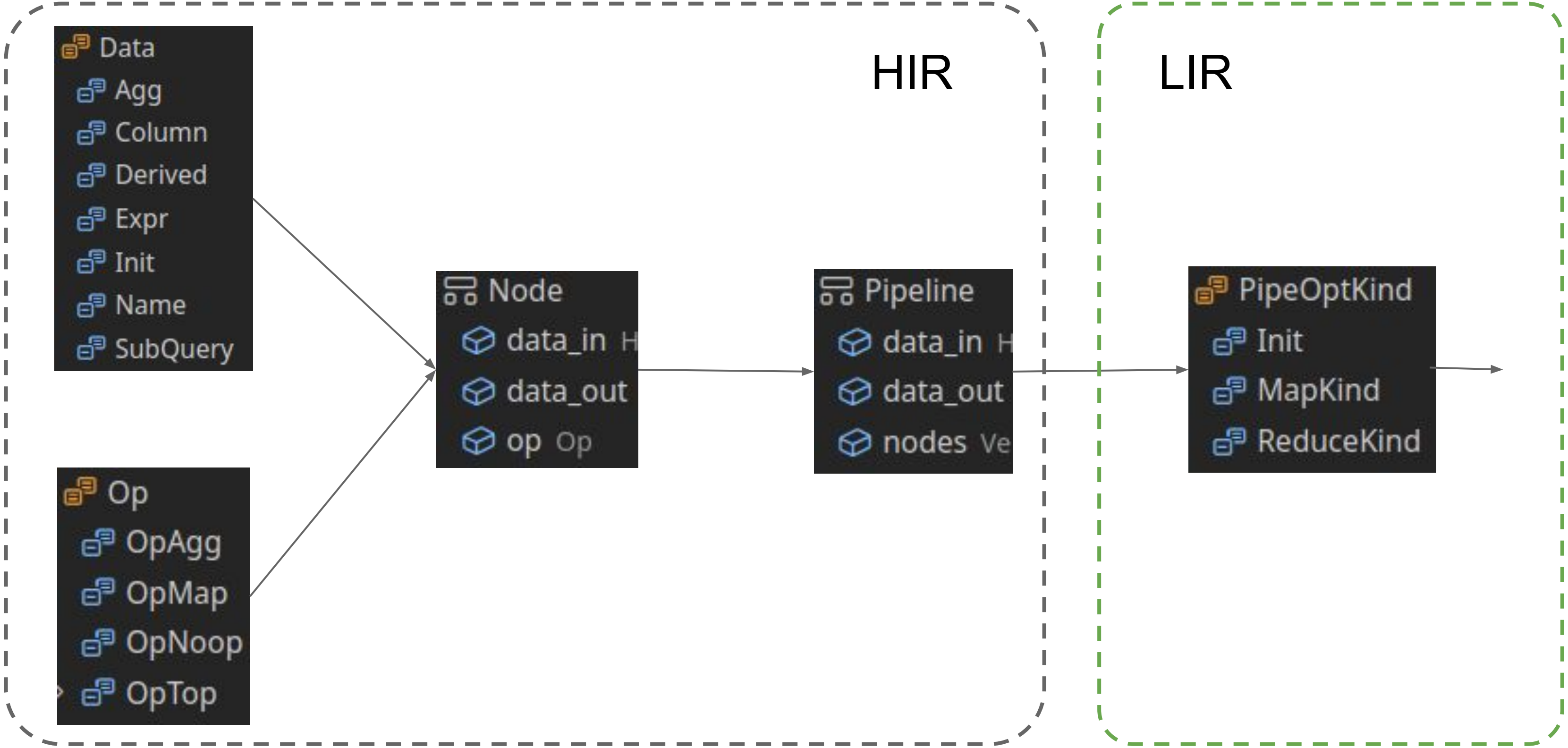
Generated map body

Reduce body

```
(
    map_body;
    s!(
    struct Args
    {
        $gen_col_type$ *part_raw_$gen_col
        int32_t id;
        int64_t ret;
    };

    void reduce(void *args)
    {
        struct Args *a = (struct Args *)a
        int32_t id = a->id;
        $gen_col_type$ *part_raw_$gen_col
        int32_t num_parts = $num_parts$;
        size_t part_len_$gen_col$ = $gen_
        size_t span = part_len_$gen_col$
```

Language



HIR

- Data
  - Agg
  - Column
  - Derived
  - Expr
  - Init
  - Name
  - SubQuery
- Op
  - OpAgg
  - OpMap
  - OpNoop
  - OpTop
- Node
  - data_in H
  - data_out
  - op Op
- Pipeline
  - data_in H
  - data_out
  - nodes Ve

LIR

- PipeOptKind
  - Init
  - MapKind
  - ReduceKind

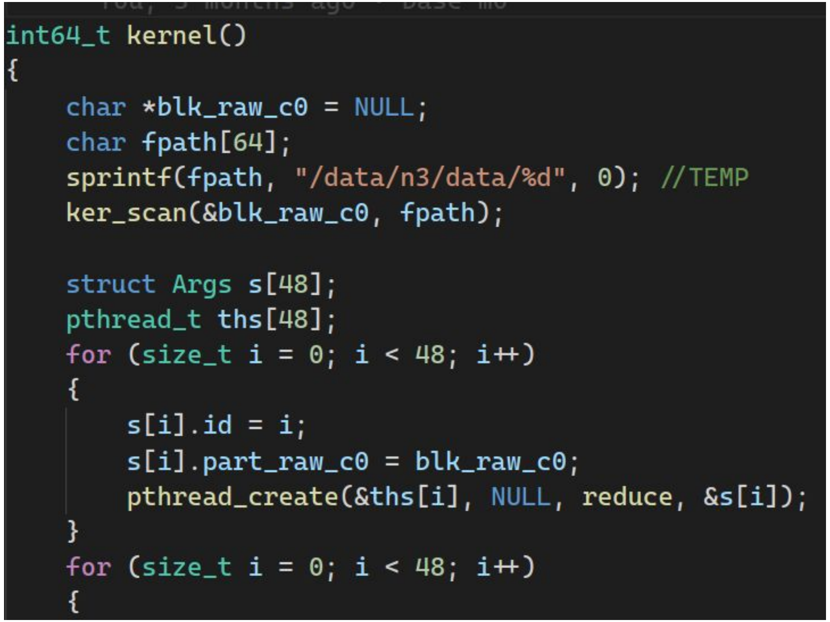
Execution

- Core
    - Decentralized, self-scheduling, JIT compilation based kernel
    - Decentralized != embarrassingly parallel
        - v.s. Popularly centralized scheduling
    - Why JIT compilation
        - Top performance
        - Arch agnostic

Execution

- Engine
  - Modified Clang based C JIT compiler
  - vs. popular LLVM IR based JIT engine(ClickHouse, Apache Impala...)
- Why C
  - Run on (almost) everything (CPU/GPU/FPGA/Accel)
  - Human debuggable
  - Fast enough compilation for OLAP

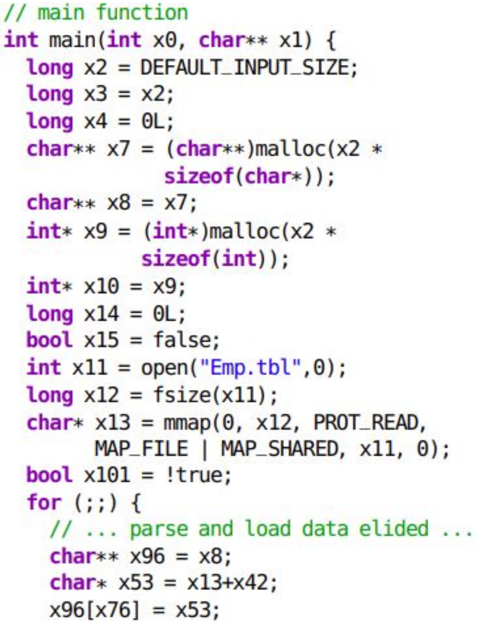
Execution



```
int64_t kernel()
{
    char *blk_raw_c0 = NULL;
    char fpath[64];
    sprintf(fpath, "/data/n3/data/%d", 0); //TEMP
    ker_scan(&blk_raw_c0, fpath);

    struct Args s[48];
    pthread_t ths[48];
    for (size_t i = 0; i < 48; i++)
    {
        s[i].id = i;
        s[i].part_raw_c0 = blk_raw_c0;
        pthread_create(&ths[i], NULL, reduce, &s[i]);
    }
    for (size_t i = 0; i < 48; i++)
    {
```

v.s.



```
// main function
int main(int x0, char** x1) {
  long x2 = DEFAULT_INPUT_SIZE;
  long x3 = x2;
  long x4 = 0L;
  char** x7 = (char**)malloc(x2 *
              sizeof(char*));
  char** x8 = x7;
  int* x9 = (int*)malloc(x2 *
            sizeof(int));
  int* x10 = x9;
  long x14 = 0L;
  bool x15 = false;
  int x11 = open("Emp.tbl",0);
  long x12 = fsize(x11);
  char* x13 = mmap(0, x12, PROT_READ,
        MAP_FILE | MAP_SHARED, x11, 0);
  bool x101 = !true;
  for (;;) {
    // ... parse and load data elided ...
    char** x96 = x8;
    char* x53 = x13+x42;
    x96[x76] = x53;
```

TensorBase generated kernel

Ruby Y. Tahboub et. al., Sigmod18

* André Kohn et. al., DOI: 10.1109/TKDE.2019.2905235

** TensorBase M0 benchmark: https://tensorbase.io/

Evaluation

Phase	Language (TensorBase M0)	Time	Ref Time (from public)	Language (Ref system)
Parsing (TPC-DS)	Rust	130 us**	~50 us*	C++
Parsing/IR/codegen (one column sum)	Rust	130 us**	~1 ms*	C++
C Kernel JIT Compilation	C/C++	**13 ms** (boost) - 20 ms (no boost) (Q#1 like, -O2)**	59 ms* (TPC-H Q#1, opt.)	C++
End-to-end Query Time (one column sum with 1.47B row NYC taxi dataset)	Almost in Rust (mixed)	**~60 ms** (compilation cached)- ~100 ms(compilation uncached)**	642 ms** In ClickHouse 20.05 (compilation cached)	C++

Evaluation

- Points (part 1)
    - Rust is lighting fast even untuned (but not Rust compilation)
    - C based JIT Compilation is lighting fast even untuned (on par with LLVM IR)
    - C based JIT Compilation is much faster than C++ (and Rust) even untuned
    - C based JIT Compilation is quite enough for OLAP even untuned

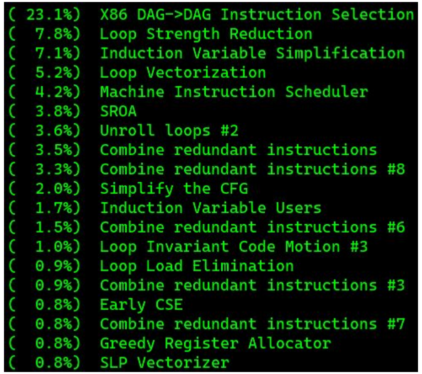
Evaluation

- Points (part 2)
  - Saturates memory bandwidth in core of such runs
    - **Can’t not be faster** in single 6-channel xeon sp with 100GB/s memory bandwidth(measured by vtune) for memory bound applications
    - Napkin math: 1.47*4/100 = ~0.06 sec (= 60msec)
    - Simple sum aggregation query => Tight loop in kernel and finally vectorized by compiler

```
size_t s = 0;
for (size_t i = 0; i < blk_len_c0; i++)
{
    int32_t c0 = blk_c0[i];
    s += c0;
}       You, 3 months ago • base m0
```

Evaluation

- Points (part 3)
    - Partial compilation
        - Makes compilation time of TensorBase is correlated to the size of hot kernel (rather than the total size of execution codes)
    - Lower bound of LLVM compilation overhead is high
        - -O0: ~9ms for helloworld (untuned)
        - Too many passes
        - Speed does not come for free



```
( 23.1%)  X86 DAG->DAG Instruction Selection
(  7.8%)  Loop Strength Reduction
(  7.1%)  Induction Variable Simplification
(  5.2%)  Loop Vectorization
(  4.2%)  Machine Instruction Scheduler
(  3.8%)  SROA
(  3.6%)  Unroll loops #2
(  3.5%)  Combine redundant instructions
(  3.3%)  Combine redundant instructions #8
(  2.0%)  Simplify the CFG
(  1.7%)  Induction Variable Users
(  1.5%)  Combine redundant instructions #6
(  1.0%)  Loop Invariant Code Motion #3
(  0.9%)  Loop Load Elimination
(  0.9%)  Combine redundant instructions #3
(  0.8%)  Early CSE
(  0.8%)  Combine redundant instructions #7
(  0.8%)  Greedy Register Allocator
(  0.8%)  SLP Vectorizer
```

Future insights

- Storage layer
    - Popular storage and compute separation is genetically less efficient
- Optimizer
    - Makes the queries which can not be optimized fastest
    - Data driven, low entropy inference (e.g. category theory)
- Execution engine

Future insights

- Tiered C compilation
  - OLTP style wants faster codegen
  - C compilation/interpretation possibly done in microseconds or less
- Alternative JIT compilation choices
  - e.g. Rust + Cranelift codegen (JIT) backend
- Scheduling

Future insights

- Modern hardware oblivious
- Distributed
  - Techniques on single node does *NOT* mean they only works for single node
  - Consistency as plugin
- Engineering
  - Contracts and formal verifications
  - Rust - C - Rust chaining and maximized engineering Rust

Future insights

- TensorBase 2020.11 (WIP)
  - Main operators on on single table
  - Storage Layer v1
  - Compatibility and hybrid deployment with ClickHouse
    - Compatible to ClickHouse Native Protocol
    - Partially compatible to ClickHouse on-disk data storage (read-only)

Future insights

- TensorBase 2020.11 (WIP) (cont.)
    - Superb in complex aggregations (e.g. group by)
    - Early results (compared to ClickHouse)
        - 6x faster in several “group by” queries on top of ClickHouse MergeTree storage with a real-world billion level dataset
        - 10x faster if do some simple optimizations
        - Faster results expected when TensorBase own storage coming

Recap

- **Abstract overhead** everywhere
  - Carefully make trade-offs
- **High-performance programming paradigm** in Rust
  - Safe(almost) + unsafe (bounded but more freedom)
- **Top performance** OLAP is firstly achieved with **engineering Rust**
  - All shown can be picked up from the open source project (tensorbase.io)

Thanks