X10: a High-Productivity Approach to High Performance Programming

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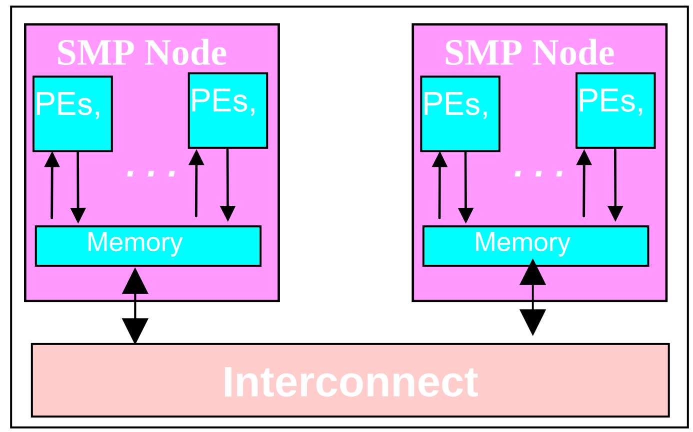
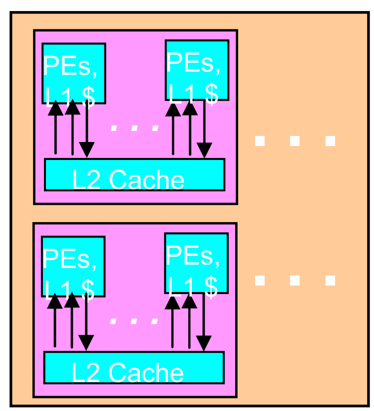
Motivation: Productivity Challenges caused by Future Hardware Trends

Challenge: Develop new language, compiler and tools technologies to support productive portable parallel abstractions for future hardware

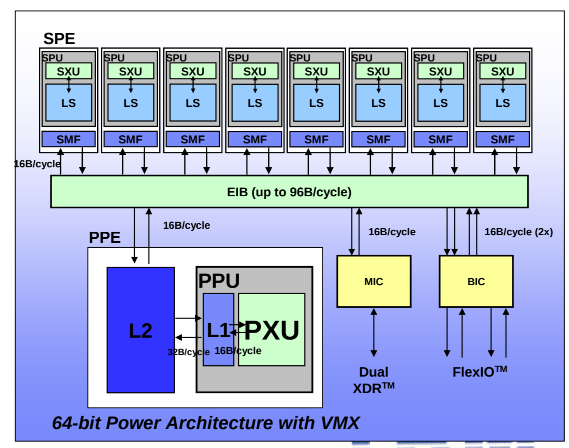
Clusters ➔ Global Address Space



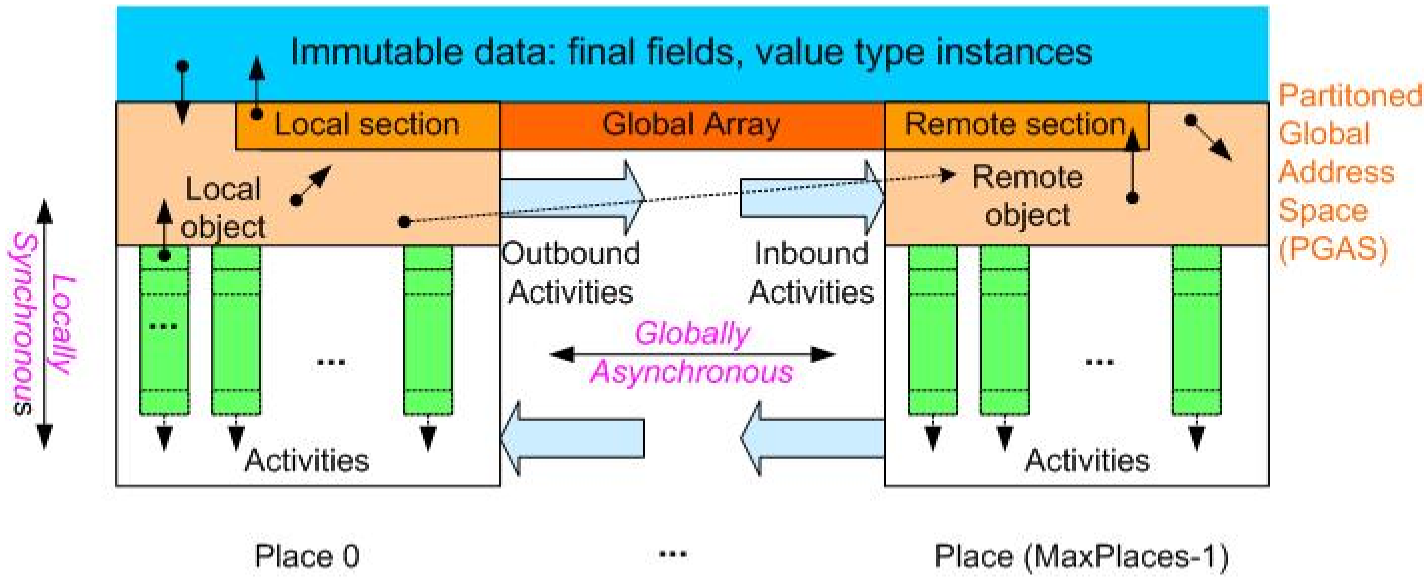
Homogeneous Multi-core



Heterogeneous Accelerators



X10 Programming Model



Storage classes:

- **Activity-local**
- **Place-local**
- **Partitioned global**
- **Immutable**

- Dynamic parallelism with a *Partitioned Global Address Space*
- *Places* encapsulate binding of activities and globally addressable data
- All concurrency is expressed as *asynchronous activities* – subsumes threads, structured parallelism, messaging, DMA transfers (beyond SPMD)
- *Atomic sections* enforce mutual exclusion of co-located data
  - No place-remote accesses permitted in atomic section
- *Immutable* data offers opportunity for single-assignment parallelism

Deadlock safety: any X10 program written with async, atomic, finish, foreach, ateach, and clocks can never deadlock

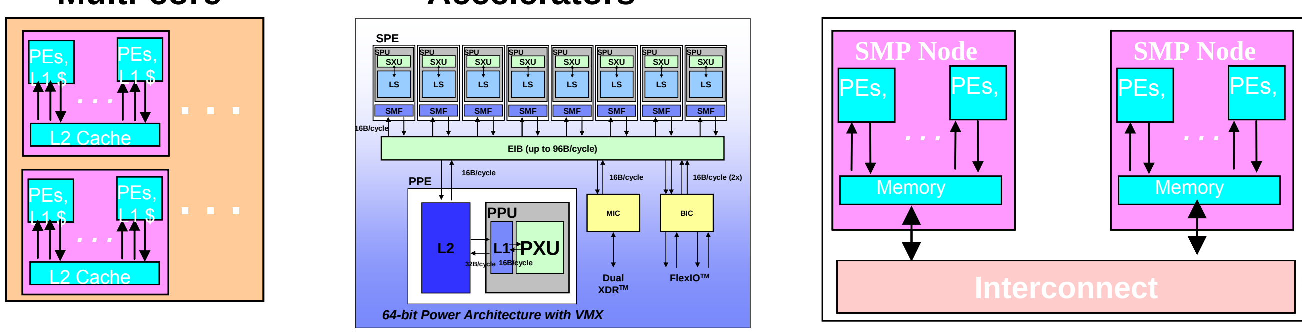
X10 Deployment

X10 language defines mapping from X10 objects & activities to X10 places

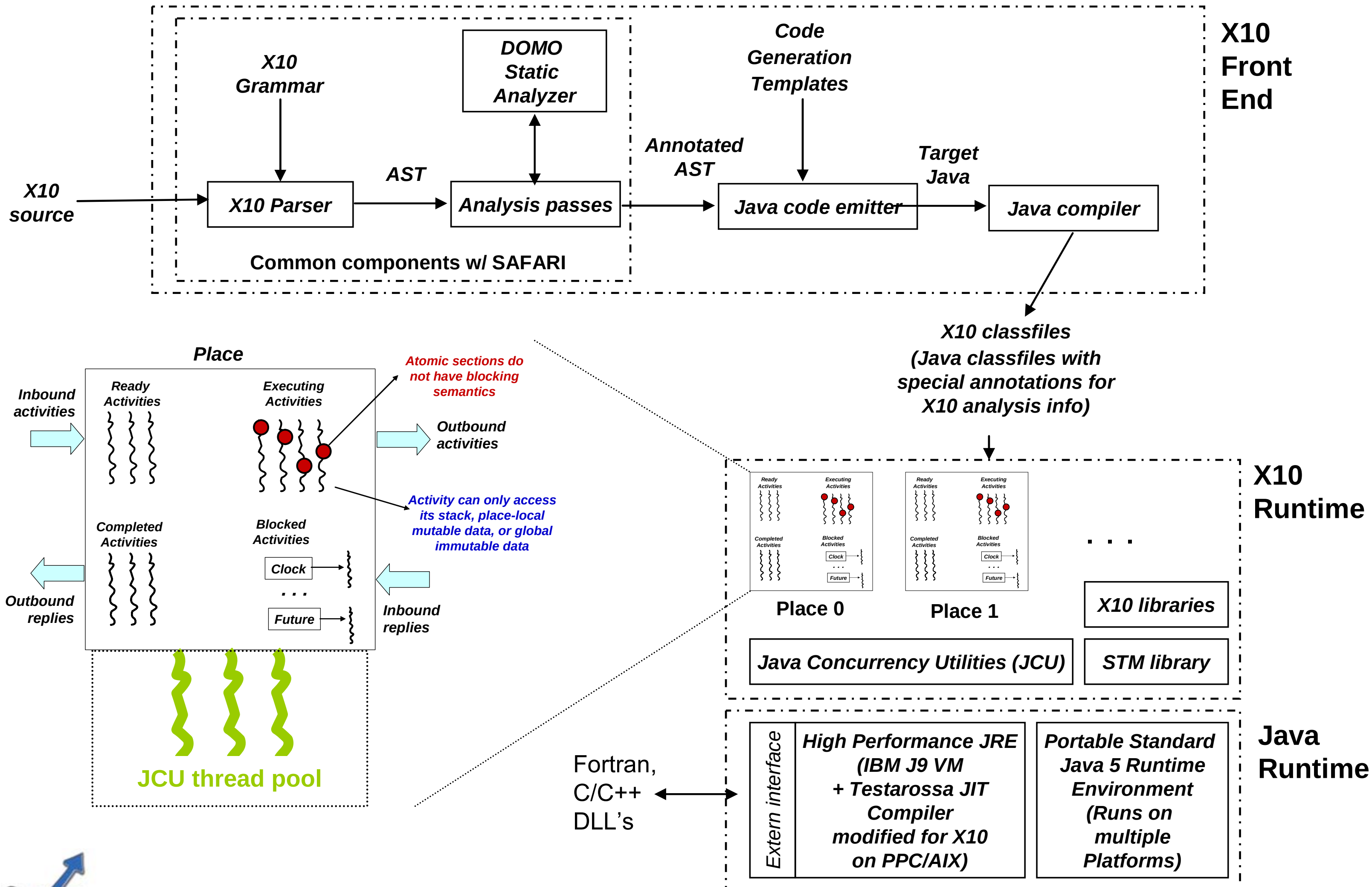
X10 deployment defines mapping from virtual X10 places to physical processing elements

X10 Data Structures → *X10 Places* → *Physical PEs*

Homogeneous Multi-core	Heterogeneous Accelerators	Clusters



Current Status: Multi-core SMP Implementation for X10



System Configuration used for Performance Results

- Hardware
  - STREAM (C/OpenMP & X10), RandomAccess (C/OpenMP & X10), FFT (X10)
    - 64-core POWER5+, p595+, 2.3 GHz, 512 GB (r28n01.pbm.ihost.com)
  - FFT (Cilk version)
    - 16-core POWER5+, p570, 1.9 GHz
  - All runs performed with page size = 4KB and SMT turned off
- Operating System
  - AIX v5.3
- Compiler
  - xlc v7.0.0.5 w/ -O3 option (also qsmp=omp for OpenMP compilation)
- X10
  - Dynamic compilation options: -J-Xjit:count=0,optLevel=veryHot
  - X10 activities use serial libraries written in C and linked with X10 runtime
  - Data size limitation: current X10 runtime is limited to a max heap size of 2GB
- All results reported are for runs that passed validation
  - Caveat: these results should *not* be treated as official benchmark measurements of the above systems

STREAM

OpenMP / C version

```
#pragma omp parallel for
for (j=0; j<N; j++) {
   b[j] = scalar*c[j];
}
```

Hybrid X10 + Serial C version

```
finish ateach(point p : dist.factory.unique()) {
    final region myR = (D | here).region;
    scale(b,scalar,c,myR.rank(0).low(),myR.rank(0).high()+1);
}
```

STREAM

OpenMP / C version

```
#pragma omp parallel for
for (j=0; j<N; j++) {
   b[j] = scalar*c[j];
}
```

Traversing array region can be error-prone

Implicitly assumes Uniform Memory Access model (no distributed arrays)

SLOC counts are comparable

Hybrid X10 + Serial C version

```
finish ateach(point p : dist.factory.unique()) {
    final region myR = (D | here).region;
    scale(b,scalar,c,myR.rank(0).low(),myR.rank(0).high()+1);
}
```

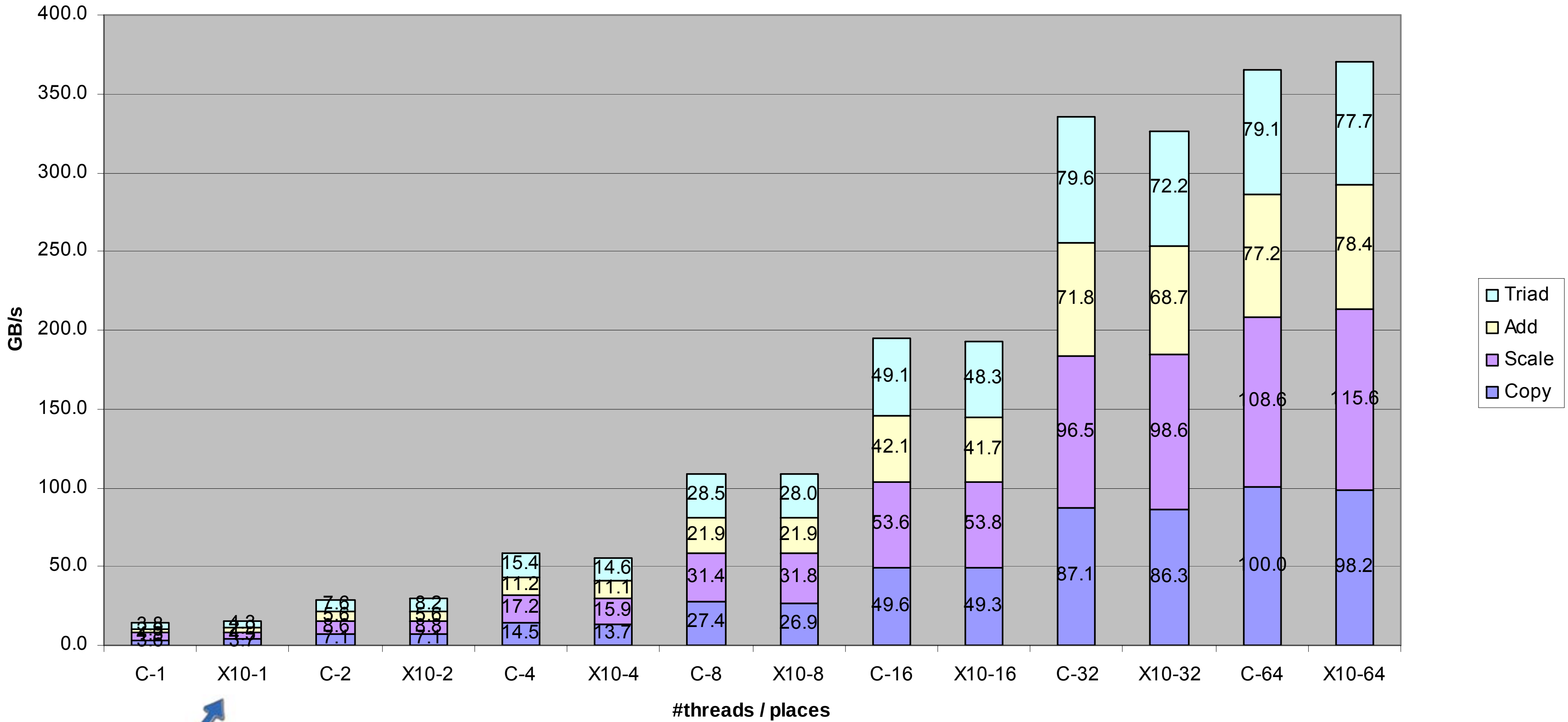
Multi-place version designed to run unchanged on an SMP or a cluster

Restrict operator simplifies computation of local region

scale( ) is a sequential C function

Performance Results for STREAM

Array size = 2^{26} elements
Combined memory for 3 arrays = 1.5GB



RandomAccess

OpenMP / C version

```
#define NUPDATE (4 * TableSize)
for (i=0; i<NUPDATE/128; i++) {
#pragma omp parallel for
   for (j=0; j<128; j++) {
      ran[j] = (ran[j] << 1) ^ ((s64Int) ran[j] < 0 ? POLY : 0);
     Table[ran[j] & (TableSize-1)] ^= ran[j];
   }
}
```

Hybrid X10 + Serial C version

```
finish ateach(point p : dist.factory.unique()) {
 final region myR = (D | here).region;
 for (int i=0; i<(4 * TableSize)/W; i++) {
   innerLoop(Table,TableSize,ran,myR.rank(0).low(),myR.rank(0).high()+1);
 }
}
```

RandomAccess

OpenMP / C version

```
#define NUPDATE (4 * TableSize)
for (i=0; i<NUPDATE/128; i++) {
#pragma omp parallel for
   for (j=0; j<128; j++) {
      ran[j] = (ran[j] << 1) ^ ((s64Int) ran[j] < 0 ? POLY : 0);
     Table[ran[j] & (TableSize-1)] ^= ran[j];
   }
}
```

Inner parallel loop is a source of inefficiency in OpenMP version

SLOC counts are comparable

Multi-place version designed to run unchanged on an SMP or a cluster

Hybrid X10 + Serial C version

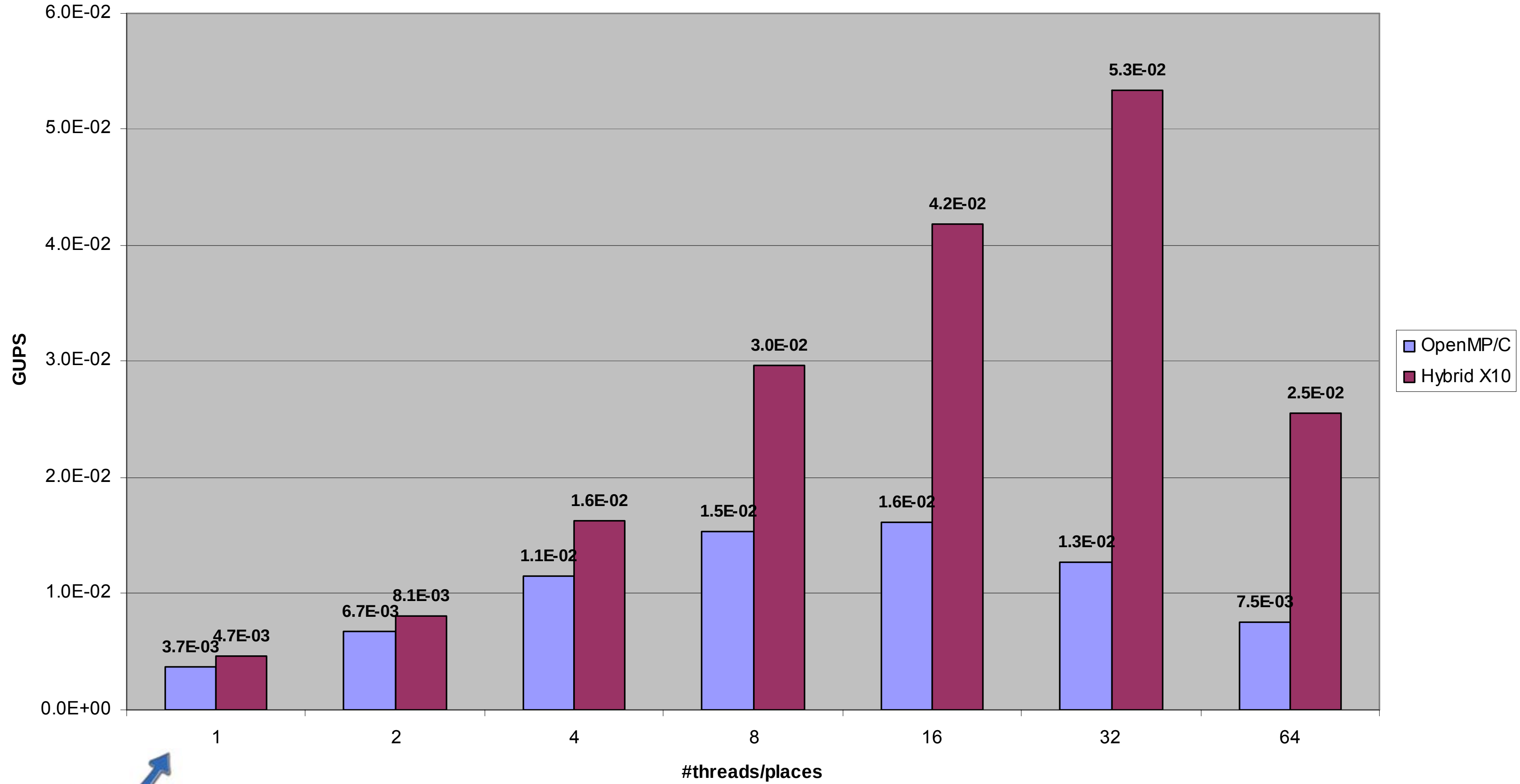
```
finish ateach(point p : dist.factory.unique()) {
 final region myR = (D | here).region;
 for (int i=0; i<(4 * TableSize)/W; i++) {
   innerLoop(Table,TableSize,ran,myR.rank(0).low(),myR.rank(0).high()+1);
 }
}
```

innerLoop() is a sequential C function

Restrict operator simplifies computation of local region

Performance Results for RandomAccess

Array size = 1.8GB



FFT: Transpose example

Cilk / C version (Recursive version)

```
#define SUB(A, i, j) (A)[(i)*SQRTN+(j)]
cilk void transpose(fftw_complex *A, int n)
{
     if (n > 1) {
       int n2 = n/2;
       spawn transpose(A, n2);
       spawn transpose(&SUB(A, n2, n2), n-n2);
       spawn transpose_and_swap(A, 0, n2, n2, n);
     } else {
       /* 1x1 transpose is a NOP */
     }
}
```

Implicit sync at function boundary

Hybrid X10 + Serial C version (Non-recursive version)

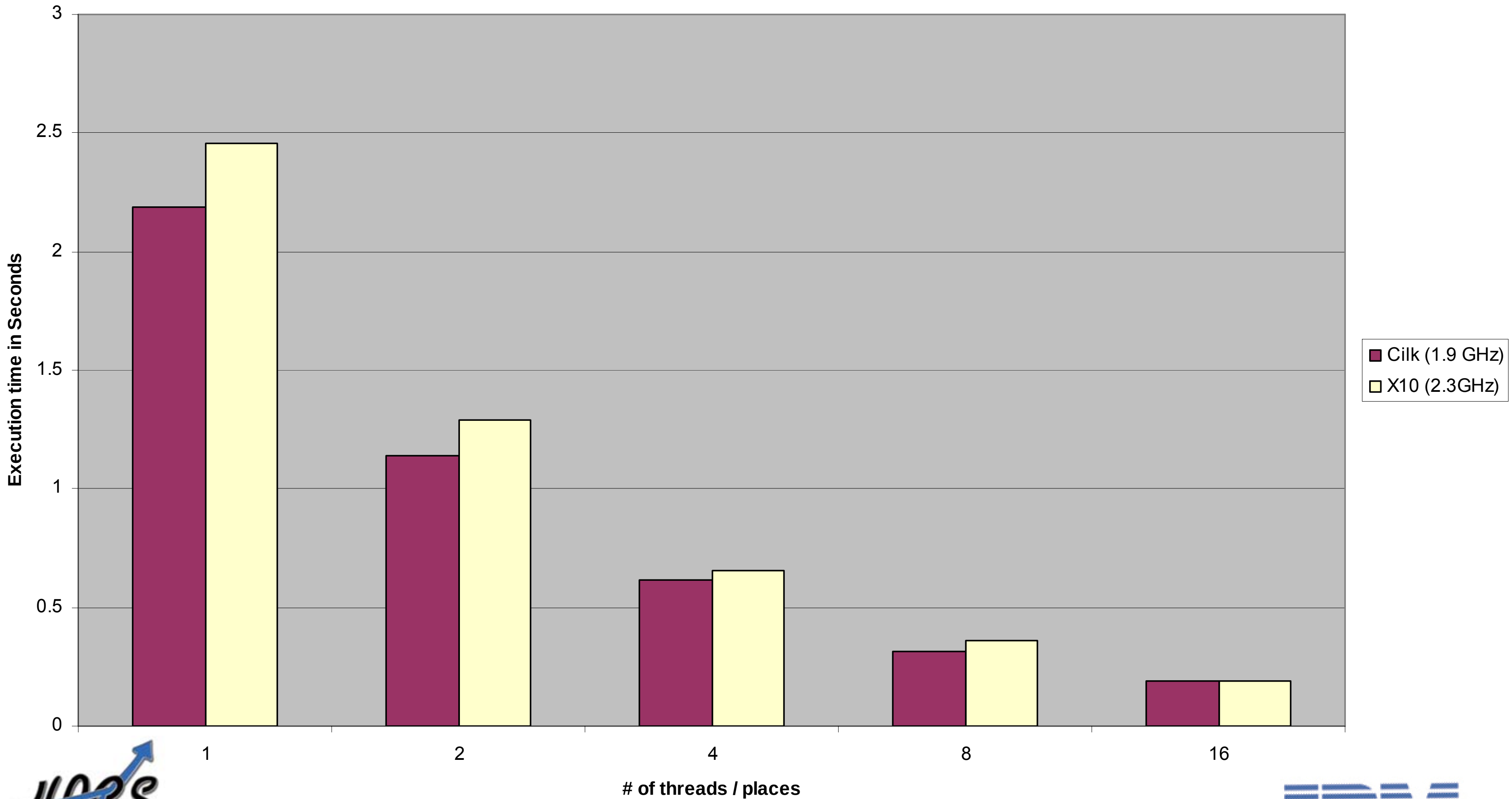
```
int nBlocks = SQRTN / bSize;
int p = 0;
finish for (int r = 0; r < nBlocks; ++r) {
    for (int c = r; c < nBlocks; ++c) { // Triangular loop
        final int topLefta_r = (bSize * r);
        final int topLefta_c = (bSize * c);
        final int topLeftb_r = (bSize * c);
        final int topLeftb_c = (bSize * r);
           async (place.factory.place(p++))
              transpose_and_swap(A, topLefta_r, topLefta_c, topLeftb_r, topLeftb_c, bSize);
     }
}
```

“finish” operator is used to wait for termination of all subactivities (async’s)

transpose_and_swap( ) is a sequential C function

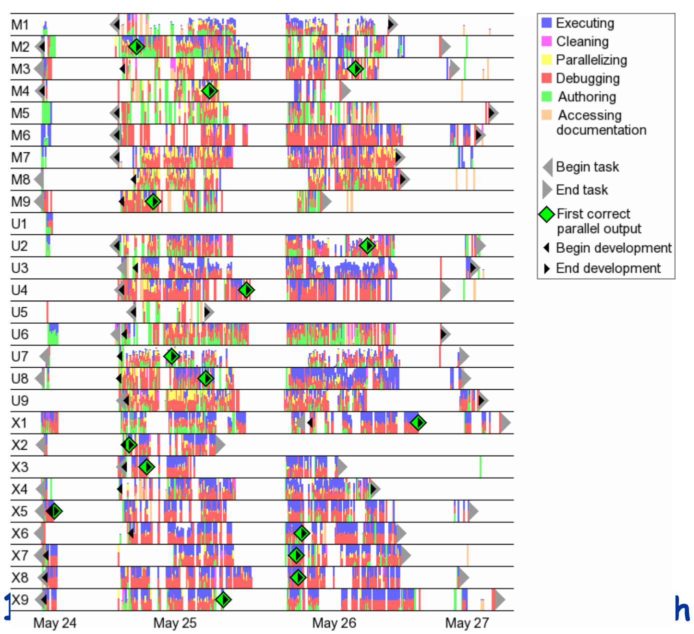
Performance Results for FFT (w/ memoized sine/cosine twiddle factors)

N = 2^24^ (SQRTN = 2^12^)

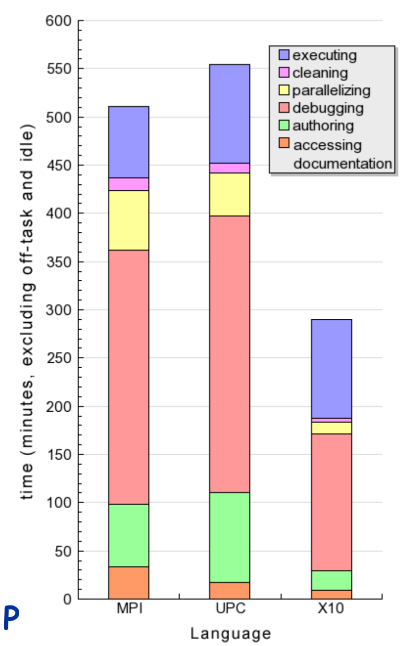


Summary

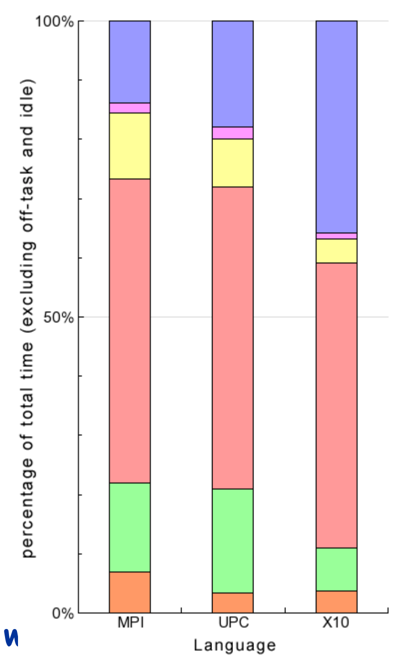
- X10 programming model provides core concurrency and distribution constructs for new era of parallel processing
- Results show competitive performance for Hybrid X10+C relative to OpenMP/C and Cilk
- Past studies have shown other productivity benefits of X10
- To find out more, come to the X10 exhibit in the Exotic Technologies area!



Absolute Time



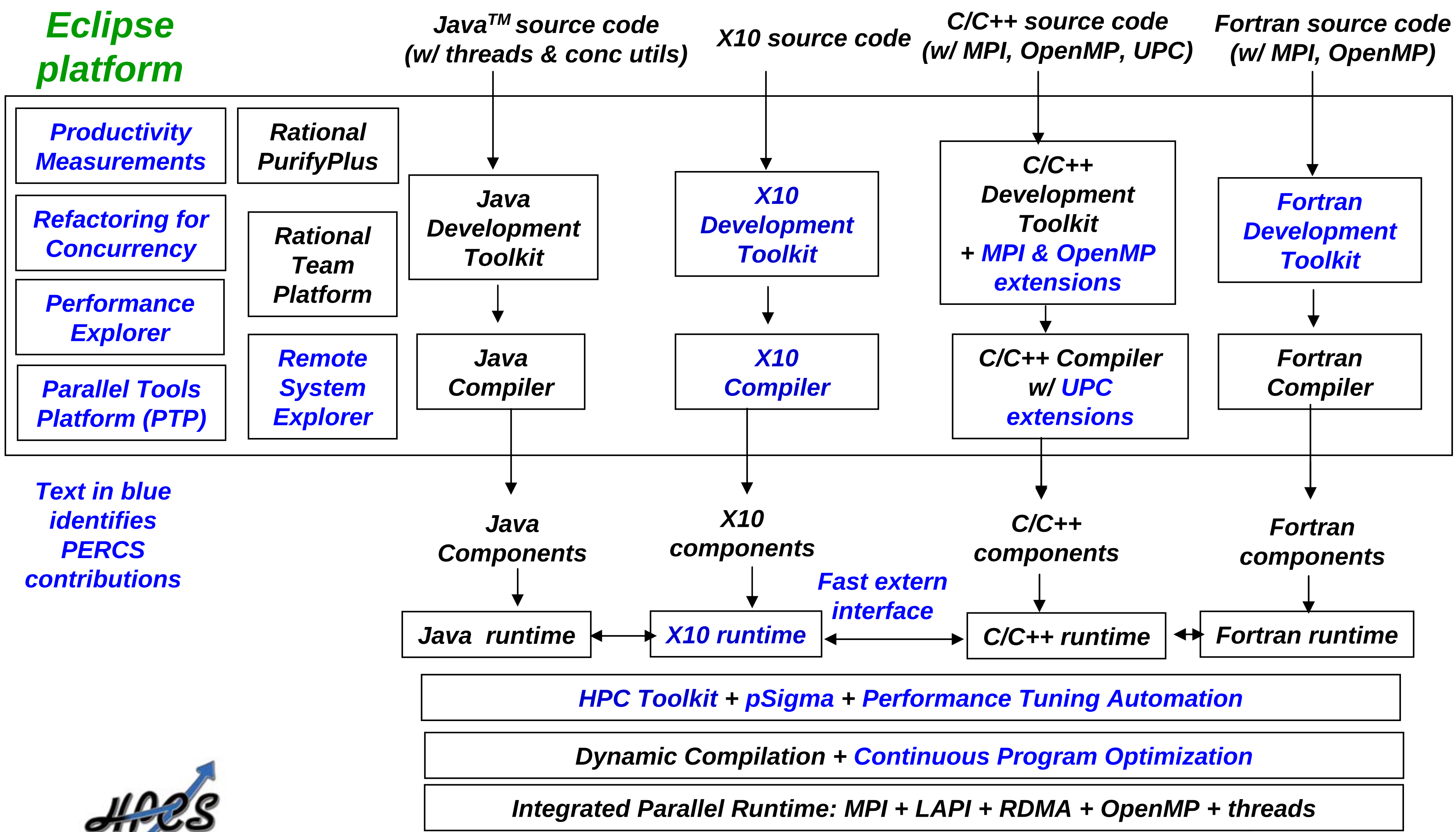
Percentage of Total



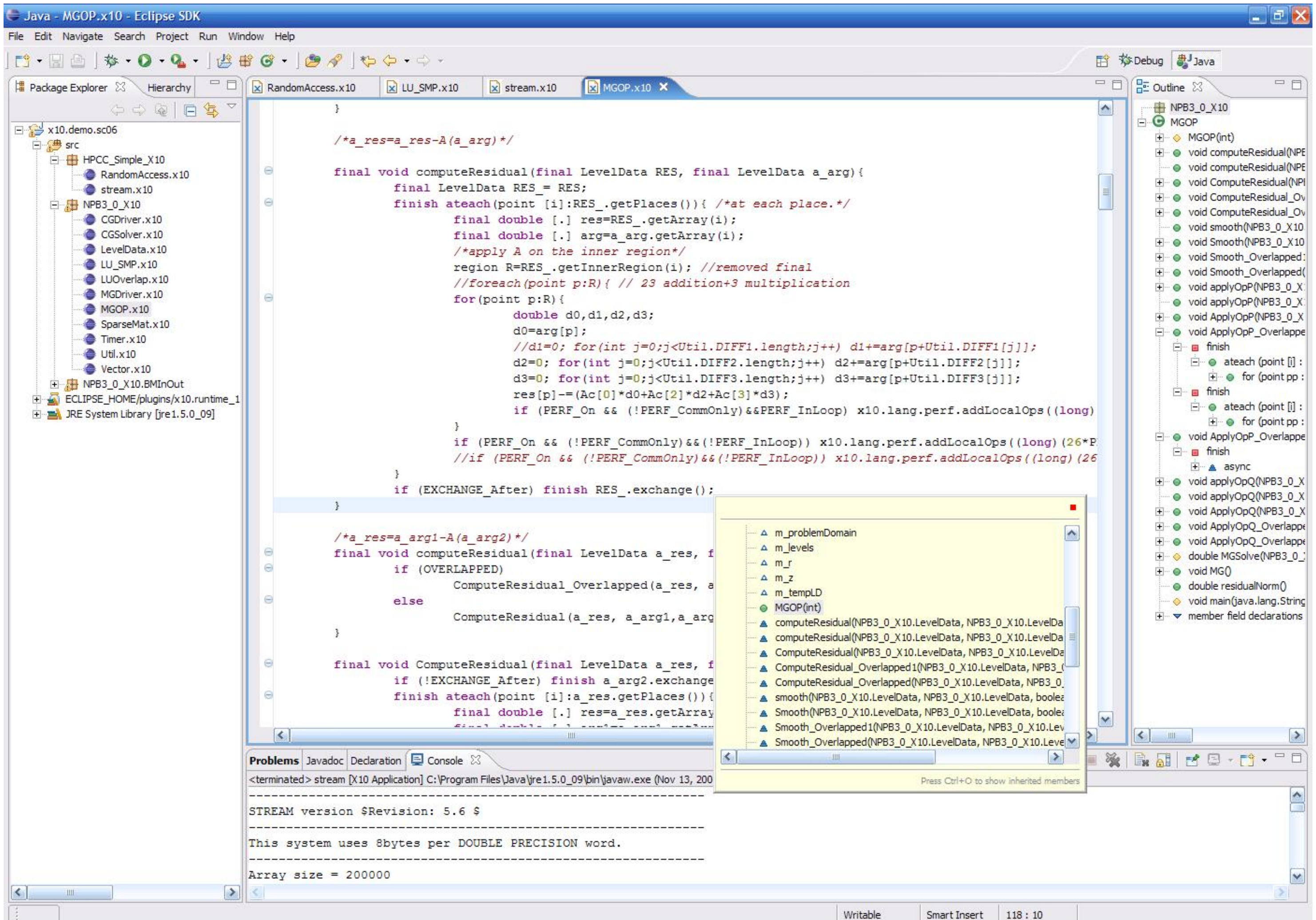
BACKUP SLIDES START HERE

X10 context: PERCS Programming Model, Tools and Compilers

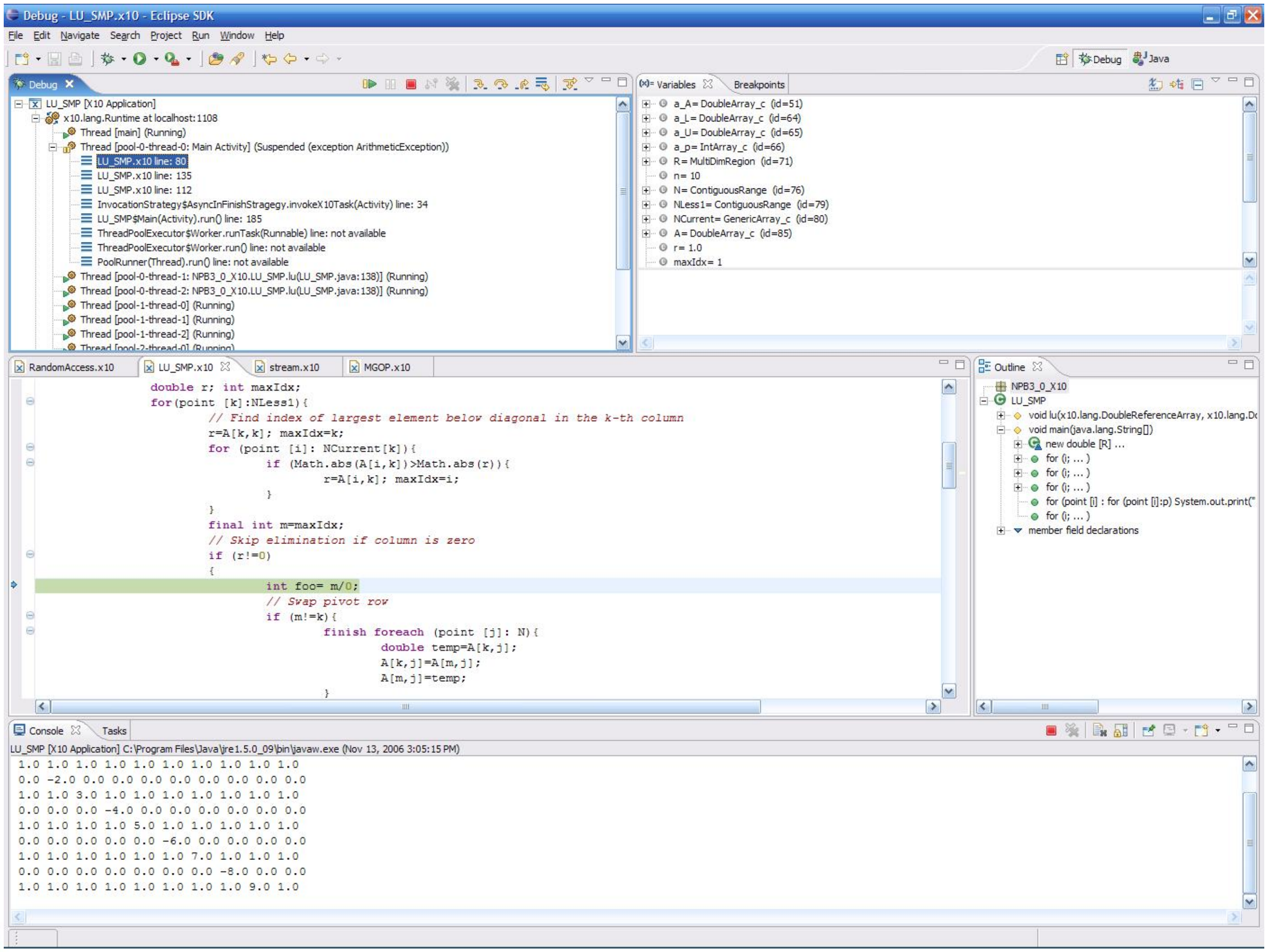
(PERCS = Productive Easy-to-use Reliable Computer System)



X10 Eclipse Development Toolkit



X10 Eclipse Debugging Toolkit



X10 Language

- async [(*Place*)] [clocked(c…)] *Stm*
  - Run Stm asynchronously at Place
- finish *Stm*
  - Execute s, wait for all asyncs to terminate (generalizes join)
- foreach (point *P* : *Reg*) *Stm*
  - Run Stm asynchronously for each point in region
- ateach (point *P* : *Dist*) *Stm*
  - Run Stm asynchronously for each point in dist, in its place.
- atomic *Stm*
  - Execute Stm atomically
- new T
  - Allocate object at this place (here)
- new T[d] / new T value [d]
  - Array of base type T and distribution d

- Region
  - Collection of index points, e.g.

    region r = [1:N,1:M];
- Distribution
  - Mapping from region to places, e.g.
    - dist d = block(r);
- next
  - suspend till all clocks that the current activity is registered with can advance
  - Clocks are a generalization of barriers and MPI communicators
- future [(*Place*)] [clocked(c…)] *Expr*
  - Compute Expr asynchronously at Place
- F. force()
  - Block until future F has been computed
- extern
  - Lightweight interface to native code

Deadlock safety: any X10 program written with above constructs (excluding future) can never deadlock
• Can be extended to restricted cases of using future

X10 Arrays, Regions, Distributions

ArrayExpr:

new ArrayType (Formal) { Stm }

Distribution Expr	-- Lifting
***ArrayExpr* [*Region*]**	-- Section
ArrayExpr* | *Distribution	-- Restriction
ArrayExpr* || *ArrayExpr	-- Union
***ArrayExpr*.overlay(*ArrayExpr*)**	-- Update
***ArrayExpr*. scan(*[fun [, ArgList]*)**	
***ArrayExpr*. reduce(*[fun [, ArgList]*)**	
***ArrayExpr*.lift(*[fun [, ArgList]*)**	

ArrayType:

***Type [Kind]* [ ]**

***Type [Kind]* [region(N)]**

***Type [Kind]* [*Region*]**

***Type [Kind]* [*Distribution*]**

Region:

Expr : Expr	-- 1-D region
[*Range, …, Range*]	-- Multidimensional Region
Region* && *Region	-- Intersection
Region* || *Region	-- Union
Region* – *Region	-- Set difference
BuiltinRegion	

Dist:

Region -> Place	-- Constant distribution
Distribution* | *Place	-- Restriction
Distribution* | *Region	-- Restriction
Distribution* || *Distribution	-- Union
Distribution* – *Distribution	-- Set difference
***Distribution*.overlay (*Distribution*)**	
BuiltinDistribution	

Language supports type safety, memory safety, place safety, clock safety.