Introduction to OpenACC directives

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Science Computing Researcher Engineer

Summary

1. Introduction
2. Parallelism
   - Offloaded Execution
     - Parallel Directives
   - Work Sharing
     - Parallel Loop
     - Merging Directives
     - Reductions
     - Memory Access
   - Routines
   - Data Management
     - Definition
     - Data Clauses
     - Shape of Arrays
     - Data Region
   - Asynchronism
3. GPU Debugging
   - PGI Auto-compare
4. Optimization Example
   - Game of Life

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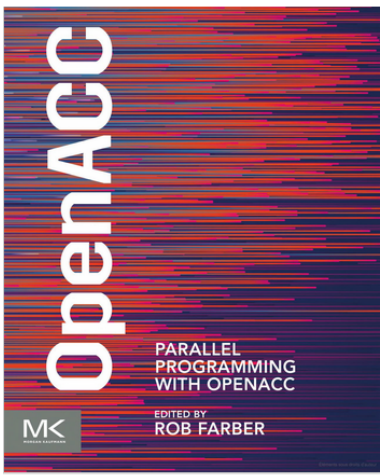
References

IDRIS/CNRS - FRANCE

- Material provided by the Institute for *Development and Resources in Intensive Scientific Computing* (IDRIS/CNRS);
- One can find more information on the ▸ IDRIS website.

Parallel Programming with OpenACC



- Farber, R. (2016).*Parallel programming with OpenACC.* Elsevier.

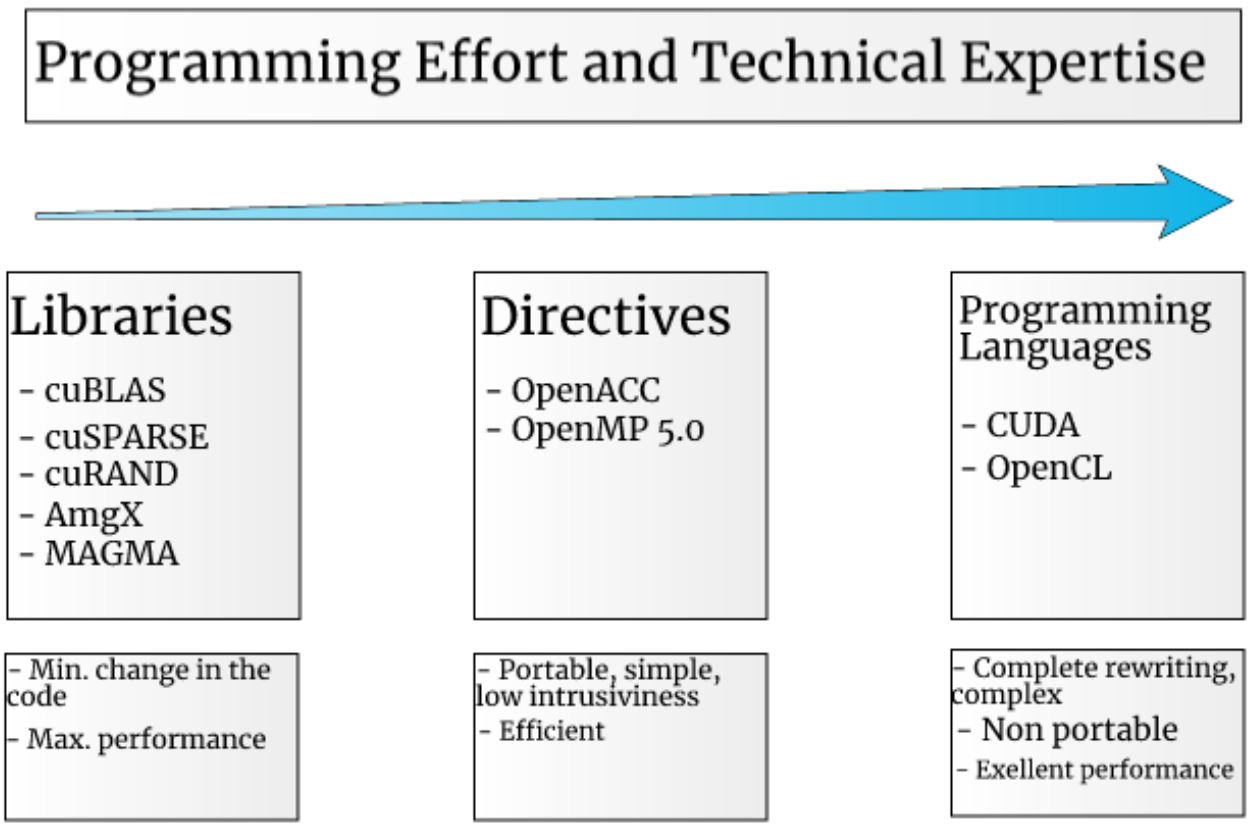
Introduction

Source files

- The source files can be downloaded at the given GitHub repository:
  - ▸ junqjr's repository

Introduction

The Ways to GPU



Introduction

Brief History

OpenACC

- https://www.openacc.org
- AMD, CRAY, NVIDIA, Oak Ridge
- First standard 1.0 (11/2011)
- Last standard 3.0 (11/2019)
- Main compilers:
  - PGI;
  - CRAY (only CRAY hardware);
  - GNU ($\geq$ 5.7).

OpenMP

- https://www.openmp.org
- First standard 4.5 (11/2015)
- Last standard 5.0 (11/2018)
- Main compilers:
  - PGI;
  - CRAY (only CRAY hardware);
  - CLANG;
  - IBM XL;
  - GNU ($\geq$ 7.0).

Introduction

Definitions

- Thread : Execution entity, serial thread of execution that runs any valid C/C++ or Fortran code;
- Worker(OpenACC) : Fine-grain parallelism. Group of threads that can operate together in a SIMD or vector fashion;
- Vector: Group of threads executing the same instruction (SIMT). Vectors cause worker threads to work in lockstep when running vector or SIMD instruction;
- Gang(OpenACC)/Teams(OpenMP) : Coarse-grain parallelism. Groups of workers which operate independently of each other;
- SIMT : Single Instruction Multiple Threads;
- SIMD : Single Instruction Multiple Data;
- Device : Accelerator on which execution can be offloaded (ex: GPU);
- Host : Machine hosting 1 or more accelerators and in charge of execution control;
- Kernel : Piece of code that runs on an accelerator;
- Execution thread : Sequence of kernels to be executed on an accelerator.

Introduction

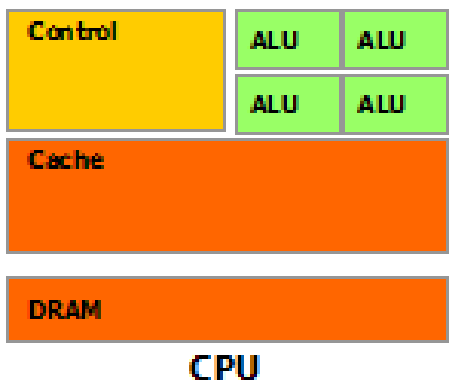
CPU and GPU Architectures

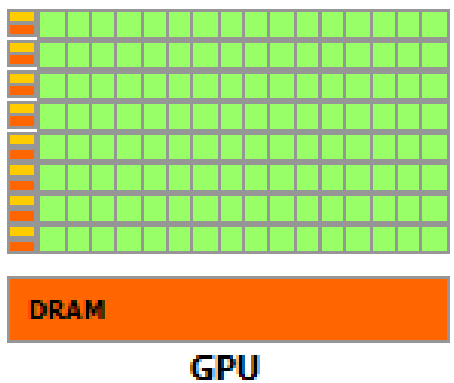
CPU

- Several Arithmetic Logic Units (ALU);
- Control unit to control the ALUs;
- Fast cache memory;
- Dynamic Random Access Memory;
- High capacity memory;
- $\approx 1/8$ of the area is dedicated to the computing.

GPU

- Hundreds of (ALU), grouped in several multiprocessors;
- Several control units;
- Several cache memories;
- One Dynamic Random Access Memory;
- High bandwidth memory;
- $\approx 3/4$ of the area is dedicated to the computing.





GPUs are designed such that more transistors are devoted to data processing rather than data caching and flow control as CPUs.

Introduction

CPU and GPU Architectures

- OpenACC uses vectorization as an parallelism approach.
- Vector instructions use hardware to effectively (from a software point of view) perform a number of operation at the same time.

Modern x86 processor

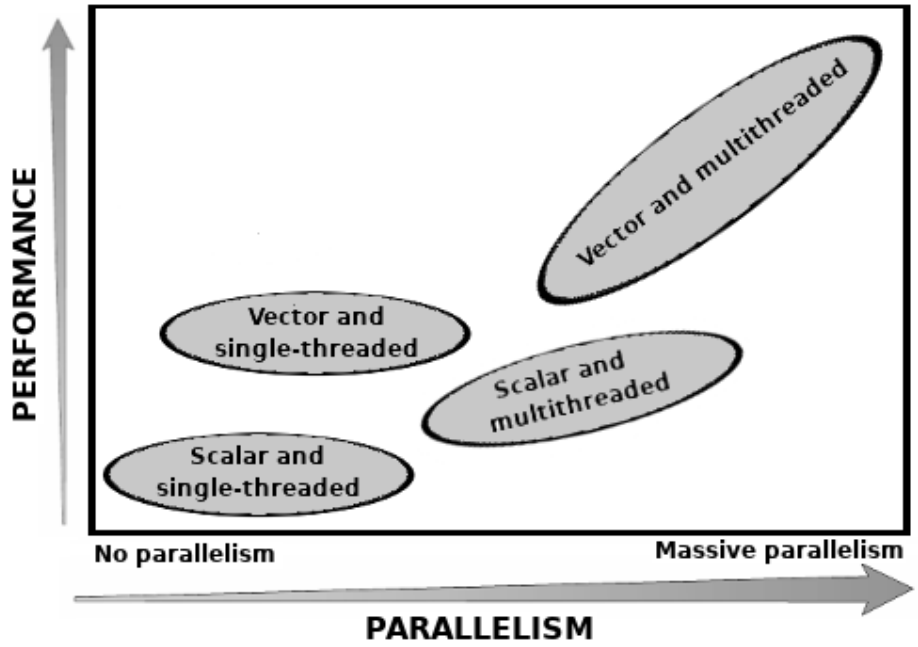
- Can issue vector instructions to hardware vector units (or multiple per-core vector units) to perform multiple data-parallel operations at the same time;
- The AVX-512 vector instruction set is the current longest vector instruction set on x86 architectures tha can perform up to 16 concurrent single-precision, 32-bit floating point operations per instruction call.
- The approach can result in a large overall performance gain when all the vector units on all the cores in a high-end processor are fully utilized.

GPU architecture

- GPUs utilize SIMD instructions to achieve similar performance multiplier effect, except that vectorization naturally occurs in hardware across a group of threads referred to as a *warp* (CUDA terminology for a set of 32 threads) rather than through the explicit inssuance of vector instructions by the programmer or compiler.

Introduction

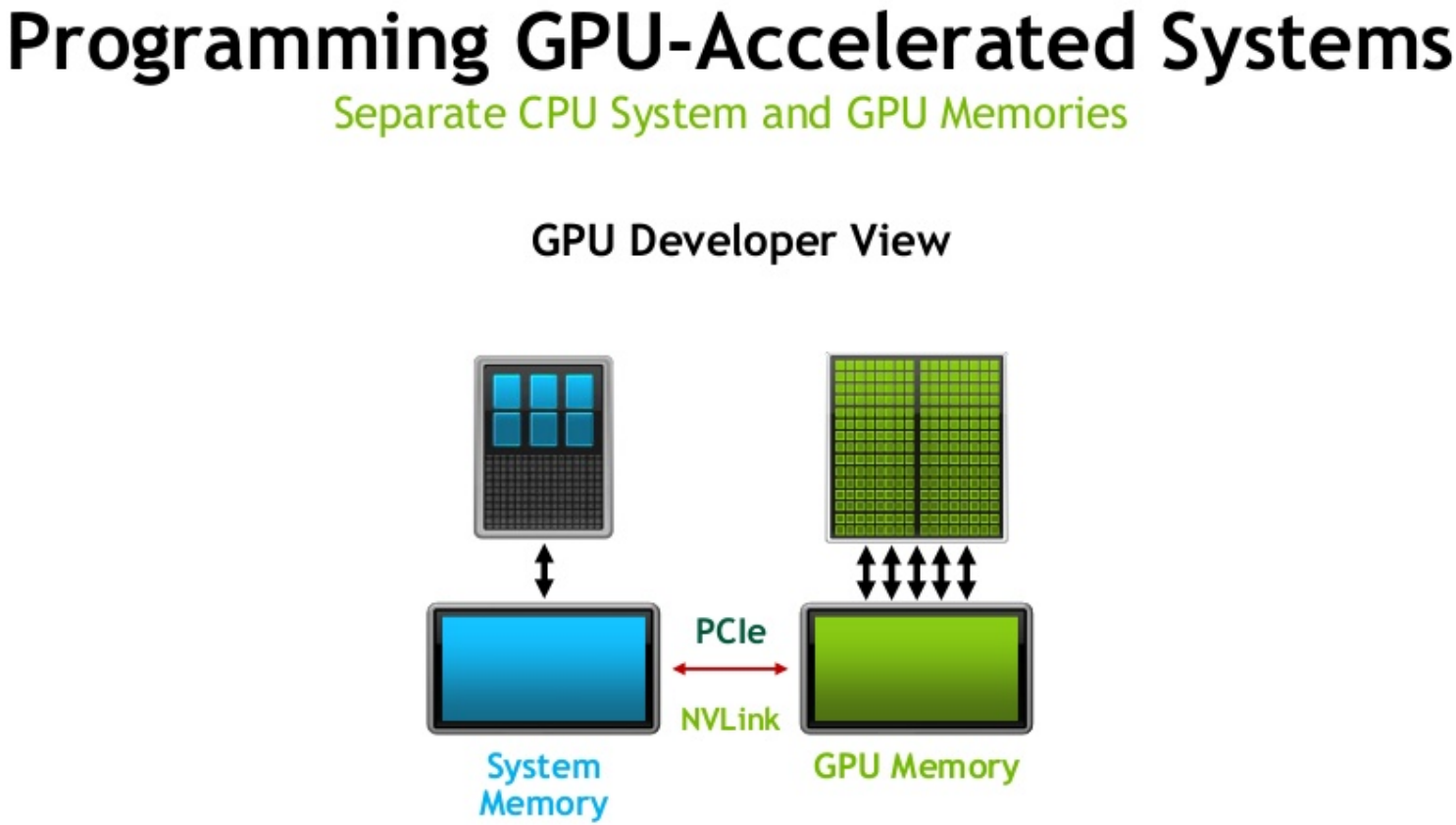
Performance Benefits of Vector and Parallel Programming on Multicore Processors



Introduction

Execution Model

Kernels, data transfers and memory allocation are managed by the host (CPU).



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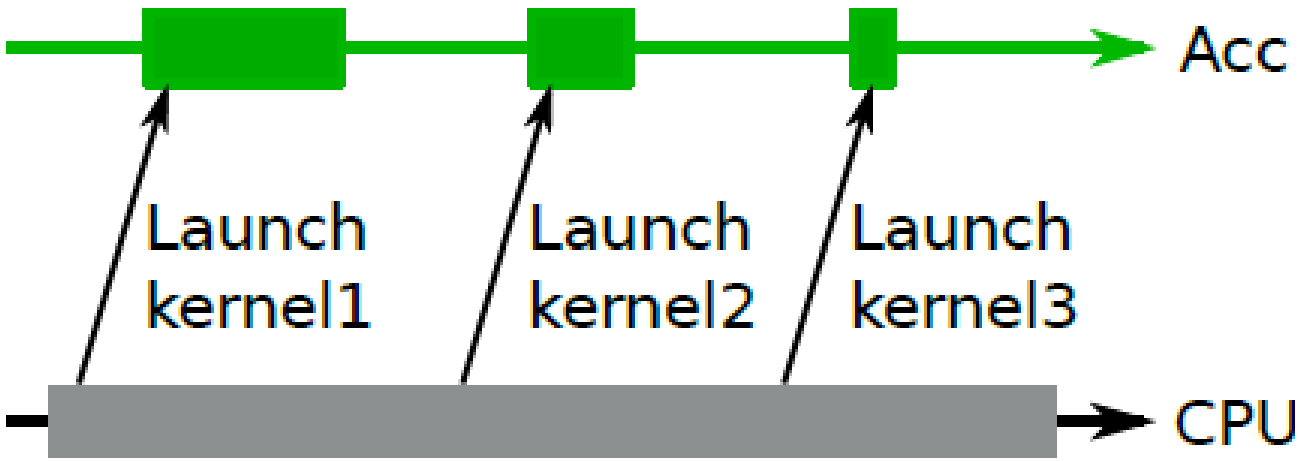
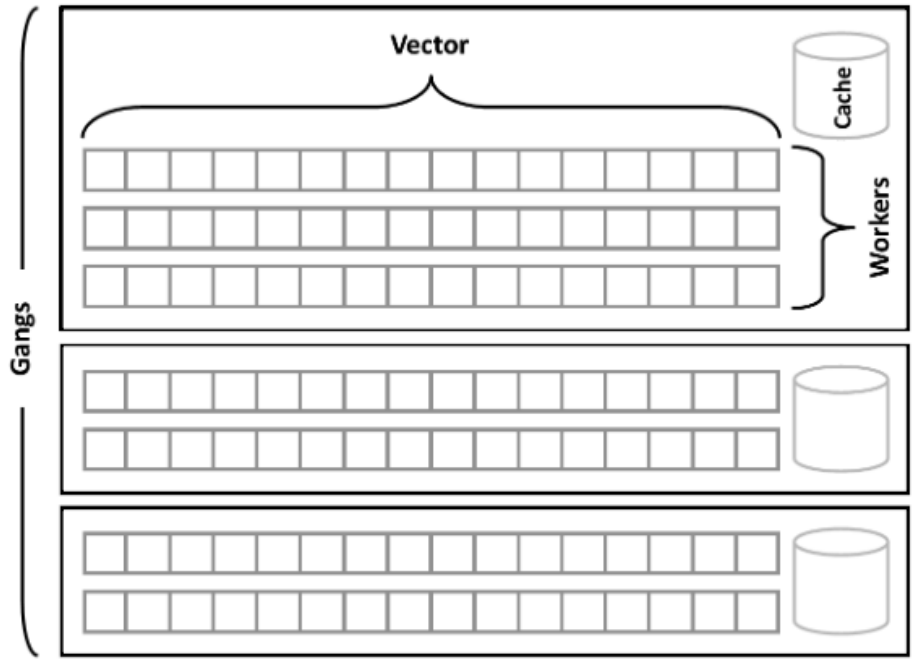


Introduction

Execution Model

Three levels of parallelism:

- Coarse grain: gang;
- Fine grain: worker;
- Vectorization: vector;
- Sequential: seq.



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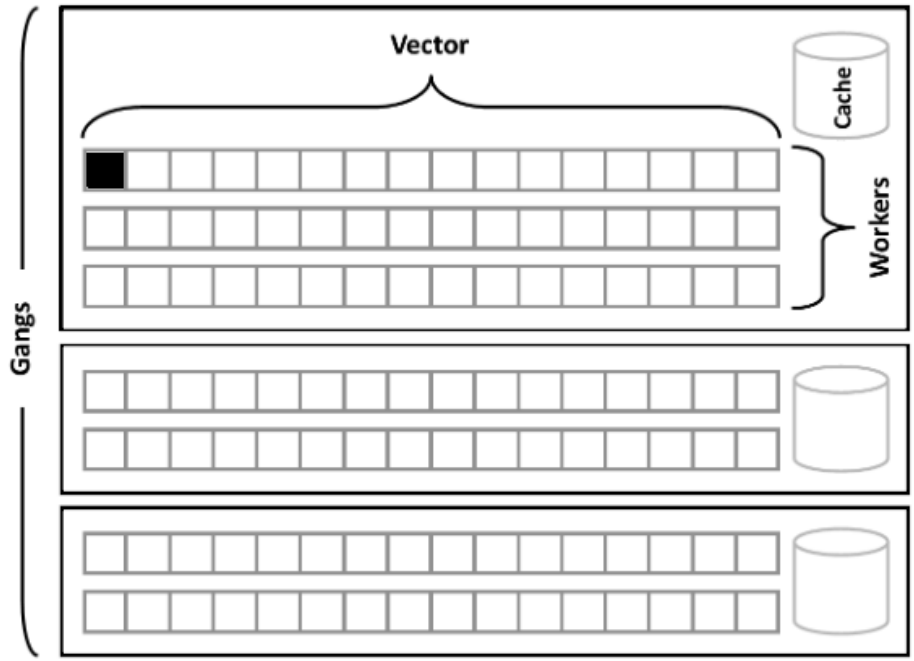

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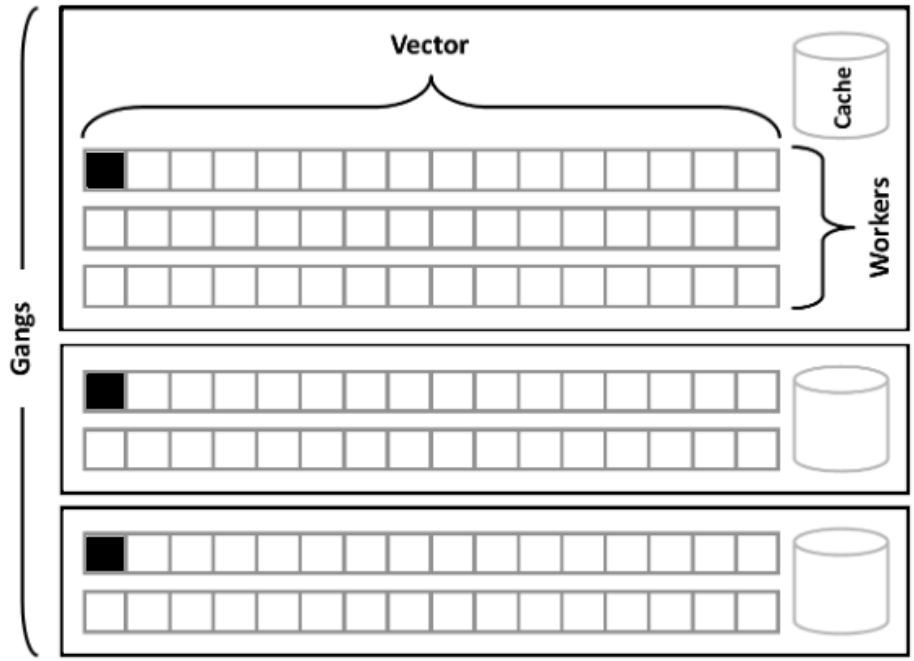

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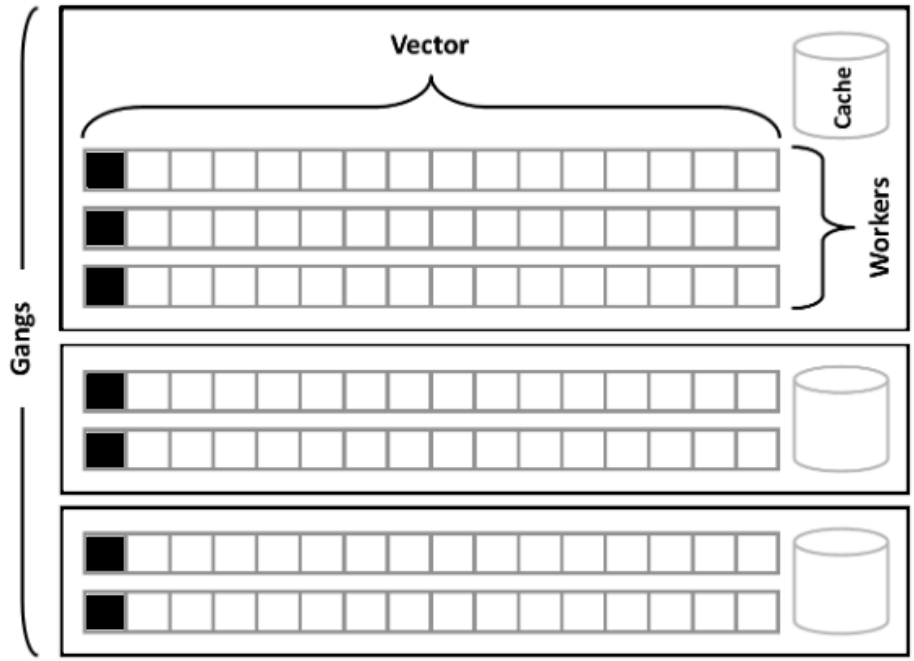

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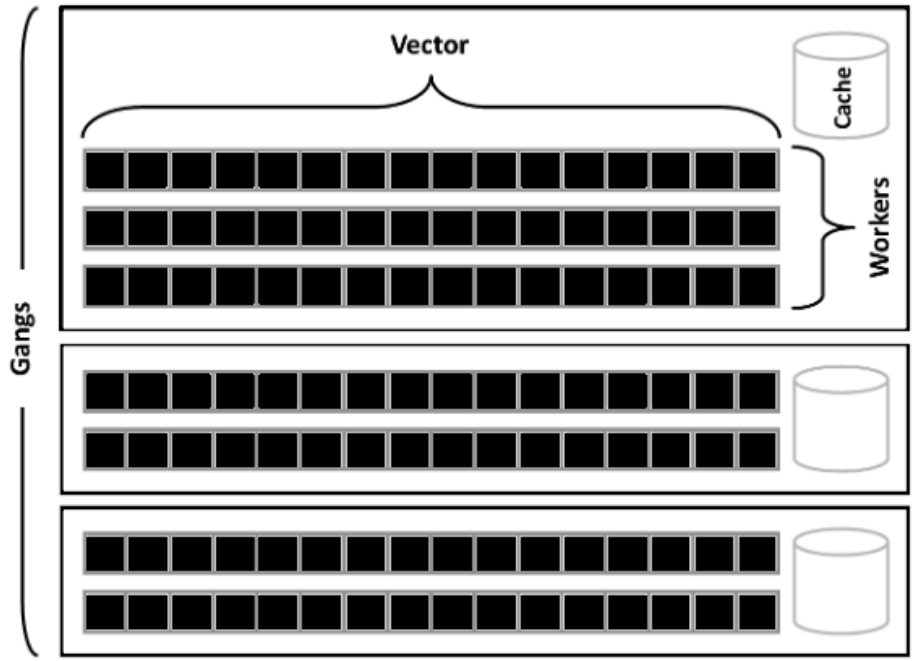


Introduction

Parallelism Models

- Gang-redundant (GR): All gangs run the same instructions redundantly;
- Gang-partitioned (GP): Work is shared between gangs (!$ACC loop gang);
- Worker-single (WS): One worker is active in GR or GP mode;
- Worker-partitioned (WP): Work is shared among workers of a gang;
- Vector-single (VS): One vector channel is active;
- Vector-partitioned (VP): Several vector channels are active.

These models must be combined in order to get the best performance from the calculator.

Introduction

Parallelism Models

- The execution of a kernel uses a set of threads that are mapped on the hardware resources of the accelerator;
- Threads are grouped within team of the same size, with one master thread per team (gang definition);
- Each team is spread on a 2-D thread-grid (worker-vector);
- One worker is actually a vector of $vector_{length}$ threads;
- The total number of threads is:

$$nb_{threads} = nb_{gangs} * nb_{workers} * vector_{length} .$$

Important Notes

- There is no synchronization among gangs;
- The compiler can decide to synchronize the threads of a gang (all or part of them);
- Threads of a worker works in SIMD* (single instruction multiple data) fashion.

All threads run the same instruction at the same time, for example on NVidia GPUs, groups of 32 threads are formed.

Introduction

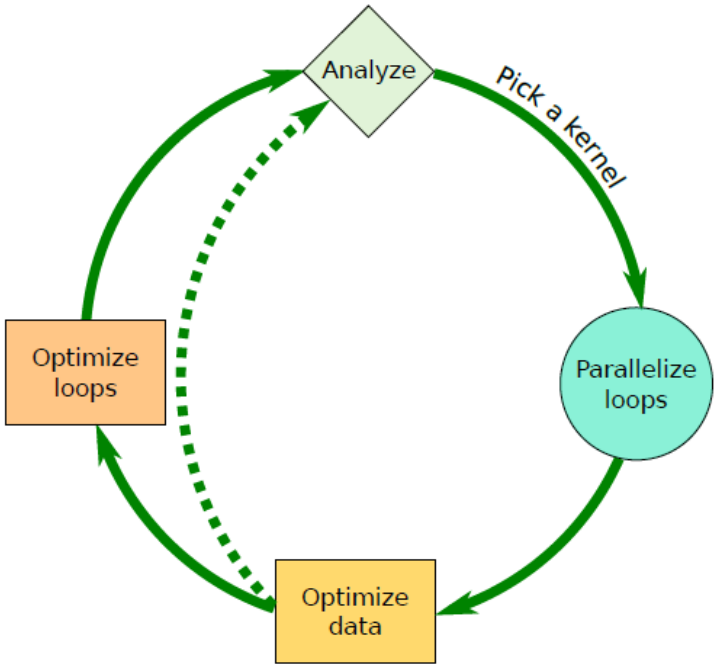
NVIDIA P100 Restrictions

- Number of gangs is restricted to $2^{31} - 1$;
- The 2-D thread-grid size ($nb_{workers} * vector_{length}$) is limited to 1024;
- Due to register limitations the size of the grid should be less than or equal to 256 if the programmer wants to be sure that a kernel can be launched;
- The size of a worker ($vector_{length}$) should be multiple of 32;
- **PGI limitation:** In a kernel that contains calls to external subroutines (not seq), the size of a worker is set at to 32.

Introduction

Porting Strategy

1. Identify the compute intensive loops;
2. Add OpenACC directives;
3. Optimize data transfers and loops;
4. Repeats 1 to 3 until everything is on the devices.



Introduction

PGI Compiler

Information

- Founded in 1989;
- Acquired by NVIDIA in 2013;
- Develops compilers, debuggers and profilers.

Compilers

- Latest version: 19.10;
- Hands-on version: 19.10;
- C: pgcc;
- C++: pgc++;
- Fortran: pgf90, pgfortran.

Activate OpenACC

- **-acc** : Activates openACC support;
- **-ta=<options>** : OpenACC options;
- **-Minfo=accel** : Display informations about compilation. The compiler will do implicit operations that are important to the developers. **Highly recommended to use!**

Tools

- nvprof: CPU/GPU profilers;
- nvvp: nvprof GUI.

Introduction

"–ta" Options

Each GPU generation presents different capabilities.
For NVIDIA hardware, it is represented by a number:

- K80: cc35;
- P100: cc60;
- V100: cc70.

A compilation using V100 features is given by:

- **-ta=tesla:cc70**

Complete documentation: ▸ OpenACC User-Guide

Memory Management

- Pinned: The memory location on the host is pinned. It might improve data transfers;
- Managed: The memory of both, host and device, are united.

Introduction

Information available with -Minfo=accel

```
 4   program loop
 5     integer :: a(10000)
 6     integer :: i
 7
 8     !$ACC parallel loop
 9     do i=1,10000
10       a(i) = i
11     enddo
12
13   end program loop
```

pgfortran -O0 -acc -ta=tesla -Minfo=accel loop.f90

```
loop:
      8, Generating Tesla code
          9, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
      8, Generating implicit copyout(a(:)) [if not already present]
```

Introduction

Information available with -Minfo=accel

```
15      !$acc parallel loop
16      do i=1,10000
17        a(i) = i
18      enddo
19      !$acc parallel loop reduction(+:summ)
20      do i=1,10000
21        summ = summ + a(i)
22      enddo
23    end program reduction
```

pgfortran -O0 -acc -ta=tesla -Minfo=accel reduction.f90

```
reduction:
     15, Generating Tesla code
         16, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
     15, Generating implicit copyout(a(:)) [if not already present]
     19, Generating Tesla code
         19, Generating reduction(+:summ)
         20, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
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15      !$acc parallel loop
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18      enddo
19      !$acc parallel loop reduction(+:summ)
20      do i=1,10000
21        summ = summ + a(i)
22      enddo
23    end program reduction
```

pgfortran -O0 -acc -ta=tesla -Minfo=accel reduction.f90

```
reduction:
     15, Generating Tesla code
         16, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
     15, Generating implicit copyout(a(:)) [if not already present]
     19, Generating Tesla code
         19, Generating reduction(+:summ)
         20, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
     19, Generating implicit copyin(a(:)) [if not already present]
         Generating implicit copy(summ) [if not already present]
```

Introduction

Data region in order to avoid CPU-GPU communication

```
15    !$acc data create (a(1:10000))
16    !$acc parallel loop
17    do i=1,10000
18      a(i) = i
19    enddo
20    !$acc parallel loop reduction(+:summ)
21    do i=1,10000
22      summ = summ + a(i)
23    enddo
24    !$acc end data
```

pgfortran -acc -ta=tesla -Minfo=accel reduction_data_region.f90

```
reduction:
     15, Generating create(a(:)) [if not already present]
     16, Generating Tesla code
         17, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
     20, Generating Tesla code
         20, Generating reduction(+:summ)
         21, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
     20, Generating implicit copy(summ) [if not already present]
```

Introduction

Code Profiling

PGI_ACC_TIME

- Command line tool;
- Environment variable for PGI compilers (PGI_ACC_TIME=1);
- Provides basic information such as:
  - Time spent in kernels;
  - Time spent in data transfers;
  - How many times a given kernel is executed;
  - The number of gangs, workers and vector size mapped to hardware.

nvprof

- Command line tools;
- Options that can give you a fine view of the code.

nvvp, pgprof and NSight Graphics Profiler

- Graphical interface for nvprof.

Introduction

PGI_ACC_TIME=1 — parallel-data-multi.f90

```
29    !$ACC parallel copyout( a(:s) )
30    !$ACC loop
31    do i=1,s
32      a(i) = i
33    enddo
34    !$ACC end parallel
35
36    do j=1,p
37      !$ACC parallel copy( a(:s) )
38      !$ACC loop
39      do i=1,s
40        a(i) = a(i) + 1
41      enddo
42      !$ACC end parallel
43    enddo
```

```
para  NVIDIA  devicenum=0
  time(us): 29,740
  29: compute region reached 1 time
      29: kernel launched 1 time
          grid: [79]  block: [128]
           device time(us): total=4 max=4 min=4 avg=4
          elapsed time(us): total=368 max=368 min=368 avg=368
  29: data region reached 2 times
      34: data copyout transfers: 1
           device time(us): total=22 max=22 min=22 avg=22
  37: compute region reached 1000 times
      37: kernel launched 1000 times
          grid: [79]  block: [128]
           device time(us): total=2,006 max=4 min=2 avg=2
          elapsed time(us): total=17,550 max=31 min=15 avg=17
  37: data region reached 2000 times
      37: data copyin transfers: 1000
           device time(us): total=13,797 max=17 min=5 avg=13
      42: data copyout transfers: 1000
           device time(us): total=13,911 max=20 min=5 avg=13
```

The grid is the number of gangs. The block is the size of one gang ($\lceil vector_{length} \times nb_{workers} \rceil$).

Introduction

PGI_ACC_TIME=1 — parallel-data-single.f90

```
28    !$ACC parallel copyout( a(:s) )
29    !$ACC loop
30    do i=1,s
31      a(i) = i
32    enddo
33    !$ACC end parallel
34
35    !$ACC data copy( a(:s) )
36    do j=1,p
37      !$ACC parallel
38      !$ACC loop
39      do i=1,s
40        a(i) = a(i) + 1
41      enddo
42      !$ACC end parallel
43    enddo
44    !$ACC end data
```

```
para  NVIDIA  devicenum=0
  time(us): 2,069
  28: compute region reached 1 time
      28: kernel launched 1 time
          grid: [79]  block: [128]
           device time(us): total=4 max=4 min=4 avg=4
          elapsed time(us): total=378 max=378 min=378 avg=378
  28: data region reached 2 times
      33: data copyout transfers: 1
           device time(us): total=22 max=22 min=22 avg=22
  35: data region reached 2 times
      35: data copyin transfers: 1
           device time(us): total=14 max=14 min=14 avg=14
      44: data copyout transfers: 1
           device time(us): total=9 max=9 min=9 avg=9
  37: compute region reached 1000 times
      37: kernel launched 1000 times
          grid: [79]  block: [128]
           device time(us): total=2,020 max=5 min=2 avg=2
          elapsed time(us): total=16,670 max=33 min=12 avg=16
```

The grid is the number of gangs. The block is the size of one gang ($\lceil vector_{length} \times nb_{workers} \rceil$).

Introduction

nvprof or pgprof

- Nvidia Toolkit provides the command line profiler: nvprof;
- **PGI_ACC_TIME=0**, the env. var. is incompatible with nvprof;
- Options:
  - **--cpu-profiling on** : Activates CPU profiling;
  - **--metrics flop_count_dp** : Number of operations;
  - **--metrics dram_read_throughput** : memory read throughput for each kernel running on the CPU;
  - **--metrics dram_write_throughput** : memory write throughput for each kernel running on the CPU;

Introduction

nvprof or pgprof - parallel-data-multi.f90

```
            Type Time(%)      Time Calls       Avg       Min       Max  Name
 GPU activities: 47.59%  6.0764ms  1000  6.0760us  4.8320us  24.352us  [CUDA memcpy HtoD]
                 40.21%  5.1337ms  1001  5.1280us  3.8080us  19.935us  [CUDA memcpy DtoH]
                 12.18%  1.5552ms  1000  1.5550us  1.4070us  13.503us  para_37_gpu
      API calls: 48.50%  115.20ms     1  115.20ms  115.20ms  115.20ms  cuDevicePrimaryCtxRetain
                 21.14%  50.208ms     1  50.208ms  50.208ms  50.208ms  cuDevicePrimaryCtxRelease
                 13.10%  31.106ms  3002  10.361us     859ns  61.105us  cuStreamSynchronize
                  5.98%  14.198ms     1  14.198ms  14.198ms  14.198ms  cuMemHostAlloc
                  4.48%  10.639ms     1  10.639ms  10.639ms  10.639ms  cuMemFreeHost
                  2.53%  6.0090ms  1001  6.0030us  4.8850us  28.241us  cuLaunchKernel
                  1.56%  3.6943ms  1000  3.6940us  3.0770us  28.117us  cuMemcpyHtoDAsync
                  1.50%  3.5689ms  1001  3.5650us  2.9210us  23.222us  cuMemcpyDtoHAsync
 OpenACC (excl): 27.17%  21.357ms  2000  10.678us  1.4670us  62.106us  acc_wait@parallel-data-multi.f90:37
                 19.31%  15.178ms  1000  15.177us  4.5620us  40.211us  acc_wait@parallel-data-multi.f90:42
                 18.10%  14.231ms     1  14.231ms  14.231ms  14.231ms  acc_exit_data@parallel-data-multi.f90:29
                  9.42%  7.4051ms  1000  7.4050us  5.7670us  390.34us  acc_enqueue_launch@parallel-data-multi.f90:37 (para_37_gpu)
                  7.67%  6.0306ms  1000  6.0300us  4.6600us  350.63us  acc_enqueue_download@parallel-data-multi.f90:42
                  6.70%  5.2692ms  1000  5.2690us  4.0230us  28.372us  acc_enter_data@parallel-data-multi.f90:37
                  5.71%  4.4901ms  1000  4.4900us  3.7610us  28.943us  acc_enqueue_upload@parallel-data-multi.f90:37
                  3.76%  2.9595ms  1000  2.9590us  2.3790us  21.317us  acc_exit_data@parallel-data-multi.f90:37
                  1.80%  1.4138ms  1000  1.4130us  1.1650us  23.892us  acc_compute_construct@parallel-data-multi.f90:37
```

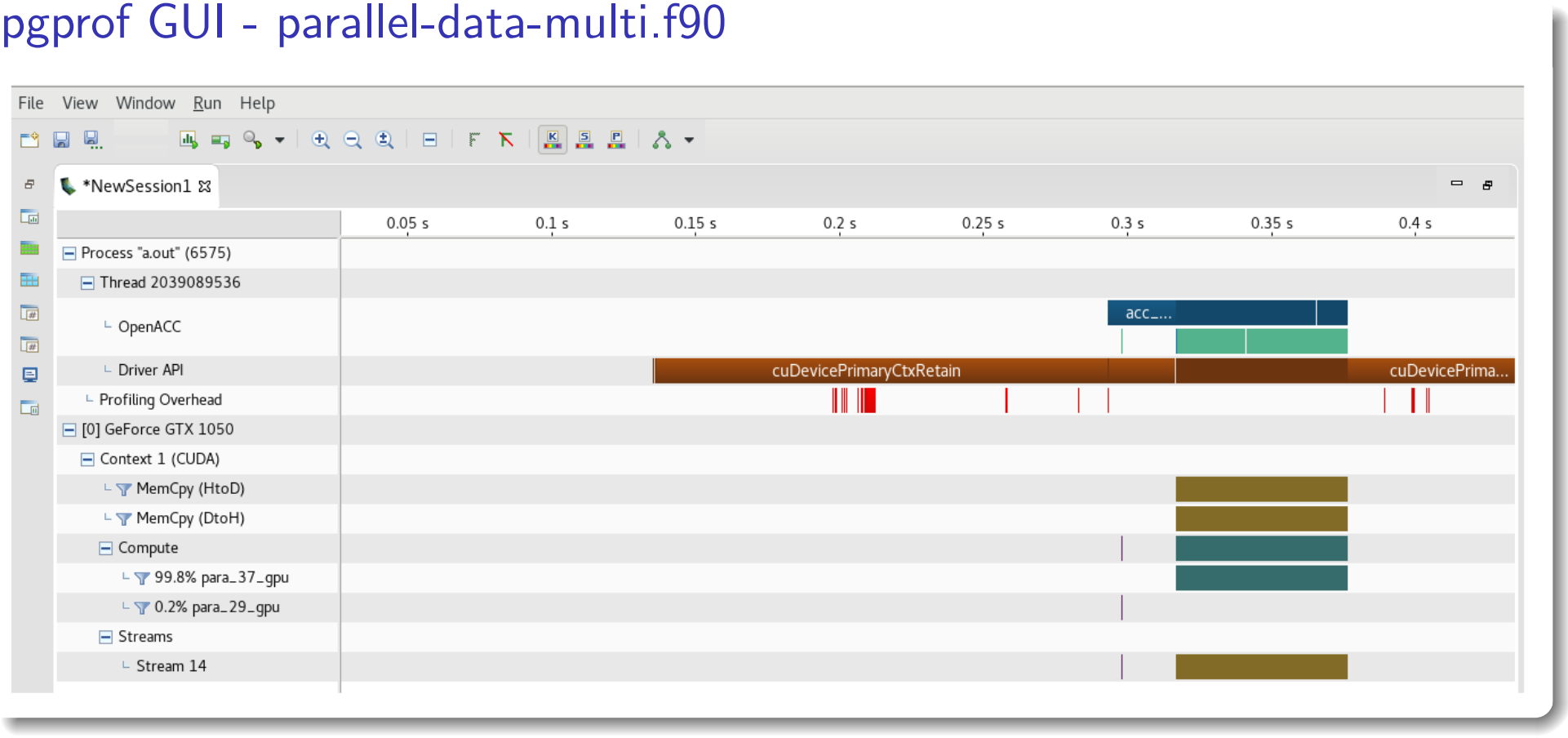
Introduction

nvprof or pgprof - parallel-data-single.f90

```
            Type Time(%)      Time Calls       Avg       Min       Max  Name
 GPU activities: 98.72%  1.4593ms  1000  1.4590us 1.4070us 12.447us  para_37_gpu
                  0.69%  10.272us     2  5.1360us 4.8960us 5.3760us  [CUDA memcpy DtoH]
                  0.37%  5.5040us     1  5.5040us 5.5040us 5.5040us  [CUDA memcpy HtoD]
                  0.21%  3.0720us     1  3.0720us 3.0720us 3.0720us  para_28_gpu
      API calls: 64.76%  143.60ms     1  143.60ms 143.60ms 143.60ms  cuDevicePrimaryCtxRetain
                 19.97%  44.288ms     1  44.288ms 44.288ms 44.288ms  cuDevicePrimaryCtxRelease
                  6.45%  14.306ms     1  14.306ms 14.306ms 14.306ms  cuMemHostAlloc
                  3.97%  8.8095ms     1  8.8095ms 8.8095ms 8.8095ms  cuMemFreeHost
                  2.94%  6.5292ms  1004  6.5030us    884ns 27.722us  cuStreamSynchronize
                  1.54%  3.4067ms  1001  3.4030us 3.0620us 23.182us  cuLaunchKernel
 OpenACC (excl): 53.03%  14.340ms     1  14.340ms 14.340ms 14.340ms  acc_exit_data@parallel-data-single.f90:28
                 26.16%  7.0745ms  1000  7.0740us 1.4780us 28.318us  acc_wait@parallel-data-single.f90:37
                 15.58%  4.2143ms  1000  4.2140us 3.7990us 21.628us  acc_enqueue_launch@parallel-data-single.f90:37 (para_37_gpu)
                  3.97%  1.0743ms  1000  1.0740us 1.0140us 16.360us  acc_compute_construct@parallel-data-single.f90:37
```

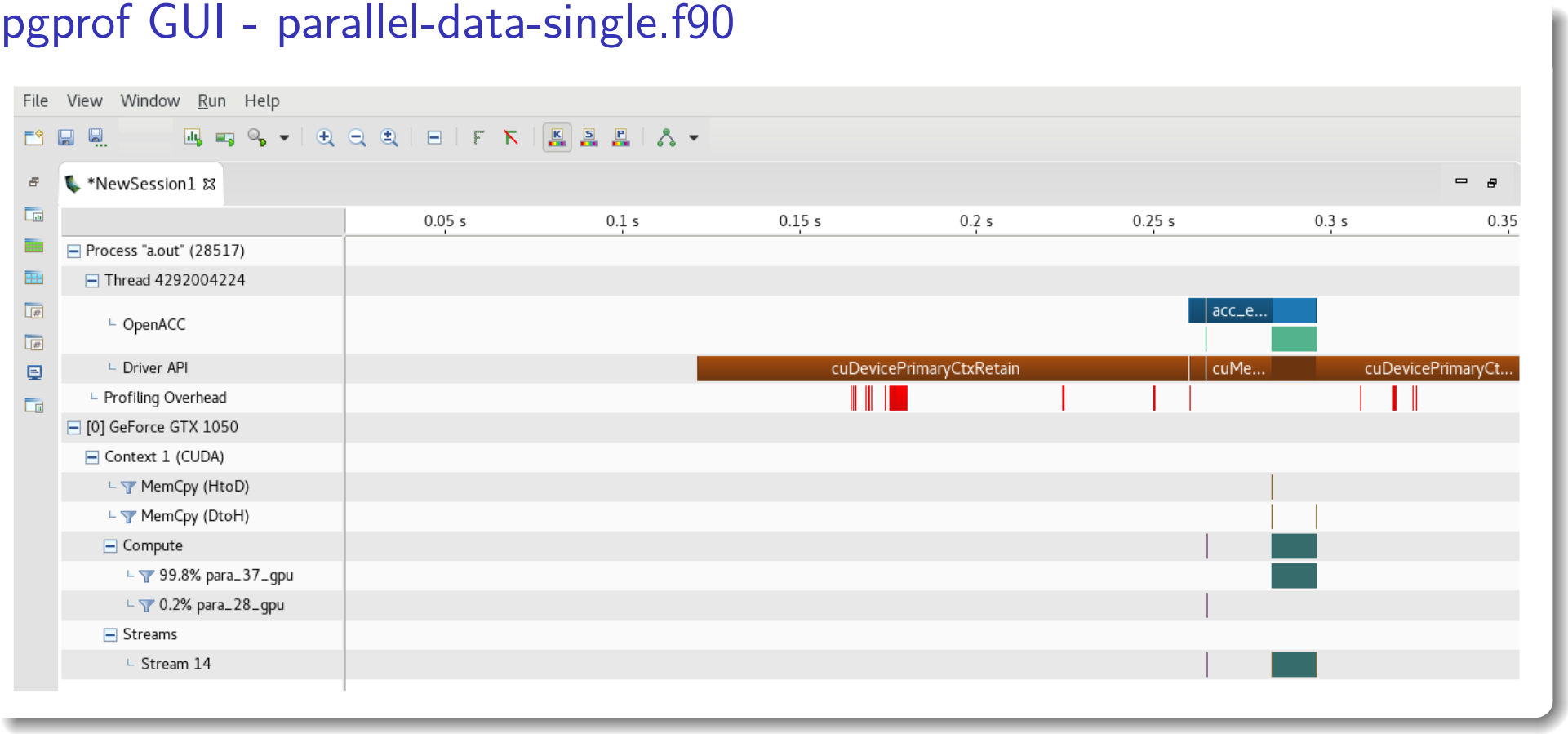
Introduction

pgprof GUI - parallel-data-multi.f90



Introduction

pgprof GUI - parallel-data-single.f90



Parallel Directives

- OpenACC features are activated through directives.
- Directives are treated as comments if the right compiler options are not set.
- The syntax is different for a Fortran or a C/C++ code.

Fortran

```
!$ACC directive <clauses>
...
!$ACC end directive
```

C/C++

```
#pragma acc directive <clauses>
{
   ...
}
```

Directive examples:
kernels, loop, parallel, data, enter data, exit data

Compute Construct

Serial

- The code runs on a single thread;
- 1 gang with 1 worker of size 1.

Kernels

- The compiler analyzes the code and decides the parallelism level of the kernel;
- One kernel is generated for each parallel parallel loop enclosed in the region.

Parallel

- Parallel region to be run on the device;
- Only one kernel is generated;
- The programmer is responsible for sharing the work manually;
- Execution is redundant by default:
  - Gang-redundant;
  - Worker-single;
  - Vector-single.

Serial Directive

Characteristics

- Inform the compiler that the enclosed region has to be offloaded to the GPU;
- Instructions are executed only by one thread, *i.e.* one gang with a worker of size one;
- **Serial** directive is equivalent to the following parameters: **num_gang(1), num_worker(1), vector_length(1)**.

Default Behavior

- Arrays present in the **serial** region not specified in a data clause (**present, copyin, copyout**, etc) or a **declare** directive are assigned to a **copy**. They are **SHARED**;
- Scalar variables are implicitly assigned to a **firstprivate** clause. The are **PRIVATE**.

Serial Directive

Game of Life - Serial – gol.f90

```
23    !$ACC serial
24    do g=1,generations
25     do r=1, rows
26      do c=1, cols
27       old_world(r,c) = world(r,c)
28      enddo
29     enddo
30     do r=1, rows
31      do c=1, cols
32       neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
33       old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
34       old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
35       if (old_world(r,c) == 1 .and. (neigh <2 .or. neigh >3) ) then
36        world(r,c) = 0
37       else if (neigh == 3) then
38        world(r,c) = 1
39       endif
40      enddo
41     enddo
42     cells = 0
43     do r=1, rows
44      do c=1, cols
45       cells = cells + world(r,c)
46      enddo
47     enddo
48     print *, "Cells alive at generation ", g, ": ", cells
49    enddo
50    !$ACC end serial
```

```
gol:
23, Accelerator serial kernel generated
 Generating Tesla code
 24, !$acc do seq
 25, !$acc do seq
 26, !$acc do seq
 30, !$acc do seq
 31, !$acc do seq
 43, !$acc do seq
 44, !$acc do seq
23, Generating implicit copy(world(:,:),old_world(:,:)) [if not already present]
```

Test

- Size : 1000x1000;
- Generations: 100;
- Elapsed time: 123.640s.

Kernels Directive

Characteristics

- Inform the compiler that the enclosed region contains instructions to be offloaded on the device;
- Each loop nest is treated as an independant kernel with its own parameters *i.e.* number of gangs, workers and vector size.

Default Behavior

- Data arrays within **kernels** region that are not specified in a data clause (**present, copyin, copyout**, etc) or a **declare** directive are assigned to a **copy**. They are **SHARED**;
- Scalar variables are implicitly assigned to a **copy** clause. The are **SHARED**.

Important Notes

- Parameters of parallel regions, such as gangs, workers, and vector length, are independent.
- Loop nests are executed consecutively.

Kernels Directive

Game of Life - Kernels – gol.f90

```
23    !$ACC kernels
24    do g=1,generations
25     do r=1, rows
26      do c=1, cols
27       old_world(r,c) = world(r,c)
28      enddo
29     enddo
30     do r=1, rows
31      do c=1, cols
32       neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
33       old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
34       old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
35       if (old_world(r,c) == 1 .and. (neigh<2 .or. neigh>3) ) then
36        world(r,c) = 0
37       else if (neigh == 3) then
38        world(r,c) = 1
39       endif
40      enddo
41     enddo
42     cells = 0
43     do r=1, rows
44      do c=1, cols
45       cells = cells + world(r,c)
46      enddo
47     enddo
48     print *, "Cells alive at generation ", g, ": ", cells
49    enddo
50    !$ACC end kernels
```

```
gol:
23, Generating implicit copy(world(:,:),old_world(:,:)) [if not already present]
24, Loop carried dependence due to exposed use of world(:,:) prevents parallelization
    Parallelization would require privatization of array old_world(i2+1,:)
    Generating Tesla code
    24, !$acc loop seq
    25, !$acc loop vector(128) ! threadidx%x
    26, !$acc loop seq
    30, !$acc loop vector(128) ! threadidx%x
    31, !$acc loop seq
    43, !$acc loop vector(128) ! threadidx%x
    44, !$acc loop seq
    45, Generating implicit reduction(+:cells)
25, Loop is parallelizable
26, Loop is parallelizable
30, Loop is parallelizable
31, Loop is parallelizable
43, Loop is parallelizable
44, Loop is parallelizable
```

Test

- Size : 1000x1000;
- Generations: 100;
- Elapsed time: 1.951s.

Parallel Directive

Characteristics

- It creates a parallel region on the device and generates one or more gangs;
- All gangs execute redundantly the instructions within the parallel region, *i.e.* gang-redundant mode;
- Only parallel loop nests with a loop directive are eligible to have their iterations spread among gangs.

loop.f90

```
8     !$ACC parallel
9     a = 0 !!! Gang redundant
10    !$ACC loop !!! Work sharing
11    do i=1,10000
12      a(i) = i
13    enddo
14    !$ACC end parallel
```

```
loop:
8, Generating Tesla code
    9, !$acc loop vector(128) ! threadidx%x
   11, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
8, Generating implicit copyout(a(:)) [if not already present]
9, Loop is parallelizable
```

Parallel Directive

Default Behavior

- Data arrays within a **parallel** region that are not specified in a data clause (**present, copyin, copyout**, etc) or a **declare** directive are assigned to a **copy**. They are **SHARED**;
- Scalar variables are implicitly assigned to a **firstprivate** clause. The are **PRIVATE**.

Important Notes

- The number of gangs, workers and vector length are constant inside the parallel region.

Parallel Directive

Game of Life - Paralel -acc=noautopar – gol.f90

```
23    !$ACC parallel
24    do g=1,generations
25     do r=1, rows
26      do c=1, cols
27       old_world(r,c) = world(r,c)
28      enddo
29     enddo
30     do r=1, rows
31      do c=1, cols
32       neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
33       old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
34       old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
35       if (old_world(r,c) == 1 .and. (neigh<2 .or. neigh>3)) then
36        world(r,c) = 0
37       else if (neigh == 3) then
38        world(r,c) = 1
39       endif
40      enddo
41     enddo
42     cells = 0
43     do r=1, rows
44      do c=1, cols
45       cells = cells + world(r,c)
46      enddo
47     enddo
48     print *, "Cells alive at generation ", g, ": ", cells
49    enddo
50    !$ACC end parallel
```

```
gol:
23, Generating Tesla code
    24, !$acc loop seq
    25, !$acc loop seq
    26, !$acc loop seq
    30, !$acc loop seq
    31, !$acc loop seq
    43, !$acc loop seq
    44, !$acc loop seq
23, Generating implicit copy(old_world(:,:),world(:,:)) [if not already present]
24, Loop carried dependence due to exposed use of world(:,:) prevents parallelization
    Parallelization would require privatization of array old_world(i2+1,:)
25, Loop is parallelizable
26, Loop is parallelizable
30, Loop is parallelizable
31, Loop is parallelizable
43, Loop is parallelizable
44, Loop is parallelizable
```

Test

- Size : 1000x1000;
- Generations: 100;
- Elapsed time: 120.167s

- The sequential code is executed redundantly by all gangs;
- The compiler option **acc=noautopar** is activated to reproduce the expected behavior of the OpenACC specification.

Parallel Directive

Game of Life - Paralel -acc=autopar – gol.f90

```
23    !$ACC parallel
24    do g=1,generations
25     do r=1, rows
26      do c=1, cols
27       old_world(r,c) = world(r,c)
28      enddo
29     enddo
30     do r=1, rows
31      do c=1, cols
32       neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
33       old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
34       old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
35       if (old_world(r,c) == 1 .and. (neigh<2 .or. neigh>3) ) then
36        world(r,c) = 0
37       else if (neigh == 3) then
38        world(r,c) = 1
39       endif
40      enddo
41     enddo
42     cells = 0
43     do r=1, rows
44      do c=1, cols
45       cells = cells + world(r,c)
46      enddo
47     enddo
48     print *, "Cells alive at generation ", g, ": ", cells
49    enddo
50    !$ACC end parallel
```

```
gol:
23, Generating Tesla code
    24, !$acc loop seq
    25, !$acc loop seq
    26, !$acc loop vector(128) ! threadidx%x
    30, !$acc loop seq
    31, !$acc loop vector(128) ! threadidx%x
    43, !$acc loop seq
    44, !$acc loop vector(128) ! threadidx%x
    45, Generating implicit reduction(+:cells)
23, Generating implicit copy(old_world(:,:),world(:,:)) [if not already present]
24, Loop carried dependence due to exposed use of world(:,:) prevents parallelization
    Parallelization would require privatization of array old_world(i2+1,:)
25, Loop is parallelizable
26, Loop is parallelizable
30, Loop is parallelizable
31, Loop is parallelizable
43, Loop is parallelizable
44, Loop is parallelizable
```

Test

- Size : 1000x1000;
- Generations: 100;
- Elapsed time: 5.067s

Parallel Directive

Default Behavior

- It is up to the compiler to decide how many workers are generated and their vector size;
- The number of gangs is set at execution time by the runtime;
- Memory is usually the limiting criterion.

Control Clauses

The programmer can set control parameters for **kernels** and **parallel** clauses:

- **num_gangs**: provide number of gangs;
- **num_workers**: provide number of workers;
- **vector_length**: provide vector length.

Important Notes

- These clauses are mainly useful if the code uses a data structure which is difficult for the compiler to analyze;
- The optimal number of gangs is highly dependent on the architecture. Use **num_gangs** with care.

Parallel Directive

parametres_paral.f90

```
14    !$acc parallel num_gangs(10)&
15    !$acc& num_workers(1)       &
16    !$acc& vector_length(128)
17    print *, "Hello I am a gang"
18    do i=1,1000
19      a(i) = i
20    enddo
21    !$acc end parallel
```

```
1   Hello I am a gang
2   Hello I am a gang
3   Hello I am a gang
4   Hello I am a gang
5   Hello I am a gang
6   Hello I am a gang
7   Hello I am a gang
8   Hello I am a gang
9   Hello I am a gang
10  Hello I am a gang
```

```
param:
14, Generating Tesla code
    18, !$acc loop gang(10), vector(128) ! blockidx%x threadidx%x
14, Generating implicit copyout(a(:)) [if not already present]
18, Loop is parallelizable
```

Parallel Directive

parametres_mod.f90

```
14    !$acc parallel num_gangs(10)&
15    !$acc& num_workers(1)       &
16    !$acc& vector_length(128)
17    print *, "Hello I am a gang"
18    !$acc loop
19    do i=1,1000
20      a(i) = i
21    enddo
22    !$acc end parallel
```

```
 1  Hello I am a gang
 2  Hello I am a gang
 3  Hello I am a gang
 4  Hello I am a gang
 5  Hello I am a gang
 6  Hello I am a gang
 7  Hello I am a gang
 8  Hello I am a gang
 9  Hello I am a gang
10  Hello I am a gang
```

```
param:
14, Generating Tesla code
    19, !$acc loop gang(10), vector(128) ! blockidx%x threadidx%x
14, Generating implicit copyout(a(:)) [if not already present]
```

Work Sharing – Loop

Loop

- Loops are at the heart of OpenACC parallelism;
- The **loop** directive , is responsible for sharing the work, i.e. the iterations of the associated loop;
- It could also activate another level of parallelism.
- Aautomatic nesting is a critical difference between **OpenACC** and **OpenMP-GPU** for which the creation of threads relies on the programmer.

Work Sharing – Loop

Clauses

The use of clauses can indicate different parallelism levels:

- **gang**: The iterations of the subsequent loop are distributed block-wise among gangs. It can be gang-redundant or gang-parallel;
- **worker**: Combined with **gangs**, threads of workers are activated, as worker-single or worker-parallel, and the task is shared among those threads.
- **vector**: Workers activate vectors in a single-instruction multiple-thread (SIMT) to share the task in vector single (VS) or vector parallel (VP) modes;
- **seq**: Iterations are sequentially executed on the device;
- **auto**: The compiler analyses the loop region and decides which options are more suitable to respect dependencies;
- **collapse(#loops)**: Merge tightly nested loops;
- **independent**: Tell the compilers that iterations are independent. Useful for the **kernel** directive;
- **private(variable-list)**: Privatize variables;
- **reduction(operation:variable-list)**: Reduction operation.

Work Sharing – Loop

Game of Life – acc=noautopar – Paralel loop – gol.f90

```
23    !$ACC parallel
24    do g=1,generations
25     !$acc loop
26     do r=1, rows
27      do c=1, cols
28       old_world(r,c) = world(r,c)
29      enddo
30     enddo
31     do r=1, rows
32      do c=1, cols
33       neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
34       old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
35       old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
36       if (old_world(r,c) == 1 .and. (neigh<2 .or. neigh>3)) then
37        world(r,c) = 0
38       else if (neigh == 3) then
39        world(r,c) = 1
40       endif
41      enddo
42     enddo
43     cells = 0
44     do r=1, rows
45      do c=1, cols
46       cells = cells + world(r,c)
47      enddo
48     enddo
49     print *, "Cells alive at generation ", g, ": ", cells
50    enddo
51    !$ACC end parallel
```

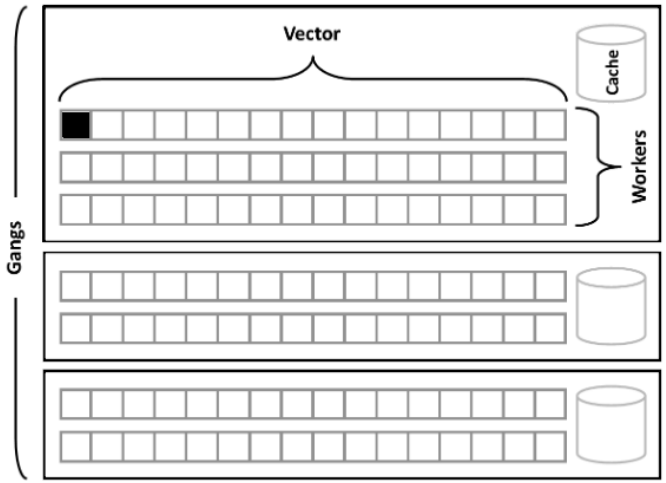
```
gol:
23, Generating Tesla code
    24, !$acc loop seq
    26, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
    27, !$acc loop seq
    31, !$acc loop seq
    32, !$acc loop seq
    44, !$acc loop seq
    45, !$acc loop seq
23, Generating implicit copy(old_world(:,:),world(:,:)) [if not already present]
24, Loop carried dependence due to exposed use of world(:,:) prevents parallelization
    Parallelization would require privatization of array old_world(i2+1,:)
27, Loop is parallelizable
31, Loop is parallelizable
32, Loop is parallelizable
44, Loop is parallelizable
45, Loop is parallelizable
```

Work Sharing – Loop

Sequential – loop_serial.f90

```
38    !$ACC serial
39    do i=1,10000
40      a(i) = i
41    enddo
42    !$ACC end serial
```

- Active threads: 1;
- Number of operations: nx.

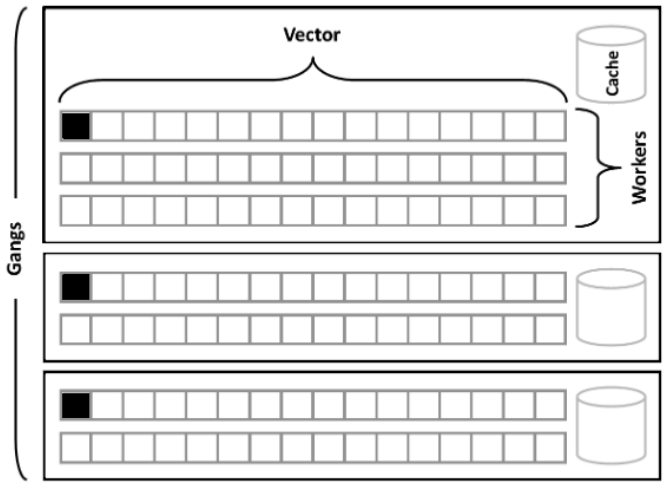



```
loop:
38, Accelerator serial kernel generated
    Generating Tesla code
    39, !$acc do seq
38, Generating implicit copyout(a(:)) [if not already present]
```

Work Sharing – Loop

Gang-Redundant Worker-Serial Vector-Single (GRWSVS) –loop_grwsvs.f90

```
39    !$ACC parallel num_gangs(10)
40    do i=1,10000
41      a(i) = i
42    enddo
43    !$ACC end parallel
```



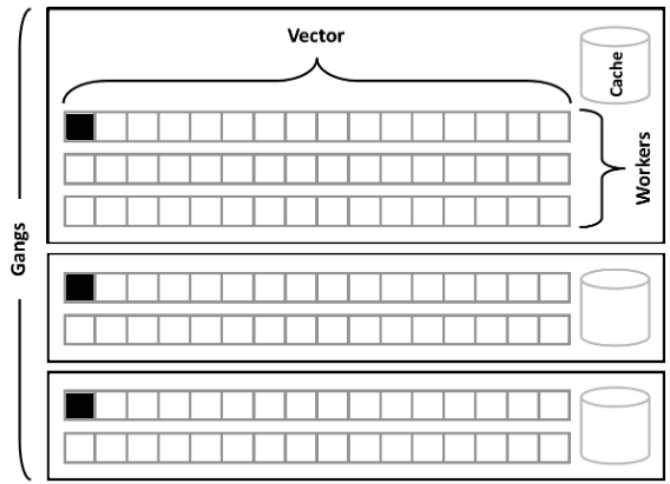
- Redundant execution by gang leaders;
- Active threads: 10;
- Number of operations: $10 \times nx$.

```
loop:
39, Generating Tesla code
    40, !$acc loop gang(10), vector(128) ! blockidx%x threadidx%x
39, Generating implicit copyout(a(:)) [if not already present]
40, Loop is parallelizable
```

Work Sharing – Loop

Gang-Parallel Worker-Single Vector-Single (GPWSVS) – loop_gpwsvs.f90

```
40    !$ACC parallel num_gangs(10)
41    !$ACC loop gang
42    do i=1,10000
43      a(i) = i
44    enddo
45    !$ACC end parallel
```



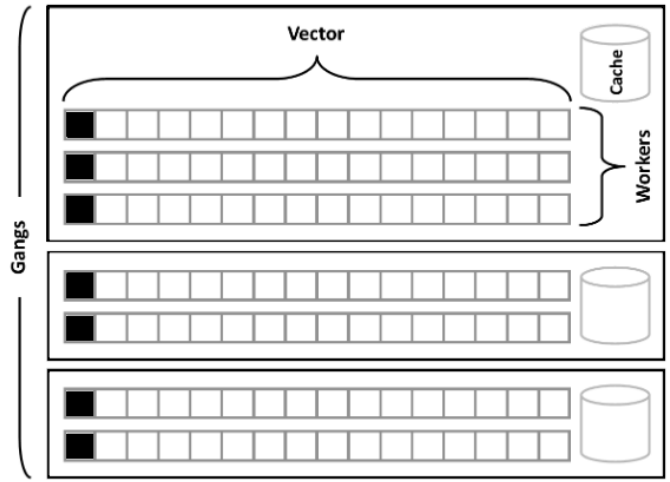
- Each gang executes a different block of iterations loop;
- Active threads: 10;
- Number of operations: nx.

```
loop:
40, Generating Tesla code
    42, !$acc loop gang(10), vector(128) ! blockidx%x threadidx%x
40, Generating implicit copyout(a(:)) [if not already present]
```

Work Sharing – Loop

Gang-Parallel Worker-Parallel Vector-Single (GPWPVS) – loop_gpwpvs.f90

```
40    !$ACC parallel num_gangs(10)
41    !$ACC loop gang worker
42    do i=1,10000
43      a(i) = i
44    enddo
45    !$ACC end parallel
```



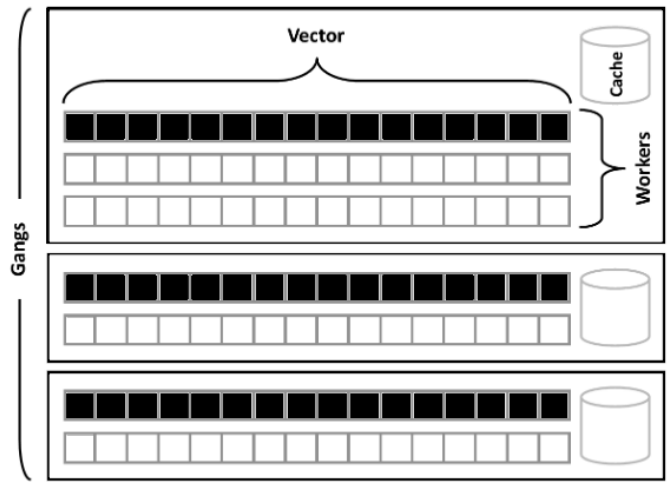
- Iterations are shared among the active workers of each gang;
- Active threads: $10 \times nb_{workers}$;
- Number of operations: nx.

```
loop:
40, Generating Tesla code
    42, !$acc loop gang(10) ! blockidx%x threadidx%y
40, Generating implicit copyout(a(:)) [if not already present]
```

Work Sharing – Loop

Gang-Parallel Worker-Single Vector-Parallel (GPWSVP) – loop_gpwsvp.f90

```
40    !$ACC parallel num_gangs(10)
41    !$ACC loop gang vector
42    do i=1,10000
43      a(i) = i
44    enddo
45    !$ACC end parallel
```



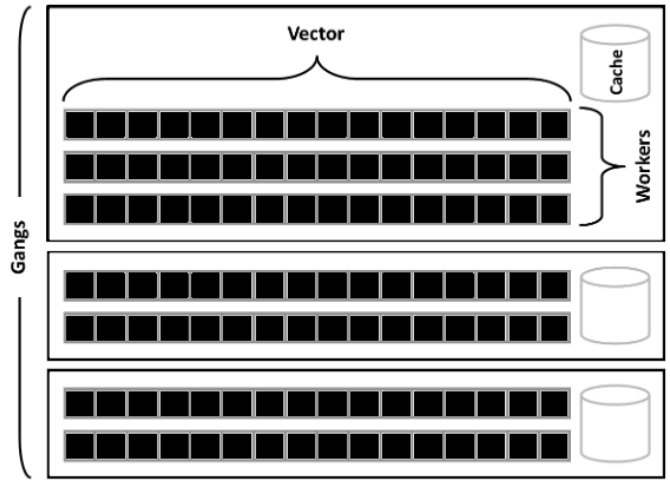
- Iterations are shared among the threads of the worker of all gangs;
- Active threads: $10 \times vector_{length}$;
- Number of operations: nx.

```
loop:
40, Generating Tesla code
    42, !$acc loop gang(10), vector(128) ! blockidx%x threadidx%x
40, Generating implicit copyout(a(:)) [if not already present]
```

Work Sharing – Loop

Gang-Parallel Worker-Parallel Vector-Parallel (GPWPVP) – loop_gpwpvp.f90

```
42    !$ACC parallel num_gangs(10)
43    !$ACC loop gang worker vector
44    do i=1,10000
45      a(i) = i
46    enddo
47    !$ACC end parallel
```



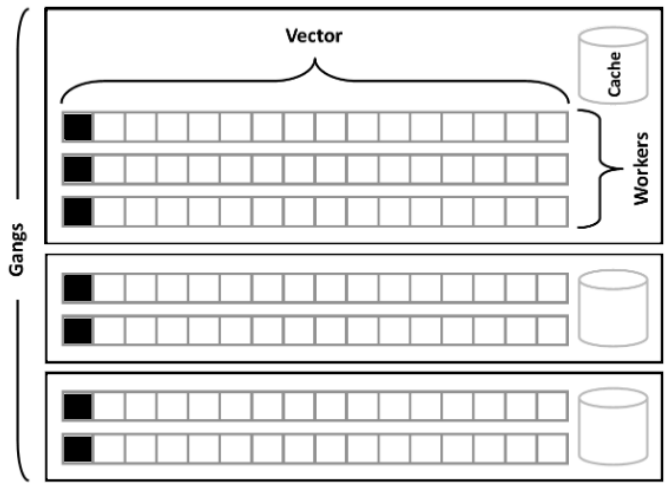
- Iterations are shared among the threads of the worker of all gangs;
- Active threads: $10 \times nb_{workers} \times vector_{length}$;
- Number of operations: nx.

```
loop:
42, Generating Tesla code
    44, !$acc loop gang(10), worker(4), vector(32) ! blockidx%x threadidx%y threadidx%x
42, Generating implicit copyout(a(:)) [if not already present]
```

Work Sharing – Loop

Gang-Reduntant Worker-Parallel Vector-Single (GRWPVS) – loop_grwpvs.f90

```
44    !$ACC parallel num_gangs(10)
45    !$ACC loop worker
46    do i=1,10000
47      a(i) = i
48    enddo
49    !$ACC end parallel
```



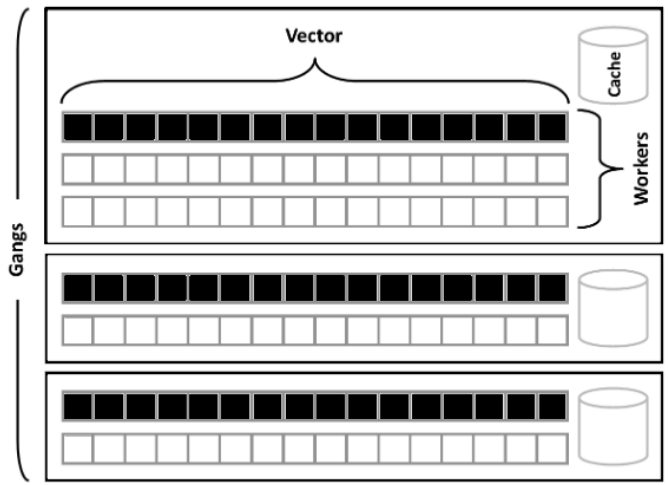
- All iterations are assigned to each active gang which share the task among workers;
- Active threads: $10 \times nb_{workers}$;
- Number of operations: $10 \times nx$.

```
loop:
44, Generating Tesla code
    46, !$acc loop gang(10) ! blockidx%x threadidx%y
44, Generating implicit copyout(a(:)) [if not already present]
46, Loop is parallelizable
```

Work Sharing – Loop

Gang-Reduntant Worker-Single Vector-Parallel (GRWPVS) – loop_grwsvp.f90

```
41    !$ACC parallel num_gangs(10)
42    !$ACC loop vector
43    do i=1,10000
44      a(i) = i
45    enddo
46    !$ACC end parallel
```



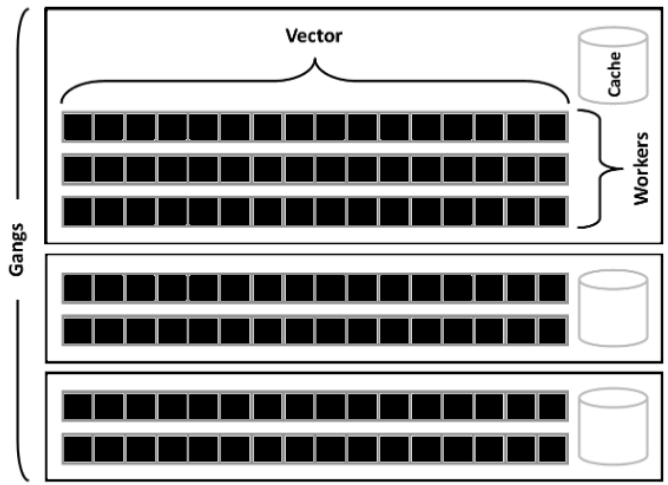
- All iterations are assigned to each active gang which share the task among vectors of one worker;
- Active threads: $10 \times vector_{length}$;
- Number of operations: $10 \times nx$.

```
loop:
41, Generating Tesla code
    43, !$acc loop vector(128) ! threadidx%x
41, Generating implicit copyout(a(:)) [if not already present]
43, Loop is parallelizable
```

Work Sharing – Loop

Gang-Reduntant Worker-Parallel Vector-Parallel (GRWPVP) – loop_grwpvp.f90

```
49    !$ACC parallel num_gangs(10)
50    !$ACC loop worker vector
51    do i=1,10000
52      a(i) = i
53    enddo
54    !$ACC end parallel
```



- All iterations are assigned to each active gang which share the task among the whole thread grid;
- Active threads: $10 \times nb_{workers} \times vector_{length}$;
- Number of operations: $10 \times nx$.

```
loop:
49, Generating Tesla code
    51, !$acc loop gang(10), worker(4), vector(32) ! blockidx%x threadidx%y threadidx%x
49, Generating implicit copyout(a(:)) [if not already present]
51, Loop is parallelizable
```

Work Sharing – Loop

Race Conditions

- There is no thread synchronization at gang level (specially at the end of a loop directive). **Risk of race condition**;
- **Race condition:** Occurs when multiple threads race to perform some operations on a shared data item. The final result can be undefined;
- OpenACC does not provide any locking mechanism aside from atomic operations to protect against race conditions;
- Synchronization is present when using the *loop* directive with **worker** and/or **vector** parallelism since the threads of a gang wait until the end of the iterations they execute to start a new portion of the code after the loop;
- **Gang** parallelism should be avoided inside parallel regions in the presence of dependencies.

pb-sync.f90

```
!$acc parallel
!$acc loop gang
do i=1,nx
  a(i) = 1.0_8
enddo
!$acc loop gang reduction(+:summ)
do i=nx,1,-1
  summ = summ + a(i)
enddo
!$acc end parallel
```

- $Summ = 5.0066080E+07$ (Race condition);

corr_sync.f90

```
!$acc parallel
!$acc loop worker vector
do i=1,nx
  a(i) = 1.0_8
enddo
!$acc loop worker vector reduction(+:summ)
do i=nx,1,-1
  summ = summ + a(i)
enddo
!$acc end parallel
```

- $Summ = 1.0000000E+08$

Work Sharing – Loop

Race Conditions - Atomic Operations

- **Atomic Operations:** An operation, such as a write or read-modify-write operation, which starts and runs to completion before another thread cans access the shared data item. **(There is no race condition on read-only data items.)**
- **acc atomic** directive example: accCounter.cpp.

```
19  high_resolution_clock::time_point t1 = high_resolution_clock::now();
20  // Here is where we define and increment the counter.
21   int counter=0;
22  #pragma acc parallel loop
23  for( int i=0; i < nCount; i++) {
24  #ifdef USE_ATOMIC
25    #pragma acc atomic update
26  #endif
27     counter++;
28  }
29  high_resolution_clock::time_point t2 = high_resolution_clock::now();
30  duration<double> time_span = duration_cast<duration<double>>(t2 - t1);
```

pgc++ -std=c++11 -acc -ta=multicore,nvidia:cc35 -Minfo=accel accCounter.cpp -o accCounter_no_atomic

```
21, Generating Tesla code
    23, #pragma acc loop seq
21, Generating Single core code
27, Accelerator restriction: induction variable live-out from loop: counter
```

Work Sharing – Loop

Race Conditions - Atomic Operations

- **Atomic Operations:** An operation, such as a write or read-modify-write operation, which starts and runs to completion before another thread cans access the shared data item. **(There is no race condition on read-only data items.)**
- **acc atomic** directive example: accCounter.cpp.

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20  // Here is where we define and increment the counter.
21   int counter=0;
22  #pragma acc parallel loop
23  for( int i=0; i < nCount; i++) {
24  #ifdef USE_ATOMIC
25    #pragma acc atomic update
26  #endif
27     counter++;
28  }
29  high_resolution_clock::time_point t2 = high_resolution_clock::now();
30  duration<double> time_span = duration_cast<duration<double>>(t2 - t1);
```

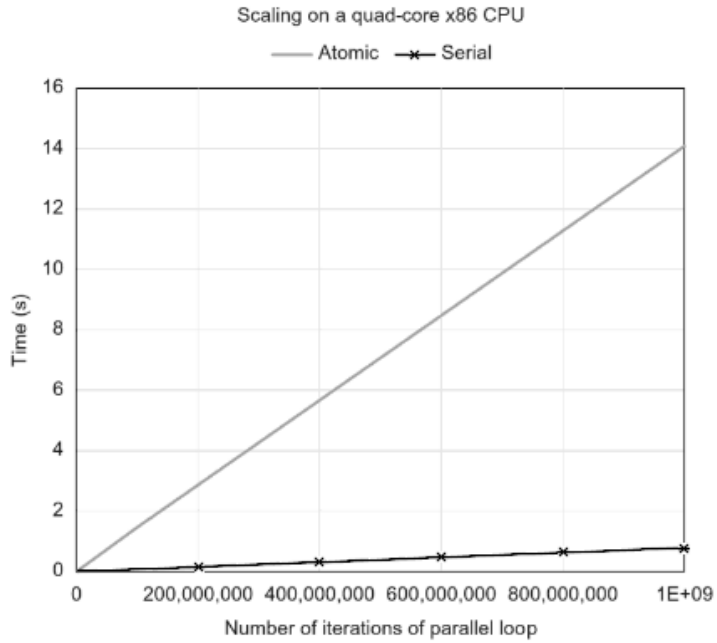
pgc++ -DUSE_ATOMIC -std=c++11 -acc -ta=multicore,nvidia:cc35 -Minfo=accel accCounter.cpp -o accCounter_w_atomic

```
21, Generating Tesla code
    23, #pragma acc loop gang, vector(128) /* blockIdx.x threadIdx.x */
21, Generating Multicore code
    23, #pragma acc loop gang
21, Generating implicit copy(counter) [if not already present]
```

Work Sharing – Loop

Atomic Operations - x86 Architecture

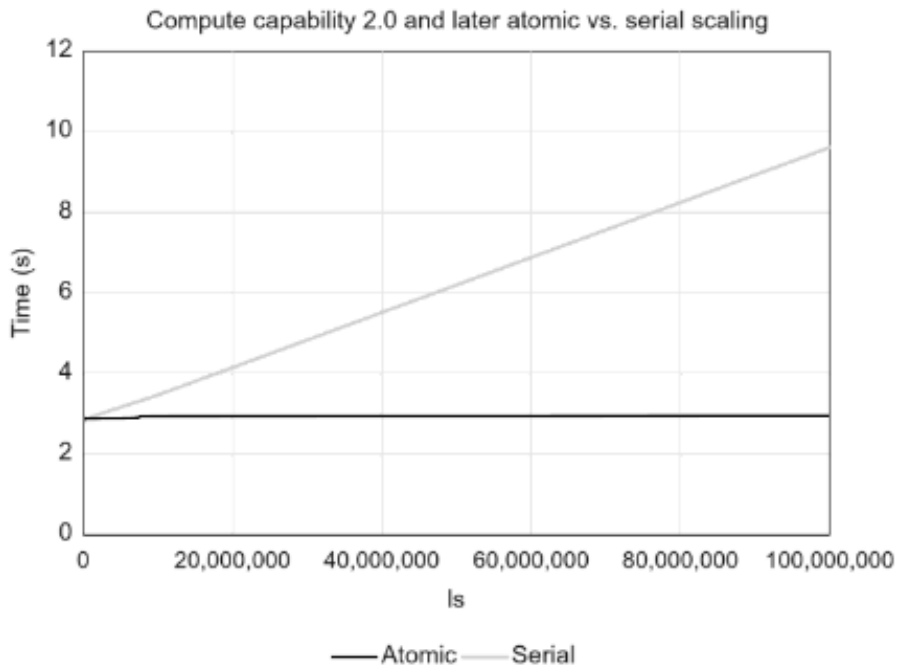
- When using **x86** architecture, the parallel runtime can be significantly worse than the serial code due to the thread and atomic operations overheads.



Work Sharing – Loop

Atomic Operations - Nvidia K40 GPU Architecture

- NVIDIA K40 presents Compute Capability 3.5;
- Serial version still scales linearly;
- Parallel version presents constant runtime;
- NVIDIA has made optimizations in hardware that allow some atomic operations to scale in a massively parallel computing environment.



Work Sharing – Loop

Lock-Free Programming

- There is no locks in OpenACC;
- *Lock-free* method guarantees progress of at least one thread executing the method. There is no *dead-locks*;
- *Dead-ocks* can occur when two threads get stuck waiting for the other thread to release a lock on a shared resource;
- *Lock-based* programs cannot provide any of the performance guarantees of a *lock-free* method. Locks are common culprit that limits or prevents scaling.

accParaCounter.cpp

```
22      high_resolution_clock::time_point t1 = high_resolution_clock::now();
23      // Here is where we define and increment the counter.
24       int counter=0;
25  #pragma acc parallel loop
26      for( int i=0; i < nCount; i+=nPartial) {
27              int partialSum=0;
28              int n = (i+nPartial < nCount)?i+nPartial:nCount;
29        #pragma acc loop worker reduction(+:partialSum)
30              for( int j=i; j < n; j++){
31                      partialSum += 1;
32              }
33        #pragma acc atomic update
34         counter += partialSum;
35      }
36      high_resolution_clock::time_point t2 = high_resolution_clock::now();
37      duration<double> time_span = duration_cast<duration<double>>(t2 - t1);
```

Work Sharing – Loop

Lock-Free Programming

- There is no locks in OpenACC;
- *Lock-free* method guarantees progress of at least one thread executing the method. There is no *dead-locks*;
- *Dead-ocks* can occur when two threads get stuck waiting for the other thread to release a lock on a shared resource;
- *Lock-based* programs cannot provide any of the performance guarantees of a *lock-free* method. Locks are common culprit that limits or prevents scaling.

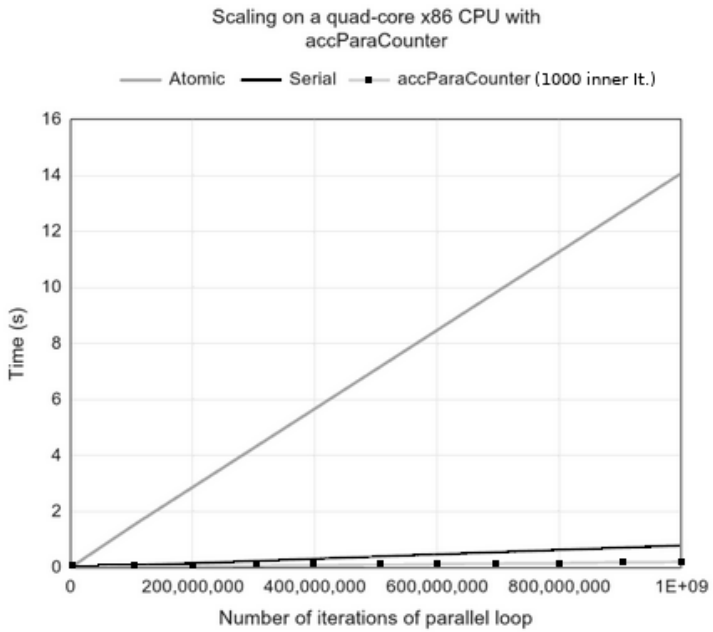
accParaCounter.cpp
pgc++ -std=c++11 -acc -ta=multicore,tesla:cc35,cc60 -Minfo=accel accParaCounter.cpp -o accParaCounter

```
main:
24, Generating Tesla code
    26, #pragma acc loop gang /* blockIdx.x */
    30, #pragma acc loop seq /* threadIdx.y */
        Generating reduction(+:partialSum)
24, Generating implicit copy(counter) [if not already present]
30, Loop is parallelizable
```

Work Sharing – Loop

Lock-Free Programming

- There is no locks in OpenACC;
- *Lock-free* method guarantees progress of at least one thread executing the method. There is no *dead-locks*;
- *Dead-ocks* can occur when two threads get stuck waiting for the other thread to release a lock on a shared resource;
- *Lock-based* programs cannot provide any of the performance guarantees of a *lock-free* method. Locks are common culprit that limits or prevents scaling.



Merging Directives

Kernels, Parallel and Loop

- One can merge read **Kernels**/ **Parallel** regions with the **loop** directive;
- The clauses available for this construct are those of both constructs.

fused.f90

```
18    !$acc kernels
19    do i=1,10000
20      a1(i) = i
21      a2(i) = i
22      b(i) = i+i*i
23    enddo
24    !$acc end kernels
25    !$acc kernels
26    !$acc loop
27    do i=1,10000
28      a1(i) = b(i)*2
29      summ1 = summ1 + a1(i)
30    enddo
31    !$acc end kernels
32    !$acc kernels loop worker vector
33    do i=1,10000
34      a2(i) = b(i)*2
35      summ2 = summ2 + a2(i)
36    enddo
```

```
fused:
18, Generating implicit copyout(a1(:),a2(:),b(:)) [if not already present]
19, Loop is parallelizable
    Generating Tesla code
    19, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
25, Generating implicit copyin(b(:)) [if not already present]
    Generating implicit copyout(a1(:)) [if not already present]
27, Loop is parallelizable
    Generating Tesla code
    27, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
    29, Generating implicit reduction(+:summ1)
32, Generating implicit copyin(b(:)) [if not already present]
    Generating implicit copyout(a2(:)) [if not already present]
33, Loop is parallelizable
    Generating Tesla code
    33, !$acc loop gang, worker(4), vector(32) ! blockidx%x threadidx%y threadidx%x
    35, Generating implicit reduction(+:summ2)
```

- $summ1 = 1146749120$
- $summ2 = 1146749120$

Reductions

Reduction directive

- A variable assigned to a **reduction** clause is privatised for each element of the parallelism level of the loop;
- At the end of the region, an operation is executed using options provided below:

Reduction operations in Fortran.

Operation	Effect
+	Summ
*	Product
max	Maximum
min	Minimum
iand	Bitwise and
ior	Bitwise or
ieor	Bitwise xor
.and.	Logical and
.or.	Logical or

Reduction operations in C/C++.

Operation	Effect
+	Summ
*	Product
max	Maximum
min	Minimum
&	Bitwise and
|	Bitwise or
&&	Logical and
||	Logical or

Restrictions

The variable have to be a scalar with a numerical value:

- Fortran: **integer**,**real**,**double prestion**,**complex**;
- C: **char**,**int**,**float**,**double**, **_Complex**;
- C++: **char**,**wchar_t**,**int**,**float**,**double**;

In the OpenACC specification 2.7, reductions are possible on arrays but the implementation is lacking in PGI (for the moment).

Reductions

Example - corr_sync.f90

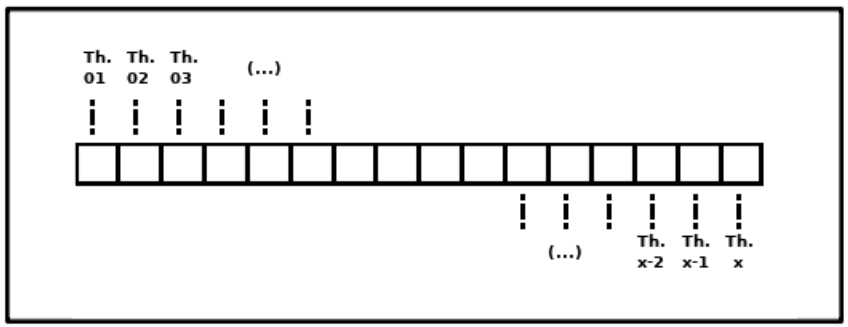
```
18  program reduction
19    real    :: a(100000000)
20    integer :: i
21    integer :: nx=100000000
22    real    :: summ=0
23    !$acc parallel
24    !$acc loop worker vector
25    do i=1,nx
26      a(i) = 1.0_8
27    enddo
28    !$acc loop worker vector reduction(+:summ)
29    do i=nx,1,-1
30      summ = summ + a(i)
31    enddo
32    !$acc end parallel
33    write (*,*) summ
34  end program reduction
```

Memory Access and Coalescing

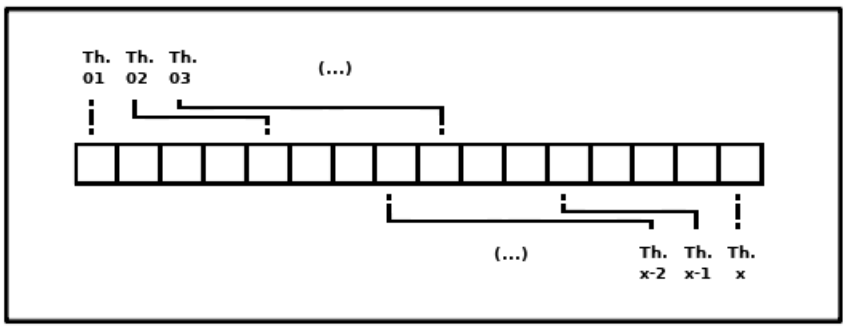
Principles

- Contiguous access to memory by the threads of a worker can be merged. This optimizes the use of memory bandwidth;
- This happens if thread i reaches memory location n, and thread $i + 1$ reaches memory location $n + 1$ and so on;
- For loop nests, the loop which has **vector** parallelism should have contiguous access to memory.

Contiguous data access.



Non-contiguous data access.



Memory Access and Coalescing

Sources

loop_nocoalescing.f90

```
22    !$ACC parallel
23    !$ACC loop gang
24    do i=1,nx
25      !$ACC loop vector
26      do j=1,nx
27        a(i,j) = 1.14d-8
28      enddo
29    enddo
30    !$ACC end parallel
```

loop_coalescing-seq.f90

```
22    !$ACC parallel
23    !$ACC loop gang vector
24    do i=1,nx
25      !$ACC loop seq
26      do j=1,nx
27        a(i,j) = 1.14d-8
28      enddo
29    enddo
30    !$ACC end parallel
```

$nx = 10000$

loop_coalescing-vec.f90

```
22    !$ACC parallel
23    !$ACC loop gang
24    do j=1,nx
25      !$ACC loop vector
26      do i=1,nx
27        a(i,j) = 1.14d-8
28      enddo
29    enddo
30    !$ACC end parallel
```

Memory Access and Coalescing

Compiling

loop_nocoalescing.f90

```
loop:
22, Generating Tesla code
    24, !$acc loop gang ! blockidx%x
    26, !$acc loop vector(128) ! threadidx%x
22, Generating implicit copyout(a(1:nx,1:nx)) [if not already present]
26, Loop is parallelizable
```

loop_coalescing-seq.f90

```
loop:
22, Generating Tesla code
    24, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
    26, !$acc loop seq
22, Generating implicit copyout(a(1:nx,1:nx)) [if not already present]
```

loop_coalescing-vec.f90

```
loop:
22, Generating Tesla code
    24, !$acc loop gang ! blockidx%x
    26, !$acc loop vector(128) ! threadidx%x
22, Generating implicit copyout(a(1:nx,1:nx)) [if not already present]
26, Loop is parallelizable
```

Memory Access and Coalescing

Computing

loop_nocoalescing.f90

```
loop  NVIDIA  devicenum=0
time(us): 126,451
22: compute region reached 1 time
    22: kernel launched 1 time
        grid: [10000]  block: [128]
         device time(us): total=94,509 max=94,509 min=94,509 avg=94,509
        elapsed time(us): total=94,553 max=94,553 min=94,553 avg=94,553
22: data region reached 2 times
    30: data copyout transfers: 24
         device time(us): total=31,942 max=1,394 min=1,211 avg=1,330
```

loop_coalescing-seq.f90

```
loop  NVIDIA  devicenum=0
time(us): 37,550
22: compute region reached 1 time
    22: kernel launched 1 time
        grid: [79]  block: [128]
         device time(us): total=5,634 max=5,634 min=5,634 avg=5,634
        elapsed time(us): total=5,677 max=5,677 min=5,677 avg=5,677
22: data region reached 2 times
    30: data copyout transfers: 24
         device time(us): total=31,916 max=1,505 min=1,174 avg=1,329
```

	W/O. Coal.	With Coal.
Time (μs)	≈ 126	≈ 36

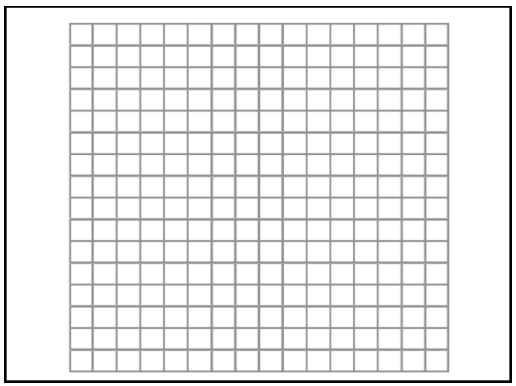
loop_coalescing-vec.f90

```
loop  NVIDIA  devicenum=0
time(us): 35,804
22: compute region reached 1 time
    22: kernel launched 1 time
        grid: [10000]  block: [128]
         device time(us): total=4,145 max=4,145 min=4,145 avg=4,145
        elapsed time(us): total=4,188 max=4,188 min=4,188 avg=4,188
22: data region reached 2 times
    30: data copyout transfers: 24
         device time(us): total=31,659 max=1,337 min=1,126 avg=1,319
```

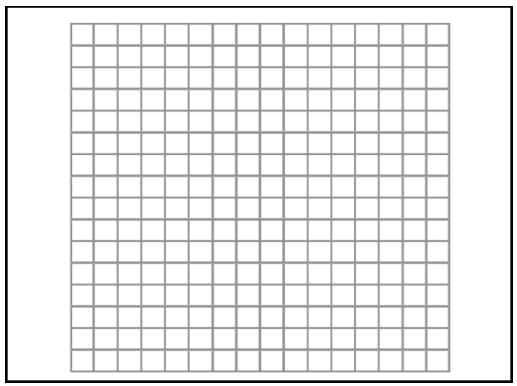
Memory Access and Coalescing

Computing

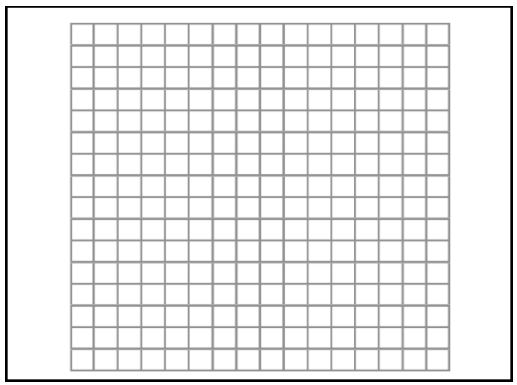
loop_nocoalescing.f90 – gang(i)/vector(j)



loop_coalescing-seq.f90 – gang-vector(i)/seq(j)



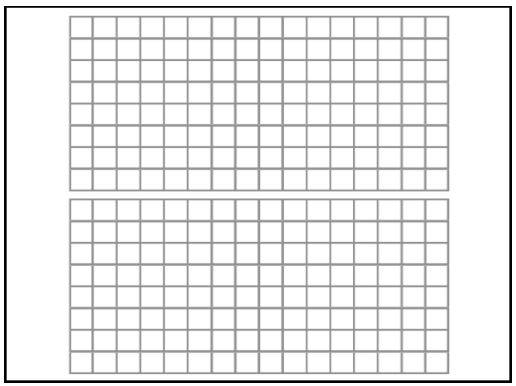
loop_coalescing-vec.f90 – gang(j)/vector(i)



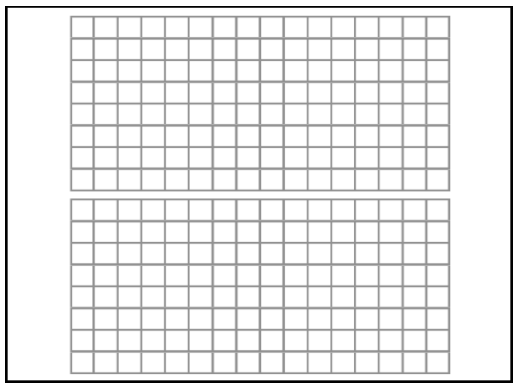
Memory Access and Coalescing

Computing

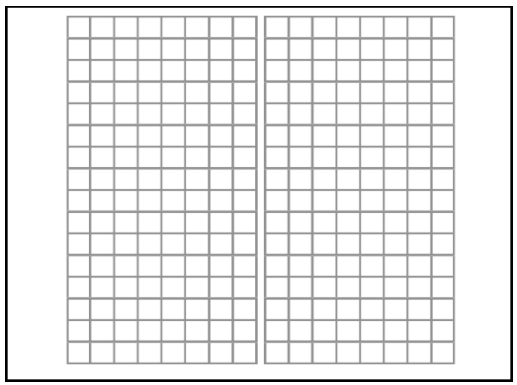
loop_nocoalescing.f90 – gang(i)/vector(j)



loop_coalescing-seq.f90 – gang-vector(i)/seq(j)



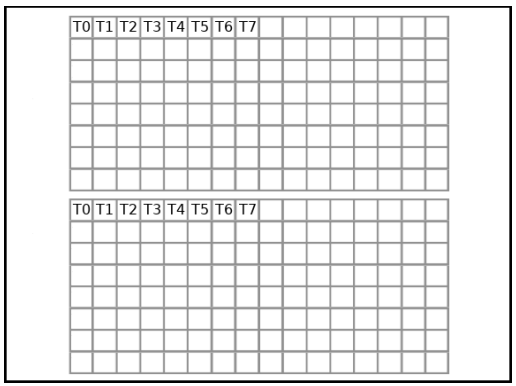
loop_coalescing-vec.f90 – gang(j)/vector(i)



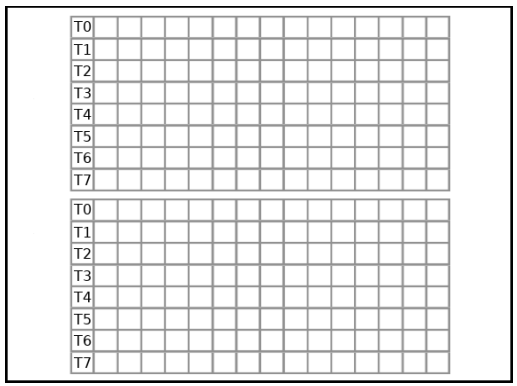
Memory Access and Coalescing

Computing

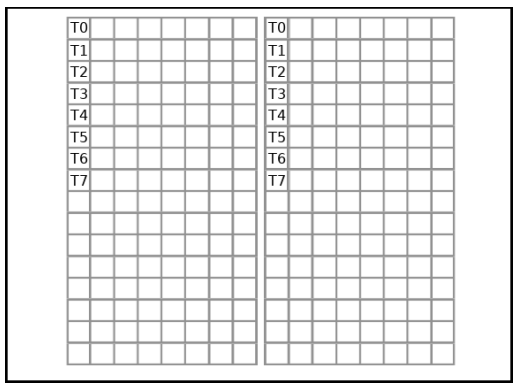
loop_nocoalescing.f90 – gang(i)/vector(j)



loop_coalescing-seq.f90 – gang-vector(i)/seq(j)



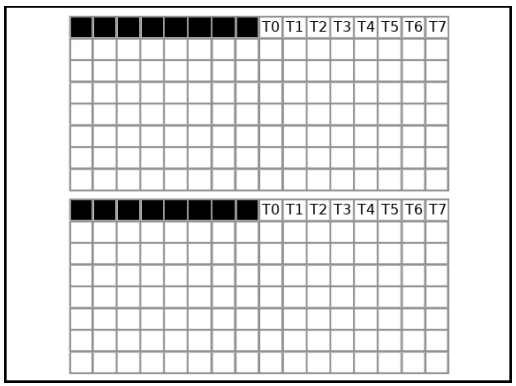
loop_coalescing-vec.f90 – gang(j)/vector(i)



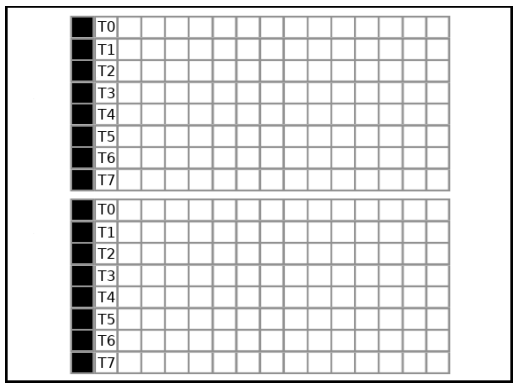
Memory Access and Coalescing

Computing

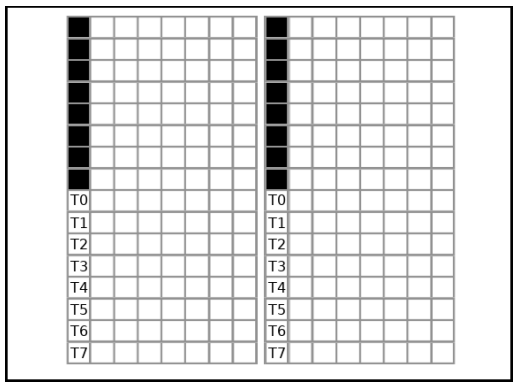
loop_nocoalescing.f90 – gang(i)/vector(j)



loop_coalescing-seq.f90 – gang-vector(i)/seq(j)



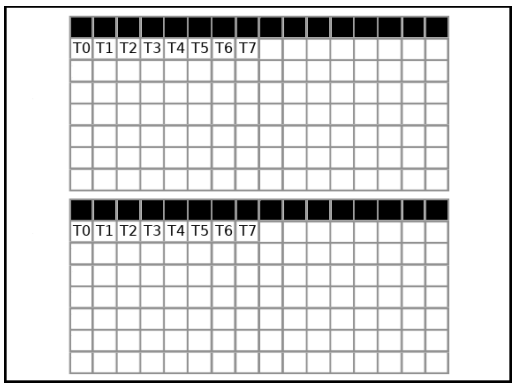
loop_coalescing-vec.f90 – gang(j)/vector(i)



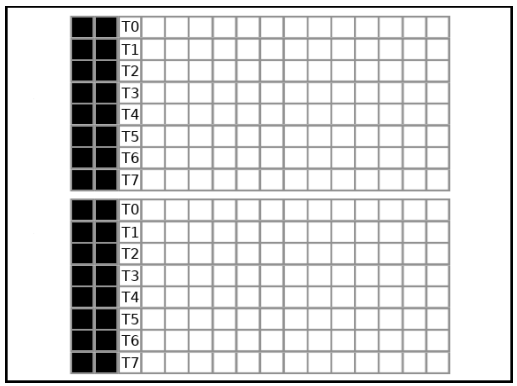
Memory Access and Coalescing

Computing

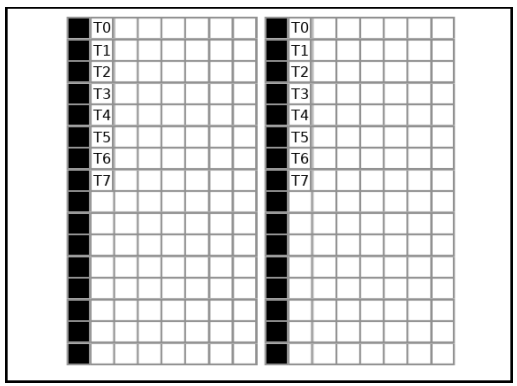
loop_nocoalescing.f90 – gang(i)/vector(j)



loop_coalescing-seq.f90 – gang-vector(i)/seq(j)



loop_coalescing-vec.f90 – gang(j)/vector(i)



Routines

- Routines and functions need to be declared using the **routine** directive;
- The **routine** directive provides information to the compiler that a device version of the function/subroutine has to be generated;
- It is mandatory to set the parallelism level inside the function (**seq, gang, worker,vector**).

routine-wrong.f90

```
22    !$ACC parallel
23    !$ACC loop
24    do i=1,s
25       call fill( a(:,:), s, i )
26    enddo
27    !$ACC end parallel
28    write(*,*) a(1,10)
29    contains
30    subroutine fill( arr, j, k )
31      integer, intent(out) :: arr(:,:)
32      integer, intent(in)  :: j, k
33      integer :: l
34      do l=1,j
35         arr(k,l) = 2
36      enddo
37    end subroutine
```

```
PGF90-S-0155-Procedures called in a compute region must have &
             acc routine information: fill (routine-wrong.f90: 25)
PGF90-S-0155-Accelerator region ignored;                    &
             see -Minfo messages (routine-wrong.f90: 22)
routine:
22, Accelerator region ignored
25, Accelerator restriction: call to 'fill' with no acc routine information
0 inform,   0 warnings,   2 severes, 0 fatal for routine
```

Routines

- Routines and functions need to be declared using the **routine** directive;
- The **routine** directive provides information to the compiler that a device version of the function/subroutine has to be generated;
- It is mandatory to set the parallelism level inside the function (**seq, gang, worker,vector**).

routine-corr.f90

```
22    !$ACC parallel copyout(a)
23    !$ACC loop
24    do i=1,s
25      call fill( a(:,:), s, i )
26    enddo
27    !$ACC end parallel
28    write(*,*) a(1,10)
29    contains
30    subroutine fill( arr, j, k )
31      !$ACC routine seq
32      integer, intent(out) :: arr(:,:)
33      integer, intent(in)  :: j, k
34      integer :: l
35      do l=1,j
36        arr(k,l) = 2
37      enddo
38    end subroutine
```

```
routine:
22, Generating copyout(a(:,:)) [if not already present]
    Generating implicit copy(.S0000) [if not already present]
    Generating Tesla code
    24, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
fill:
30, Generating acc routine seq
    Generating Tesla code
```

Data on Device

Opening a Data Region

- There are several ways of making data visible on devices by opening different kinds of data regions.

Computation offloading
Routines and functions need to be declared using the

- **serial**;
- **parallel**;
- **kernel**.

Global region
An implicit data region is opened during the lifetime of the program. The management of this region is done with the use of the **enter data** and **exit data** directives.

Local regions
To open a data region inside a programming unit (function, subroutine) it is necessary to use the **data** directive inside a code block.

Data region associated to programming unit lifetime
A data region is created when a procedure is called (function or subroutine). It is available during the lifetime of the procedure. To make data visible use the **declare** directive.

Notes
The actions taken for the data inside these regions depend on the clause in which they appear.

Data on Device

Data Clauses

Abbreviations and definitions:

- H : Host;
- D : Device;
- Variable: The variable can be a scalar or an array as well.

Data Movement

- **copyin** : The variable is copied $H \rightarrow D$. Memory is allocated when entering the the region;
- **copyout** : The variable is copied $D \rightarrow H$. Memory is allocated when entering the the region;
- **copy** : **copyin** + **copyout**.

No Data Movement

- **create** : The memory is allocated when entering the region;
- **present** : The variable is already in the device;
- **delete** : It dellocates memory on the device used by the variable.

Note

By default, the clauses check if the variable is already on the device. If so, no action is taken. It is possible to see clauses prefixed with **present_or_** or **p** for OpenACC 2.0 compatibility.

Other Clauses from the OpenACC 2.7 Standard.

- **deviceptr (Sec. 2.7.3, pg. 41, OpenACC-2.7 Std.)**;
- **no_create (Sec. 2.7.9, pg. 44, OpenACC-2.7 Std.)**;
- **attach (Sec. 2.7.11, pg. 45, OpenACC-2.7 Std.)**;
- **dettach (Sec. 2.7.12, pg. 45, OpenACC-2.7 Std.)**.

Data on Device

Shape of Arrays

- It is necessary to specify the shape of an array when transferring data;
- Fortran and C++ do not use the same syntax when transferring arrays.

Fortran – array-shape.f90

```
22  !Copy a 2-D array on the GPU - matrix "a"
23  !$ACC parallel loop gang copy(a(1:s,1:s))
24  do j=1,s
25    !$ACC loop worker vector
26    do i=1,s
27      a(i,j) = 0
28    enddo
29  enddo
30  !Copyout columns 100 to 199 included
31  !to the host
32  !$ACC parallel loop gang copy(a(1:s,100:199))
33  do j=100,199
34    !$ACC loop worker vector
35    do i=1,s
36      a(i,j) = 42
37    enddo
38  enddo
```

- The array shape have to be provided in parentheses;
- It is necessary to provide the first and last indices.

Data on Device

Shape of Arrays

- It is necessary to specify the shape of an array when transferring data;
- Fortran and C++ do not use the same syntax when transferring arrays.

Fortran – array-shape.f90

```
array_shape:
23, Generating copy(a(1:s,1:s)) [if not already present]
    Generating Tesla code
    24, !$acc loop gang ! blockidx%x
    26, !$acc loop worker(4), vector(32) ! threadidx%y threadidx%x
26, Loop is parallelizable
32, Generating copy(a(1:s,100:199)) [if not already present]
    Generating Tesla code
    33, !$acc loop gang ! blockidx%x
    35, !$acc loop worker(4), vector(32) ! threadidx%y threadidx%x
35, Loop is parallelizable
```

- The array shape have to be provided in parentheses;
- It is necessary to provide the first and last indices.

Data on Device

Shape of Arrays

- It is necessary to specify the shape of an array when transferring data;
- Fortran and C++ do not use the same syntax when transferring arrays.

C/C++ – array-shape.cpp

```
28  // Copy the array "a" by giving first element
29  // and the size of the array
30  #pragma acc parallel loop gang copy (a[0:s][0:s])
31  for (int i=0; i<s; ++i )
32    #pragma acc loop worker vector
33    for ( int j=0; j<s; ++j )
34      a[i][j]=0;
35  // Copy copy columns 99 to 198
36  #pragma acc parallel loop gang copy (a[0:s][99:100])
37  for (int i=0; i<s; ++i)
38    #pragma acc loop worker vector
39    for (int j=99; j<199; ++j)
40      a[i][j]=42;
```

- The array shape have to be provided in square brackets;
- It is necessary to provide the first index and the number of elements.

Data on Device

Shape of Arrays

- It is necessary to specify the shape of an array when transferring data;
- Fortran and C++ do not use the same syntax when transferring arrays.

C/C++ – array-shape.cpp

```
main:
26, Generating copy(a[:s][:s]) [if not already present]
    Generating Tesla code
    31, #pragma acc loop gang /* blockIdx.x */
    33, #pragma acc loop worker(4), vector(32) /* threadIdx.y threadIdx.
33, Loop is parallelizable
34, Generating copy(a[:s][99:100]) [if not already present]
    Generating Tesla code
    37, #pragma acc loop gang /* blockIdx.x */
    39, #pragma acc loop worker(4), vector(32) /* threadIdx.y threadIdx.
39, Loop is parallelizable
```

- The array shape have to be provided in square brackets;
- It is necessary to provide the first index and the number of elements.

Data on Device

Restrictions

- In Fortran, the last index of an assumed-size dummy array must be specified;
  The dummy argument is a deferred-shape array with (:) bounds.
- In C/C++, the number of elements of a dynamically allocated array must be specified.

Notes

- The shape must be specified when using a slice;
  A slice is subset of elements from an array which is rearranged into another array.
- If the first index is omitted, it is considered as the default of the language
  - **Fortran:** 1;
  - **C/C++:** 0.

Data Region

Parallel Regions

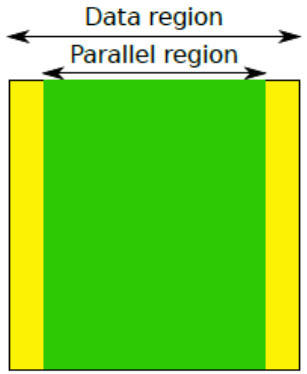
Compute constructs **serial**, **parallel**, **kernels** have a data region associated with variables which are necessary to execution.

parallel-data.f90

```
20    !$ACC parallel copyout( a(:10000) )
21    !$ACC loop
22    do i=1,10000
23      a(i) = i
24    enddo
25    !$ACC end parallel
```

```
parallel_data:
20, Generating copyout(a(:)) [if not already present]
    Generating Tesla code
    22, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
```

```
parallel_data  NVIDIA  devicenum=0
time(us): 30
20: compute region reached 1 time
 20: kernel launched 1 time
  grid: [79]  block: [128]
  device time(us): total=4 max=4 min=4 avg=4
  elapsed time(us): total=373 max=373 min=373 avg=373
20: data region reached 2 times
 25: data copyout transfers: 1
  device time(us): total=26 max=26 min=26 avg=26
```




```
            Type  Time(%)  Name
GPU activities:   67.24%  [CUDA memcpy DtoH]
                  32.76%  parallel_data_20_gpu
     API calls:   65.14%  cuDevicePrimaryCtxRetain
                  21.76%  cuDevicePrimaryCtxRelease
                   7.61%  cuMemHostAlloc
                   5.08%  cuMemFreeHost
```

Data Region

Amdahl's Law and Scaling

- Parallel programming can ideally deliver a factor of N speedup when running on a parallel computer that has N processing elements;
- Amdahl's law is an approximation that models the ideal speedup, S, considering an strong scalability, than can happen when serial programs are modified to run in parallel.
- Strong scalability considers a constant problem size when the problem is parallelized.

Data Region

Amdahl's Law and Scaling

- The expected speedup, $S(N)$ of a parallel code over the serial code when using N processors is dictated by the proportion of a program that can be made parallel, P, and the portion that cannot be parallelized, $(1 - P)$:

$$S(N) = \frac{1}{(1 - P) + \frac{P}{N}}$$

OpenACC developers have two goals:

1. Express the parallel sections of code so they run as fast as possible. Ideally they should run N times faster when using N processors.
2. Utilize whatever techniques or inventiveness they have to minimize the $(1 - P)$ serial time.

Data transfers are included in the $(1 - P)$ portion of the code!

Data Region

parallel-data-multi.f90 – p=1000 and s=10000

```
28      !$ACC parallel copyout( a(:s) )
29      !$ACC loop
30      do i=1,s
31        a(i) = i
32      enddo
33      !$ACC end parallel
34      do j=1,p
35        !$ACC parallel copy( a(:s) )
36        !$ACC loop
37        do i=1,s
38          a(i) = a(i) + 1
39        enddo
40        !$ACC end parallel
41      enddo
```

```
parallel_data:
28, Generating copyout(a(:s)) [if not already present]
    Generating Tesla code
    30, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
35, Generating copy(a(:s)) [if not already present]
    Generating Tesla code
    37, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
```

```
time(us): 26,006
28: compute region reached 1 time
 28: kernel launched 1 time
  grid: [79]  block: [128]
   device time(us): total=3 max=3 min=3 avg=3
  elapsed time(us): total=372 max=372 min=372 avg=372
28: data region reached 2 times
 33: data copyout transfers: 1
  device time(us): total=21 max=21 min=21 avg=21
35: compute region reached 1000 times
 35: kernel launched 1000 times
  grid: [79]  block: [128]
   device time(us): total=2,032 max=12 min=2 avg=2
  elapsed time(us): total=19,385 max=56 min=15 avg=19
35: data region reached 2000 times
 35: data copyin transfers: 1000
  device time(us): total=11,589 max=36 min=7 avg=11
 40: data copyout transfers: 1000
  device time(us): total=12,361 max=40 min=7 avg=12
```

Notes

- Compute region reached 1000 times;
- Data region reached 2000 times (**copyin**+**copyout**).

Data Region

parallel-data-single.f90 – p=1000 and s=10000

```
27      !$ACC parallel copyout( a(:s) )
28      !$ACC loop
29      do i=1,s
30        a(i) = i
31      enddo
32      !$ACC end parallel
33      !$ACC data copy( a(:s) )
34      do j=1,p
35        !$ACC parallel
36        !$ACC loop
37        do i=1,s
38          a(i) = a(i) + 1
39        enddo
40        !$ACC end parallel
41      enddo
42      !$ACC end data
```

```
parallel_data:
27, Generating copyout(a(:s)) [if not already present]
    Generating Tesla code
    29, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
33, Generating copy(a(:s)) [if not already present]
35, Generating Tesla code
    37, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
```

```
time(us): 2,076
27: compute region reached 1 time
 27: kernel launched 1 time
  grid: [79]  block: [128]
   device time(us): total=4 max=4 min=4 avg=4
  elapsed time(us): total=357 max=357 min=357 avg=357
27: data region reached 2 times
 32: data copyout transfers: 1
  device time(us): total=20 max=20 min=20 avg=20
33: data region reached 2 times
 33: data copyin transfers: 1
  device time(us): total=15 max=15 min=15 avg=15
 42: data copyout transfers: 1
  device time(us): total=9 max=9 min=9 avg=9
35: compute region reached 1000 times
 35: kernel launched 1000 times
  grid: [79]  block: [128]
   device time(us): total=2,028 max=12 min=2 avg=2
  elapsed time(us): total=17,143 max=47 min=13 avg=17
```

Notes

- Compute region reached 1000 times;
- Data region reached 3 times.

Data Region

optm.f90 – p=1000 and s=10000

```
27    !$ACC data copyout( a(:s) )
28    !$ACC parallel loop
29    do i=1,s
30      a(i) = i
31    enddo
32    do j=1,p
33      !$ACC parallel loop
34      do i=1,s
35        a(i) = a(i) + 1
36      enddo
37    enddo
38    !$ACC end data
```

```
parallel_data:
28, Generating copyout(a(:s)) [if not already present]
29, Generating Tesla code
    30, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
34, Generating Tesla code
    35, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
```

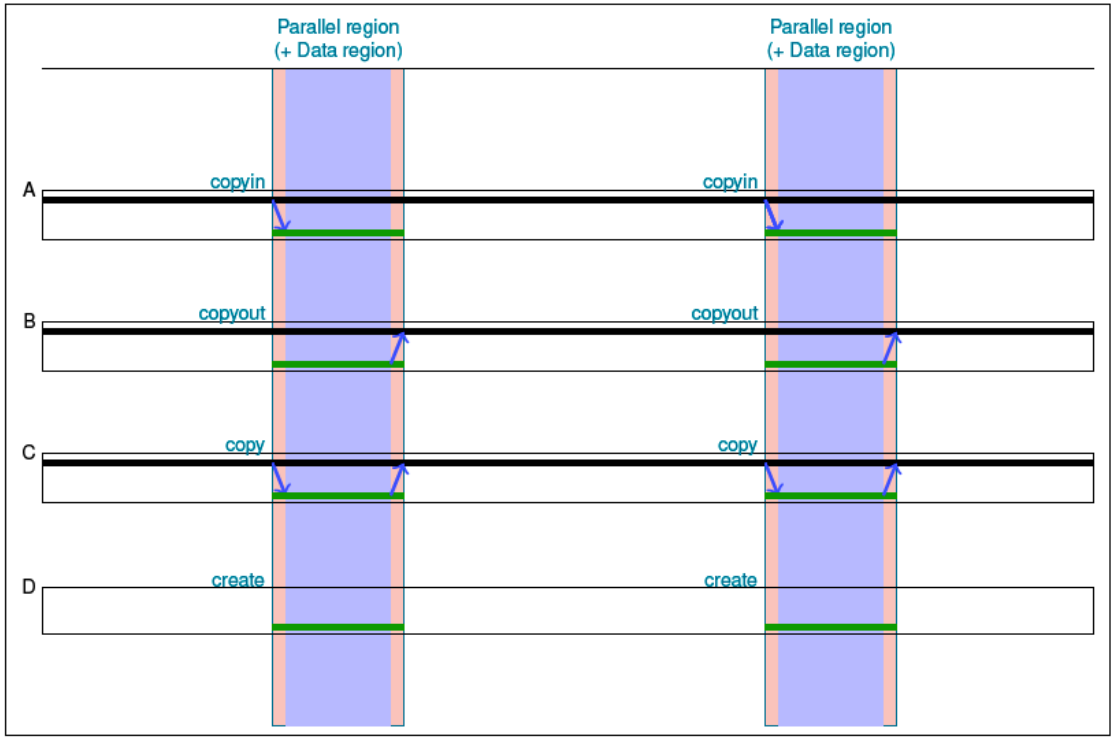
```
time(us): 2,040
28: data region reached 2 times
 39: data copyout transfers: 1
  device time(us): total=23 max=23 min=23 avg=23
29: compute region reached 1 time
 29: kernel launched 1 time
  grid: [79]  block: [128]
   device time(us): total=4 max=4 min=4 avg=4
  elapsed time(us): total=379 max=379 min=379 avg=379
34: compute region reached 1000 times
 34: kernel launched 1000 times
  grid: [79]  block: [128]
   device time(us): total=2,013 max=5 min=2 avg=2
  elapsed time(us): total=16,992 max=29 min=14 avg=16
```

Notes

- Compute region reached 1000 times;
- Data region reached 2 times.

Data Region

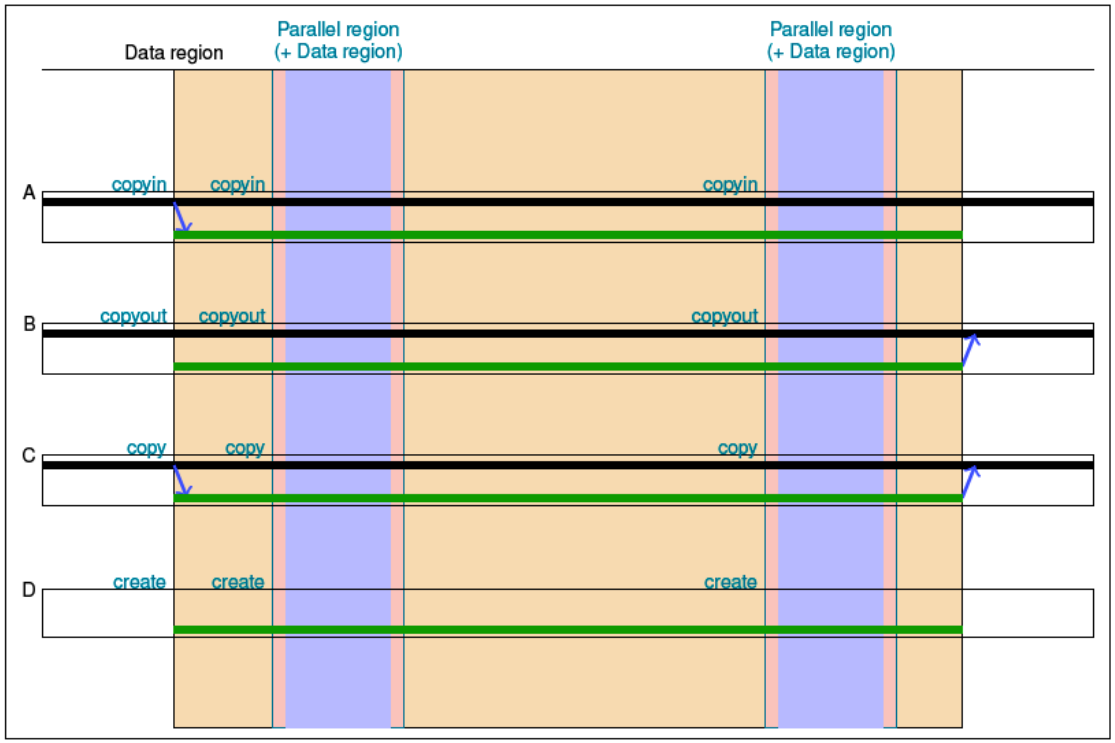
Visual Example – Multiple data and parallel regions



- 8 transfers;
- 2 allocations.

Data Region

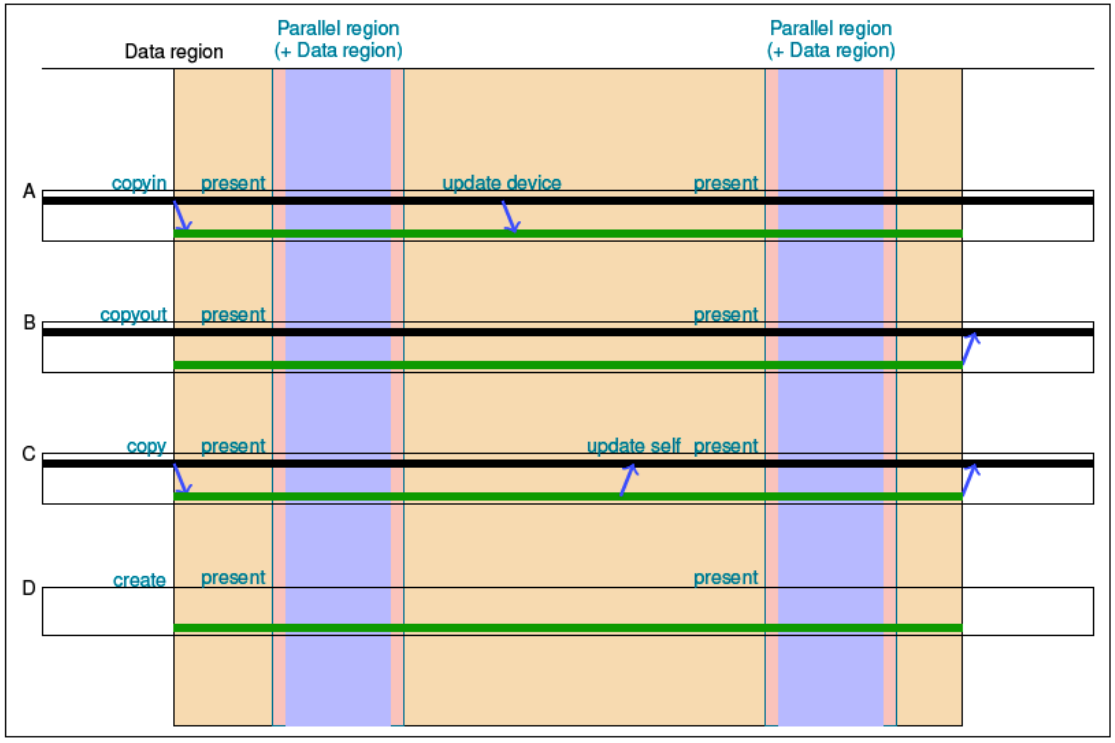
Visual Example – Multiple parallel regions within a single data region



- 4 transfers;
- 1 allocations;
- A, B and C are now transferred at entry and exit of the data region.

Data Region

Visual Example – Using **update** in parallel and data regions



- 6 transfers and 1 allocation;
- Clauses check for data presence. However, it is a good practice to use the **present** clause in order to make the code clear;
- The **update** clause can be used to make sure data is up to date in the host or device.
  - The **update** clause is used inside a data region;
  - The **update** clause cannot be used inside a parallel region.

Data Region

Update – **self** or **host** – update-err.f90 – p=42, s=1000

```
29   !$ACC data copyout( a(:s) )
30   !$ACC parallel loop
31   do i=1,s
32     a(i) = 0
33   enddo
34   do j=1,p
35     call random_number(test)
36     rng = floor(test*100)
37     !$ACC parallel loop copyin(rng) &
38     !$ACC& copyout(a)
39     do i=1,s
40       a(i) = a(i) + rng
41     enddo
42   enddo
43   ! write(*,*) "before update self", a(p)
44   !!$ACC update self(a(p:p))
45   ! write(*,*) "after update self", a(p)
46   !$ACC serial
47   a(p) = p
48   !$ACC end serial
49   write(*,*) "before end data", a(p)
50   !$ACC end data
51   write(*,*) "after end data", a(p)
```

The **self** and **host** clauses update the variable in the $H \rightarrow D$ direction.

```
before end data           0
after end data           42
```

```
para:
29, Generating copyout(a(:s)) [if not already present]
30, Generating Tesla code
    31, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
37, Generating copyout(a(:)) [if not already present]
    Generating copyin(rng) [if not already present]
    Generating Tesla code
    39, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
46, Accelerator serial kernel generated
    Generating Tesla code
```

The **"a"** array is not initialized on the host before the end of the data region in update-err.f90.

Data Region

Update – **self** or **host** – update-err.f90 – p=42, s=1000

```
29  !$ACC data copyout( a(:s) )
30  !$ACC parallel loop
31  do i=1,s
32    a(i) = 0
33  enddo
34  do j=1,p
35    call random_number(test)
36    rng = floor(test*100)
37    !$ACC parallel loop copyin(rng) &
38    !$ACC& copyout(a)
39    do i=1,s
40      a(i) = a(i) + rng
41    enddo
42  enddo
43  ! write(*,*) "before update self", a(p)
44  !!$ACC update self(a(p:p))
45  ! write(*,*) "after update self", a(p)
46  !$ACC serial
47  a(p) = p
48  !$ACC end serial
49  write(*,*) "before end data", a(p)
50  !$ACC end data
51  write(*,*) "after end data", a(p)
```

The **self** and **host** clauses update the variable in the $H \rightarrow D$ direction.

```
 before end data            0
 after end data            42
```

```
para  NVIDIA  devicenum=0
time(us): 497
29: data region reached 2 times
 50: data copyout transfers: 1
  device time(us): total=22 max=22 min=22 avg=22
30: compute region reached 1 time
 30: kernel launched 1 time
  grid: [79]  block: [128]
   device time(us): total=4 max=4 min=4 avg=4
  elapsed time(us): total=362 max=362 min=362 avg=362
37: compute region reached 42 times
 37: kernel launched 42 times
  grid: [79]  block: [128]
   device time(us): total=86 max=3 min=2 avg=2
  elapsed time(us): total=738 max=27 min=15 avg=17
37: data region reached 84 times
 37: data copyin transfers: 42
  device time(us): total=383 max=10 min=8 avg=9
46: compute region reached 1 time
 46: kernel launched 1 time
  grid: [1]  block: [1]
   device time(us): total=2 max=2 min=2 avg=2
  elapsed time(us): total=17 max=17 min=17 avg=17
```

The **"a"** array is not initialized on the host before the end of the data region in update-err.f90.

Data Region

Update – **self** or **host** – update-corr.f90 – p=42, s=1000

```
28  !$ACC data copyout( a(:s) )
29  !$ACC parallel loop
30  do i=1,s
31    a(i) = 0
32  enddo
33  do j=1,p
34    call random_number(test)
35    rng = floor(test*100)
36    !$ACC parallel loop copyin(rng) &
37    !$ACC& copyout(a)
38    do i=1,s
39      a(i) = a(i) + rng
40    enddo
41  enddo
42  write(*,*) "before update self", a(p)
43  !$ACC update self(a(p:p))
44  write(*,*) "after update self", a(p)
45  !$ACC serial
46  a(p) = p
47  !$ACC end serial
48  write(*,*) "before end data", a(p)
49  !$ACC update host(a(p:p))
50  write(*,*) "second update host", a(p)
51  !$ACC end data
52  write(*,*) "after end data", a(p)
```

The **self** and **host** clauses update the variable in the $H \rightarrow D$ direction.

```
before update self            0
after update self          2259
before end data            2259
second update host           42
after end data             42
```

```
para:
     28, Generating copyout(a(:s)) [if not already present]
     29, Generating Tesla code
         30, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
     36, Generating copyout(a(:)) [if not already present]
         Generating copyin(rng) [if not already present]
         Generating Tesla code
         38, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
     43, Generating update self(a(p))
     45, Accelerator serial kernel generated
         Generating Tesla code
     49, Generating update self(a(p))
```

The **"a"** array is initialized on the host after the **update** directive.

Data Region

Update – **self** or **host** – update-corr.f90 – p=42, s=1000

```
28  !$ACC data copyout( a(:s) )
29  !$ACC parallel loop
30  do i=1,s
31    a(i) = 0
32  enddo
33  do j=1,p
34    call random_number(test)
35    rng = floor(test*100)
36    !$ACC parallel loop copyin(rng) &
37    !$ACC& copyout(a)
38    do i=1,s
39      a(i) = a(i) + rng
40    enddo
41  enddo
42  write(*,*) "before update self", a(p)
43  !$ACC update self(a(p:p))
44  write(*,*) "after update self", a(p)
45  !$ACC serial
46  a(p) = p
47  !$ACC end serial
48  write(*,*) "before end data", a(p)
49  !$ACC update host(a(p:p))
50  write(*,*) "second update host", a(p)
51  !$ACC end data
52  write(*,*) "after end data", a(p)
```

The **self** and **host** clauses update the variable in the $H \rightarrow D$ direction.

```
before update self            0
after update self          2259
before end data            2259
second update host           42
after end data               42
```

```
para NVIDIA devicenum=0
time(us): 517
28: data region reached 2 times
 51: data copyout transfers: 1
      device time(us): total=9 max=9 min=9 avg=9
29: compute region reached 1 time
 29: kernel launched 1 time
     grid: [79]  block: [128]
      device time(us): total=3 max=3 min=3 avg=3
     elapsed time(us): total=407 max=407 min=407 avg=407
36: compute region reached 42 times
 36: kernel launched 42 times
     grid: [79]  block: [128]
      device time(us): total=86 max=3 min=2 avg=2
     elapsed time(us): total=745 max=38 min=16 avg=17
36: data region reached 84 times
 36: data copyin transfers: 42
      device time(us): total=391 max=18 min=8 avg=9
43: update directive reached 1 time
 43: data copyout transfers: 1
      device time(us): total=21 max=21 min=21 avg=21
45: compute region reached 1 time
    45: kernel launched 1 time
        grid: [1]  block: [1]
         device time(us): total=3 max=3 min=3 avg=3
        elapsed time(us): total=32 max=32 min=32 avg=32
49: update directive reached 1 time
    49: data copyout transfers: 1
         device time(us): total=4 max=4 min=4 avg=4
```

The **"a"** array is initialized on the host after the **update** directive.

Data Region

Update – **device**

The **device** clause updates the variable in the $D \rightarrow H$ direction.

Data Region

Global Data Regions – **declare**

Important Notes The lifetime of data inside the **declare** directive is the same lifetime of the scope of the code region where it is used. Example:

Zone	Scope
Module	Summ
Function	Product
Subroutine	Maximum

module.f90

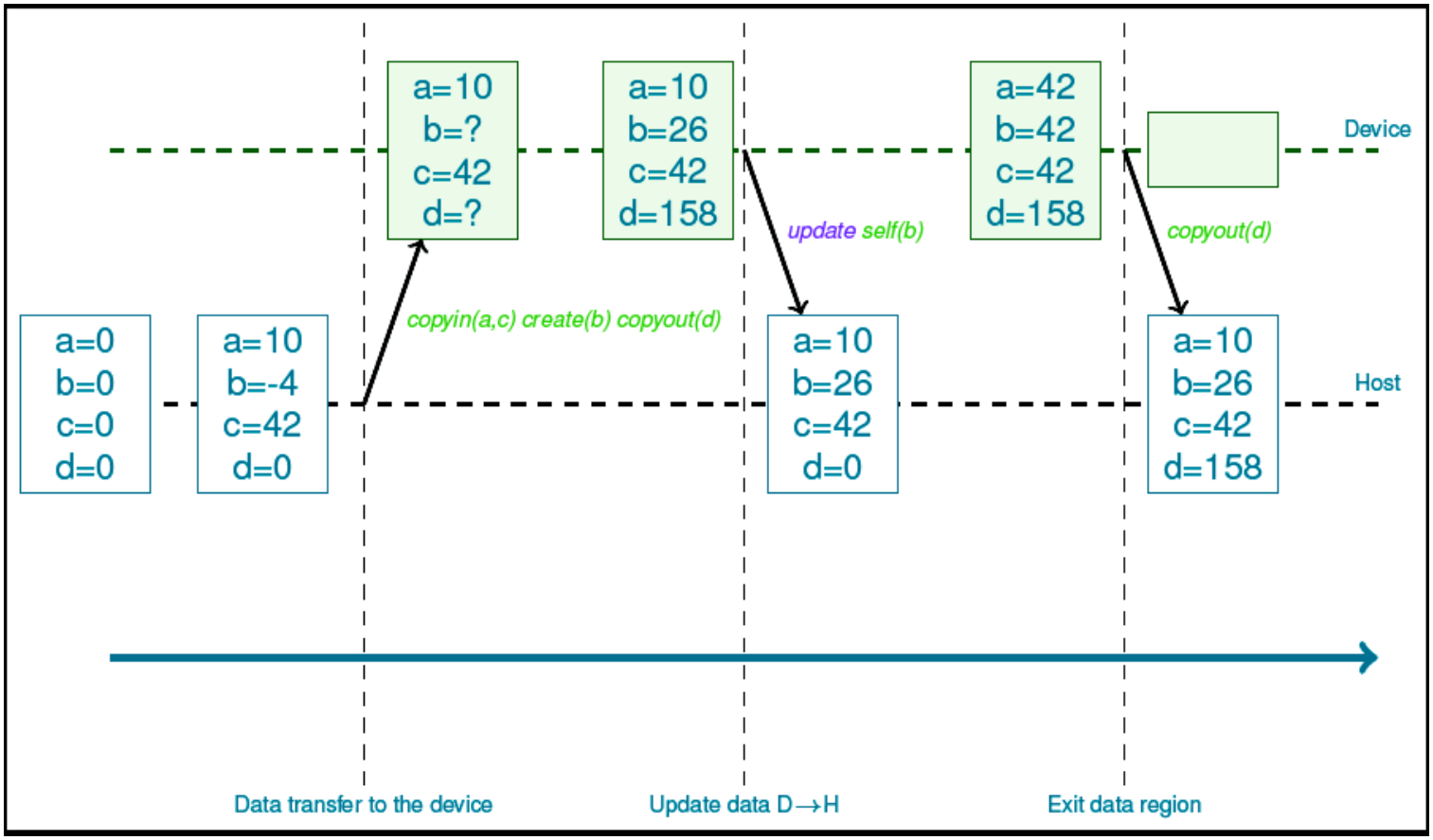
```
4  module var
5    integer :: i
6    integer, parameter :: maxi=10000
7    integer :: a(maxi)
8    !$ACC declare copyout( i, maxi, a(:) )
9  end module var
10
11 program loop
12   use var
13   !$ACC parallel loop
14   do i=1,maxi
15     a(i) = i
16   enddo
17   write(*,*) a(maxi)
18 end program loop
```

```
loop:
13, Generating Tesla code
    14, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
13, Generating implicit copyout(a(:)) [if not already present]
```

```
Accelerator Kernel Timing data
loop  NVIDIA  devicenum=0
time(us): 15
13: compute region reached 1 time
 13: kernel launched 1 time
  grid: [79]  block: [128]
   device time(us): total=4 max=4 min=4 avg=4
  elapsed time(us): total=360 max=360 min=360 avg=360
13: data region reached 2 times
 17: data copyout transfers: 1
  device time(us): total=11 max=11 min=11 avg=11
```

Data Region

Time line



Data Region

Important Notes

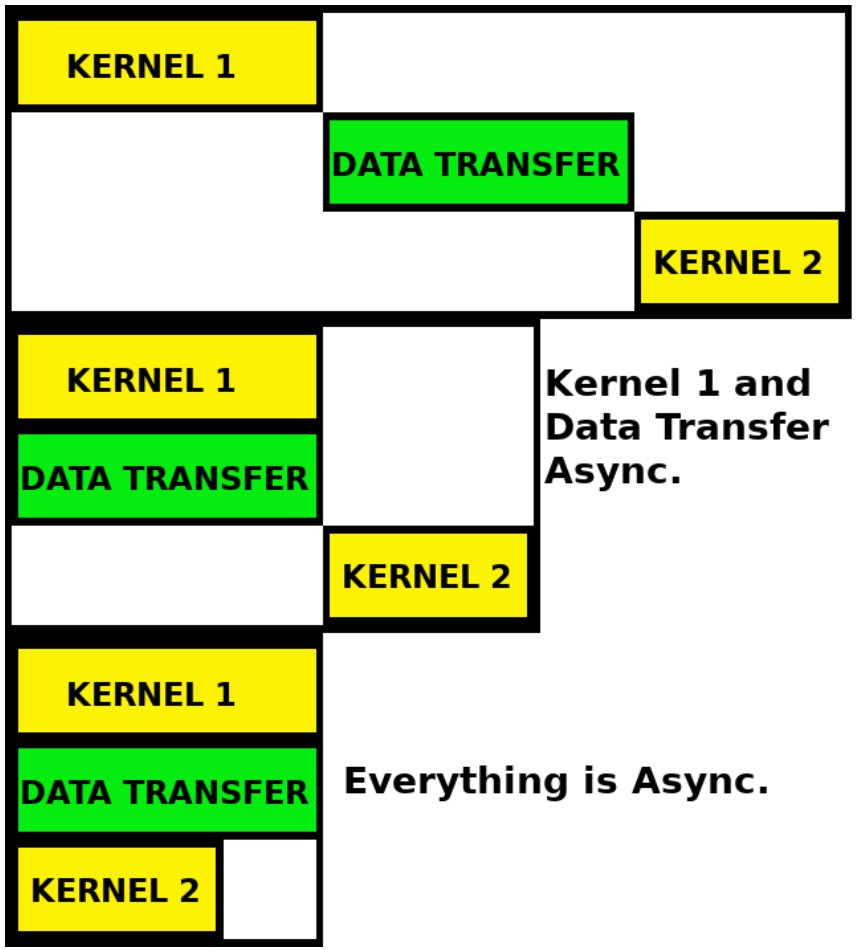
- Data transfers between the host and the device are costly;
- It is mandatory to minimize these transfers to achieve good performance;
- It is possible to use data clauses whitin **kernels**/**parallel** and/or **data** regions;
  - The **update** directive can be used to avoid unexpected bahaviors.

Asynchronism

Introduction

- By default kernels are executed synchronously;
- The accelerator is able to manage several execution threads, running concurrently;
- In order to achieve better performance it is recommended to maximize overlaps between:
  - Computations and data transfers;
  - kernel/kernel if they are independent.

Asynchronism is activated by adding the async(execution thread number) clause to one of these directives: **parallel, kernels, serial, enter data, exit data, update** and **wait**.
In all cases **async** is optional.
It is possible to specify a number inside the clause to create several execution threads.



Asynchronism

sync.f90 – s=10000

```
25  !$ACC enter data create( a(1:s), b(1:s),&
26  !$ACC& c(1:s) )
27  ! b is initialized on host
28  do i=1,s
29    b(i) = i
30  enddo
31  !$ACC parallel loop
32  do i=1,s
33    a(i) = 42
34  enddo
35  ! Update vector b located on device
36  ! with data from the host
37  !$ACC update device(b)
38  !$ACC parallel loop
39  do i=1,s
40    c(i) = 1
41  enddo
42  !$ACC exit data delete( a(1:s), b(1:s),&
43  !$ACC& c(1:s) )
```

```
async:
25, Generating enter data create(c(1:s),b(1:s),a(1:s))
31, Generating Tesla code
 32, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
31, Generating implicit copyout(a(1:10000)) [if not already present]
37, Generating update device(b(:))
38, Generating Tesla code
 39, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
38, Generating implicit copyout(c(1:10000)) [if not already present]
42, Generating exit data delete(c(1:s),b(1:s),a(1:s))
```

```
async  NVIDIA  devicenum=0
time(us): 26
25: data region reached 1 time
31: compute region reached 1 time
 31: kernel launched 1 time
  grid: [79]  block: [128]
   device time(us): total=4 max=4 min=4 avg=4
  elapsed time(us): total=357 max=357 min=357 avg=357
31: data region reached 2 times
37: update directive reached 1 time
 37: data copyin transfers: 1
      device time(us): total=19 max=19 min=19 avg=19
38: compute region reached 1 time
 38: kernel launched 1 time
  grid: [79]  block: [128]
   device time(us): total=3 max=3 min=3 avg=3
  elapsed time(us): total=30 max=30 min=30 avg=30
38: data region reached 2 times
42: data region reached 1 time
```

Asynchronism

async-1.f90 – s=10000

```
25  !$ACC enter data create( a(1:s), b(1:s),&
26  !$ACC& c(1:s) )
27  ! b is initialized on host
28  do i=1,s
29    b(i) = i
30  enddo
31  !$ACC parallel loop async(1)
32  do i=1,s
33    a(i) = 42
34  enddo
35  ! Update vector b located on device
36  ! with data from the host
37  !$ACC update device(b)
38  !$ACC parallel loop
39  do i=1,s
40    c(i) = 1
41  enddo
42  !$ACC exit data delete( a(1:s), b(1:s),&
43  !$ACC& c(1:s) )
```

```
async:
25, Generating enter data create(c(1:s),b(1:s),a(1:s))
31, Generating Tesla code
 32, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
31, Generating implicit copyout(a(1:10000)) [if not already present]
37, Generating update device(b(:))
38, Generating Tesla code
 39, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
38, Generating implicit copyout(c(1:10000)) [if not already present]
42, Generating exit data delete(c(1:s),b(1:s),a(1:s))
```

```
async  NVIDIA  devicenum=0
time(us): 23
25: data region reached 1 time
31: compute region reached 1 time
 31: kernel launched 1 time
  grid: [79]  block: [128]
   device time(us): total=4 max=4 min=4 avg=4
  elapsed time(us): total=355 max=355 min=355 avg=355
31: data region reached 2 times
37: update directive reached 1 time
 37: data copyin transfers: 1
  device time(us): total=16 max=16 min=16 avg=16
38: compute region reached 1 time
 38: kernel launched 1 time
  grid: [79]  block: [128]
   device time(us): total=3 max=3 min=3 avg=3
  elapsed time(us): total=33 max=33 min=33 avg=33
38: data region reached 2 times
42: data region reached 1 time
```

Asynchronism

async-2.f90 – s=10000

```
25  !$ACC enter data create( a(1:s), b(1:s),&
26  !$ACC& c(1:s) )
27  ! b is initialized on host
28  do i=1,s
29    b(i) = i
30  enddo
31  !$ACC parallel loop async(1)
32  do i=1,s
33    a(i) = 42
34  enddo
35  ! Update vector b located on device
36  ! with data from the host
37  !$ACC update device(b) async(2)
38  !$ACC parallel loop
39  do i=1,s
40    c(i) = 1
41  enddo
42  !$ACC exit data delete( a(1:s), b(1:s),&
43  !$ACC& c(1:s) )
```

```
async:
25, Generating enter data create(c(1:s),b(1:s),a(1:s))
31, Generating Tesla code
 32, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
31, Generating implicit copyout(a(1:10000)) [if not already present]
37, Generating update device(b(:))
38, Generating Tesla code
 39, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
38, Generating implicit copyout(c(1:10000)) [if not already present]
42, Generating exit data delete(c(1:s),b(1:s),a(1:s))
```

```
Timing may be affected by asynchronous behavior
set PGI_ACC_SYNCHRONOUS to 1 to disable async() clauses
async  NVIDIA  devicenum=0
time(us): 25
25: data region reached 1 time
31: compute region reached 1 time
 31: kernel launched 1 time
  grid: [79]  block: [128]
   device time(us): total=4 max=4 min=4 avg=4
  elapsed time(us): total=378 max=378 min=378 avg=378
31: data region reached 2 times
37: update directive reached 1 time
 37: data copyin transfers: 1
  device time(us): total=17 max=17 min=17 avg=17
38: compute region reached 1 time
 38: kernel launched 1 time
  grid: [79]  block: [128]
   device time(us): total=4 max=4 min=4 avg=4
  elapsed time(us): total=35 max=35 min=35 avg=35
38: data region reached 2 times
42: data region reached 1 time
```

Asynchronism

async-3.f90 – s=10000

```
25  !$ACC enter data create( a(1:s), b(1:s),&
26  !$ACC& c(1:s) )
27  ! b is initialized on host
28  do i=1,s
29    b(i) = i
30  enddo
31  !$ACC parallel loop async(1)
32  do i=1,s
33    a(i) = 42
34  enddo
35  ! Update vector b located on device
36  ! with data from the host
37  !$ACC update device(b) async(2)
38  !$ACC parallel loop async(3)
39  do i=1,s
40    c(i) = 1
41  enddo
42  !$ACC exit data delete( a(1:s), b(1:s),&
43  !$ACC& c(1:s) )
```

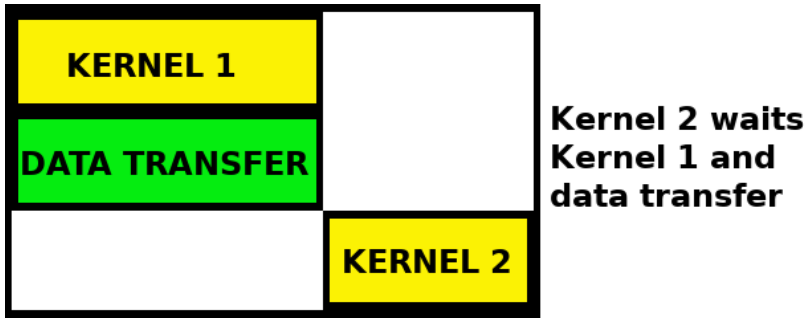
```
async:
25, Generating enter data create(c(1:s),b(1:s),a(1:s))
31, Generating Tesla code
 32, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
31, Generating implicit copyout(a(1:10000)) [if not already present]
37, Generating update device(b(:))
38, Generating Tesla code
 39, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
38, Generating implicit copyout(c(1:10000)) [if not already present]
42, Generating exit data delete(c(1:s),b(1:s),a(1:s))
```

```
Timing may be affected by asynchronous behavior
set PGI_ACC_SYNCHRONOUS to 1 to disable async() clauses
async  NVIDIA  devicenum=0
time(us): 22
25: data region reached 1 time
31: compute region reached 1 time
 31: kernel launched 1 time
  grid: [79]  block: [128]
   device time(us): total=4 max=4 min=4 avg=4
  elapsed time(us): total=369 max=369 min=369 avg=369
31: data region reached 2 times
37: update directive reached 1 time
 37: data copyin transfers: 1
  device time(us): total=15 max=15 min=15 avg=15
38: compute region reached 1 time
 38: kernel launched 1 time
  grid: [79]  block: [128]
   device time(us): total=3 max=3 min=3 avg=3
  elapsed time(us): total=33 max=33 min=33 avg=33
38: data region reached 2 times
42: data region reached 1 time
```

Asynchronism

Wait Clause

- The **wait** clause can be used in of dependent kernels;
- **Wait** can be used alone or with a list of **kernels** numbers, *i.e.* **wait(1,2)**.



Asynchronism

wait.f90 – s=10000

```
25  !$ACC enter data create( a(1:s), b(1:s),&
26  !$ACC& c(1:s) )
27  ! b is initialized on host
28  do i=1,s
29    b(i) = i
30  enddo
31  !$ACC parallel loop async(1)
32  do i=1,s
33    a(i) = 42
34  enddo
35  ! Update vector b located on device
36  ! with data from the host
37  !$ACC update device(b) async(2)
38  !$ACC parallel loop async(3)
39  do i=1,s
40    c(i) = 1
41  enddo
42  !$ACC parallel loop wait(2)
43  do i=1,s
44    b(i) = b(i)*i
45  enddo
46  !$ACC exit data delete( a(1:s), b(1:s),&
47  !$ACC& c(1:s) )
```

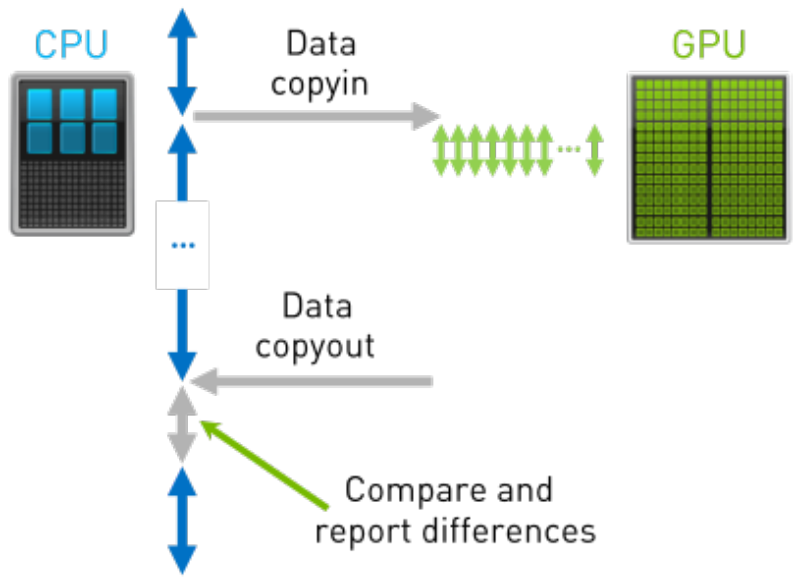
```
async:
25, Generating enter data create(b(1:s),c(1:s),a(1:s))
31, Generating Tesla code
 32, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
31, Generating implicit copyout(a(1:10000)) [if not already present]
37, Generating update device(b(:))
38, Generating Tesla code
 39, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
38, Generating implicit copyout(c(1:10000)) [if not already present]
42, Generating Tesla code
 43, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
42, Generating implicit copy(b(1:10000)) [if not already present]
46, Generating exit data delete(c(1:s),b(1:s),a(1:s))
```

```
Timing may be affected by asynchronous behavior
set PGI_ACC_SYNCHRONOUS to 1 to disable async() clauses
async  NVIDIA  devicenum=0
time(us): 28
25: data region reached 1 time
31: compute region reached 1 time
 31: kernel launched 1 time
  grid: [79]  block: [128]
   device time(us): total=4 max=4 min=4 avg=4
  elapsed time(us): total=382 max=382 min=382 avg=382
31: data region reached 2 times
37: update directive reached 1 time
 37: data copyin transfers: 1
  device time(us): total=16 max=16 min=16 avg=16
38: compute region reached 1 time
 38: kernel launched 1 time
  grid: [79]  block: [128]
   device time(us): total=3 max=3 min=3 avg=3
  elapsed time(us): total=34 max=34 min=34 avg=34
38: data region reached 2 times
42: compute region reached 1 time
 42: kernel launched 1 time
  grid: [79]  block: [128]
   device time(us): total=5 max=5 min=5 avg=5
  elapsed time(us): total=21 max=21 min=21 avg=21
42: data region reached 2 times
46: data region reached 1 time
```

GPU Debugging

PGI Auto-compare for OpenACC

- Results can diverge between programs running on a CPU versus a GPU due to programming errors, precision of numerical intrinsics, or variations in compiler optimizations.
- OpenACC auto-compare runs compute regions redundantly on both the CPU and GPU.
- When data is copied from the GPU back to the CPU, GPU results are compared with those computed on the CPU.
- Auto-compare works on both structured and unstructured data regions, with difference reports controlled by environment variables to quickly pinpoint where results start to diverge and adapt the program or compiler options as needed.



GPU Debugging

PGI Auto-compare for OpenACC

The auto-compare is activated during compilation as the race condition example, **pb-sync.f90**:

- **pgf90 -acc -ta=tesla:cc35,cc60,autocompare -Minfo=accel pb-sync.f90**

```
23    !$acc parallel
24    !$acc loop gang
25    do i=1,nx
26      a(i) = 1.0_8
27    enddo
28    !$acc loop gang reduction(+:summ)
29    do i=nx,1,-1
30      summ = summ + a(i)
31    enddo
32    !$acc end parallel
```

```
reduction:
23, Generating Tesla code
 25, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
 29, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
 Generating reduction(+:summ)
23, Generating implicit copy(summ) [if not already present]
 Generating implicit copyout(a(:nx)) [if not already present]
```

```
PCAST Float summ in function reduction, pb_sync.f90:32
idx: 0 FAIL ABS  act: 5.00267200e+07 exp: 1.67772160e+07 dif: 3.32495040e+07
compared 2 blocks, 100000001 elements, 400000004 bytes
1 errors found in 1 blocks
absolute tolerance = 0.00000000000000000e+00, abs=0

Accelerator Kernel Timing data
pb_sync.f90
reduction  NVIDIA  devicenum=0
time(us): 41,027
23: compute region reached 1 time
 23: kernel launched 1 time
  grid: [65535]  block: [128]
   device time(us): total=9,036 max=9,036 min=9,036 avg=9,036
  elapsed time(us): total=9,077 max=9,077 min=9,077 avg=9,077
 23: reduction kernel launched 1 time
  grid: [1]  block: [256]
   device time(us): total=83 max=83 min=83 avg=83
  elapsed time(us): total=111 max=111 min=111 avg=111
23: data region reached 2 times
 23: data copyin transfers: 1
  device time(us): total=7 max=7 min=7 avg=7
 32: data copyout transfers: 25
  device time(us): total=31,901 max=1,433 min=12 avg=1,276
```

Optimization Example - Game of Life

4000x2000 - 100 gen.

Serial

```
22  CALL CPU_TIME(TIME_INI)
23  allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24  old_world(:,:) = 0
25  call fill_world
26  do g=1,generations
27   cells = 0
28   do r=1, rows
29    do c=1, cols
30     old_world(r,c) = world(r,c)
31    enddo
32   enddo
33   do r=1, rows
34    do c=1, cols
35     neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
36     old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
37     old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
38     if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3)) then
39      world(r,c) = 0
40     else if (neigh == 3) then
41      world(r,c) = 1
42     endif
43    enddo
44   enddo
45   do r=1, rows
46    do c=1, cols
47     cells = cells + world(r,c)
48    enddo
49   enddo
50   print *, "Cells alive at generation ", g, ": ", cells
51  enddo
52  deallocate(world, old_world)
53  CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation          45 :        997185
 Cells alive at generation          46 :        988790
 Cells alive at generation          47 :        981380
 Cells alive at generation          48 :        974253
 Cells alive at generation          49 :        967943
 Cells alive at generation          50 :        959634
 Total time=     10.29104113578796
```

make.out

```
pgf90 -O0 -acc=noautopar -ta=tesla:cc35,cc60 -Minfo=all -c gol.f90 -o gol.o
pgf90 -O0 -acc=noautopar -ta=tesla:cc35,cc60 -Minfo=all gol.o -o gol
```


- Gardener, M. (1970). MATHEMATICAL GAMES: The fantastic combinations of John Conway's new solitaire game" life,".*Scientific American*, 223, 120-123.
- Wainwright, R. (2010). Conway's Game of Life: Early Personal Recollections. *In: Adamatzky A. (eds) Game of Life Cellular Automata*. Springer, London.

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Serial

```
22    CALL CPU_TIME(TIME_INI)
23    allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24    old_world(:,:) = 0
25    call fill_world
26    do g=1,generations
27     cells = 0
28     do r=1, rows
29      do c=1, cols
30       old_world(r,c) = world(r,c)
31      enddo
32     enddo
33     do r=1, rows
34      do c=1, cols
35       neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
36       old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
37       old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
38       if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3)) then
39        world(r,c) = 0
40       else if (neigh == 3) then
41        world(r,c) = 1
42       endif
43      enddo
44     enddo
45     do r=1, rows
46      do c=1, cols
47       cells = cells + world(r,c)
48      enddo
49     enddo
50     print *, "Cells_alive_at_generation_", g, ":_", cells
51    enddo
52    deallocate(world, old_world)
53    CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation          45 :        997185
 Cells alive at generation          46 :        988790
 Cells alive at generation          47 :        981380
 Cells alive at generation          48 :        974253
 Cells alive at generation          49 :        967943
 Cells alive at generation          50 :        959634
 Total time=     10.29104113578796
```

make.out

```
pgf90 -O0 -acc=noautopar -ta=tesla:cc35,cc60 -Minfo=all -c gol.f90 -o gol.o
pgf90 -O0 -acc=noautopar -ta=tesla:cc35,cc60 -Minfo=all gol.o -o gol
```

Intel Core i7-8700 3.2GHz 12Mo Smart Cache
(up to 4.60 GHz)
Prix : 380,90 €

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #1

```
22    CALL CPU_TIME(TIME_INI)
23    allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24    old_world(:,:) = 0
25    call fill_world
26    do g=1,generations
27     cells = 0
28     !$ACC parallel
29     do r=1, rows
30      do c=1, cols
31       old_world(r,c) = world(r,c)
32      enddo
33     enddo
34     !$ACC end parallel
35     do r=1, rows
36      do c=1, cols
37       neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
38       old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
39       old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
40       if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3) ) then
41        world(r,c) = 0
42       else if (neigh == 3) then
43        world(r,c) = 1
44       endif
45      enddo
46     enddo
47     do r=1, rows
48      do c=1, cols
49       cells = cells + world(r,c)
50      enddo
51     enddo
52     print *, "Cells alive at generation ", g, ": ", cells
53    enddo
54    deallocate(world, old_world)
55    CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation           45 :       997185
 Cells alive at generation           46 :       988790
 Cells alive at generation           47 :       981380
 Cells alive at generation           48 :       974253
 Cells alive at generation           49 :       967943
 Cells alive at generation           50 :       959634
 Total time=      34.91349506378174
```

make.err

```
gol:
28, Generating Tesla code
    29, !$acc loop seq
    30, !$acc loop seq
28, Generating implicit copyin(world(1:rows,1:cols))[if not already present]
    Generating implicit copyout(old_world(1:rows,1:cols))[if not already present]
29, Loop is parallelizable
30, Loop is parallelizable
```

Nvidia GeForce GTX 1050 2Go
Prix : 161,98 €

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #1

```
22    CALL CPU_TIME(TIME_INI)
23    allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24    old_world(:,:) = 0
25    call fill_world
26    do g=1,generations
27     cells = 0
28     !$ACC parallel
29     do r=1, rows
30      do c=1, cols
31       old_world(r,c) = world(r,c)
32      enddo
33     enddo
34     !$ACC end parallel
35     do r=1, rows
36      do c=1, cols
37       neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
38       old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
39       old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
40       if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3)) then
41        world(r,c) = 0
42       else if (neigh == 3) then
43        world(r,c) = 1
44       endif
45      enddo
46     enddo
47     do r=1, rows
48      do c=1, cols
49       cells = cells + world(r,c)
50      enddo
51     enddo
52     print *, "Cells alive at generation ", g, ": ", cells
53    enddo
54    deallocate(world, old_world)
55    CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation          45 :       997185
 Cells alive at generation          46 :       988790
 Cells alive at generation          47 :       981380
 Cells alive at generation          48 :       974253
 Cells alive at generation          49 :       967943
 Cells alive at generation          50 :       959634
 Total time=     34.91349506378174
```

make.err

```
gol:
28, Generating Tesla code
    29, !$acc loop seq
    30, !$acc loop seq
28, Generating implicit copyin(world(1:rows,1:cols))[if not already present]
    Generating implicit copyout(old_world(1:rows,1:cols))[if not already present]
29, Loop is parallelizable
30, Loop is parallelizable
```

- fill_world routine cannot be parallelized with OpenACC. Random number routine is not yet available to the PGI 19.10 compiler;
- noautopar is used in oder to be in control of the optimization procedure;
- The generation loop presents a dependency and cannot be parallelized;
- Time is increasing due to gang redundancy from **$ACC parallel** directive.

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #1

```
22  CALL CPU_TIME(TIME_INI)
23  allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24  old_world(:,:) = 0
25  call fill_world
26  do g=1,generations
27   cells = 0
28   !$ACC parallel
29   do r=1, rows
30    do c=1, cols
31     old_world(r,c) = world(r,c)
32    enddo
33   enddo
34   !$ACC end parallel
35   do r=1, rows
36    do c=1, cols
37     neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
38     old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
39     old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
40     if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3)) then
41      world(r,c) = 0
42     else if (neigh == 3) then
43      world(r,c) = 1
44     endif
45    enddo
46   enddo
47   do r=1, rows
48    do c=1, cols
49     cells = cells + world(r,c)
50    enddo
51   enddo
52   print *, "Cells alive at generation ", g, ": ", cells
53  enddo
54  deallocate(world, old_world)
55  CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation           45 :        997185
 Cells alive at generation           46 :        988790
 Cells alive at generation           47 :        981380
 Cells alive at generation           48 :        974253
 Cells alive at generation           49 :        967943
 Cells alive at generation           50 :        959634
 Total time=     34.91349506378174
```

gol.err

```
Accelerator Kernel Timing data
gol  NVIDIA  devicenum=0
time(us): 24,307,904
28: compute region reached 50 times
 28: kernel launched 50 times
  grid: [1]  block: [1]
   device time(us): total=24,056,960 max=545,493 min=475,765 avg=481,139
  elapsed time(us): total=24,059,713 max=545,542 min=475,800 avg=481,194
28: data region reached 100 times
 28: data copyin transfers: 100
      device time(us): total=123,399 max=1,432 min=1,166 avg=1,233
 34: data copyout transfers: 100
      device time(us): total=127,545 max=1,492 min=1,200 avg=1,275
```

- fill_world routine cannot be parallelized with OpenACC. Random number routine is not yet available to the PGI 19.10 compiler;
- noautopar is used in oder to be in control of the optimization procedure;
- The generation loop presents a dependency and cannot be parallelized;
- Time is increasing due to gang redundancy from **$ACC parallel** directive.

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #2

```
22  CALL CPU_TIME(TIME_INI)
23  allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24  old_world(:,:) = 0
25  call fill_world
26  do g=1,generations
27   cells = 0
28   !$ACC parallel
29   do r=1, rows
30    do c=1, cols
31     old_world(r,c) = world(r,c)
32    enddo
33   enddo
34   !$ACC end parallel
35   !$ACC parallel
36   do r=1, rows
37    do c=1, cols
38     neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
39     old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
40     old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
41     if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3)) then
42      world(r,c) = 0
43     else if (neigh == 3) then
44      world(r,c) = 1
45     endif
46    enddo
47   enddo
48   !$ACC end parallel
49   do r=1, rows
50    do c=1, cols
51     cells = cells + world(r,c)
52    enddo
53   enddo
54   print *, "Cells alive at generation ", g, ": ", cells
55  enddo
56  deallocate(world, old_world)
57  CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation           45 :        997185
 Cells alive at generation           46 :        988790
 Cells alive at generation           47 :        981380
 Cells alive at generation           48 :        974253
 Cells alive at generation           49 :        967943
 Cells alive at generation           50 :        959634
 Total time=     80.00242805480957
```

make.err

```
gol:
28, Generating Tesla code
    29, !$acc loop seq
    30, !$acc loop seq
28, Generating implicit copyout(old_world(1:rows,1:cols)) [if not already present]
    Generating implicit copyin(world(1:rows,1:cols)) [if not already present]
29, Loop is parallelizable
30, Loop is parallelizable
35, Generating Tesla code
    36, !$acc loop seq
    37, !$acc loop seq
35, Generating implicit copy(world(1:rows,1:cols)) [if not already present]
    Generating implicit copyin(old_world(0:rows+1,0:cols+1)) [if not already present]
36, Loop is parallelizable
37, Loop is parallelizable
```

- 2nd loop is parallelized;
- Time is increasing due to gang redundancy from **$ACC parallel** directive.

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #2

```
22  CALL CPU_TIME(TIME_INI)
23  allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24  old_world(:,:) = 0
25  call fill_world
26  do g=1,generations
27   cells = 0
28   !$ACC parallel
29   do r=1, rows
30    do c=1, cols
31     old_world(r,c) = world(r,c)
32    enddo
33   enddo
34   !$ACC end parallel
35   !$ACC parallel
36   do r=1, rows
37    do c=1, cols
38     neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
39     old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
40     old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
41     if (old_world(r,c) == 1 .and. (neigh<2 .or. neigh>3) ) then
42      world(r,c) = 0
43     else if (neigh == 3) then
44      world(r,c) = 1
45     endif
46    enddo
47   enddo
48   !$ACC end parallel
49   do r=1, rows
50    do c=1, cols
51     cells = cells + world(r,c)
52    enddo
53   enddo
54   print *, "Cells alive at generation ", g, ": ", cells
55  enddo
56  deallocate(world, old_world)
57  CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation           45 :       997185
 Cells alive at generation           46 :       988790
 Cells alive at generation           47 :       981380
 Cells alive at generation           48 :       974253
 Cells alive at generation           49 :       967943
 Cells alive at generation           50 :       959634
 Total time=     80.00242805480957
```

gol.err

```
Accelerator Kernel Timing data
gol  NVIDIA  devicenum=0
time(us): 68,714,075
28: compute region reached 50 times
 28: kernel launched 50 times
  grid: [1]  block: [1]
   device time(us): total=24,131,149 max=546,650 min=478,350 avg=482,622
  elapsed time(us): total=24,133,536 max=546,708 min=478,388 avg=482,670
28: data region reached 100 times
 28: data copyin transfers: 100
  device time(us): total=123,208 max=1,554 min=1,166 avg=1,232
 34: data copyout transfers: 100
  device time(us): total=127,980 max=1,515 min=1,204 avg=1,279
35: compute region reached 50 times
 35: kernel launched 50 times
  grid: [1]  block: [1]
   device time(us): total=43,957,428 max=884,821 min=868,052 avg=879,148
  elapsed time(us): total=43,959,444 max=884,855 min=868,102 avg=879,188
35: data region reached 100 times
 35: data copyin transfers: 200
  device time(us): total=246,842 max=1,531 min=1,162 avg=1,234
 48: data copyout transfers: 100
  device time(us): total=127,468 max=1,394 min=1,204 avg=1,274
```

- 2nd loop is parallelized;
- Time is increasing due to gang redundancy from **$ACC parallel** directive.

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #3

```
22  CALL CPU_TIME(TIME_INI)
23  allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24  old_world(:,:) = 0
25  call fill_world
26  do g=1,generations
27   !$ACC parallel
28   do r=1, rows
29    do c=1, cols
30     old_world(r,c) = world(r,c)
31    enddo
32   enddo
33   !$ACC end parallel
34   !$ACC parallel
35   do r=1, rows
36    do c=1, cols
37     neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
38     old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
39     old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
40     if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3) ) then
41      world(r,c) = 0
42     else if (neigh == 3) then
43      world(r,c) = 1
44     endif
45    enddo
46   enddo
47   !$ACC end parallel
48   cells = 0
49   !$ACC parallel
50   do r=1, rows
51    do c=1, cols
52     cells = cells + world(r,c)
53    enddo
54   enddo
55   !$ACC end parallel
56   print *, "Cells alive at generation ", g, ": ", cells
57  enddo
58  deallocate(world, old_world)
59  CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation           45 :        997185
 Cells alive at generation           46 :        988790
 Cells alive at generation           47 :        981380
 Cells alive at generation           48 :        974253
 Cells alive at generation           49 :        967943
 Cells alive at generation           50 :        959634
 Total time=     87.45015597343445
```

make.err

```
gol:
27, Generating Tesla code
    28, !$acc loop seq
    29, !$acc loop seq
27, Generating implicit copyout(old_world(1:rows,1:cols)) [if not already present]
    Generating implicit copyin(world(1:rows,1:cols)) [if not already present]
28, Loop is parallelizable
29, Loop is parallelizable
34, Generating Tesla code
    35, !$acc loop seq
    36, !$acc loop seq
34, Generating implicit copy(world(1:rows,1:cols)) [if not already present]
    Generating implicit copyin(old_world(0:rows+1,0:cols+1)) [if not already present]
35, Loop is parallelizable
36, Loop is parallelizable
49, Generating Tesla code
    50, !$acc loop seq
    51, !$acc loop seq
    52, Generating implicit reduction(+:cells)
49, Generating implicit copyin(world(1:rows,1:cols)) [if not already present]
50, Loop is parallelizable
51, Loop is parallelizable
```

- 3rd loop is parallelized;
- A **reduction** clause is proposed by the compiler;
- Time is increasing due to gang redundancy from **$ACC parallel** directive.

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #3

```
22    CALL CPU_TIME(TIME_INI)
23    allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24    old_world(:,:) = 0
25    call fill_world
26    do g=1,generations
27     !$ACC parallel
28     do r=1, rows
29      do c=1, cols
30       old_world(r,c) = world(r,c)
31      enddo
32     enddo
33     !$ACC end parallel
34     !$ACC parallel
35     do r=1, rows
36      do c=1, cols
37       neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
38       old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
39       old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
40       if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3) ) then
41        world(r,c) = 0
42       else if (neigh == 3) then
43        world(r,c) = 1
44       endif
45      enddo
46     enddo
47     !$ACC end parallel
48     cells = 0
49     !$ACC parallel
50     do r=1, rows
51      do c=1, cols
52       cells = cells + world(r,c)
53      enddo
54     enddo
55     !$ACC end parallel
56     print *, "Cells alive at generation ", g, ": ", cells
57    enddo
58    deallocate(world, old_world)
59    CALL CPU_TIME(TIME_END)
```

gol.err

```
Accelerator Kernel Timing data
gol  NVIDIA  devicenum=0
time(us): 76,131,242
27: compute region reached 50 times
 27: kernel launched 50 times
  grid: [1]  block: [1]
   device time(us): total=24,040,550 max=554,259 min=475,706 avg=480,811
  elapsed time(us): total=24,042,408 max=554,314 min=475,740 avg=480,848
27: data region reached 100 times
 27: data copyin transfers: 100
  device time(us): total=123,469 max=1,388 min=1,162 avg=1,234
 33: data copyout transfers: 100
  device time(us): total=127,652 max=1,465 min=1,202 avg=1,276
34: compute region reached 50 times
 34: kernel launched 50 times
  grid: [1]  block: [1]
   device time(us): total=43,810,816 max=881,837 min=858,809 avg=876,216
  elapsed time(us): total=43,812,794 max=881,876 min=858,845 avg=876,255
34: data region reached 100 times
 34: data copyin transfers: 200
  device time(us): total=246,924 max=1,497 min=1,162 avg=1,234
 47: data copyout transfers: 100
  device time(us): total=128,736 max=1,759 min=1,204 avg=1,287
49: compute region reached 50 times
 49: data copyin transfers: 50
  device time(us): total=396 max=35 min=7 avg=7
 49: kernel launched 50 times
  grid: [1]  block: [1]
   device time(us): total=7,528,219 max=152,493 min=149,245 avg=150,564
  elapsed time(us): total=7,529,896 max=152,531 min=149,279 avg=150,597
 49: reduction kernel launched 50 times
  grid: [1]  block: [256]
   device time(us): total=148 max=3 min=2 avg=2
  elapsed time(us): total=2,029 max=75 min=23 avg=40
49: data region reached 100 times
 49: data copyin transfers: 100
  device time(us): total=123,516 max=1,471 min=1,164 avg=1,235
55: download reached 50 times
 55: data copyout transfers: 50
  device time(us): total=816 max=23 min=8 avg=16
```

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #4

```
22  CALL CPU_TIME(TIME_INI)
23  allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24  old_world(:,:) = 0
25  call fill_world
26  do g=1,generations
27   cells = 0
28   !$ACC parallel copy(cells)
29   !$ACC loop
30   do r=1, rows
31    do c=1, cols
32     old_world(r,c) = world(r,c)
33    enddo
34   enddo
35   !$ACC loop
36   do r=1, rows
37    do c=1, cols
38     neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
39     old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
40     old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
41     if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3)) then
42      world(r,c) = 0
43     else if (neigh == 3) then
44      world(r,c) = 1
45     endif
46    enddo
47   enddo
48   !$ACC loop reduction(+:cells)
49   do r=1, rows
50    do c=1, cols
51     cells = cells + world(r,c)
52    enddo
53   enddo
54   !$ACC end parallel
55   print *, "Cells alive at generation ", g, ": ", cells
56  enddo
57  deallocate(world, old_world)
58  CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation          45 :        997185
 Cells alive at generation          46 :        988790
 Cells alive at generation          47 :        981380
 Cells alive at generation          48 :        974253
 Cells alive at generation          49 :        967943
 Cells alive at generation          50 :        959634
 Total time=     11.68190693855286
```

make.err

```
gol:
28, Generating Tesla code
 30, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
 31, !$acc loop seq
 36, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
 37, !$acc loop seq
 49, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
     Generating reduction(+:cells)
 50, !$acc loop seq
28, Generating copy(cells) [if not already present]
 Generating implicit copyin(old_world(0:rows+1,0:cols+1)) [if not already present]
 Generating implicit copyout(old_world(1:rows,1:cols)) [if not already present]
 Generating implicit copy(world(1:rows,1:cols)) [if not already present]
31, Loop is parallelizable
37, Loop is parallelizable
50, Loop is parallelizable
```

- One **parallel** region and multiple **loop** directives;
- A **reduction** clause is used on the last parallel loop;
- GPWPVP level;
- Still more expensive than serial solution.

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #4

```
22  CALL CPU_TIME(TIME_INI)
23  allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24  old_world(:,:) = 0
25  call fill_world
26  do g=1,generations
27   cells = 0
28   !$ACC parallel copy(cells)
29   !$ACC loop
30   do r=1, rows
31    do c=1, cols
32     old_world(r,c) = world(r,c)
33    enddo
34   enddo
35   !$ACC loop
36   do r=1, rows
37    do c=1, cols
38     neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
39     old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
40     old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
41     if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3)) then
42      world(r,c) = 0
43     else if (neigh == 3) then
44      world(r,c) = 1
45     endif
46    enddo
47   enddo
48   !$ACC loop reduction(+:cells)
49   do r=1, rows
50    do c=1, cols
51     cells = cells + world(r,c)
52    enddo
53   enddo
54   !$ACC end parallel
55   print *, "Cells alive at generation ", g, ": ", cells
56  enddo
57  deallocate(world, old_world)
58  CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation           45 :        997185
 Cells alive at generation           46 :        988790
 Cells alive at generation           47 :        981380
 Cells alive at generation           48 :        974253
 Cells alive at generation           49 :        967943
 Cells alive at generation           50 :        959634
 Total time=     11.68190693855286
```

gol.err

```
Accelerator Kernel Timing data
gol  NVIDIA  devicenum=0
time(us): 623,314
28: compute region reached 50 times
 28: kernel launched 50 times
  grid: [32]  block: [128]
   device time(us): total=121,508 max=2,603 min=2,378 avg=2,430
  elapsed time(us): total=123,326 max=2,633 min=2,407 avg=2,466
 28: reduction kernel launched 50 times
  grid: [1]  block: [256]
   device time(us): total=193 max=4 min=3 avg=3
  elapsed time(us): total=987 max=31 min=17 avg=19
28: data region reached 200 times
 28: data copyin transfers: 250
  device time(us): total=246,221 max=1,448 min=5 avg=984
 54: data copyout transfers: 250
  device time(us): total=255,392 max=1,576 min=5 avg=1,021
```

- One **parallel** region and multiple **loop** directives;
- A **reduction** clause is used on the last parallel loop;
- GPWPVP level;
- Still more expensive than serial solution.

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #5

```
22  CALL CPU_TIME(TIME_INI)
23  allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24  old_world(:,:) = 0
25  call fill_world
26  !$ACC data copy( world(0:rows+1,0:cols+1) ) &
27  !$ACC& create (old_world(0:rows+1,0:cols+1))
28  do g=1,generations
29   cells = 0
30   !$ACC parallel copy(cells)
31   !$ACC loop
32   do r=1, rows
33    do c=1, cols
34     old_world(r,c) = world(r,c)
35    enddo
36   enddo
37   !$ACC loop
38   do r=1, rows
39    do c=1, cols
40     neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
41     old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
42     old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
43     if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3) ) then
44      world(r,c) = 0
45     else if (neigh == 3) then
46      world(r,c) = 1
47     endif
48    enddo
49   enddo
50   !$ACC loop reduction(+:cells)
51   do r=1, rows
52    do c=1, cols
53     cells = cells + world(r,c)
54    enddo
55   enddo
56   !$ACC end parallel
57   print *, "Cells alive at generation ", g, ": ", cells
58  enddo
59  !$ACC end data
60  deallocate(world, old_world)
61  CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation           45 :       997185
 Cells alive at generation           46 :       988790
 Cells alive at generation           47 :       981380
 Cells alive at generation           48 :       974253
 Cells alive at generation           49 :       967943
 Cells alive at generation           50 :       959634
 Total time=     10.53407311439514
```

make.err

```
gol:
26, Generating create(old_world(0:rows+1,0:cols+1)) [if not already present]
 Generating copy(world(0:rows+1,0:cols+1)) [if not already present]
30, Generating copy(cells) [if not already present]
 Generating Tesla code
 32, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
 33, !$acc loop seq
 38, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
 39, !$acc loop seq
 51, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
     Generating reduction(+:cells)
 52, !$acc loop seq
33, Loop is parallelizable
39, Loop is parallelizable
52, Loop is parallelizable
```

- Single **parallel** and **data** regions and multiple **loop** directives;
- A **reduction** clause is used on the last parallel loop;
- GPWPVP level;
- Same cost of serial solution;
- Non-contiguous nested loops.

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #5

```
22  CALL CPU_TIME(TIME_INI)
23  allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24  old_world(:,:) = 0
25  call fill_world
26  !$ACC data copy( world(0:rows+1,0:cols+1) ) &
27  !$ACC& create (old_world(0:rows+1,0:cols+1))
28  do g=1,generations
29   cells = 0
30   !$ACC parallel copy(cells)
31   !$ACC loop
32   do r=1, rows
33    do c=1, cols
34     old_world(r,c) = world(r,c)
35    enddo
36   enddo
37   !$ACC loop
38   do r=1, rows
39    do c=1, cols
40     neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
41     old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
42     old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
43     if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3) ) then
44      world(r,c) = 0
45     else if (neigh == 3) then
46      world(r,c) = 1
47     endif
48    enddo
49   enddo
50   !$ACC loop reduction(+:cells)
51   do r=1, rows
52    do c=1, cols
53     cells = cells + world(r,c)
54    enddo
55   enddo
56   !$ACC end parallel
57   print *, "Cells alive at generation ", g, ": ", cells
58  enddo
59  !$ACC end data
60  deallocate(world, old_world)
61  CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation           45 :       997185
 Cells alive at generation           46 :       988790
 Cells alive at generation           47 :       981380
 Cells alive at generation           48 :       974253
 Cells alive at generation           49 :       967943
 Cells alive at generation           50 :       959634
 Total time=     10.53407311439514
```

gol.err

```
Accelerator Kernel Timing data
gol  NVIDIA  devicenum=0
time(us): 127,424
26: data region reached 2 times
 26: data copyin transfers: 4
  device time(us): total=2,474 max=1,282 min=4 avg=618
 59: data copyout transfers: 2
  device time(us): total=2,536 max=1,327 min=1,209 avg=1,268
30: compute region reached 50 times
 30: kernel launched 50 times
  grid: [32]  block: [128]
   device time(us): total=121,389 max=2,525 min=2,366 avg=2,427
  elapsed time(us): total=122,869 max=2,569 min=2,394 avg=2,457
 30: reduction kernel launched 50 times
  grid: [1]  block: [256]
   device time(us): total=186 max=5 min=3 avg=3
  elapsed time(us): total=1,110 max=80 min=18 avg=22
30: data region reached 100 times
 30: data copyin transfers: 50
  device time(us): total=310 max=10 min=4 avg=6
 56: data copyout transfers: 50
  device time(us): total=529 max=13 min=4 avg=10
```

- Single **parallel** and **data** regions and multiple **loop** directives;
- A **reduction** clause is used on the last parallel loop;
- GPWPVP level;
- Same cost of serial solution;
- Non-contiguous nested loops.

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #6

```
22  CALL CPU_TIME(TIME_INI)
23  allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24  old_world(:,:) = 0
25  call fill_world
26  !$ACC data copy( world(0:rows+1,0:cols+1) ) &
27  !$ACC& create (old_world(0:rows+1,0:cols+1))
28  do g=1,generations
29   cells = 0
30   !$ACC parallel copy(cells)
31   !$ACC loop gang vector
32   do r=1, rows
33    !$ACC loop seq
34    do c=1, cols
35     old_world(r,c) = world(r,c)
36    enddo
37   enddo
38   !$ACC loop
39   do c=1, cols
40    do r=1, rows
41     neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
42     old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
43     old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
44     if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3) ) then
45      world(r,c) = 0
46     else if (neigh == 3) then
47      world(r,c) = 1
48     endif
49    enddo
50   enddo
51   !$ACC loop reduction(+:cells)
52   do r=1, rows
53    do c=1, cols
54     cells = cells + world(r,c)
55    enddo
56   enddo
57   !$ACC end parallel
58   print *, "Cells alive at generation ", g, ": ", cells
59  enddo
60  !$ACC end data
61  deallocate(world, old_world)
62  CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation           45 :        997185
 Cells alive at generation           46 :        988790
 Cells alive at generation           47 :        981380
 Cells alive at generation           48 :        974253
 Cells alive at generation           49 :        967943
 Cells alive at generation           50 :        959634
 Total time=     9.730012893676758
```

make.err

```
gol:
26, Generating create(old_world(0:rows+1,0:cols+1)) [if not already present]
    Generating copy(world(0:rows+1,0:cols+1)) [if not already present]
30, Generating copy(cells) [if not already present]
    Generating Tesla code
    32, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
    34, !$acc loop seq
    39, !$acc loop gang ! blockidx%x threadidx%x
    40, !$acc loop seq
    52, !$acc loop gang ! blockidx%x threadidx%x
        Generating reduction(+:cells)
    53, !$acc loop seq
40, Loop is parallelizable
53, Loop is parallelizable
```

- Single **parallel** and **data** regions and multiple **loop** directives;
- GPWPVP level;
- First loop rewritten in contigous fashion (gang-vector[i]/seq[j]);
- Cheaper than serial.

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #6

```
22  CALL CPU_TIME(TIME_INI)
23  allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24  old_world(:,:) = 0
25  call fill_world
26  !$ACC data copy( world(0:rows+1,0:cols+1) ) &
27  !$ACC& create (old_world(0:rows+1,0:cols+1))
28  do g=1,generations
29   cells = 0
30   !$ACC parallel copy(cells)
31   !$ACC loop gang vector
32   do r=1, rows
33    !$ACC loop seq
34    do c=1, cols
35     old_world(r,c) = world(r,c)
36    enddo
37   enddo
38   !$ACC loop
39   do c=1, cols
40    do r=1, rows
41     neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
42     old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
43     old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
44     if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3) ) then
45      world(r,c) = 0
46     else if (neigh == 3) then
47      world(r,c) = 1
48     endif
49    enddo
50   enddo
51   !$ACC loop reduction(+:cells)
52   do r=1, rows
53    do c=1, cols
54     cells = cells + world(r,c)
55    enddo
56   enddo
57   !$ACC end parallel
58   print *, "Cells alive at generation ", g, ": ", cells
59  enddo
60  !$ACC end data
61  deallocate(world, old_world)
62  CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation           45 :        997185
 Cells alive at generation           46 :        988790
 Cells alive at generation           47 :        981380
 Cells alive at generation           48 :        974253
 Cells alive at generation           49 :        967943
 Cells alive at generation           50 :        959634
 Total time=     9.730012893676758
```

gol.err

```
Accelerator Kernel Timing data
gol  NVIDIA  devicenum=0
time(us): 960,564
26: data region reached 2 times
 26: data copyin transfers: 4
  device time(us): total=2,477 max=1,284 min=5 avg=619
 60: data copyout transfers: 2
  device time(us): total=2,531 max=1,326 min=1,205 avg=1,265
30: compute region reached 50 times
 30: kernel launched 50 times
  grid: [4000]  block: [1]
   device time(us): total=954,268 max=19,975 min=19,022 avg=19,085
  elapsed time(us): total=955,917 max=20,007 min=19,053 avg=19,118
 30: reduction kernel launched 50 times
  grid: [1]  block: [256]
   device time(us): total=400 max=8 min=8 avg=8
  elapsed time(us): total=1,696 max=95 min=23 avg=33
30: data region reached 100 times
 30: data copyin transfers: 50
  device time(us): total=311 max=8 min=6 avg=6
 57: data copyout transfers: 50
  device time(us): total=577 max=19 min=10 avg=11
```

- Single **parallel** and **data** regions and multiple **loop** directives;
- GPWPVP level;
- First loop rewritten in contigous fashion (gang-vector[i]/seq[j]);
- Cheaper than serial.

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #7

```
22    CALL CPU_TIME(TIME_INI)
23    allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24    old_world(:,:) = 0
25    call fill_world
26    !$ACC data copy( world(0:rows+1,0:cols+1) ) &
27    !$ACC& create (old_world(0:rows+1,0:cols+1))
28    do g=1,generations
29     cells = 0
30     !$ACC parallel copy(cells)
31     !$ACC loop gang
32     do c=1, cols
33      !$ACC loop vector
34      do r=1, rows
35       old_world(r,c) = world(r,c)
36      enddo
37     enddo
38     !$ACC loop
39     do c=1, cols
40      do r=1, rows
41       neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
42       old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
43       old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
44       if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3) ) then
45        world(r,c) = 0
46       else if (neigh == 3) then
47        world(r,c) = 1
48       endif
49      enddo
50     enddo
51     !$ACC loop reduction(+:cells)
52     do r=1, rows
53      do c=1, cols
54       cells = cells + world(r,c)
55      enddo
56     enddo
57     !$ACC end parallel
58     print *, "Cells alive at generation ", g, ": ", cells
59    enddo
60    !$ACC end data
61    deallocate(world, old_world)
62    CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation           45 :        997185
 Cells alive at generation           46 :        988790
 Cells alive at generation           47 :        981380
 Cells alive at generation           48 :        974253
 Cells alive at generation           49 :        967943
 Cells alive at generation           50 :        959634
 Total time=     6.911005973815918
```

make.err

```
gol:
26, Generating create(old_world(0:rows+1,0:cols+1)) [if not already present]
    Generating copy(world(0:rows+1,0:cols+1)) [if not already present]
30, Generating copy(cells) [if not already present]
    Generating Tesla code
    32, !$acc loop gang ! blockidx%x
    34, !$acc loop vector(128) ! threadidx%x
    39, !$acc loop gang ! blockidx%x threadidx%x
    40, !$acc loop seq
    52, !$acc loop gang ! blockidx%x threadidx%x
        Generating reduction(+:cells)
    53, !$acc loop seq
34, Loop is parallelizable
40, Loop is parallelizable
53, Loop is parallelizable
```

- Single **parallel** and **data** regions and multiple **loop** directives;
- GPWPVP level;
- First loop rewritten in contigous fashion (gang[j]/seq[i]).

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #7

```
22    CALL CPU_TIME(TIME_INI)
23    allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24    old_world(:,:) = 0
25    call fill_world
26    !$ACC data copy( world(0:rows+1,0:cols+1) ) &
27    !$ACC& create (old_world(0:rows+1,0:cols+1))
28    do g=1,generations
29     cells = 0
30     !$ACC parallel copy(cells)
31     !$ACC loop gang
32     do c=1, cols
33      !$ACC loop vector
34      do r=1, rows
35       old_world(r,c) = world(r,c)
36      enddo
37     enddo
38     !$ACC loop
39     do c=1, cols
40      do r=1, rows
41       neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
42       old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
43       old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
44       if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3) ) then
45        world(r,c) = 0
46       else if (neigh == 3) then
47        world(r,c) = 1
48       endif
49      enddo
50     enddo
51     !$ACC loop reduction(+:cells)
52     do r=1, rows
53      do c=1, cols
54       cells = cells + world(r,c)
55      enddo
56     enddo
57     !$ACC end parallel
58     print *, "Cells alive at generation ", g, ": ", cells
59    enddo
60    !$ACC end data
61    deallocate(world, old_world)
62    CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation           45 :        997185
 Cells alive at generation           46 :        988790
 Cells alive at generation           47 :        981380
 Cells alive at generation           48 :        974253
 Cells alive at generation           49 :        967943
 Cells alive at generation           50 :        959634
 Total time=     6.911005973815918
```

gol.err

```
Accelerator Kernel Timing data
  gol  NVIDIA  devicenum=0
    time(us): 959,563
    26: data region reached 2 times
        26: data copyin transfers: 4
             device time(us): total=2,497 max=1,281 min=4 avg=624
        60: data copyout transfers: 2
             device time(us): total=2,587 max=1,329 min=1,258 avg=1,293
    30: compute region reached 50 times
        30: kernel launched 50 times
            grid: [4000]  block: [1]
             device time(us): total=953,343 max=19,882 min=18,935 avg=19,066
            elapsed time(us): total=954,949 max=19,917 min=18,963 avg=19,098
        30: reduction kernel launched 50 times
            grid: [1]  block: [256]
             device time(us): total=399 max=8 min=7 avg=7
            elapsed time(us): total=1,685 max=95 min=22 avg=33
    30: data region reached 100 times
        30: data copyin transfers: 50
             device time(us): total=321 max=12 min=3 avg=6
        57: data copyout transfers: 50
             device time(us): total=416 max=14 min=4 avg=8
```

- Single **parallel** and **data** regions and multiple **loop** directives;
- GPWPVP level;
- First loop rewritten in contigous fashion (gang[j]/seq[i]).

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #8

```
22  CALL CPU_TIME(TIME_INI)
23  allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24  old_world(:,:) = 0
25  call fill_world
26  !$ACC data copy( world(0:rows+1,0:cols+1) ) &
27  !$ACC& create (old_world(0:rows+1,0:cols+1))
28  do g=1,generations
29   cells = 0
30   !$ACC parallel copy(cells)
31   !$ACC loop gang
32   do c=1, cols
33    !$ACC loop vector
34    do r=1, rows
35     old_world(r,c) = world(r,c)
36    enddo
37   enddo
38   !$ACC loop gang vector
39   do r=1, rows
40    !$ACC loop seq
41    do c=1, cols
42     neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
43     old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
44     old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
45     if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3) ) then
46      world(r,c) = 0
47     else if (neigh == 3) then
48      world(r,c) = 1
49     endif
50    enddo
51   enddo
52   !$ACC loop reduction(+:cells)
53   do r=1, rows
54    do c=1, cols
55     cells = cells + world(r,c)
56    enddo
57   enddo
58   !$ACC end parallel
59   print *, "Cells alive at generation ", g, ": ", cells
60  enddo
61  !$ACC end data
62  deallocate(world, old_world)
63  CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation           45 :       997185
 Cells alive at generation           46 :       988790
 Cells alive at generation           47 :       981380
 Cells alive at generation           48 :       974253
 Cells alive at generation           49 :       967943
 Cells alive at generation           50 :       959634
 Total time=     7.931918859481812
```

make.err

```
gol:
26, Generating create(old_world(0:rows+1,0:cols+1)) [if not already present]
    Generating copy(world(0:rows+1,0:cols+1)) [if not already present]
30, Generating copy(cells) [if not already present]
    Generating Tesla code
    32, !$acc loop gang ! blockidx%x
    34, !$acc loop vector(128) ! threadidx%x
    39, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
    41, !$acc loop seq
    53, !$acc loop gang ! blockidx%x threadidx%x
        Generating reduction(+:cells)
    54, !$acc loop seq
34, Loop is parallelizable
54, Loop is parallelizable
```

- Single **parallel** and **data** regions and multiple **loop** directives;
- GPWPVP level;
- Second loop rewritten in contigous fashion (gang-vector[i]/seq[j]);
- The modification increased the cost.

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #8

```
22  CALL CPU_TIME(TIME_INI)
23  allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24  old_world(:,:) = 0
25  call fill_world
26  !$ACC data copy( world(0:rows+1,0:cols+1) ) &
27  !$ACC& create (old_world(0:rows+1,0:cols+1))
28  do g=1,generations
29   cells = 0
30   !$ACC parallel copy(cells)
31   !$ACC loop gang
32   do c=1, cols
33    !$ACC loop vector
34    do r=1, rows
35     old_world(r,c) = world(r,c)
36    enddo
37   enddo
38   !$ACC loop gang vector
39   do r=1, rows
40    !$ACC loop seq
41    do c=1, cols
42     neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
43     old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
44     old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
45     if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3) ) then
46      world(r,c) = 0
47     else if (neigh == 3) then
48      world(r,c) = 1
49     endif
50    enddo
51   enddo
52   !$ACC loop reduction(+:cells)
53   do r=1, rows
54    do c=1, cols
55     cells = cells + world(r,c)
56    enddo
57   enddo
58   !$ACC end parallel
59   print *, "Cells alive at generation ", g, ": ", cells
60  enddo
61  !$ACC end data
62  deallocate(world, old_world)
63  CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation          45 :       997185
 Cells alive at generation          46 :       988790
 Cells alive at generation          47 :       981380
 Cells alive at generation          48 :       974253
 Cells alive at generation          49 :       967943
 Cells alive at generation          50 :       959634
 Total time=     7.931918859481812
```

gol.err

```
Accelerator Kernel Timing data
  gol  NVIDIA  devicenum=0
    time(us): 176,785
    26: data region reached 2 times
        26: data copyin transfers: 4
             device time(us): total=2,467 max=1,277 min=4 avg=616
        61: data copyout transfers: 2
             device time(us): total=2,550 max=1,327 min=1,223 avg=1,275
    30: compute region reached 50 times
        30: kernel launched 50 times
            grid: [4000]  block: [1]
             device time(us): total=170,560 max=3,427 min=3,396 avg=3,411
            elapsed time(us): total=172,076 max=3,467 min=3,423 avg=3,441
        30: reduction kernel launched 50 times
            grid: [1]  block: [256]
             device time(us): total=402 max=12 min=7 avg=8
            elapsed time(us): total=1,269 max=34 min=21 avg=25
    30: data region reached 100 times
        30: data copyin transfers: 50
             device time(us): total=319 max=9 min=5 avg=6
        58: data copyout transfers: 50
             device time(us): total=487 max=13 min=4 avg=9
```

- Single **parallel** and **data** regions and multiple **loop** directives;
- GPWPVP level;
- Second loop rewritten in contigous fashion (gang-vector[i]/seq[j]);
- The modification increased the cost.

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #9

```
22  CALL CPU_TIME(TIME_INI)
23  allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24  old_world(:,:) = 0
25  call fill_world
26  !$ACC data copy( world(0:rows+1,0:cols+1) ) &
27  !$ACC& create (old_world(0:rows+1,0:cols+1))
28  do g=1,generations
29   cells = 0
30   !$ACC parallel copy(cells)
31   !$ACC loop gang
32   do c=1, cols
33    !$ACC loop vector
34    do r=1, rows
35     old_world(r,c) = world(r,c)
36    enddo
37   enddo
38   !$ACC loop gang
39   do c=1, cols
40    !$ACC loop vector
41    do r=1, rows
42     neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
43     old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
44     old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
45     if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3) ) then
46      world(r,c) = 0
47     else if (neigh == 3) then
48      world(r,c) = 1
49     endif
50    enddo
51   enddo
52   !$ACC loop reduction(+:cells)
53   do r=1, rows
54    do c=1, cols
55     cells = cells + world(r,c)
56    enddo
57   enddo
58   !$ACC end parallel
59   print *, "Cells alive at generation ", g, ": ", cells
60  enddo
61  !$ACC end data
62  deallocate(world, old_world)
63  CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation           45 :        997185
 Cells alive at generation           46 :        988790
 Cells alive at generation           47 :        981380
 Cells alive at generation           48 :        974253
 Cells alive at generation           49 :        967943
 Cells alive at generation           50 :        959634
 Total time=     6.136991024017334
```

make.err

```
gol:
26, Generating create(old_world(0:rows+1,0:cols+1)) [if not already present]
    Generating copy(world(0:rows+1,0:cols+1)) [if not already present]
30, Generating copy(cells) [if not already present]
    Generating Tesla code
    32, !$acc loop gang ! blockidx%x
    34, !$acc loop vector(128) ! threadidx%x
    39, !$acc loop gang ! blockidx%x
    41, !$acc loop vector(128) ! threadidx%x
    53, !$acc loop gang ! blockidx%x threadidx%x
        Generating reduction(+:cells)
    54, !$acc loop seq
34, Loop is parallelizable
41, Loop is parallelizable
54, Loop is parallelizable
```

- Single **parallel** and **data** regions and multiple **loop** directives;
- GPWPVP level;
- Second loop rewritten in contigous fashion (gang[j]-vector[i]).

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #9

```
22  CALL CPU_TIME(TIME_INI)
23  allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24  old_world(:,:) = 0
25  call fill_world
26  !$ACC data copy( world(0:rows+1,0:cols+1) ) &
27  !$ACC& create (old_world(0:rows+1,0:cols+1))
28  do g=1,generations
29   cells = 0
30   !$ACC parallel copy(cells)
31   !$ACC loop gang
32   do c=1, cols
33    !$ACC loop vector
34    do r=1, rows
35     old_world(r,c) = world(r,c)
36    enddo
37   enddo
38   !$ACC loop gang
39   do c=1, cols
40    !$ACC loop vector
41    do r=1, rows
42     neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
43     old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
44     old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
45     if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3) ) then
46      world(r,c) = 0
47     else if (neigh == 3) then
48      world(r,c) = 1
49     endif
50    enddo
51   enddo
52   !$ACC loop reduction(+:cells)
53   do r=1, rows
54    do c=1, cols
55     cells = cells + world(r,c)
56    enddo
57   enddo
58   !$ACC end parallel
59   print *, "Cells alive at generation ", g, ": ", cells
60  enddo
61  !$ACC end data
62  deallocate(world, old_world)
63  CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation           45 :        997185
 Cells alive at generation           46 :        988790
 Cells alive at generation           47 :        981380
 Cells alive at generation           48 :        974253
 Cells alive at generation           49 :        967943
 Cells alive at generation           50 :        959634
 Total time=     6.136991024017334
```

gol.err

```
Accelerator Kernel Timing data
  gol  NVIDIA  devicenum=0
    time(us): 182,817
    26: data region reached 2 times
        26: data copyin transfers: 4
             device time(us): total=2,472 max=1,281 min=4 avg=618
        61: data copyout transfers: 2
             device time(us): total=2,581 max=1,374 min=1,207 avg=1,290
    30: compute region reached 50 times
        30: kernel launched 50 times
            grid: [4000]  block: [1]
             device time(us): total=176,547 max=6,297 min=3,464 avg=3,530
            elapsed time(us): total=178,119 max=6,336 min=3,492 avg=3,562
        30: reduction kernel launched 50 times
            grid: [1]  block: [256]
             device time(us): total=400 max=8 min=8 avg=8
            elapsed time(us): total=1,286 max=37 min=22 avg=25
    30: data region reached 100 times
        30: data copyin transfers: 50
             device time(us): total=307 max=9 min=3 avg=6
        58: data copyout transfers: 50
             device time(us): total=510 max=13 min=4 avg=10
```

- Single **parallel** and **data** regions and multiple **loop** directives;
- GPWPVP level;
- Second loop rewritten in contigous fashion (gang[j]-vector[i]).

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #10

```
22  CALL CPU_TIME(TIME_INI)
23  allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24  old_world(:,:) = 0
25  call fill_world
26  !$ACC data copy( world(0:rows+1,0:cols+1) ) &
27  !$ACC& create (old_world(0:rows+1,0:cols+1))
28  do g=1,generations
29   cells = 0
30   !$ACC parallel copy(cells)
31   !$ACC loop gang
32   do c=1, cols
33    !$ACC loop vector
34    do r=1, rows
35     old_world(r,c) = world(r,c)
36    enddo
37   enddo
38   !$ACC loop gang
39   do c=1, cols
40    !$ACC loop vector
41    do r=1, rows
42     neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
43     old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
44     old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
45     if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3) ) then
46      world(r,c) = 0
47     else if (neigh == 3) then
48      world(r,c) = 1
49     endif
50    enddo
51   enddo
52   !$ACC loop gang vector
53   do r=1, rows
54    !$ACC loop seq reduction(+:cells)
55    do c=1, cols
56     cells = cells + world(r,c)
57    enddo
58   enddo
59   !$ACC end parallel
60   print *, "Cells alive at generation ", g, ": ", cells
61  enddo
62  !$ACC end data
63  deallocate(world, old_world)
64  CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation           45 :        997185
 Cells alive at generation           46 :        988790
 Cells alive at generation           47 :        981380
 Cells alive at generation           48 :        974253
 Cells alive at generation           49 :        967943
 Cells alive at generation           50 :        959634
 Total time=     6.449497938156128
```

make.err

```
gol:
26, Generating create(old_world(0:rows+1,0:cols+1)) [if not already present]
    Generating copy(world(0:rows+1,0:cols+1)) [if not already present]
30, Generating copy(cells) [if not already present]
    Generating Tesla code
    32, !$acc loop gang ! blockidx%x
    34, !$acc loop vector(128) ! threadidx%x
    39, !$acc loop gang ! blockidx%x
    41, !$acc loop vector(128) ! threadidx%x
    53, !$acc loop gang, vector(128) ! blockidx%x threadidx%x
    55, !$acc loop seq
34, Loop is parallelizable
41, Loop is parallelizable
```

- Single **parallel** and **data** regions and multiple **loop** directives;
- GPWPVP level;
- Third loop rewritten in contigous fashion (gang-vector[i]/seq[j]);
- The modification increased the cost.

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #10

```
22  CALL CPU_TIME(TIME_INI)
23  allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24  old_world(:,:) = 0
25  call fill_world
26  !$ACC data copy( world(0:rows+1,0:cols+1) ) &
27  !$ACC& create (old_world(0:rows+1,0:cols+1))
28  do g=1,generations
29   cells = 0
30   !$ACC parallel copy(cells)
31   !$ACC loop gang
32   do c=1, cols
33    !$ACC loop vector
34    do r=1, rows
35     old_world(r,c) = world(r,c)
36    enddo
37   enddo
38   !$ACC loop gang
39   do c=1, cols
40    !$ACC loop vector
41    do r=1, rows
42     neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
43     old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
44     old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
45     if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3) ) then
46      world(r,c) = 0
47     else if (neigh == 3) then
48      world(r,c) = 1
49     endif
50    enddo
51   enddo
52   !$ACC loop gang vector
53   do r=1, rows
54    !$ACC loop seq reduction(+:cells)
55    do c=1, cols
56     cells = cells + world(r,c)
57    enddo
58   enddo
59   !$ACC end parallel
60   print *, "Cells alive at generation ", g, ": ", cells
61  enddo
62  !$ACC end data
63  deallocate(world, old_world)
64  CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation           45 :        997185
 Cells alive at generation           46 :        988790
 Cells alive at generation           47 :        981380
 Cells alive at generation           48 :        974253
 Cells alive at generation           49 :        967943
 Cells alive at generation           50 :        959634
 Total time=     6.449497938156128
```

gol.err

```
Accelerator Kernel Timing data
  gol  NVIDIA  devicenum=0
    time(us): 183,847
    26: data region reached 2 times
        26: data copyin transfers: 4
             device time(us): total=2,475 max=1,280 min=5 avg=618
        62: data copyout transfers: 2
             device time(us): total=2,525 max=1,322 min=1,203 avg=1,262
    30: compute region reached 50 times
        30: kernel launched 50 times
            grid: [32]  block: [128]
             device time(us): total=178,057 max=3,644 min=3,493 avg=3,561
            elapsed time(us): total=179,522 max=3,672 min=3,521 avg=3,590
    30: data region reached 100 times
        30: data copyin transfers: 50
             device time(us): total=315 max=9 min=5 avg=6
        59: data copyout transfers: 50
```

- Single **parallel** and **data** regions and multiple **loop** directives;
- GPWPVP level;
- Third loop rewritten in contigous fashion (gang-vector[i]/seq[j]);
- The modification increased the cost.

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #11

```
22  CALL CPU_TIME(TIME_INI)
23  allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24  old_world(:,:) = 0
25  call fill_world
26  !$ACC data copy( world(0:rows+1,0:cols+1) ) &
27  !$ACC& create (old_world(0:rows+1,0:cols+1))
28  do g=1,generations
29   cells = 0
30   !$ACC parallel copy(cells)
31   !$ACC loop gang
32   do c=1, cols
33    !$ACC loop vector
34    do r=1, rows
35     old_world(r,c) = world(r,c)
36    enddo
37   enddo
38   !$ACC loop gang
39   do c=1, cols
40    !$ACC loop vector
41    do r=1, rows
42     neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
43     old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
44     old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
45     if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3) ) then
46      world(r,c) = 0
47     else if (neigh == 3) then
48      world(r,c) = 1
49     endif
50    enddo
51   enddo
52   !$ACC loop gang
53   do c=1, cols
54    !$ACC loop vector reduction(+:cells)
55    do r=1, rows
56     cells = cells + world(r,c)
57    enddo
58   enddo
59   !$ACC end parallel
60   print *, "Cells alive at generation ", g, ": ", cells
61  enddo
62  !$ACC end data
63  deallocate(world, old_world)
64  CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation           45 :        997185
 Cells alive at generation           46 :        988790
 Cells alive at generation           47 :        981380
 Cells alive at generation           48 :        974253
 Cells alive at generation           49 :        967943
 Cells alive at generation           50 :        959634
 Total time=     4.712203025817871
```

make.err

```
gol:
26, Generating create(old_world(0:rows+1,0:cols+1)) [if not already present]
    Generating copy(world(0:rows+1,0:cols+1)) [if not already present]
30, Generating copy(cells) [if not already present]
    Generating Tesla code
    32, !$acc loop gang ! blockidx%x
    34, !$acc loop vector(128) ! threadidx%x
    39, !$acc loop gang ! blockidx%x
    41, !$acc loop vector(128) ! threadidx%x
    53, !$acc loop gang ! blockidx%x
    55, !$acc loop vector(128) ! threadidx%x
        Generating reduction(+:cells)
34, Loop is parallelizable
41, Loop is parallelizable
55, Loop is parallelizable
```

- Single **parallel** and **data** regions and multiple **loop** directives;
- GPWPVP level;
- Third loop rewritten in contigous fashion (gang[j]/vector[i]).

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #11

```
22  CALL CPU_TIME(TIME_INI)
23  allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24  old_world(:,:) = 0
25  call fill_world
26  !$ACC data copy( world(0:rows+1,0:cols+1) ) &
27  !$ACC& create (old_world(0:rows+1,0:cols+1))
28  do g=1,generations
29   cells = 0
30   !$ACC parallel copy(cells)
31   !$ACC loop gang
32   do c=1, cols
33    !$ACC loop vector
34    do r=1, rows
35     old_world(r,c) = world(r,c)
36    enddo
37   enddo
38   !$ACC loop gang
39   do c=1, cols
40    !$ACC loop vector
41    do r=1, rows
42     neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
43     old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
44     old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
45     if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3) ) then
46      world(r,c) = 0
47     else if (neigh == 3) then
48      world(r,c) = 1
49     endif
50    enddo
51   enddo
52   !$ACC loop gang
53   do c=1, cols
54    !$ACC loop vector reduction(+:cells)
55    do r=1, rows
56     cells = cells + world(r,c)
57    enddo
58   enddo
59   !$ACC end parallel
60   print *, "Cells alive at generation ", g, ": ", cells
61  enddo
62  !$ACC end data
63  deallocate(world, old_world)
64  CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation          45 :       997185
 Cells alive at generation          46 :       988790
 Cells alive at generation          47 :       981380
 Cells alive at generation          48 :       974253
 Cells alive at generation          49 :       967943
 Cells alive at generation          50 :       959634
 Total time=     4.712203025817871
```

gol.err

```
Accelerator Kernel Timing data
  gol  NVIDIA  devicenum=0
    time(us): 121,749
    26: data region reached 2 times
        26: data copyin transfers: 4
             device time(us): total=2,471 max=1,278 min=4 avg=617
        62: data copyout transfers: 2
             device time(us): total=2,525 max=1,321 min=1,204 avg=1,262
    30: compute region reached 50 times
        30: kernel launched 50 times
            grid: [2000]  block: [128]
             device time(us): total=115,851 max=2,398 min=2,261 avg=2,317
            elapsed time(us): total=117,247 max=2,439 min=2,289 avg=2,344
    30: data region reached 100 times
        30: data copyin transfers: 50
             device time(us): total=351 max=26 min=5 avg=7
        59: data copyout transfers: 50
             device time(us): total=551 max=19 min=4 avg=11
```

- Single **parallel** and **data** regions and multiple **loop** directives;
- GPWPVP level;
- Third loop rewritten in contigous fashion (gang[j]/vector[i]).

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #11

```
22  CALL CPU_TIME(TIME_INI)
23  allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24  old_world(:,:) = 0
25  call fill_world
26  !$ACC data copy( world(0:rows+1,0:cols+1) ) &
27  !$ACC& create (old_world(0:rows+1,0:cols+1))
28  do g=1,generations
29   cells = 0
30   !$ACC parallel copy(cells)
31   !$ACC loop gang
32   do c=1, cols
33    !$ACC loop vector
34    do r=1, rows
35     old_world(r,c) = world(r,c)
36    enddo
37   enddo
38   !$ACC loop gang
39   do c=1, cols
40    !$ACC loop vector
41    do r=1, rows
42     neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
43     old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
44     old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
45     if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3) ) then
46      world(r,c) = 0
47     else if (neigh == 3) then
48      world(r,c) = 1
49     endif
50    enddo
51   enddo
52   !$ACC loop gang
53   do c=1, cols
54    !$ACC loop vector reduction(+:cells)
55    do r=1, rows
56     cells = cells + world(r,c)
57    enddo
58   enddo
59   !$ACC end parallel
60   print *, "Cells alive at generation ", g, ": ", cells
61  enddo
62  !$ACC end data
63  deallocate(world, old_world)
64  CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation           45 :       997185
 Cells alive at generation           46 :       988790
 Cells alive at generation           47 :       981380
 Cells alive at generation           48 :       974253
 Cells alive at generation           49 :       967943
 Cells alive at generation           50 :       959634
 Total time=     4.712203025817871
```

gol.err

```
Accelerator Kernel Timing data
  gol  NVIDIA  devicenum=0
    time(us): 121,749
    26: data region reached 2 times
        26: data copyin transfers: 4
             device time(us): total=2,471 max=1,278 min=4 avg=617
        62: data copyout transfers: 2
             device time(us): total=2,525 max=1,321 min=1,204 avg=1,262
    30: compute region reached 50 times
        30: kernel launched 50 times
            grid: [2000]  block: [128]
             device time(us): total=115,851 max=2,398 min=2,261 avg=2,317
            elapsed time(us): total=117,247 max=2,439 min=2,289 avg=2,344
    30: data region reached 100 times
        30: data copyin transfers: 50
             device time(us): total=351 max=26 min=5 avg=7
        59: data copyout transfers: 50
             device time(us): total=551 max=19 min=4 avg=11
```

Final Ratio

$$\frac{T_{serial}[sec]}{T_{GTX-1050}[sec]} \times \frac{P_{serial}[€]}{P_{GTX-1050}[]}$$

$$\frac{10.29[sec]}{4.71[sec]} \times \frac{380.9[€]}{161.98[€]}$$

$$\approx 5.14$$

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #11 - Kernels with contiguous data

```
22  CALL CPU_TIME(TIME_INI)
23  allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24  old_world(:,:) = 0
25  call fill_world
26  !$ACC data copy( world(0:rows+1,0:cols+1) ) &
27  !$ACC& create (old_world(0:rows+1,0:cols+1))
28  do g=1,generations
29   cells = 0
30   !$ACC kernels copy(cells)
31   !$ACC loop
32   do c=1, cols
33    do r=1, rows
34     old_world(r,c) = world(r,c)
35    enddo
36   enddo
37   !$ACC loop
38   do c=1, cols
39    do r=1, rows
40     neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
41     old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
42     old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
43     if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3) ) then
44      world(r,c) = 0
45     else if (neigh == 3) then
46      world(r,c) = 1
47     endif
48    enddo
49   enddo
50   !$ACC loop
51   do c=1, cols
52    do r=1, rows
53     cells = cells + world(r,c)
54    enddo
55   enddo
56   !$ACC end kernels
57   print *, "Cells alive at generation ", g, ": ", cells
58  enddo
59  !$ACC end data
60  deallocate(world, old_world)
61  CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation           45 :       997185
 Cells alive at generation           46 :       988790
 Cells alive at generation           47 :       981380
 Cells alive at generation           48 :       974253
 Cells alive at generation           49 :       967943
 Cells alive at generation           50 :       959634
 Total time=     4.718765020370483
```

make.err

```
gol:
26, Generating create(old_world(0:rows+1,0:cols+1)) [if not already present]
    Generating copy(world(0:rows+1,0:cols+1)) [if not already present]
30, Generating copy(cells) [if not already present]
32, Loop is parallelizable
33, Loop is parallelizable
    Generating Tesla code
    32, !$acc loop gang, vector(4) ! blockidx%y threadidx%y
    33, !$acc loop gang, vector(32) ! blockidx%x threadidx%x
38, Loop is parallelizable
39, Loop is parallelizable
    Generating Tesla code
    38, !$acc loop gang, vector(4) ! blockidx%y threadidx%y
    39, !$acc loop gang, vector(32) ! blockidx%x threadidx%x
51, Loop is parallelizable
52, Loop is parallelizable
    Generating Tesla code
    51, !$acc loop gang, vector(4) ! blockidx%y threadidx%y
    52, !$acc loop gang, vector(32) ! blockidx%x threadidx%x
    53, Generating implicit reduction(+:cells)
```

- **Parallel** directives are replaced by **kernels** ones;
- The compiler manages the paralllism;
- Memory access and data contiguity is up to the developper;
- The new version presentes the same performance with less effort.

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #11 - Kernels with contiguous data

```
22  CALL CPU_TIME(TIME_INI)
23  allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24  old_world(:,:) = 0
25  call fill_world
26  !$ACC data copy( world(0:rows+1,0:cols+1) ) &
27  !$ACC& create (old_world(0:rows+1,0:cols+1))
28  do g=1,generations
29   cells = 0
30   !$ACC kernels copy(cells)
31   !$ACC loop
32   do c=1, cols
33    do r=1, rows
34     old_world(r,c) = world(r,c)
35    enddo
36   enddo
37   !$ACC loop
38   do c=1, cols
39    do r=1, rows
40     neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
41     old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
42     old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
43     if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3) ) then
44      world(r,c) = 0
45     else if (neigh == 3) then
46      world(r,c) = 1
47     endif
48    enddo
49   enddo
50   !$ACC loop
51   do c=1, cols
52    do r=1, rows
53     cells = cells + world(r,c)
54    enddo
55   enddo
56   !$ACC end kernels
57   print *, "Cells alive at generation ", g, ": ", cells
58  enddo
59  !$ACC end data
60  deallocate(world, old_world)
61  CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation           45 :       997185
 Cells alive at generation           46 :       988790
 Cells alive at generation           47 :       981380
 Cells alive at generation           48 :       974253
 Cells alive at generation           49 :       967943
 Cells alive at generation           50 :       959634
 Total time=     4.718765020370483
```

gol.err

```
Accelerator Kernel Timing data
gol  NVIDIA  devicenum=0
time(us): 166,310
26: data region reached 2 times
    26: data copyin transfers: 4
         device time(us): total=2,483 max=1,285 min=4 avg=620
    59: data copyout transfers: 2
         device time(us): total=2,542 max=1,331 min=1,211 avg=1,271
30: compute region reached 50 times
    33: kernel launched 50 times
        grid: [125x500]  block: [32x4]
         device time(us): total=39,926 max=816 min=794 avg=798
        elapsed time(us): total=41,321 max=844 min=821 avg=826
    39: kernel launched 50 times
        grid: [125x500]  block: [32x4]
         device time(us): total=63,119 max=1,265 min=1,261 avg=1,262
        elapsed time(us): total=63,934 max=1,283 min=1,275 avg=1,278
    52: kernel launched 50 times
        grid: [125x500]  block: [32x4]
         device time(us): total=53,498 max=1,073 min=1,068 avg=1,069
        elapsed time(us): total=54,268 max=1,090 min=1,082 avg=1,085
    52: reduction kernel launched 50 times
        grid: [1]  block: [256]
         device time(us): total=3,872 max=78 min=77 avg=77
        elapsed time(us): total=4,783 max=162 min=91 avg=95
30: data region reached 100 times
    30: data copyin transfers: 50
         device time(us): total=301 max=7 min=5 avg=6
    56: data copyout transfers: 50
         device time(us): total=569 max=37 min=4 avg=11
```

Optimization Example - Game of Life (4000x2000 - 100 gen.)

Step #11 - Multicore (fair comparison) - **kernel2multi-core**

```
22  CALL CPU_TIME(TIME_INI)
23  allocate(world(0:rows+1,0:cols+1), old_world(0:rows+1,0:cols+1))
24  old_world(:,:) = 0
25  call fill_world
26  !$ACC data copy( world(0:rows+1,0:cols+1) ) &
27  !$ACC& create (old_world(0:rows+1,0:cols+1))
28  do g=1,generations
29   cells = 0
30   !$ACC kernels copy(cells)
31   !$ACC loop
32   do c=1, cols
33    do r=1, rows
34     old_world(r,c) = world(r,c)
35    enddo
36   enddo
37   !$ACC loop
38   do c=1, cols
39    do r=1, rows
40     neigh = old_world(r-1,c-1)+old_world(r,c-1)+&
41     old_world(r+1,c-1)+old_world(r-1,c)+old_world(r+1,c)+&
42     old_world(r-1,c+1)+old_world(r,c+1)+old_world(r+1,c+1)
43     if (old_world(r,c) == 1 .and. (neigh<2.or.neigh>3) ) then
44      world(r,c) = 0
45     else if (neigh == 3) then
46      world(r,c) = 1
47     endif
48    enddo
49   enddo
50   !$ACC loop
51   do c=1, cols
52    do r=1, rows
53     cells = cells + world(r,c)
54    enddo
55   enddo
56   !$ACC end kernels
57   print *, "Cells alive at generation ", g, ": ", cells
58  enddo
59  !$ACC end data
60  deallocate(world, old_world)
61  CALL CPU_TIME(TIME_END)
```

gol.out

```
 Cells alive at generation          45 :       997185
 Cells alive at generation          46 :       988790
 Cells alive at generation          47 :       981380
 Cells alive at generation          48 :       974253
 Cells alive at generation          49 :       967943
 Cells alive at generation          50 :       959634
 Total time=     1.720873832702637
```

make.err

```
pgf90 -O0 -acc=noautopar -ta=multicore -Minfo=all -c gol.f90 -o gol.o
pgf90 -O0 -acc=noautopar -ta=multicore -Minfo=all gol.o -o gol
gol:
32, Loop is parallelizable
    Generating Multicore code
    32, !$acc loop gang
33, Loop is parallelizable
38, Loop is parallelizable
    Generating Multicore code
    38, !$acc loop gang
39, Loop is parallelizable
51, Loop is parallelizable
    Generating Multicore code
    51, !$acc loop gang
52, Loop is parallelizable
53, Generating implicit reduction(+:cells)
```

Final *Fair* Ratio

$$\frac{T_{multi-core}[sec]}{T_{GTX-1050}[sec]} \times \frac{P_{multi-core}[€]}{P_{GTX-1050}[]}$$

$$\frac{1.72[sec]}{4.71[sec]} \times \frac{380.9[€]}{161.98[€]}$$

$$\approx 0.86$$