FastBit Indexing for Searching and Analyzing Massive Data

John Wu

Scientific Data Management

Berkeley Lab

John.Wu@nersc.gov

http://sdm.lbl.gov/fastbit

SDM

U.S. Department of Energy Contract No. DE-AC02-05CH11231

BERKELEY LAB

FastBit Overview

- A bitmap indexing software package that provides extremely efficient search operations over large datasets
  - Measured >10X faster than the most popular bitmap index implementation
  - Contains innovative techniques: efficient compression (patent 2004), multi-level encoding, binning
- Used in many scientific and commercial applications
  - Combustion, astrophysics, network security, drug discovery
- One of 100 most innovative new products in 2008, R&D 100 Award

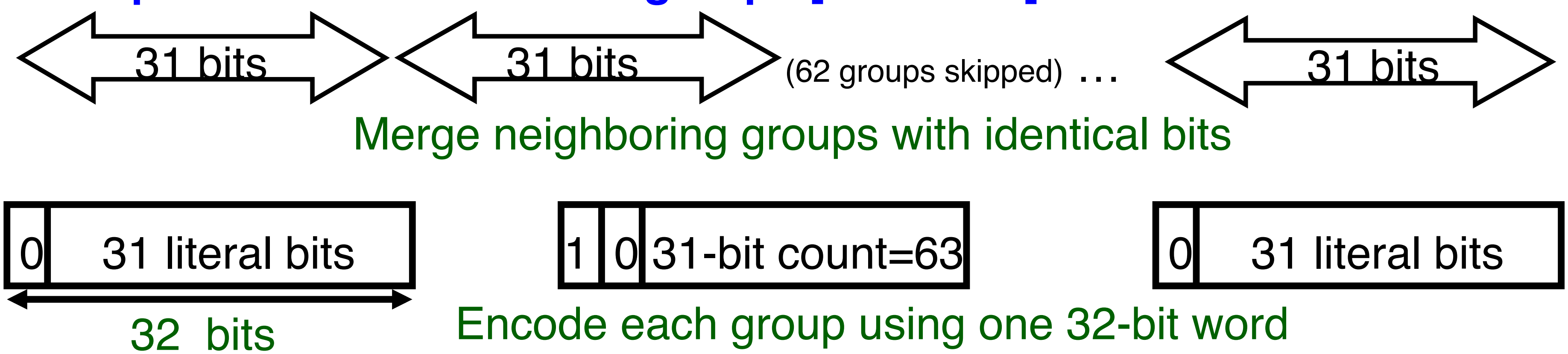
FastBit Technology 1: Compression

[Wu, Otoo, and Shoshani 2006]

Example: 2015 bits

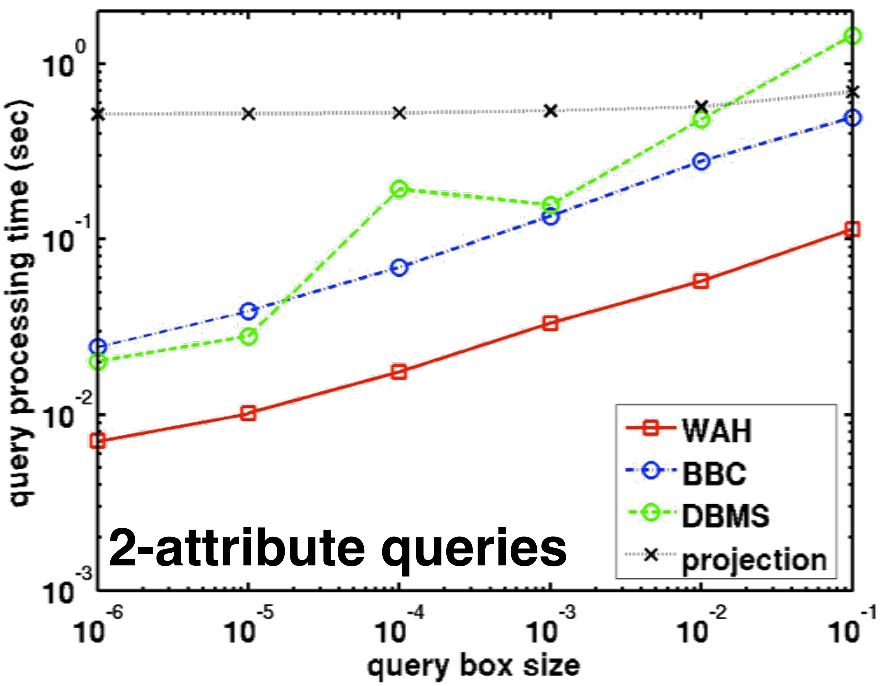
10000000000000000000011100000000000000000000000000000…………………00000000000000000000000000000011111111111111111111111111

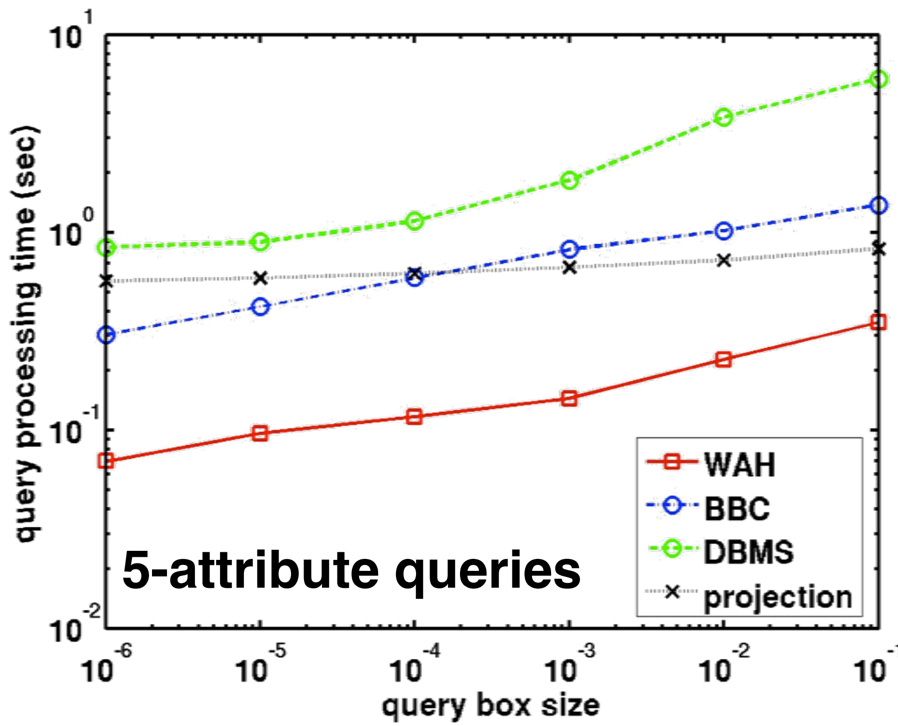
Main Idea: Use run-length-encoding, but...
partition bits into 31-bit groups [not 32 bit] on 32-bit machines



- Name: Word-Aligned Hybrid (WAH) code (US patent)
- Key features: WAH is compute-efficient
  - ➢ Uses the run-length encoding (simple)
  - ➢ Allows operations directly on compressed bitmaps
  - ➢ Never breaks any words into smaller pieces during operations
  - ➢ Worst case index size 4N words, not N*N (without compression)

Compressed Index Performance

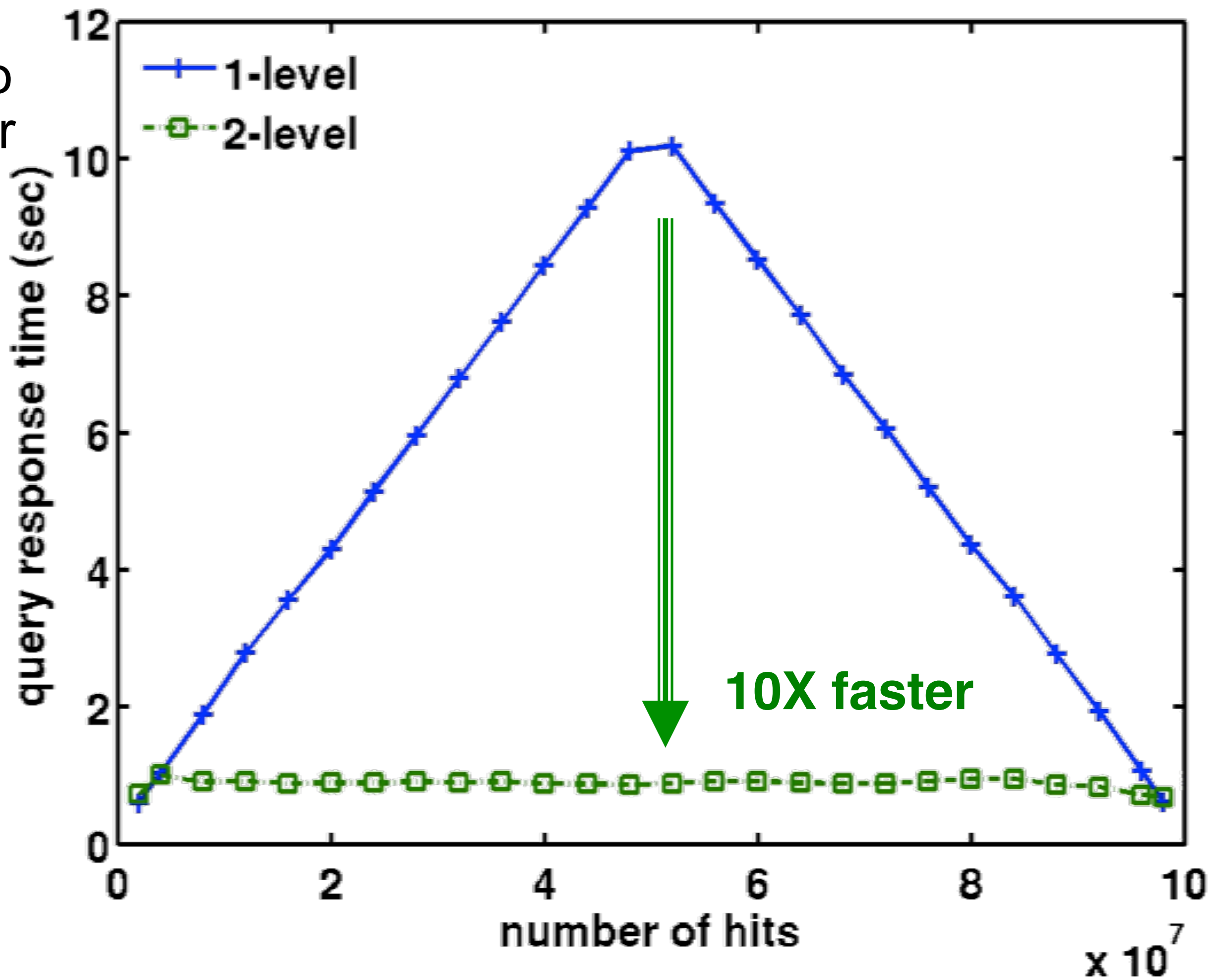




- **WAH compressed indexes are 10X faster than DBMS, 5X faster than our own version of BBC**
- Based on 12 most queried variables from a STAR dataset with 2.2 million rows, average column cardinality 222,000

FastBit Technology 2: Multi-Level Encoding

- Prove theoretically that the second level needs to have only a small number of bins (15 ~ 50 depending on the skewness of the data)
- Only two levels are necessary
- Result: 5X speedup on average
- Combined with WAH, could achieve 50X speedup



[Wu, Shoshani and Stockinger 2010]

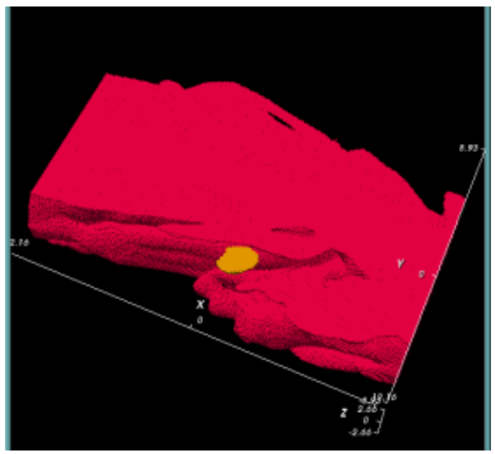
SDM

Efficient Numerical Searches

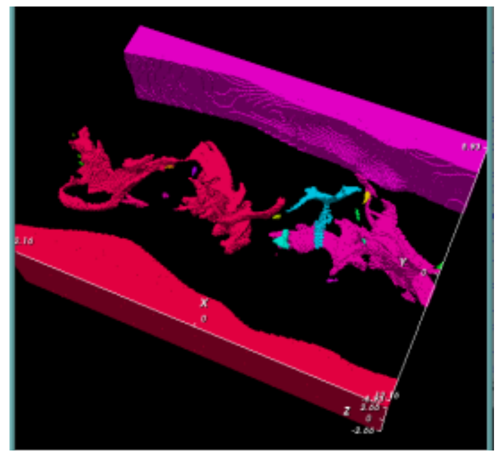
Scientific data contains many variables, multivariate searches are challenging for most techniques, FastBit is very effective for such operations

Application below: locating the flame front in a burning methane jet

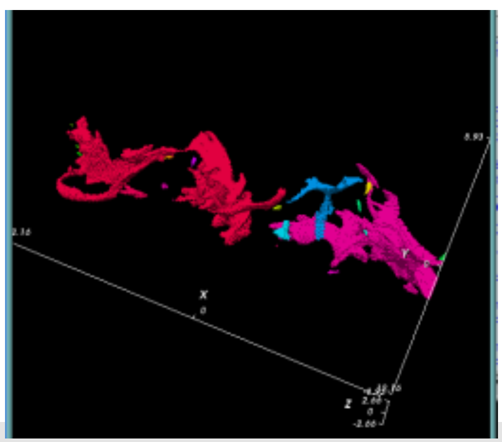
[Stockinger, Wu, Shalf, Bethel 2005]



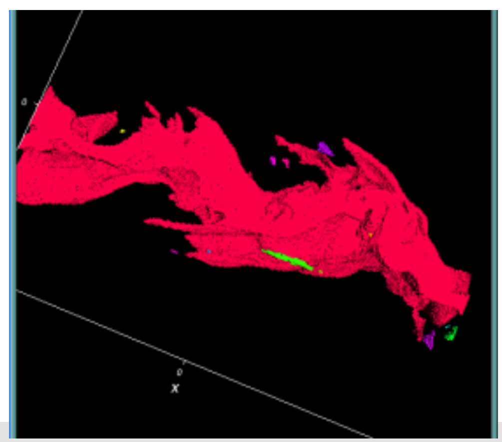
a) $CH_4 > 0.3$



b) temp < 3

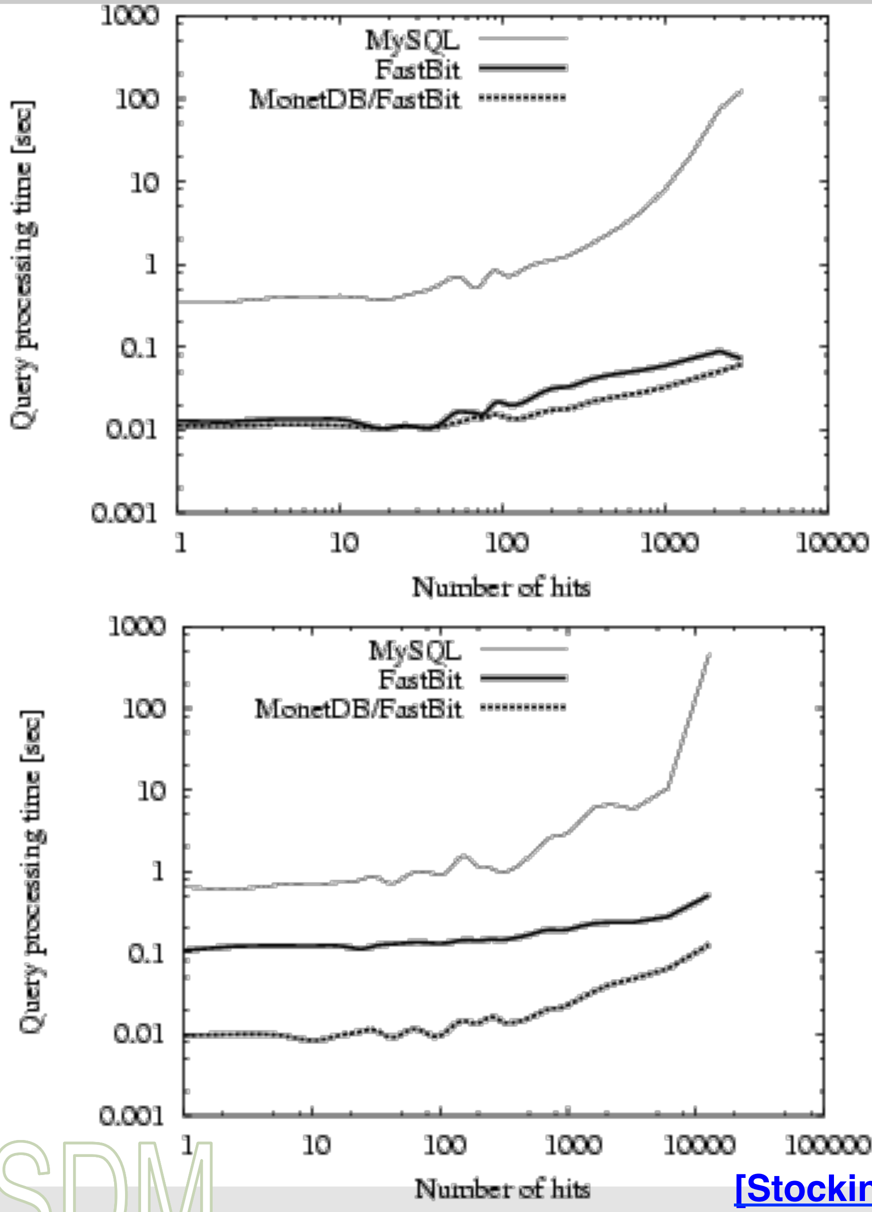


c) $CH_4 > 0.3$ AND temp < 3



d) $CH_4 > 0.3$ AND temp < 4

Efficient Keyword Searches



- FastBit provides efficient indexing techniques for not only numbers, but also text values
- FastBit can answer queries hundreds of times faster in many cases
- Test data: Enron email archive
- Searches involving mixed keywords and numerical values: message contains "California" and sender = "kenneth.lay@enron.com" and date="2001/07/18"
- Comparing against MySQL and a version of MonetDB with FastBit
- More on text searches later by Kamesh Madduri

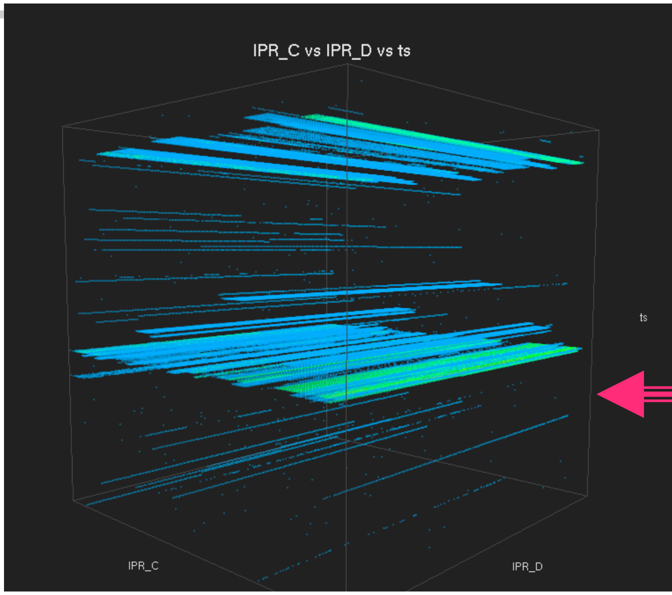
[Stockinger, Cieslewicz, Wu, Rotem, Shoshani 2008]

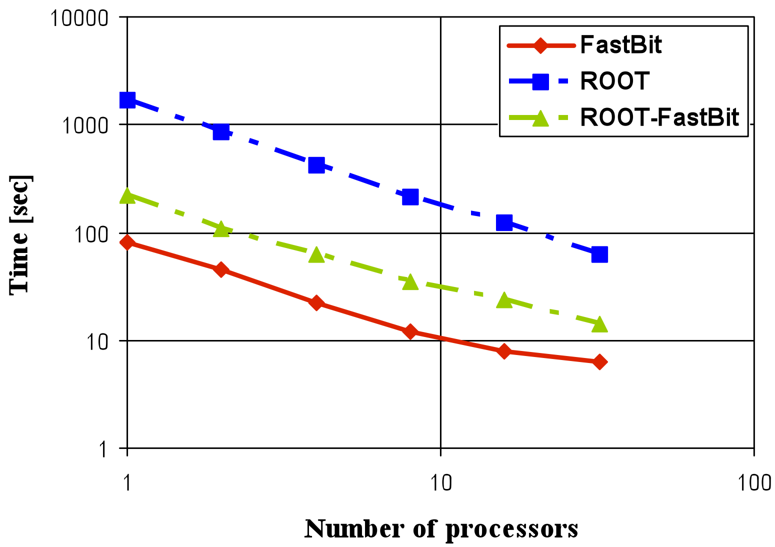
Example application (after data is collected): Forensic Network Data Analysis

- Application scenario: post-incident analysis, looking back into historical records to determine the root cause
- Use network session records produced by BRO intrusion detection system (IDS)
  - Billions of session records available, usually in ASCII text
  - Existing analysis tools can efficiently utilize only a small fraction of the records
- FastBit enables interactive analysis of a large number of records
  - Finding malicious network scans, characterized by a small number of hosts contacting nearly all machines in a network
  - Improving quality of IDS alarms by correlating real-time observations with historical trends
- New features required of FastBit
  - Group-by operator
  - Conditional histogram

Bro IDS

Dynamic Histograms In FastBit



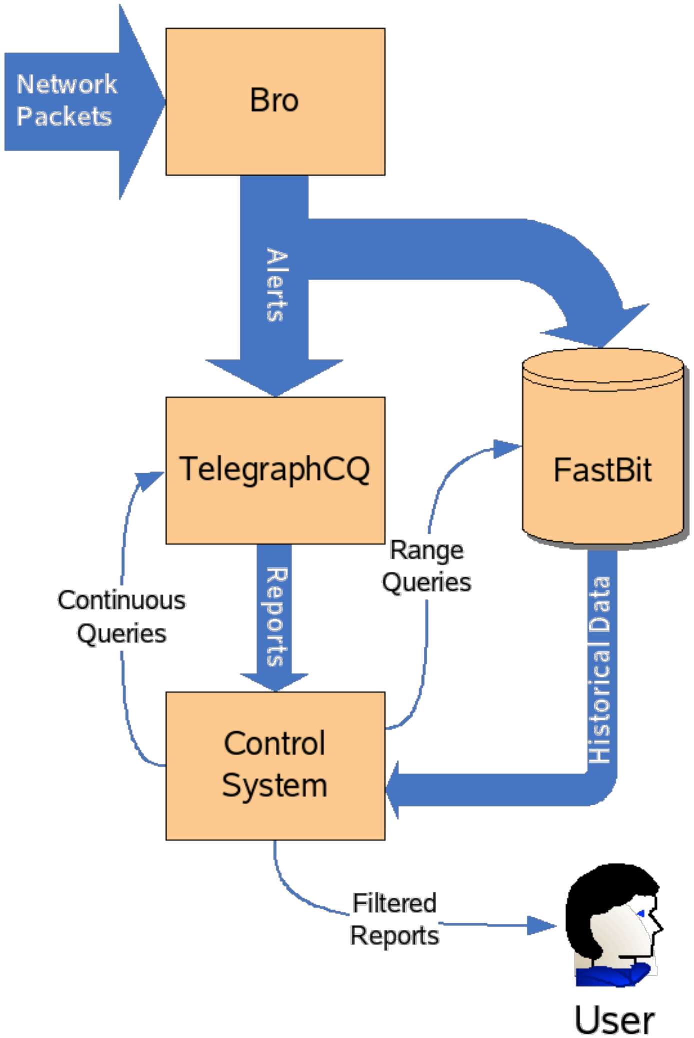


[Stockinger, Bethel, Campbell, Dart, Wu 2006]

- Conditional histograms are common in data analysis
  - E.g., finding the number of malicious network connections in a particular time window
- Top left: a histogram of number of connections to port 5554 of machine in LBNL IP address space (two-horizontal axes), vertical axis is time
  - Two sets of scans are visible as two sheets
- Bottom left: FastBit computes conditional histograms much faster than common data analysis tools
  - 10X faster than ROOT
  - FastBit indexes improve ROOT by 5X

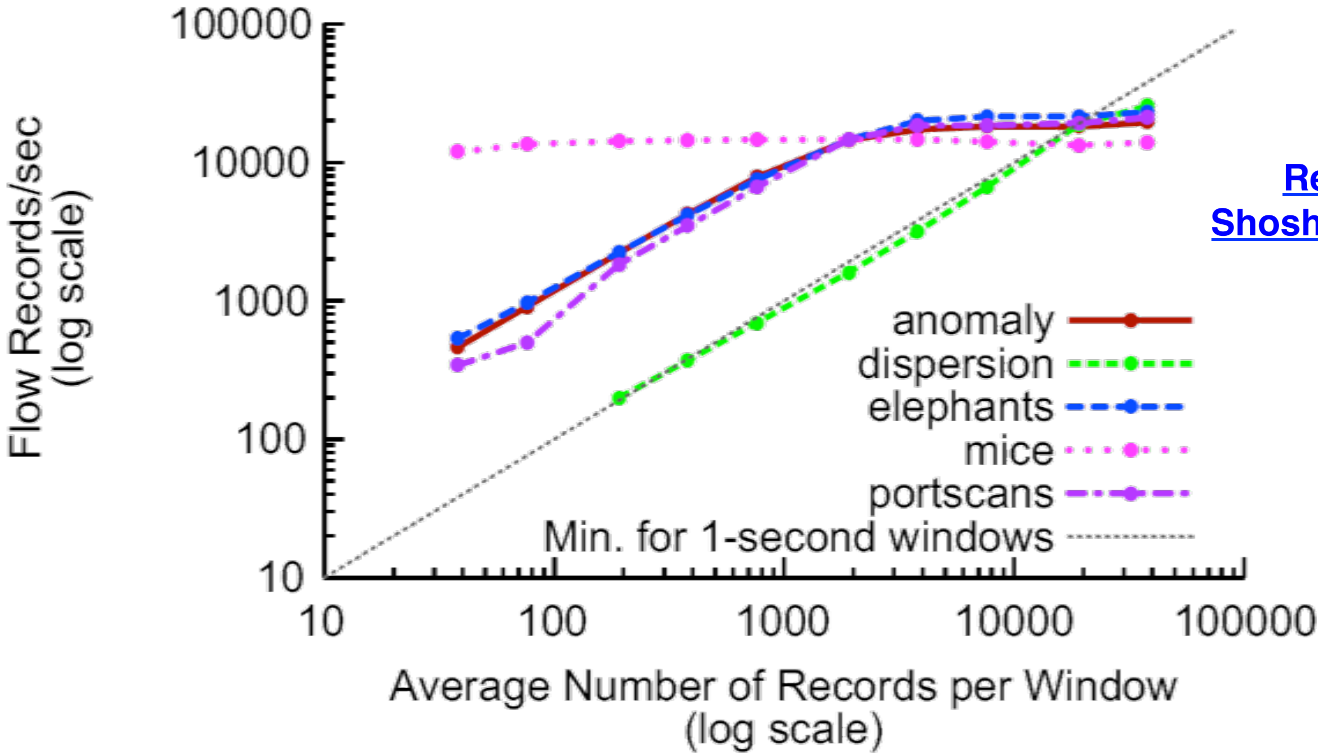
SDM

Example Application (while data is collected): Real-Time Network Data Analysis



- Application scenario: detect anomalous traffic before it can do any damage
- Existing stream data analysis tool examines current time window only
  - Need to compare current observation with past trends
  - Ex: Host A is contacting many others, is this common in the past? or has this happened in the past?
- Need to do all these in real-time
  - Process current data (efficient stream engine)
  - Archive and index incoming data (efficient index update)
  - Answer queries in archived data (efficient query processing on read-only data)
- New feature required of FastBit: efficient index update

FastBit for Network Traffic Streams



Reiss, Stockinger, Wu, Shoshani, Hellerstein 2007

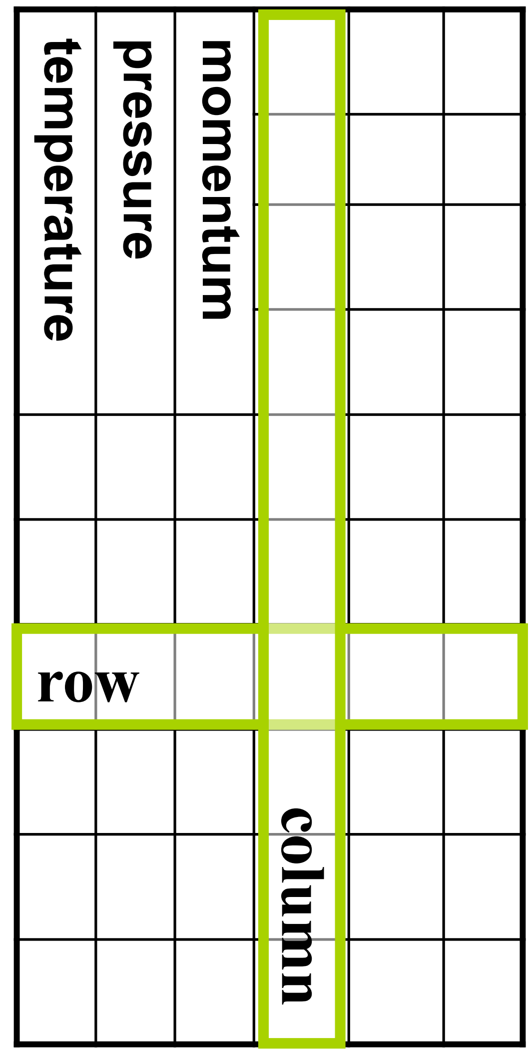
- Working with UCB database group, implemented a prototype system that integrates FastBit with TelegraphCQ, a stream query engine
- Tested the integrated system with a benchmark of 5 realistic queries
- Graph above shows that the combined system easily handles 10,000 network sessions per second on a 2.4GHz P4 system
- A typical desktop computer is sufficient to handle network traffic to a large supercomputer center (~ 500 network sessions per second)

Summary of FastBit Technology

- FastBit is extremely efficient in many applications: high-energy physics, combustion, astrophysics, network security, drug discovery, …
- The efficiency comes from new methods and algorithms, careful software engineering, and rigorous theoretical analyses to prove optimality
- Efficient compression for bitmaps
  - Our compression is 10X faster than nearest competitor
  - Proven optimal in computational complexity theory
- Multi-level bitmap encoding
  - Two-level indexes 3-5 times faster than one-level indexes
  - Proven that two levels are sufficient in theory
- Binning for numerical data with a very large number of distinct values
  - Developed a clustering technique that is 3-5 times faster than no binning for high-cardinality data

Overview of FastBit Software

- Task: given a large collection of data, efficiently locate records satisfying a set of conditions
- Example data – structured data:
  - High-energy physics data – billions of collision events, with hundreds of variables
  - Simulation data on a mesh – each mesh point may be viewed as a record/row, each variable a column
- Example queries:
  - Count how many records where pressure > 1000 and temperature between 500 and 1000
  - Select all records where momentum > …
- FastBit solves this search problem with
  - Column data organization
  - Bitmap index
- FastBit is an award-winning open-source software
  - R&D100 award (Wu, Shoshani, Otoo, Stockinger, 2008)
  - Used in a number of research projects



What FastBit Is Not

- Not a database management system (DBMS)
  - It is much closer to BigTable (NoSQL) than to ORACLE
  - Most SQL commands are not supported
- Not a plug-in for a DBMS
  - It is a stand-alone data processing tool
  - No DBMS is needed in order to use FastBit
- Not an internet search engine
  - FastBit is primarily for structured data; internet search engines are for text (unstructured) data
- Not a client-server system
  - We have used FastBit in server programs, but by itself, it is not a client-server system

How Do I Use FastBit

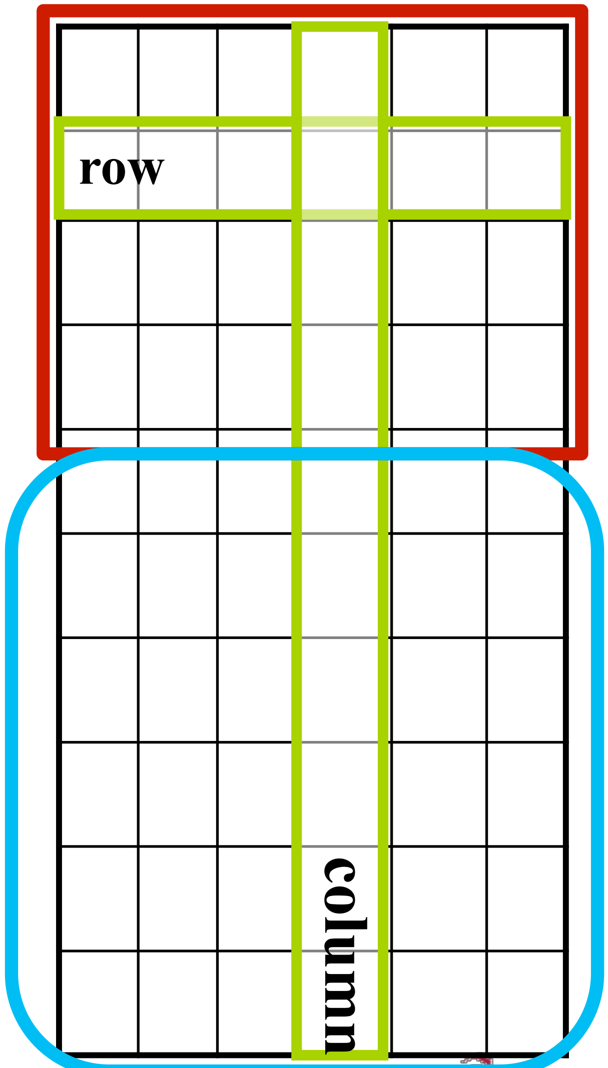
- Command-line tools
  - A handful of command-line tools are available to load data, build indexes, and query data
- Write your own program using FastBit as a library
  - Two levels of API:
    - Class table
    - Class part + query
  - FastBit is written in C++
    - Other languages may access FastBit through C API

Exercise I: Install FastBit Software

- Download FastBit from http://codeforge.lbl.gov/projects/fastbit
- Jun 2011 version: ibis1.2.4
- Unpack fastbit-ibis1.2.4.tar.gz
  - tar xvzf fastbit-ibis1.2.4.tar.gz && cd fastbit-ibis1.2.4
- Installation instruction on a Unix-type system
  - Prerequisite – C++ compiler (e.g., g++), pthread library, make, gzip, tar (pretty standard stuff)
  - Commands: ./configure && make –j 2
- Installation instruction on MS Windows
  - Prerequisite – pthreads-w32, VisualStudio (or another C++ compiler)
  - Compile with VisualStudio
    - Start VisualStudio, open win/ibis.sln
  - Compile with MinGW
    - cd win && make –f MinGW.mak ibis
- Compilation will take 15 minutes or more

FastBit Data Model

- FastBit is designed to search multi-dimensional append-only data
  - Conceptually in table format
    - rows ➔ objects
    - columns ➔ attributes
- FastBit uses vertical (column-oriented) data organization
  - Efficient for searching
- Physical data layout
  - A data table is split into “partitions”
  - Each partition is a directory in a file system
  - Each directory has a metadata file describing the data partition
  - Each column is represented by a file



Metadata File

BEGIN HEADER

DataSet.Name=testData

Number_of_rows=1000000

Number_of_columns=6

Table_State=1

index = <binning none/><encoding equality/>

END HEADER

BEGIN Column

name=i9

description=integers 0, 1, ..., and 9

data_type=Int

index = <encoding range/>

END Column

Basic Bitmap Index

Data values	b_0 =0	b_1 =1	b_2 =2	b_3 =3	b_4 =4	b_5 =5
0	1	0	0	0	0	0
1	0	1	0	0	0	0
5	0	0	0	0	0	1
3	0	0	0	1	0	0
1	0	1	0	0	0	0
2	0	0	1	0	0	0
0	1	0	0	0	0	0
4	0	0	0	0	1	0
1	0	1	0	0	0	0

A < 2 (b_0, b_1) 2 < A (b_3, b_4, b_5)

- First commercial version
  - Model 204, P. O'Neil, 1987
- Easy to build: faster than building B-trees
- Efficient for querying: only bitwise logical operations
  - $A < 2 \rightarrow b_0$ OR b_1
  - $A > 2 \rightarrow b_3$ OR b_4 OR b_5
- Efficient for multi-dimensional queries
  - Use bitwise operations to combine the partial results
- Size: one bit per distinct value per row
  - Definition: Cardinality == number of distinct values
  - Compact for low cardinality attributes, say, cardinality < 100
  - Worst case: cardinality = N, number of rows; index size: N*N bits

Strategies to Improve Bitmap Index

- Compression
  - Reduce the size of each individual bitmap
  - Best known compression method: Byte-aligned Bitmap Code [Antoshenkov 1994], used in Oracle bitmap index
  - Word-Aligned Hybrid (WAH) code trades some disk space for much more efficient query processing
- Encoding
  - Basic equality encoding, in Model 204
  - Multi-component encoding [Chan and Ioannidis 1998]
  - Multi-level encoding
- Binning
  - Equal-width binning, equal-depth binning, …
  - Has to perform candidate check to rule out false positives, time for candidate check dominates the total query response time
  - Order-preserving Bin-based Clustering (OrBiC)

Indexing Option String

- Syntax
  - <binning … /> <encoding … /> <compression … />
- Binning options
  - Basic binning option: linear scale, log scale, equal-weight
  - Examples:
    - <binning none/>
    - <binning nbins=1000/>
    - <binning begin=10, end=20, scale=linear, nbins=10/>
    - <binning precision=2/>
- Encoding options
  - Three basic options: equality, range and interval
  - Combinations:
    - multi-level, e.g., <encoding interval-equality/>
    - multi-component, e.g., <encoding equality ncomp=2/>
- Compression options
  - Public release only supports WAH compression, most users should leave this part out

Indexing Option Suggestions

- Not specifying any option == default option
  - Use the default unless you known something about your data and query
- The following recommendations primarily depends on the column cardinality and the type of query
  - Definition: column cardinality == number of distinct values actually appear in the data partition
- Cardinality < 100:
  - Equality queries: <binning none/> <encoding equality/>
  - Range queries: <binning none/> <encoding interval/>
- Cardinality < 1,000,000 (Nrows/10):
  - Have disk space (index size 2X raw data size):

    <binning none/> <encoding interval-equality/>
- Very high cardinality: <binning none/> <encoding binary/>
- Small number of values to be queried: use them as bin boundaries, treat the number of bins as the column cardinality above

FastBit Command-Line Tools

- All source code for these tools are in examples directory
- Ardea: convert text version of the data records into FastBit raw binary data format – an operation common known as "load"
  - ardea –d output-dir –t text-file –m columnname:type
- Ibis: query existing data
  - ibis –d data-dir –q "select c1,c2 where c3 > 5 and c4 < 6"

Exercise II: Use Command-Line Tools

- cd tests
- ../examples/ardea -d tmp -m "a:int, b:float, c:short" -t test0.csv
  - ls –l tmp

    total 4

    -rw-r--r-- 1 John Users 400 Jun 18 14:40 -part.txt

    -rw-r--r-- 1 John Users 400 Jun 18 14:40 a

    -rw-r--r-- 1 John Users 400 Jun 18 14:40 b

    -rw-r--r-- 1 John Users 200 Jun 18 14:40 c
- ../examples/ibis –d tmp –build-index “<binning none/>”
- ../examples/ibis –d tmp –q “where a < 5”
- ../examples/ibis –d tmp –q “select a, b, c where a < 5” –v
- More details can be found in doc/quickstart.html, or at http://crd.lbl.gov/~kewu/fastbit/doc/quickstart.html
- Generate synthetic data with tests/setqgen.cpp
- Larger sample data available from http://sdm.lbl.gov/fastbit/data/

Software Layering

- Abstract view: ibis::table and ibis::tablex
  - A table is immutable; to add new records, use tablex
  - A query (through function select) produces another table
  - Additional functions include: build indexes, get conditional histograms, get column values, …
- Concrete view: ibis::part and ibis::query
  - Each part (partition) is vertically organized
  - An index for a column of a partition is built in memory
  - A query on partition produces a compressed bitmap representing the rows satisfying the specified conditions

Ingesting Data

- Key functions from ibis::tables, used in examples/ardea.cpp

```
                                   // create a tablex object
ibis::tablex* ta = ibis::tablex::create();
                                   // parse the metadat string
ta->parseNamesAndTypes(metadata.c_str());
              // read CSV file, store content in memory
ierr = ta->readCSV(csvfiles[i], nrpf, del);
      // write the content from memory to the named directory
ierr = ta->write(outdir, “name”, “some description");
```

Simple Queries

- Key functions from ibis::table, used in examples/thula.cpp

```
                // create a table data object from a directory name
ibis::table *tbl = ibis::table::create(“directory-name”);
                                    // a selection forms its own table
ibis::table *res = tbl->select(“select clause”, “where clause”);
              // create a cursor for row-wise access to the results
ibis::table::cursor *csr = res->createCursor();
                        // fetch the next row and dump it to std::cout
while (0 == csr->fetch())
    csr->dump(std::cout);
```

Low-Level Query Functions

- Requires the use of ibis::part and ibis::query (examples/rara.cpp)

```
                                  // construct a partition from the given directory
ibis::part apart(argv[1], static_cast<const char*>(0));
                              // create a query object with the current user name
ibis::query aquery(ibis::util::userName(), &apart);
                              // assign the query conditions as the where clause
int ierr = aquery.setWhereClause(argv[2]);
                                                      // select columns to print
ierr = aquery.setSelectClause(sel.c_str());
                                                          // evaluate the query
ierr = aquery.evaluate();
                                                    // print the selected values
aquery.printSelected(std::cout);
```

Histogram Functions

- Conditional histograms are commonly used in data analyses
  - Count the number of events collected every hour for all events from a particular day (1-D)
  - Count the number of network connection attempts per minute per destination port for a specific duration of time (2-D)
- Class ibis::part also has a set of functions to compute histograms
  - get1DDistribution
  - get2DDistribution
  - get3DDistribution
  - May use regular bins or adaptive bins
  - May be weighted by another variable
- FastBit uses indexes to reduce the amount of data accessed and speeds up the histogram computations

Exercise III: Minimal Query Program

- Write a C++ program that takes a directory name and a query string as arguments, compute the number of records in the directory satisfying the query conditions
- Compile and link
- Example

```
#include <table.h>
int main(int argc, char** argv) {
    ibis::table *tbl = ibis::table::create(argv[1]);
    ibis::table *res = tbl->select(0, argv[2]);
    std::cout << "The number of records satisfying \"" << argv[2] << "\" in "
              << argv[1] << " is " << res->nRows() << std::endl;
    delete res;
    delete tbl;
    return 0;
}
```

Index Sizes to Expect

- Indexes are built for one column and one partition at a time
- The maximum size of an index is primarily determined by three parameters: the number of rows N, the number of bitmaps used B, and the bitmap encoding used.
- The range and interval encoded indexes are not compressible in the worst case, therefore their sizes are N * B bits
- Under the equality encoding, for a binned index, B is the number of bins, otherwise the number of bitmaps is the number of distinct values (i.e., column cardinality)
  - For small B, say, B < 100, N * B bits are needed because bitmaps are likely not compressible
  - For B < N / 10, the common case, index size is about 2 N words
- For columns with extremely high cardinality, use binary encoding, which requires log B bitmaps and N * log B bits

Updating Data and Indexes

- Most efficient way to add new records is to add a partition to an existing table
- Modifying an existing row must be implemented as a deletion following by an append
- Updating an index on a partition will cause a whole new index to be written, which can take a long time compared to the time to answer a query
- To improve response time, such updates are allowed to be delayed, presumably till the system is no longer busy

Parallelism

- Using ibis::part and ibis::query, each parallel processing element could work on one data partition
  - Additional code required to synthesize the final result
- Additional parallelism can come from having each processor answer a part of a query
  - For a query involving “a > 2 and b < 3”, process the condition involving a and b on two separate threads or processors
  - Require additional code to combine the partition results
- Prefer to have more partitions than the number of processors to improve load balancing
- The original version of FastBit was a CORBA server program
  - Current code were the core of the multithreaded server, minus the CORBA functions
  - All existing code is thread-safe

THANKS!

ANY QUESTIONS?

More information at

http://sdm.lbl.gov/fastbit

FastBit mailing list

https://hpcrdm.lbl.gov/cgi-bin/mailman/listinfo/fastbit-users

List of contributors

https://codeforge.lbl.gov/.../AUTHORS