Implementing Connected Component Labeling as a User Defined Operator for SciDB

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SciDB

SciDB is an all-in-one data management and advanced analytics platform that features:

• Complex analytics inside a next-generation parallel array database, i.e. not row-based or column-based like RDBMS’s based on table data model.
  o Supports extensive and flexible algebra operators that can be efficiently “wired” together for more complex operations.

• Based on the “shared nothing architecture” for data parallelism, data versioning and provenance to support science applications.

• Open source.

• A better performer than Hadoop (MapReduce), 2-10 times faster, in almost all benchmarks that we have performed so far.

• Extensible through user-defined types, functions and operators
System Layout

Each node: Eight 2.6GHz Sandybridge Cores & 32 GB of RAM
Event Identification needs CCL

• Our interest: Identifying weather events as connected spatio-temporal regions in large multi-year climate datasets.
  • For example, snowstorm climatology in thirty-plus (30+) years of GEOS-5 MERRA (http://gmao.gsfc.nasa.gov/research/merra/)
  • Thresholding to generate a mask array (foreground & background mesh points).
  • Grouping of (adjacent) foreground mesh points into uniquely labeled connected regions, hence CCL
CCL implementation in SciDB

- **Requirements:**
  - Flexible array dimensionality
  - Flexible connectivity in any of the array dimensions
  - Periodic Boundary Conditions - BCs (due to need to support earth science applications)

- **Algorithm - Weighted Quick Union with Half-Path compression (WQU)** e.g. as in [http://algs4.cs.princeton.edu/15uf/](http://algs4.cs.princeton.edu/15uf/):
  - Efficient
  - Easy implementation considering the requirements.

- **SciDB MemArray** (data structure for handling larger-than-RAM arrays)
  - Used extensively for efficient indexing and searching throughout.
CCL implementation in SciDB

- Flexible connectivity achieved by an auxiliary array of the same dimension as the mask array but length 3 in each dimension e.g. for 2-D

4-connectivity

8-connectivity

X-connectivity
Preparation steps

1. Thresholding already done to prepare the mask array
Preparation step

Partition mask array into SciDB chunks

- Schema supplied by the user to set chunk sizes (and overlap if any) e.g.
  \(<\text{mask:int8}> [x=0:17,9,1,y=0:19,10,1]\)

- Chunk assignment to instances is managed by SciDB using a heuristic hash function
Implementation steps

1. Stage 1 - CCL is computed by each instance, one chunk at a time
   - Apply the auxiliary connectivity array (4-connectivity in this case) to each foreground mask (using “flattened” coordinates) to determine pairs of adjacent cells.
   - Eliminate duplicate pairs
   - Apply WQU to each pair to determine CCLs for the chunk
   - Write chunk CCLs to MemArray
Implementation steps

2. Stage 2a - Equivalency resolution
   - Write chunks’ boundary labels to MemArray
   - Replicate the MemArray on all instances so that each instance now has all boundary labels
Implementation steps

3. Stage 2b - Equivalency resolution (cont’d)

On each instance

- Set up pairs of adjacent boundary labels
- Apply WQU to each pair to resolve equivalencies
- Write resolved boundary labels into 1-D MemArray using boundary labels from the Stage 1 as index (for later fast access in Stage 3)
Implementation steps

4. Stage 3 - Relabeling of Stage 1 using resolved labels from Stage 2b
   - On each instance, iterate over each chunk and relabel:
     
     ```
     if stage2b_array[stage1_label] is not NULL :
         new_label <- stage2b_array[stage1_label]
     else :
         new_label <- stage1_label
     ```
Implementation steps

5. Stage 4 – Final Relabeling

- Replace out-of-order labels from Stage 3 (represented by “flattened” coordinates from the original mask array) with sequential integers for legibility
Operator invocation

The operator is invoked (using the Array Functional Interface - AFL - interface via the iquery client):

\texttt{iquery -anq \textasciitilde store(ccl(mask\_array, con\_array), ccl\_array)\textasciitilde}

where

\begin{itemize}
  \item \texttt{ccl} : the new CCL operator
  \item \texttt{store} : the SciDB native operator to “write” results into an array
  \item \texttt{mask\_array} : the binary mask array
  \item \texttt{con\_array} : the connectivity array
  \item \texttt{ccl\_array} : array into which the resulting labels are written
\end{itemize}
Operator invocation with periodic BCs

Periodic BCs in both X- and Y-directions for our example:

```
operator -aq "store(ccl(mask_array, con_array, 1, 2), ccl_array)"
```
Real life example

- Thirty-plus (30+) years of potential blizzard conditions on the globe
- Binary mask created by applying thresholds to GEOS-5 MERRA
- Total grid (array) size: $O(10^{11})$
- Foreground cells: $O(10^8)$
- Spatio-Temporal CCLs (with periodic BCs in longitudinal direction): $O(10^6)$
Sample results (from Winter 2010 blizzard over Eastern U.S.)

Mask

Connected Components

2010-2-5 13:30

2010-2-5 14:30
Sample results (from Winter 2010 blizzard over Eastern U.S.)
Wall time - seconds  min(max)

<table>
<thead>
<tr>
<th></th>
<th>84 instances</th>
<th>56 instances</th>
<th>28 instances</th>
<th>14 instances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1 (local chunk labeling)</td>
<td>12(18)</td>
<td>21(27)</td>
<td>41(54)</td>
<td>88(114)</td>
</tr>
<tr>
<td>Stage 2a (replicate)</td>
<td>6(14)</td>
<td>6(12)</td>
<td>7(9)</td>
<td>9(12)</td>
</tr>
<tr>
<td>Stage 2b (resolve)</td>
<td>705(975)</td>
<td>705(935)</td>
<td>715(950)</td>
<td>725(940)</td>
</tr>
<tr>
<td>Stage 3 (relabeling)</td>
<td>33(55)</td>
<td>85(120)</td>
<td>115(160)</td>
<td>240(320)</td>
</tr>
<tr>
<td>Stage 4 (Final sequential labeling)</td>
<td>49(81)</td>
<td>90(125)</td>
<td>180(240)</td>
<td>364(475)</td>
</tr>
</tbody>
</table>

Comments
- Array schema - need to choose with care – significant effect on performance
  
  `<ccl:int64> [t=0:323591,720,0,z=0:0,1,0,y=0:360,91,0,x=0:539,135,0]`

- Good scaling for Stages 1, 3 & 4
- Boundary labels replication (Stage 2a) not terrible; dependent on array & schema
- As expected, no scaling for Stage 2b; further work needed to improve efficiency
Concluding remarks

• Array grows as time slices are added
• Expensive to re-compute labels for whole array each time new time slices are added
• Working on incremental implementation so that completed labels are excluded from new computation
Acknowledgement

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