JÜLICH
FORSCHUNGSZENTRUM

OpenACC Tutorial

GridKa School 2017: `make science && run`

Andreas Herten, Forschungszentrum Jülich, 31 August 2017

Outline

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The GPU Platform

CPU vs. GPU

A matter of specialties

Graphics: Lee [1] and Shearings Holidays [2]

CPU vs. GPU

A matter of specialties

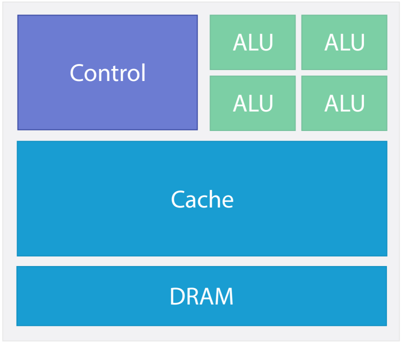
Transporting one

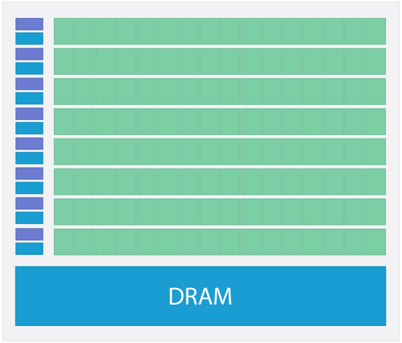
Transporting many

Graphics: Lee [1] and Shearings Holidays [2]

CPU vs. GPU

Chip





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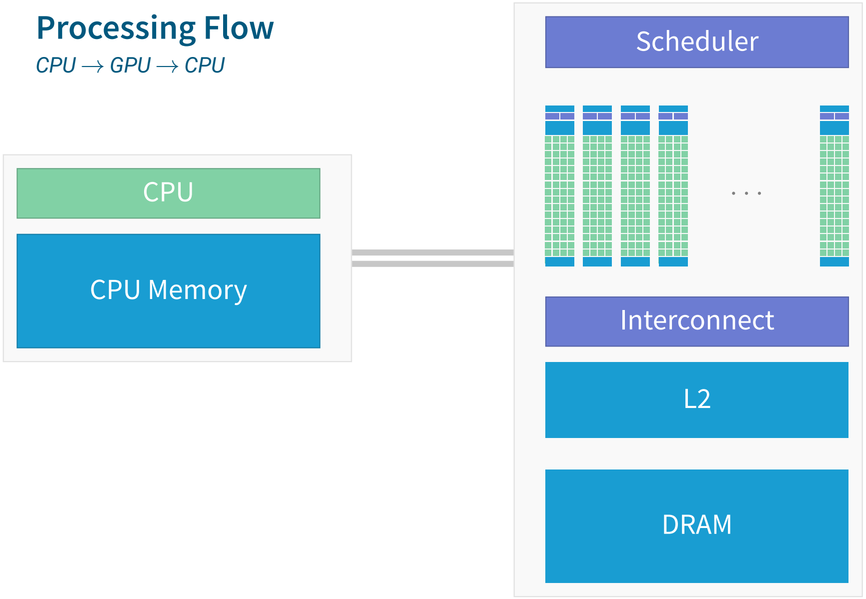
Processing Flow

CPU → GPU → CPU



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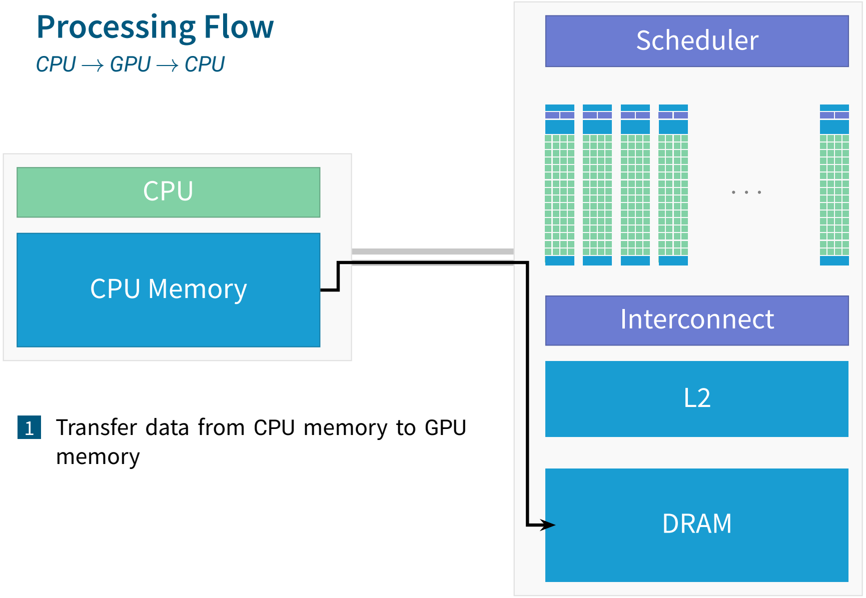
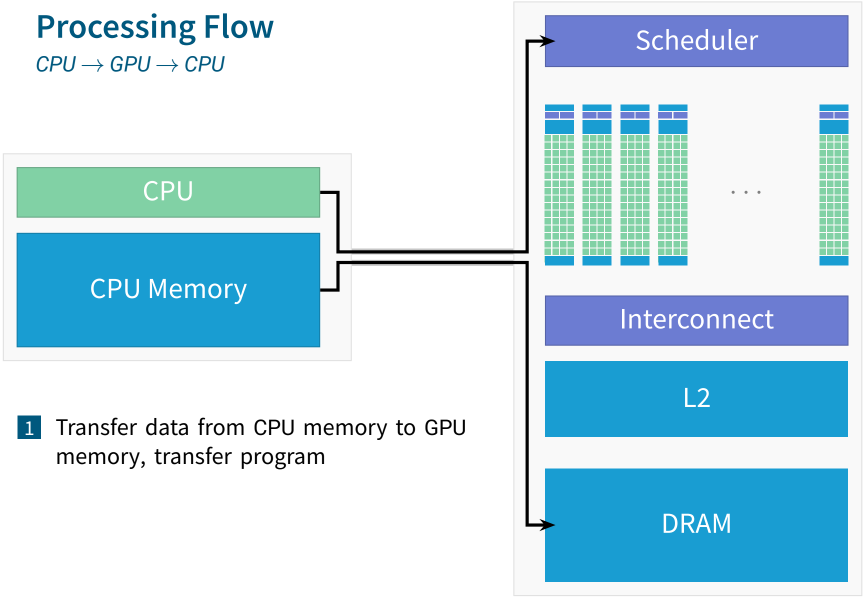


1 Transfer data from CPU memory to GPU memory

Processing Flow

CPU → GPU → CPU



1 Transfer data from CPU memory to GPU memory, transfer program

Processing Flow

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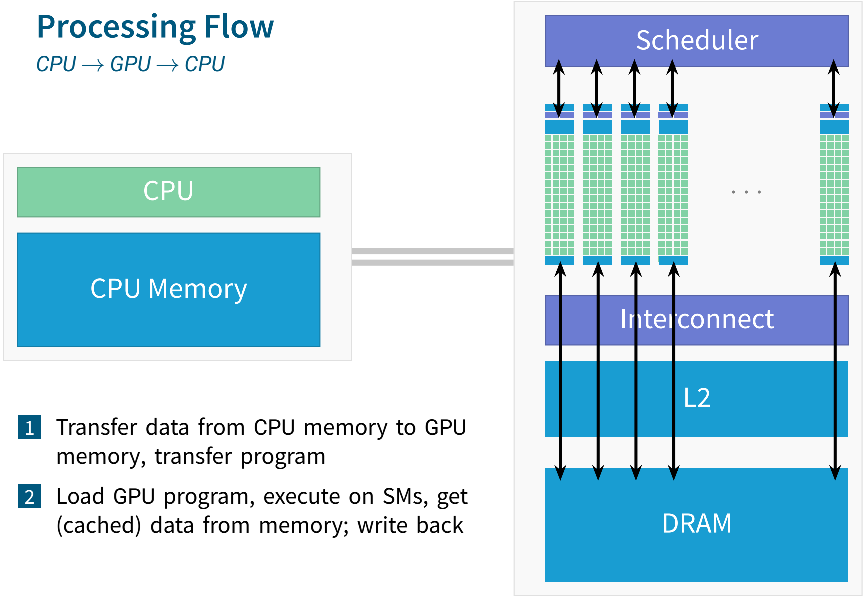

1. Transfer data from CPU memory to GPU memory, transfer program
2. Load GPU program, execute on SMs, get (cached) data from memory; write back

Processing Flow

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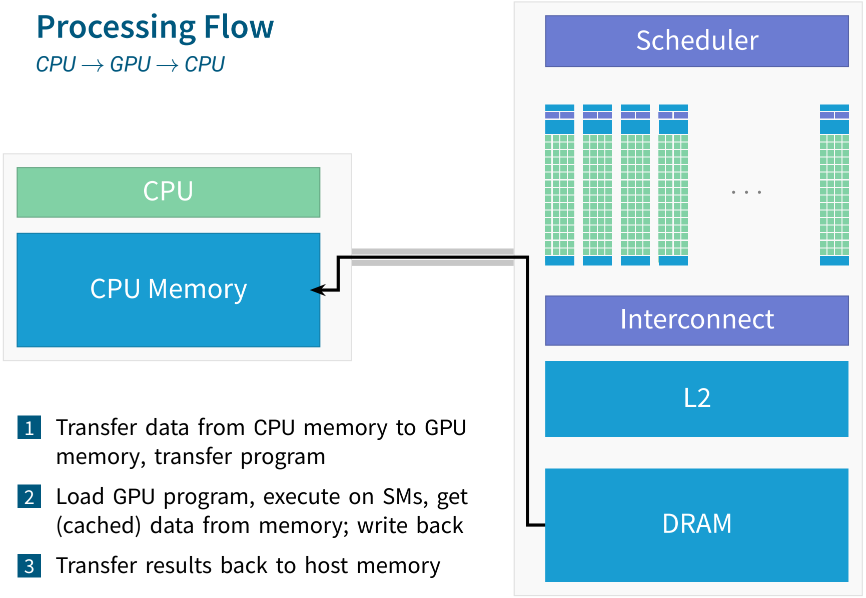

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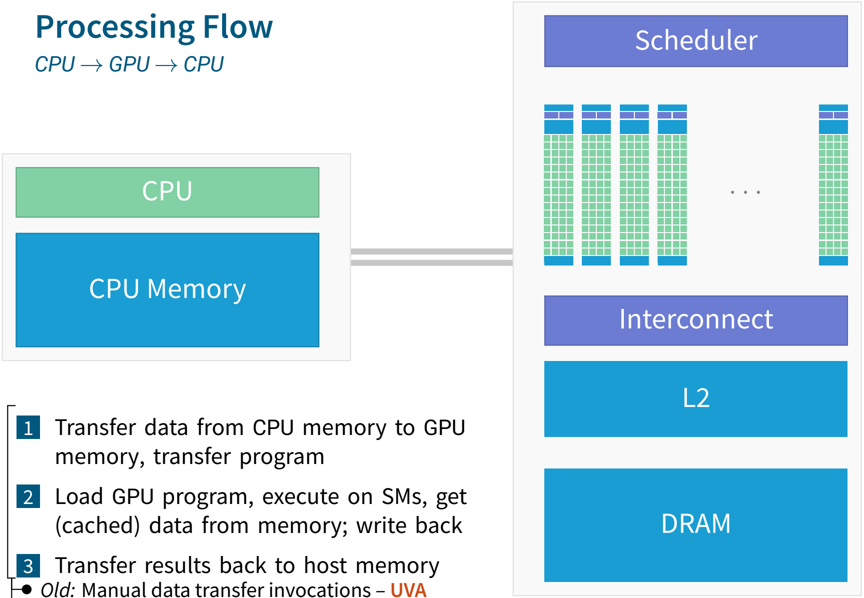

1. Transfer data from CPU memory to GPU memory, transfer program
2. Load GPU program, execute on SMs, get (cached) data from memory; write back
3. Transfer results back to host memory

- *Old:* Manual data transfer invocations – **UVA**
- *New:* Driver automatically transfers data – **UM**

CUDA Threading Model

Warp the kernel, it’s a thread!

- Methods to exploit parallelism:

CUDA Threading Model

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CUDA Threading Model

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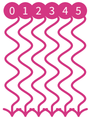

CUDA Threading Model

Warp the kernel, it's a thread!

- Methods to exploit parallelism:
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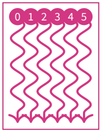

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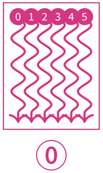

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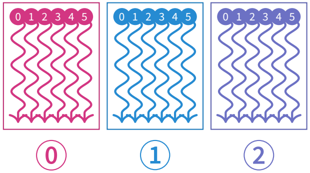

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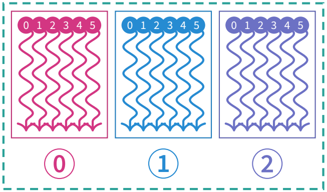

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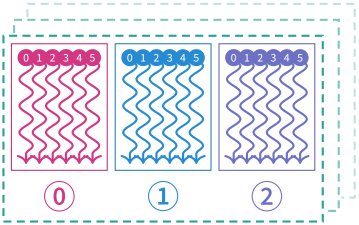
  - Threads & blocks in 3D



CUDA Threading Model

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- Methods to exploit parallelism:
  - Threads → $\boxed{\text{Block}}$
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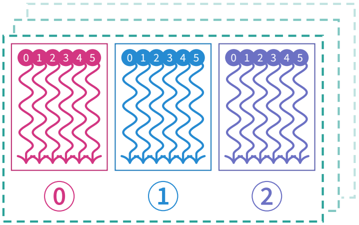
  - Threads & blocks in 3D
- **Threads**: parallel execution units
  - Lightweight → fast switchting!
  - 1000s threads execute simultaneously



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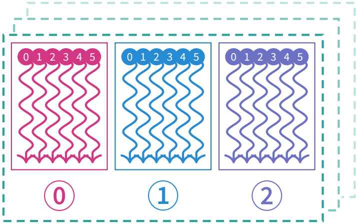
- Parallel execution unit: **kernel**



Getting GPU-Acquainted

Preparations

Task 0*: Setup

- Login to JURON

  `ssh -i mykey train0XX@juron.fz-juelich.de`

- Directory of tasks

  `cd $HOME/GPU/Tasks/Tasks/`

- Solutions are always given! You decide when to look.
  Directory of solutions: `$HOME/GPU/Tasks/Solutions/`

- Load required modules

  `module load pgi [cuda]`

- `vim` is available as editor (or copy files with `scp` or `rsync`)

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Getting GPU-Acquainted

Some Applications

TASK 0

Task 0: Getting Started

- Change to `GPU/Tasks/Task0/` directory
- Read `Instructions.rst`

Getting GPU-Acquainted

Some Applications

Task 0

Dot Product

GEMM

Task 0: Getting Started

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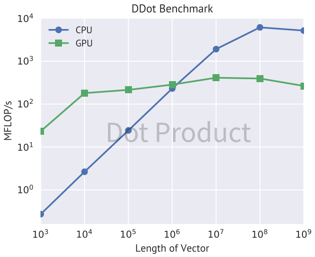
N-Body

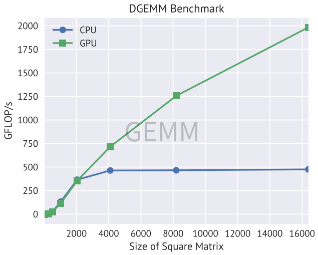
Mandelbrot

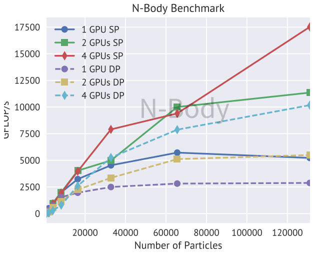
Getting GPU-Acquainted

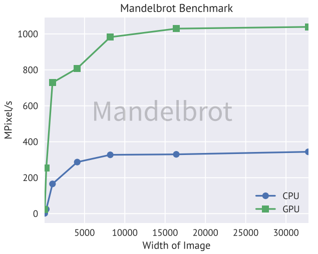
Some Applications

Task 0









Primer on Parallel Scaling

Amdahl's Law

Possible maximum speedup for *N* parallel processors

Total Time $t = t_{\text{serial}} + t_{\text{parallel}}$

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Speedup $s(N) = t/t(N) = \frac{t_{\text{s}}+t_{\text{p}}}{t_{\text{s}}+t_{\text{p}}/N}$ Efficiency: $\varepsilon = {}^{s}/_{N}$

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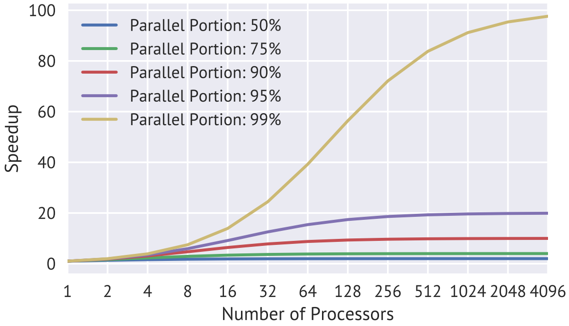
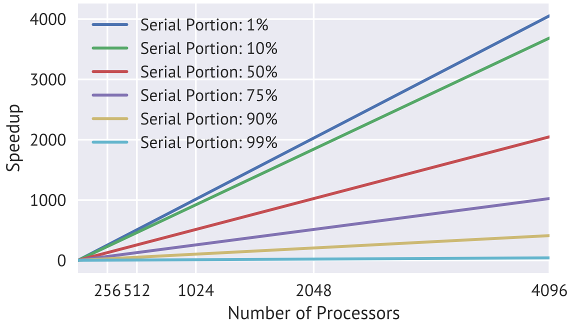


Primer on Parallel Scaling II

Gustafson-Barsis's Law

[...] speedup should be measured by scaling the problem to the number of processors, not fixing problem size.

– John Gustafson



Parallelism

Parallel programming is not easy!

Things to consider:

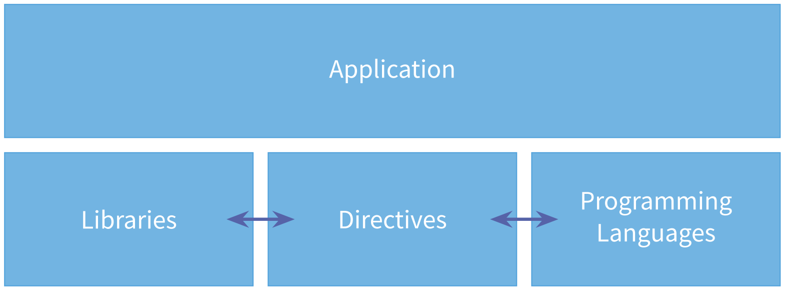
- Is my application **computationally intensive** *enough*?
- What are the levels of **parallelism**?
- How much **data** needs to be **transferred**?
- Is the **gain** worth the pain?

Possibilities

Different levels of *closeness* to GPU when GPU-programming, which **can** ease the *pain*…

- OpenACC
- OpenMP
- Thrust
- PyCUDA
- CUDA Fortran
- CUDA
- OpenCL

Summary of Acceleration Possibilities



Drop-in Acceleration

Easy Acceleration

Flexible Acceleration

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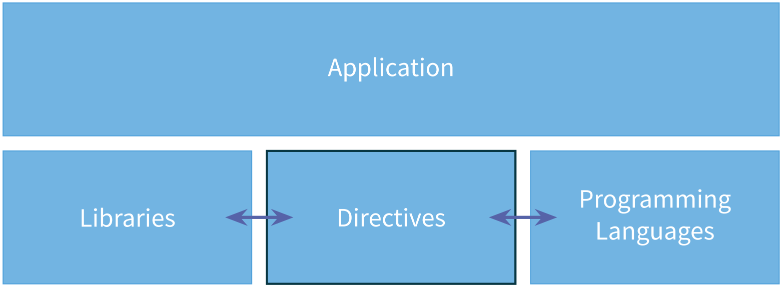

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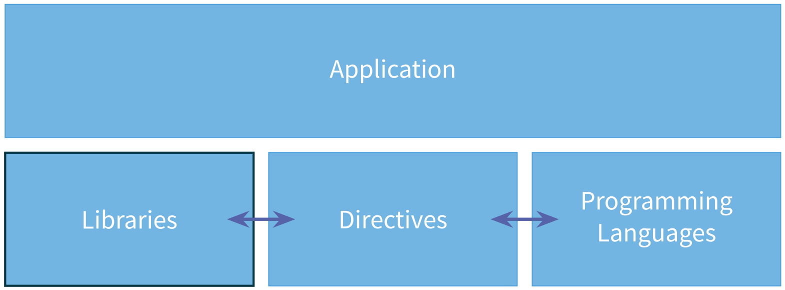

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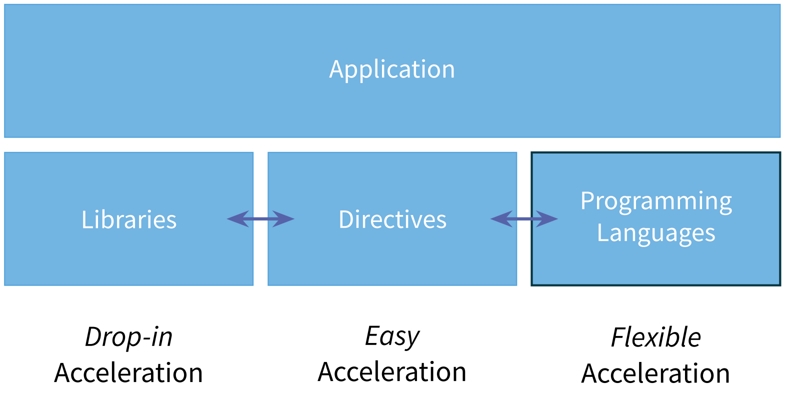

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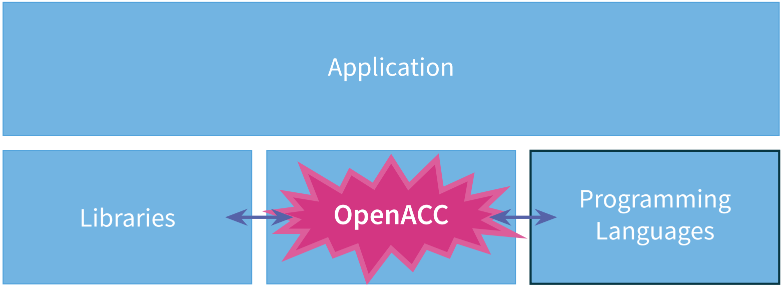

Drop-in
Acceleration

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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
2016	OpenACC 2.6 proposed (deep copy, …)

→ `https://www.openacc.org/`

Also: Best practice guide

Open{MP↔ACC}

Everything's connected

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

  But OpenMP 4.0 now also has offloading feature
- Fork/join model

  Master thread launches parallel child threads; merge after execution

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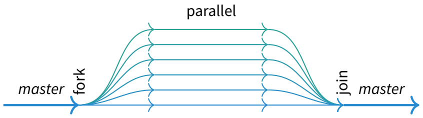

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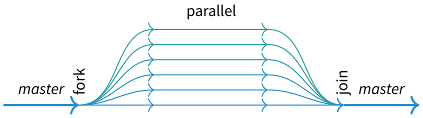

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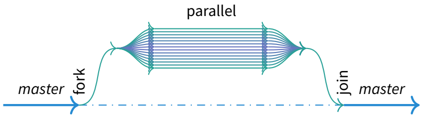


OpenACC

Modus Operandi

Three-step program

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

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 accelerators; heterogeneous programs
- OpenACC: Compiler directives, library routines, environment variables
- Portable across host systems and accelerator architectures

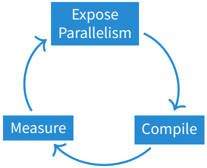
2 Compiler

Simple and abstracted

- Compiler support
  - PGI *Best performance, great support, free*
  - GCC *Beta, limited coverage, OSS*
  - Cray *???*
- Trust compiler to generate intended parallelism; 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 $\rightarrow$ **Portability**

3 $uccess

Iteration is key



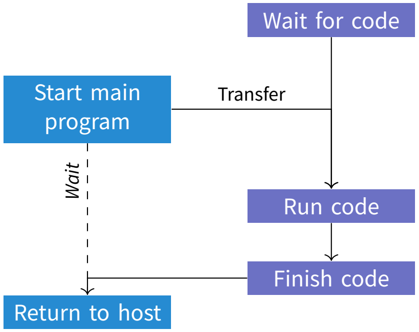
- Serial to parallel: fast
- Serial to fast parallel: more time needed
- Start simple $\rightarrow$ refine

$\Rightarrow$ **Productivity**

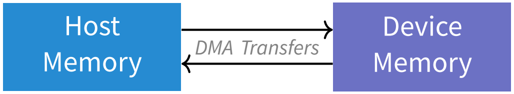
- Because of *generalness*: Sometimes not last bit of hardware performance accessible
- But: Use OpenACC together with other accelerator-targeting techniques (CUDA, libraries, …)

OpenACC Execution Model

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



OpenACC Memory Model



- Usually: Two separate memory spaces
- Data needs to be transferred to device for computation; needs to be transferred back for further evaluation
  - Transfers hidden from programmer – caution: latency, bandwidth, memory size
  - Memories are not coherent
  - Compiler helps; GPU runtime helps

OpenACC Programming Model

A binary perspective

- OpenACC interpretation needs to be activated as compile flag

PGI	`pgcc -acc [-ta=tesla]`
GCC	`gcc -fopenacc`

- 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

OpenACC Programming Model

A source code perspective

- Compiler directives, ignored by incapable compilers
- Similar to OpenMP
- Support for GPU, multicore CPU, other accelerators (Intel Xeon Phi)
- Syntax **C/C++**

  ```
  #pragma acc directive [clause, [, clause] ...] newline
  ```
- Syntax **Fortran**

  ```
  !$acc directive [clause, [, clause] ...]
  !$acc end directive
  ```

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];
    }
}
```

OpenACC by Example

OpenACC Workflow

Identify available parallelism

↓

Parallelize loops with OpenACC

↓

Optimize data locality

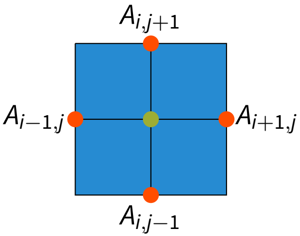
↓

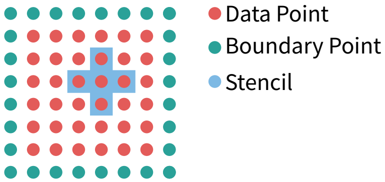
Optimize loop performance

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++ ) {
            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++;
}
```

Jacobi Solver

Source code

Iterate until converged

```
while ( error > tol && iter < iter_max ) {
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            A[(ny-1)*nx+ix] = A[1*nx+ix];
    }
    // same for iy
    iter++;
}
```

Iterate until converged

Iterate across matrix elements

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++ ) {
            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++;
}
```

Iterate until converged

Iterate across matrix elements

Calculate new value from neighbors

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++ ) {
            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++;
}
```

Iterate until converged

Iterate across matrix elements

Calculate new value from neighbors

Accumulate error

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++ ) {
            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++;
}
```

Iterate until converged

Iterate across matrix elements

Calculate new value from neighbors

Accumulate error

Swap input/output

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++ ) {
            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++;
}
```

Iterate until converged

Iterate across matrix elements

Calculate new value from neighbors

Accumulate error

Swap input/output

Set boundary conditions

OpenACC Workflow

Identify available parallelism

↓

Parallelize loops with OpenACC

↓

Optimize data locality

↓

Optimize loop performance

Identify Parallelism

Generate Profile

TASK 1

- Use `pgprof` to analyze unaccelerated version of Jacobi solver
- Investigate!

Task 1: Analyze Application

- Change to `Task1/` directory
- Compile: `make task1`
  Usually, compile just with `make` (but this exercise is special)
- Submit *profiling run* to the batch system:
  `make task1_profile`
  Study `bsub` call and `pgprof` call; try to understand

Identify Parallelism

Generate Profile

TASK 1

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Task 1: Analyze Application

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- Compile: `make task1`
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- Submit *profiling run* to the batch system:
  `make task1_profile`
  Study `bsub` call and `pgprof` call; try to understand

??? Where is hotspot? Which parts should be accelerated?

Profile of Application

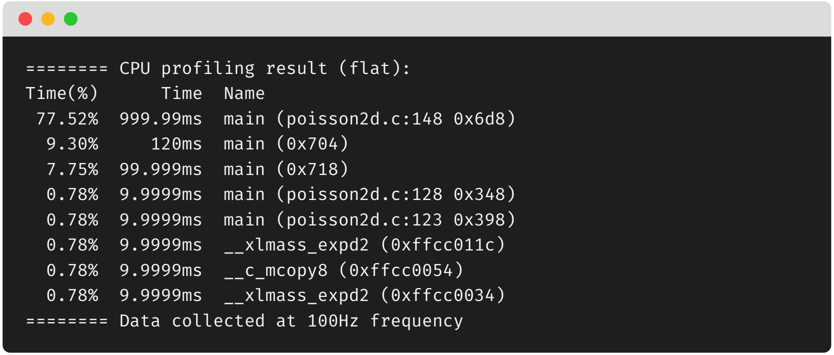
Info during compilation

```
$ 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



```
======== 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

What is independent?

```
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++ ) {
            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++;
}
```

Code Independency Analysis

What is independent?

```
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++ ) {
            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

OpenACC Workflow

Identify available parallelism

↓

Parallelize loops with OpenACC

↓

Optimize data locality

↓

Optimize loop performance

Parallel Loops: Parallel

Maybe the second most important directive

- Programmer identifies block containing parallelism → compiler generates GPU code (*kernel*)
- Program launch creates *gangs* of parallel threads on GPU
- 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}
```

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];
}
}
```

Kernel 1

Kernel 2

Parallel Jacobi

Add parallelism

TASK 2

- Add OpenACC parallelism to main loop in Jacobi
- Profile code

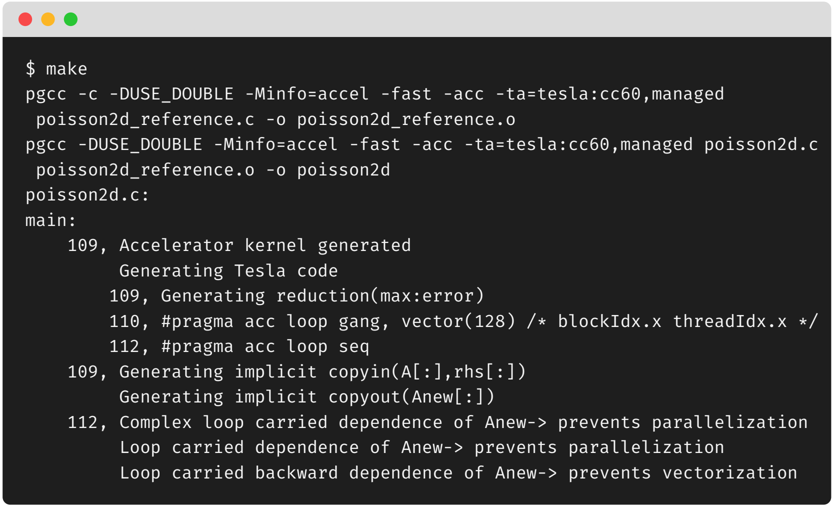
→ Congratulations, you are a GPU developer!

Task 2: A First Parallel Loop

- Change to `Task2/` directory
- Compile: `make`
- Submit parallel run to the batch system: `make run`
  Adapt the `bsub` call and run with other number of iterations, matrix sizes
- Profile: `make profile`
  `pgprof` or `nvprof` is prefix to call to `poisson2d`

Parallel Jacobi

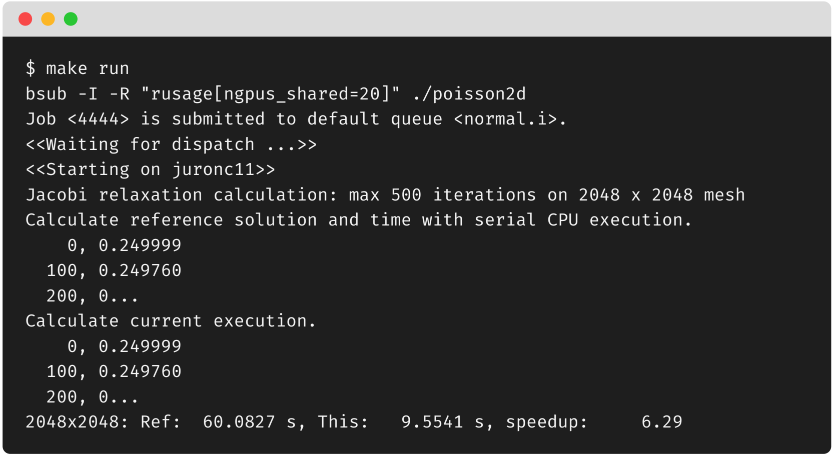
Compilation result



```
$ make
pgcc -c -DUSE_DOUBLE -Minfo=accel -fast -acc -ta=tesla:cc60,managed
 poisson2d_reference.c -o poisson2d_reference.o
pgcc -DUSE_DOUBLE -Minfo=accel -fast -acc -ta=tesla:cc60,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, Generating implicit copyin(A[:],rhs[:])
         Generating implicit copyout(Anew[:])
    112, 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
bsub -I -R "rusage[ngpus_shared=20]" ./poisson2d
Job <4444> is submitted to default queue <normal.i>.
<<Waiting for dispatch ...>>
<<Starting on juronc11>>
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:  60.0827 s, This:   9.5541 s, speedup:     6.29
```

`pgprof` / `nvprof`

NVIDIA's command line profiler

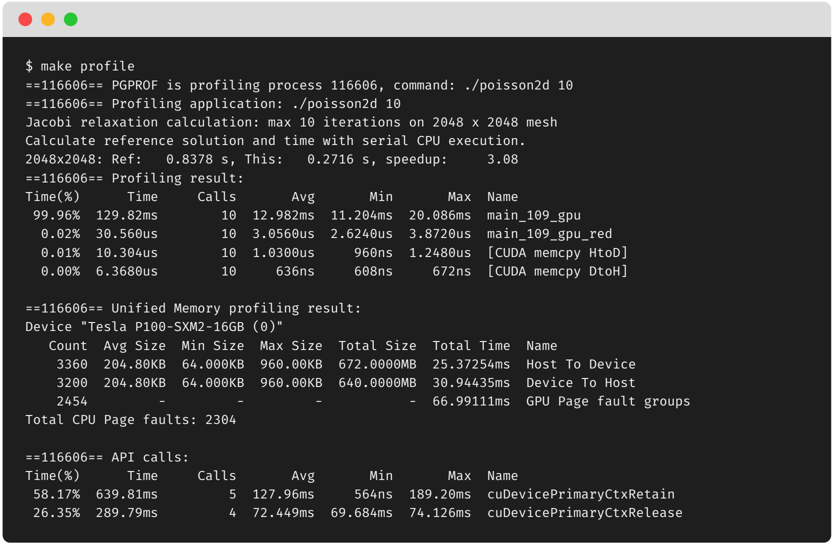
- Profiles applications, mainly for NVIDIA GPUs, but also CPU code
- GPU: CUDA kernels, API calls, OpenACC
- `pgprof` vs `nvprof`: Twins with other configurations
- Generate concise performance reports, full timelines; measure events and metrics (hardware counters)

⇒ Powerful tool for GPU application analysis

→ `http://docs.nvidia.com/cuda/profiler-users-guide/`

Profile of Jacobi

With pgprof



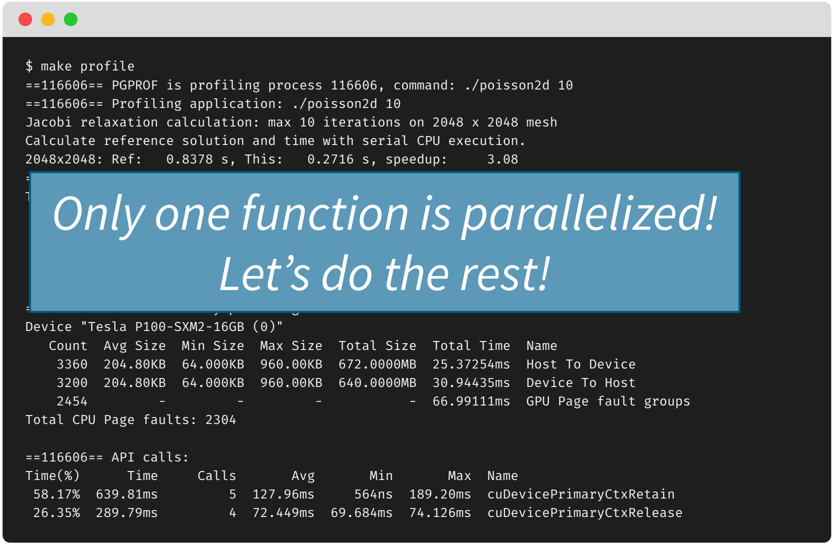
```
$ make profile
==116606== PGPROF is profiling process 116606, command: ./poisson2d 10
==116606== Profiling application: ./poisson2d 10
Jacobi relaxation calculation: max 10 iterations on 2048 x 2048 mesh
Calculate reference solution and time with serial CPU execution.
2048x2048: Ref:   0.8378 s, This:   0.2716 s, speedup:     3.08
==116606== Profiling result:
Time(%)      Time     Calls       Avg       Min       Max  Name
 99.96%  129.82ms        10  12.982ms  11.204ms  20.086ms  main_109_gpu
  0.02%  30.560us        10  3.0560us  2.6240us  3.8720us  main_109_gpu_red
  0.01%  10.304us        10  1.0300us     960ns  1.2480us  [CUDA memcpy HtoD]
  0.00%  6.3680us        10     636ns     608ns     672ns  [CUDA memcpy DtoH]

==116606== Unified Memory profiling result:
Device "Tesla P100-SXM2-16GB (0)"
   Count  Avg Size  Min Size  Max Size  Total Size  Total Time  Name
    3360  204.80KB  64.000KB  960.00KB  672.0000MB  25.37254ms  Host To Device
    3200  204.80KB  64.000KB  960.00KB  640.0000MB  30.94435ms  Device To Host
    2454         -         -         -           -  66.99111ms  GPU Page fault groups
Total CPU Page faults: 2304

==116606== API calls:
Time(%)      Time     Calls       Avg       Min       Max  Name
 58.17%  639.81ms         5  127.96ms     564ns  189.20ms  cuDevicePrimaryCtxRetain
 26.35%  289.79ms         4  72.449ms  69.684ms  74.126ms  cuDevicePrimaryCtxRelease
```

Profile of Jacobi

With `pgprof`



```
$ make profile
==116606== PGPROF is profiling process 116606, command: ./poisson2d 10
==116606== Profiling application: ./poisson2d 10
Jacobi relaxation calculation: max 10 iterations on 2048 x 2048 mesh
Calculate reference solution and time with serial CPU execution.
2048x2048: Ref:   0.8378 s, This:   0.2716 s, speedup:     3.08
=
T

=
Device "Tesla P100-SXM2-16GB (0)"
   Count  Avg Size  Min Size  Max Size  Total Size  Total Time  Name
    3360  204.80KB  64.000KB  960.00KB  672.0000MB  25.37254ms  Host To Device
    3200  204.80KB  64.000KB  960.00KB  640.0000MB  30.94435ms  Device To Host
    2454         -         -         -           -  66.99111ms  GPU Page fault groups
Total CPU Page faults: 2304

==116606== API calls:
Time(%)      Time     Calls       Avg       Min       Max  Name
 58.17%  639.81ms         5  127.96ms     564ns  189.20ms  cuDevicePrimaryCtxRetain
 26.35%  289.79ms         4  72.449ms  69.684ms  74.126ms  cuDevicePrimaryCtxRelease
```

Only one function is parallelized!

Let's do the rest!

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] ...] newline
structured block
```

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 created here

`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
  - Similar to OpenMP

`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
  - 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

Parallel Jacobi II

Add more parallelism

TASK 3

- Add OpenACC parallelism to other loops of `while` (L:123 – L:141)
- Use either `kernels` or `parallel`
- Do they perform equally well?

Task 3: More Parallel Loops

- Change to `Task3/` directory
- Change source code
- Compile: `make`
  Study the compiler output!
- Submit parallel run to the batch system: `make run`

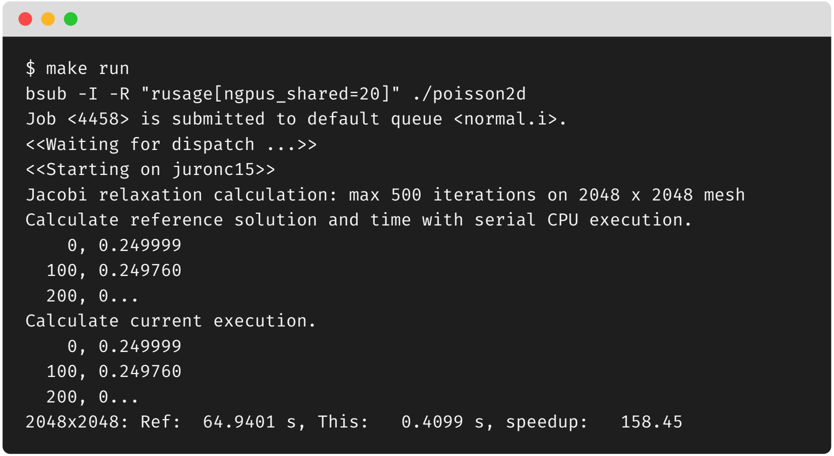
Parallel Jacobi II

Compilation result

```
$ make
pgcc -c -DUSE_DOUBLE -Minfo=accel -fast -acc -ta=tesla:cc60,managed
 poisson2d_reference.c -o poisson2d_reference.o
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

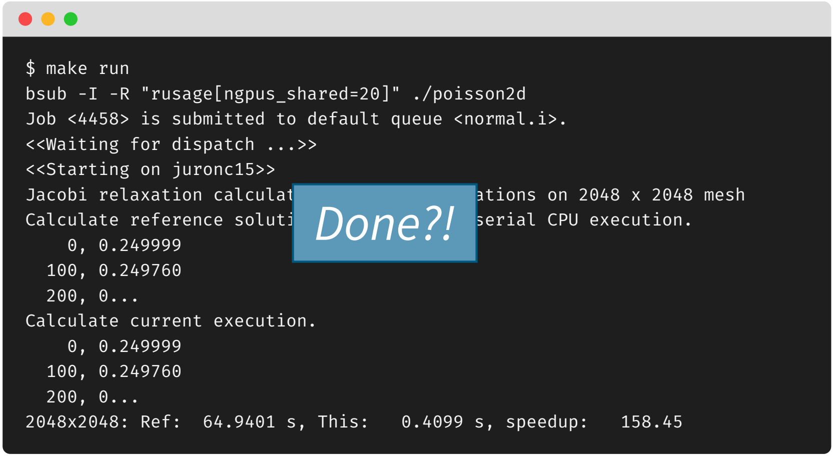
Run result



```
$ make run
bsub -I -R "rusage[ngpus_shared=20]" ./poisson2d
Job <4458> is submitted to default queue <normal.i>.
<<Waiting for dispatch ...>>
<<Starting on juronc15>>
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:  64.9401 s, This:   0.4099 s, speedup:   158.45
```

Parallel Jacobi II

Run result



```
$ make run
bsub -I -R "rusage[ngpus_shared=20]" ./poisson2d
Job <4458> is submitted to default queue <normal.i>.
<<Waiting for dispatch ...>>
<<Starting on juronc15>>
Jacobi relaxation calculat                  ations on 2048 x 2048 mesh
Calculate reference soluti                  serial CPU execution.
    0, 0.249999
  100, 0.249760
  200, 0...
Calculate current execution.
    0, 0.249999
  100, 0.249760
  200, 0...
2048x2048: Ref:  64.9401 s, This:   0.4099 s, speedup:   158.45
```

Done?!

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++;
}
```

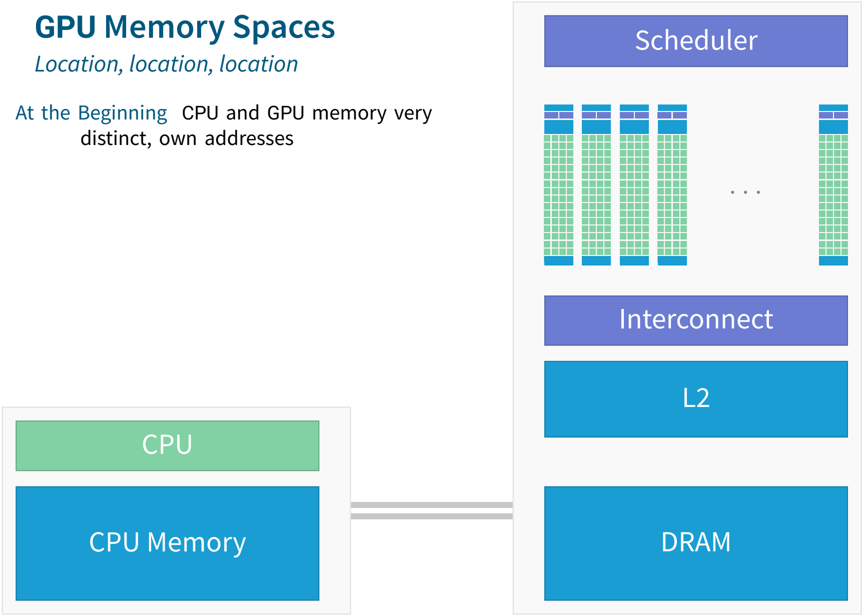
Automatic Data Transfers

- 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!

GPU Memory Spaces

Location, location, location

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



GPU Memory Spaces

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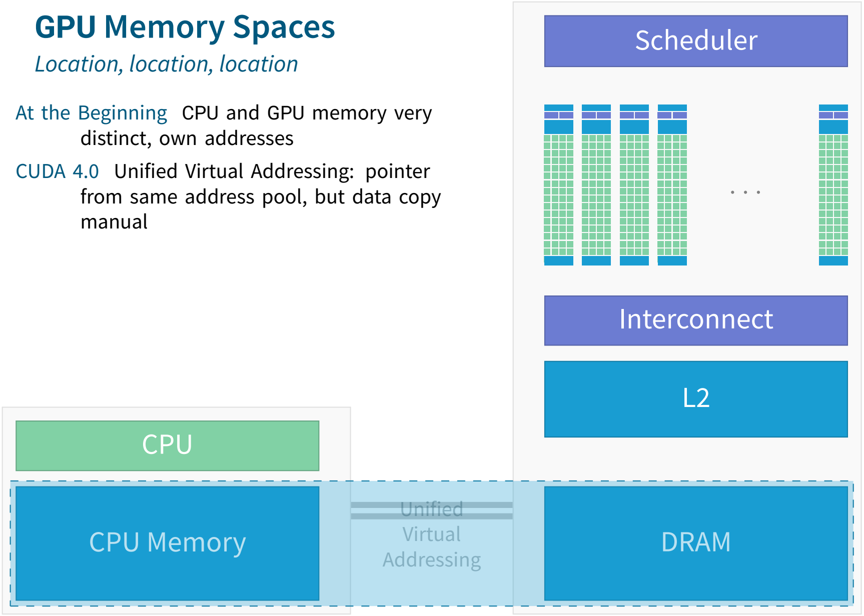
CUDA 4.0 Unified Virtual Addressing: pointer from same address pool, but data copy manual



GPU Memory Spaces

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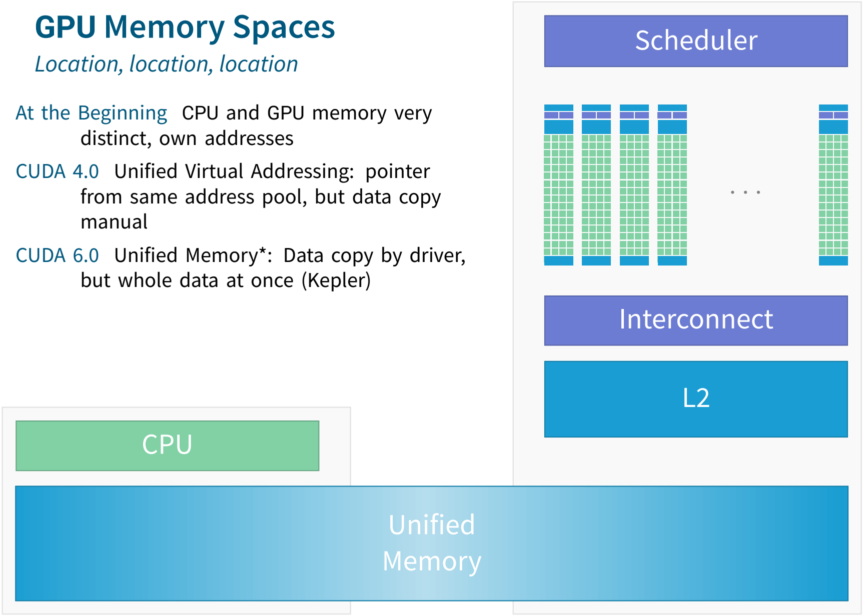
CUDA 6.0 Unified Memory*: Data copy by driver, but whole data at once (Kepler)



GPU Memory Spaces

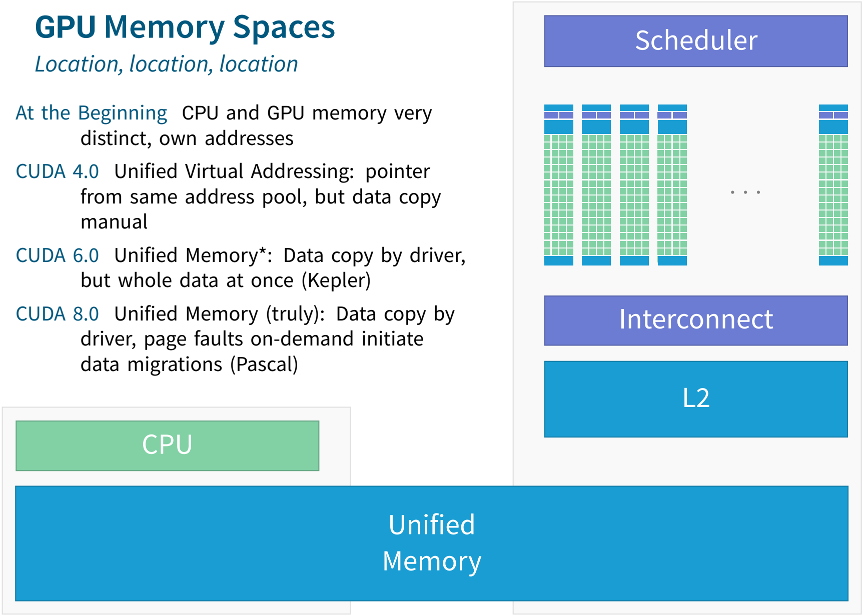
Location, location, location

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

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)



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])`

Data Copies

Tell compiler which data is needed where

TASK 4

- Add `copy` clauses to parallel regions
- Profile with Visual Profiler

Task 4: Data Copies

- Change to `Task4/` directory
- Work on TODOs
- Compile: `make`
- Submit parallel run to the batch system: `make run`
  It might take some time
- Generate profile with `make profile_tofile`

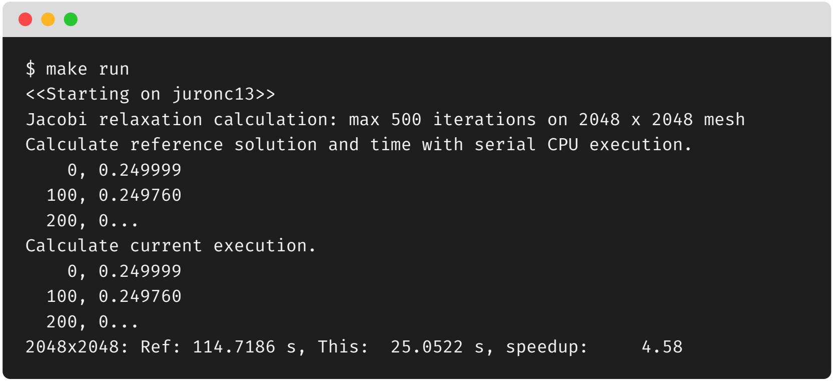
Data Copies

Compiler Output

```
$ make
pgcc -c -DUSE_DOUBLE -Minfo=accel -fast -acc -ta=tesla:cc60
poisson2d_reference.c -o poisson2d_reference.o
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 */
```

Data Copies

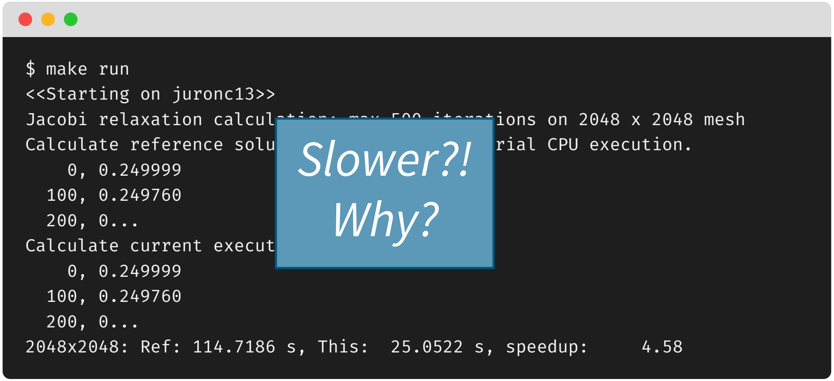
Run Result



```
$ make run
<<Starting on juronc13>>
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: 114.7186 s, This:  25.0522 s, speedup:     4.58
```

Data Copies

Run Result



```
$ make run
<<Starting on juronc13>>
Jacobi relaxation calculation: max 500 iterations on 2048 x 2048 mesh
Calculate reference solu                    rial CPU execution.
    0, 0.249999
  100, 0.249760
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    0, 0.249999
  100, 0.249760
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2048x2048: Ref: 114.7186 s, This:  25.0522 s, speedup:     4.58
```

Slower?! Why?

PGI/NVIDIA Visual Profiler

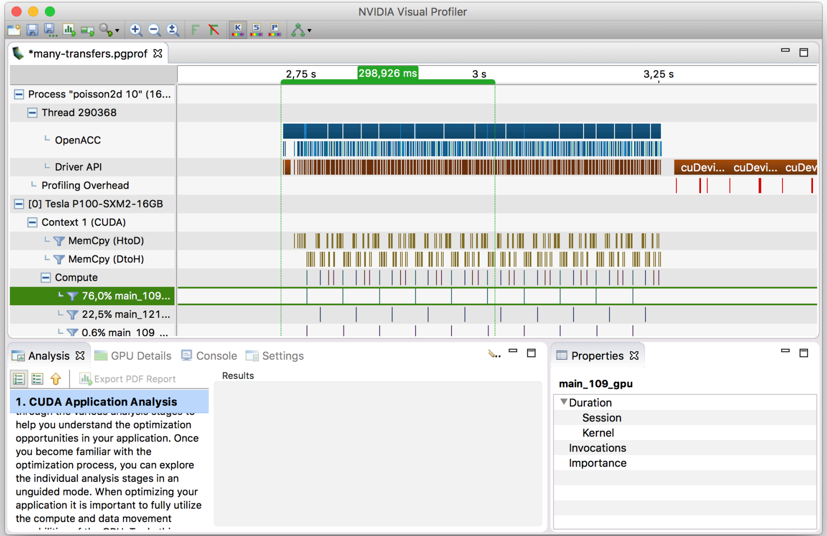
- GUI tool accompanying `pgprof` / `nvprof`

PGI	Start `pgprof` without parameters
NVIDIA	Start `nvvp`

- Timeline view of all things GPU
  $\rightarrow$ Study stages and interplay of application
- Interactive or with input from command line profilers
- View launch and run configurations
- Guided and unguided analysis

$\rightarrow$ `https://developer.nvidia.com/nvidia-visual-profiler`

PGI/NVIDIA Visual Profiler



1. CUDA Application Analysis

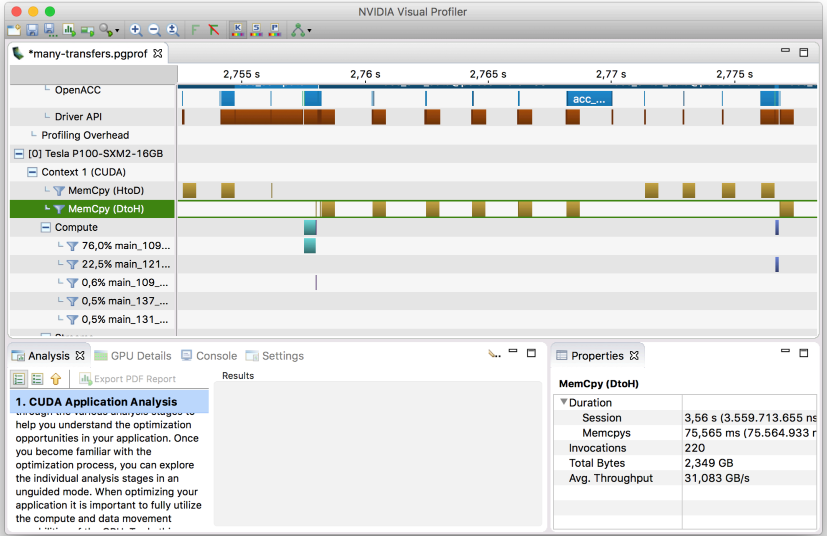
help you understand the optimization opportunities in your application. Once you become familiar with the optimization process, you can explore the individual analysis stages in an unguided mode. When optimizing your application it is important to fully utilize the compute and data movement

main_109_gpu

- Duration
  - Session
  - Kernel
- Invocations
- Importance

Jacboi in Visual Profiler

Zoom in to kernel calls



1. CUDA Application Analysis

through the various analysis stages to help you understand the optimization opportunities in your application. Once you become familiar with the optimization process, you can explore the individual analysis stages in an unguided mode. When optimizing your application it is important to fully utilize the compute and data movement

MemCpy (DtoH)

Duration	
Session	3,56 s (3.559.713.655 ns
Memcpys	75,565 ms (75.564.933 r
Invocations	220
Total Bytes	2,349 GB
Avg. Throughput	31,083 GB/s

OpenACC Workflow

Identify available parallelism

↓

Parallelize loops with OpenACC

↓

Optimize data locality

↓

Optimize loop performance

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++
}
```

Analyze Jacobi Data Flow

In code

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

$$\begin{tikzcd}\text{A, Anew resident on } \textbf{host} \arrow[r, "\text{copy}"] & \text{A, Anew resident on } \textbf{device}\end{tikzcd}$$

```
#pragma acc parallel loop
```

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

```
    iter++
}
```

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++) {
    // ...
}}
```

A, Anew resident on **device**

```
    iter++
}
```

Analyze Jacobi Data Flow

In code

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

A, Anew resident on **host** —copy→ A, Anew resident on **device**

```
#pragma acc parallel loop
```

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

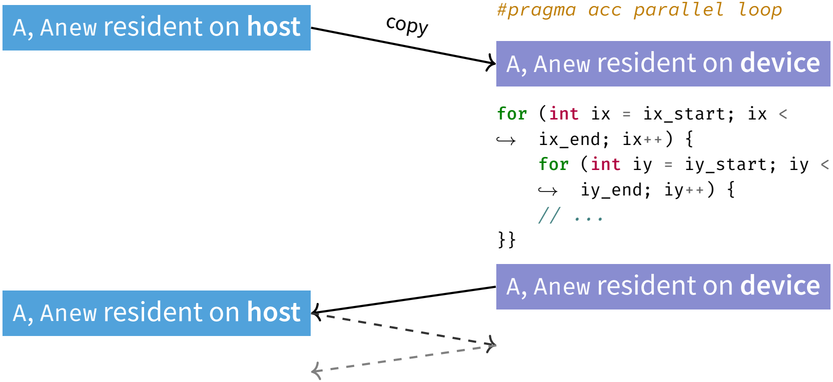
A, Anew resident on **host** ← A, Anew resident on **device**

```
    iter++
}
```

Analyze Jacobi Data Flow

In code

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



A, Anew resident on **host**
copy
A, Anew resident on **device**
A, Anew resident on **device**
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++) {
    // ...
}}
```

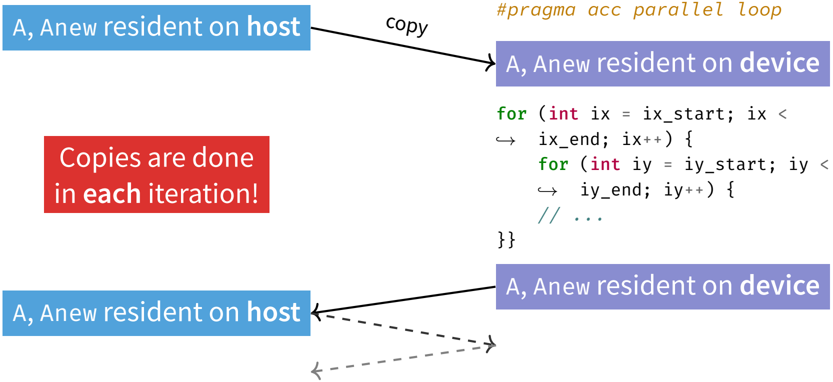
```
    iter++
}
```

Analyze Jacobi Data Flow

In code

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

```
#pragma acc parallel loop
```



A, Anew resident on **host**
copy
A, Anew resident on **device**
Copies are done in **each** iteration!
A, Anew resident on **device**
A, Anew resident on **host**

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

```
    iter++
}
```

Analyze Jacobi Data Flow

Summary

- Meanwhile, whole algorithm is using GPU
- At beginning of `while` loop, data copied to device; at end of loop, coped by to host
- Depending on type of parallel regions in `while` loop: Data copied in between regions as well

Analyze Jacobi Data Flow

Summary

- Meanwhile, whole algorithm is using GPU
- At beginning of `while` loop, data copied to device; at end of loop, coped by to host
- Depending on type of parallel regions in `while` loop: Data copied in between regions as well
- **Slow! Data copies are expensive!**

Data Regions

To manually specify data locations

- 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] ...] newline
{structured block}
```

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];
}
}
```

Data Region

One data set to rule them all

TASK 5

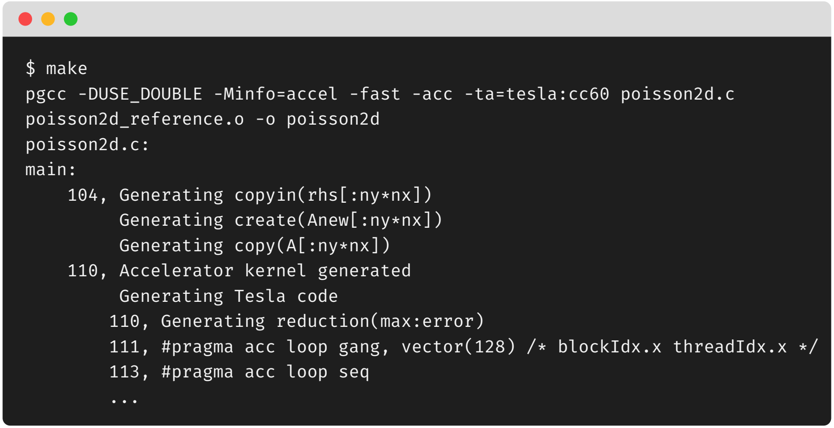
- Add `data` region such that all data resides on device during iterations
- Optional: See your success in Visual Profiler

Task 5: Data Region

- Change to `Task5/` directory
- Work on TODOs
- Compile: `make`
- Submit to the batch system: `make run`
- Generate profile with `make profile_tofile`

Data Region

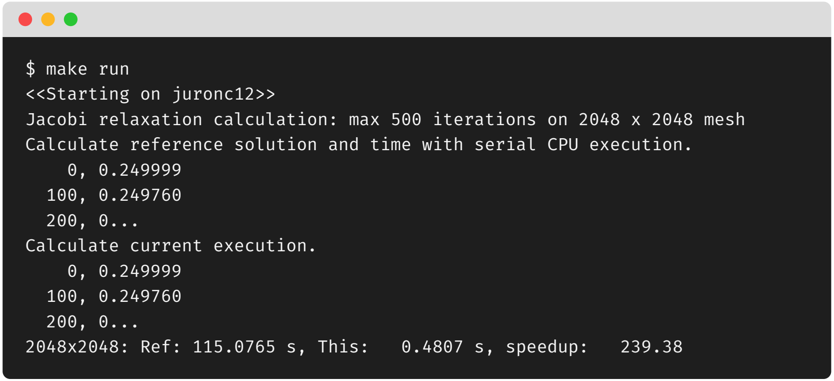
Compiler Output



```
$ make
pgcc -DUSE_DOUBLE -Minfo=accel -fast -acc -ta=tesla:cc60 poisson2d.c
poisson2d_reference.o -o poisson2d
poisson2d.c:
main:
    104, Generating copyin(rhs[:ny*nx])
         Generating create(Anew[:ny*nx])
         Generating copy(A[:ny*nx])
    110, Accelerator kernel generated
         Generating Tesla code
        110, Generating reduction(max:error)
        111, #pragma acc loop gang, vector(128) /* blockIdx.x threadIdx.x */
        113, #pragma acc loop seq
        ...
```

Data Region

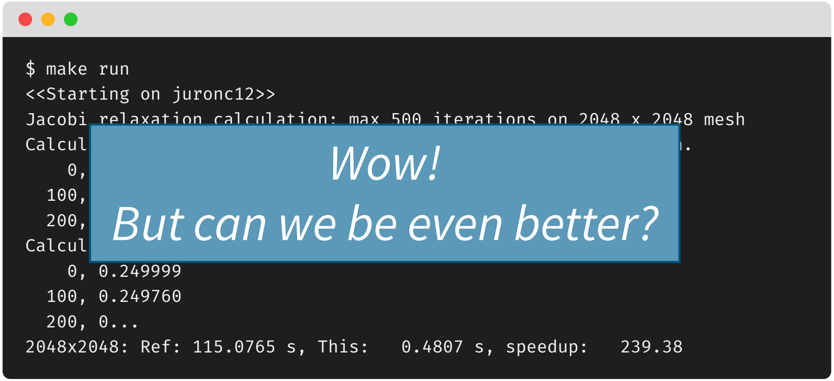
Run Result



```
$ make run
<<Starting on juronc12>>
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: 115.0765 s, This:   0.4807 s, speedup:   239.38
```

Data Region

Run Result



```
$ make run
<<Starting on juronc12>>
Jacobi relaxation calculation: max 500 iterations on 2048 x 2048 mesh
Calcul                                                               .
    0,
  100,
  200,
Calcul
    0, 0.249999
  100, 0.249760
  200, 0...
2048x2048: Ref: 115.0765 s, This:   0.4807 s, speedup:   239.38
```

Wow!

But can we be even better?

OpenACC Workflow

Identify available parallelism

↓

Parallelize loops with OpenACC

↓

Optimize data locality

↓

Optimize loop performance

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 }
```

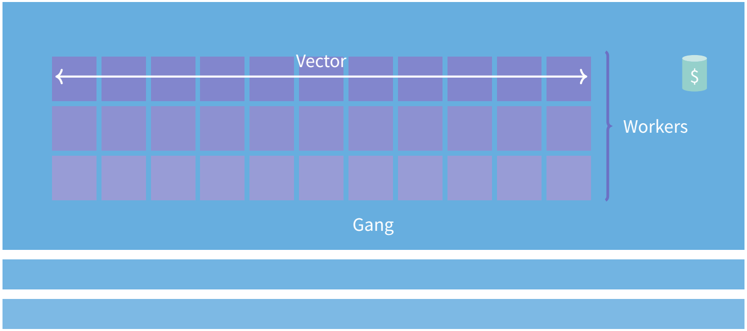
Understanding Compiler Output

```
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



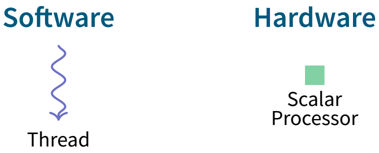
Vector
Vector threads work in lockstep (SIMD/SIMT parallelism)

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

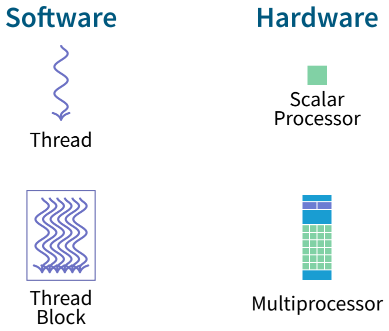
CUDA Execution Model



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

CUDA Parallelism

CUDA Execution Model

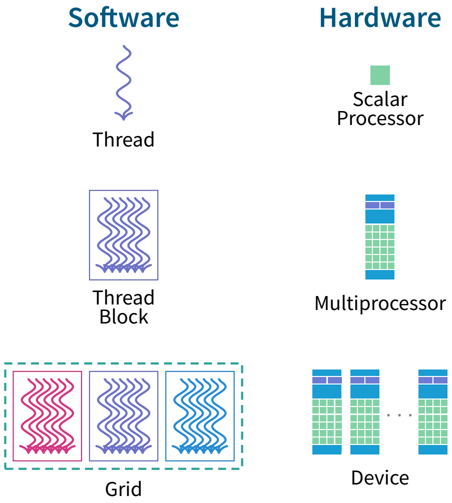


- **Threads** executed by scalar processors (*CUDA cores*)

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

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

Unsequentialize inner loop

TASK 6

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

Task 6: More Parallelism

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

More Parallelism

Compiler Output

```
$ make
pgcc -DUSE_DOUBLE -Minfo=accel -fast -acc -ta=tesla:cc60 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 */
        ...
```

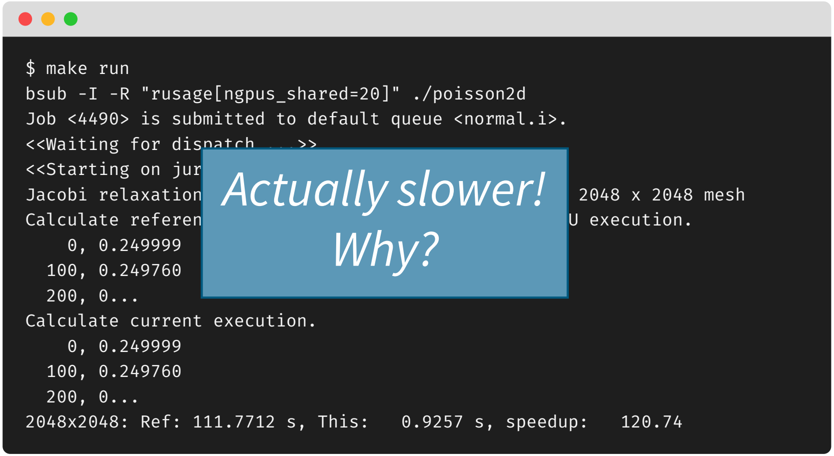
Data Region

Run Result

```
$ make run
bsub -I -R "rusage[ngpus_shared=20]" ./poisson2d
Job <4490> is submitted to default queue <normal.i>.
<<Waiting for dispatch ...>>
<<Starting on juronc11>>
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: 111.7712 s, This:   0.9257 s, speedup:   120.74
```

Data Region

Run Result



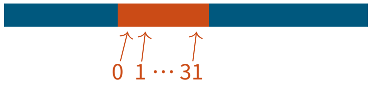
```
$ make run
bsub -I -R "rusage[ngpus_shared=20]" ./poisson2d
Job <4490> is submitted to default queue <normal.i>.
<<Waiting for dispatch ...>>
<<Starting on jur
Jacobi relaxation                              2048 x 2048 mesh
Calculate referen                              U execution.
    0, 0.249999
  100, 0.249760
  200, 0...
Calculate current execution.
    0, 0.249999
  100, 0.249760
  200, 0...
2048x2048: Ref: 111.7712 s, This:   0.9257 s, speedup:   120.74
```

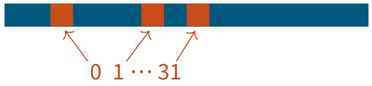
Actually slower!
Why?

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’s Access Pattern

Coalesced or uncoalesced, that is the question

```
#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]));
        //...
```

- Fast-running index: `ix`
- Slow-running index: `iy`
- But vector loop over `iy`!
- Consecutive threads access far away memory location!

Fixing Access Pattern

Loop change

TASK 7

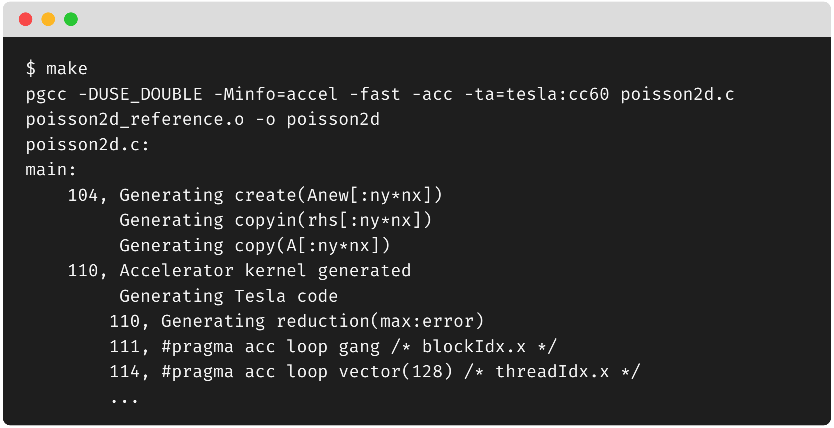
- Interchange loop order for Jacobi loops
- Also: Compare to loop-fixed CPU reference version

Task 7: Loop Ordering

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

Fixing Access Pattern

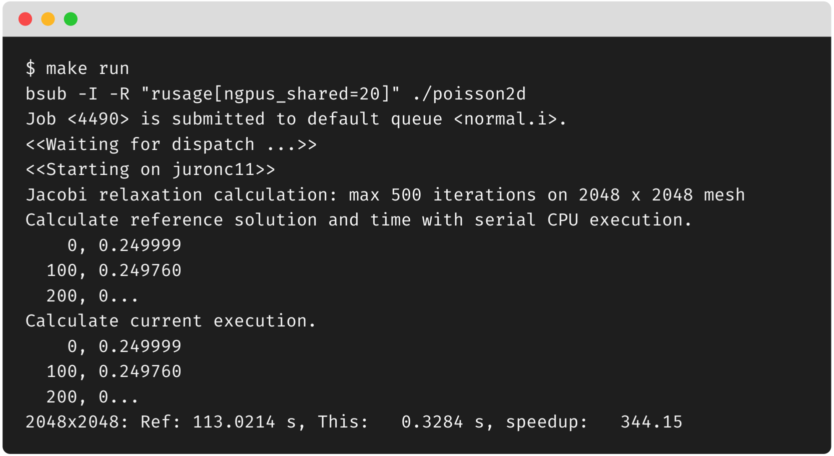
Compiler output (unchanged)



```
$ make
pgcc -DUSE_DOUBLE -Minfo=accel -fast -acc -ta=tesla:cc60 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

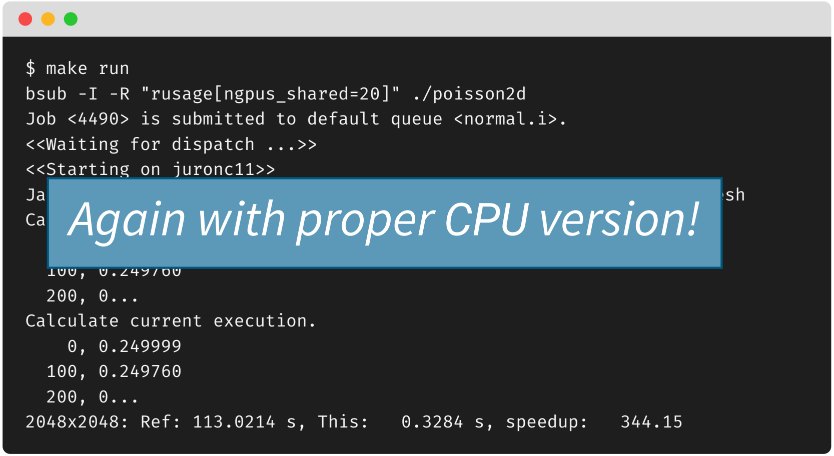
Run Result



```
$ make run
bsub -I -R "rusage[ngpus_shared=20]" ./poisson2d
Job <4490> is submitted to default queue <normal.i>.
<<Waiting for dispatch ...>>
<<Starting on juronc11>>
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



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Job <4490> is submitted to default queue <normal.i>.
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<<Starting on juronc11>>
Ja                                                     sh
Ca

  100, 0.249760
  200, 0...
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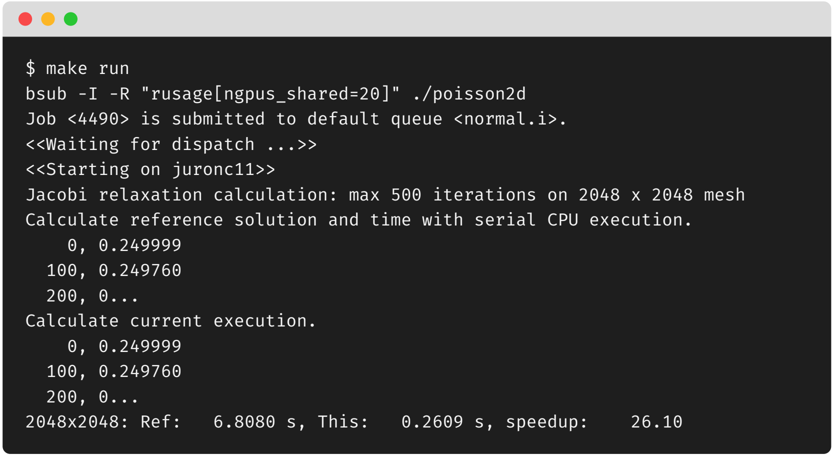
  100, 0.249760
  200, 0...
2048x2048: Ref: 113.0214 s, This:   0.3284 s, speedup:   344.15
```

Again with proper CPU version!

Fixing Access Pattern

Run Result II



```
$ make run
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Job <4490> is submitted to default queue <normal.i>.
<<Waiting for dispatch ...>>
<<Starting on juronc11>>
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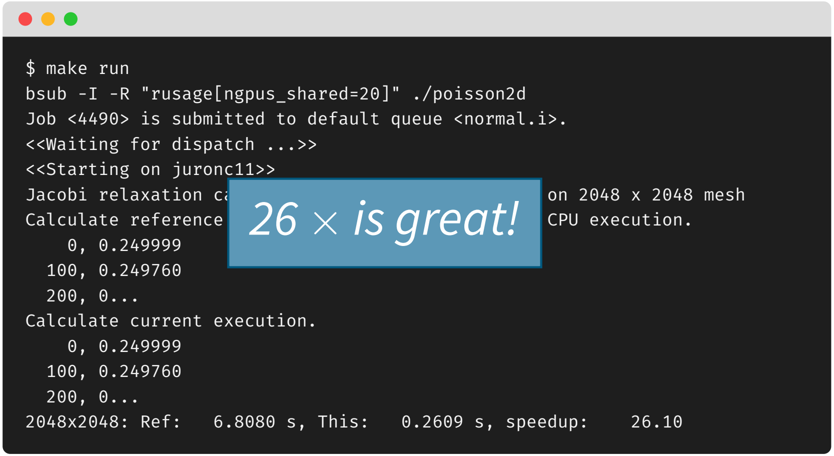
  100, 0.249760
  200, 0...
Calculate current execution.
    0, 0.249999
  100, 0.249760
  200, 0...
2048x2048: Ref:   6.8080 s, This:   0.2609 s, speedup:    26.10
```

Fixing Access Pattern

Run Result II



```
$ make run
bsub -I -R "rusage[ngpus_shared=20]" ./poisson2d
Job <4490> is submitted to default queue <normal.i>.
<<Waiting for dispatch ...>>
<<Starting on juronc11>>
Jacobi relaxation ca                              on 2048 x 2048 mesh
Calculate reference                               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
```

26 × is great!

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

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  - Memory pages of memory can be moved by kernel, e.g. swapped to disk
  - Additional indirection
- 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`

OpenACC Workflow

Identify available parallelism

↓

Parallelize loops with OpenACC

↓

Optimize data locality

↓

Optimize loop performance

Interoperability

Interoperability

- OpenACC can operate together with
  - Applications
  - Libraries
  - CUDA

The Keyword

OpenACC's Rosetta Stone

```
host_data use_device
```

The Keyword

OpenACC's Rosetta Stone

`host_data use_device`

- Background
  - — GPU and CPU are different devices, have different memory
  - → Distinct address spaces
- OpenACC hides handling of addresses from user
  - — For every chunk of accelerated data, **two** addresses exist
  - — One for CPU data, one for GPU data
  - — OpenACC uses appropriate address in accelerated kernel
- **But:** Automatic handling not working when out of OpenACC (OpenACC will default to host address)

→ `host_data use_device` uses the address of the GPU device data for scope

The host_data Construct

That's all you need

- Usage:

```
double* foo = new double[N];          // foo on Host
#pragma acc data copyin(foo[0:N])  // foo on Device
{
  ...
  #pragma acc host_data use_device(foo)
  some_lfunc(foo);                    // Device: OK!
  ...
}
```

- Directive can be used for structured block as well

The Inverse: `deviceptr`

When CUDA is involved

- For the inverse case:
  - Data has been copied by CUDA or a CUDA-using library
  - Pointer to data residing on devices is returned
  - $\rightarrow$ Use this data in OpenACC context
- `deviceptr` clause declares data to be on device

The Inverse: `deviceptr`

When CUDA is involved

- For the inverse case:
  - — Data has been copied by CUDA or a CUDA-using library
  - — Pointer to data residing on devices is returned
  - → Use this data in OpenACC context
- `deviceptr` clause declares data to be on device
- Usage:

```
float * n;
int n = 4223;
cudaMalloc((void**)&x,(size_t)n*sizeof(float));
// ...
#pragma acc kernels deviceptr(x)
for (int i = 0; i < n; i++) {
    x[i] = i;
}
```

Interoperability

Tasks

Task 1

Introduction to BLAS

- Use case: Anything linear algebra
- **BLAS**: Basic Linear Algebra Subprograms
  - Vector-vector, vector-matrix, matrix-matrix operations
  - Specification of routines
  - Examples: *S*`AXPY`, *D*`GEMV`, *Z*`GEMM`

  → `http://www.netlib.org/blas/`
- **cuBLAS**: NVIDIA's linear algebra routines with BLAS interface, readily accelerated

  → `http://docs.nvidia.com/cuda/cublas/`
- **Task 1**: Use cuBLAS for vector addition, everything else with OpenACC

Task 8-1

cuBLAS OpenACC Interaction

- cuBLAS routine used:

```
cublasDaxpy(cublasHandle_t handle, int n,
            const double         *alpha,
            const double         *x, int incx,
            double               *y, int incy)
```

- `handle` capsules GPU auxiliary data, needs to be created and destroyed with `cublasCreate` and `cublasDestroy`
- `x` and `y` point to addresses on **device**!
- cuBLAS library needs to be linked with `-lcublas`

Task 8-1

Vector Addition with cuBLAS

TASK 8-1

- Use cuBLAS for vector addition

Task 8-1: OpenACC +cuBLAS

- Change to `Task8-1/` directory
- Work on TODOs in `vecAddRed.c`
  - Use `host_data use_device` to provide correct pointer
  - Check cuBLAS documentation for details on `cublasDaxpy()`
- Compile: `make`
- Submit to the batch system: `make brun`

Task 8-2

CUDA Need-to-Know

- Use case:
  - Working on legacy code
  - Need the *raw* power (/flexibility) of CUDA
- CUDA need-to-knows:
  - Thread → Block → Grid
    Total number of threads should map to your problem; threads are alway given per block
  - A kernel is called from every thread on GPU device
    Number of kernel threads: *triple chevron syntax*

    ```
    kernel<<<nBlocks, nThreads>>>(arg1, arg2, ...)
    ```
  - Kernel: Function with `__global__` prefix
    Aware of its index by global variables, e.g. `threadIdx.x`

→ http://docs.nvidia.com/cuda/

Task 8-2

Vector Addition with CUDA Kernel

TASK 8-2

- CUDA kernel for vector addition, rest OpenACC
- Marrying CUDA **C** and OpenACC:
  - All direct CUDA interaction wrapped in wrapper file `cudaWrapper.cu`, compiled with `nvcc` to object file (`-c`)
  - `vecAddRed.c` calls external function from `cudaWrapper.cu` (`extern`)

Task 8-2: OpenACC +CUDA

- Change to `Task8-2/` directory
- Work on TODOs in `vecAddRed.c` and `cublasWrapper.cu`
  - Use `host_data use_device` to provide correct pointer
  - Implement computation in kernel, implement call of kernel
- Compile: `make`
- Submit to the batch system: `make brun`

Task 8-3

Vector Addition with Thrust

8-3

- **Thrust**
  - Template library for CUDA C/C++ (similar to STL)
  - Offers many pre-made algorithms for popular computing tasks
  - Usually works with C++ iterators, but understands C arrays as well
  - → `http://thrust.github.io/`
- Use Thrust for reduction, everything else of vector addition with OpenACC

Task 8-3: OpenACC +CUDA

- Change to `Task8-3/` directory
- Work on TODOs in `vecAddRed.c` and `thrustWrapper.cu`
  - Use `host_data use_device` to provide correct pointer
  - Implement call to `thrust::reduce` using `c_ptr`
- Compile: `make`
- Submit to the batch system: `make brun`

Task 8-4

Stating the Problem

- We want to solve the Poisson equation

$$\Delta\Phi(x, y) = -\rho(x, y)$$

  with periodic boundary conditions in x and y
- Needed, e.g., for finding electrostatic potential Φ for a given charge distribution ρ
- Model problem

$$\begin{aligned} \rho(x, y) &= \cos(4\pi x)\sin(2\pi y) \\ (x, y) &\in [0, 1)^2 \end{aligned}$$

- Analytically known: $\Phi(x, y) = \Phi_0 \cos(4\pi x)\sin(2\pi y)$
- Let's solve the Poisson equation with a Fourier Transform!

Task 8-4

Introduction to Fourier Transforms

- Discrete Fourier Transform and Re-Transform:

$$\hat{f}_k = \sum_{j=0}^{N-1} f_j e^{-\frac{2\pi i k}{N} j} \quad \Leftrightarrow \quad f_j = \sum_{k=0}^{N-1} \hat{f}_k e^{\frac{2\pi i j}{N} k}$$

- Time for all $\hat{f}_k$: $\mathcal{O}(N^2)$
- Fast Fourier Transform: Recursively splitting $\rightarrow \mathcal{O}(N \log(N))$
- Find derivatives in Fourier space:

$$f'_j = \sum_{k=0}^{N-1} i k \hat{f}_k e^{\frac{2\pi i j}{N} k}$$

It's just multiplying by ik!

Task 8-4

Plan for FFT Poisson Solution

Start with charge density ρ

1. Fourier-transform ρ
   $\hat{\rho} \leftarrow \mathcal{F}(\rho)$
2. *Integrate* ρ in Fourier space twice
   $\hat{\phi} \leftarrow -\hat{\rho} / \left(k_x^2 + k_y^2\right)$
3. Inverse Fourier-transform $\hat{\phi}$
   $\phi \leftarrow \mathcal{F}^{-1}(\hat{\phi})$

Task 8-4

Plan for FFT Poisson Solution

Start with charge density ρ

1. Fourier-transform ρ
   $\hat{\rho} \leftarrow \mathcal{F}(\rho)$

   cuFFT

2. *Integrate* ρ in Fourier space twice
   $\hat{\phi} \leftarrow -\hat{\rho} / \left(k_x^2 + k_y^2\right)$

   OpenACC

3. Inverse Fourier-transform $\hat{\phi}$
   $\phi \leftarrow \mathcal{F}^{-1}(\hat{\phi})$

   cuFFT

Task 8-4

cuFFT

- cuFFT: NVIDIA’s (Fast) Fourier Transform library
  - 1D, 2D, 3D transforms; complex and real data types
  - Asynchronous execution
  - Modeled after FFTW library (API)
  - Part of CUDA Toolkit
  - → `https://developer.nvidia.com/cufft`

```
cufftDoubleComplex *src, *tgt;                 // Device data!
cufftHandle plan;
// Setup 2d complex-complex trafo w/ dimensions (Nx, Ny)
cufftCreatePlan(plan, Nx, Ny, CUFFT_Z2Z);
cufftExecZ2Z(plan, src, tgt, CUFFT_FORWARD); // FFT
cufftExecZ2Z(plan, tgt, tgt, CUFFT_INVERSE); // iFFT
// Inplace trafo  ^-----^
cufftDestroy(plan);                            // Clean-up
```

Task 8-4

Synchronizing cuFFT

- CUDA Streams enable interleaving of computational tasks
- cuFFT uses streams for asynchronous execution
- cuFFT runs in default CUDA stream;
  OpenACC not $\rightarrow$ trouble

$\Rightarrow$ Force cuFFT on OpenACC stream

```
#include <openacc.h>
// Obtain the OpenACC default stream id
cudaStream_t accStream =
   (cudaStream_t) acc_get_cuda_stream(acc_async_sync) ;
// Execute all cufft calls on this stream
cufftSetStream(accStream);
```

Task 8-4

OpenACC and cuFFT

TASK 8-4

- Use case: Fourier transforms
- Use cuFFT and OpenACC to solve Poisson's Equation

Task 8-4: OpenACC +cuFFT

- Change to `Task8-4/` directory
- Work on TODOs in `poisson.c`

`solveRSpace`	Force cuFFT on correct stream; implement data handling with `host_data use_device`
`solveKSpace`	Implement data handling and parallelism

- Compile: `make`
- Submit to the batch system: `make brun`

Conclusions

Conclusions

- OpenACC directives and clauses
  `#pragma acc parallel loop copyin(A[0:N]) reduction(max:err) vector`
- Start easy, optimize from there
- PGI / NVIDIA Visual Profiler help to find bottlenecks
- OpenACC is interoperable to other GPU programming models
- Don’t forget the CPU version!

Conclusions

- OpenACC directives and clauses
  `#pragma acc parallel loop copyin(A[0:N]) reduction(max:err) vector`
- Start easy, optimize from there
- PGI / NVIDIA Visual Profiler help to find bottlenecks
- OpenACC is interoperable to other GPU programming models
- Don’t forget the CPU version!

Thank you
for your attention!
a.herten@fz-juelich.de

List of Tasks

Task 0*: Setup
Task 0: Getting Started
Task 1: Analyze Application
Task 2: A First Parallel Loop
Task 3: More Parallel Loops
Task 4: Data Copies
Task 5: Data Region
Task 6: More Parallelism
Task 7: Loop Ordering
Task 7’: Pinned Memory
Task 8-1: OpenACC +cuBLAS
Task 8-2: OpenACC +CUDA
Task 8-3: OpenACC +CUDA
Task 8-4: OpenACC +cuFFT

Glossary I

API	A programmatic interface to software by well-defined functions. Short for application programming interface. 79
CUDA	Computing platform for GPUs from NVIDIA. Provides, among others, CUDA C/C++. 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 33, 46, 79, 93, 94, 95, 96, 131, 152, 156, 157, 162, 163, 164, 169, 170, 176, 177
GCC	The GNU Compiler Collection, the collection of open source compilers, among others for C and Fortran. 45, 49

Glossary II

NVIDIA	US technology company creating GPUs. 39, 79, 92, 97, 98, 105, 106, 146, 147, 148, 159, 169, 173, 174, 177
OpenACC	Directive-based programming, primarily for many-core machines. 2, 33, 38, 39, 40, 41, 42, 43, 44, 46, 47, 48, 49, 50, 51, 52, 53, 62, 69, 70, 72, 74, 76, 79, 82, 87, 97, 98, 99, 100, 108, 117, 124, 127, 131, 132, 146, 147, 148, 150, 152, 153, 154, 156, 157, 159, 160, 161, 163, 164, 167, 168, 170, 171, 173, 174, 176
OpenCL	The *Open Computing Language*. Framework for writing code for heterogeneous architectures (CPU, GPU, DSP, FPGA). The alternative to CUDA. 33

Glossary III

OpenMP	Directive-based programming, primarily for multi-threaded machines. 2, 33, 40, 41, 42, 50, 84, 85, 86
Pascal	GPU architecture from NVIDIA (announced 2016). 93, 94, 95, 96
Thrust	A parallel algorithms library for (among others) GPUs. See `https://thrust.github.io/`. 33
CPU	Central Processing Unit. 4, 5, 6, 7, 8, 9, 10, 11, 12, 45, 50, 79, 93, 94, 95, 96, 140, 143, 153, 154, 173, 174, 177

Glossary IV

GPU Graphics Processing Unit. 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 23, 24, 25, 26, 33, 45, 48, 50, 70, 76, 79, 92, 93, 94, 95, 96, 97, 98, 105, 115, 116, 118, 146, 147, 148, 153, 154, 160, 162, 173, 174, 177

References I

[3] Gene M. Amdahl. “Validity of the Single Processor Approach to Achieving Large Scale Computing Capabilities”. In: *Proceedings of the April 18-20, 1967, Spring Joint Computer Conference*. AFIPS ’67 (Spring). Atlantic City, New Jersey: ACM, 1967, pp. 483–485. DOI: `10.1145/1465482.1465560`. URL: `http://doi.acm.org/10.1145/1465482.1465560`.

[4] John L. Gustafson. “Reevaluating Amdahl’s Law”. In: *Commun. ACM* 31.5 (May 1988), pp. 532–533. ISSN: 0001-0782. DOI: `10.1145/42411.42415`. URL: `http://doi.acm.org/10.1145/42411.42415`.

References: Images, Graphics

[1] Mark Lee. *Picture: kawasaki ninja*. URL: `https://www.flickr.com/photos/pochacco20/39030210/` (pages 4, 5).

[2] Shearings Holidays. *Picture: Shearings coach 636*. URL: `https://www.flickr.com/photos/shearings/13583388025/` (pages 4, 5).