Less Watts, More Performance: An Intelligent Storage Engine for Data Appliances

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ABSTRACT

In this demonstration, we present IBEX, a novel storage engine featuring *hybrid*, FPGA-accelerated query processing. In IBEX, a *field-programmable gate array* (FPGA) is inserted along the path between the storage devices and the database engine. The FPGA acts as an *intelligent storage engine* supporting query off-loading from the database engine. Apart from significant performance improvements for many common SQL queries, the demo will show how IBEX reduces data movement, CPU-usage, and overall energy consumption in database appliances.

1. INTRODUCTION

Modern data appliances such as IBM's Netezza [6] and Oracle's Exadata[10] are moving toward architectures with widespread query off-loading to different elements of the system. The goal is both to speed up query processing and to reduce data movement since the network bandwidth is still one of the dominant bottlenecks in cluster based appliances. An important element in these systems are *intelligent storage engines*, *i.e.*, storage engines that already filter data before sending it by executing queries in part or whole on behalf of the processing nodes.

In this demonstration, we present IBEX, an intelligent storage engine for a data appliance that we are building at ETH Zurich [1], that is based on *field-programmable gate arrays* (FPGAs). FPGAs are massively parallel semiconductor devices that have attractive properties for data processing, which have been shown in a number of recent research papers [2, 7, 8, 11]. Unlike existing approaches, IBEX supports pushing down more complex operators (*e.g.*, `GROUP BY` and aggregation) to the intelligent storage engine than simply selection and projection. As far as we are aware, this is the first demonstration of an intelligent storage engine at a database conference and, thus, will serve to illustrate an important architectural trend through a system that is far more flexible than what is commercially available.

The demonstration will allow attendees to see how off-loading query processing to an FPGA based hardware accelerator *improves performance* and also *reduces energy consumption.* Query processing in relational databases often involves many function calls [3], and may cause substantial CPU-activity. As the low-power[1] FPGA is doing work for the CPU, the CPU can switch to a sleep state and consume less power. Alternatively, the CPU has spare cycles to do other useful work, and with extensive off-loading a less powerful CPU with a lower TDP might suffice to achieve equivalent performance.

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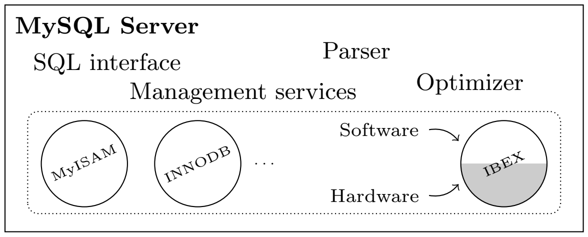


Figure 1: IBEX as a *pluggable* storage engine.

For the purposes of this demonstration, we chose MySQL as the database engine for simplicity. MySQL 5.1 has introduced a *pluggable* storage engine architecture that makes it particularly easy to develop new storage engines (Figure 1). However, the ideas behind IBEX can be applied to many different engines from OLTP to OLAP and from row to column stores.

Integrating an FPGA into a DBMS is difficult and requires profound knowledge of both the database and the FPGA domain. We have been working in this area for quite some time now, gathering many insights. As such, the work we demonstrate here combines many elements developed over the years, involving compiling query plans to circuits (Glacier [9]), techniques for runtime-reconfiguration of FPGAs (Skeleton Automata [12]), as well as low-level hardware components such as a SATA controller for FPGAs (Groundhog [13]), to name a few.

Goals. The demonstration has two objectives. *(a)* One is to discuss *performance improvements* and *energy savings* on a per query basis. The fact that MySQL supports multiple storage engines makes live comparisons of IBEX with MyISAM and INNODB possible. *(b)* The other is to provide attendees with a better understanding of intelligent storage engines, from a software as well as a hardware perspective.

[1]An FPGA consumes between one and two orders of magnitude less power than a server processor under full load.

2. THE SOFTWARE ARCHITECTURE

MySQL implements the *Volcano Iterator Model* [5], *e.g.*, to scan a table, MySQL repeatedly calls the storage engine method `rnd_next(uchar *buf)`, which fetches the next row of a table. Typically, query execution tasks such as *selection*, *aggregation*, and *projection* are performed in higher-level components above the storage engine. However, the MySQL storage engine interface does already provide a mechanism to push *selection* down to the storage engine, which is used, for example, by the NDB storage engine designed for cluster environments.

MySQL ⟷ Storage Engine Interface. Besides *selection* we would like to to push *projection* and `GROUP-BY` *aggregation* down to the IBEX storage engine. Therefore, we have extended the existing storage engine interface of MySQL with two additional methods: `proj_push(...)` and `grpby_push(...)`. The query optimizer can detect whether these methods are implemented by a given storage engine and optimize queries appropriately. On the other hand, a storage engine that implements these methods receives additional preprocessing information from MySQL.

Software Storage Engine ⟷ FPGA Interface. There are several ways to physically connect an FPGA to a host machine running a database. For our FPGA board, this can be done using PCI-Express or Ethernet—for this demo we will use Ethernet because it allows us to take the FPGA board out of the PC, making the demo more ostensive.

We base our interface to the FPGA on MSR's SIRC (simple interface for reconfigurable computing [4]), which provides a uniform communication interface to the FPGA, hiding from the application the physical communication channel used and low-level protocol details. In essence, SIRC provides access to the input and output buffers on the FPGA, depicted in Figure 3, by means of a few C++-methods. Auxiliary methods to access a register file are used for control flow and parametrization of the hardware engine.

On top of this low-level communication interface to the FPGA, we built a higher-level class that enables accessing persistent storage via the FPGA. Apart from providing basic read/write block (a number of 512-byte sectors) methods, we also support *scanning* an entire table with *projection*, `GROUP-BY` *aggregation*, and *selection* possibly pushed down to the FPGA, as depicted in Figure 2.

```
setProjection(columns);
setGroupByAgg(columns, aggtype, groupbykey);
setSelection(columns, predicates, tt);
scanTable(startLBA);
while(fetchResult()) { ... }
```

Figure 2: Full-table scan with multiple operators pushed down to the FPGA (tt = truth table).

Before scanning a table, we need to specify the computation that we want to push down to the FPGA. For *projection*, we simply indicate, which columns we want to retrieve. For `GROUP-BY` *aggregation*, besides the aggregate columns we also need to specify the aggregation type (`COUNT`, `SUM`, etc.) for every column, as well as the `GROUP-BY` key. Finally, for *selection*, we need to submit the columns that need to be evaluated against a `WHERE`-clause predicate together with the corresponding predicates for each column and a truth table (`tt`) that represents the Boolean concatenation of multiple predicates in the same `WHERE`-clause (see Section 3.1 for more details). The table scan is then initiated by calling `scanTable(startLBA)`, which submits the first *logical block address* (LBA) of the corresponding table to the FPGA. The results are then retrieved in multiple chunks by repeatedly calling `fetchResult()`.

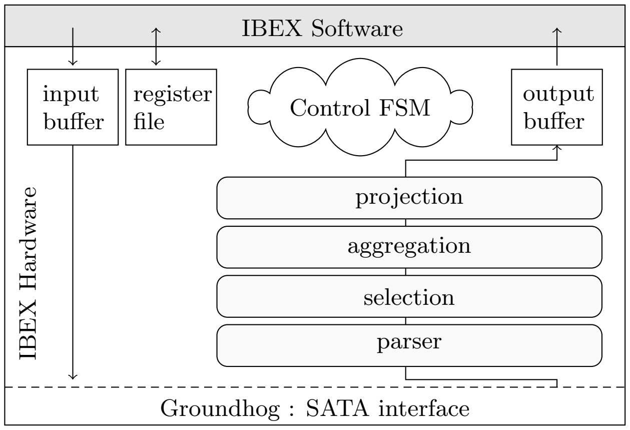


Figure 3: Query engine on the FPGA.

3. THE HARDWARE ARCHITECTURE

The high-level hardware architecture of IBEX is shown in Figure 3. Communication between the software side and the FPGA is realized via input and output buffers, as well as a register file for control flow and parametrization of the hardware query engine.

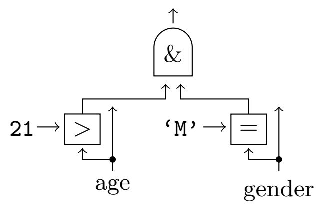
The demonstration focuses on read-only queries. Nevertheless, IBEX also supports updates bypassing the FPGA through Groundhog [13], an open-source SATA controller for FPGAs.

When a table is read, the data passes through a series of pipelined hardware components (*parser*, *selection*, *aggregation*, and *projection*), before it reaches the output buffer, from which it is sent to the software component. The *parser component* is the first in the pipeline. It consumes 16 bits per clock cycle of the raw byte stream delivered by Groundhog [13] and separates the columns of a row from each other by writing the respective values to different FIFO-buffers. We only need to buffer the data for the relevant columns of a given query. The *selection component* concurrently evaluates (potentially) multiple predicates on a record and then computes the Boolean expression corresponding to the `WHERE`-clause. If the Boolean result is *false*, the respective record is discarded at this stage. Otherwise, the record is forwarded to the next stage. The *aggregation component* performs the necessary aggregations on the records that have passed the *selection component*, in the event of a `GROUP BY` query. The *projection component*, finally, materializes the projected columns and writes the projected result record to the output buffer for transmission to the IBEX software.

At the demonstration, the inner workings of all of these components will be presented in detail. Here, for lack of space, we will only discuss the *selection component* and the *aggregation component* in more detail in the two sections below.

3.1 Selection Component

Instead of hard-wiring predicate evaluation, we created



Addr.	Value
00	0
01	0
10	0
11	1

Figure 4: Truth table for the evaluation of complex Boolean expressions versus hard-wiring.

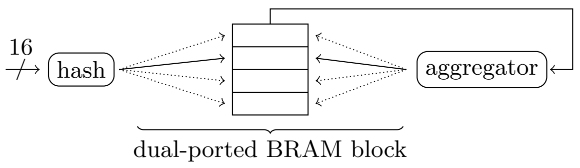


Figure 5: Dual-ported BRAM based hash table.

a template circuit for every supported column type, which can be parameterized at runtime—similar to the *Skeleton Automata* technique for XML that we described in [12]. For instance, to evaluate `table.age > 21`, we simply need to store the value `21` as well as the desired comparator `>` ($\in$ {`=`,`<>`,`<`,`>`,`<=`,`>=`}) in local memory of the template-circuit. String and regular expression matching on `VARCHAR` and `TEXT` columns can be performed with parameterizable finite state machines, again using similar techniques as discussed in our previous work [12].

The problem that remains is combining multiple predicates into a single Boolean expression. Consider, for example, the following query:

```
SELECT * FROM table WHERE age > 21 AND gender = 'M'
```

Hard-wiring the Boolean `AND` operator, as illustrated on the left-hand side in Figure 4, is not an option since we need to change this wiring at runtime, *e.g.*, without having to reprogram the entire FPGA. A template-based approach, as we proposed for evaluating individual predicates, is also not feasible since the Boolean expressions in a `WHERE`-clause are unpredictable and can be arbitrarily complex.

Instead of wiring the output of the predicate evaluation circuits through series of gates we can combine those wires into a single address bus to an on-chip memory block, which then serves as a look-up table to evaluate a given Boolean expression—an example is displayed on the right-hand side in Figure 4 (here, for a single `AND` operator). Thus, before we run a query on the FPGA, we compute the truth table for the `WHERE`-clause in software and load that truth table into the dedicated on-chip memory on the FPGA.

3.2 Aggregation Component

Aggregation in `GROUP BY` queries quickly becomes a costly operation in existing relational databases. Using a hash-based scheme our aggregation component is able to compute multiple aggregates on the fly at line rate, as data is loaded from persistent storage. To achieve this, we use established techniques to leverage hardware parallelism. In particular, in IBEX, we aggressively use *pipeline parallelism* and *parallel collision resolution.*

Pipeline parallelism. Once a SATA read command has been issued, data needs to be processed at line rate, *i.e.*, every clock cycle the next 16 bits of data have to be consumed. This seems to be a problem because to process a key, we need to probe the hash table, update the aggregate, write it back to memory, and in the next clock cycle be ready to process the next key. Fortunately, on an FPGA all these steps can be pipelined, as illustrated in Figure 5. In addition, dual-ported BRAM blocks allow us to read and write data from/to the same BRAM block simultaneously. Thus, as we are probing one key, we can write back the aggregate for a different key.[2]

Parallel collision resolution. Since we are using hashing there exists the possibility of a collision, *i.e.*, two keys could be mapped to the same BRAM address. Typically collisions are resolved by finding an alternative address in the hash table using techniques such as *linear probing*, *double hashing*, etc. But such a strategy would make the time it takes to process a key unpredictable—clearly, this is not what we want.

However, if we construct our hash table from multiple parallel BRAM blocks, then we can proactively and in parallel look up an alternative address in each of the BRAM blocks and resolve collisions without delaying processing. While this technique significantly reduces the probability of a collision, n alternative addresses might still not be sufficient for each and every case. If a tuple causes a collision that cannot be resolved with n parallel lookups, that tuple is forwarded to the IBEX software component, where it can be taken care of later.

4. DEMONSTRATION SETUP

We bring a MySQL server installed on a high-end laptop, which communicates to an FPGA via Gigabit Ethernet using the SIRC framework [4] (see Section 2). The FPGA has a direct SATA link to an SSD, as illustrated in Figure 6. Additionally, we bring an electricity meter to measure the power consumption of the laptop during query execution.

We run the MySQL client on the laptop, and attendees will be able to execute either a set of predefined queries or type their own SQL queries at the MySQL prompt. A number of large tables using the MyISAM, INNODB and IBEX storage engine will be pre-installed. Tables that use IBEX will be stored on the SDD connected to the FPGA board, whereas tables using other storage engines are stored on an (equivalent) local SDD of the laptop. If time allows, visitors can even create and populate their own tables using IBEX or another storage engine.

4.1 Storage Engine Performance

Query execution times are reported directly by MySQL and displayed on the client terminal. Our test database will contain tables which are replicated among the different storage engines. Thus, the performance of different engines can be directly compared for a particular query. For many SQL queries, IBEX will significantly outperform the other storage engines in MySQL . To give an example, running the following simple `GROUP BY` aggregation query

```
SELECT id, count(id) FROM table GROUP BY id
```

on a one-gigabyte table with a single column of type `INT`, consisting of four different groups, was executed in **54.18 sec-**

[2]Potential race conditions that could occur when two identical keys directly follow each other are avoided by an extra circuit that detects and handles this situation.

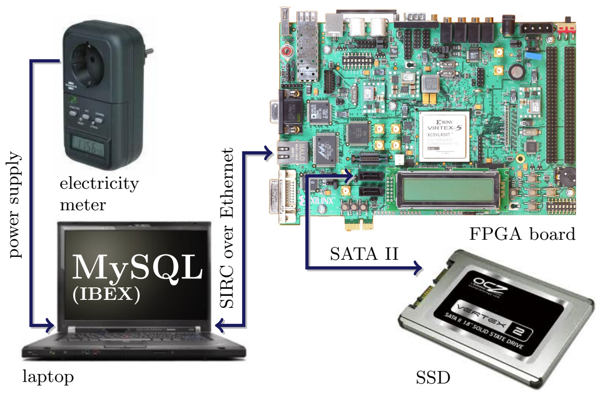


Figure 6: Hybrid Mysql Server Setup.

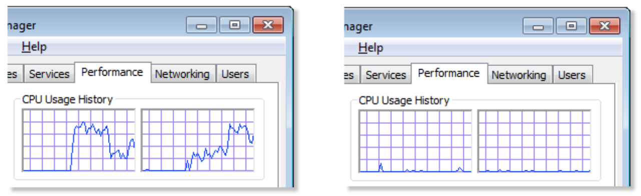

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Figure 7: CPU-usage during query execution: storage engine MyISAM (left) versus IBEX (right).

onds with MyISAM, in **179.27 seconds** with INNODB, and in only **3.71 seconds** with IBEX. For one gigabyte of data, 3.71 seconds corresponds to a throughput of 276 MiB/s, which is about the maximum sequential read speed on a SATA II SSD.

4.2 CPU-usage and Power Consumption

Besides performance improvements, we also demonstrate how our system improves energy consumption. At the demo, we will monitor CPU-usage of the laptop running the MySQL server. Figure 7 displays two screenshots of the CPU-usage monitor on our dual core laptop during execution of the same `GROUP BY` query used in the previous section.

While the CPU is involved quite significantly when the query is executed using the MyISAM storage engine, it is virtually idle with IBEX since almost the entire computation is pushed down to the FPGA.

The reduced CPU-usage with IBEX directly translates to less power consumption of the host system, which is visible on our electricity meter that measures the wall-power consumed by the laptop. During query execution with the MyISAM storage engine, our laptop consumes 45 watts of power, whereas with IBEX power consumption is only 31.5 watts. The FPGA itself running the hardware component of IBEX only consumes 2.8 watts of power.[3]

Since IBEX not only consumes less power but also executes queries faster than MyISAM, energy savings are even more significant. For the `GROUP BY` query above, the system roughly needs E = 45 × 54.18 = **2438 joules** of energy using MyISAM, whereas only E = 31.5 × 3.71 = **117 joules** are required with IBEX to execute the same query.

[3]FPGA power consumption was estimated using the Xilinx Power Analyzer tool.

4.3 Understanding the System

We have added a number of hooks to our system that allow visitors to better understand the inner workings of our system. The MySQL server can be run in *verbose* mode, such that for every query on tables using the IBEX storage engine the parts of the query that are pushed down to the FPGA are displayed on the server console. On the FPGA side, our circuits are equipped with monitoring circuitry that allow us to inspect and display data passing through the FPGA at runtime. Finally, there will also be the possibility to look at C++ source code of the IBEX storage engine, as well as the VHDL and Verilog code of its hardware counterpart.

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