Supporting Irregular Applications with Partitioned Global Address Space Languages: UPC and UPC++

Kathy Yelick
Lawrence Berkeley National Laboratory

With results from the DEGAS and UPC groups
NERSC Celebrates 40th Birthday

5000 users, 1900+ publications per year

Lectures available at www.nersc.gov

Petaflop and Petabyte systems for science

John Kuriyan for Martin Karplus
Saul Perlmutter
George Smoot
Warren Washington
Programming Challenges and Solutions

Message Passing Programming
Divide up domain in pieces
Each compute one piece
Exchange (send/receive) data

Global Address Space Programming
Each start computing
Grab whatever you need whenever

PVM, MPI, and many libraries

Global Address Space Languages and Libraries

~10% of NERSC apps use some kind of PGAS-like model
Shared Memory vs. Message Passing

Shared Memory

• Advantage: Convenience
  – Can share data structures
  – Just annotate loops
  – Closer to serial code

• Disadvantages
  – No locality control
  – Does not scale
  – Race conditions

Message Passing

• Advantage: Scalability
  – Locality control
  – Communication is all explicit in code (cost transparency)

• Disadvantage
  – Need to rethink data structures
  – Tedious pack/unpack code
  – When to say “receive”
**PGAS Languages**

- **Global address space**: thread may directly read/write remote data
  - Hides the distinction between shared/distributed memory
- **Partitioned**: data is designated as local or global
  - Does not hide this: critical for locality and scaling
Science Across the “Irregularity” Spectrum

Massive Independent Jobs for Analysis and Simulations

Nearest Neighbor Simulations

All-to-All Simulations

Random access, large data Analysis

Data analysis and simulation
Hello World in UPC

• Any legal C program is also a legal UPC program
• If you compile and run it as UPC with P threads, it will run P copies of the program.
• Using this fact, plus the a few UPC keywords:

```
#include <upc.h>  /* needed for UPC extensions */
#include <stdio.h>

main() {
    printf("Thread %d of %d: hello UPC world\n", MYTHREAD, THREADS);
}
```
Example: Monte Carlo Pi Calculation

- Estimate Pi by throwing darts at a unit square
- Calculate percentage that fall in the unit circle
  - Area of square = $r^2 = 1$
  - Area of circle quadrant = $\frac{1}{4} \times \pi r^2 = \pi/4$
- Randomly throw darts at $x,y$ positions
- If $x^2 + y^2 < 1$, then point is inside circle
- Compute ratio:
  - # points inside / # points total
  - $\pi = 4 \times \text{ratio}$
Pi in UPC

• Independent estimates of pi:

```c
main(int argc, char **argv) {
    int i, hits, trials = 0;
    double pi;

    if (argc != 2) trials = 1000000;
    else trials = atoi(argv[1]);

    srand(MYTHREAD*17);

    for (i=0; i < trials; i++) hits += hit();
    pi = 4.0*hits/trials;

    printf("PI estimated to %f.", pi);
}
```

Each thread gets its own copy of these variables

Each thread can use input arguments

Initialize random in math library

Each thread calls “hit” separately
Helper Code for Pi in UPC

• Required includes:
   
   ```
   #include <stdio.h>
   #include <math.h>
   #include <upc.h>
   ```

• Function to throw dart and calculate where it hits:
   
   ```
   int hit()
   {
       int const rand_max = 0xFFFFFFFF;
       double x = ((double) rand()) / RAND_MAX;
       double y = ((double) rand()) / RAND_MAX;
       if ((x*x + y*y) <= 1.0) {
           return(1);
       } else {
           return(0);
       }
   }
   ```
Shared vs. Private Variables
Private vs. Shared Variables in UPC

- Normal C variables and objects are allocated in the private memory space for each thread.
- Shared variables are allocated only once, with thread 0
  ```c
  shared int ours; // use sparingly: performance
  int mine;
  ```
- Shared variables may not have dynamic lifetime: may not occur in a function definition, except as static. Why?
• Parallel computing of pi, but with a bug

```
shared int hits;
main(int argc, char **argv) {
    int i, my_trials = 0;
    int trials = atoi(argv[1]);
    my_trials = (trials + THREADS - 1)/THREADS;
    srand(MYTHREAD*17);
    for (i=0; i < my_trials; i++)
        hits += hit();
    upc_barrier;
    if (MYTHREAD == 0) {
        printf("PI estimated to %f.", 4.0*hits/trials);
    }
}
```

What is the problem with this program?
UPC Synchronization

- UPC has two basic forms of barriers:
  - Barrier: block until all other threads arrive
    ```c
    upc_barrier
    ```
  - Split-phase barriers
    ```c
    upc_notify;  // this thread is ready for barrier
    upc_wait;    // wait for others to be ready
    ```

- UPC also has locks for protecting shared data:
  - Locks are an opaque type (details hidden):
    ```c
    upc_lock_t *upc_global_lock_alloc(void);
    ```
  - Critical region protected by lock/unlock:
    ```c
    void upc_lock(upc_lock_t *l)
    void upc_unlock(upc_lock_t *l)
    ```
    use at start and end of critical region
Pi in UPC: Shared Memory Style

- Like pthreads, but use shared accesses judiciously

```c
shared int hits;

main(int argc, char **argv) {
    int i, my_hits, my_trials = 0;
    upc_lock_t *hit_lock = upc_all_lock_alloc();
    int trials = atoi(argv[1]);
    my_trials = (trials + THREADS - 1)/THREADS;
    srand(MYTHREAD*17);
    for (i=0; i < my_trials; i++)
        my_hits += hit();
    upc_lock(hit_lock);
    hits += my_hits;
    upc_unlock(hit_lock);
    upc_barrier;
    if (MYTHREAD == 0)
        printf("PI: %f", 4.0*hits/trials);
}
```
Pi in UPC: Data Parallel Style with Collectives

• The previous version of Pi works, but is not scalable:
  – On a large # of threads, the locked region will be a bottleneck
• Use a reduction for better scalability

```c
#include <bupc_collectivev.h>

// shared int hits;
main(int argc, char **argv) {
  ...
  for (i=0; i < my_trials; i++)
    my_hits += hit();
  my_hits = bupc_allv_reduce(int, my_hits, 0, UPC_ADD);
  // upc_barrier;
  if (MYTHREAD == 0)
    printf("PI: %f", 4.0*my_hits/trials);
}
```

Berkeley collectives
no shared variables
barrier implied by collective
Shared Arrays Are Cyclic By Default

- Shared scalars always live in thread 0
- Shared arrays are spread over the threads
- Shared array elements are spread across the threads

```c
shared int x[THREADS] /* 1 element per thread */
shared int y[3][THREADS] /* 3 elements per thread */
shared int z[3][3] /* 2 or 3 elements per thread */
```

- In the pictures below, assume THREADS = 4
  - Blue elts have affinity to thread 0

Think of linearized C array, then map in round-robin

As a 2D array, y is logically blocked by columns

z is not
Pi in UPC: Shared Array Version

- Alternative fix to the race condition
- Have each thread update a separate counter:
  - But do it in a shared array
  - Have one thread compute sum

```c
shared int all_hits [THREADS];
main(int argc, char **argv) {
    ... declarations an initialization code omitted
    for (i=0; i < my_trials; i++)
        all_hits[MYTHREAD] += hit();
    upc_barrier;
    if (MYTHREAD == 0) {
        for (i=0; i < THREADS; i++)
            hits += all_hits[i];
        printf("PI estimated to %f.", 4.0*hits/trials);
    }
}
```

all_hits is shared by all processors, just as hits was
update element with local affinity
shared void *upc_alloc(size_t nbytes);

- nbytes: size of memory in bytes
- Non-collective: called by one thread
- The calling thread allocates a contiguous memory space in the shared space with affinity to itself.

shared [] double [n] p2 = upc_alloc(n*sizeof(double));

void upc_free(shared void *ptr);
- Non-collective function; frees the dynamically allocated shared memory pointed to by ptr
Distributed Arrays Directory Style

• Many UPC programs avoid the UPC style arrays in factor of directories of objects

```c
typedef shared [] double *sdblptr;
shared sdblptr directory[THREADS];
directory[i]=upc_alloc(local_size*sizeof(double));
```

• These are also more general:
  • Multidimensional, unevenly distributed
  • Ghost regions around blocks
Arrays in a Global Address Space

- Key features of Titanium arrays
  - Generality: indices may start/end and any point
  - Domain calculus allow for slicing, subarray, transpose and other operations without data copies
- Use domain calculus to identify ghosts and iterate:
  \[
  \text{foreach (p in gridA.shrink(1).domain()) ...}
  \]
- Array copies automatically work on intersection
  \[
  \text{gridB.copy(gridA.shrink(1));}
  \]

Joint work with Titanium group

Useful in grid computations including AMR
**UPC Compiler Implementation**

**UPC-to-C translator**
- UPC code
- UPC source-to-source translator
- C code
- Pros: portable, can use any backend C compiler
- Cons: may lose program information between the two compilation phases
- Example: Berkeley UPC

**UPC-to-object-code compiler**
- UPC code
- UPC source-to-object-code compiler
- Machine Instr.
- Pros: better for implementing UPC specific optimizations
- Cons: less portable
- Example: GCC UPC and most vendor UPC compilers
Important for performance:
• Communication overlap with computation
• Communication overlap with communication (pipelining)
• Low overhead communication

#include<upc_nb.h>

upc_handle_t h = upc_memcpy_nb(shared void * restrict dst,
                               shared const void * restrict src,
                               size_t n);

void upc_sync(upc_handle_t h); // blocking wait
int upc_sync_attempt(upc_handle_t h); // non-blocking
Communication Strategies for 3D FFT

- Three approaches:
  - **Chunk:**
    - Wait for 2\textsuperscript{nd} dim FFTs to finish
    - Minimize # messages
  - **Slab:**
    - Wait for chunk of rows destined for 1 proc to finish
    - Overlap with computation
  - **Pencil:**
    - Send each row as it completes
    - Maximize overlap and
    - Match natural layout

chunk = all rows with same destination

slab = all rows in a single plane with same destination

pencil = 1 row

Joint work with Chris Bell, Rajesh Nishtala, Dan Bonachea
FFT Performance on BlueGene/P

- UPC implementation consistently outperform MPI
- Uses highly optimized local FFT library on each node
- UPC version avoids send/receive synchronization
  - Lower overhead
  - Better overlap
  - Better bisection bandwidth
- Numbers are getting close to HPC record on BG/P

HPC Challenge Peak as of July 09 is ~4.5 Tflops on 128k Cores
UPC 1.3 Atomic Operations

- More efficient than using locks when applicable

```c
def upc_lock()
    upc_update()
    upc_unlock()
```

- Hardware support for atomic operations are available, but

  Only support limited operations on a subset of data types. e.g.,
  - Atomic_CAS on uint64_t
  - Atomic_Add on double

  Atomic ops from different processors *may not* be atomic to each other
UPC + Remote Invocation for Scalable Meraculous Application used in Genomics Grand Challenge

Meraculous Assembly Pipeline

reads

k-mers

New analysis filters errors using probabilistic “Bloom Filter”

contigs

New fast I/O using SeqDB over HDF5

Graph algorithm scales to 15K cores on NERSC’s Edison using DEGAS language rather than shared memory hardware

Meraculous assembler is use in production at the Joint Genome Institute

- Wheat assembly is a “grand challenge”
- Hardest part is contig generation (large in-memory hash table)

Human: 44 hours to 20 secs

Wheat: “doesn’t run” to 32 secs

Future work: Scaffolds using Scalable Alignment

DEGAS X-Stack project

- Gives tera- to petabyte “shared” memory
- Combines with new math/data algorithm for mapping to anchor 92% of wheat chromosome

Dynamic Exascale Global Address Space project, joint work JGI, Early Career and Mantissa
Beyond Put/Get: Event-Driven Execution

- DAG Scheduling in a distributed (partitioned) memory context
- Assignment of work is static; schedule is dynamic
- Ordering needs to be imposed on the schedule
  - Critical path operation: Panel Factorization
- General issue: dynamic scheduling in partitioned memory
  - Can deadlock in memory allocation
  - “memory constrained” lookahead

Uses a Berkeley extension to UPC to remotely synchronize

some edges omitted
DEGAS Programming System: UPC++

A template-based programming system enabling PGAS features for C++ applications

DEGAS is a DOE-funded X-Stack project led by Lawrence Berkeley National Lab (PI: Kathy Yelick), in collaboration with LLNL, Rice Univ., UC Berkeley, and UT Austin.
Communication-avoiding algorithms generalized to compilers, and communication optimizations in PGAS
Making PGAS more Dynamic; DAG Programming more Locality-Aware

**DEGAS Overview**

**PGAS**
- Asynchronous remote put/get for random access
- Good locality control and scaling
  
  E.g. `*p = ...` or `... = a[i];`

**DAGs**
- Asynchronous invocation
- Good for dynamic load balancing and event-driven execution

```
finish { ... async f (x)...}
```

**DEGAS**
Hierarchical locality control
(1) Remote put/get and atomics
(2) Remote invocation
(3) Distributed load balance
UPC++ Generic Programming for PGAS

• Enable “modern” language features with PGAS
  – Interoperable with MPI, OpenMP, CUDA,…

• UPC++ uses templates to express shared data
  ```
  shared_var<int> s;  // shared int s in UPC
  shared_array<int> sa(8);  // shared int sa[8]
  // in UPC
  ```

• UPC++ provides remote invocation
  ```
  // Remote Procedure Call
  upcxx::async(place)(Function f, T1 arg1, T2 arg2,…);
  upcxx::wait();

  // Explicit task synchronization
  upcxx::event e;
  upcxx::async(place, &e)(Function f, T1 arg1, …);
  e.wait();
  ```
The difference between UPC++ and UPC is about 0.2 µs (~220 cycles).

GUPS Performance on MIC and BlueGene/Q

**MIC**

Giga Updates Per Second

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**BlueGene/Q**

Giga Updates Per Second

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One-Sided vs Two-Sided

one-sided put message

address  data payload

network interface  host CPU

two-sided message

message id  data payload

network interface  memory

- A one-sided put/get message can be handled directly by a network interface with RDMA support
  - Avoid interrupting the CPU or storing data from CPU (preposts)
- A two-sided messages needs to be matched with a receive to identify memory address to put data
  - Offloaded to Network Interface in networks like Quadrics
  - Need to download match tables to interface (from host)
  - Ordering requirements on messages can also hinder bandwidth
Bandwidths on Cray XE6 (Hopper)
Cray XE6 Application Performance

Percentage UPC over MPI speedup

- ep
- ft
- is
- lu
- mg
- sp
- bt
- Harmonic mean

64 procs
256 procs
Summary

• UPC designed to be consistent with C
  – Ability to use pointers and arrays interchangeably
• Designed for high performance
  – Memory consistency explicit; Small implementation
  – Transparent runtime
• gcc version of UPC:
  http://www.gccupc.org/
• Berkeley compiler
  http://upc.lbl.gov
• Language specification and other documents
  https://code.google.com/p/upc-specification
  https://upc-lang.org
• Vendor compilers: Cray, IBM, HP, SGI,…
UPC++ Asynchronous Remote Execution Enables Scalable Data Fusion

PGAS before X-Stack
- Asynchronous remote put/get
- Good locality control and scaling
  E.g. \( *p = \ldots \) or \( \ldots = a[i]; \gamma \)

New: Asynchronous invocation
- Event-driven execution & load balancing
- Hierarchical synchronization and places
  finish \{ \ldots \text{async} \ f \ (x) \ldots \}

- Seismic modeling for energy applications “fuses” observational data into simulation.
- PGAS illusion of scalable shared memory to construct matrix and measure data “fit”
- New UPC++ dialect supports PGAS libraries; future distributed data structure library

DEGAS
Dynamic Exascale Global Address Space from LBNL, Rice, UTAustin, UCB, LLNL
Mini-GMG in UPC++ uses high level array library for Productivity and Performance

Before X-Stack
• MPI’s explicit communication inhibits productivity and performance portability

“MG V-cycle”

Before X-Stack

New: UPC++ Multidimensional Arrays
• Provides productivity via high-level array abstraction
• Encapsulates performance critical

Used miniGMG benchmark which proxies MG solver in combustion codesign center

Each process exchanges data with 26 neighbors. UPC++ multidimensional arrays give an easy interface to users and optimize strided data accesses automatically.

“Fine-grained” like OpenMP -- insufficient locality control
“Bulk” like MPI with 1-sided communication; perfect match to scalability but no productivity advantage
“Array” version uses multi-dimensional array constructs for productivity and ~MPI performance
Future runtime optimizations should close Array/Bulk gap

DEGAS
Dynamic Exascale Global Address Space from LBNL, Rice, UT Austin, UCB, LLNL
GASNet Asynchronous One-Sided Communication Aids in Performance Portability and Scaling for NWChem

- Production chemistry code
  - 60K downloads worldwide
  - 200-250 scientific application publications per year
  - Over 6M LoC, 25K files

- New version on GASNet for
  - Improved performance
  - Portability with other PGAS

[Diagram showing performance comparison between GA over GASNET and GA base version]

NWChem was written in the early 1990s, has 25k files and 6m lines of Fortran. It contains its own internal tasking model, memory management, and application checkpoint/restart.

Execution on 100K+ processors
Optimizations:

- Blocked vs. cyclic (default) array layout
- Use private pointer to the thread block in shared array

![Graph showing speedup relative to OMP(1) with different thread counts and configurations.]
Dynamic load balancing in UPC (and UPC++) is an option

```c
taskq_put(...);
taskq_execute(...);
int taskq_all_isEmpty(taskq_t *taskq);
Etc.
```

Can be used optionally within a node, across nodes, on a certain subproblem, etc.

_Hierarchical Work Stealing on Manycore Clusters_
Min, Iancu, Yelick. PGAS 2011
Single Program Multiple Data (SPMD) is too restrictive.

Hierarchical machines and Applications:

- **Option 1:** Dynamic parallelism creation (e.g., Chapel)
  - Recursively divide until... you run out of work (or hardware)
  - Runtime needs to match parallelism to hardware hierarchy

- **Option 2:** Hierarchical SPMD with “Mix-ins” (e.g., UPC++)
  - Hardware threads can be grouped into units hierarchically
  - Add dynamic parallelism with voluntary tasking on a group
  - Add data parallelism with collectives on a group

Hierarchical memory model may be necessary (what to expose vs hide)

Two approaches to supporting the hierarchical control...
One-sided communication works everywhere

PGAS programming model

*p1 = *p2 + 1;
A[i] = B[i];

upc_memput(A,B,64);

It is implemented using one-sided communication: put/get

Support for one-sided communication (DMA) appears in:

• Fast one-sided network communication (RDMA, Remote DMA)
• Move data to/from accelerators
• Move data to/from I/O system (Flash, disks,..)
• Movement of data in/out of local-store (scratchpad) memory
Vertical PGAS

- New type of wide pointer?
  - Points to slow (offchip memory)
  - The type system could get unwieldy quickly

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<tr>
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Shared partitioned on-chip

Shared off-chip DRAM or NVRAM
LBNL / UCB Collaborators

- Dan Bonachea
- Paul Hargrove
- Amir Kamil
- Khaled Ibrahim
- Costin Iancu
- Yili Zheng
- Michael Driscoll
- Evangelos Georganas
- Penporn Koanantakool
- Steven Hofmeyr
- Leonid Oliker
- Eric Roman
- John Shalf

- Erich Strohmaier
- Samuel Williams
- Cy Chan
- Didem Unat
- James Demmel, UCB
- Scott French
- Edgar Solomonik
- Eric Hoffman
- Wibe de Jong

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- John Mellor-Crummey, Rice
- Krste Asanović UCB
- Mattan Erez, UT Austin
- Dan Quinlan, LLNL

Thanks!