Programming Scientific Computations in X10

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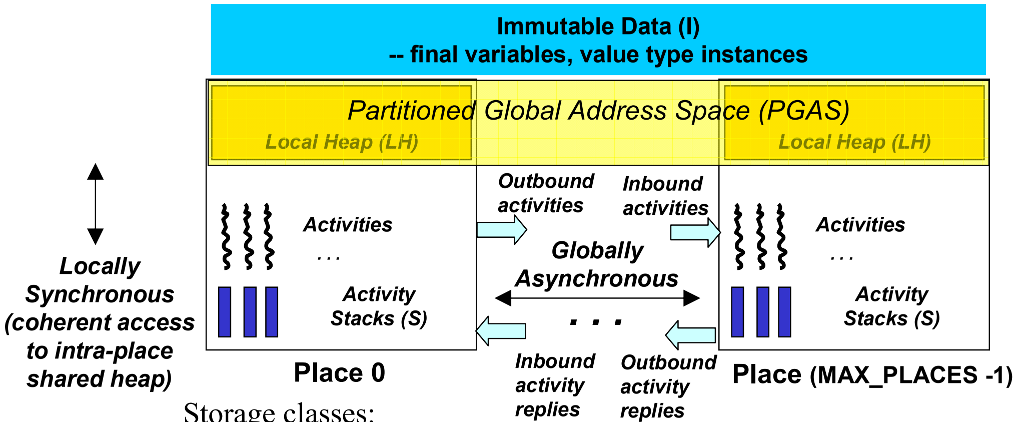
Overview

- **X10 is designed for general large-scale and heterogeneous parallel programming**
  - Based on Java with extension to support fine-grained parallelism (data and task parallelism)
  - Not SPMD!
- **Focus on features relevant for programming scientific computing applications**
  - Abstractions for multi-dimensional arrays
  - Serial and parallel looping constructs
  - Constructs for task parallelism
- **Examples: NPB CG and MG benchmarks, LU Factorization, etc.**
  - Build distributed data structures
  - Synchronize concurrent computations
  - Exploit the fine-grained parallelism supported by X10
  - Issues regarding how to handle the hierarchical and heterogeneous nature of the emerging large-scale computer platforms will be addressed in later studies.
- **New features under consideration**

X10 Programming Model



Storage classes:

- Immutable Data (I)
- PGAS
  - Local Heap (LH)
  - Remote Heap (RH)
- Activity Stacks (S)

- *Place* = collection of activities & objects
  - Activities and data objects do not move after being created
- *Scalar object, O* -- maps to a single place specified by O.location
- *Array object, A* – may be local to a place or distributed across multiple places, as specified by A.distribution
- Locality rule: direct access via a remote heap reference is not permitted

X10 Reference Implementation (Operational since 2/2005)

Foo.x10

X10 source program --- must contain a class named Foo with a "public static void main(String[] args) method

x10c Foo.x10

x10c

X10 compiler --- translates Foo.x10 to Foo.java, uses javac to generate Foo.class from Foo.java

Foo.class

Foo.java

X10 program translated into Java --- // #line pseudocomment in Foo.java specifies source line mapping in Foo.x10

x10 Foo

X10 Virtual Machine (JVM + J2SE libraries + X10 libraries + X10 Multithreaded Runtime)

X10 extern interface

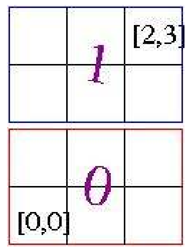
External DLL's

X10 Abstract Performance Metrics

X10 Program Output

Abstractions for Multi-dimensional Arrays

- **Point, Region,** and **Distribution**
  - **Point**: a vector of integers
  - **Region**: a (rectangular) set of Points
  - **Distribution**: a map from a Region to a set of Places
- **X10 arrays**: defined on Distribution




```
point p=[0,1,2,3];

region r1=[0:2, p[0]:p[1]];
region r2=[0:2, p[2]:p[3]];

dist d1=(r1->place.factory.place(0));
dist d2=(r2->place.factory.place(1));

final double [.] A_dist=new double
    [d1||d2];
final double [.] A_local=new double
    [r1||r2];
```

```
final double [.] A_local=new double [(r1||r2)->here];
```


Serial and Parallel Looping Constructs

- Serial loop:
  - **for (point p: r1) {…}**
  - **for (point p[i,j]: r1) {…}**
- Parallel loop:
  - **foreach (point p: r2) {…}**
  - **foreach (point p[i,j]: r2) {…}**
- Distributed parallel loop:
  - **ateach (point p: d1||d2) {…}**
  - **ateach (point p[i,j]: d1||d2) {…}**

```
region R=[-1:256,-1:256], r=[0:255,0:255];

final point North=[0,1], South=[0,-1],
          West=[-1,0], East=[1,0];

final double [.] A=new double [R];
…
for (point p: r)
    A[p]=(A[p+North]+A[p+South]+A[p+West]
          +A[p+East]-4*A[p])*h;
/*
foreach (point p: r)
    A[p]=(A[p+North]+A[p+South]+A[p+West]
          +A[p+East]-4*A[p])*h;
*/
```

Constructs for Task Parallelism

- Spawning an asynchronous activity:
  - **async (P) S**
    - Create a new activity to execute statement S at place P
  - **future (P) {E}**
    - Create a new activity to evaluate expression E at place P
- Converting local termination to global termination:
  - **finish S**
    - Execute S as usual, but wait until all activities spawned (transitively) by S have terminated before completing the execution of finish S
  - **future (P) {E}.force()**
    - Caller blocks until return value is obtained from future (and all activities spawned transitively by E have terminated)
- Clocks and (conditional and unconditional) atomic blocks
  - Synchronization

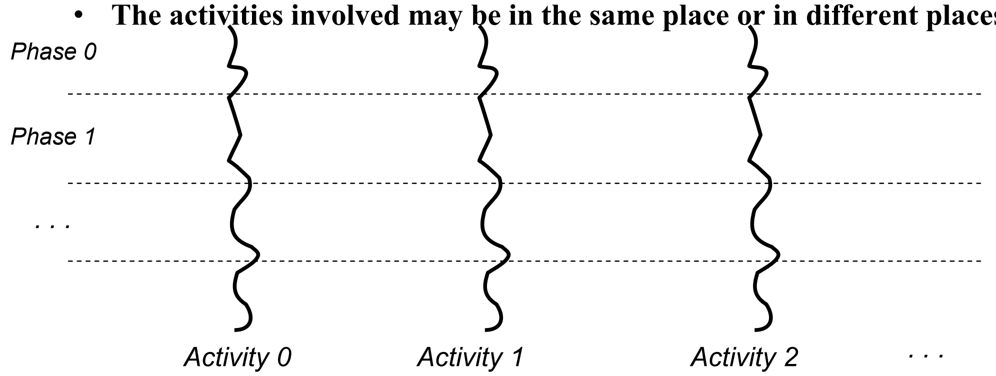
finish

```
foreach (point p: r)
    A[p]=(A[p+North]+A[p+South]+A[p+West]
            +A[p+East]-4*A[p])*h;

/*
for (point p: r) async ( here )
    A[p]=(A[p+North]+A[p+South]+A[p+West]
            +A[p+East]-4*A[p])*h;
*/

final dist D=dist.factory.unique();
ateach (point p: D)
    System.out.println (here.toString());

/*
for (point p:D) async ( D[p] )
    System.out.println (here.toString());
*/
```

More examples to come!

X10 clocks: Motivation

- Activity coordination using finish and force() is accomplished by checking for activity termination
- However, there are many cases in which a producer-consumer relationship exists among the activities, and a “barrier”-like coordination is needed without waiting for activity termination
- **Clock** is a generalization of barriers
  - **The activities involved may be in the same place or in different places**



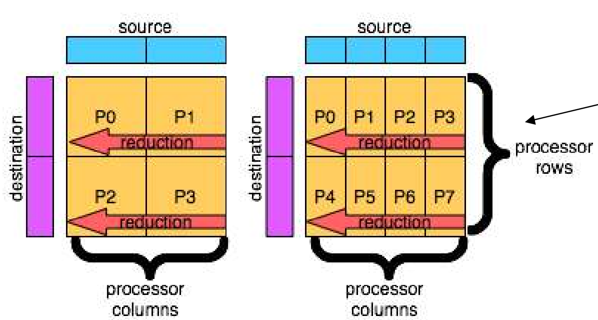
Atomic Blocks

- **Unconditional atomic block:**
  - **atomic S**, where **S** is a statement
  - The above statement is executed by an activity as if in a single step, during which all other concurrent activities in the same place are suspended.
- **Conditional atomic block:**
  - **when (C) S**, where **C** is a Boolean expression
  - The above statement is executed atomically when **C** becomes true.
  - In our examples, point-to-point synchronization is implemented using conditional atomic blocks.
  - Using conditional blocks can lead to deadlock!

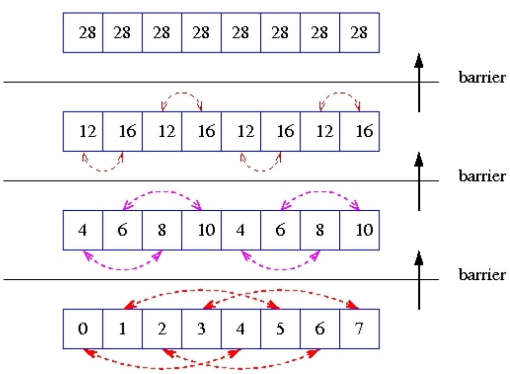
NPB CG

- **Use inverse power method to compute an approximation to the smallest eigenvalue of sparse symmetric positive definite matrix**

```
public static Vector cg(SparseMat A, Vector x, Vector r){
    double d, rho;
    double alpha, rho0,beta;
    Vector p=new Vector(A.m_N);
    Vector q=new Vector(A.m_N);
    Vector z=new Vector(A.m_N);

    r.copy(x); p.copy(x); rho=r.dot(r);

    for (int i=0;i<10;i++){
        A.multiply(q,p);
        d=p.dot(q);
        alpha=rho/d;
        z.axpy(alpha,p,z);
        rho0=rho;
        r.axpy(-alpha,q,r);
        rho=r.dot(r);
        beta=rho/rho0;
        p.axpy(beta,p,r);
    }
    return z;
}
```



All Reduction (Barrier) in Matrix-Vector Multiplication (CG)

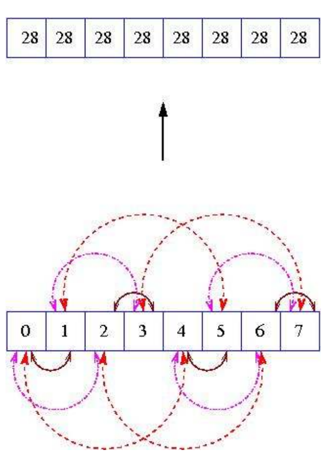



```
final dist ALLPLACES=dist.factory.unique();
final double [.] A=new double [ALLPLACES] (point[i]){return i;};
final double [.] B=new double [ALLPLACES];
final int factor=place.MAX_PLACES;
final int phases=(int)(Math.log(factor)/Math.log(2));
finish async{
        final clock clk=clock.factory.clock();
        ateach (point [i]:ALLPLACES) clocked(clk){
                boolean red=true;
                int Factor=factor;
                int shift;
                for (int j=0;j<phases;j++){
                        shift=Factor/2;
                        final int
                        destProcID=(i+shift)%Factor
                                        +i/Factor*Factor;
                        if (red){
                                B[i]=future(A.distribution[destProcID])
                                        {A[destProcID]}.force();
                                B[i]+=A[i];
                        }
                        else{
                                A[i]=future(ALLPLACES[destProcID])
                                        {B[destProcID]}.force();
                                A[i]+=B[i];
                        }
                        next;
                        Factor/=2; red=!red;
                }
                if (!red) A[i]=B[i];
        }
}
```

B[i]=A[destProcID]

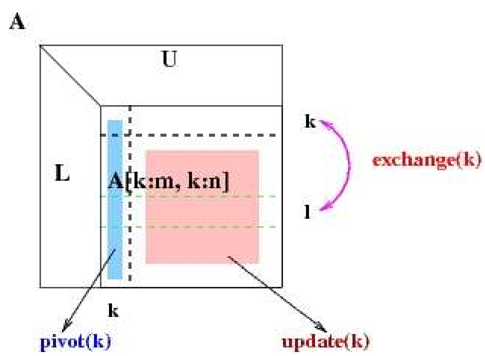
A[i]=B[destProcID]

All Reduction (Point-to-Point) in Matrix-Vector Multiplication (CG)




```
final dist ALLPLACES=dist.factory.unique;
final double [.] A=new double [ALLPLACES] (point[i]){return i;};
final double [.] B=new double [ALLPLACES];
final int [.] Flag1=new int [ALLPLACES] (point [i]){return -1;};
final int [.] Flag2=new int [ALLPLACES] (point [i]){return -1;};
final int factor=place.MAX_PLACES;
final int phases=(int)(Math.log(factor)/Math.log(2));

finish  ateach (point [i]:ALLPLACES){
   int Factor=factor;
   int shift;
   for (int j=0;j<phases;j++){
           shift=Factor/2;
           final int destProcID=(i+shift)%Factor+i/Factor*Factor;
           when (Flag1[destProcID]==(j-1)) {}
                   B[i]=A[destProcID];
                   async (ALLPLACES[destProcID]) atomic
                           Flag2[destProcID]++;
           when (Flag2[i]==j) {}
                   A[i]+=B[i];
                   Flag1[i]++;

           Factor/=2;
   }
}
```

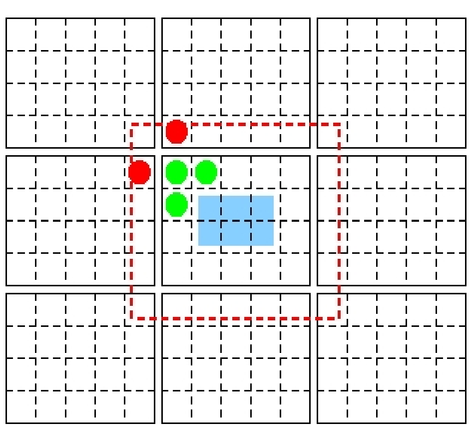
LU Factorization




```
public void lu(final double [.] a_A){ //the matrix is assumed to have any distribution
        assert a_A.rank==2;
        m_A=a_A;
        m_R=a_A.region;
        m_D=a_A.distribution;
        m=m_R.rank(0).size(); n=m_R.rank(1).size();
        final int steps=Math.min(m,n)-1;
        final region STEPS=[0:steps-1];
        m_p=new int [steps+1] (point [i]) {m_p[i]=i;};

        /* flags for synchronization*/
        m_rowScore=new int [[0:m-1]] (point [i]) {return m;};
        m_update[0]=true; m_update[1]=true;

        double res;
        for (point [k]:STEPS){
           when (m_update[0]) {}
                res=pivot(k);
           if (res!=0){
                final int score=n-k;
                when ((m_rowScore[k]==score) && (m_rowScore[m_pivotInfo]==score)){}
                    exchange(k);
                when (m_update[1]){m_update[0]=false;m_update[1]=false;}
                    async update(k);
           }
           else{
                when (m_update[1]){};
           }
        }
}
```


NPB MG

- Use multigrid method to solve Poisson’s equation (3D)



- Construct the distributed array

```
value Wrapper{
            double [.] m_array;
            Wrapper(final double [.] a_array){
                       m_array=a_array;
            }
            …
}
…
region [ ] m_REGIONs;
dist [] m_DIST;
Wrapper value [.] m_u;
…
for (point p: m_placeGrid){
…
      m_DIST[i]=m_REGIONs[i]->place.factory.place(i);
      m_u[i]=new Wrapper(new double [m_DIST[i]]);
…
}
```

Overlapping Communications and Computations in MG

- **Bulk-synchronous style**:
  - Update ghost values first
  - Perform local stencil operations in parallel

```
finish updateGhost();
finish ateach(point [i]: AllPLACES){
        for (point p:localRegion(i))
                stencilOp(p);
}
```

- **Overlapping communication with computation**:

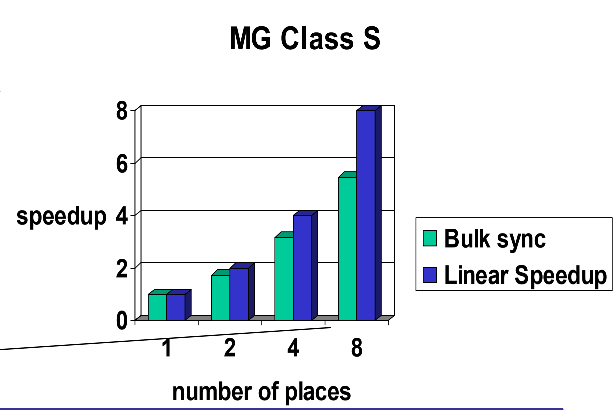
```
finish {
  //Inner region
  ateach(point [i]:ALLPLACES){
      for (point p: InnerLocalRegion(i))
          stencilOp(p);
  }

  // Ghost layer
  finish updateGhost();

  //Boundary layer
  ateach(point [i]:ALLPLACES){
      for (point p: LocalRegion(i)-InnerLocalRegion(i))
          stencilOp(p);
  }
}
```


An Abstract Performance Model (Simulation)

- **Abstract system parameters**:
  - FP results per clock
  - Communication latency
  - Communication Bandwidth
- **Computation cost:**
  - Flops/FP_PERCLOCK
- **Inter-place communication cost**:
  - LATENCY + Doubles*8/BANDWIDTH
- **Costs are inserted into code manually and the runtime computes the length of critical path**
- **Ideal speedup as the measure of how much parallelism that can be expressed in X10**

Comp cost: 3,272,372
CPL: 599,912
% .
= **Ideal** speedup: 5.46

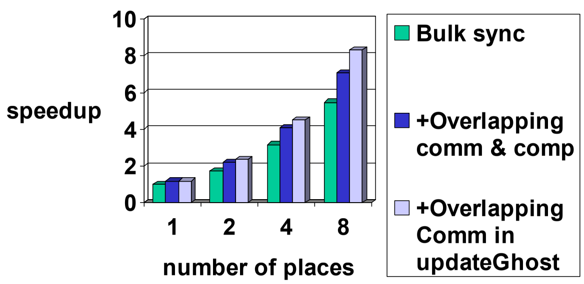
- **A case where comm and comp ratio is high:**
  - FP_PERCLOCK=4
  - LATENCY=375 (cycles)
  - BANDWIDTH=5.3 (bytes/cycle)
  - The small test problem: 32x32x32 (Class S)
    Computation cost: 3,272,372 (cycles)



Multiple Levels of Parallelism

- **Overlapping communication with computation in stencil operations in MG**
- **Overlapping communications in updating the ghost values in MG**
  – Three phases one for each dimension (3D grid)
  – At each phase, the two faces of ghost values can be updated simultaneously

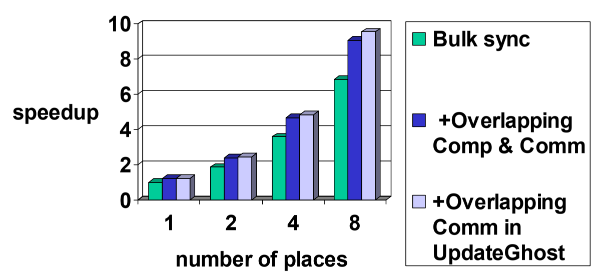
- **Fine-grained parallelism**
  – Replacing unordered for loops with foreach loops
  – For MG, the stencil operations can speed up by a factor of 5382 (at most)
  – The speedup factors (1,2,4,8)
    5382.2, 27.6, 32.8, 37.3




```
finish ateach (point [i]: AllPLACES){
        foreach (point p:localRegion(i)){
            stencilOp(p);
}
}
```


More Abstract Performance Metrics

- **Smaller latency:**
  – FP_PERCLOCK=4
  – LATENCY=37.5 cycles
  – BANDWIDTH=5.3 bytes/cycle
  – The small test problem: 32x32x32 (Class S)
    Computation cost: 3,272,372 cycles
- **Latency is the bottleneck of scalability**



Latency	Speedup			
	1	2	4	8
375	5382.2	27.6	32.8	37.3
37.5	5382.2	53.0	77.3	112.3

Mapping Fine-Grained Parallelism onto Coarse-Grained Machine

- **Explicitly:**
  - Instead of having one activity per point, one can spawn an activity for a sub region
    - Hierarchical tiled region
    - Hierarchical tiled array
- **Implicitly:**
  - Compilation and runtime technologies to optimize the foreach loop
  - Programmers express the logical parallelism in their code and let compiler and runtime to handle the mapping from logical parallelism to hardware threads.

Improvements and New Features

- **Expressing logical parallelism in X10 is easy. The challenge is how to map fine-grained parallelism to coarse-grained machine.**
- **Improvements and new features**
  - Arrays:
    - Array views
    - Array copy method
    - More dimension independent syntax
    - HTR and HTA
    - Automatic support for ghost values
  - Dependent types
  - Implicit syntax
    - B[i]=A[destProcID]
    - B[i]=future(A.distribution[destProcID]){A[destProcID]}.force();
    - Add implicit finish to **foreach (point: R) S**
      finish for (point:R) async S
    - Add implicit finish to **ateach (point: D) S**
      finish for (point:R) async (D[p]) S
  - Multi-phase clock ?

Acknowledgement
- Kaushik Datta. Titanium Group, UC Berkeley.

X10 Applications/Benchmarks

- **Java Grande Forum**
  - OOPSLA Onwards! 2005
  - Showed substantial (SLOC) benefit in serial → parallel → distributed transition for X10 vs Java (qua C-like language).
- **SSCA**
  - SSCA#1 (PSC study)
  - SSCA#2 (Bader et al, UNM/GT)
  - SSCA#3 (Rabbah, MIT)
- **Sweep3d**
  - Jim Browne

- **NAS PB**
  - CG, MG (IBM)
  - CG, FT, EP (Padua et al, UIUC)
  - Cannon, LU variant (UIUC)
- **AMR** (port from Titanium)
  - In progress, IBM
- **SpecJBB**
  - Purdue