Titanium: A Java Dialect for High Performance Computing

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(slides courtesy of Kathy Yelick)

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Titanium Group (Past and Present)

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- Andrew Begel
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(and many undergrad researchers)

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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 methods with**
  - Structured grids
  - Locally-structured grids (AMR)
  - Unstructured grids (in progress)

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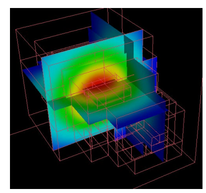
Common Requirements

- **Algorithms for numerical PDE computations are**
  - communication intensive
  - memory intensive
- **AMR makes these harder**
  - more small messages
  - more complex data structures
  - most of the programming effort is debugging the boundary cases
  - locality and load balance trade-off is hard



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Titanium

- Based on Java, a cleaner C++
  - classes, automatic memory management, etc.
  - compiled to C and then native binary (no JVM)
- Same parallelism model as UPC and CAF
  - SPMD with a global address space
  - Dynamic Java threads are not supported
- Optimizing compiler
  - static (compile-time) optimizer, not a JIT
  - communication and memory optimizations
  - synchronization analysis (e.g. static barrier analysis)
  - cache and other uniprocessor optimizations

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Summary of Features Added to Java

- **Multidimensional arrays with iterators & copy ops**
- **Immutable (“value”) classes**
- **Templates**
- **Operator overloading**
- **Scalable SPMD parallelism**
- **Global address space**
- **Checked Synchronization**
- **Zone-based memory management (regions)**
- **Support for N-dim points, rectangles & point sets**
- **Libraries for collective communication, distributed arrays, bulk I/O, performance profiling**

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Outline

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

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SPMD Execution Model

- Titanium has the same execution model as UPC and CAF
- Basic Java programs may be run as Titanium, 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());
  }
}
```

- Any non-trivial program will have communication and synchronization

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SPMD Model

- All processors start together and execute same code, but not in lock-step
- Basic control done using
  - Ti.numProcs() => total number of processors
  - Ti.thisProc() => id of executing processor
- Bulk-synchronous style

```
read all particles and compute forces on mine
 Ti.barrier();
 write to my particles using new forces
 Ti.barrier();
```

- This is neither message passing nor data-parallel

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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 to understanding compiler messages

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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 processors will have the same value after the broadcast.

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Example of Data Input

- Same example, but reading from keyboard
- Shows use of Java exceptions

```
int myCount = 0;
int single allCount = 0;
if (Ti.thisProc() == 0)
  try {
     DataInputStream kb = new
            DataInputStream(System.in);
     myCount =
          Integer.valueOf(kb.readLine()).intValue();
  } catch (Exception e) {
     System.err.println("Illegal Input");
  }
allCount = broadcast myCount from 0;
```

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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 in such loops, if statements, etc. 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]

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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 all particles and compute forces on mine
        Ti.barrier();
        write to my particles using new forces
        Ti.barrier();
      }
    }
  }
```

- **Single methods inferred by the compiler**

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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**
- **Compiler Optimizations & Future work**

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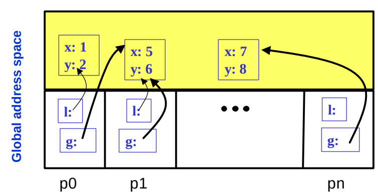
Global Address Space

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



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Use of Global / Local

- **As seen, global references (pointers) may point to remote locations**
  - easy to port shared-memory programs
- **Global pointers are more expensive than local**
  - True even when data is on the same processor
  - Use local declarations in critical inner loops
- **Costs of global:**
  - space (processor number + memory address)
  - dereference time (check to see if local)
- **May declare references as local**
  - Compiler will automatically infer them when possible

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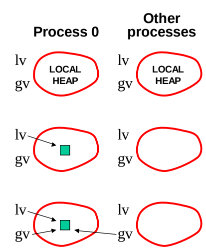
Global Address Space

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

```
class C { int val;... }
C gv;        // global pointer
C local lv; // local pointer

if (Ti.thisProc() == 0) {
     lv = new C();
}
gv = broadcast  lv from 0;
gv.val = ...;
... = gv.val;
```



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Shared/Private vs Global/Local

- Titanium's global address space is based on pointers rather than shared variables
- There is no distinction between a private and shared heap for storing objects
  - Although recent compiler analysis infers this distinction and uses it for performing optimizations [Liblit et. al 2003]
- All objects may be referenced by global pointers or by local ones
- There is no direct support for distributed arrays
  - Irregular problems do not map easily to distributed arrays, since each processor will own a set of objects (sub-grids)
  - For regular problems, Titanium uses pointer dereference instead of index calculation
  - Important to have local "views" of data structures

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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] arr;
arr = new int [1:100];
arr[1] = 4*arr[1];
```

- Will discuss these more later…

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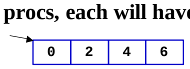
Explicit Communication: Exchange

- To create shared data structures
  - each processor builds its own piece
  - pieces are exchanged (for object, 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:



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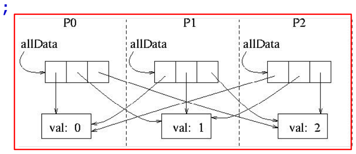
Building Distributed Structures

- Distributed structures are built with exchange:

```
class Boxed {
    public Boxed (int j) { val = j;}
    public int val;
}
```




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

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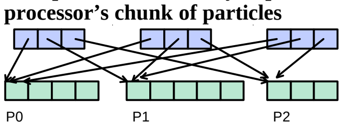
Distributed Data Structures

- 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



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Region-Based Memory Management

- An advantage of Java over C/C++ is:
  - Automatic memory management
- But unfortunately, garbage collection:
  - Has a reputation of slowing serial code
  - Is hard to implement and scale in a distributed environment
- Titanium takes the following approach:
  - Memory management is safe – cannot deallocate live data
  - Garbage collection is used by default (most platforms)
  - Higher performance is possible using region-based explicit memory management

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Region-Based Memory Management

- Need to organize data structures
- Allocate set of objects (safely)
- Delete them with a single explicit call (fast)
  - David Gay's Ph.D. thesis

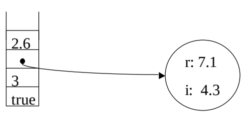
```
PrivateRegion r = new PrivateRegion();
for (int j = 0; j < 10; j++) {
    int[] x = new ( r ) int[j + 1];
    work(j, x);
}
try { r.delete(); }
catch (RegionInUse oops) {
     System.out.println(“failed to delete”);
  }
}
```


Outline

- **Titanium Execution Model**
- **Titanium Memory Model**
- **Support for Serial Programming**
  - **Immutables**
  - **Operator overloading**
  - **Multidimensional arrays**
  - **Templates**
- **Performance and Applications**
- **Compiler/Language Status**
- **Compiler Optimizations & Future work**

Java Objects

- **Primitive scalar types: boolean, double, int, etc.**
  - **implementations will store these on the program stack**
  - **access is fast -- comparable to other languages**
- **Objects: user-defined and standard library**
  - **always allocated dynamically**
  - **passed by pointer value (object sharing) into functions**
  - **has level of indirection (pointer to) implicit**
  - **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 datatypes**
- **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**
- **Example uses:**
  - **Complex numbers, xyz components of a field vector at a grid cell (velocity, 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

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
  - Allows efficient support of complex types through a general language mechanism

Operator Overloading

- For convenience, Titanium provides operator overloading
  - important for readability in scientific code
  - Very similar to operator overloading in C++
  - Must be used judiciously

```
class Complex {
  private double real;
  private double imag;
  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;
```

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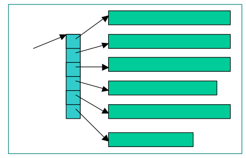
Arrays in Java

- Arrays in Java are objects
- Only 1D arrays are directly supported
- Multidimensional arrays are arrays of arrays
- General, but slow - due to memory layout, difficulty of compiler analysis, and bounds checking



- 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

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Multidimensional Arrays in Titanium

- New multidimensional array added
  - One array may be a subarray of another
    - e.g., a is interior of b, or a is all even elements of b
    - can easily refer to rows, columns, slabs or boundary regions as sub-arrays of a larger array
  - Indexed by Points (tuples of ints)
  - Constructed over a rectangular set of Points, called Rectangular Domains (RectDomains)
  - Points, Domains and RectDomains are built-in immutable classes, with handy literal syntax
- Expressive, flexible and fast
- Support for AMR and other grid computations
  - domain operations: intersection, shrink, border
  - bounds-checking can be disabled after debugging phase

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Unordered Iteration

- Memory hierarchy optimizations are essential
- Compilers can sometimes do these, but hard in general
- Titanium adds explicitly unordered iteration over domains
  - Helps the compiler with loop & dependency analysis
  - Simplifies bounds-checking
  - Also avoids some indexing details - more concise

```
foreach (p in r) { … A[p] … }
```

  - p is a Point (tuple of ints) that can be used to index arrays
  - r is a RectDomain or Domain
- Additional operations on domains to subset and xform
- Note: foreach is not a parallelism construct

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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];
```

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Simple Array Example

- Matrix sum in Titanium

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

No array allocation here

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

Syntactic sugar

Optional stride

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

Equivalent loops

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

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Naïve MatMul with Titanium Arrays

```
public static void matMul(double [2d] a, double [2d] b,
                          double [2d] c) {
  int n = c.domain().max()[1];  // assumes square
  for (int i = 0; i < n; i++) {
    for (int j = 0; j < n; j++) {
        for (int k = 0; k < n; k++) {
           c[i,j] += a[i,k] * b[k,j];
        }
     }
   }
}
```


Better 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];
    }
  }
}
```

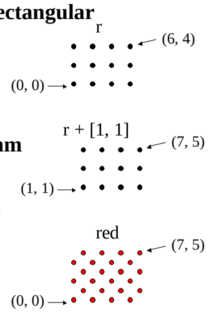
Current performance: comparable to 3 nested loops in C

Recent upgrades: automatic blocking for memory hierarchy (Geoff Pike's PhD thesis)

Example: Domain

- **Domains in general are not rectangular**
- **Built using set operations**
  - union, +
  - intersection, *
  - difference, -
- **Example is red-black algorithm**

```
Point<2> lb = [0, 0];
Point<2> ub = [6, 4];
RectDomain<2> r = [lb : ub : [2, 2]];
...
Domain<2> red = r + (r + [1, 1]);
foreach (p in red) {
       ...
}
```

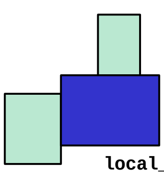


Example using Domains and foreach

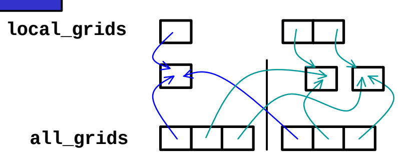
- **Gauss-Seidel red-black computation in multigrid**

```
void gsrb() {
  boundary (phi);
  for (Domain<2> d = red; d != null;
                       d = (d = = red ? black : null)) {
    foreach (q in d)         unordered iteration
      res[q] = ((phi[n(q)] + phi[s(q)] + phi[e(q)] + phi[w(q)])*4
                + (phi[ne(q) + phi[nw(q)] + phi[se(q)] + phi[ sw(q)])
                20.0*phi[q] - k*rhs[q]) * 0.05;
    foreach (q in d) phi[q] += res[q];
  }
}
```


Example: A Distributed Data Structure

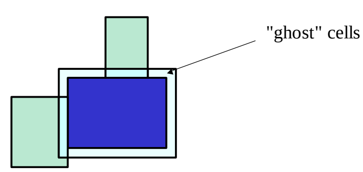


- **Data can be accessed across processor boundaries**



Example: Setting Boundary Conditions

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



Templates

- **Many applications use containers:**
  - E.g., arrays parameterized by dimensions, element types
  - Java supports this kind of parameterization through inheritance
    - Can only put Object types into containers
    - Inefficient when used extensively
- **Titanium provides a template mechanism closer to that of C++**
  - E.g. Can be instantiated with "double" or immutable class
  - Used to build a distributed array package
  - Hides the details of exchange, indirection within the data structure, etc.

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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 );      ← Not an object
int x = list.pop();  ← Strongly typed, No dynamic cast
```

- Addresses programmability and performance

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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]] );
```

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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**
- **Compiler Optimizations & Future work**

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SciMark Benchmark

- **Numerical benchmark for Java, C/C++**
  - purely sequential
- **Five kernels:**
  - FFT (complex, 1D)
  - Successive Over-Relaxation (SOR)
  - Monte Carlo integration (MC)
  - Sparse matrix multiply
  - dense LU factorization
- **Results are reported in MFlops**
  - We ran them through Titanium as 100% pure Java with no extensions
- **Download and run on your machine from:**
  - http://math.nist.gov/scimark2
  - C and Java sources are provided

Roldan Pozo, NIST, http://math.nist.gov/~Rpozo

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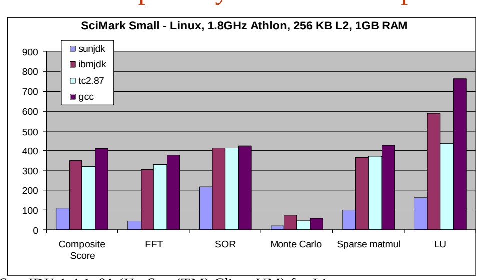
Java Compiled by Titanium Compiler



–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)

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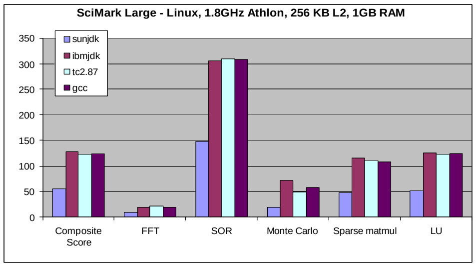
Java Compiled by Titanium Compiler



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Sequential Performance of Java

- **State of the art JVM's**
  - **often very competitive with C performance**
  - **within 25% in worst case, sometimes better than C**
- **Titanium compiling pure Java**
  - **On par with best JVM's and C performance**
  - **This is without leveraging Titanium's lang. extensions**
- **We can try to do even better using a traditional compilation model**
  - Berkeley Titanium compiler:
    - Compiles Java + extensions into C
    - No JVM, no dynamic class loading, whole program compilation
    - Do not currently optimize Java array accesses (prototype)

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Language Support for Performance

- **Multidimensional arrays**
  - Contiguous storage
  - Support for sub-array operations without copying
- **Support for small objects**
  - E.g., complex numbers
  - Called “immutables” in Titanium
  - Sometimes called “value” classes
- **Unordered loop construct**
  - Programmer specifies loop iterations independent
  - Eliminates need for dependence analysis (short term solution?) Same idea used by vectorizing compilers.

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Array Performance Issues

- **Array representation is fast, but access methods can be slow, e.g., bounds checking, strides**
- **Compiler optimizes these**
  - common subexpression elimination
  - eliminate (or hoist) bounds checking
  - strength reduce: e.g., naïve code has 1 divide per dimension for each array access
- **Currently +/- 20% of C/Fortran for large loops**
- **Future: small loop and cache tiling optimizations**

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Applications in Titanium

- Benchmarks and Kernels
  - Fluid solvers with Adaptive Mesh Refinement (AMR)
  - Scalable Poisson solver for infinite domains
  - Conjugate Gradient
  - 3D Multigrid
  - Unstructured mesh kernel: EM3D
  - Dense linear algebra: LU, MatMul
  - Tree-structured n-body code
  - Finite element benchmark
  - SciMark serial benchmarks
- Larger applications
  - Heart and Cochlea simulation
  - Genetics: micro-array selection
  - Ocean modeling with AMR (in progress)

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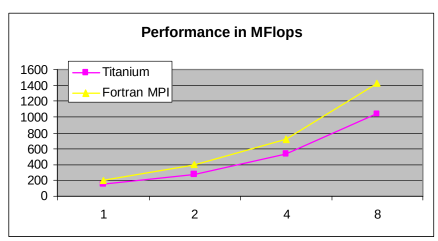
NAS MG in Titanium



- Preliminary Performance for MG code on IBM SP
  - Speedups are nearly identical
  - About 25% serial performance difference

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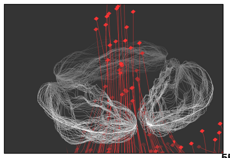
Heart Simulation - Immersed Boundary Method

- 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 prosthetics
  - Artificial heart valves
  - Cochlear implants



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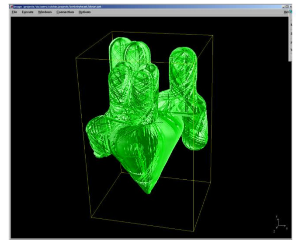
Simulating Fluid Flow in Biological Systems

- Immersed Boundary Method
  - Material (e.g., heart muscles, cochlea structure) modeled by grid of material points
  - Fluid space modeled by a regular lattice
- Irregular material points need to interact with regular fluid lattice
  - Trade-off between load balancing of fibers and minimizing communication
  - Memory and communication intensive
  - Includes a Navier-Stokes solver and a 3-D FFT solver
- Heart simulation is complete, Cochlea simulation is close to done
  - First time that immersed boundary simulation has been done on distributed-memory machines
  - Working on a Ti library for doing other immersed boundary simulations



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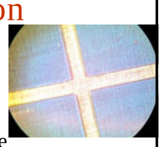
MOOSE Application



- Problem: Genome Microarray construction
  - Used for genetic experiments
  - Possible medical applications long-term
- Microarray Optimal Oligo Selection Engine (MOOSE)
  - A parallel engine for selecting the best oligonucleotide sequences for genetic microarray testing from a sequenced genome (based on uniqueness and various structural and chemical properties)
  - First parallel implementation for solving this problem
  - Uses dynamic load balancing within Titanium
  - Significant memory and I/O demands for larger genomes

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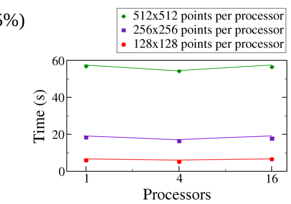
Scalable Parallel Poisson Solver

- **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**



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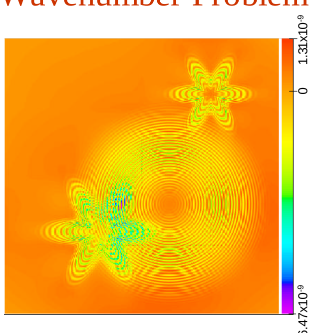
Error on High-Wavenumber Problem

- **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**



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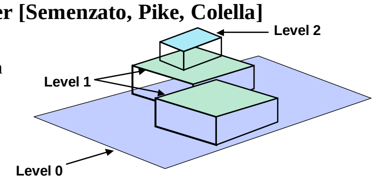
AMR Poisson

- **Poisson Solver [Semenzato, Pike, Colella]**
  - 3D AMR
  - finite domain
  - variable coefficients
  - multigrid across levels
- **Performance of Titanium implementation**
  - Sequential multigrid performance +/- 20% of Fortran
  - On fixed, well-balanced problem of 8 patches, each 72^3
  - parallel speedups of 5.5 on 8 processors



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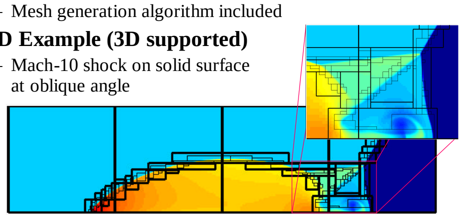
AMR Gas Dynamics

- **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: Self-gravitating gas dynamics package**

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Outline

- **Titanium Execution Model**
- **Titanium Memory Model**
- **Support for Serial Programming**
- **Performance and Applications**
- **Compiler/Language Status**
- **Compiler Optimizations & Future work**

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Titanium Compiler Status

- Titanium compiler runs on almost any machine
  - Requires a C compiler (and decent C++ to compile translator)
  - Pthreads for shared memory
  - Communication layer for distributed memory (or hybrid)
    - Recently moved to live on GASNet: shared with UPC
    - Obtained Myrinet, Quadrics, and improved LAPI implementation
- Recent language extensions
  - Indexed array copy (scatter/gather style)
  - Non-blocking array copy under development
- Compiler optimizations
  - Cache optimizations, for loop optimizations
  - Communication optimizations for overlap, pipelining, and scatter/gather under development

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Implementation Portability Status

- **Titanium has been tested on**:
  - POSIX-compliant workstations & SMPs
  - Clusters of uniprocessors or SMPs
  - Cray T3E
  - IBM SP
  - SGI Origin 2000
  - Compaq AlphaServer
  - MS Windows/GNU Cygwin
  - and others…

Automatic portability: Titanium applications run on all of these!

Very important productivity feature for debugging & development

- **Supports many communication layers**
  - High performance networking layers:
    - IBM/LAPI, Myrinet/GM, Quadrics/Elan, Cray/shmem, Infiniband (soon)
  - Portable communication layers:
    - MPI-1.1, TCP/IP (UDP)

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Programmability

- Heart simulation developed in ~1 year
  - Extended to support 2D structures for Cochlea model in ~1 month
- 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

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Robustness

- Robustness is the primary motivation for language “safety” in Java
  - Type-safe, array bounds checked, auto memory management
  - Study on C++ vs. Java from Phipps at Spirus:
    - C++ has 2-3x more bugs per line than Java
    - Java had 30-200% more lines of code per minute
- Extended in Titanium
  - Checked synchronization avoids barrier/collective deadlocks
  - More abstract array indexing, retains bounds checking
- No attempt to quantify benefit of safety for Titanium yet
  - Would like to measure speed of error detection (compile time, runtime exceptions, etc.)
  - Anecdotal evidence suggests the language safety features are very useful in application debugging and development

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Calling Other Languages

- **We have built interfaces to**
  - PETSc : scientific library for finite element applications
  - Metis: graph partitioning library
  - KeLP: scientific C++ library
- **Two issues with cross-language calls**
  - accessing Titanium data structures (arrays) from C
    - possible because Titanium arrays have same format on inside
  - having a common message layer
    - Titanium is built on lightweight communication

Outline

- **Titanium Execution Model**
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- **Support for Serial Programming**
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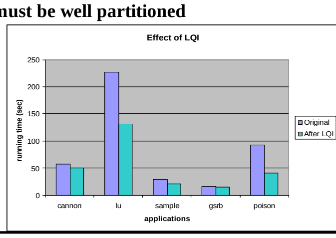
- **Compiler/Language Status**
- **Compiler Optimizations & Future work**
  - Local pointer identification (LQI)
  - Communication optimizations
  - Feedback-directed search-based optimizations

Local Pointer Analysis

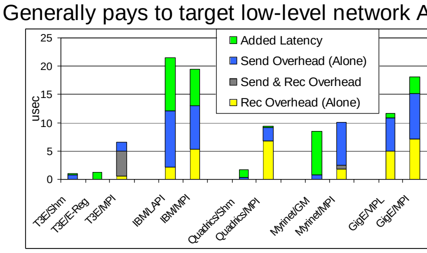
- **Global pointer access is more expensive than local**
- **Compiler analysis can frequently infer that a given global pointer always points locally**
  - **Replace global pointer with a local one**
  - **Local Qualification Inference (LQI)** [Liblit]
  - **Data structures must be well partitioned**

Same idea can be applied to UPC's pointer-to-shared…



Communication Optimizations

- Possible communication optimizations
  - Communication overlap, aggregation, caching
- Effectiveness varies by machine
  - Generally pays to target low-level network API



[Bell, Bonachea et al] at IPDPS'03

Split-C Experience: Latency Overlap

- **Titanium borrowed ideas from Split-C**
  - global address space
  - SPMD parallelism
- **But, Split-C had explicit non-blocking accesses built in to tolerate network latency on remote read/write**

```
int *global p;
x := *p;   /* get */
*p := 3;   /* put */
sync;      /* wait for my puts/gets */
```

- **Also one-way communication**

```
*p :- x;         /* store */
all_store_sync;  /* wait globally */
```

- **Conclusion: useful, but complicated**

Titanium: Consistency Model

- **Titanium adopts the Java memory consistency model**
- **Roughly: Access to shared variables that are not synchronized have undefined behavior**
- **Use synchronization to control access to shared variables**
  - barriers
  - synchronized methods and blocks
- **Open question: Can we leverage the relaxed consistency model to automate communication overlap optimizations?**
  - difficulty of alias analysis is a significant problem

Sources of Memory/Comm. Overlap

- **Would like compiler to introduce put/get/store**
- **Hardware also reorders**
  - out-of-order execution
  - write buffered with read by-pass
  - non-FIFO write buffers
  - weak memory models in general
- **Software already reorders too**
  - register allocation
  - any code motion
- **System provides enforcement primitives**
  - e.g., memory fence, volatile, etc.
  - tend to be heavyweight and have unpredictable performance
- **Open question: Can the compiler hide all this?**

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Feedback-directed search-based optimization

- Use machines, not humans for architecture-specific tuning
  - Code generation + search-based selection
    - Can adapt to cache size, # registers, network buffering
  - Used in
    - Signal processing: FFTW, SPIRAL, UHFFT
    - Dense linear algebra: Atlas, PHiPAC
    - Sparse linear algebra: Sparsity
    - **Rectangular grid-based computations: Titanium compiler**
      - Cache tiling optimizations - automated search for best tiling parameters for a given architecture

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Current Work & Future Plans

- Unified communication layer with UPC: GASNet
- Exploring communication overlap optimizations
  - Explicit (programmer-controlled) and automated
  - Optimize regular and irregular communication patterns
- Analysis and refinement of cache optimizations
  - along with other sequential optimization improvements
- Additional language support for unstructured grids
  - arrays over general domains, with multiple values per grid point
- Continued work on existing and new applications

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