Titanium: A Java Dialect for High Performance Computing

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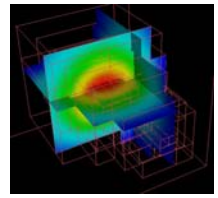
Motivation: Target Problems

- Many modeling problems in astrophysics, biology, material science, and other areas require
  - Enormous range of spatial and temporal scales
- To solve interesting problems, one needs:
  - Adaptive methods
  - Large scale parallel machines
- Titanium is designed for
  - Structured grids
  - Locally-structured grids (AMR)
  - Unstructured grids (in progress)



Source: J. Bell, LBNL

Titanium Background

- Based on Java, a cleaner C++
  - Classes, automatic memory management, etc.
  - Compiled to C and then machine code, no JVM
- Same parallelism model at UPC and CAF
  - SPMD parallelism
  - Dynamic Java threads are not supported
- Optimizing compiler
  - Analyzes global synchronization
  - Optimizes pointers, communication, memory

Summary of Features Added to Java

- Multidimensional arrays: iterators, subarrays, copying
- Immutable (“value”) classes
- Templates
- Operator overloading
- Scalable SPMD parallelism replaces threads
- Global address space with local/global reference distinction
- Checked global synchronization
- Zone-based memory management (regions)
- Libraries for collective communication, distributed arrays, bulk I/O, performance profiling

Outline

- Titanium Execution Model
  - SPMD
  - Global Synchronization
  - Single
- Titanium Memory Model
- Support for Serial Programming
- Performance and Applications
- Compiler/Language Status

SPMD Execution Model

- Titanium has the same execution model as UPC and CAF
- Basic Java programs may be run as Titanium programs, but all processors do all the work.
- E.g., parallel hello world

```
class HelloWorld {
    public static void main (String [] argv) {
      System.out.println(“Hello from proc “
                         + Ti.thisProc()
                         + “ out of “
                         + Ti.numProcs());
      }
   }
```

- Global synchronization done using `Ti.barrier()`

Barriers and Single

- Common source of bugs is barriers or other collective operations inside branches or loops

```
barrier, broadcast, reduction, exchange
```

- A “single” method is one called by all procs

```
public single static void allStep(...)
```

- A “single” variable has same value on all procs

```
int single timestep = 0;
```

- Single annotation on methods is optional, but useful in understanding compiler messages
- Compiler proves that all processors call barriers together

Explicit Communication: Broadcast

- Broadcast is a one-to-all communication

```
broadcast <value> from <processor>
```

- For example:

```
int count = 0;
int allCount = 0;
if (Ti.thisProc() == 0) count = computeCount();
allCount = broadcast count from 0;
```

- The processor number in the broadcast must be single; all constants are single.
  - All processors must agree on the broadcast source.
- The `allCount` variable could be declared single.
  - All will have the same value after the broadcast.

More on Single

- Global synchronization needs to be controlled

```
if (this processor owns some data) {
    compute on it
    barrier
}
```

- Hence the use of “single” variables in Titanium
- If a conditional or loop block contains a barrier, all processors must execute it
  - conditions must contain only single variables
- Compiler analysis statically enforces freedom from deadlocks due to barrier and other collectives being called non-collectively "Barrier Inference" [Gay & Aiken]

Single Variable Example

- Barriers and single in N-body Simulation

```
class ParticleSim {
  public static void main (String [] argv) {
  int single allTimestep = 0;
  int single allEndTime = 100;
  for (; allTimestep < allEndTime; allTimestep++){
    read remote particles, compute forces on mine
    Ti.barrier();
    write to my particles using new forces
    Ti.barrier();
  }
 }
}
```

- Single methods inferred by the compiler

Using Broadcast to Assign Single

- Broadcast returns a single value
- The following example will have a randomly chosen process initiate the broadcast at each step

```
int myChoice = (int) (Math.random() *
                      Ti.numProcs());
for (int single i = 0; i < 100; i++) {
  master = broadcast myChoice from master;
}
```

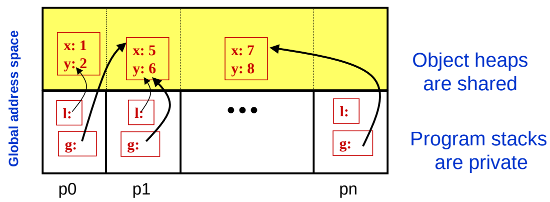
- The example is contrived, but this paradigm is used to assign single values that come from user input or a file, for example.

Outline

- Titanium Execution Model
- Titanium Memory Model
  - Global and Local References
  - Exchange: Building Distributed Data Structures
  - Region-Based Memory Management
- Support for Serial Programming
- Performance and Applications
- Compiler/Language Status

Global Address Space

- Globally shared address space is partitioned
- References (pointers) are either local or global (meaning possibly remote)



Use of Global / Local

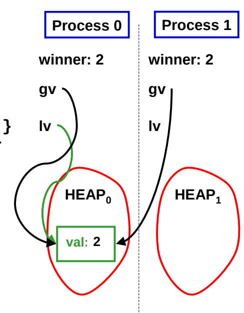
- Global references (pointers) may point to remote locations
  - Reference are global by default
  - Easy to port shared-memory programs
- Global pointers are more expensive than local
  - True even when data is on the same processor
  - Costs of global:
    - space (processor number + memory address)
    - dereference time (check to see if local)
- May declare references as local
  - Compiler will automatically infer local when possible
  - This is an important performance-tuning mechanism

Global Address Space

- Processes allocate locally
- References can be passed to other processes

```
class C { public int val;... }
C gv;        // global pointer
C local lv; // local pointer
if (Ti.thisProc() == 0) {
      lv = new C();
}
gv = broadcast lv from 0;
//data race
gv.val = Ti.thisProc()+1;

int winner = gv.val
```



Aside on Titanium Arrays

- Titanium adds its own multidimensional array class for performance
- Distributed data structures are built using a 1D Titanium array
- Slightly different syntax, since Java arrays still exist in Titanium, e.g.:

```
int [1d] a;
a = new int [1:100];
a[1] = 2*a[1] - a[0] – a[2];
```

- Will discuss these more later…

Explicit Communication: Exchange

- To create shared data structures
  - each processor builds its own piece
  - pieces are exchanged (for objects, just exchange pointers)
- Exchange primitive in Titanium

```
int [1d] single allData;
allData = new int [0:Ti.numProcs()-1];
allData.exchange(Ti.thisProc()*2);
```

- E.g., on 4 procs, each will have copy of allData:

allData → | 0 | 2 | 4 | 6 |

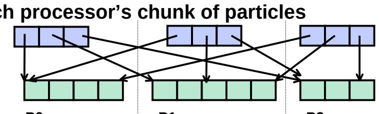
Distributed Data Structures

- Building distributed arrays:

```
Particle [1d] single [1d] allParticle =
         new Particle [0:Ti.numProcs-1][1d];
Particle [1d] myParticle =
         new Particle [0:myParticleCount-1];
allParticle.exchange(myParticle);
```

All to all broadcast

- Now each processor has array of pointers, one to each processor's chunk of particles



Region-Based Memory Management

- An advantage of Java over C/C++ is:
  - Automatic memory management
- But garbage collection:
  - Has a reputation of slowing serial code
  - Does not scale well in a parallel environment
- Titanium approach:
  - Preserves safety – cannot deallocate live data
  - Garbage collection is the default (on most platforms)
  - Higher performance is possible using region-based explicit memory management
  - Takes advantage of memory management phases

Region-Based Memory Management

- Need to organize data structures
- Allocate set of objects (safely)
- Delete them with a single explicit call (fast)

```
PrivateRegion r = new PrivateRegion();
for (int j = 0; j < 10; j++) {
   int[] x = new ( r ) int[j + 1];
   work(j, x);
}
try { r.delete(); }
 catch (RegionInUse oops) {
    System.out.println("failed to delete");
 }
}
```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- Titanium Execution Model
- Titanium Memory Model
- Support for Serial Programming
  - Immutables
  - Operator overloading
  - Multidimensional arrays
  - Templates
- Performance and Applications
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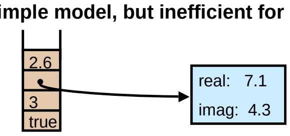
Java Objects

- Primitive scalar types: boolean, double, int, etc.
  - implementations store these on the program stack
  - access is fast -- comparable to other languages
- Objects: user-defined and standard library
  - always allocated dynamically in the heap
  - passed by pointer value (object sharing)
  - has implicit level of indirection
  - simple model, but inefficient for small objects



Java Object Example

```
class Complex {
  private double real;
  private double imag;
  public Complex(double r, double i) {
      real = r; imag = i; }
  public Complex add(Complex c) {
      return new Complex(c.real + real, c.imag + imag);
  public double getReal { return real; }
  public double getImag { return imag; }
}
Complex c = new Complex(7.1, 4.3);
c = c.add(c);
class VisComplex extends Complex { ... }
```


Immutable Classes in Titanium

- For small objects, would sometimes prefer
  - to avoid level of indirection and allocation overhead
  - pass by value (copying of entire object)
  - especially when immutable -- fields never modified
    - extends the idea of primitive values to user-defined types
- Titanium introduces immutable classes
  - all fields are implicitly final (constant)
  - cannot inherit from or be inherited by other classes
  - needs to have 0-argument constructor
- Examples: Complex, xyz components of a force
- Note: considering lang. extension to allow mutation

Example of Immutable Classes

- The immutable complex class nearly the same

```
immutable class Complex {
    Complex () {real=0; imag=0;}
    ...
}
```

new keyword → `immutable`

Zero-argument constructor required

Rest unchanged. No assignment to fields outside of constructors.

- Use of immutable complex values

```
Complex c1 = new Complex(7.1, 4.3);
Complex c2 = new Complex(2.5, 9.0);
c1 = c1.add(c2);
```

- Addresses performance and programmability
  - Similar to C structs in terms of performance
  - Support for Complex with a general mechanism

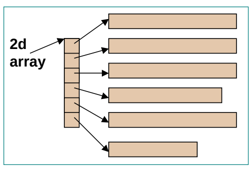
Operator Overloading

- Titanium provides operator overloading
  - Convenient in scientific code
  - Feature is similar to that in C++

```
class Complex {
  ...
  public Complex op+(Complex c) {
    return new Complex(c.real + real, c.imag + imag);
}
Complex c1 = new Complex(7.1, 4.3);
Complex c2 = new Complex(5.4, 3.9);
Complex c3 = c1 + c2;
```

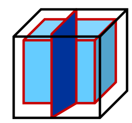

Arrays in Java

- Arrays in Java are objects
- Only 1D arrays are directly supported
- Multidimensional arrays are arrays of arrays
- General, but slow



- Subarrays are important in AMR (e.g., interior of a grid)
  - Even C and C++ don't support these well
  - Hand-coding (array libraries) can confuse optimizer
- Can build multidimensional arrays, but we want
  - Compiler optimizations and nice syntax

Multidimensional Arrays in Titanium



- New multidimensional array added
  - Supports subarrays without copies
    - can refer to rows, columns, slabs interior, boundary, even elements…
  - Indexed by Points (tuples of ints)
  - Built on a rectangular set of Points, RectDomain
  - Points, Domains and RectDomains are built-in immutable classes, with useful literal syntax
- Support for AMR and other grid computations
  - domain operations: intersection, shrink, border
  - bounds-checking can be disabled after debugging

Unordered Iteration

- Motivation:
  - Memory hierarchy optimizations are essential
  - Compilers sometimes do these, but hard in general
- Titanium has explicitly unordered iteration
  - Helps the compiler with analysis
  - Helps programmer avoid indexing details

```
foreach (p in r) { … A[p] … }
```

    - p is a Point (tuple of ints), can be used as array index
    - r is a RectDomain or Domain
- Additional operations on domains to transform
- Note: foreach is not a parallelism construct

Point, RectDomain, Arrays in General

- Points specified by a tuple of ints

```
Point<2> lb = [1, 1];
Point<2> ub = [10, 20];
```

- RectDomains given by 3 points:
  - lower bound, upper bound (and optional stride)

```
RectDomain<2> r = [lb : ub];
```

- Array declared by num dimensions and type

```
double [2d] a;
```

- Array created by passing RectDomain

```
a = new double [r];
```

Simple Array Example

- Matrix sum in Titanium

```
Point<2> lb = [1,1];
Point<2> ub = [10,20];
RectDomain<2> r = [lb:ub];

double [2d] a = new double [r];
double [2d] b = new double [1:10,1:20];
double [2d] c = new double [lb:ub:[1,1]];

for (int i = 1; i <= 10; i++)
   for (int j = 1; j <= 20; j++)
      c[i,j] = a[i,j] + b[i,j];

foreach(p in c.domain()) { c[p] = a[p] + b[p]; }
```

No array allocation here

Syntactic sugar

Optional stride

Equivalent loops

More Array Operations

- Titanium arrays have a rich set of operations

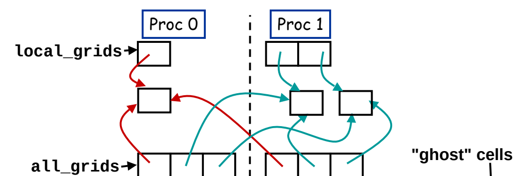
- None of these modify the original array, they just create another view of the data in that array
- You create arrays with a RectDomain and get it back later using A.domain() for array A
  - A Domain is a set of points in space
  - A RectDomain is a rectangular one
- Operations on Domains include +, -, * (union, different intersection)

MatMul with Titanium Arrays

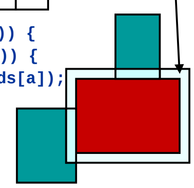
```
public static void matMul(double [2d] a,
                          double [2d] b,
                          double [2d] c) {
  foreach (ij in c.domain()) {
    double [1d] aRowi = a.slice(1, ij[1]);
    double [1d] bColj = b.slice(2, ij[2]);
    foreach (k in aRowi.domain()) {
      c[ij] += aRowi[k] * bColj[k];
    }
  }
}
```

Current performance: comparable to 3 nested loops in C

Example: Setting Boundary Conditions




```
foreach (l in local_grids.domain()) {
  foreach (a in all_grids.domain()) {
     local_grids[l].copy(all_grids[a]);
  }
}
```



- Can allocate arrays in a global index space.
- Let compiler computer intersections

Templates

- Many applications use containers:
  - Parameterized by dimensions, element types,…
  - Java supports parameterization through inheritance
    - Can only put Object types into containers
    - Inefficient when used extensively
- Titanium provides a template mechanism closer to C++
  - Can be instantiated with non-object types (double, Complex) as well as objects
- Example: Used to build a distributed array package
  - Hides the details of exchange, indirection within the data structure, etc.

Example of Templates

```
template <class Element> class Stack {
    . . .
    public Element pop() {...}
    public void push( Element arrival ) {...}
}

template Stack<int> list = new template Stack<int>();
list.push( 1 );
int x = list.pop();
```

Not an object

Strongly typed,
No dynamic cast

- Addresses programmability and performance

Using Templates: Distributed Arrays

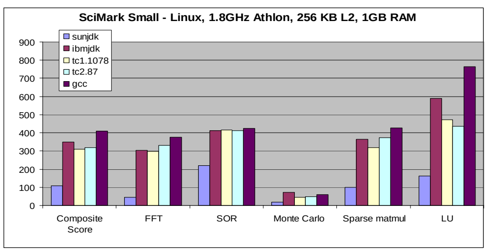
```
template <class T, int single arity>
public class DistArray {
  RectDomain <arity> single rd;
  T [arity d][arity d] subMatrices;
  RectDomain <arity> [arity d] single subDomains;
  ...
 /* Sets the element at p to value */
  public void set (Point <arity> p, T value) {
    getHomingSubMatrix (p) [p] = value;
  }
}
```

```
template DistArray <double, 2> single A =
     new template
         DistArray<double, 2> ( [[0,0]:[aHeight, aWidth]] );
```


Outline

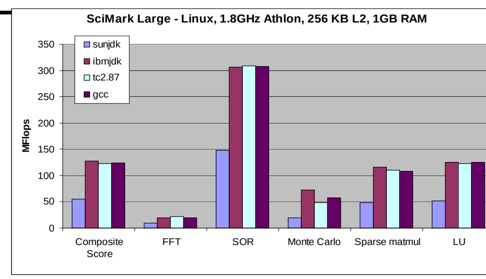
- Titanium Execution Model
- Titanium Memory Model
- Support for Serial Programming
- Performance and Applications
  - Serial Performance on pure Java (SciMark)
  - Parallel Applications
  - Compiler status & usability results
- Compiler/Language Status

Java Compiled by Titanium Compiler



- Sun JDK 1.4.1_01 (HotSpot(TM) Client VM) for Linux
- IBM J2SE 1.4.0 (Classic VM cxia32140-20020917a, jitc JIT) for 32-bit Linux
- Titaniumc v2.87 for Linux, gcc 3.2 as backend compiler -O3. no bounds check
- gcc 3.2, -O3 (ANSI-C version of the SciMark2 benchmark)

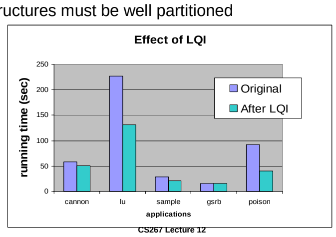
Java Compiled by Titanium Compiler



- Same as previous slide, but using a larger data set
- More cache misses, etc.

Local Pointer Analysis

- Global pointer access is more expensive than local
- Compiler analysis can frequently infer that a given global pointer always points locally
  - Replace global pointer with a local one
  - Local Qualification Inference (LQI)
  - Data structures must be well partitioned

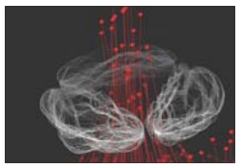


Applications in Titanium

- Benchmarks and Kernels
  - Scalable Poisson solver for infinite domains
  - NAS PB: MG, FT, IS, CG
  - Unstructured mesh kernel: EM3D
  - Dense linear algebra: LU, MatMul
  - Tree-structured n-body code
  - Finite element benchmark
- Larger applications
  - Gas Dynamics with AMR
  - Heart and Cochlea simulation (ongoing)
  - Genetics: micro-array selection
  - Ocean modeling with AMR (in progress)

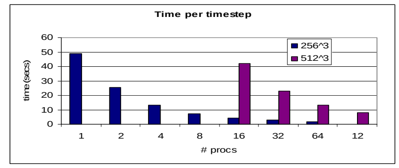
Heart Simulation: Immersed Boundary Method

- Problem: compute blood flow in the heart
  - Modeled as an elastic structure in an incompressible fluid.
    - The “immersed boundary method” [Peskin and McQueen].
    - 20 years of development in model
  - Many other applications: blood clotting, inner ear, paper making, embryo growth, and more
- Can be used for design of prosthetics
  - Artificial heart valves
  - Cochlear implants

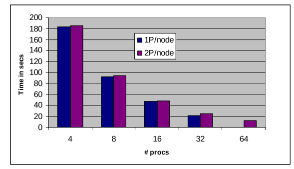


Performance of IB Code

- IBM SP performance (seaborg)

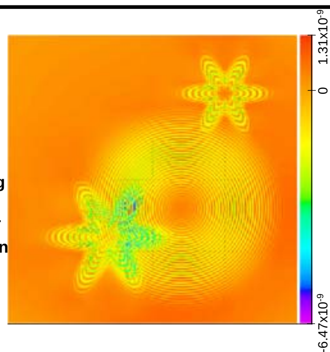


- Performance on a PC cluster at Caltech



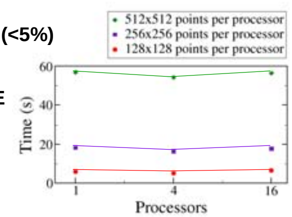
Error on High-Wavenumber Problem

- Charge is
  - 1 charge of concentric waves
  - 2 star-shaped charges.
- Largest error is where the charge is changing rapidly. Note:
  - discretization error
  - faint decomposition error
- Run on 16 procs



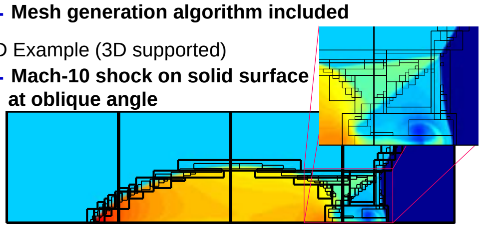
Scalable Parallel Poisson Solver

- MLC for Finite-Differences by Balls and Colella
- Poisson equation with infinite boundaries
  - arise in astrophysics, some biological systems, etc.
- Method is scalable
  - Low communication (<5%)
- Performance on
  - SP2 (shown) and T3E
  - scaled speedups
  - nearly ideal (flat)
- Currently 2D and non-adaptive



AMR Gas Dynamics

- Hyperbolic Solver [McCorquodale and Colella]
  - Implementation of Berger-Colella algorithm
  - Mesh generation algorithm included
- 2D Example (3D supported)
  - Mach-10 shock on solid surface at oblique angle



- Future: 3D Ocean Model based on Chombo algorithms
  - [Wen and Colella]

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- Compiler/Language Status

Titanium Compiler Status

- Titanium runs on almost any machine
  - Requires a C compiler and C++ for the translator
  - Pthreads for shared memory
  - GASNet for distributed memory, which exists on
    - Quadrics (Elan), IBM/SP (LAPI), Myrinet (GM), Infiniband, UDP, Shem* (Altix and X1), Dolphin* (SCI), and MPI
    - Shared with Berkeley UPC compiler
- Recent language and compiler work
  - Indexed (scatter/gather) array copy
  - Non-blocking array copy*
  - Loop level cache optimizations
  - Inspector/Executor*

* Work is still in progress

Programmability

- Immersed boundary method developed in ~1 year
  - Extended to support 2D structures ~1 month
  - Reengineered over ~6 months
- Preliminary code length measures
  - Simple torus model
    - Serial Fortran torus code is 17045 lines long (2/3 comments)
    - Parallel Titanium torus version is 3057 lines long.
  - Full heart model
    - Shared memory Fortran heart code is 8187 lines long
    - Parallel Titanium version is 4249 lines long.
  - Need to be analyzed more carefully, but not a significant overhead for distributed memory parallelism

Titanium and UPC Project Ideas

- Past 267 project ideas
  - Tree-based N-Body code in Titanium
  - Finite element code in Titanium
- Future project ideas for Titanium and UPC
  - Splash benchmarks in either language
  - Missing NAS benchmarking in Titanium
  - Your favorite application
- What makes it interesting?
  - Understanding the performance and scalability
    - Why does it perform as it does?
    - Performance model
    - Effectiveness of optimizations in application, runtime, compiler?

Titanium Group (Past and Present)

- Susan Graham
- Katherine Yelick
- Paul Hilfinger
- Phillip Colella (LBNL)
- Alex Aiken

- Greg Balls
- Andrew Begel
- Dan Bonachea
- Kaushik Datta
- David Gay
- Ed Givelberg
- Arvind Krishnamurthy

- Ben Liblit
- Peter McQuorquodale (LBNL)
- Sabrina Merchant
- Carleton Miyamoto
- Chang Sun Lin
- Geoff Pike
- Luigi Semenzato (LBNL)
- Armando Solar-Lezama
- Jimmy Su
- Tong Wen (LBNL)
- Siu Man Yau
- and many undergraduate researchers

http://titanium.cs.berkeley.edu