第十八讲：MySQL 执行器的设计与实现

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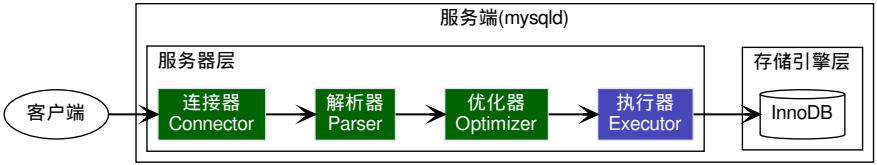
前情提要

本节内容



- 连接器
  - ☑ 连接管理器 Connection Manager
  - ☑ 线程管理器 Thread Manager
  - ☑ 用户模块 User Module
- 解析器
  - ☑ 网络模块 Net Module
  - ☑ 派发模块 Commander Dispatcher
  - ☑ 词法分析 Lexical Analysis
  - ☑ 语法分析 Syntax Analysis
- 优化器
  - ☑ 准备模块 Prepare Module
  - ☑ 追踪日志 Optimizer Trace
  - ☑ 优化模块 Optimize Module
- 执行器
  - ☐ 火山模型 Volcano Model
  - ☐ 执行模块 Execution Module

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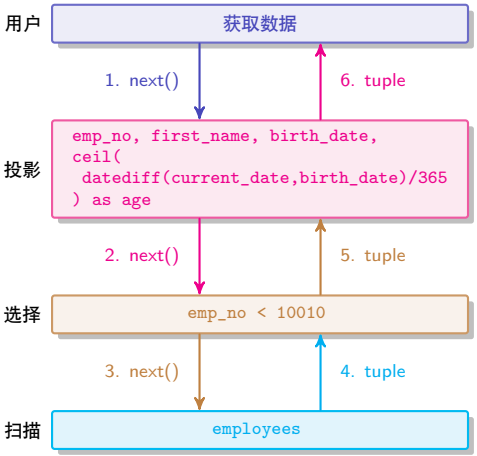
火山模型

火山模型

- 数据库中的火山模型 (Volcano Model)，又称为迭代器模型
  - 最早由 Goetz Graefe 在 1990 年代提出
  - 旨在解决早期数据库系统中由于硬件资源限制所带来的性能问题
  - 是一种面向数据流的查询执行模型，在各种数据库系统中应用最广泛
- 火山模型将关系代数中的每一种操作 (Operator) 抽象为一个迭代器 (Iterator)
  - 操作如扫描 (Scan)、选择 (Selection)、投影 (Projection)、连接 (Join) 等
  - 火山模型的执行树是通过 Operator 构成，每个 Operator 是执行树的一个节点
  - 实际执行时，根节点到叶子节点自上而下地递归调用 next() 函数，实现数据的处理和传递
- 每个迭代器都遵循 open-next-close 协议进行工作，分别实现以下接口
  - open 方法用于初始化迭代器
  - next 方法用于获取下一行数据
  - close 方法用于释放资源
- 除了火山模型，还有以下执行器模型
  - Materialization Model (物化模型)
  - Vectorized / Batch Model (批式模型)

火山模型示例



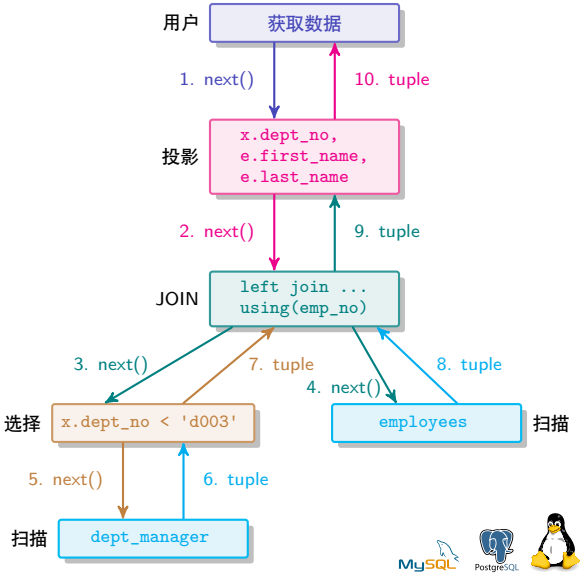
- 火山模型采用拉的形式驱动
- 每层调用 next() 函数，返回 tuple 结果
- 右图是下面测试查询语句的执行示意图

```sql
select
  emp_no,
  first_name,
  birth_date,
  ceil(datediff(current_date, birth_date)/365)
    as age
from
  employees
where
  emp_no < 10010;
```

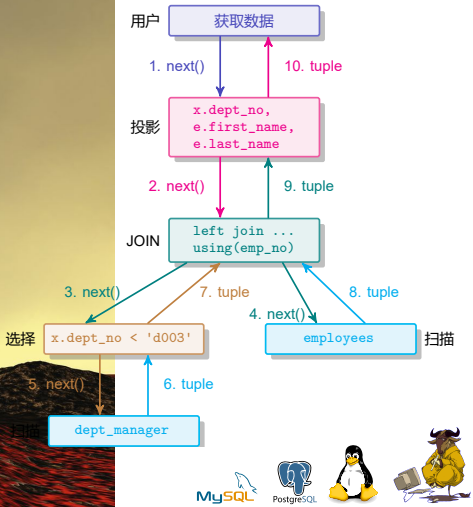
火山模型示例贰

- 两表 Join 的查询

```
1  select
2    x.dept_no,
3    e.first_name,
4    e.last_name
5  from
6    dept_manager x
7    left join
8      employees e
9        using (emp_no)
9  where
10   x.dept_no < 'd004';
```



火山模型示例


用户
获取数据
1. next()
10. tuple
投影
x.dept_no,
e.first_name,
e.last_name
2. next()
9. tuple
JOIN
left join ...
using(emp_no)
3. next()
7. tuple
8. tuple
4. next()
选择
x.dept_no < 'd003'
employees
扫描
5. next()
6. tuple
dept_manager
MySQL
PostgreSQL

迭代器实现

- RowIterator 类是所有迭代器的基类 [1]，它通过纯虚函数声明必要的接口
- RowIterator 类对的 open-next-close 协议的实现如下表

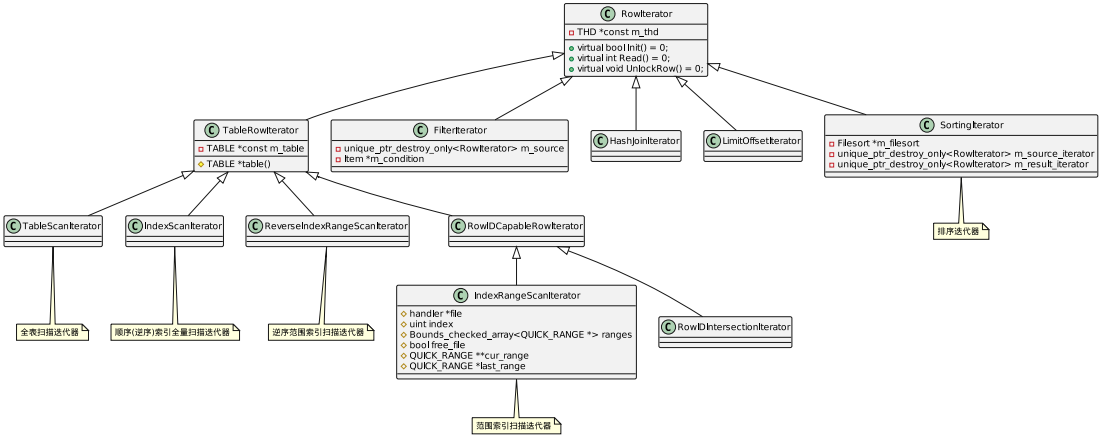
协议中的接口	RowIterator 类的方法	功能说明
open	`RowIterator::Init()`	打开所有必须的资源
next	`RowIterator::Read()`	读取一行，将行放入记录缓存中
close	`RowIterator::UnlockRow()`	将一行过滤出结果集后

- RowIterator 在 ☞ sql/iterators/row_iterator.h 中实现

```
82  class RowIterator {
83   public:
84    // NOTE: Iterators should typically be instantiated using NewIterator,
85    // in sql/iterators/timing_iterator.h.
86    explicit RowIterator(THD *thd) : m_thd(thd) {}
87    virtual ~RowIterator() = default;
```

[1] https://dev.mysql.com/doc/dev/mysql-server/8.0.37/classRowIterator.html

RowIterator 相关类继承关系



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执行阶段

创建访问路径 AccessPath

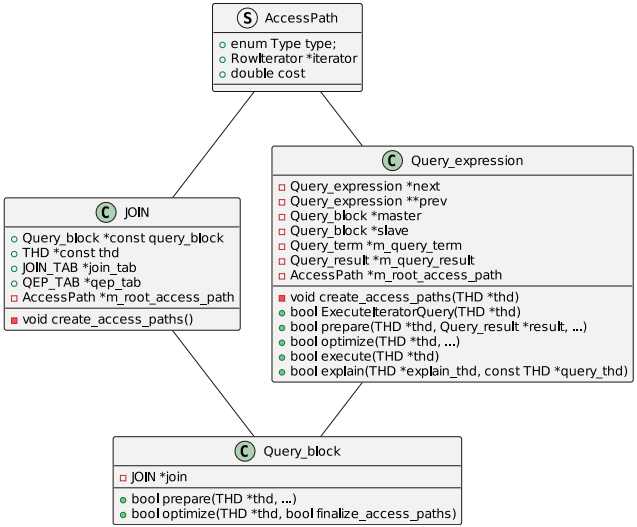
- 优化器生成执行路径 `JOIN::create_access_paths()` ☞ sql/sql_executor.cc

```
2959  void JOIN::create_access_paths() {
2960    assert(m_root_access_path == nullptr);
2961
2962    AccessPath *path = create_root_access_path_for_join();
2963    path = attach_access_paths_for_having_and_limit(path);
2964    path = attach_access_path_for_update_or_delete(path);
2965
2966    m_root_access_path = path;
2967  }
```

- 优化器生成执行路径 `Query_expression::create_access_paths()` ☞ sql/sql_union.cc

```
1417  void Query_expression::create_access_paths(THD *thd) {
1418    if (is_simple()) {
1419      JOIN *join = first_query_block()->join;
1420      assert(join && join->is_optimized());
1421      m_root_access_path = join->root_access_path();
1422      return;
1423    }
1424    // ...
```

AccessPath 关系类图

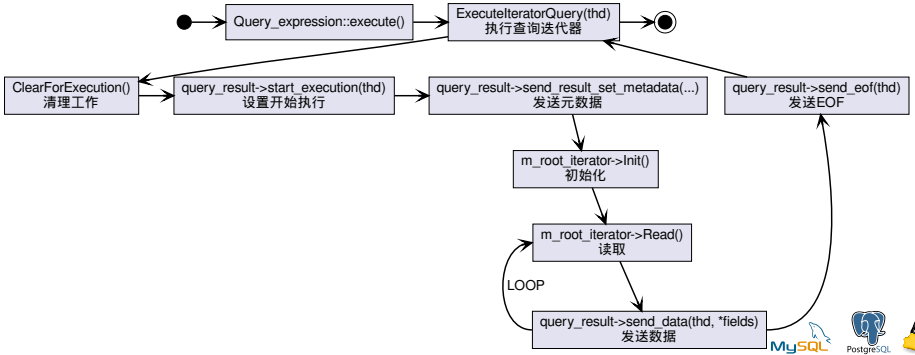


迭代执行过程

- 执行路径创建迭代器 ☞ sql/join_optimizer/access_path.cc

```
378  unique_ptr_destroy_only<RowIterator> CreateIteratorFromAccessPath(
379      THD *thd, MEM_ROOT *mem_root, AccessPath *top_path, JOIN *top_join,
380      bool top_eligible_for_batch_mode) {
381    assert(IteratorsAreNeeded(thd, top_path));
```

- 然后通过火山模型执行并发送结果给客户端



迭代器执行细节

- Query_expression::ExecuteIteratorQuery() 在 ☞ sql/sql_union.cc 中实现

```
bool Query_expression::ExecuteIteratorQuery(THD *thd) {
    // ...
    if (m_root_iterator->Init()) {
      return true;
    }
    for (;;) {
      int error = m_root_iterator->Read();
      // ...
      if (query_result->send_data(thd, *fields)) {
        return true;
      }
      thd->get_stmt_da()->inc_current_row_for_condition();
    }
  }
  // ...
  return query_result->send_eof(thd);
}
```

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代码调试

调试语句 exe01.sql

```
mysql> \. exe01.sql
+--------+------------+------------+------+
| emp_no | first_name | birth_date | age  |
+--------+------------+------------+------+
|  10001 | Georgi     | 1953-09-02 |   71 |
|  10002 | Bezalel    | 1964-06-02 |   61 |
|  10003 | Parto      | 1959-12-03 |   65 |
|  10004 | Chirstian  | 1954-05-01 |   71 |
|  10005 | Kyoichi    | 1955-01-21 |   70 |
|  10006 | Anneke     | 1953-04-20 |   72 |
|  10007 | Tzvetan    | 1957-05-23 |   68 |
|  10008 | Saniya     | 1958-02-19 |   67 |
|  10009 | Sumant     | 1952-04-19 |   73 |
+--------+------------+------------+------+
9 rows in set (0.01 sec)
```

- 运行 exe01.sql 查询语句并调试结果

```
1  select
2    emp_no,
3    first_name,
4    birth_date,
5    ceil(datediff(current_date, birth_date)/365)
6      as age
7  from
8    employees
9  where
10   emp_no < 10010;
```

添加调试的关键断点

- 在创建 AccessPath 和 Iterator 处添加断点

```
b create_access_paths
b CreateIteratorFromAccessPath
b ExecuteIteratorQuery
```

- 查看断点

```
(gdb) i b
Num     Type           Disp Enb Address            What
4       breakpoint     keep y   0x0000555558d14072 in JOIN::create_access_paths()
                                  at /opt/src/mysql-server/sql/sql_executor.cc:2960
        breakpoint already hit 15 times
5       breakpoint     keep y   <MULTIPLE>
        breakpoint already hit 29 times
5.1                           y   0x0000555558d14072 in JOIN::create_access_paths()
                                  at /opt/src/mysql-server/sql/sql_executor.cc:2960
5.2                           y   0x0000555558ee0487 in Query_expression::create_access_paths(THD*)
                                  at /opt/src/mysql-server/sql/sql_union.cc:1417
6       breakpoint     keep y   <MULTIPLE>
        breakpoint already hit 26 times
6.1                           y   0x0000555558d23b78 in CreateIteratorFromAccessPath(THD*, AccessPath*, JOIN*, bool)
                                  at /opt/src/mysql-server/sql/join_optimizer/access_path.h:1730
6.2                           y   0x000055555938badc in CreateIteratorFromAccessPath(THD*, MEM_ROOT*, AccessPath*, JOIN*,
                                  at /opt/src/mysql-server/sql/join_optimizer/access_path.cc:380
(gdb)
```

Trace 日志片段分析

通过 mysqld.trace 日志 [1] 可以观察执行器执行的详细逻辑

```
T@10: | | | | | >Query_expression::execute <= 进入执行器
T@10: | | | | | | THD::enter_stage: 'executing' /opt/src/mysql-server/sql/sql_union.cc:1670
...
T@10: | | | | | | >InitIndexRangeScan <= 初始化火山模型
T@10: | | | | | | | >handler::ha_index_init
T@10: | | | | | | | | >int ha_innobase::index_init
T@10: | | | | | | | | | >ha_innobase::change_active_index
T@10: | | | | | | | | | | >dict_index_t* ha_innobase::innobase_get_index
...
T@10: | | | | | | >int IndexRangeScanIterator::Read <= 读取一条数据，后续陆续读取 n 条
T@10: | | | | | | | >handler::ha_multi_range_read_next
T@10: | | | | | | | | >int handler::multi_range_read_next
T@10: | | | | | | | | | >int handler::read_range_first
T@10: | | | | | | | | | | >handler::ha_index_first
T@10: | | | | | | | | | | | >int ha_innobase::index_first
T@10: | | | | | | | | | | | | | >int ha_innobase::index_read
T@10: | | | | | | | | | | | | | | | >row_search_mvcc
...
T@10: | | | | | | <int IndexRangeScanIterator::Read
T@10: | | | | | | >bool Query_result_send::send_data
...
T@10: | | | | | | | >bool Protocol_classic::end_row  <= 发送数据结果
T@10: | | | | | | | | net write: Memory: 0x7fff30006500  Bytes: (27)
05 31 30 30 30 31 06 47 65 6F 72 67 69 0A 31 39 35 33 2D 30 39 2D 30 32 02 37
31
```

结束