Beyond C/C++

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Current Landscape

For scientific code, at least 90%:

- Python for scripting / high-level
- Fortran or C/C++ for everything else
- Parallelism via OpenMP and MPI

Much of the remainder: accelerators

- CUDA / OpenCL / OpenAcc
- These are basically C extensions

Good: Big ecosystems, lots of reference material.
But what about fresh ideas?

Why choose what?

- Popularity – can others use/extend my code?
- Portability – will it run across platforms?
- Performance – will it run fast (portably)?
- Ecosystem – can I get libraries?

Why not C/C++

I write a lot of C/C++, but know:

- Aliasing is a tremendous pain
- No real multi-dimensional arrays
- Complex number support can be painful

Modern C++ keeps getting better...
but numerical code is still a problem

Fortran ($\neq$ F77)

- Not the language dinosaur you think it is!
- Use SciPy/NumPy? You use Fortran!
- Standard bindings for OpenMP and MPI
- Sane support for multi-dimensional arrays, complex numbers
- Relatively easy to optimize
- Coming soon to LLVM: `https://t.co/LhjkdYztMu`
- Since Fortran 2003: Standard way to bind with C
- Since Fortran 2008: Co-arrays (more on this later)

Wait, Python?

Big selling points:

- Not all code is performance critical!
- For performance-bound code
  - Compiled extensions (Cython and predecessors)
  - JIT options (Numba, PyPy)
- Easy to bind to compiled code (SWIG, f2py, Cython)
- "Batteries included": libraries cover a lot of ground
- Often used to support *Domain Specific Languages*

C plus a bit

Common mode: C/C++ with extensions for extra parallelism

- **Cilk+**
- **UPC** and predecessors
- CUDA
- ISPC?

Cilk+

MIT project from 90s → Cilk Arts → Intel

C/C++ plus

- `cilk_for` (parallel loops)
- `cilk_spawn` (asynchronous function launch)
- `cilk_sync` (synchronize)
- Reducers (no mutex, apply reduction at sync)
- Array operations
- SIMD-enabled functions
- Work-stealing scheduler

Implementations: GCC, CLang, Intel compiler

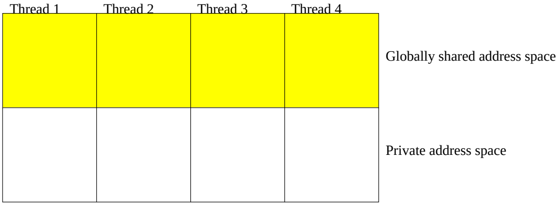
```
void reducer_list_test() {
  using namespace std;
  cilk::reducer< cilk::op_list_append<char> >
    letters_reducer;

  // Build the list in parallel
  cilk_for (char ch = 'a'; ch <= 'z'; ch++) {
    simulated_work();
    letters_reducer->push_back(ch);
  }

  // Reducer result as a standard STL list then output
  const list<char> &letters = letters_reducer.get_value();
  cout << "Letters from reducer_list:";
  for (auto i = letters.begin(); i != letters.end(); i++)
    cout << " " << *i;
  cout << endl;
}
```

https://www.cilkplus.org/tutorial-cilk-plus-reducers

Big picture

- Message passing: scalable, harder to program (?)
- Shared memory: easier to program, less scalable (?)
- Global address space:
  - Use shared address space (programmability)
  - Distinguish local/global (performance)
  - Runs on distributed or shared memory hw

Partitioned Global Address Space (PGAS)



- Partition a shared address space:
  - *Local* addresses live on local processor
  - *Remote* addresses live on other processors
  - May also have *private* address spaces
  - Programmer controls data placement
- Several examples: UPC, Titanium, Fortran 2008

Unified Parallel C

Unified Parallel C (UPC) is:

- Explicit parallel extension to ANSI C
- A partitioned global address space language
- Similar to C in design philosophy: concise, low-level, ... and "enough rope to hang yourself"
- Based on ideas from Split-C, AC, PCP

References

- http://upc.lbl.gov
- http://upc.gwu.edu

Based on slides by Kathy Yelick (UC Berkeley),
in turn based on slides by Tarek El-Ghazawi (GWU)

Execution model

- `THREADS` parallel threads, `MYTHREAD` is local index
- Number of threads can be specified at compile or run-time
- Synchronization primitives (barriers, locks)
- Parallel iteration primitives (forall)
- Parallel memory access / memory management
- Parallel library routines

Hello world

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

int main()
{
    printf("Hello from %d of %d\n",
           MYTHREAD, THREADS);
}
```

Shared variables

```
shared int ours;
int mine;
```

- Normal variables allocated in private memory per thread
- Shared variables allocated once, on thread 0
- Shared variables cannot have dynamic lifetime
- Shared variable access is more expensive

Shared arrays

```
shared int x[THREADS];          /* 1 per thread */
shared double y[3*THREADS]; /* 3 per thread */
shared int z[10];               /* Varies */
```

- Shared array elements have *affinity* (where they live)
- Default layout is cyclic
  - e.g. `y[i]` has affinity to thread `i % THREADS`

Hello world++ = π via Monte Carlo

Write

$$\pi = 4\frac{\text{Area of unit circle quadrant}}{\text{Area of unit square}}$$

If (X, Y) are chosen uniformly at random on $[0, 1]^2$, then

$$\pi/4 = P\{X^2 + Y^2 < 1\}$$

Monte Carlo calculation of π: sample points from the square and compute fraction that fall inside circle.

π in C

```
int main()
{
    int i, hits = 0, trials = 1000000;
    srand(17);  /* Seed random number generator */
    for (i = 0; i < trials; ++i)
        hits += trial_in_disk();
    printf("Pi approx %g\n", 4.0*hits/trials);
}
```

π in UPC, Version 1

```
shared int all_hits[THREADS];
int main() {
    int i, hits = 0, tot = 0, trials = 1000000;
    srand(1+MYTHREAD*17);
    for (i = 0; i < trials; ++i)
        hits += trial_in_disk();
    all_hits[MYTHREAD] = hits;
    upc_barrier;
    if (MYTHREAD == 0) {
        for (i = 0; i < THREADS; ++i)
            tot += all_hits[i];
        printf("Pi approx %g\n", 4.0*tot/trials/THREADS);
    }
}
```

Synchronization

- Barriers: `upc_barrier`
- Split-phase barriers: `upc_notify` and `upc_wait`

```
upc_notify;
Do some independent work
upc_wait;
```

- Locks (to protect critical sections)

Locks

Locks are dynamically allocated objects of type `upc_lock_t`:

```
upc_lock_t* lock = upc_all_lock_alloc();
upc_lock(lock);         /* Get lock */
upc_unlock(lock);       /* Release lock */
upc_lock_free(lock);    /* Free */
```

π in UPC, Version 2

```
shared int tot;
int main() {
    int i, hits = 0, trials = 1000000;
    upc_lock_t* tot_lock = upc_all_lock_alloc();
    srand(1+MYTHREAD*17);
    for (i = 0; i < trials; ++i)
        hits += trial_in_disk();
    upc_lock(tot_lock);
    tot += hits;
    upc_unlock(tot_lock);
    upc_barrier;
    if (MYTHREAD == 0) { upc_lock_free(tot_lock); print ...}
}
```

Collectives

UPC also has collective operations (typical list)

```
#include <bupc_collectivev.h>
int main() {
    int i, hits = 0, trials = 1000000;
    srand(1+MYTHREAD*17);
    for (i = 0; i < trials; ++i)
        hits += trial_in_disk();
    hits = bupc_allv_reduce(int, hits, 0, UPC_ADD);
    if (MYTHREAD == 0) printf(...);
}
```

Loop parallelism with upc_forall

UPC adds a special type of extended `for` loop:

```
upc_forall(init; test; update; affinity)
    statement;
```

- Assume no dependencies across threads
- Just run iterations that match affinity expression
  - Integer: `affinity % THREADS == MYTHREAD`
  - Pointer: `upc_threadof(affinity) == MYTHREAD`
- Really syntactic sugar (could do this with `for`)

Example

Note that x, y, and z all have the same layout.

```
shared double x[N], y[N], z[N];
int main() {
    int i;
    upc_forall(i=0; i < N; ++i; i)
        z[i] = x[i] + y[i];
}
```

Array layouts

- Sometimes we don't want cyclic layout
  (think nearest neighbor stencil...)
- UPC provides *layout specifiers* to allow block cyclic layout
- Block sizes expressions must be compile time constant (except THREADS)
- Element `i` has affinity with `(i / blocksize) % THREADS`
- In higher dimensions, affinity determined by linearized index

Array layouts

Examples:

```
shared double a[N];      /* Block cyclic */
shared[*] double a[N];   /* Blocks of N/THREADS */
shared[]  double a[N];   /* All elements on thread 0 */
shared[M] double a[N];   /* Block cyclic, block size M */
shared[M1][M2] double a[N][M1][M2]; /* Blocks of M1*M2 */
```

1D Jacobi Poisson example

```
shared[*] double u_old[N], u[N], f[N];  /* Block layout */
void jacobi_sweeps(int nsweeps) {
    int i, it;
    upc_barrier;
    for (it = 0; it < nsweeps; ++it) {
        upc_forall(i=1; i < N-1; ++i; &(u[i]))
            u[i] = (u_old[i-1] + u_old[i+1] - h*h*f[i])/2;
        upc_barrier;
        upc_forall(i=0; i < N; ++i; &(u[i]))
            u_old[i] = u[i];
        upc_barrier;
    }
}
```

1D Jacobi pros and cons

Good points about Jacobi example:

- Simple code (1 slide!)
- Block layout minimizes communication

Bad points:

- Shared array access is relatively slow
- Two barriers per pass

1D Jacobi: take 2

```
shared double ubound[2][THREADS];  /* For ghost cells*/
double uold[N_PER+2], uloc[N_PER+2], floc[N_PER+2];
void jacobi_sweep(double h2) {
  int i;
  if (MYTHREAD>0)       ubound[1][MYTHREAD-1]=uold[1];
  if (MYTHREAD<THREADS) ubound[0][MYTHREAD+1]=uold[N_PER];
  upc_barrier;
  uold[0]       = ubound[0][MYTHREAD];
  uold[N_PER+1] = ubound[1][MYTHREAD];
  for (i = 1; i < N_PER+1; ++i)
    uloc[i] = (uold[i-1] + uold[i+1] - h2*floc[i])/2;
  for (i = 1; i < N_PER+1; ++i)
    uold[i] = uloc[i];
}
```

1D Jacobi: take 3

```
void jacobi_sweep(double h2) {
  int i;
  if (MYTHREAD>0)        ubound[1][MYTHREAD-1]=uold[1];
  if (MYTHREAD<THREADS) ubound[0][MYTHREAD+1]=uold[N_PER];
  upc_notify; /******* Start split barrier *******/
  for (i = 2; i < N_PER; ++i)
    uloc[i] = (uold[i-1] + uold[i+1] - h2*floc[i])/2;
  upc_wait;   /******* End split barrier   *******/
  uold[0]       = ubound[0][MYTHREAD];
  uold[N_PER+1] = ubound[1][MYTHREAD];
  for (i = 1; i < N_PER+1; i += N_PER)
    uloc[i] = (uold[i-1] + uold[i+1] - h2*floc[i])/2;
  for (i = 1; i < N_PER+1; ++i) uold[i] = uloc[i];
}
```

Sharing pointers

Have pointers to global address space. Either pointer or referenced data might be shared:

```
int* p;                 /* Ordinary pointer */
shared int* p;          /* Local pointer to shared data */
shared int* shared p;   /* Shared pointer to shared data */
int* shared p;          /* Legal, but bad idea */
```

Pointers to shared are larger and slower than standard pointers.

UPC pointers

Pointers to shared objects have three fields:

- Thread number
- Local address of block
- Phase (position in block)

Access with `upc_threadof` and `upc_phaseof`;
go to start with `upc_resetphase`.

Dynamic allocation

- Can dynamically allocate shared memory
- Functions can be collective or not
- Collective functions must be called by every thread, return same value at all threads

Global allocation

```
shared void*
upc_global_alloc(size_t nblocks, size_t nbytes);
```

- Non-collective – just called at one thread
- Layout of `shared [nbytes] char[nblocks * nbytes]`

Collective global allocation

```
shared void*
upc_all_alloc(size_t nblocks, size_t nbytes);
```

- Collective – everyone calls, everyone receives same pointer
- Layout of `shared [nbytes] char[nblocks * nbytes]`

UPC free

```
void upc_free(shared void* p);
```

- Frees dynamically allocated shared memory
- *Not* collective

Example: Shared integer stack

Shared linked-list representation of a stack (think work queues).
All data will be kept at thread 0.

```
typedef struct list_t {
    int x;
    shared struct list_t* next;
} list_t;

shared struct list_t* shared head;
upc_lock_t* list_lock;
```

Example: Shared integer stack

```
void push(int x) {
    shared list_t* item =
        upc_global_alloc(1, sizeof(list_t));
    upc_lock(list_lock);
    item->x = x;
    item->next = head;
    head = item;
    upc_unlock(list_lock);
}
```

Example: Shared integer stack

```
int pop(int* x) {
    shared list_t* item;
    upc_lock(list_lock);
    if (head == NULL) {
        upc_unlock(list_lock);
        return -1;
    }
    item = head;
    head = head->next;
    *x = item->x;
    upc_free(item);
    upc_unlock(list_lock);
    return 0;
}
```

Memory consistency

UPC has two types of accesses:

- Strict: will always appear in order (sequential consistency)
- Relaxed: may appear out of order to other threads

Several ways to specify:

- Include <upc_relaxed.h>
- Add `strict` or `relaxed` as type qualifier
- Use pragmas

The `upc_fence` is a strict null reference – ensures shared references issued earlier are complete.

Performance

People won't use it if it's too slow! So:

- Maximize single-node performance (can link with tuned libraries, build on fast compilers)
- Use fast communication (GASNet layer provides fast one-sided communication for Berkeley UPC)
- Manage the details intelligently (language provides access to some low-level details, such as memory layout).

Case studies as part of UPC tutorial slides. With care, can sometimes get better performance than MPI!

But performance tuning is still nontrivial... not a magic bullet.