Big Spatial Data Management on Hadoop and Beyond

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Computer Science and Engineering
Once upon a time...
Claudius Ptolemy (AD 90 – AD 168)
Al Idrisi (1099–1165)
Cholera cases in the London epidemic of 1854
FIGURE 3—Children under 15 years of age in 1940.
Figure 3—Children under 15 years of age in 1940.
Cool computer technology...!! Can I use it in my application?

My pleasure. Here it is.

I have BIG data. I need HELP...!!

Oh...!! But, it is not made for me. Can’t make use of it as is.
1969

Kindly let me understand your needs.
Kindly let me get the technology you have.
HELP..!! I have **BIG** data. Your technology is not helping me.

mmm...Let me check with my good friends there.

Cool **Database** technology...!! Can I use it in my application?

Oh...!! But, it is not made for me. Can’t make use of it **as is**

My pleasure. Here it is.
Kindly let me understand your needs

Kindly let me get the technology you have
HELP..!! Again, I have BIG data. Your technology is not helping me.

Let me check with my other good friends there.

Sorry, seems like the DBMS technology cannot scale more.

Cool Big Data technology..!! Can I use it in my application?

My pleasure. Here it is.

Oh...!! But, it's not made for me. Can't make use of it as is.

Oh...!! But, it's not made for me. Can't make use of it as is.
Kindly let me understand your needs.

Kindly let me get the technology you have.
Big Spatial Data Management
Tons of Spatial data out there…

- Geotagged Microblogs
- Geotagged Pictures
- Medical Data
- Smart Phones
- Sensor Networks
- VGI
- Satellite Images
- Traffic Data
Spatial Data & Hadoop → SpatialHadoop

Spatial Data

Hadoop

points = LOAD 'points' AS (id:int, x:int, y:int);
result = FILTER points BY
  x < xmax AND x >= xmin AND
  y < ymax AND y >= ymin;

Takes 193 seconds

SpatialHadoop

points = LOAD 'points' AS (id:int, location:point);
result = FILTER points BY
  Overlap(location, rectangle (xmin, ymin, xmax, ymax));

Finishes in 2 seconds
80,000 downloads in one year

Conducted more than seven keynotes, tutorials, and invited talks

Industry

Academia

Students Projects

Collaboration

>500GB public datasets for benchmarking and testing

Incubated by Eclipse Foundation and renamed to GeoJinni

11/30/18
The Built-in Approach of SpatialHadoop

**The On-top Approach**

- Spatial Modules
- User Programs
- Pig Latin
- Hadoop Java APIs
- Job Monitoring and Scheduling
- MapReduce Runtime
- Storage (HDFS)

**From Scratch Approach**

- (Spatial) User Program + MapReduce APIs + Job Monitoring and Scheduling + MapReduce Runtime + Storage + ...

**The Built-in Approach (SpatialHadoop)**

- User Programs
- Pig Latin
- Hadoop Java APIs
- Job Monitoring and Scheduling
- Early Pruning
- Spatial Indexing
- Spatial Language
- Spatial Operators
- MapReduce Runtime
- Storage (HDFS)
Agenda

- The ecosystem of SpatialHadoop
  - Motivation
  - Internal system design
  - Applications
  - Related work
  - Experiments
- Open Research Problems
SpatialHadoop Architecture


Language
Pigeon [ICDE’14]

Visualization
[VLDB’15, ICDE’16]

Operations
Basic operations – CG_Hadoop [SIGSPATIAL’13]

MapReduce
Spatial File Splitter
Spatial Record Reader

Indexing
Grid – R-tree – R+-tree – Quad tree [VLDB’15]
Indexing

Applications:
- SHAHED [ICDE’15]
- MNTG [SSTD’13, ICDE’14]
- TAREEG [SIGMOD’14, SIGSPATIAL’14]

Language
- Pigeon [ICDE’14]

Visualization
- [VLDB’15, ICDE’16]

Operations
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- Spatial File Splitter
- Spatial Record Reader

Indexing
- Grid – R-tree – R+-tree – Quad tree [VLDB’15]
Data Loading in Hadoop

- Blindly chops down a big file into 128MB chunks
- Values of records are not considered
- Relevant records are typically assigned to two different blocks
- HDFS is too restrictive where files cannot be modified
Two-layer Index Layout

Global Indexing

Locally Indexed HDFS Bocks

Data Nodes

Global Index

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Uniform Grid

Works only for uniformly distributed data
R-tree

- Read a sample
- Bulk load the sample into an R-tree
  - Leaf node capacity $C$
    \[ C = \frac{k \cdot B}{|R|(1 + \alpha)} \]
  - $k$: Sample size
  - $B$: HDFS Block capacity
  - $|R|$: Input size
  - $\alpha$: Index overhead
- Use MBR of leaf nodes as partition boundaries
R-tree

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- Bulk load the sample into an R-tree
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  - $k$: Sample size
  - $B$: HDFS Block capacity
  - $|R|$: Input size
  - $\alpha$: Index overhead
- Use MBR of leaf nodes as partition boundaries
- Partition the data
R-tree

› Read a sample
› Bulk load the sample into an R-tree
  › Leaf node capacity \( C \)
    \[
    C = \frac{k \cdot B}{|R|(1 + \alpha)}
    \]
  › \( k \): Sample size
  › \( B \): HDFS Block capacity
  › \(|R|\): Input size
  › \( \alpha \): Index overhead
› Use MBR of leaf nodes as partition boundaries
› Partition the data
› Optional: Build R-tree Local indexes
R-tree-based Index of a 400 GB road network
Non-indexed Heap File
MapReduce Layer

Applications: SHAHED [ICDE’15] – MNTG [SSTD’13, ICDE’14]
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Basic operations – CG_Hadoop
[SIGSPATIAL’13, TSAS*]

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* Under review

ST-Hadoop [TODS*]

Demo paper

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Map plan – SpatialHadoop

Indexed Input File(s)

Number of splits

Spatial File Splitter

Filter Function

Map task

Split

Spatial Record Reader

Map

Split

Spatial Record Reader

Map

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Operations


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Operations Layer

- Basic Operations: e.g., Range query and KNN
- Spatial Join Operations
- Computational geometry operations: e.g., Polygon Union, Voronoi diagram, Delaunay Triangulation, and Convex Hull
- User-defined operations: e.g., kNN join
Range Query

Use the **global index** to prune disjoint partitions

Use **local indexes** to find matching records
KNN over Indexed Data

First iteration runs as before and result is tested for correctness

✗ Answer is incorrect

Second iteration processes other blocks that might contain an answer

✓ Answer is correct

$k=3$
Spatial Join

Join Directly

Partition – Join
Spatial Join

Join Directly

- Total of 36 overlapping pairs

Partition – Join

- Only 16 overlapping pairs
CG_Hadoop

Polygon Union

Delaunay Triangulation

Voronoi Diagram

Convex Hull Farthest/closest pair

Skyline

A. Eldawy, Y. Li, M. F. Mokbel, R. Janardan. “CG_Hadoop: Computational Geometry in MapReduce”, ACM SIGSPATIAL’13

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Convex Hull

Find the minimal convex polygon that contains all points

Input

Output
Convex Hull in CG_Hadoop

1. Partition
2. Pruning
3. Local hull
4. Global hull

Hadoop

SpatialHadoop

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**Visualization**

**Applications:** SHAHED [ICDE’15] – MNTG [SSTD’13, ICDE’14]  
TAREEG[SIGMOD’14, SIGSPATIAL’14]

**Language**  
Pigeon [ICDE’14]

**Visualization**  
[VLDB’15, ICDE’16]

**Operations**  
Basic operations – CG_Hadoop  
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**MapReduce**  
Spatial File Splitter  
Spatial Record Reader

**Indexing**  
Grid – R-tree – R+-tree – Quad tree  
[VLDB’15]
The goal of HadoopViz is not to propose new visualization techniques, instead its goal is to **scale out** existing techniques.
Heat Map From 2009 to 2014
Month-by-Month

Jan-2009

72 Frames × 14 Billion points per frame
Total = 1 Trillion points

Created in 3 hours on 10 nodes instead of 60 hours

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Abstract Visualization

Input

Partition

1. smooth

3. plot

2. Create canvas

4. merge

5. write

Output Image
Example: Satellite Data Visualization

1. **Smooth**: Recover holes

![Smooth Example](image1)

2. **Create Canvas**: Initialize a 2D Matrix with zeros

\[
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\]

3. **Plot**: Update the matrix

\[
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 22 & 0 & 0 & 7 & 0 & 0 \\
0 & 0 & 15 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\]

4. **Merge**: Matrix addition

\[
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\]

5. **Write**: Generate the image

![Plot Example](image2)
Example: Road Network Visualization

1. **Smooth**: Merge intersections
2. **Create Canvas**: Create a blank image
3. **Plot**: Draw roads as polygons
4. **Merge**: Plot an image on the other
5. **Write**: Encode as PNG and write to file
Map of California – 2GB
Generated in 2 minutes on 10-node cluster instead of one hour
Multi-level Visualization

- Abstract multi-level visualization algorithm
- The choice of partitioning technique changes for each zoom level

\[ z_\theta = \left\lfloor \frac{1}{2} \log \left( \frac{B}{k |t|} \right) \right\rfloor \]

- \( B \): Block capacity
- \( k \): Partitioning parameter
- \( |t| \): Tile size

Default Hadoop partitioning

Threshold level \( z_\theta \)

Spatial Partitioning

Zoom Level

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Applications


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SHAHED — A system for querying and visualizing spatio-temporal satellite data

http://shahed.cs.umn.edu/

Visualize animated heat maps or still images

Run spatio-temporal selection and aggregate queries


TAREEG – Web-based extractor for OpenStreetMap data using MapReduce

http://tareeg.net/

L. Alarabi, A. Eldawy, R. Alghamdi, M. F. Mokbel. “TAREEG: A MapReduce-Based System for Extracting Spatial Data from OpenStreetMap”, ACM SIGSPATIAL’14

“TAREEG: A MapReduce-Based Web Service for Extracting Spatial Data from OpenStreetMap”, SIGMOD’14
Agenda

- The ecosystem of SpatialHadoop
  - Motivation
  - Internal system design
  - Applications
  - Related work
  - Experiments
- Other research projects
- Future work
SpatialHadoop is the only extensible system that can be easily expanded by researchers and developers.
Experimental Results

Throughput of Range Query

- **SpatialHadoop**
- **500X**
- **Hadoop**

Speedup of **CG_Hadoop**

- **260X**

Spatial Join

- Running time with different indexes

Visualization Speedup

- **48X**

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- Future directions
Future Research Directions

- Extend HadoopViz
  - Interactive visualization
  - Support more case studies

- Migrate spatial indexes to Spark to support spatial data mining operations

- Improve HDFS spatial indexes to support dynamic data
Adaptive Multilevel Visualization

Image tiles
Big enough to consider preprocessing

Data tiles
Small data sizes in those areas
Not worth of preprocessing

Empty tiles
Covered by parent data tiles

Empty tiles
No data in there
Dynamic Indexes
Advanced Analytic Queries

Partitioning

Local VD

Pruning

Vertical Merge

Pruning

Horizontal Merge

Final output
Sphinx: Distributed SQL Engine for Big Spatial Data

Cloudera Impala

Sphinx

Query Parser

Spatial Data types/ Functions
Spatial Indexing Command

Query Planner

Range Query Plans
Spatial Join Plans

Query Executor

R-tree Scanner
Spatial Join

Storage

Spatial Indexes

HDFS

A. Eldawy, M. Elganainy, I. Sabek, A. Bakeer, A. Abdelmotaleb, M. F. Mokbel “Sphinx: Distributed Execution of Interactive SQL Queries on Big Spatial Data”, poster in ACM SIGSPATIAL’15
Summary
Thank You

Questions?