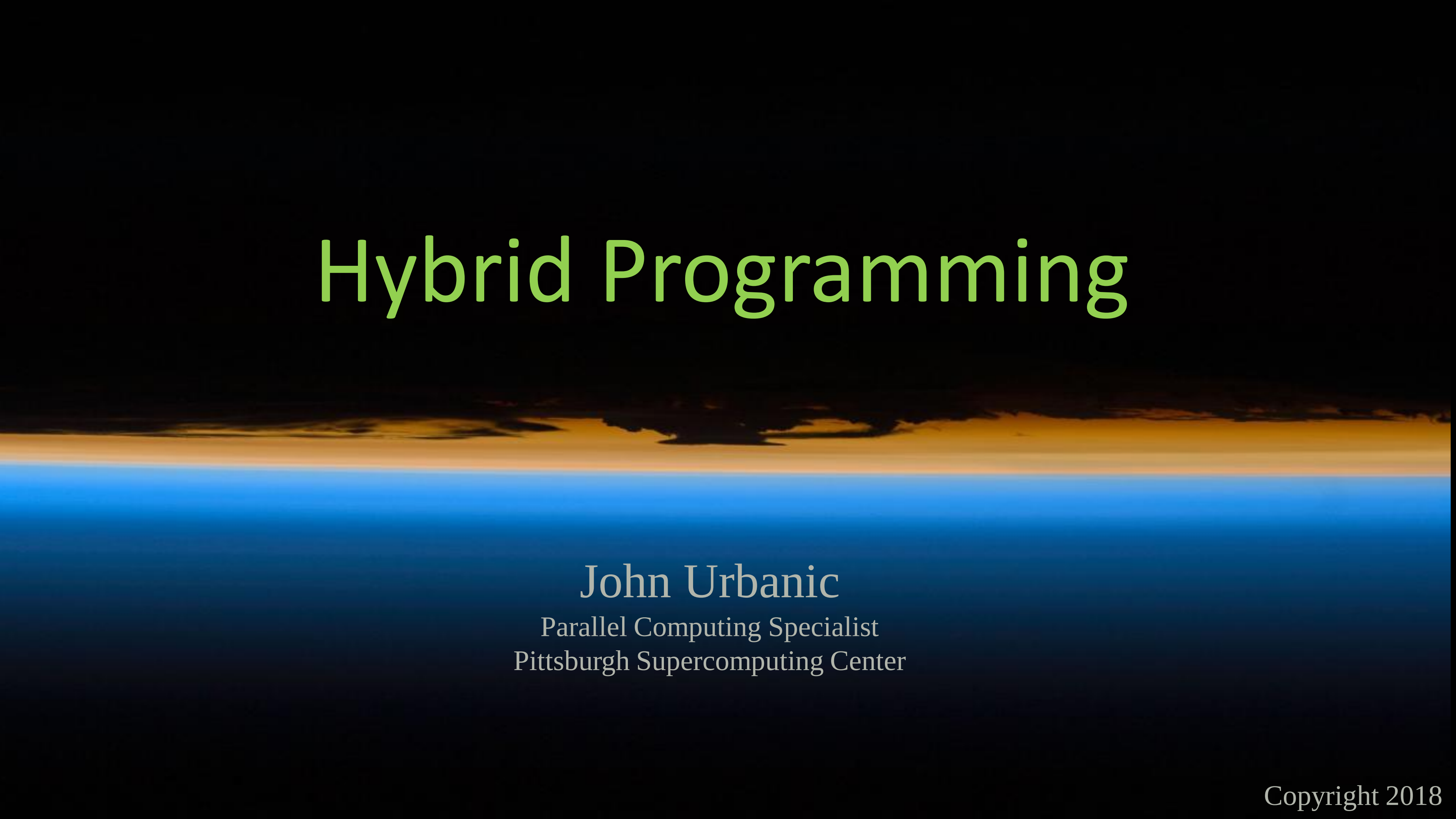

Hybrid Programming

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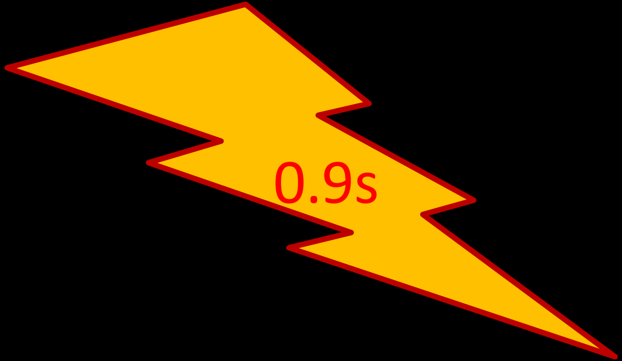
Assuming you know basic MPI

- This is a rare group that can discuss this topic meaningfully.
- I have mentioned MPI 3.0’s “improvements” to its hybrid capabilities. These are primarily tying up loose ends and formally specifying that things work as you would expect, and as they largely do. Your MPI 1/2 knowledge will be more than sufficient here.

Hybrid OpenACC Programming (Fast & Wrong)

```
#pragma acc data copy(Temperature_last), create(Temperature)
while ( dt_global > MAX_TEMP_ERROR && iteration <= max_iterations ) {

    #pragma acc kernels
    for(i = 1; i <= ROWS; i++) {
        for(j = 1; j <= COLUMNS; j++) {
            Temperature[i][j] = 0.25 * (Temperature_last[i+1][j] + Temperature_last[i-1][j] +
                                        Temperature_last[i][j+1] + Temperature_last[i][j-1]);
        }
    }

    if(my_PE_num != npes-1){
        MPI_Send(&Temperature[ROWS][1], COLUMNS, MPI_DOUBLE, my_PE_num+1, DOWN, MPI_COMM_WORLD);
    }

    if(my_PE_num != 0){
        MPI_Recv(&Temperature_last[0][1], COLUMNS, MPI_DOUBLE, my_PE_num-1, DOWN, MPI_COMM_WORLD, &status);
    }

    if(my_PE_num != 0){
        MPI_Send(&Temperature[1][1], COLUMNS, MPI_DOUBLE, my_PE_num-1, UP, MPI_COMM_WORLD);
    }

    if(my_PE_num != npes-1){
        MPI_Recv(&Temperature_last[ROWS+1][1], COLUMNS, MPI_DOUBLE, my_PE_num+1, UP, MPI_COMM_WORLD, &status);
    }

    dt = 0.0;

    #pragma acc kernels
    for(i = 1; i <= ROWS; i++){
        for(j = 1; j <= COLUMNS; j++){
            dt = fmax( fabs(Temperature[i][j]-Temperature_last[i][j]), dt);
            Temperature_last[i][j] = Temperature[i][j];
        }
    }

    MPI_Reduce(&dt, &dt_global, 1, MPI_DOUBLE, MPI_MAX, 0, MPI_COMM_WORLD);
    MPI_Bcast(&dt_global, 1, MPI_DOUBLE, 0, MPI_COMM_WORLD);

    if((iteration % 100) == 0) {
        if (my_PE_num == npes-1){
            #pragma acc update host(Temperature)
            track_progress(iteration);
        }
    }

    iteration++;
}
```

MPI routines using host data



Hybrid OpenACC Programming (Slow and Right)

```
#pragma acc data copy(Temperature_last), create(Temperature)
while ( dt_global > MAX_TEMP_ERROR && iteration <= max_iterations ) {

    #pragma acc kernels
    for(i = 1; i <= ROWS; i++) {
        for(j = 1; j <= COLUMNS; j++) {
            Temperature[i][j] = 0.25 * (Temperature_last[i+1][j] + Temperature_last[i-1][j] +
                                        Temperature_last[i][j+1] + Temperature_last[i][j-1]);
        }
    }

    #pragma acc update host(Temperature, Temperature_last)

    if(my_PE_num != npes-1){
        MPI_Send(&Temperature[ROWS][1], COLUMNS, MPI_DOUBLE, my_PE_num+1, DOWN, MPI_COMM_WORLD);
    }

    if(my_PE_num != 0){
        MPI_Recv(&Temperature_last[0][1], COLUMNS, MPI_DOUBLE, my_PE_num-1, DOWN, MPI_COMM_WORLD, &status);
    }

    if(my_PE_num != 0){
        MPI_Send(&Temperature[1][1], COLUMNS, MPI_DOUBLE, my_PE_num-1, UP, MPI_COMM_WORLD);
    }

    if(my_PE_num != npes-1){
        MPI_Recv(&Temperature_last[ROWS+1][1], COLUMNS, MPI_DOUBLE, my_PE_num+1, UP, MPI_COMM_WORLD, &status);
    }

    #pragma acc update device(Temperature, Temperature_last)

    dt = 0.0;

    #pragma acc kernels
    for(i = 1; i <= ROWS; i++){
        for(j = 1; j <= COLUMNS; j++){
            dt = fmax( fabs(Temperature[i][j]-Temperature_last[i][j]), dt);
            Temperature_last[i][j] = Temperature[i][j];
        }
    }

    MPI_Reduce(&dt, &dt_global, 1, MPI_DOUBLE, MPI_MAX, 0, MPI_COMM_WORLD);
    MPI_Bcast(&dt_global, 1, MPI_DOUBLE, 0, MPI_COMM_WORLD);

    if((iteration % 100) == 0) {
        if (my_PE_num == npes-1){
            #pragma acc update host(Temperature)
            track_progress(iteration);
        }
    }

    iteration++;
}
```

Update data entering and leaving MPI section

9.3 s

Hybrid OpenACC Programming (Much Better)

```
#pragma acc data copy(Temperature_last), create(Temperature)
while ( dt_global > MAX_TEMP_ERROR && iteration <= max_iterations ) {

    #pragma acc kernels
    for(i = 1; i <= ROWS; i++) {
        for(j = 1; j <= COLUMNS; j++) {
            Temperature[i][j] = 0.25 * (Temperature_last[i+1][j] + Temperature_last[i-1][j] +
                                        Temperature_last[i][j+1] + Temperature_last[i][j-1]);
        }
    }

    #pragma acc update host(Temperature[1:1][1:COLUMNS],Temperature[ROWS:1][1:COLUMNS])

    if(my_PE_num != npes-1){
        MPI_Send(&Temperature[ROWS][1], COLUMNS, MPI_DOUBLE, my_PE_num+1, DOWN, MPI_COMM_WORLD);
    }

    if(my_PE_num != 0){
        MPI_Recv(&Temperature_last[0][1], COLUMNS, MPI_DOUBLE, my_PE_num-1, DOWN, MPI_COMM_WORLD, &status);
    }

    if(my_PE_num != 0){
        MPI_Send(&Temperature[1][1], COLUMNS, MPI_DOUBLE, my_PE_num-1, UP, MPI_COMM_WORLD);
    }

    if(my_PE_num != npes-1){
        MPI_Recv(&Temperature_last[ROWS+1][1], COLUMNS, MPI_DOUBLE, my_PE_num+1, UP, MPI_COMM_WORLD, &status);
    }

    #pragma acc update device(Temperature_last[0:1][1:COLUMNS], Temperature_last[ROWS+1:1][1:COLUMNS])

    dt = 0.0;

    #pragma acc kernels
    for(i = 1; i <= ROWS; i++){
        for(j = 1; j <= COLUMNS; j++){
            dt = fmax( fabs(Temperature[i][j]-Temperature_last[i][j]), dt);
            Temperature_last[i][j] = Temperature[i][j];
        }
    }

    MPI_Reduce(&dt, &dt_global, 1, MPI_DOUBLE, MPI_MAX, 0, MPI_COMM_WORLD);
    MPI_Bcast(&dt_global, 1, MPI_DOUBLE, 0, MPI_COMM_WORLD);

    if((iteration % 100) == 0) {
        if (my_PE_num == npes-1){
            #pragma acc update host(Temperature)
            track_progress(iteration);
        }
    }

    iteration++;
}
```

1.1s

Hybrid OpenMP Programming
(Most “complex” version: MPI_THREAD_MULTIPLE)

```
#include <mpi.h>
#include <omp.h>

//Last thread of PE 0 sends its number to PE 1

main(int argc, char* argv[]){

   int provided, myPE, thread, last_thread, data=0, tag=0;
   MPI_Status status;

   MPI_Init_thread(&argc, &argv, MPI_THREAD_MULTIPLE, &provided);
   MPI_Comm_rank(MPI_COMM_WORLD, &myPE);

   #pragma omp parallel firstprivate(thread, data, tag, status)
   {
       thread = omp_get_thread_num();
       last_thread = omp_get_num_threads()-1;

       if ( thread==last_thread && myPE==0 )
           MPI_Send(&thread, 1, MPI_INT, 1, tag, MPI_COMM_WORLD);
       else if ( thread==last_thread && myPE==1 )
           MPI_Recv(&data, 1, MPI_INT, 0, tag, MPI_COMM_WORLD, &status);

       printf("PE %d, Thread %d, Data %d\n", myPE, thread, data);
   }

   MPI_Finalize();
}
```

```
% export OMP_NUM_THREADS=4
% aprun -n3 -N1 -d4 a.out
PE 0, Thread 0, Data 0
PE 1, Thread 0, Data 0
PE 2, Thread 0, Data 0
PE 2, Thread 3, Data 0
PE 0, Thread 3, Data 0
PE 1, Thread 3, Data 3
PE 0, Thread 2, Data 0
PE 2, Thread 2, Data 0
PE 1, Thread 2, Data 0
PE 0, Thread 1, Data 0
PE 1, Thread 1, Data 0
PE 2, Thread 1, Data 0
```

Output for 4 threads run on 3 PEs

Mix and Match

- PGI Compile:
  ```
  mpicc -acc laplace_hybrid.c
  mpf90 -acc laplace_hybrid.f90
  mpicc -mp -acc laplace_hybrid.c
  etc…
  ```

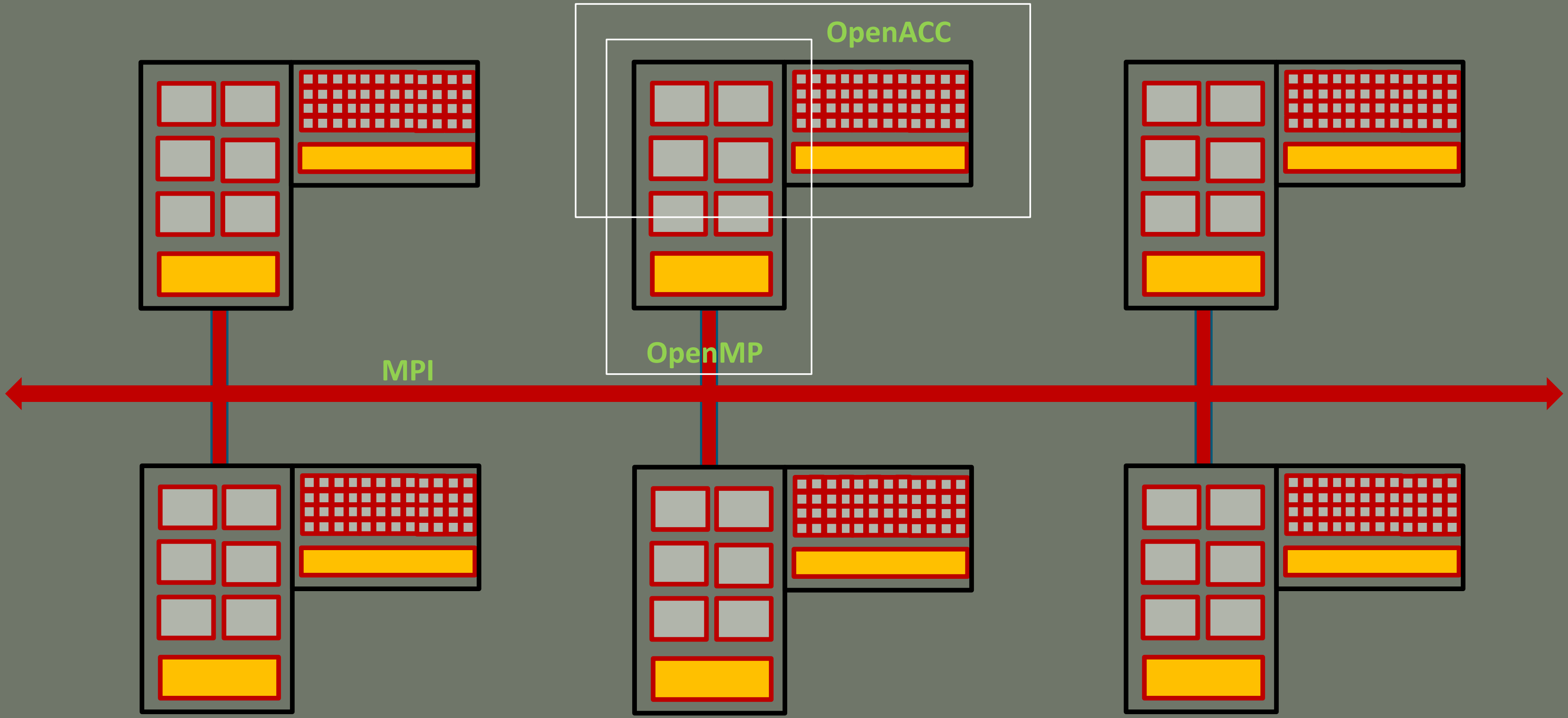
- Running:
  ```
  interact ?
       -n 4
       -N1 -n4
       -p GPU -N1 -n4
       -p GPU -N4 -n4
       -N1 -n28
       -N4 -n112
       etc…
  ```

- Intel bonus detail:
  ```
  export I_MPI_PIN_DOMAIN=omp     (or you may not actually get multiple cores!)
  Details at https://software.intel.com/en-us/articles/hybrid-applications-intelmpi-openmp
  ```

Bottom Line…

- Each one of these approaches occupies its own space.
- If you understand this, you will not be confused as to how they fit together.
- Once again…

In Conclusion…


OpenACC
OpenMP
MPI