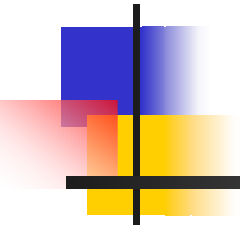
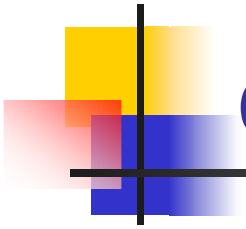


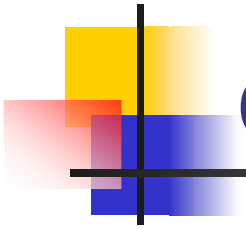
Compiler Supported High-level Abstractions for Sparse Disk-resident Datasets

Renato Ferreira
Gagan Agrawal
Joel Saltz
Ohio State University



General Motivation

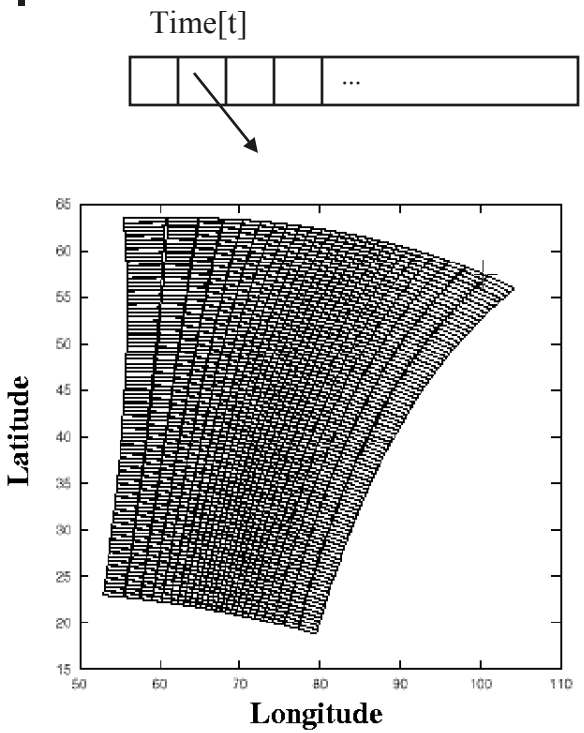
- Computing is playing an increasingly more significant role in a variety of scientific areas
- Traditionally, the focus was on simulating scientific phenomenon or processes
  - Software tools motivated by various computational solvers
- Recently, analysis of data is being considered key to advances in sciences
  - Data from computational simulations
  - Digitized images
  - Data from sensors



Challenges in Supporting Processing

- Massive amounts of data are becoming common
  - Data from simulations of large grids, parameters studies
  - Sensors collecting high resolution data, over long periods of time
- Datasets can be quite complex
- Applications scientists need high-performance as well as ease of implementing and modifying analysis

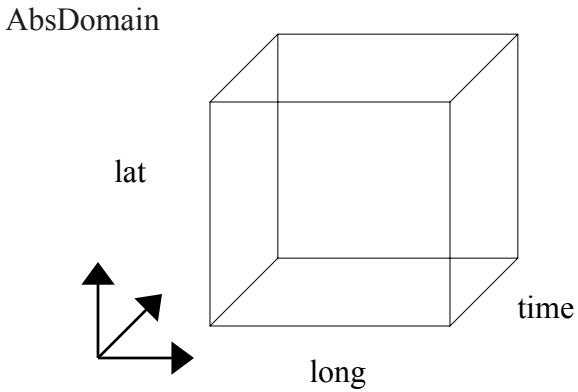
Motivating Application: Satellite Data Processing

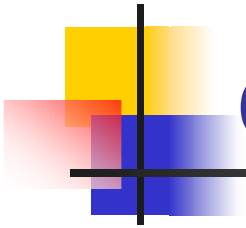


- Data collected by satellites is a collection of chunks, each of which captures an irregular section of earth captured at time t
- The entire dataset comprises multiples pixels for each point in earth at different times, but not for all times
- Typical processing is a reduction along the time dimension - hard to write on the raw data format

Supporting High-level Abstractions

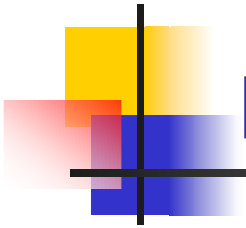
- View the dataset as a dense 3-d array, where many values can be zero
- Simplify the specification of processing on the datasets
- Challenge: how do we achieve efficient processing ?
  - Locality in accessing data
  - Avoiding unnecessary computations





Outline

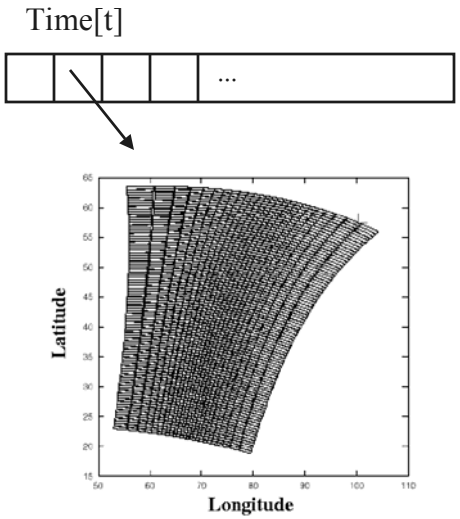
- Compiler front-end
- Execution strategy for irregular/sparse applications
- Supporting compiler analyses
- Performance enhancements
  - Dense applications
  - Code motion for conditionals
- Experimental results
- Conclusion

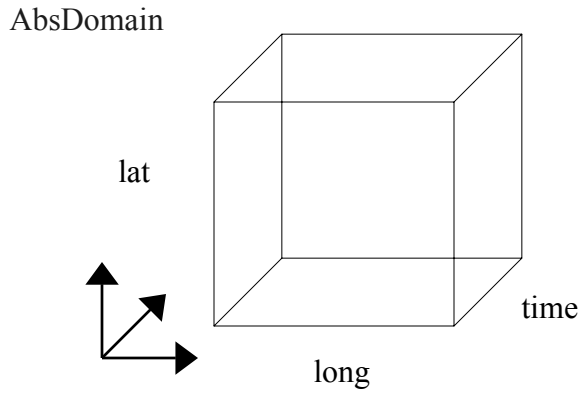


Programming Interface

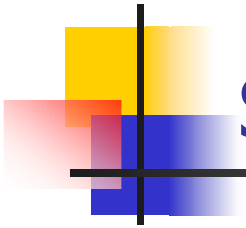
- Multi-dimensional collections
  - Domain
  - RectDomain
- Foreach loop
  - Iterates of the elements of a collection
- Reduction interface
  - Defines reduction variables
    - Update within the foreach
    - Associative and commutative operations
    - Only used for self updates

Satellite Data Processing






```
public class Element {
  short bands[5];
  short lat, long;
}
public class SatelliteApp {
  SatelliteData satdata;
  OutputData output;
  public static void main(String[] args) {
    Point[2] q;
    pixel val;
    RectDomain[3d] AbsDomain = ...
    foreach (q in AbsDomain)
      if (val = satdata.getData(q)) {
        Point[2] p = (q[1], q[2]);
        output[p].Accumulate(val);
      }
  }
}
```

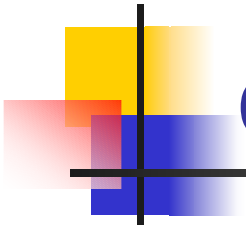


Sparse Execution Strategy

- Iterating over AbsDomain
  - Sparse domain
  - Poor locality
- Iterating over input elements
  - Need to map element to loop iteration

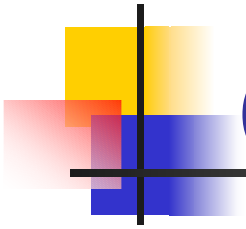
```
Foreach element e
  I = Iters(e)
  Foreach i in I
    If (i in the Input Range)
      Perform computation for e
```

Computing function Iters()



- Iters (element -> abstract domain)
  - l-value of element = <t, i>
  - r-value of element = <b1, b2, b3, b4, b5, lat, long>
  - Iters(elem = <l-value, r-value>) → <t, lat, long>

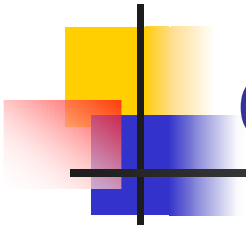
- Find the dominating constraints for the return statements within the functions in the low-level data layout (getData)



(Chunk-wise) Dense Strategy

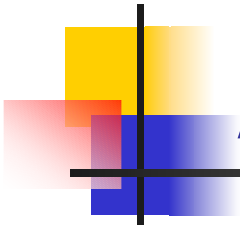
- Exploit the regularity on the dataset
  - Eliminate overhead of sparse strategy
- Simpler, more efficient implementation

```
Foreach input block
  Extract D (descriptor of the data)
    I = (Iters(D) ∩ Input Range)
    Foreach i in I
      Perform computation for Input[i]
```



Other Implementation Issues

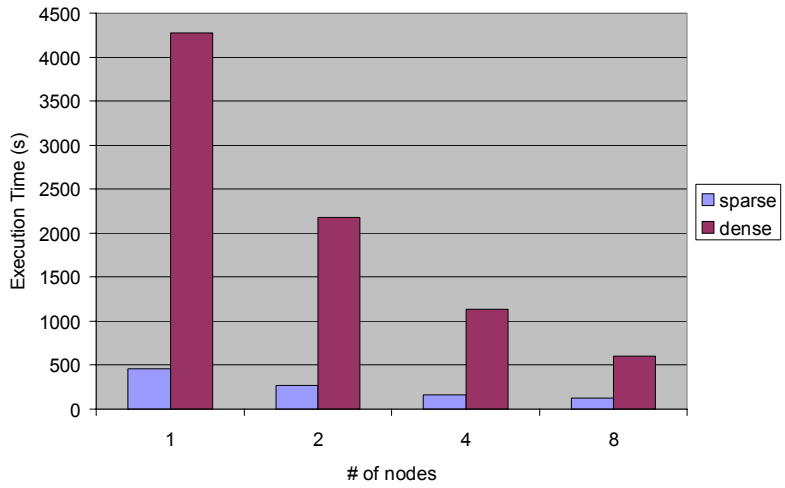
- Generating code for efficient execution
  - ADR run-time system
- Memory requirements
  - Tiling of the output
- Extract subscript and range functions from user application
  - Program Slicing (ICS 2000)
- Compiler and runtime communication analysis (PACT 2001)



Active Data Repository

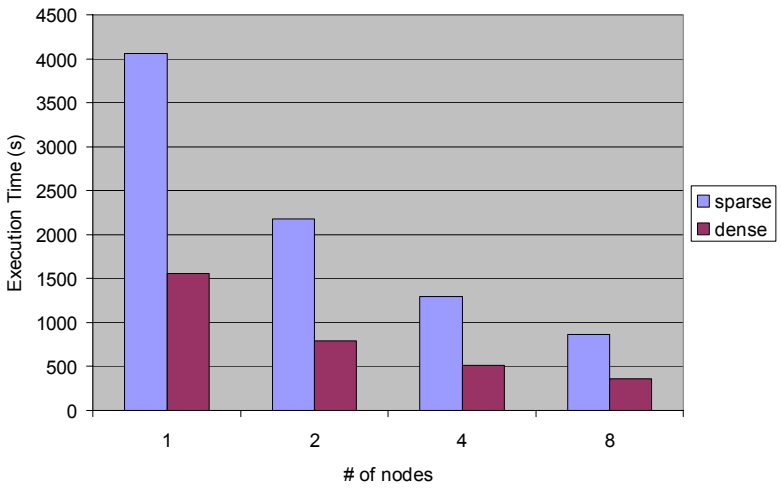
- Specialized run-time support for processing disk-based multi-dimensional datasets
  - Push processing into storage manager
  - Asynchronous operations
- Dataset is divided in blocks
  - Distribute across the nodes of a parallel machine
  - Spatial indexing mechanism
- Customizable for a variety of applications
  - Through virtual functions
  - Supplied by the compiler

Experimental Results: Sparse Application



- Cluster of Pentium II 400MHz
  - Linux
  - 256MB main memory
  - 18GB local disk
  - Gigabit switch
- Total data of 2.7GB
  - Process about 1.9GB
  - Output 446MB
- 5 to 10 times faster

Experimental Results: Dense Application

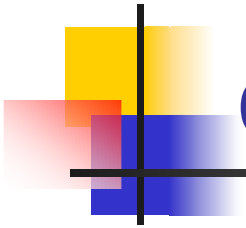


- Multi-grid Virtual Microscope
  - Based on VMScope
  - Stores data on different resolutions
- Total data of 3.3GB
  - Process about 3GB
  - Output 1.6GB
- 2 to 3 times faster

Improving the Performance

- Virtual Microscope with subsampling
- Extra conditionals
  - From execution strategy
  - From application

```
for(i0 = low1; i0 <= hi1; i0++)
  for (i1 = low2; i1 <= hi2; i1++) {
    ipt[0] = i0;
    ipt[1] = i1;
    opt[0] = (i0-v0)/2;
    opt[1] = (i1-v1)/2;
    if ((tlow1 <= opt[0] <= thi1) &&
        (tlow2 <= opt[1] <= thi2))
      if ((i0 % 2 == 0) && (i1 % 2 == 0))
        O[opt].Accum(I[ipt]);
  }
```



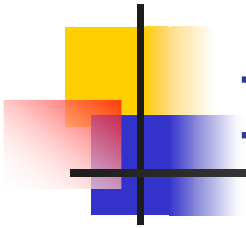
Conditional Motion

- Eliminate redundant conditionals
- Views of a conditional
  - Syntactically different conditions
- Dominating constraints
  - Downward propagation
  - Upward propagation
- Omega Library
  - Generate code for a set of conditionals

Conditional Motion Example

```
for(i0 = low1; i0 <= hi1; i0++)
  for (i1 = low2; i1 <= hi2; i1++) {
    ipt[0] = i0;
    ipt[1] = i1;
    opt[0] = (i0-v0)/2;
    opt[1] = (i1-v1)/2;
    if ((tlow1 <= opt[0] <= thi1) &&
        (tlow2 <= opt[1] <= thi2))
      if ((i0 % 2 == 0) && (i1 % 2 == 0))
        O[opt].Accum(I[ipt]);
  }
```

```
if (2*low2 <= -v1+thi2 && low2 <= v1+2*thi2)
  for(t1 = max(2*(v0+2*tlow1+1)/2, 2*(low1+1)/2);
      t1 <= min(v0+2*thi1,hi1); t1+=2)
    for(t2 = max(2*(2*tlow2+va1+1)/2, 2*(low2+1)/2);
        t2 <= min(v1+2*thi2,hi2); t2+=2)
      s1(t1, t2);
```

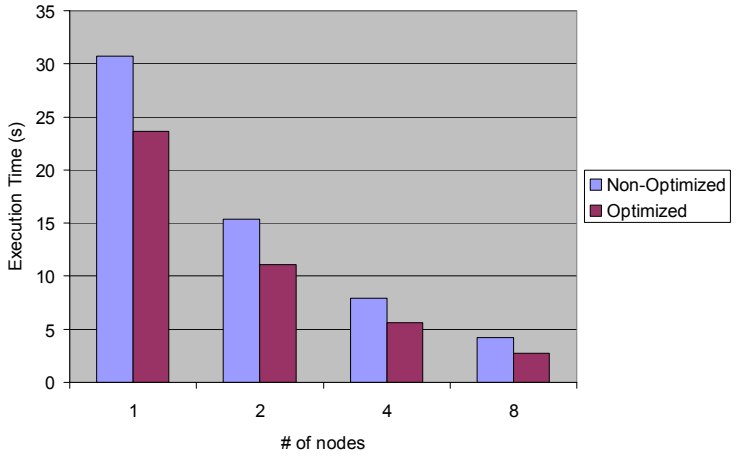


Input to Omega Library

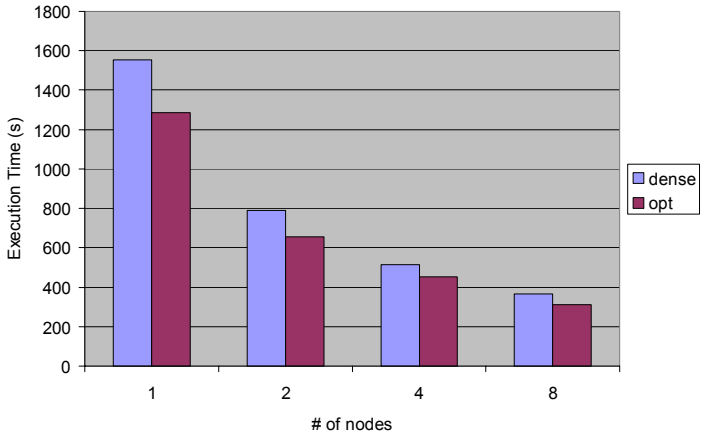
```
R := {[i0,i1] : low1 <= i0 <= hi1 and
                low2 <= i1 <= hi2 and
                exists (i00: i00*2 = i0) and
                exists (i11: i11*2 = i1)};
S := {[i0,i1] : tlow1 * 2 + v0 <= i0 <= thi1 * 2 + v0 and
               tlow2 * 2 + v1 <= i1 <= thi2 * 2 + v1};
U := (R intersects S)
codegen U;
```

Conditional Motion

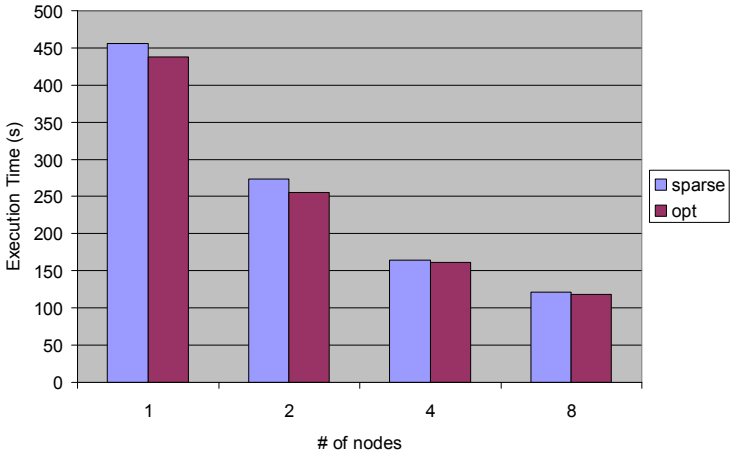
subsampling vscope:

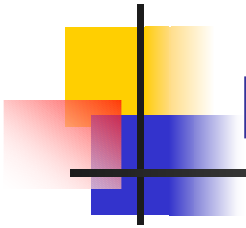


mg-vscope:



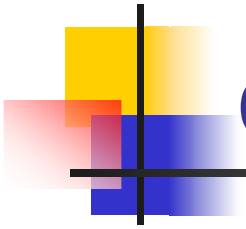
satellite:





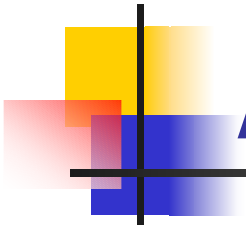
Related Work

- Parallelizing irregular applications
  - Disk-resident datasets, different class of applications
- Out-of-core compilers
  - High-level abstractions, different applications, language, and runtime system
- Data-centric locality transformations
  - Focus on disk-resident datasets
- Synthesizing sparse applications from dense ones
  - Different class of applications, disk-resident datasets
- Code motion techniques
  - Target eliminating redundant conditionals



Conclusion

- High-level abstractions simplify application development
- Data-centric execution strategies help support efficient processing
- Data parallel framework is convenient to describe the applications
- Choice of strategies has substantial impact on the performance



Application Loops

Foreach ($r \in R$) {

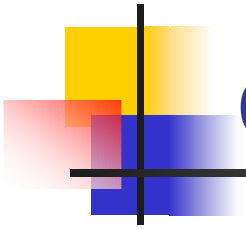
$O_1[S_{L1}(r)] = F_1(O_1[S_{L1}(r)], I_1[S_{R1}(r), \ldots, I_n[S_{Rn}(r)]);$

…

$O_m[S_{Lm}(r)] = F_m(O_m[S_{Lm}(r)], I_1[S_{R1}(r), \ldots, I_n[S_{Rn}(r)]);$

}

- Loop fission techniques to create canonical loops
- Program slicing techniques to extract the functions



Canonical Loops

- Facilitate the task for the run-time system
- Left hand side subscript functions
  - Output collections are congruent; or
  - All output collections fit in main memory
- Right hand side subscript functions
  - Input collections are congruent
  - $F_i(O_i, I_1, I_2, \ldots I_n) = g_0(O_i)\ op_1\ g_1(I_1)\ op_2\ g_2(I_2) \ldots op_n\ g_n(I_n)$;
  - op_1 to op_n are commutative and associative

Program Slicing

```
public class VMPixel {
  char[3] colors;
  void Initialize(){
    colors[0] = colors[1] = colors[2] = 0;
  }
  void Accum(VMPixel p, int avg) {
    colors[0] += p.colors[0]/avg;
    colors[1] += p.colors[1]/avg;
    colors[2] += p.colors[2]/avg;
  }
}

public class VMPixelOut extends VMPixel
          implements Reducinterface;

Public Class VMScope {
  static Point[2] lowpoint [0,0];
  static Point[2] hipoint[MaxX-1, MaxY-1];
  static RectDomain[2] VMSlide = [lowpoint:hipoint];
  static VMPixel[2d] Vscope = new VMPixel[VMSlide];
```

```
public static void main(String[] args) {
    Point[2] lowend = [args[0], args[1]];
    Point[2] hiend = [args[2],args[3]];
    RectDomain[2] querybox = [lowend:hiend];
    int subsamp = args[4];
    RectDomain[2] OutDomain =
                                [[0,0]:(hiend-lowend)/subsamp];
    VMPixelOut[2d] Output = new VMPixelOut[OutDomain];
    Point[2] p;
    foreach (p in OutDomain)
      Output[p].Initialize();
    foreach (p in querybox) {
      Point[2] q = (p - lowend)/subsamp;
      Output[q].Accum(Vscope[p], subsamp*subsamp);
    }
  }
}
```