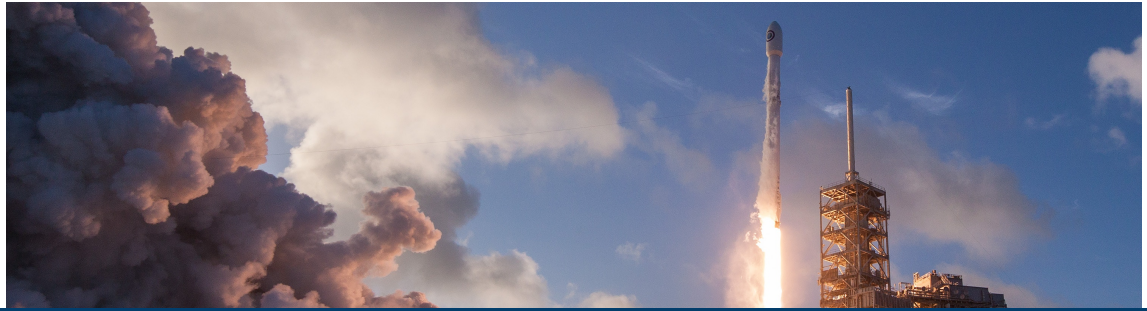

PRODUCTIVE GPU PROGRAMMING WITH OPENACC
GSP GPU COURSE 2018

9 August 2018 | Andreas Herten | Forschungszentrum Jülich, Jülich Supercomputing Centre

Member of the Helmholtz Association

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Overview, Outline

What you will learn today

- Parallelization strategies with OpenACC
- OpenACC on CPU, GPU

What you will not learn today

- Analyze program in-detail
- Strategies for complex programs
- How to leave the matrix

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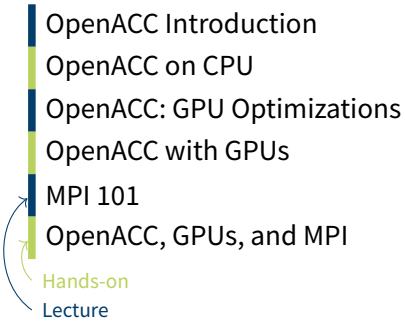

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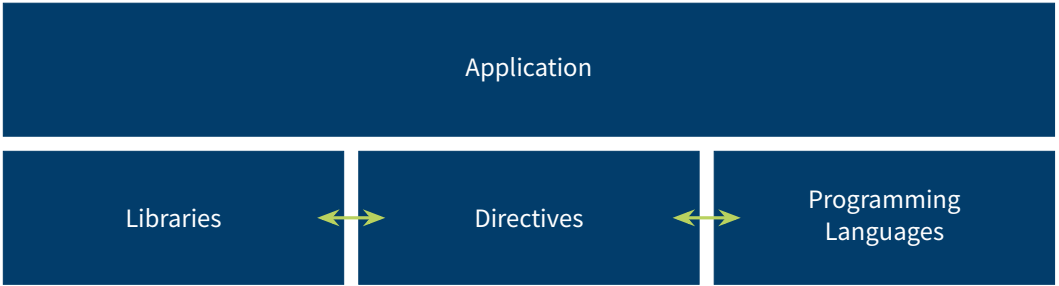
OpenACC Introduction

Primer on GPU Computing

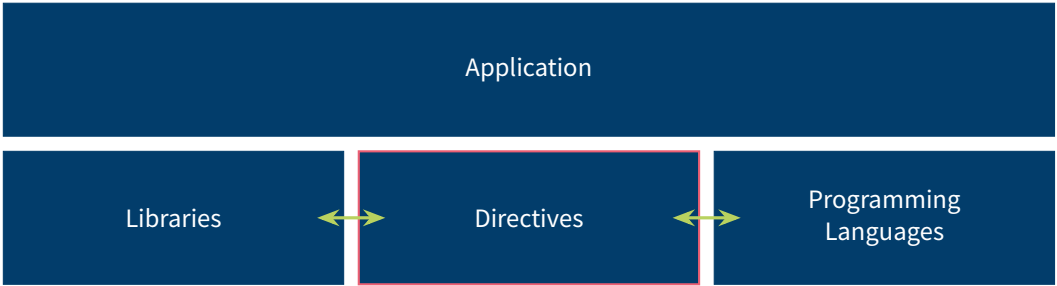


Drop-in Acceleration

Easy Acceleration

Flexible Acceleration

Primer on GPU Computing



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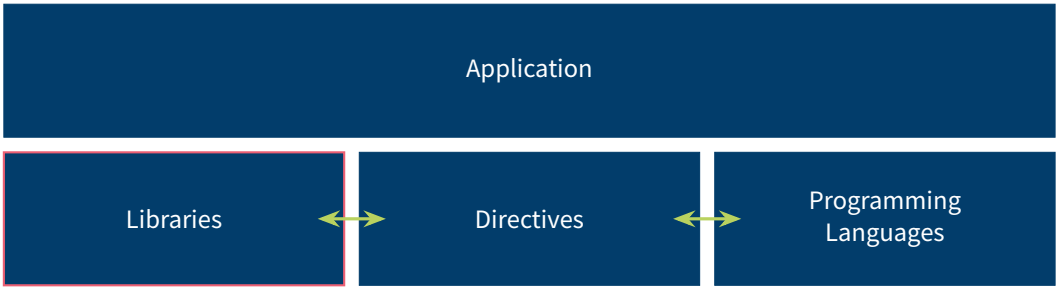

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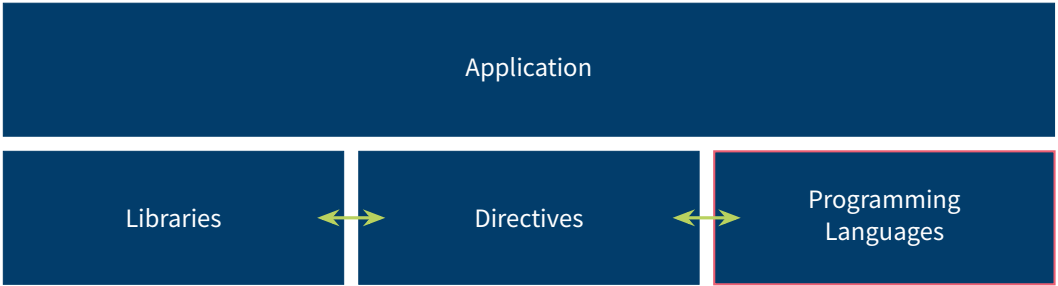
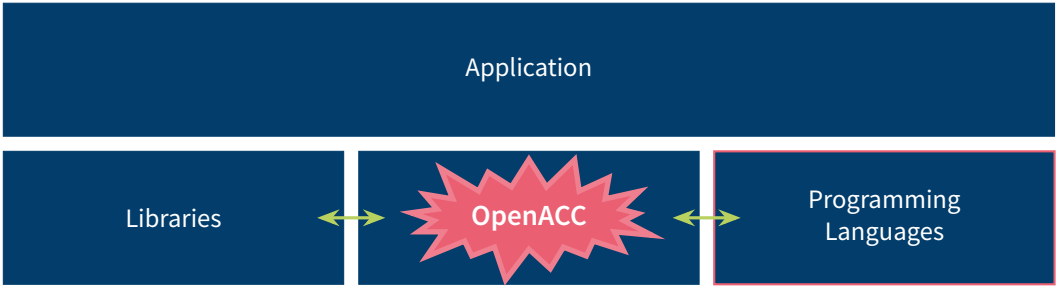


Primer on GPU Computing



About OpenACC

History

2011 OpenACC 1.0 specification is released
NVIDIA, Cray, PGI, CAPS

2013 OpenACC 2.0: More functionality, portability

2015 OpenACC 2.5: Enhancements, clarifications

2017 OpenACC 2.6: Deep copy, …

→ `https://www.openacc.org/` (*see also: Best practice guide*)

Support

- Compiler: PGI, GCC, Cray, *Sunway*
- Languages: C/C++, Fortran

Open{MP↔ACC}

Everything's connected

- OpenACC modeled after OpenMP …
- … but specific for accelerators
- Might eventually be absorbed into OpenMP

  But OpenMP >4.0 also has offloading feature
- OpenACC more descriptive, OpenMP more prescriptive
- Basic principle same: Fork/join model

  Master thread launches parallel child threads; merge after execution

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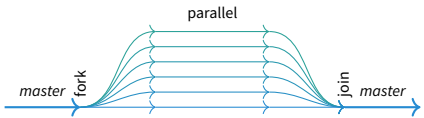

OpenMP

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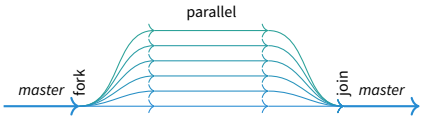
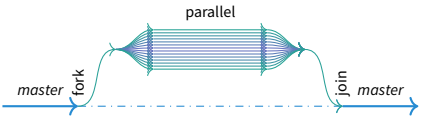


OpenMP



OpenACC

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Modus Operandi

Three-step program

1. Annotate code with directives, indicating parallelism
2. OpenACC-capable compiler generates accelerator-specific code
3. $success

1 Directives

pragmatic

- Compiler directives state intend to compiler

C/C++

```
#pragma acc kernels
for (int i = 0; i < 23; i++)
// ...
```

Fortran

```
!$acc kernels
do i = 1, 24
! ...
!$acc end kernels
```

- Ignored by compiler which does not understand OpenACC
- High level programming model for many-core machines, especially accelerators
- OpenACC: Compiler directives, library routines, environment variables
- Portable across host systems and accelerator architectures

2 Compiler

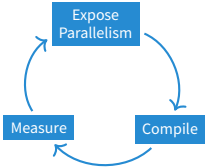
Simple and abstracted

- Compiler support
  - PGI *Best performance, great support, free*
  - GCC *Beta, limited coverage, OSS*
  - Cray *???*
- Trust compiler to generate intended parallelism; always check status output!
- No need to know ins'n'outs of accelerator; leave it to expert compiler engineers*
- One code can target different accelerators: GPUs, or even multi-core CPUs → **Portability**

*: *Eventually you want to tune for device; but that's possible*

3 $success

Iteration is key



- Serial to parallel: fast
- Serial to fast parallel: more time needed
- Start simple $\rightarrow$ refine

$\Rightarrow$ **Productivity**

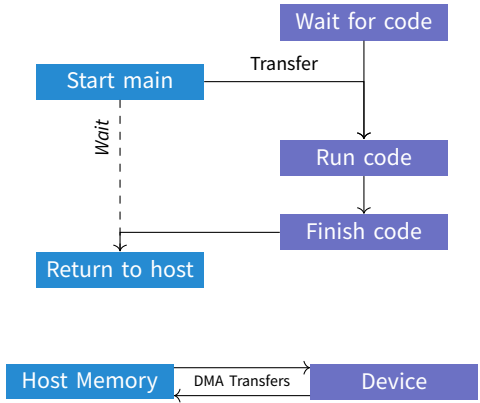
- Because of *generalness*: Sometimes not last bit of hardware performance accessible
- But: Use OpenACC together with other accelerator-targeting techniques (CUDA, libraries, …)

OpenACC Accelerator Model

For computation and memory spaces

- Main program executes on host
- Device code is transferred to accelerator
- Execution on accelerator is started
- Host waits until return (except: async)

- Two separate memory spaces; data transfers back and forth
  - Transfers hidden from programmer
  - Memories not coherent!
  - Compiler helps; GPU runtime helps



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OpenACC Programming Model

A binary perspective

- OpenACC interpretation needs to be activated as compile flag

  PGI `pgcc -acc [-ta=tesla|-ta=multicore]`

  GCC `gcc -fopenacc`

  → Ignored by incapable compiler!

- Additional flags possible to improve/modify compilation

  `-ta=tesla:cc60` Use compute capability 6.0

  `-ta=tesla:lineinfo` Add source code correlation into binary

  `-ta=tesla:managed` Use unified memory

  `-fopenacc-dim=geom` Use *geom* configuration for threads

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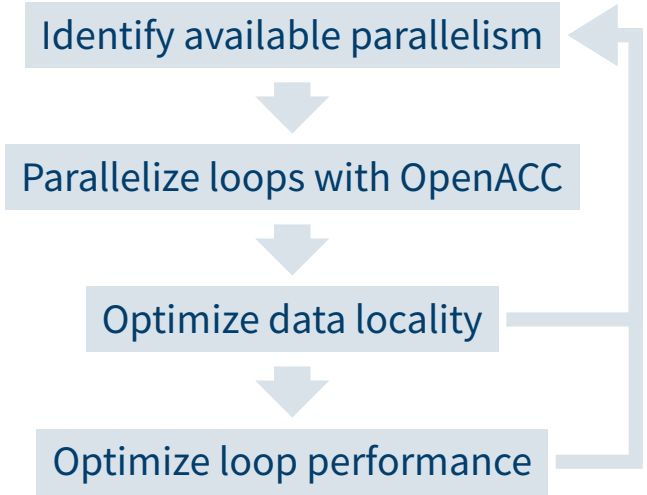
A Glimpse of OpenACC

```
#pragma acc data copy(x[0:N],y[0:N])
#pragma acc parallel loop
{
    for (int i=0; i<N; i++) {
        x[i] = 1.0;
        y[i] = 2.0;
    }
    for (int i=0; i<N; i++) {
        y[i] = i*x[i]+y[i];
    }
}
```

Parallelization Workflow

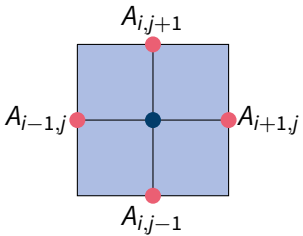


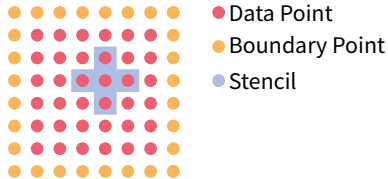
First Steps in OpenACC

Jacobi Solver

Algorithmic description

- Example for acceleration: **Jacobi solver**
- Iterative solver, converges to correct value
- Each iteration step: compute average of neighboring points
- Example: 2D Poisson equation: $\nabla^2 A(x,y) = B(x,y)$





$$A_{k+1}(i,j) = -\frac{1}{4}\left(B(i,j) - (A_k(i-1,j) + A_k(i,j+1), +A_k(i+1,j) + A_k(i,j-1))\right)$$

Jacobi Solver

Source code

```
while ( error > tol && iter < iter_max ) {
    error = 0.0;
    for (int ix = ix_start; ix < ix_end; ix++) {
        for (int iy = iy_start; iy < iy_end; iy++) {
            Anew[iy*nx+ix] = -0.25 * (rhs[iy*nx+ix] -
                (  A[iy*nx+ix+1] + A[iy*nx+ix-1]
                 + A[(iy-1)*nx+ix] + A[(iy+1)*nx+ix]));
            error = fmaxr(error, fabsr(Anew[iy*nx+ix]-A[iy*nx+ix]));
    }}
    for (int iy = iy_start; iy < iy_end; iy++) {
        for( int ix = ix_start; ix < ix_end; ix++ ) {
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    }}
    for (int ix = ix_start; ix < ix_end; ix++) {
            A[0*nx+ix]      = A[(ny-2)*nx+ix];
            A[(ny-1)*nx+ix] = A[1*nx+ix];
    }
    // same for iy
    iter++;
}
```


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Iterate until converged

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Jacobi Solver

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Iterate until converged

Iterate across matrix elements

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Jacobi Solver

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Iterate until converged

Iterate across matrix elements

Calculate new value from neighbors

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Jacobi Solver

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Iterate until converged

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Calculate new value from neighbors

Accumulate error

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Jacobi Solver

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Iterate until converged

Iterate across matrix elements

Calculate new value from neighbors

Accumulate error

Swap input/output

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Jacobi Solver

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Iterate until converged

Iterate across matrix elements

Calculate new value from neighbors

Accumulate error

Swap input/output

Set boundary conditions

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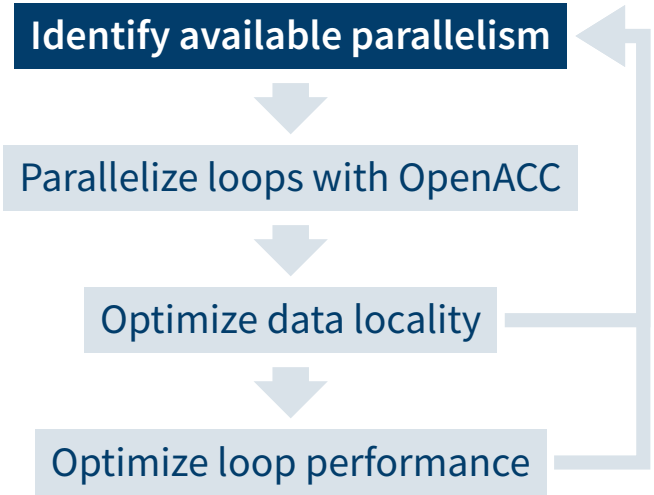
Parallelization Workflow



Profiling

*Pro*file

> *[…] premature optimization is the root of all evil.*
>
> *– Donald Knuth [2]*

- Investigate hot spots of your program!

→ Profile!

- Many tools, many levels: perf, PAPI, Score-P, Intel Advisor, NVIDIA Visual Profiler, …
- Here: Examples from PGI

Profiling

Profile

> *[…] premature optimization is the root of all evil.*
> ***Yet we should not pass up our [optimization] opportunities […]***
> *– Donald Knuth [2]*

- Investigate hot spots of your program!

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- Many tools, many levels: perf, PAPI, Score-P, Intel Advisor, NVIDIA Visual Profiler, …
- Here: Examples from PGI

Profile of Application

Info during compilation

```
$ pgcc -DUSE_DOUBLE -Minfo=all,intensity -fast -Minfo=ccff -Mprof=ccff
poisson2d_reference.o poisson2d.c -o poisson2d
poisson2d.c:
main:
     68, Generated vector simd code for the loop
         FMA (fused multiply-add) instruction(s) generated
     98, FMA (fused multiply-add) instruction(s) generated
    105, Loop not vectorized: data dependency
    123, Loop not fused: different loop trip count
         Loop not vectorized: data dependency
         Loop unrolled 8 times
```

- Automated optimization of compiler, due to `-fast`
- Vectorization, FMA, unrolling

Profile of Application

Info during run

```
$ pgprof --cpu-profiling on [...] ./poisson2d
======== CPU profiling result (flat):
Time(%)      Time  Name
 77.52%  999.99ms  main (poisson2d.c:148 0x6d8)
  9.30%     120ms  main (0x704)
  7.75%  99.999ms  main (0x718)
  0.78%  9.9999ms  main (poisson2d.c:128 0x348)
  0.78%  9.9999ms  main (poisson2d.c:123 0x398)
  0.78%  9.9999ms  __xlmass_expd2 (0xffcc011c)
  0.78%  9.9999ms  __c_mcopy8 (0xffcc0054)
  0.78%  9.9999ms  __xlmass_expd2 (0xffcc0034)
======== Data collected at 100Hz frequency
```

- 78 % in `main()`
- Since everything is in `main` – limited helpfulness
- Let's look into `main`!

Code Independency Analysis

Independence is key

```
while ( error > tol && iter < iter_max ) {
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    }}
    for (int iy = iy_start; iy < iy_end; iy++) {
        for( int ix = ix_start; ix < ix_end; ix++ ) {
            A[iy*nx+ix] = Anew[iy*nx+ix];
    }}
    for (int ix = ix_start; ix < ix_end; ix++) {
            A[0*nx+ix]      = A[(ny-2)*nx+ix];
            A[(ny-1)*nx+ix] = A[1*nx+ix];
    }
    // same for iy
    iter++;
}
```

Data dependency between iterations

Independent loop iterations

Independent loop iterations

Independent loop iterations

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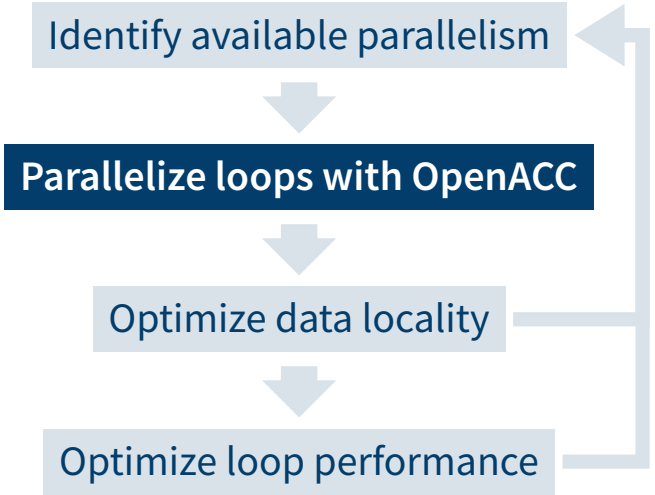
Parallelization Workflow



Parallel Loops: Parallel

Maybe the second most important directive

- Programmer identifies block containing parallelism
  $\rightarrow$ compiler generates parallel code (*kernel*)
- Program launch creates *gangs* of parallel threads on parallel device
- Implicit barrier at end of parallel region
- Each gang executes same code sequentially

OpenACC: `parallel`

```
#pragma acc parallel [clause, [, clause] ...] newline
{structured block}
```

Parallel Loops: Parallel

Clauses

Diverse clauses to augment the parallel region

`private(var)`	A copy of variables `var` is made for each gang
`firstprivate(var)`	Same as `private`, except `var` will initialized with value from host
`if(cond)`	Parallel region will execute on accelerator only if `cond` is true
`reduction(op:var)`	Reduction is performed on variable `var` with operation `op`; supported: `+ * max min …`
`async[(int)]`	No implicit barrier at end of parallel region

Parallel Loops: Loops

Maybe the third most important directive

- Programmer identifies loop eligible for parallelization
- Directive must be directly before loop
- Optional: Describe type of parallelism

OpenACC: `loop`

```
#pragma acc loop [clause, [, clause] ...] newline
{structured block}
```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Parallel Loops: Loops

Clauses

`independent`	Iterations of loop are data-independent (implied if in `parallel` region (and no `seq` or `auto`))
`collapse(int)`	Collapse `int` tightly-nested loops
`seq`	This loop is to be executed sequentially (not parallel)
`tile(int[,int])`	Split loops into loops over tiles of the full size
`auto`	Compiler decides what to do

Parallel Loops: Parallel Loops

Maybe the most important directive

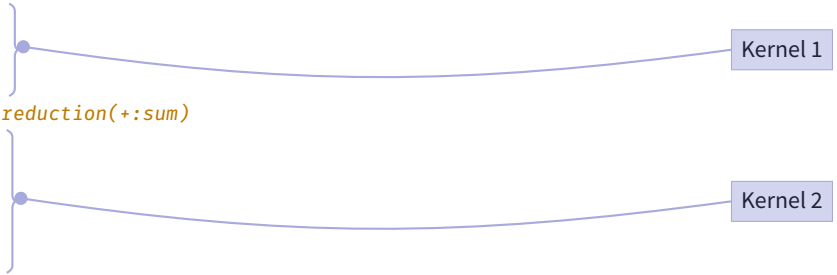
- Combined directive: shortcut
  Because its used so often
- Any clause that is allowed on `parallel` or `loop` allowed
- Restriction: May not appear in body of another parallel region

OpenACC: `parallel loop`

```
#pragma acc parallel loop [clause, [, clause] ...]
```

Parallel Loops Example

```
double sum = 0.0;
#pragma acc parallel loop
for (int i=0; i<N; i++) {
    x[i] = 1.0;
    y[i] = 2.0;
}
#pragma acc parallel loop reduction(+:sum)
{
for (int i=0; i<N; i++) {
    y[i] = i*x[i]+y[i];
    sum+=y[i];
}
}
```



Parallel Jacobi

TASK 2

Add parallelism

- Add OpenACC parallelism to main loop in Jacobi solver source code (CPU parallelism)

→ Congratulations, you are a parallel developer!

Task 2: A First Parallel Loop

- Change to `Task2/` directory
- Compile: `make`; see `README.md`
- Submit run to the batch system: `make run`
  Adapt the `bsub` call and run with other number of iterations, matrix sizes
- Change number of CPU threads via `$ACC_NUM_CORES` or `$OMP_NUM_THREADS`

? What's your speed-up? What's the best configuration for cores?

E Compare it to OpenMP

Parallel Jacobi

Source Code

```
110   #pragma acc parallel loop reduction(max:error)
111   for (int ix = ix_start; ix < ix_end; ix++)
112   {
113     for (int iy = iy_start; iy < iy_end; iy++)
114       {
115         Anew[iy*nx+ix] = -0.25 * (rhs[iy*nx+ix] - ( A[iy*nx+ix+1] + A[iy*nx+ix-1]
116                                                   + A[(iy-1)*nx+ix] +
                                                      ↪  A[(iy+1)*nx+ix] ));
117           error = fmaxr( error, fabsr(Anew[iy*nx+ix]-A[iy*nx+ix]));
118       }
119   }
```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Parallel Jacobi

Compilation result

```
$ make
pgcc -DUSE_DOUBLE -Minfo=accel -fast -acc -ta=multicore poisson2d.c poisson2d_reference.o
  -o poisson2d
poisson2d.c:
main:
     110, Generating Multicore code
          111, #pragma acc loop gang
     110, Generating reduction(max:error)
     113, Accelerator restriction: size of the GPU copy of A,rhs,Anew is unknown
          Complex loop carried dependence of Anew-> prevents parallelization
          Loop carried dependence of Anew-> prevents parallelization
          Loop carried backward dependence of Anew-> prevents vectorization
```

Parallel Jacobi

Run result

```
$ make run
srun --partition=gpus --gres=gpu:1  ./poisson2d
Jacobi relaxation calculation: max 500 iterations on 2048 x 2048 mesh
Calculate reference solution and time with serial CPU execution.
    0, 0.249999
  100, 0.249760
  200, 0...
Calculate current execution.
    0, 0.249999
  100, 0.249760
  200, 0...
2048x2048: Ref:  60.5136 s, This:   8.2483 s, speedup:     7.34
```

Parallel Jacobi: OpenMP

E

- OpenMP pragma is quite similar

```
#pragma acc parallel loop reduction(max:error)
#pragma omp parallel for  reduction(max:error)
for (int ix = ix_start; ix < ix_end; ix++) { ... }
```

- PGI's compiler output is a bit different (but states the same)

```
$ pgcc -DUSE_DOUBLE -Minfo=mp -fast -mp poisson2d.c poisson2d_reference.o -o poisson2d
poisson2d.c:
main:
    112, Parallel region activated
         Parallel loop activated with static block schedule
    123, Parallel region terminated
         Begin critical section
         End critical section
         Barrier
```

- Run time should be very similar!

More Parallelism: Kernels

More freedom for compiler

- Kernels directive: second way to expose parallelism
- Region may contain parallelism
- Compiler determines parallelization opportunities

→ More freedom for compiler

- Rest: Same as for `parallel`

OpenACC: `kernels`

```
#pragma acc kernels [clause, [, clause] ...]
```

Kernels Example

```
double sum = 0.0;
#pragma acc kernels
{
for (int i=0; i<N; i++) {
    x[i] = 1.0;
    y[i] = 2.0;
}
for (int i=0; i<N; i++) {
    y[i] = i*x[i]+y[i];
    sum+=y[i];
}
}
```

`kernels` vs. `parallel`

- Both approaches equally valid; can perform equally well

`kernels` vs. `parallel`

- Both approaches equally valid; can perform equally well
- `kernels`
  - Compiler performs parallel analysis
  - Can cover large area of code with single directive
  - Gives compiler additional leeway
- `parallel`
  - Requires parallel analysis by programmer
  - Will also parallelize what compiler may miss
  - More explicit
  - Similar to OpenMP

`kernels` vs. `parallel`

- Both approaches equally valid; can perform equally well
- `kernels`
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  - Gives compiler additional leeway
- `parallel`
  - Requires parallel analysis by programmer
  - Will also parallelize what compiler may miss
  - More explicit
  - Similar to OpenMP
- Both regions may not contain other `kernels`/`parallel` regions
- No braunching into or out
- Program must not depend on order of evaluation of clauses
- At most: One `if` clause

OpenACC on the GPU

Changes for GPU-OpenACC

Immensely complicated changes

- Necessary for previous code to run on GPU: `-ta=tesla` instead of `-ta=multicore`

Changes for GPU-OpenACC

Immensely complicated changes

- Necessary for previous code to run on GPU: `-ta=tesla` instead of `-ta=multicore`

⇒ **That's it!**

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Changes for GPU-OpenACC

Immensely complicated changes

- Necessary for previous code to run on GPU: `-ta=tesla` instead of `-ta=multicore`

⇒ **That's it!**

- But we can optimize!

Changes for GPU-OpenACC

Immensely complicated changes

- Necessary for previous code to run on GPU: `-ta=tesla` instead of `-ta=multicore`

⇒ **That's it!**

- But we can optimize!
- First: A task

Parallel Jacobi on GPU

TASK 3

More parallelism, more corrres

- Add OpenACC parallelism to other loops of `while` (L:123 – L:141)
  Use either `kernels` or `parallel`
- Make sure to use `-ta=tesla` when compiling.

Task 3: More Parallel Loops on GPU

- Change to `Task3/` directory
- Compile: `make`
- Submit parallel run to the batch system: `make run`

? What's your speed-up?

Parallel Jacobi II

Compilation result

```
$ make
pgcc -DUSE_DOUBLE -Minfo=accel -fast -acc -ta=tesla:cc70,managed poisson2d.c poisson2d_reference.o -o poisson2d
poisson2d.c:
main:
    109, Accelerator kernel generated
         Generating Tesla code
        109, Generating reduction(max:error)
        110, #pragma acc loop gang, vector(128) /* blockIdx.x threadIdx.x */
        112, #pragma acc loop seq
    109, ...
    121, Accelerator kernel generated
         Generating Tesla code
        124, #pragma acc loop gang /* blockIdx.x */
        126, #pragma acc loop vector(128) /* threadIdx.x */
    121, Generating implicit copyin(Anew[:])
         Generating implicit copyout(A[:])
    126, Loop is parallelizable
    133, Accelerator kernel genera...
```

Parallel Jacobi II

Run result

```
$ make run
srun --partition=gpus --gres=gpu:1  ./poisson2d
Jacobi relaxation calculation: max 500 iterations on 2048 x 2048 mesh
Calculate reference solution and time with serial CPU execution.
    0, 0.249999
  100, 0.249760
  200, 0...
Calculate current execution.
    0, 0.249999
  100, 0.249760
  200, 0...
2048x2048: Ref:  40.3299 s, This:   0.3243 s, speedup:   124.36
```

Parallel Jacobi II

Run result

```
$ make run
srun --partition=gpus --gres=gpu:1  ./poisson2d
Jacobi relaxation calculation: max 500 iterations on 2048 x 2048 mesh
Calculate reference solution and time with serial CPU execution.
    0, 0.249999
  100, 0.249760
  200, 0...
Calculate current execution.
    0, 0.249999
  100, 0.249760
  200, 0...
2048x2048: Ref:  40.3299 s, This:   0.3243 s, speedup:   124.36
```

Done?!

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Parallel Jacobi

```
while ( error > tol && iter < iter_max ) {
    error = 0.0;
    #pragma acc parallel loop reduction(max:error)
    for (int ix = ix_start; ix < ix_end; ix++) {
        for (int iy = iy_start; iy < iy_end; iy++) {
            Anew[iy*nx+ix] = -0.25 * (rhs[iy*nx+ix] -
                (  A[iy*nx+ix+1] + A[iy*nx+ix-1]
                 + A[(iy-1)*nx+ix] + A[(iy+1)*nx+ix]));
            error = fmaxr(error, fabsr(Anew[iy*nx+ix]-A[iy*nx+ix]));
    }}
    #pragma acc parallel loop
    for (int iy = iy_start; iy < iy_end; iy++) {
        for( int ix = ix_start; ix < ix_end; ix++ ) {
            A[iy*nx+ix] = Anew[iy*nx+ix];
    }}
    #pragma acc parallel loop
    for (int ix = ix_start; ix < ix_end; ix++) {
            A[0*nx+ix]      = A[(ny-2)*nx+ix];
            A[(ny-1)*nx+ix] = A[1*nx+ix];
    }
    // same for iy
    iter++;
}
```


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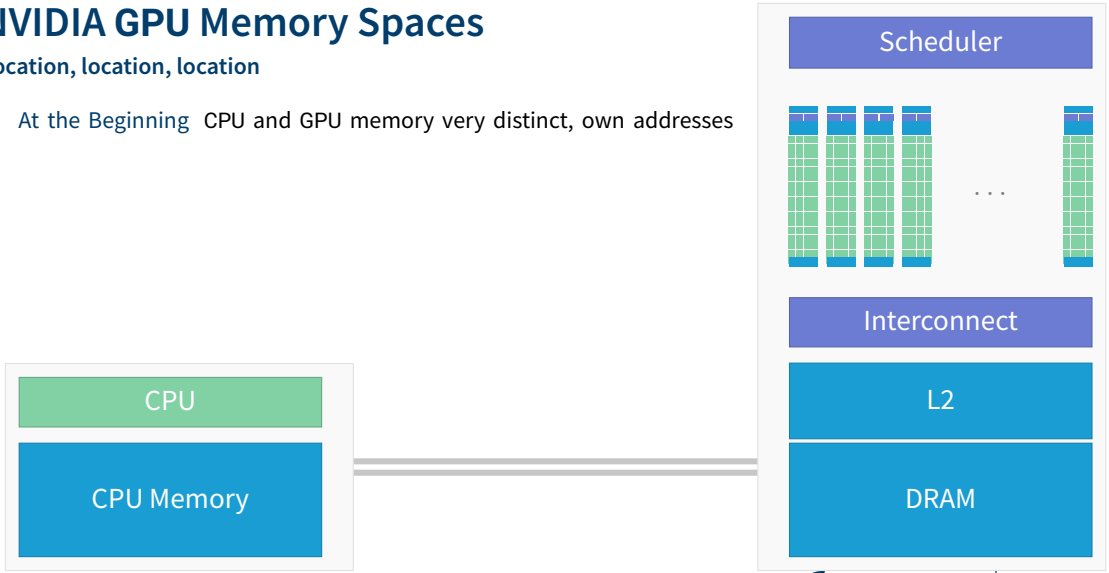
Automatic Data Transfers

- Up to now: We did not care about **data transfers**
- Compiler and runtime care
- Magic keyword: `-ta=tesla:managed`
- Only feature of (recent) NVIDIA GPUs!

NVIDIA GPU Memory Spaces

Location, location, location

At the Beginning CPU and GPU memory very distinct, own addresses

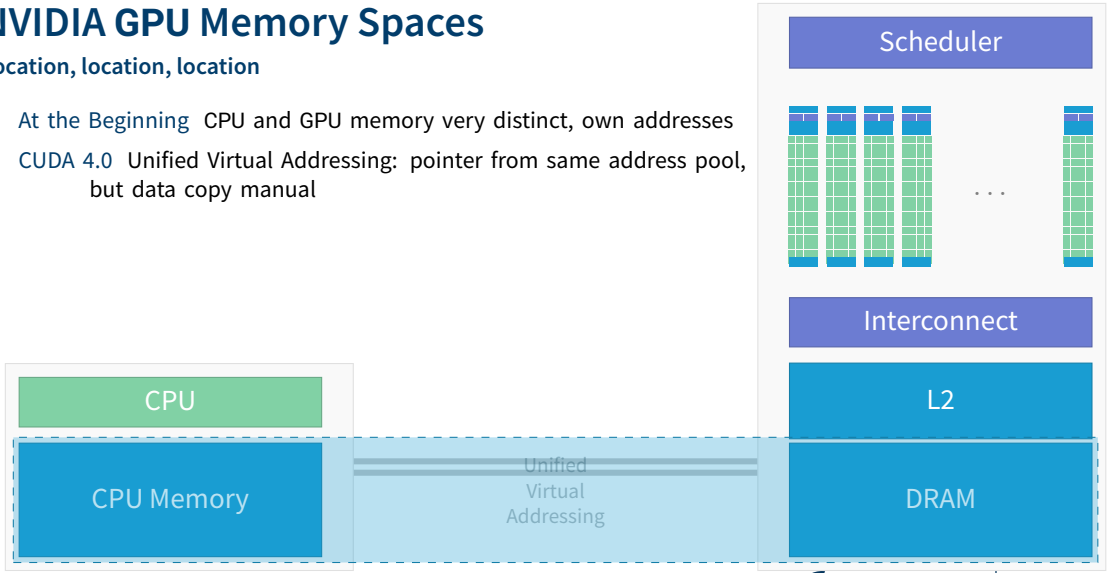


NVIDIA GPU Memory Spaces

Location, location, location

At the Beginning CPU and GPU memory very distinct, own addresses

CUDA 4.0 Unified Virtual Addressing: pointer from same address pool, but data copy manual



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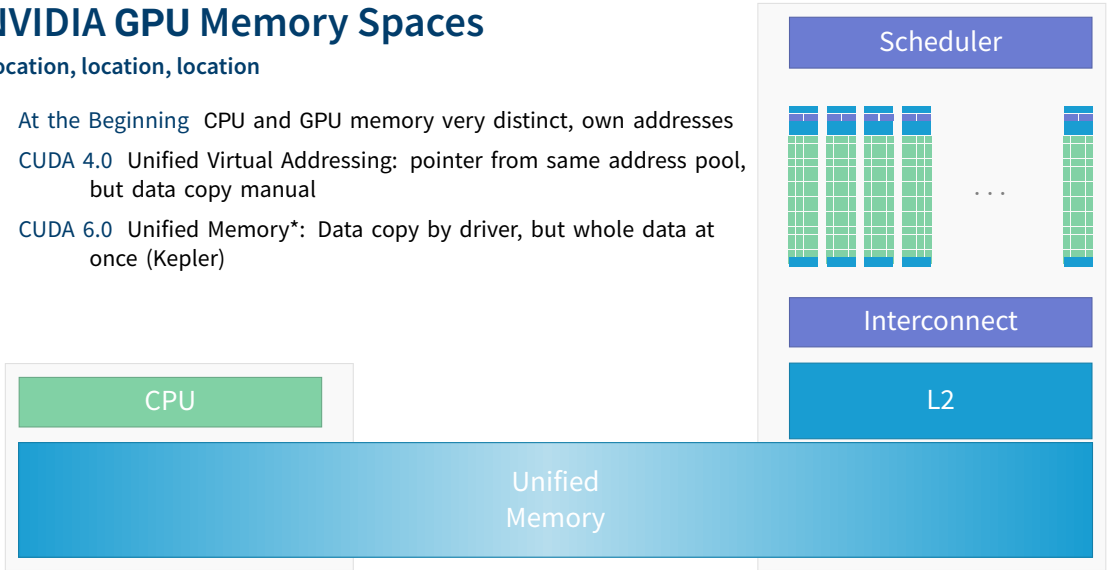
CUDA 4.0 Unified Virtual Addressing: pointer from same address pool, but data copy manual

CUDA 6.0 Unified Memory*: Data copy by driver, but whole data at once (Kepler)



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NVIDIA GPU Memory Spaces

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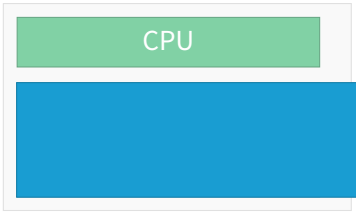
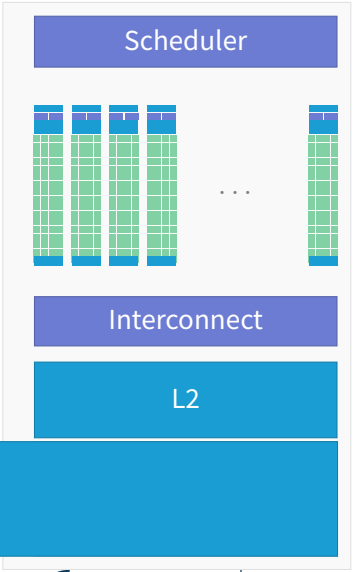
CUDA 4.0 Unified Virtual Addressing: pointer from same address pool, but data copy manual

CUDA 6.0 Unified Memory*: Data copy by driver, but whole data at once (Kepler)

CUDA 8.0 Unified Memory (truly): Data copy by driver, page faults on-demand initiate data migrations (Pascal)





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Portability

- Managed memory: Only NVIDIA GPU feature
- Great OpenACC features: Portability

→ Code should also be fast without `-ta=tesla:managed`!

- Let's remove it from compile flags!

Portability

- Managed memory: Only NVIDIA GPU feature
- Great OpenACC features: Portability

→ Code should also be fast without `-ta=tesla:managed`!

- Let's remove it from compile flags!

```
$ make
pgcc -c -DUSE_DOUBLE -Minfo=accel -fast -acc -ta=tesla:cc60
poisson2d_reference.c -o poisson2d_reference.o
poisson2d.c:
PGC-S-0155-Compiler failed to translate accelerator region
(see -Minfo messages): Could not find allocated-variable index for
symbol (poisson2d.c: 110)
...
PGC/power Linux 17.4-0: compilation completed with severe errors
```

Copy Statements

- Compiler implicitly created `copy` clauses to copy data to device

```
134, Generating implicit copyin(A[:])
     Generating implicit copyout(A[nx*(ny-1)+1:nx-2])
```

- It couldn't determine length of copied data …
- …but before: no problem – Unified Memory!

Copy Statements

- Compiler implicitly created `copy` clauses to copy data to device

```
134, Generating implicit copyin(A[:])
     Generating implicit copyout(A[nx*(ny-1)+1:nx-2])
```

- It couldn't determine length of copied data …
- …but before: no problem – Unified Memory!
- Now: Problem! We need to give that information! (see also later)

OpenACC: `copy`

```
#pragma acc parallel copy(A[start:end])
```

Also: `copyin(B[s:e])` `copyout(C[s:e])` `present(D[s:e])` `create(E[s:e])`

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Data Copies

Get that data!

TASK 4

- Add `copy` clause to parallel regions
- Check correctness with Visual Profiler

Task 4: Data Copies

- Change to `Task4/` directory
- Work on `TODO`s
- Compile: `make`
- Submit parallel run to the batch system: `make run`

? What's your speed-up?

Data Copies

Compiler Output

```
$ make
pgcc -DUSE_DOUBLE -Minfo=accel -fast -acc -ta=tesla:cc70 poisson2d.c poisson2d_reference.o -o poisson2d
poisson2d.c:
main:
    109, Generating copy(A[:ny*nx],Anew[:ny*nx],rhs[:ny*nx])
         ...
    121, Generating copy(Anew[:ny*nx],A[:ny*nx])
         ...
    131, Generating copy(A[:ny*nx])
         Accelerator kernel generated
         Generating Tesla code
        132, #pragma acc loop gang, vector(128) /* blockIdx.x threadIdx.x */
    137, Generating copy(A[:ny*nx])
         Accelerator kernel generated
         Generating Tesla code
        138, #pragma acc loop gang, vector(128) /* blockIdx.x threadIdx.x */
```


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Data Copies

Run Result

```
$ make run
srun --partition=gpus --gres=gpu:1  ./poisson2d
Jacobi relaxation calculation: max 500 iterations on 2048 x 2048 mesh
Calculate reference solution and time with serial CPU execution.
    0, 0.249999
  100, 0.249760
  200, 0...
Calculate current execution.
    0, 0.249999
  100, 0.249760
  200, 0...
2048x2048: Ref:  60.0229 s, This:  69.5278 s, speedup:     0.86
```

Data Copies

Run Result

```
$ make run
srun --partition=gpus --gres=gpu:1  ./poisson2d
Jacobi relaxation calculation: max 500 iterations on 2048 x 2048 mesh
Calculate reference solution and time                xecution.
    0, 0.249999
  100, 0.249760
  200, 0...
Calculate current execution.
    0, 0.249999
  100, 0.249760
  200, 0...
2048x2048: Ref:  60.0229 s, This:  69.5278 s, speedup:     0.86
```

Slower?!
Why?

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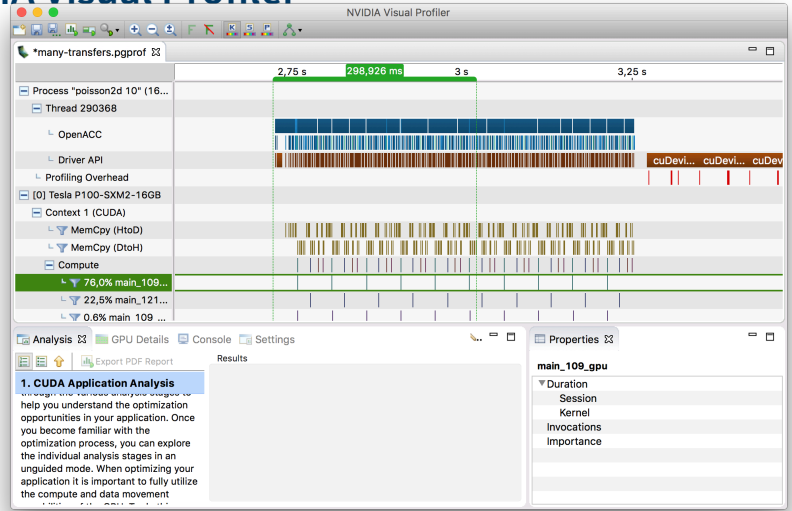
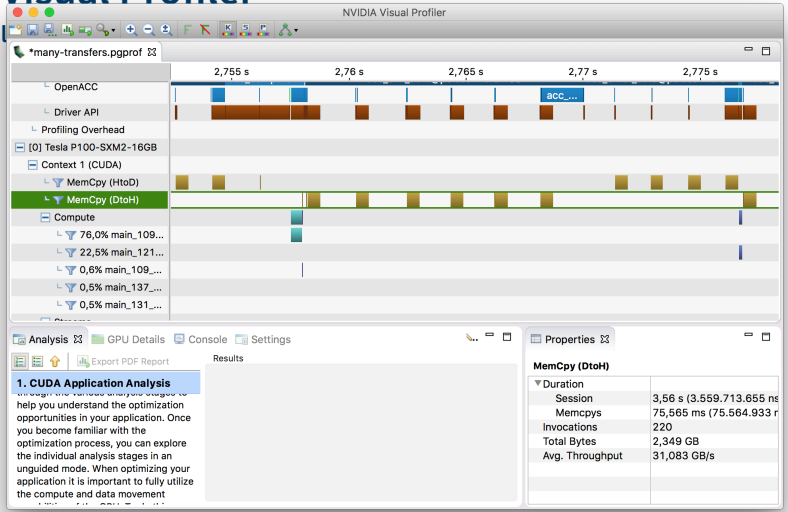
PGI/NVIDIA Visual Profiler

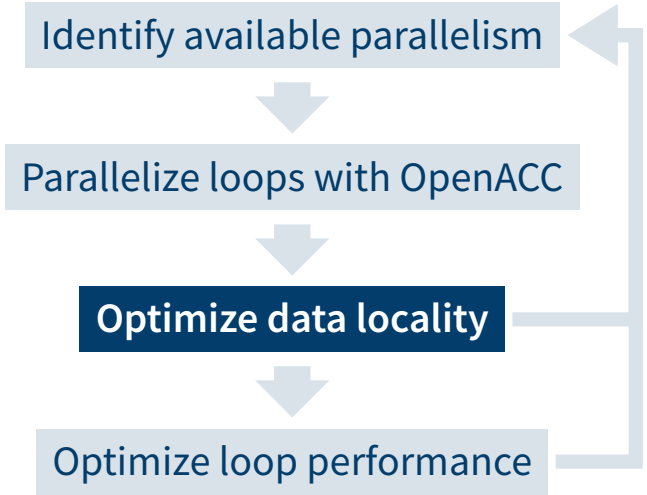


Jacboi in Visual Profiler

Zoom in to kernel



Parallelization Workflow



Analyze Jacobi Data Flow

In code

```
while (error > tol && iter < iter_max) {
    error = 0.0;
```

A, Anew resident on **host**

```
#pragma acc parallel loop


for (int ix = ix_start; ix < ix_end; ix++)
↪  {
    for (int iy = iy_start; iy < iy_end;
    ↪  iy++) {
    // ...
}}
```

```
    iter++
}
```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Analyze Jacobi Data Flow

In code

```
while (error > tol && iter < iter_max) {
    error = 0.0;
```

A, Anew resident on **host**

copy

```
#pragma acc parallel loop
```

A, Anew resident on **device**

```
for (int ix = ix_start; ix < ix_end; ix++)
↪  {
    for (int iy = iy_start; iy < iy_end;
    ↪  iy++) {
    // ...
}}
```

```
    iter++
}
```


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Analyze Jacobi Data Flow

In code

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```

A, Anew resident on **host**

copy

```
#pragma acc parallel loop
```

A, Anew resident on **device**

```
for (int ix = ix_start; ix < ix_end; ix++)
↪  {
    for (int iy = iy_start; iy < iy_end;
    ↪  iy++) {
    // ...
}}
```

A, Anew resident on **device**

```
    iter++
}
```


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Analyze Jacobi Data Flow

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```

A, Anew resident on **host**

copy

```
#pragma acc parallel loop
```

A, Anew resident on **device**

```
for (int ix = ix_start; ix < ix_end; ix++)
↪  {
    for (int iy = iy_start; iy < iy_end;
    ↪  iy++) {
    // ...
}}
```

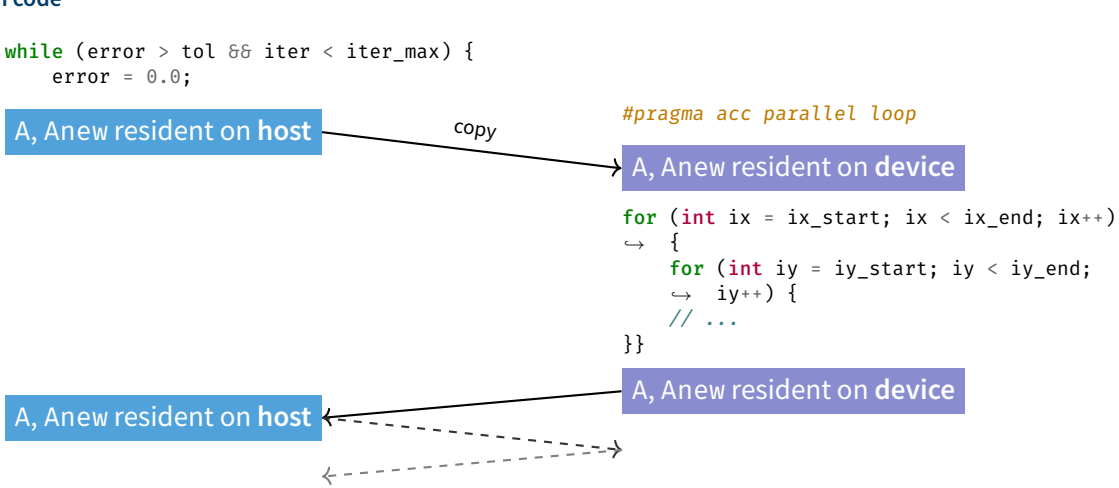
A, Anew resident on **device**

A, Anew resident on **host**

```
    iter++
}
```

Analyze Jacobi Data Flow

In code



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Analyze Jacobi Data Flow

In code

```
while (error > tol && iter < iter_max) {
    error = 0.0;
```

A, Anew resident on **host**

copy

```
#pragma acc parallel loop
```

A, Anew resident on **device**

```
for (int ix = ix_start; ix < ix_end; ix++)
↪  {
    for (int iy = iy_start; iy < iy_end;
    ↪  iy++) {
    // ...
}}
```

Copies are done in **each** iteration!

A, Anew resident on **device**

A, Anew resident on **host**

```
    iter++
}
```


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Data Regions

To manually specify data locations: `data` construct

- Defines region of code in which data remains on device
- Data is shared among all kernels in region
- Explicit data transfers

OpenACC: `data`

```
#pragma acc data [clause, [, clause] ...]
```


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Data Regions

Clauses

Clauses to augment the data regions

`copy(var)`	Allocates memory of `var` on GPU, copies data to GPU at beginning of region, copies data to host at end of region Specifies size of `var`: `var[`*`lowerBound:size`*`]`
`copyin(var)`	Allocates memory of `var` on GPU, copies data to GPU at beginning of region
`copyout(var)`	Allocates memory of `var` on GPU, copies data to host at end of region
`create(var)`	Allocates memory of `var` on GPU
`present(var)`	Data of `var` is not copies automatically to GPU but considered present

Data Region Example

```
#pragma acc data copyout(y[0:N]) create(x[0:N])
{
double sum = 0.0;
#pragma acc parallel loop
for (int i=0; i<N; i++) {
    x[i] = 1.0;
    y[i] = 2.0;
}
#pragma acc parallel loop
for (int i=0; i<N; i++) {
    y[i] = i*x[i]+y[i];
}
}
```


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Data Regions II

Looser regions: `enter data` directive

- Define data regions, but not for structured block
- Closest to `cudaMemcpy()`
- Still, explicit data transfers

OpenACC: `enter data`

```
#pragma acc enter data [clause, [, clause] ...]
#pragma acc exit data [clause, [, clause] ...]
```


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Data Region

TASK 5

More parallelism, Data locality

- Add `data` regions such that all data resides on device during iterations
- Optional: See your success in Visual Profiler

Task 5: Data Region

- Change to `Task5/` directory
- Work on `TODO`s
- Compile: `make`
- Submit parallel run to the batch system: `make run`

? What's your speed-up?

- Generate profile with `make profile_tofile`

Parallel Jacobi II

Source Code

```
105  #pragma acc data copy(A[0:nx*ny]) copyin(rhs[0:nx*ny]) create(Anew[0:nx*ny])
106  while ( error > tol && iter < iter_max )
107  {
108      error = 0.0;
109
110      // Jacobi kernel
111      #pragma acc parallel loop reduction(max:error)
112      for (int ix = ix_start; ix < ix_end; ix++)
113      {
114          for (int iy = iy_start; iy < iy_end; iy++)
115          {
116              Anew[iy*nx+ix] = -0.25 * (rhs[iy*nx+ix] - ( A[iy*nx+ix+1] + A[iy*nx+ix-1]
117                                                        + A[(iy-1)*nx+ix] + A[(iy+1)*nx+ix] ));
118              error = fmaxr( error, fabsr(Anew[iy*nx+ix]-A[iy*nx+ix]));
119          }
120      }
121
122      // A <-> Anew
123      #pragma acc parallel loop
124      for (int iy = iy_start; iy < iy_end; iy++)
125      // …
126  }
```


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Parallel Jacobi II

Compilation result

```
$ make
pgcc -DUSE_DOUBLE -Minfo=accel -fast -acc -ta=tesla:cc70 poisson2d.c poisson2d_reference.o
  -o poisson2d
poisson2d.c:
 poisson2d.c:
 main:
     105, Generating copyin(rhs[:ny*nx])
          Generating create(Anew[:ny*nx])
          Generating copy(A[:ny*nx])
     111, Accelerator kernel generated
          Generating Tesla code
         111, Generating reduction(max:error)
         112, #pragma acc loop gang, vector(128) /* blockIdx.x threadIdx.x */
         114, #pragma acc loop seq
     114, Complex loop carried dependence of Anew-> prevents parallelization
          Loop carried dependence of Anew-> prevents parallelization
```

Parallel Jacobi II

Run result

```
$ make run
srun --partition=gpus --gres=gpu:1  ./poisson2d
Jacobi relaxation calculation: max 500 iterations on 2048 x 2048 mesh
Calculate reference solution and time with serial CPU execution.
    0, 0.249999
  100, 0.249760
  200, 0...
Calculate current execution.
    0, 0.249999
  100, 0.249760
  200, 0...
2048x2048: Ref:  59.5508 s, This:   0.3328 s, speedup:   178.95
```

Parallel Jacobi II

Run result

```
$ make run
srun --partition=gpus --gres=gpu:1  ./poisson2d
Jacobi relaxation calculation: max 500 iterations on 2048 x 2048 mesh
Calculate reference s
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  100, 0.249760
  200, 0...
Calculate current exe
    0, 0.249999
  100, 0.249760
  200, 0...
2048x2048: Ref:  59.5508 s, This:   0.3328 s, speedup:   178.95
```

Nice!
But can we be even better?

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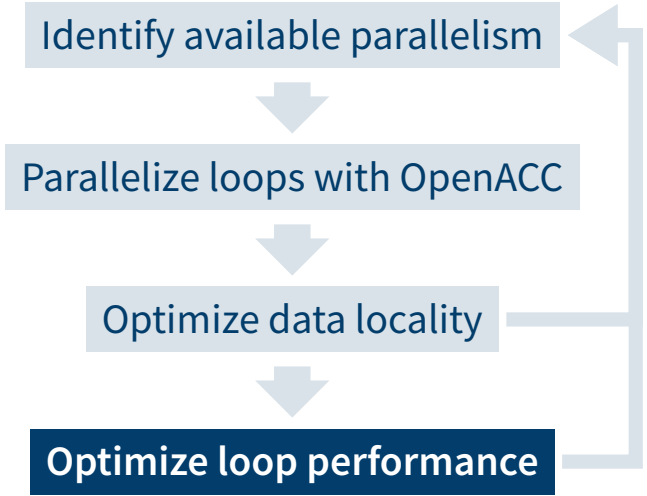
Parallelization Workflow



Understanding Compiler Output

```
110, Accelerator kernel generated
     Generating Tesla code
    110, Generating reduction(max:error)
    111, #pragma acc loop gang, vector(128) /* blockIdx.x threadIdx.x */
    114, #pragma acc loop seq
    114, Complex loop carried dependence of Anew-> prevents parallelization
```

```
110   #pragma acc parallel loop reduction(max:error)
111   for (int ix = ix_start; ix < ix_end; ix++)
112   {
113       // Inner loop
114       for (int iy = iy_start; iy < iy_end; iy++)
115       {
116           Anew[iy*nx+ix] = -0.25 * (rhs[iy*nx+ix] - ( A[iy*nx+ix+1] +  A[iy*nx+ix-1] +
          ↪  A[(iy-1)*nx+ix] + A[(iy+1)*nx+ix] ));
117           error = fmaxr( error, fabsr(Anew[iy*nx+ix]-A[iy*nx+ix]));
118       }
119   }
```

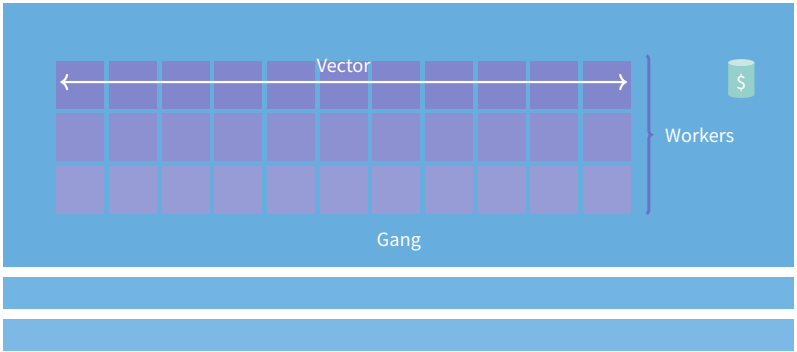
Understanding Compiler Output

```
110, Accelerator kernel generated
     Generating Tesla code
    110, Generating reduction(max:error)
    111, #pragma acc loop gang, vector(128) /* blockIdx.x threadIdx.x */
    114, #pragma acc loop seq
    114, Complex loop carried dependence of Anew-> prevents parallelization
```

- Outer loop: Parallelism with `gang` and `vector`
- Inner loop: Sequentially per thread (`#pragma acc loop seq`)
- Inner loop was never parallelized!
- **Rule of thumb: Expose as much parallelism as possible**

OpenACC Parallelism

3 Levels of Parallelism



Vector
Vector threads work in lockstep (SIMD/SIMT parallelism)

Worker
Has 1 or more vector; workers share common resource (*cache*)

Gang
Has 1 or more workers; multiple gangs work independently from each other

CUDA Parallelism

CUDA Execution Model

Software

Thread

Hardware

Scalar Processor

- **Threads** executed by scalar processors (*CUDA cores*)

CUDA Parallelism

CUDA Execution Model

Software

Thread

Thread Block

Hardware

Scalar Processor

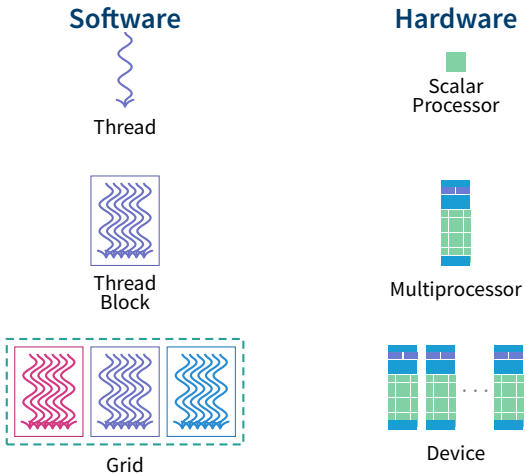
Multiprocessor

- **Threads** executed by scalar processors (*CUDA cores*)

- Thread **blocks**: Executed on multiprocessors (*SM*)
- Do not migrate
- Several concurrent thread blocks can reside on multiprocessor
  Limit: Multiprocessor resources (register file; shared memory)

CUDA Parallelism

CUDA Execution Model



- **Threads** executed by scalar processors (*CUDA cores*)

- Thread **blocks**: Executed on multiprocessors (*SM*)
- Do not migrate
- Several concurrent thread blocks can reside on multiprocessor
  Limit: Multiprocessor resources (register file; shared memory)

- Kernel launched as **grid** of thread blocks
- Blocks, grids: Multiple dimensions

From OpenACC to CUDA

`map(||acc,||<<<>>>)`

- In general: Compiler free to do what it thinks is best
- Usually

gang	Mapped to blocks *(coarse grain)*
worker	Mapped to threads *(fine grain)*
vector	Mapped to threads *(fine SIMD/SIMT)*
seq	*No parallelism; sequential*

- Exact mapping compiler dependent
- Performance tips
  - Use vector size divisible by 32
  - Block size: `num_workers` $\times$ `vector_length`

Declaration of Parallelism

Specify configuration of threads

- Three **clauses** of parallel region (`parallel`, `kernels`) for changing distribution/configuration of group of threads
- Presence of keyword: Distribute using this level
- Optional size: Control size of parallel entity

OpenACC: `gang worker vector`

```
#pragma acc parallel loop gang vector
```

Also: `worker`

Size: `num_gangs(n)`, `num_workers(n)`, `vector_length(n)`

Understanding Compiler Output II

```
110, Accelerator kernel generated
     Generating Tesla code
    110, Generating reduction(max:error)
    111, #pragma acc loop gang, vector(128) /* blockIdx.x threadIdx.x */
    114, #pragma acc loop seq
    114, Complex loop carried dependence of Anew-> prevents parallelization
```

- Compiler reports configuration of parallel entities
  - **Gang** mapped to `blockIdx.x`
  - **Vector** mapped to `threadIdx.x`
  - **Worker** not used
- Here: 128 threads per block; as many blocks as needed

  128 seems to be default for Tesla/NVIDIA

More Parallelism

TASK 6

Unsequentialize inner loop

- Add `vector` clause to inner loop
- Study result with profiler

Task 6: More Parallelism

- Change to `Task6/` directory
- Work on TODOs
- Compile: `make`
- Submit to the batch system: `make run`
- Generate profile with `make profile_tofile`

? What's your speed-up?

More Parallelism

Compiler Output

```
$ make
pgcc -DUSE_DOUBLE -Minfo=accel -fast -acc -ta=tesla:cc70 poisson2d.c poisson2d_reference.o
  -o poisson2d
poisson2d.c:
main:
    104, Generating create(Anew[:ny*nx])
         Generating copyin(rhs[:ny*nx])
         Generating copy(A[:ny*nx])
    110, Accelerator kernel generated
         Generating Tesla code
        110, Generating reduction(max:error)
        111, #pragma acc loop gang /* blockIdx.x */
        114, #pragma acc loop vector(128) /* threadIdx.x */
        ...
```

Data Region

Run Result

```
$ make run
srun --partition=gpus --gres=gpu:1  ./poisson2d
Jacobi relaxation calculation: max 500 iterations on 2048 x 2048 mesh
Calculate reference solution and time with serial CPU execution.
    0, 0.249999
  100, 0.249760
  200, 0...
Calculate current execution.
    0, 0.249999
  100, 0.249760
  200, 0...
2048x2048: Ref:  60.8886 s, This:   0.7658 s, speedup:    79.51
```

Data Region

Run Result

```
$ make run
srun --partition=gpus --gres=gpu:1  ./poisson2d
Jacobi relaxation calculation: max 500 iterations on 2048 x 2048 mesh
Calculate reference solution ar                                  n.
    0, 0.249999
  100, 0.249760
  200, 0...
Calculate current execution.
    0, 0.249999
  100, 0.249760
  200, 0...
2048x2048: Ref:  60.8886 s, This:   0.7658 s, speedup:    79.51
```

Actually slower!
Why?

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Memory Coalescing

Memory in batch

- Coalesced access *good*
  - Threads of warp (group of 32 contiguous threads) access adjacent words
  - Few transactions, high utilization
- Uncoalesced access *bad*
  - Threads of warp access scattered words
  - Many transactions, low utilization
- Best **performance**: `threadIdx.x` should access contiguously

Jacobi Access Pattern

A coalescion of data

Improve memory access pattern: Loop order in main loop

```
#pragma acc parallel loop reduction(max:error)
for (int ix = ix_start; ix < ix_end; ix++) {
    #pragma acc loop vector
    for (int iy = iy_start; iy < iy_end; iy++) {
        Anew[ iy*nx + ix ] = -0.25 *
        ↪  (rhs[iy*nx+ix] -
            (  A[iy*nx+ix+1] + A[iy*nx+ix-1]
             + A[(iy-1)*nx+ix] + A[(iy+1)*nx+ix]));
        //...
```

`ix` Outer run index; accesses consecutive memory locations

`iy` Inner run index; accesses offset memory locations

→ Change order to optimize pattern!

Jacobi Access Pattern

A coalescion of data

Improve memory access pattern: Loop order in main loop

```
#pragma acc parallel loop reduction(max:error)
for (int iy = iy_start; iy < iy_end; iy++) {
    #pragma acc loop vector
    for (int ix = ix_start; ix < ix_end; ix++) {
        Anew[iy*nx + ix] = -0.25 *
        ↪  (rhs[iy*nx+ix] -
            (  A[iy*nx+ix+1] + A[iy*nx+ix-1]
             + A[(iy-1)*nx+ix] + A[(iy+1)*nx+ix]));
        //...
```

`ix` Outer run index; accesses consecutive memory locations

`iy` Inner run index; accesses offset memory locations

→ Change order to optimize pattern!

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Fixing Access Pattern

Loop change

TASK 7

- Interchange loop order for Jacobi loops
- Also: Compare to loop-fixed CPU reference version

Task 7: Loop Ordering

- Change to `Task7/` directory
- Work on `TODO`s
- Compile: `make`
- Submit to the batch system: `make run`

? What's your speed-up?

Fixing Access Pattern

Compiler output (unchanged)

```
$ make
pgcc -DUSE_DOUBLE -Minfo=accel -fast -acc -ta=tesla:cc70 poisson2d.c poisson2d_reference.o
  -o poisson2d
poisson2d.c:
main:
    104, Generating create(Anew[:ny*nx])
         Generating copyin(rhs[:ny*nx])
         Generating copy(A[:ny*nx])
    110, Accelerator kernel generated
         Generating Tesla code
        110, Generating reduction(max:error)
        111, #pragma acc loop gang /* blockIdx.x */
        114, #pragma acc loop vector(128) /* threadIdx.x */
        ...
```

Fixing Access Pattern

Run Result

```
$ make run
srun --partition=gpus --gres=gpu:1  ./poisson2d
Jacobi relaxation calculation: max 500 iterations on 2048 x 2048 mesh
Calculate reference solution and time with serial CPU execution.
    0, 0.249999
  100, 0.249760
  200, 0...
Calculate current execution.
    0, 0.249999
  100, 0.249760
  200, 0...
2048x2048: Ref: 113.0214 s, This:   0.3284 s, speedup:   344.15
```

Fixing Access Pattern

Run Result

```
$ make run
srun --partition=gpus --gres=gpu:1  ./poisson2d
Jacobi relaxation calculation: max 500 iterations on 2048 x 2048 mesh
Calculate reference solution and time with serial CPU
    0, 0.249999
  100, 0.249760
  200, 0...
Calculate current execution
    0, 0.249999
  100, 0.249760
  200, 0...
2048x2048: Ref: 113.0214 s, This:   0.3284 s, speedup:   344.15
```

Fix also CPU version!

Fixing Access Pattern

Run Result II

```
$ make run
srun --partition=gpus --gres=gpu:1  ./poisson2d
Jacobi relaxation calculation: max 500 iterations on 2048 x 2048 mesh
Calculate reference solution and time with serial CPU execution.
    0, 0.249999
  100, 0.249760
  200, 0...
Calculate current execution.
    0, 0.249999
  100, 0.249760
  200, 0...
2048x2048: Ref:   6.2612 s, This:   0.2187 s, speedup:    28.63
```

Fixing Access Pattern

Run Result II

```
$ make run
srun --partition=gpus --gres=gpu:1  ./poisson2d
Jacobi relaxation calculation: max 500 iterations on 2048 x 2048 mesh
Calculate reference solution and time with serial CPU execution.
    0, 0.249999
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  200, 0...
2048x2048: Ref:   6.2612 s, This:   0.2187 s, speedup:    28.63
```

26 × is great!

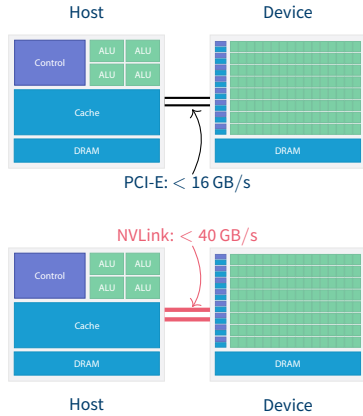
Aside: Data Transfer with NVLink

- One feature of Minsky not showcased in tutorial: NVLink between CPU and GPU
- Task 3 on P100 + PCI-E:

```
$ nvprof ./poisson2d
2048x2048: Ref:  73.1076 s, This:   0.4600 s, speedup:   158.93
Device "Tesla P100-PCIE-12GB (0)"
   Count  Avg Size  Min Size  Max Size  Total Size  Total Time  Name
     657  149.63KB  4.0000KB  0.9844MB  96.00000MB  9.050452ms  Host To Device
     193  169.78KB  4.0000KB  0.9961MB  32.00000MB  2.679974ms  Device To Host
```

- Task 3 on P100 + NVLink:

```
2048x2048: Ref:  49.7252 s, This:   0.5574 s, speedup:    89.21
Device "Tesla P100-SXM2-16GB (0)"
   Count  Avg Size  Min Size  Max Size  Total Size  Total Time  Name
     480  204.80KB  64.000KB  960.00KB  96.00000MB  3.325184ms  Host To Device
     160  204.80KB  64.000KB  960.00KB  32.00000MB  1.102954ms  Device To Host
```



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Fixing Access Pattern

Run Result II

```
$ make run
srun --partition=gpus --gres=gpu:1  ./poisson2d
Jacobi relaxation calculation: max 500 iterations on 2048 x 2048 mesh
Calculate reference solution and time with serial CPU execution.
    0, 0.249999
  100, 0.249760
  200, 0...
Calculate current execution.
    0, 0.249999
  100, 0.249760
  200, 0...
2048x2048: Ref:   6.8080 s, This:   0.2609 s, speedup:    26.10
```

Fixing Access Pattern

Run Result II

```
$ make run
srun --partition=gpus --gres=gpu:1  ./poisson2d
Jacobi relaxation calculation: max 500 iterations on 2048 x 2048 mesh
Calculate reference solution and time with serial CPU execution.
    0, 0.249999
  100, 0.249760
  200, 0...
Calculate current execution.
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  100, 0.249760
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```

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Page-Locked Memory

Pageability

- Host memory allocated with `malloc()` is pageable
  - Memory pages of memory can be moved by kernel, e.g. swapped to disk
  - Additional indirection

Page-Locked Memory

Pageability

- Host memory allocated with `malloc()` is pageable
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- NVIDIA GPUs can allocate **page-locked memory** (*pinned* memory)
  - \+ Faster (safety guards are skipped)
  - \+ Interleaving of execution and copy (asynchronous)
  - \+ Directly map into GPU memory*
  - − Scarce resource; OS performance could degrade

Page-Locked Memory

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  - \+ Faster (safety guards are skipped)
  - \+ Interleaving of execution and copy (asynchronous)
  - \+ Directly map into GPU memory*
  - − Scarce resource; OS performance could degrade
- OpenACC: Very easy to use pinned memory
  `-ta=tesla:pinned`

Page-Locked Memory

Loop change

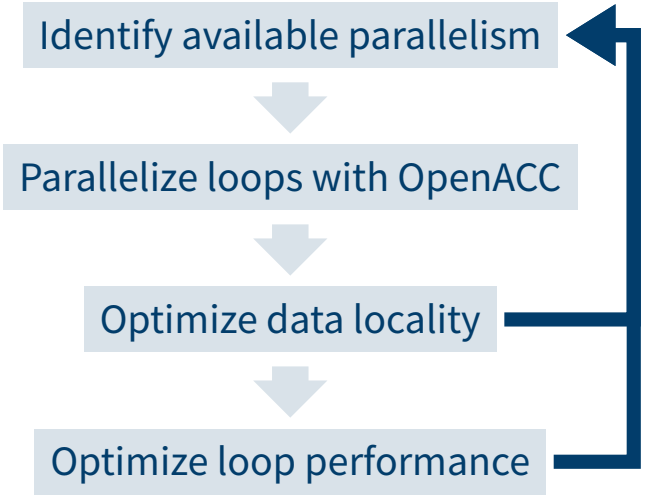
TASK 7'

- Compare performance with and without pinned memory
- Also test unified memory again

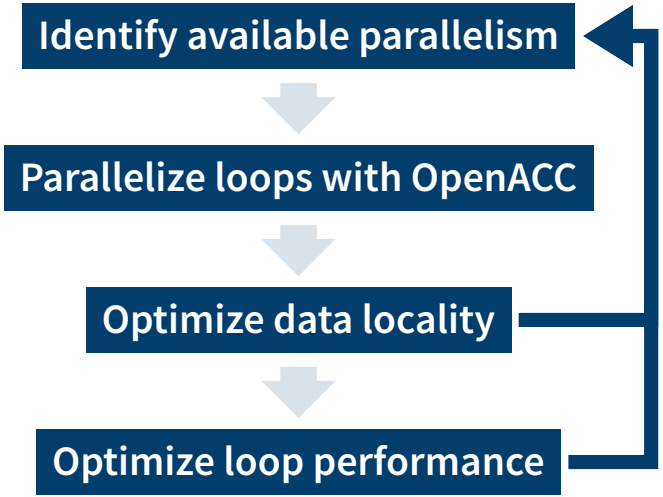
Task 7': Pinned Memory

- Like in Task 7, but change compilation to include `pinned` or `managed`
- Submit to the batch system: `make run`

Parallelization Workflow



Parallelization Workflow



Conclusions & Summary

- **OpenACC** can be used to efficiently exploit parallelism
- … on the CPU, similar to OpenMP,
- … on the GPU, for which it is specially designed for,
- … on multiple GPUs, working well together with MPI (not shown today).

- It can work well with other GPU-leveraging tools
- There are still many more tuning possibilities and keywords not mentioned (*time…*)

→ Great online resources to **deepen your knowledge** (see appendix)

Conclusions & Summary

- **OpenACC** can be used to efficiently exploit parallelism
- … on the CPU, similar to OpenMP,
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- There are still many more tuning possibilities and keywords not m… e…)

→ Great online resources to **deepen your knowledge** (see a…

Thank you for your attention!

a.herten@fz-juelich.de

APPENDIX

Appendix

- List of Tasks
- Further Reading
- Glossary
- References

List of Tasks

Task 2: A First Parallel Loop
Task 3: More Parallel Loops on GPU
Task 4: Data Copies
Task 5: Data Region
Task 6: More Parallelism
Task 7: Loop Ordering
Task 7': Pinned Memory

Further Reading

Further Resources on OpenACC

- www.openacc.org: Official home page of OpenACC
- developer.nvidia.com/openacc-courses: OpenACC courses, upcoming (live) and past (recorded)
- https://nvidia.qwiklab.com/quests/3: Qwiklabs for OpenACC; various levels
- Book: **Chandrasekaran and Juckeland** *OpenACC for Programmers: Concepts and Strategies* https://www.amazon.com/OpenACC-Programmers-Strategies-Sunita-Chandrasekaran/dp/0134694287 [3]
- Book: **Farber** *Parallel Programming with OpenACC* https://www.amazon.com/Parallel-Programming-OpenACC-Rob-Farber/dp/0124103979 [4]

Glossary

Glossary I

CUDA Computing platform for GPUs from NVIDIA. Provides, among others, CUDA C/C++. 18, 67, 68, 69, 70, 104

GCC The GNU Compiler Collection, the collection of open source compilers, among others for C and Fortran. 17, 20

MPI The Message Passing Interface, a API definition for multi-node computing. 129, 130

NVIDIA US technology company creating GPUs. 11, 66, 67, 68, 69, 70, 71, 72, 79, 123, 124, 125, 137, 138, 139

NVLink NVIDIA's communication protocol connecting CPU $\leftrightarrow$ GPU and GPU $\leftrightarrow$ GPU with high bandwidth. 120, 138

Glossary II

OpenACC Directive-based programming, primarily for many-core machines. 2, 3, 4, 10, 11, 12, 13, 14, 15, 16, 18, 19, 20, 21, 22, 32, 39, 40, 42, 44, 46, 51, 57, 58, 59, 60, 61, 71, 72, 73, 74, 81, 88, 91, 97, 100, 104, 105, 123, 124, 125, 127, 128, 129, 130, 135

OpenMP Directive-based programming, primarily for multi-threaded machines. 12, 13, 14, 46, 50, 53, 54, 55, 129, 130

P100 A large GPU with the Pascal architecture from NVIDIA. It employs NVLink as its interconnect and has fast *HBM2* memory. 120

PAPI The Performance API, a C/C++ API for querying performance counters. 33, 34

Pascal GPU architecture from NVIDIA (announced 2016). 67, 68, 69, 70, 138

perf Part of the Linux kernel which facilitates access to performance counters; comes with command line utilities. 33, 34

Glossary III

PGI Compiler creators. Formerly *The Portland Group, Inc.*; since 2013 part of NVIDIA. 17, 20, 33, 34, 50

POWER CPU architecture from IBM, earlier: PowerPC. See also POWER8. 139

POWER8 Version 8 of IBM's POWERprocessor, available also under the OpenPOWER Foundation. 139

CPU Central Processing Unit. 2, 3, 4, 17, 46, 67, 68, 69, 70, 114, 117, 120, 129, 130, 137, 139

GPU Graphics Processing Unit. 2, 3, 4, 6, 7, 8, 9, 10, 17, 19, 57, 58, 59, 60, 61, 66, 67, 68, 69, 70, 71, 72, 89, 120, 123, 124, 125, 129, 130, 137, 138

References

References I

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