Near Storage SQL Processing
MIT CSAIL Research Proposal

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1 Introduction

With the ever-growing data collected and available, technology for fast and efficient data storage is becoming increasingly crucial for supporting complex queries on large datasets. For big-data applications, a large number of analytic platforms rely on relational database systems, such as MySQL and Postgres, to store large datasets and running complex SQL queries. An SQL database system brings data from flash drive via PCIe bus to CPU cache to perform analysis of the fetched data.

One can improve database system by adding in-storage accelerators in the datapath for processing data-intensive SQL operations. Such a bump-in-the-wire accelerator architecture has two advantages: 1) it reduces the amount of disk IOs, and 2) it can fully utilize internal storage bandwidth. For lots of SQL queries, a large data set is scanned and only a small set of results is produced. Therefore, disk IOs can be reduced dramatically by offloading SQL operations to the secondary storage. The second benefit comes from the imbalance between the storage network I/O bandwidth and the SSD IO bandwidth. With storage technology advancements, such as 3D NAND flash, the internal bandwidth of flash drives can exceed the PCIe and the network bandwidth. For some advanced flash drives, the internal aggregate bandwidth can be 10X higher than the PCIe bandwidth. Therefore, by offloading IO-intensive SQL operations, one could boost query performance by fully utilizing all the flash bandwidth.

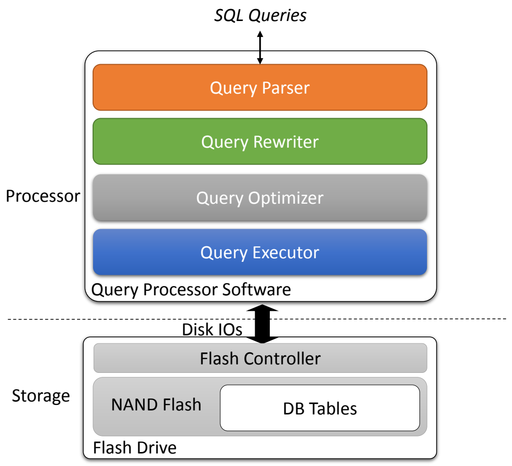
In this proposal, we focus on using in-storage accelerators to improve SQL query processing by offloading *aggregate* and *join* operations, which are both IO-intensive, to the flash drives.

- Aggregate Accelerator: There are five aggregate functions in SQL: AVG, COUNT, MIN, MAX and SUM. Aggregate functions are often used with GROUPBY operation, where rows are grouped based on column values, and each group of rows is summarized by applying the aggregate functions. In order to fully saturate IO, we propose to use a wire-speed accelerator capable of aggregating multiple rows per clock cycle.
- JOIN Accelerator: An SQL JOIN operation combines columns from one or more tables in a relational database. A popular implementation of JOIN operation use the hash join algorithm. To hash join table A and B, a hash table is first constructed with values of a column in table A. Then the values of a column in table B are read to find a match in the hash table. In order to reduce the amount of IOs from flash to CPU, we propose an in-storage accelerator in the data path. The accelerator 1) constructs an in-storage bloom-filter when data from table A is read, 2) uses the constructed bloom filter to reduce the amount of data from table B needed to be sent to CPU for the hash-join.

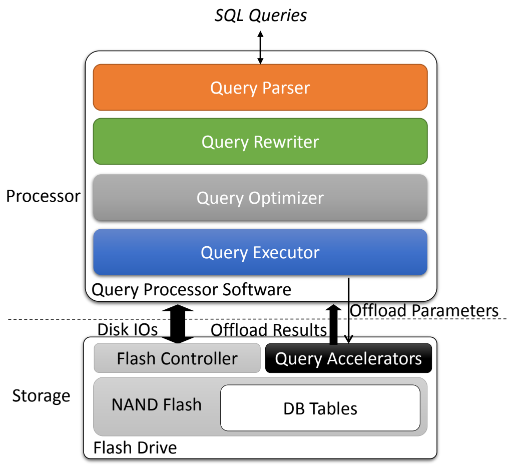
Other IO-intensive operations, such as filtering, are also beneficial for offloading, but we are not focusing on them since they have been fairly well studied.

2 System Architecture

A relational query processor takes a declarative SQL statement, validates it, optimizes it into a procedural dataflow execution plan, and execute that dataflow program on behalf of a client. A relational query processor typically have four major software components 1) Query Parser, 2) Query Rewriter, 3) Query Optimizer and 4)Plan Executor. The first three components generate a query plan, and the Plan Executor then issues disk IOs to the storage device, and execute the plan as shown in Figure 1a. In this proposal, we want to modify the Plan Executor such that it adds a side channel to the storage device. Via this side channel, IO-intensive operations can be offloaded to the accelerators in the flash drive, as shown in Figure 1b. As a result of such a in-storage accelerator architecture, 1) the total IOs between the processor and storage are dramatically reduced, and 2) accelerators can utilize the entire aggregate internal NAND flash bandwidth.



(a) Traditional Query processing stack



(b) Query processing stack with In-storage Accelerators

Figure 1: DBMS Query Processing Architectures

In particular, we propose to offload two important IO-intensive SQL functions inside the in-storage accelerators, Aggregate and JOIN.

2.1 Wire-speed Aggregate Accelerator

Aggregate functions are often used with GROUPBY database operations, where rows are grouped based on column values and each group of rows is summarized by applying the aggregate functions. When number of groups are much smaller than total number of rows in a table, storage IO can be greatly reduced by offloading aggregate functions with GROUPBY to the flash drive.

Due to the large bandwidth of the internal flash drive, multiple rows of data can arrive at the same clock cycle. Previous work on aggregate accelerators typically uses a binary tree to aggregate results, in which case only a row can be processed per clock cycle.

We propose a novel wire-speed aggregate accelerator on wide datapath, in a bump-in-the-wire fashion (See Figure 2). This is achieved by first striping the wide input across an array of single-aggregators, each of which can perform aggregations on a pair of elements every cycle. The resulting streams of aggregated elements are merged together using a hierarchy of multi-aggregators, which use sorting network-based high-throughput merge sorters and an sorting-network-like aggregator network that operate on the duplicate keys that may exist between the streams. All components in the accelerator are pipelined, so that high performance can be achieved without requiring significant on-chip buffers. The details of the accelerator work can be found in the submitted FPL paper attached.

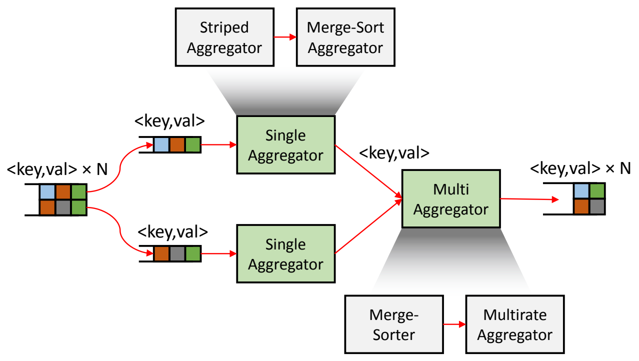


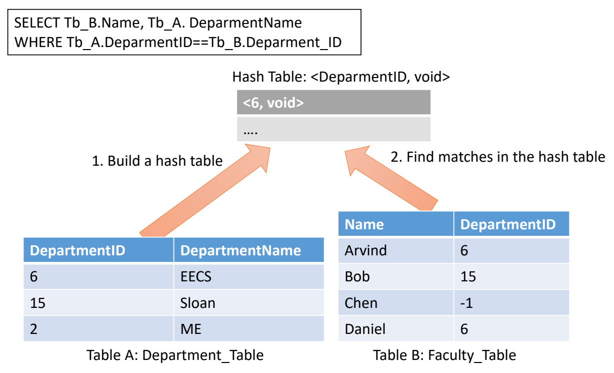
Figure 2: Accelerator architecture overview

2.2 Hash-Join Accelerator

An SQL JOIN operation combines columns from one or more tables in a relational database. A popular implementation of JOIN operations uses the hash join algorithm. JOIN is typically IO-intensive operations because all rows of the joining tables have to be read from the secondary storage.

As show in Figure 3a, to hash-join Table A and B, a hash table is first constructed with values of the departmentID column in table A. Then the values of the departmentID column in table B are fetched to find a match in the hash table. Such an algorithm requires all the data records to be retrieved from the secondary storage to CPU.

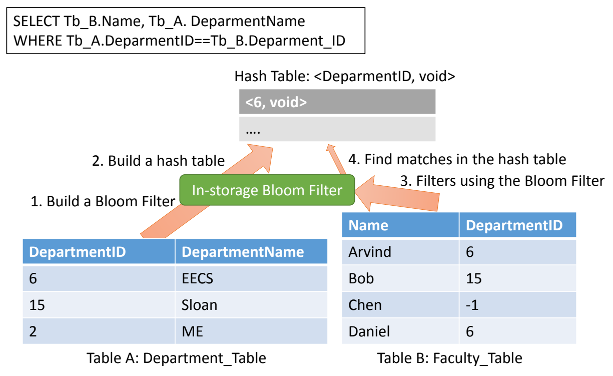
We propose accelerator for hash-join which implements a in-storage bloom-filter in datapath as shown in Figure 3b. When rows of table A is read from flash to CPU for the hash table construction, it constructs a bloom-filter in the datapath. When the rows of table B are streamed from flash to join the hash table, they are filtered with the constructed bloom filter before sending to CPU. If the bloom-filter selectivity is high, i.e., only a relatively few rows need to be joined, such a mechanism can greatly reduced required IO from storage to CPU.


SELECT Tb_B.Name, Tb_A. DeparmentName
WHERE Tb_A.DeparmentID==Tb_B.Deparment_ID
Hash Table: <DeparmentID, void>
<6, void>
....
1. Build a hash table
2. Find matches in the hash table
Table A: Department_Table
Table B: Faculty_Table

DepartmentID	DepartmentName
6	EECS
15	Sloan
2	ME

Name	DepartmentID
Arvind	6
Bob	15
Chen	-1
Daniel	6

(a) Hash-join Operations without accelerators


SELECT Tb_B.Name, Tb_A. DeparmentName
WHERE Tb_A.DeparmentID==Tb_B.Deparment_ID
Hash Table: <DeparmentID, void>
<6, void>
....
2. Build a hash table
4. Find matches in the hash table
3. Filters using the Bloom Filter
1. Build a Bloom Filter
In-storage Bloom Filter
Table A: Department_Table
Table B: Faculty_Table

DepartmentID	DepartmentName
6	EECS
15	Sloan
2	ME

Name	DepartmentID
Arvind	6
Bob	15
Chen	-1
Daniel	6

(b) Accelerated Hash-join Operations with In-storage Bloom filter

Figure 3: Hash-join Operations

3 Evaluation Benchmarks

To evaluate the work, we propose to run some synthetic SQL queries with aggregate functions and join, as well as some queries from TPC-H, and TPC-DS. By comparing the same query on the same dataset running on the traditional relational database systems, such as MySQL and Postgres, we can illustrate the performance benefits of the new architecture with accelerators.

Below are examples of SQL queries we plan to evaluate.

1. Query A: Synthetic query for evaluating aggregate accelerator

   ```
   SELECT department, years in company, SUM(salary) as sal sum
   FROM employee GROUP BY department, years_in_company
   ```

2. Query B: Modified Q14 of TPC-H for evaluating hash-join accelerator

   ```
   SELECT sum(l_extendedprice * (1-l_discount)) as promo_revenue
   FROM lineitem, part
   WHERE l_partkey = p_partkey
   and l_shipdate >= 1995-09-01
   and l_shipdate < 1995-10-01
   ```

3. Query C: Q52 of TPC-DS for evaluating complex queries by both accelerators

   ```
   SELECT dt.d_year, item.i_brand_id brand_id, item.i_brand brand,
   SUM(ss_ext_sales_price) ext_price
   FROM date_dim dt, store sales, item
   WHERE dt.d date sk = store sales.ss sold date sk AND
   store sales.ss item sk = item.i item sk AND
   item.i manager id = 1 AND dt.d moy = 11 AND dt.d year = 2000
   GROUP BY dt.d year, item.i brand, item.i brand id
   ORDER BY dt.d year, ext price DESC, brand id
   ```

4 Development Environment Requirement

- Bluespec: HLS Compiler to generate hardware specifcations. bluespec.com/
- Connectal: software/hardware co-design library which enables RPC-like interfaces between host and FPGA. https://github.com/cambridgehackers/connectal
- Vivado: Synthesis and implementation tools for Xilinx FPGAs

5 Milestone

In this project, we need to implement hardware and software components, as well as integrating those system components as a SQL database system. For the hardware component development, I have a fairly clear grasp of the required domain-specific knowledge and expertise. For software component development, especially regarding to the integration with hardware accelerators, help from the experts in the database domain in Samsung will be greatly appreciated.

Also, please note that the entire work of the proposed project might not be able to fit in the 3-month internship period. So continuing collaboration with Samsung after the internship is expected.

The tasks of the internship can be broken into four phases:

1. In the first phase, we will need to set up Bluespec, and the software/hardware codesign library, connectal, on Samsung's development platform. Knowledge and help about the development platform from the Samsung Semiconductor will be needed.

2. In second phase, I will implement the standalone aggregate accelerator. And a hand-coded Query A from Section 3 will be used to evaluate to accelerator.
3. In third phase, I will implement the standalone hash-join accelerator. And a hand-coded Query B from Section 3 will be used to evaluate to accelerator.
4. In final phase, the accelerators needed to be integrated with software query processor. Query C from Section 3 will used to evaluate the overall system. For this phase, help from experts from the software domain will be of great help.

Below is the detailed timeline of the project.

	Weeks (05.2018 – 8.2018)												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Post-Intern**
Development Environment Setup	🟦	🟦	🟦										
Aggregate Accelerator Implementation			🟦	🟦	🟦	🟦							
Aggregate Accelerator Evaluation							🟦						
Hash-Join Accelerator Implementation								🟦	🟦	🟦	🟦		
Hash-Join Accelerator Evaluation												🟦	
SW/HW Integration and Evaluation												🟦	🟦

Figure 4: Project Timeline