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MODULE FIVE:
DATA MANAGEMENT

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OpenACC
More Science, Less Programming

lrz

MODULE OVERVIEW

OpenACC Data Management

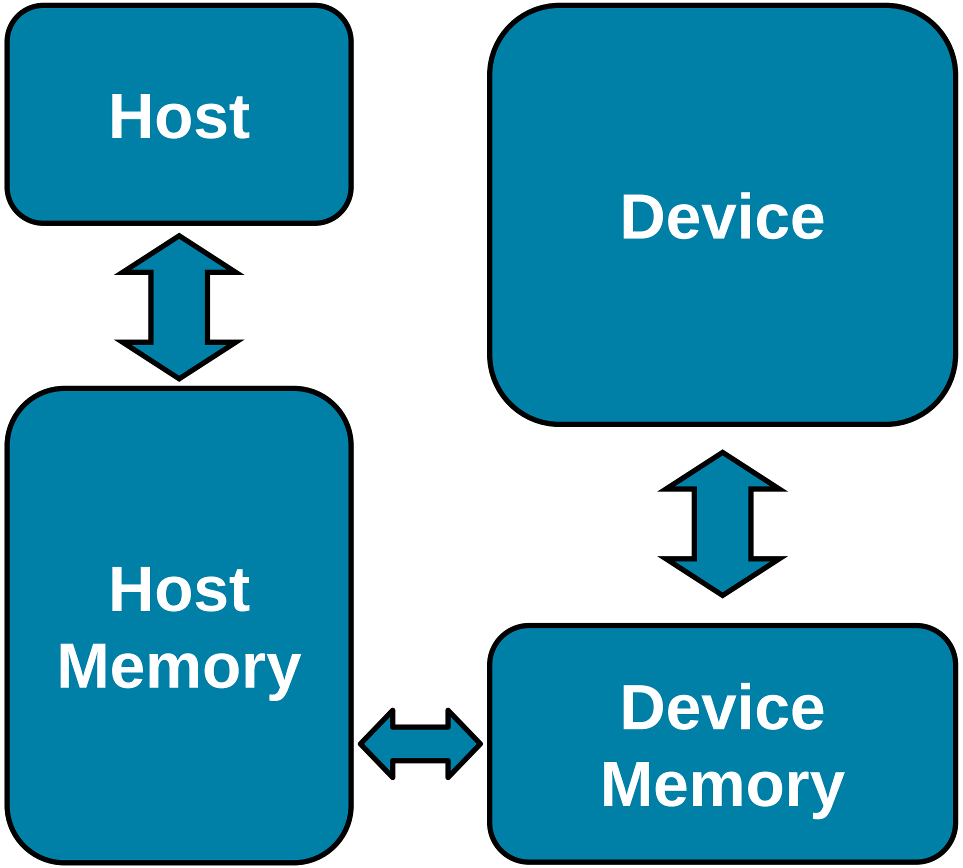
- Explicit Data Management
- OpenACC Data Regions and Clauses
- Unstructured Data Lifetimes
- Data Synchronization

EXPLICIT MEMORY MANAGEMENT

EXPLICIT MEMORY MANAGEMENT

Requirements

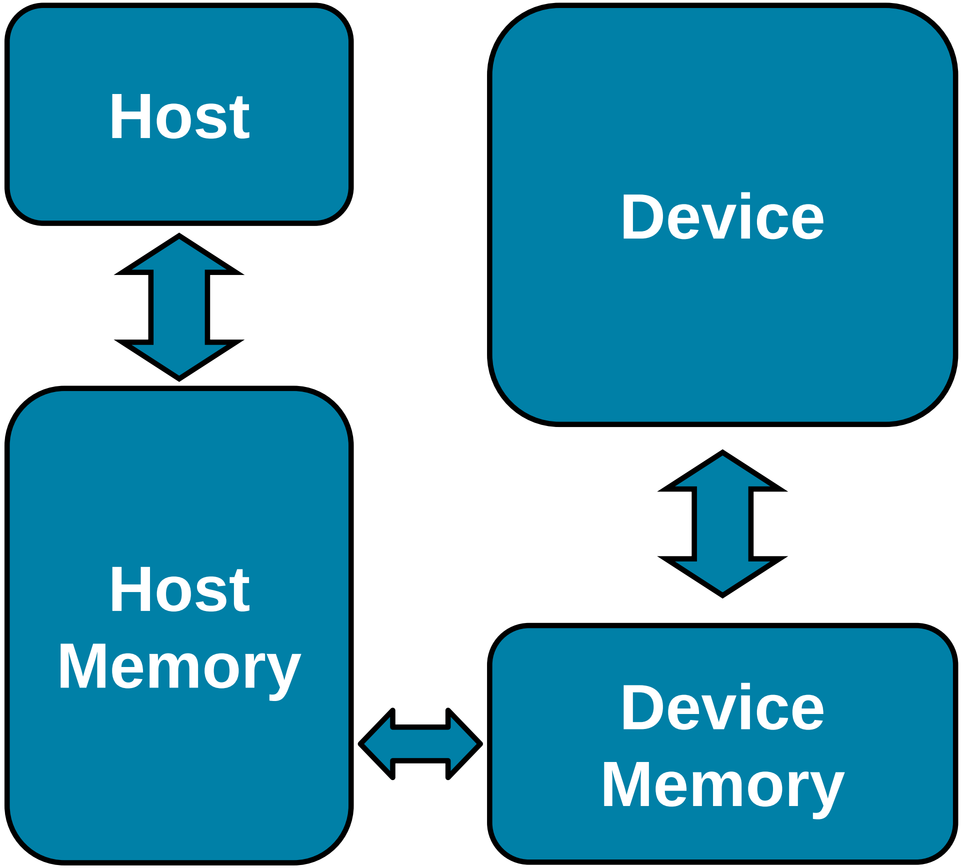
- Data must be visible on the **device** when we run our **parallel** code
- Data must be visible on the **host** when we run our **sequential** code
- When the host and device don’t share memory, data movement must occur
- To maximize performance, the programmer should avoid all unnecessary data transfers



EXPLICIT MEMORY MANAGEMENT

Key problems

- Many parallel accelerators (such as devices) have a separate memory space from the host
- These separate memories can become out-of-sync and contain completely different data
- Transferring between these two memories can be a very time consuming process



OPENACC DATA DIRECTIVE

OPENACC DATA DIRECTIVE

Definition

- The data directive defines a lifetime for data on the device
- During the region data should be thought of as residing on the accelerator
- Data clauses allow the programmer to control the allocation and movement of data

```
#pragma acc data clauses
{

  < Sequential and/or Parallel code >

}
```

```
!$acc data clauses

  < Sequential and/or Parallel code >

!$acc end data
```

DATA CLAUSES

`copy( list )`	**Allocates memory on device and copies data from host to device when entering region and copies data to the host when exiting region.** **Principal use:** For many important data structures in your code, this is a logical default to input, modify and return the data.
`copyin( list )`	**Allocates memory on device and copies data from host to device when entering region.** **Principal use:** Think of this like an array that you would use as just an input to a subroutine.
`copyout( list )`	**Allocates memory on device and copies data to the host when exiting region.** **Principal use:** A result that isn’t overwriting the input data structure.
`create( list )`	**Allocates memory on device but does not copy.** **Principal use:** Temporary arrays.

IMPLIED DATA REGIONS

IMPLIED DATA REGIONS

Definition

- Every **kernels** and **parallel** region has an implicit data region surrounding it
- This allows data to exist solely for the duration of the region
- All data clauses usable on a **data** directive can be used on a **parallel** and **kernels** as well

```
#pragma acc kernels copyin(a[0:100])
{
  for( int i = 0; i < 100; i++ )
  {
    a[i] = 0;
  }
}
```

IMPLIED DATA REGIONS

Explicit vs Implicit Data Regions

Explicit

```
#pragma acc data copyin(a[0:100])
{
  #pragma acc kernels
  {
    for( int i = 0; i < 100; i++ )
    {
      a[i] = 0;
    }
  }
}
```

Implicit

```
#pragma acc kernels copyin(a[0:100])
{
  for( int i = 0; i < 100; i++ )
  {
    a[i] = 0;
  }
}
```

These two codes are functionally the same.

OpenACC
More Science, Less Programming

EXPLICIT VS. IMPLICIT DATA REGIONS

Limitation

Explicit — **1 Data Copy**

```
#pragma acc data copyout(a[0:100])
{

   #pragma acc kernels
   {
      a[i] = i;
   }

   #pragma acc kernels
   {
      a[i] = 2 * a[i];
   }

}
```

Implicit — **2 Data Copies**

```
   #pragma acc kernels copyout(a[0:100])
   {
      a[i] = i;
   }

   #pragma acc kernels copy(a[0:100])
   {
      a[i] = 2 * a[i];
   }
```

The code on the left will perform better than the code on the right.

UNSTRUCTURED DATA DIRECTIVES

UNSTRUCTURED DATA DIRECTIVES

Enter Data Directive

- Data lifetimes aren't always neatly structured.
- The **enter data** directive handles device memory **allocation**
- You may use either the **create** or the **copyin** clause for memory allocation
- The enter data directive is **not** the start of a data region, because you may have multiple enter data directives

```
#pragma acc enter data clauses

  < Sequential and/or Parallel code >

#pragma acc exit data clauses
```

```
!$acc enter data clauses

  < Sequential and/or Parallel code >

!$acc exit data clauses
```

UNSTRUCTURED DATA DIRECTIVES

Exit Data Directive

- The **exit data** directive handles device memory **deallocation**
- You may use either the **delete** or the **copyout** clause for memory deallocation
- You should have as many **exit data** for a given array as **enter data**
- These can exist in different functions

```
#pragma acc enter data clauses

  < Sequential and/or Parallel code >

#pragma acc exit data clauses
```

```
!$acc enter data clauses

  < Sequential and/or Parallel code >

!$acc exit data clauses
```

UNSTRUCTURED DATA CLAUSES

`copyin (` *`list`* `)`	Allocates memory on device and copies data from host to device on enter data.
`copyout (` *`list`* `)`	Allocates memory on device and copies data back to the host on exit data.
`create (` *`list`* `)`	Allocates memory on device without data transfer on enter data.
`delete (` *`list`* `)`	Deallocates memory on device without data transfer on exit data

UNSTRUCTURED DATA DIRECTIVES

Basic Example

```
#pragma acc parallel loop
for(int i = 0; i < N; i++){
  c[i] = a[i] + b[i];
}
```

UNSTRUCTURED DATA DIRECTIVES

Basic Example

```
#pragma acc enter data copyin(a[0:N],b[0:N]) create(c[0:N])

  #pragma acc parallel loop
  for(int i = 0; i < N; i++){
    c[i] = a[i] + b[i];
  }

#pragma acc exit data copyout(c[0:N])
```

UNSTRUCTURED DATA DIRECTIVES

Basic Example

```
#pragma acc enter data copyin(a[0:N],b[0:N]) create(c[0:N])

  #pragma acc parallel loop
  for(int i = 0; i < N; i++){
    c[i] = a[i] + b[i];
  }

#pragma acc exit data copyout(c[0:N])
```

Action

[illegible]

UNSTRUCTURED DATA DIRECTIVES

Basic Example – proper memory deallocation

```
#pragma acc enter data copyin(a[0:N],b[0:N]) create(c[0:N])

  #pragma acc parallel loop
  for(int i = 0; i < N; i++){
    c[i] = a[i] + b[i];
  }

#pragma acc exit data copyout(c[0:N]) delete(a,b)
```

Action

Deallocate A B
from
device

CPU MEMORY **device MEMORY**

UNSTRUCTURED VS STRUCTURED

With a simple code

Unstructured

- Can have multiple starting/ending points
- Can branch across multiple functions
- Memory exists until explicitly deallocated

```
#pragma acc enter data copyin(a[0:N],b[0:N]) \
  create(c[0:N])

  #pragma acc parallel loop
  for(int i = 0; i < N; i++){
    c[i] = a[i] + b[i];
  }

#pragma acc exit data copyout(c[0:N]) \
  delete(a,b)
```

Structured

- Must have explicit start/end points
- Must be within a single function
- Memory only exists within the data region

```
#pragma acc data copyin(a[0:N],b[0:N]) \
  copyout(c[0:N])
{
  #pragma acc parallel loop
  for(int i = 0; i < N; i++){
    c[i] = a[i] + b[i];
  }

}
```

UNSTRUCTURED DATA DIRECTIVES

Branching across multiple functions

```
int* allocate_array(int N){
  int* ptr = (int *) malloc(N * sizeof(int));
  #pragma acc enter data create(ptr[0:N])
  return ptr;
}

void deallocate_array(int* ptr){
  #pragma acc exit data delete(ptr)
  free(ptr);
}

int main(){
  int* a = allocate_array(100);
  #pragma acc kernels
  {
    a[0] = 0;
  }
  deallocate_array(a);
}
```

- In this example enter data and exit data are in different functions
- This allows the programmer to put device allocation/deallocation with the matching host versions
- This pattern is particularly useful in C++, where structured scopes may not be possible.

PLEASE START LAB NOW!

DATA SYNCHRONIZATION

OPENACC UPDATE DIRECTIVE

update: Explicitly transfers data between the host and the device

Useful when you want to synchronize data in the middle of a data region

Clauses:

- **self:** makes host data agree with device data
- **device:** makes device data agree with host data

```
#pragma acc update self(x[0:count])
#pragma acc update device(x[0:count])
```

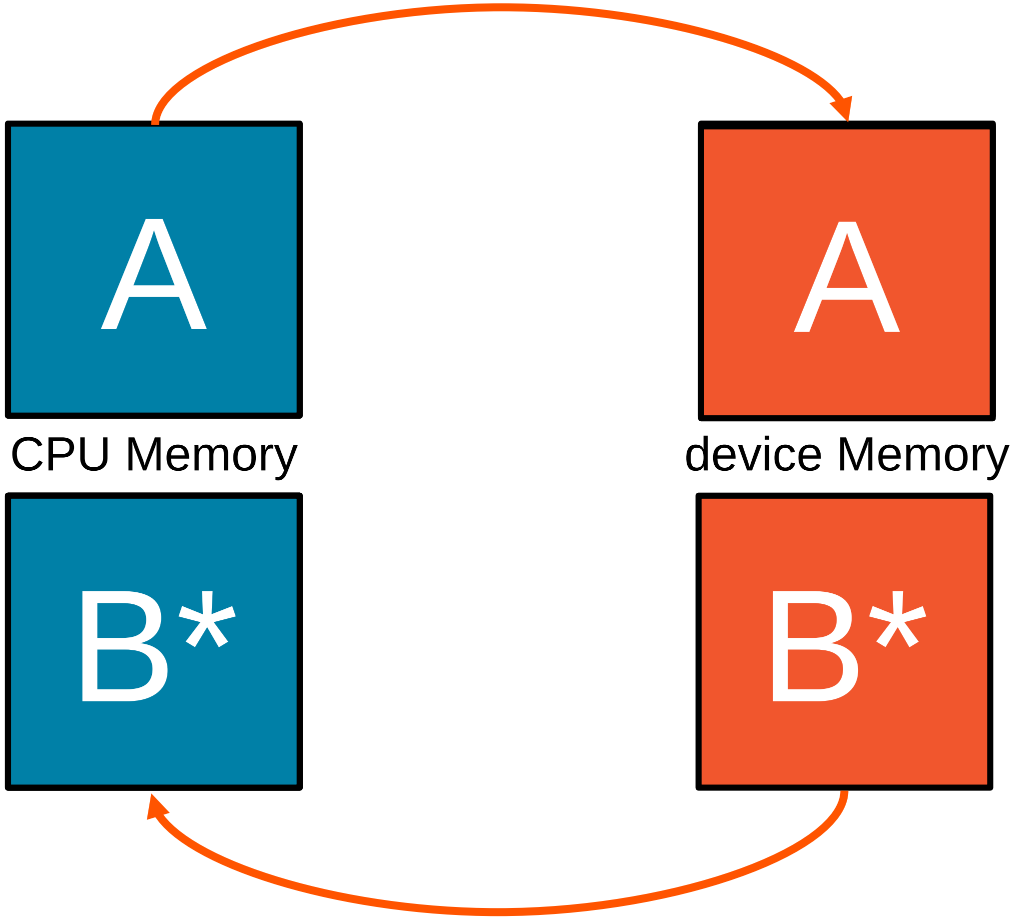
C/C++

```
!$acc update self(x(1:end_index))
!$acc update device(x(1:end_index))
```

Fortran

OPENACC UPDATE DIRECTIVE

The data must exist on both the CPU and device for the update directive to work.



`#pragma acc update device(A[0:N])`

A

CPU Memory

B*

A

device Memory

B*

`#pragma acc update self(A[0:N])`

SYNCHRONIZE DATA WITH UPDATE

```
int* allocate_array(int N){
  int* A=(int*) malloc(N*sizeof(int));
  #pragma acc enter data create(A[0:N])
  return A;
}

void deallocate_array(int* A){
  #pragma acc exit data delete(A)
  free(A);
}

void initialize_array(int* A, int N){
  for(int i = 0; i < N; i++){
    A[i] = i;
  }
  #pragma acc update device(A[0:N])
}
```

- Inside the **initialize** function we alter the host copy of **‘A’**
- This means that after calling **initialize** the host and device copy of **‘A’** are out-of-sync
- We use the **update** directive with the **device** clause to update the device copy of **‘A’**
- Without the **update** directive later compute regions will use incorrect data.

COPYING DATA IN DATA REGIONS

```
#pragma acc enter data copyin(A[:m*n],Anew[:m*n])
#pragma acc parallel loop copy(A,Anew)
for( int j = 1; j < n-1; j++)
```

- But wouldn't this code now result in my arrays being copied twice, once by the `data` region and then again by the `parallel loop`? In fact, the OpenACC runtime is smart enough to handle exactly this case. Data will be copied _in_ only the first time its encountered in a data clause and _out_ only the last time its encountered in a data clause. This allows you to create fully-working directives within your functions and then later _"hoist"_ the data movement to a higher level without changing your code at all. This is part of incrementally accelerating your code to avoid incorrect results.

C/C++ STRUCTS/CLASSES

C STRUCTS

Without dynamic data members

- Dynamic data members are anything contained within a struct that can have a **variable size**, such as dynamically allocated arrays
- OpenACC is easily able to copy our struct to device memory because everything in our float3 struct has a **fixed size**
- But what if the struct had dynamically allocated members?

```
typedef struct {
  float x, y, z;
} float3;

int main(int argc, char* argv[]){
  int N = 10;
  float3* f3 = malloc(N * sizeof(float3));

  #pragma acc enter data create(f3[0:N])

  #pragma acc kernels
  for(int i = 0; i < N; i++){
    f3[i].x = 0.0f;
    f3[i].y = 0.0f;
    f3[i].z = 0.0f;
  }

  #pragma acc exit data delete(f3)
  free(f3);
}
```

C STRUCTS

With dynamic data members

- OpenACC does not have enough information to copy the struct and its dynamic members
- You must first copy the struct into device memory, then allocate/copy the dynamic members into device memory
- To deallocate, first deal with the dynamic members, then the struct
- OpenACC will automatically *attach* your dynamic members to the struct

```
typedef struct {
  float *arr;
  int n;
} vector;

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

  vector v;
  v.n = 10;
  v.arr = (float*) malloc(v.n*sizeof(float));

  #pragma acc enter data copyin(v)
  #pragma acc enter data create(v.arr[0:v.n])

  ...

  #pragma acc exit data delete(v.arr)
  #pragma acc exit data delete(v)
  free(v.arr);
}
```

C++ STRUCTS/CLASSES

With dynamic data members

- C++ Structs/Classes work the same exact way as they do in C
- The main difference is that now we have to account for the implicit “this” pointer

```
class vector {
  private:
    float *arr;
    int n;
  public:
    vector(int size){
      n = size;
      arr = new float[n];
      #pragma acc enter data copyin(this)
      #pragma acc enter data create(arr[0:n])
    }
    ~vector(){
      #pragma acc exit data delete(arr)
      #pragma acc exit data delete(this)
      delete(arr);
    }
};
```

MODULE REVIEW

KEY CONCEPTS

In this module we discussed…

- Why explicit data management is necessary for best performance
- Structured and Unstructured Data Lifetimes
- Explicit and Implicit Data Regions
- The **data**, **enter data**, **exit data**, and **update** directives
- Data Clauses

LAB ASSIGNMENT

In this module's lab you will…

- Update the code from the previous module to use explicit data directives
- Analyze the different between using CUDA Managed Memory and explicit data management in the lab code.