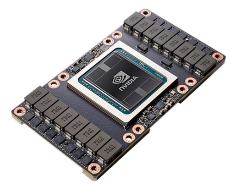
GPU Programming with OpenMP
Part 4: Tools and advanced topics



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Overview

- Nsight profiling tools
  - Nsight Systems
  - Nsight Compute
  - Using the command line interface
  - Running the profiler in batch mode
- Asynchronous offloading
  - `nowait` clause
  - `depend` clause
- Pinned host memory
- Multi-GPU

Nsight profiling tools

Nsight profiling tools

- **Note**: To open displays for the user interfaces, you need to use X-window forwarding when you enter the interactive session:

```
$ hpcintrogpush -X
```

- Before you use the profiler, always load cuda:

```
$ module load cuda/11.8
```

- **Note**: Only one "profiler context" per GPU is allowed, so you get an error if another user is currently profiling on the same GPU.

Nsight systems

- `nsys / nsys-ui`
  - You may generate a timeline for your application that shows (CUDA) API functions and offload execution
  - First you need to generate a profile report using the command line tool `nsys`, e.g.;

```
$ nsys profile matmult_f.nvc++ \
mnk_offload 2048 2048 2048
```

  - Generated file: `report1.qdrep`

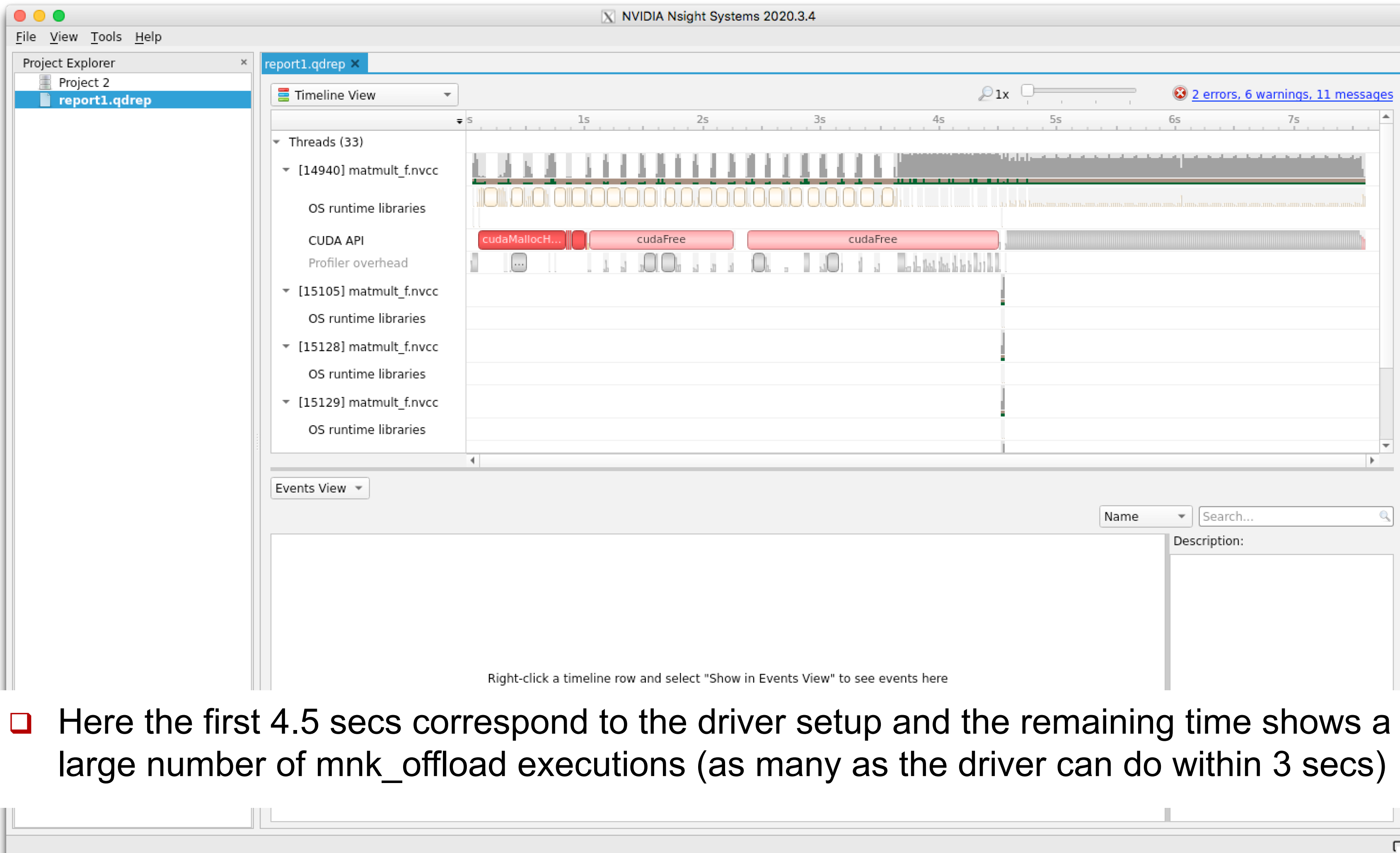
Nsight systems

- Now start the Nsight Systems user interface:

```
$ nsys-ui &
```

- Window opens – see next slide
- Open the file `report1.qdrep`. Click close on errors and warnings (we ignore these for now)!
- If you maximize the window you see the timeline for the driver running the `mnk_offload` function

Nsight systems



- Here the first 4.5 secs correspond to the driver setup and the remaining time shows a large number of mnk_offload executions (as many as the driver can do within 3 secs)

Nsight compute

- `nv-nsight-cu`
  - The Nsight profiler can be used via a user interface that has customizable metric collection and presentations (tables, charts, etc.)
  - Built-in rules expertise and suggestions
- Standalone, IDE Integration, Remote Targets
  - OS: Linux (x86, Power, Tegra, Arm SBSA), Windows, MacOSX (host only)
  - GPUs: Volta, Turing, Ampere GPUs (NVIDIA only!)
- https://developer.nvidia.com/nsight-compute

Command line interface

- `nv-nsight-cu-cli`
  - The simplest way to get quick textual performance information for your offload executions
  - ~20 specific output sections of interest available

```
$ nv-nsight-cu-cli --list-sections
```

  - Default: SpeedOfLight, LaunchStatistics, Occupancy
- For example you can profile the driver running version `mnk_offload` in the matmult assignment

```
$ TMPDIR=. MFLOPS_MAX_IT=1 nv-nsight-cu-cli \
./matmult_f.nvc++ mnk_offload 2048 2048 2048
```

```
$ TMPDIR=. MFLOPS_MAX_IT=1 nv-nsight-cu-cli ./matmult_f.nvc++ mnk_offload 2048 2048 2048
==PROF== Connected to process 27597 (~/HPC_course_02614_OpenMP/src/assign3_matmult/matmult_f.nvc++)
==PROF== Profiling "nvkernel_matmult_mnk_offload_..." - 1: 0%....50%....100% - 11 passes
   98304.000   6528.841 300 # matmult_mnk_offload

Section: GPU Speed Of Light Throughput
    ---------------------------------------------------------------------- --------------- ------------------------------
    DRAM Frequency                                                          cycle/nsecond                           1.22
    SM Frequency                                                            cycle/usecond                         765.65
    Elapsed Cycles                                                                  cycle                     19,854,813
    Memory [%]                                                                          %                         107.69
    DRAM Throughput                                                                     %                          48.55
    Duration                                                                      msecond                          25.93
    L1/TEX Cache Throughput                                                             %                          50.59
    L2 Cache Throughput                                                                 %                         107.69
    SM Active Cycles                                                                cycle                  19,798,035.23
    Compute (SM) [%]                                                                    %                          25.05
    ---------------------------------------------------------------------- --------------- ------------------------------
    INF   The kernel is utilizing greater than 80.0% of the available compute or memory performance of the device. To
          further improve performance, work will likely need to be shifted from the most utilized to another unit.
          Start by analyzing workloads in the Memory Workload Analysis section.

    Section: Launch Statistics
    ---------------------------------------------------------------------- --------------- ------------------------------
    Block Size                                                                                                       128
    Function Cache Configuration                                                                 cudaFuncCachePreferNone
    Grid Size                                                                                                     32,768
    Registers Per Thread                                                  register/thread                             96
    Shared Memory Configuration Size                                                Kbyte                          16.38
    Driver Shared Memory Per Block                                            Kbyte/block                           1.02
    Dynamic Shared Memory Per Block                                            byte/block                              0
    Static Shared Memory Per Block                                             byte/block                              0
    Threads                                                                        thread                      4,194,304
    Waves Per SM                                                                                                   60.68
    ---------------------------------------------------------------------- --------------- ------------------------------

    Section: Occupancy
    ---------------------------------------------------------------------- --------------- ------------------------------
    Block Limit SM                                                                  block                             32
    Block Limit Registers                                                           block                              5
    Block Limit Shared Mem                                                          block                            164
    Block Limit Warps                                                               block                             16
    Theoretical Active Warps per SM                                                  warp                             20
    Theoretical Occupancy                                                               %                          31.25
    Achieved Occupancy                                                                  %                          30.96
    Achieved Active Warps Per SM                                                     warp                          19.81
    ---------------------------------------------------------------------- --------------- ------------------------------
```

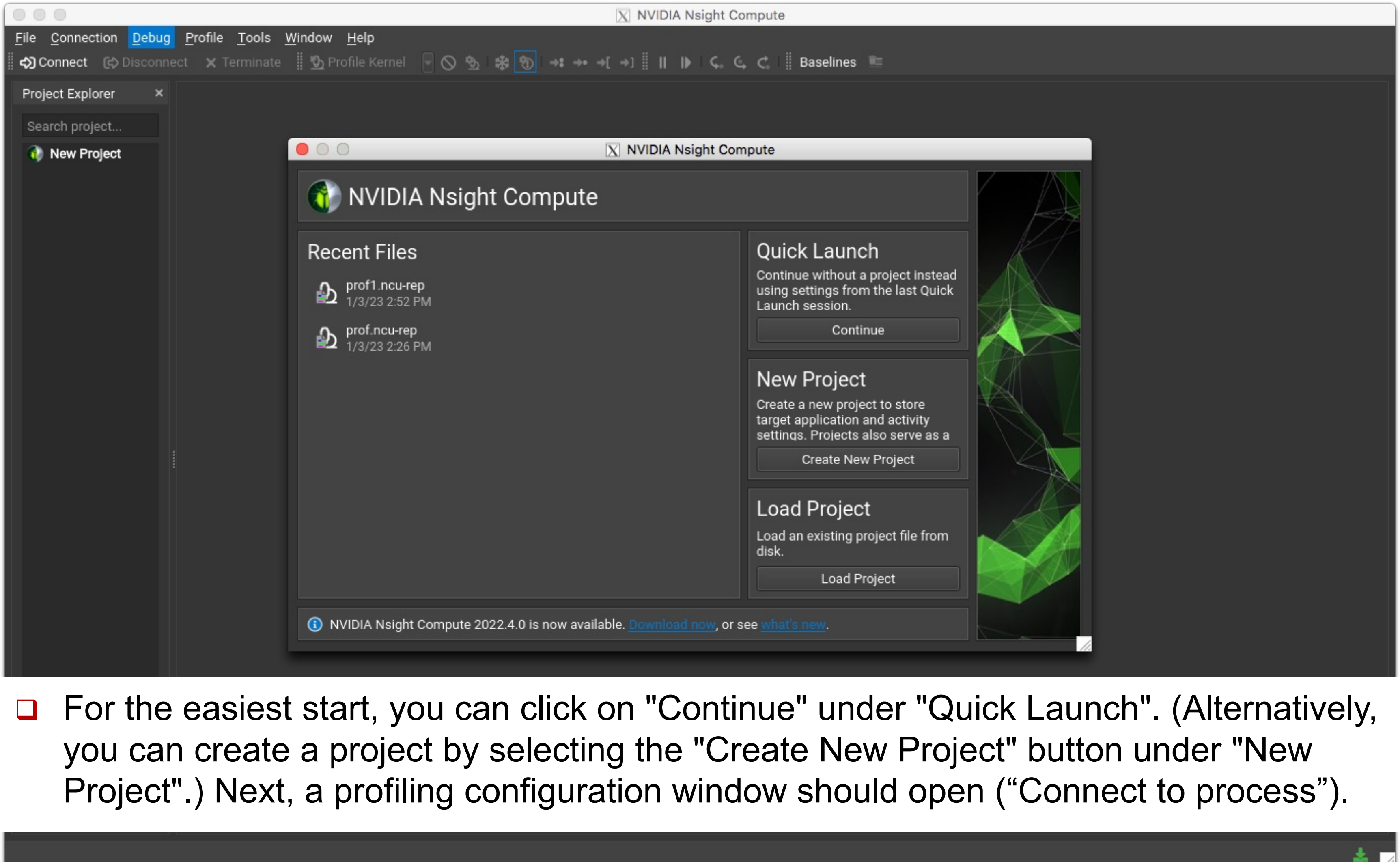
Command line interface

- `--section MemoryWorkloadAnalysis`
  - Outputs the achieved memory bandwidth etc.

```
$ MFLOPS_MAX_IT=0 nv-nsight-cu-cli --section MemoryWorkloadAnalysis ./matmult_f.nvc++ mnk_offload 2048 2048 2048
==PROF== Connected to process 16739 (~/HPC_course_02614_OpenMP/src/assign3_matmult/matmult_f.nvc++)
==PROF== Profiling "nvkernel_matmult_mnk_offload_..." - 0: 0%....50%....100% - 11 passes
   98304.000   5985.350 300 # matmult_mnk_offload
==PROF== Disconnected from process 16739
[16739] matmult_f.nvc++@127.0.0.1
  nvkernel_matmult_mnk_offload_F1L115_14, 2023-Jan-03 15:15:02, Context 1, Stream 14
    Section: Memory Workload Analysis
    ---------------------------------------------------------------------- --------------- ------------------------------
    Memory Throughput                                                          Gbyte/second                         733.82
    Mem Busy                                                                              %                         107.41
    Max Bandwidth                                                                         %                          71.43
    L1/TEX Hit Rate                                                                       %                          10.43
    L2 Compression Success Rate                                                           %                              0
    L2 Compression Ratio                                                                                                 0
    L2 Hit Rate                                                                           %                          65.11
    Mem Pipes Busy                                                                        %                          24.73
    ---------------------------------------------------------------------- --------------- ------------------------------
```

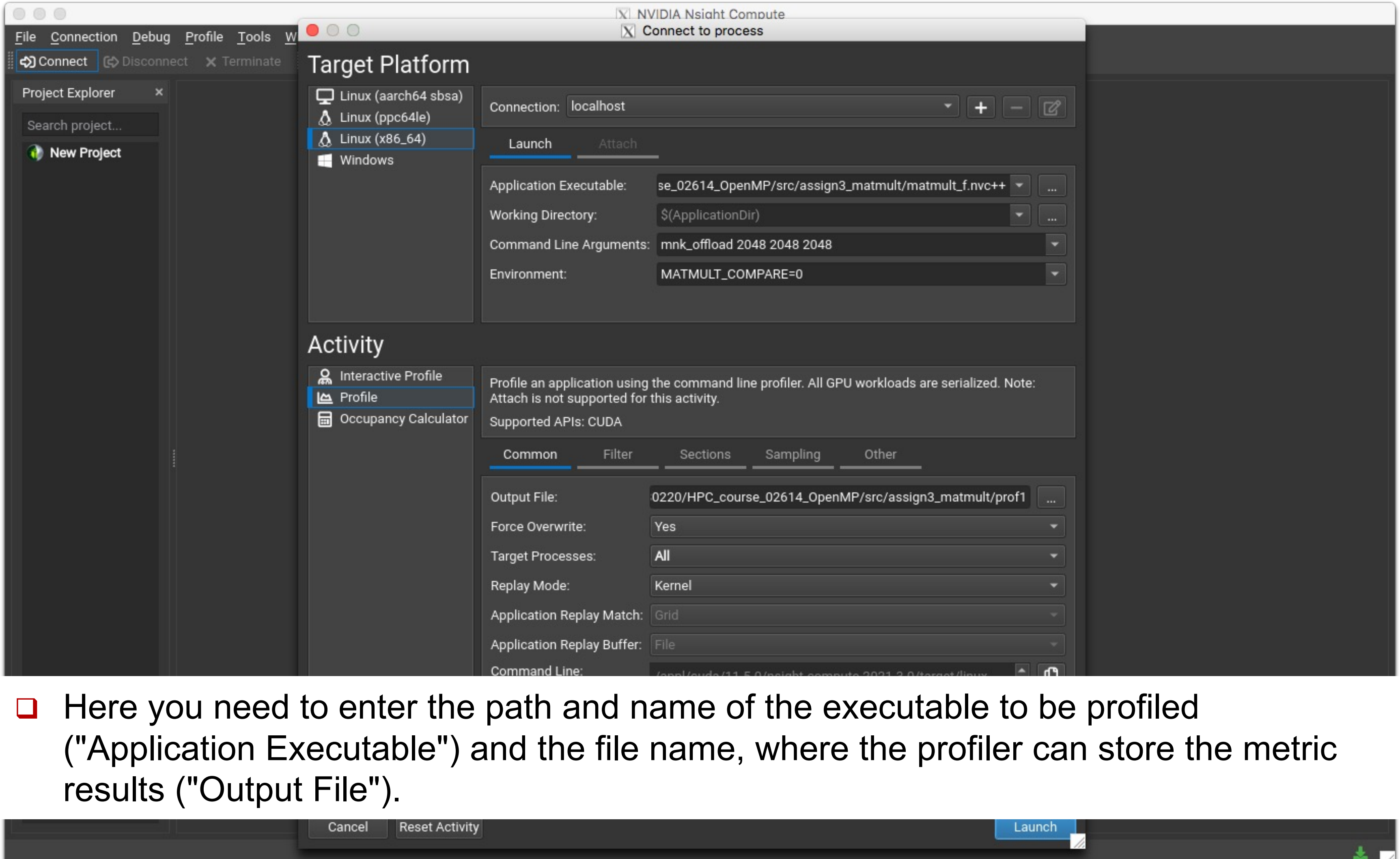
- Advanced options
  - `--set detailed` – more details and recommendations
  - `--target-processes all` – child processes are also profiled

Nsight compute



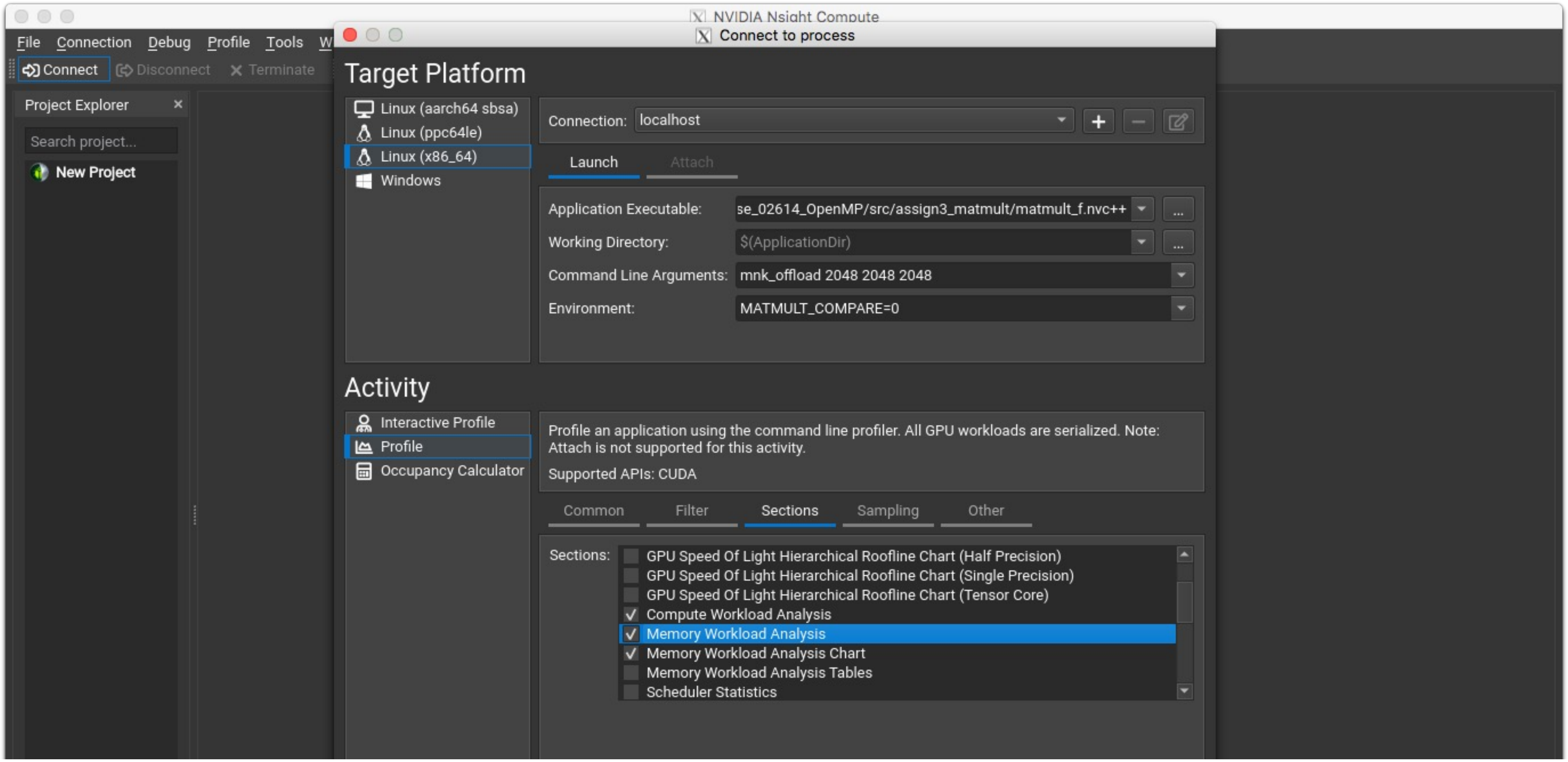
- For the easiest start, you can click on "Continue" under "Quick Launch". (Alternatively, you can create a project by selecting the "Create New Project" button under "New Project".) Next, a profiling configuration window should open ("Connect to process").

Nsight compute



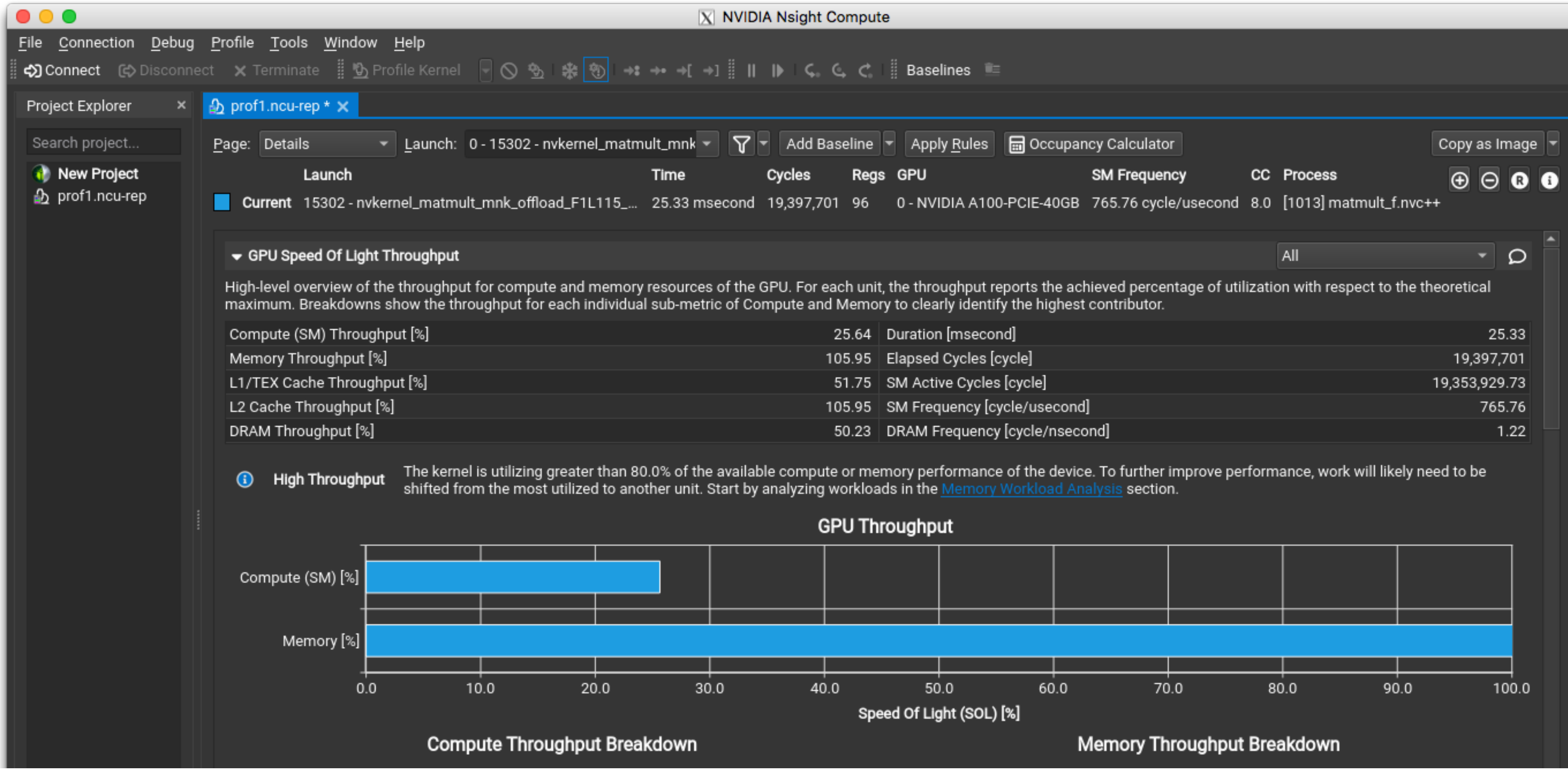
- Here you need to enter the path and name of the executable to be profiled ("Application Executable") and the file name, where the profiler can store the metric results ("Output File").

Nsight compute



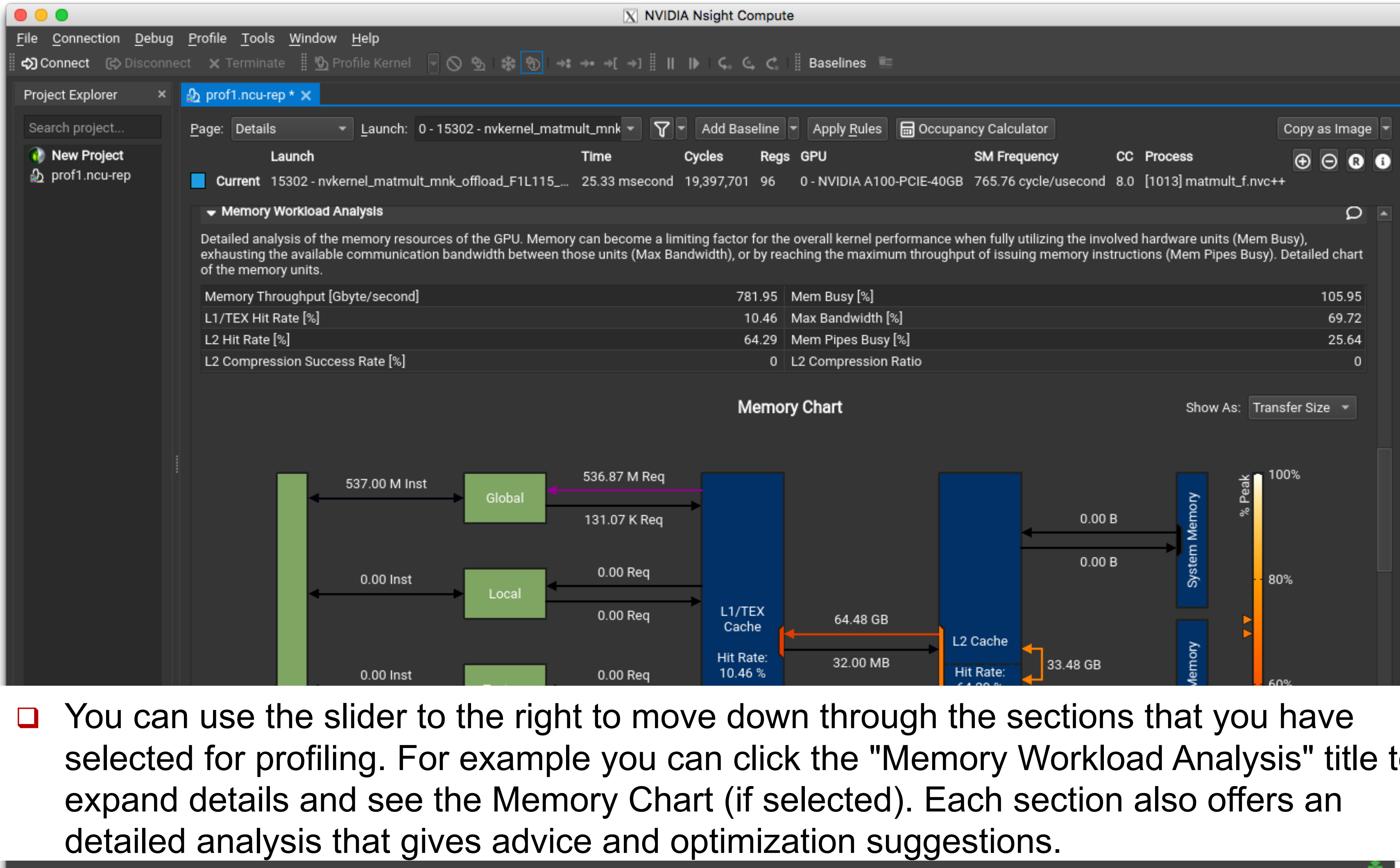
- In the "Activity" part, when you click the "Sections" tab, you can also select specific profiling sections you are interested in. You may also enter a comma-separated list of metric names in the "Other" tab. Clicking the "Launch" button will start the profiling of the kernel and it will run several times in order to collect all the requested metrics.

Nsight compute



- When done the window will show the profiling results section by section (typically the "GPU Speed of Light" section at the top, if selected). The "GPU Speed of Light" section outputs, e.g., the SM utilization and the Memory utilization, which indicates whether the kernel is compute or memory bound.

Nsight compute



❑ You can use the slider to the right to move down through the sections that you have selected for profiling. For example you can click the "Memory Workload Analysis" title to expand details and see the Memory Chart (if selected). Each section also offers an detailed analysis that gives advice and optimization suggestions.

Running the profiler in batch mode

- Batch script to get exclusive profiling on a GPU
  - Recommended – gives more reliable results

```
#!/bin/sh
#BSUB -J proftest
#BSUB -q hpcintrogpu
#BSUB -n 4
#BSUB -R "span[hosts=1]"
#BSUB -gpu "num=1:mode=exclusive_process"
#BSUB -W 10
#BSUB -R "rusage[mem=2048]"

export TMPDIR=$__LSF_JOB_TMPDIR__
module load cuda/11.8

export MFLOPS_MAX_IT=1

nv-nsight-cu-cli -o profile_$LSB_JOBID \
    --section MemoryWorkloadAnalysis \
    --section MemoryWorkloadAnalysis_Chart \
    --section ComputeWorkloadAnalysis \
./matmult_f.nvc++ mnk_offload 2048 2048 2048
```

Running the profiler in batch mode

- You can modify the sections of interest by adding/removing them as needed
- Submit with: `$ bsub < scriptname`
  - After the job is finished, you will find a profile with the name `profile_JOBID.ncu-rep` in your folder
  - This profile can be now opened in the Nsight GUI in your interactive session with the command:

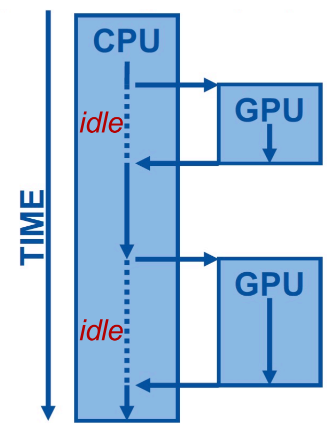
```
TMPDIR=. nv-nsight-cu-cli --open-in-ui \
-i profile_9172161.ncu-rep
```

  - Note: the JOBID 9172161 is appended by the profiler

Asynchronous offloading

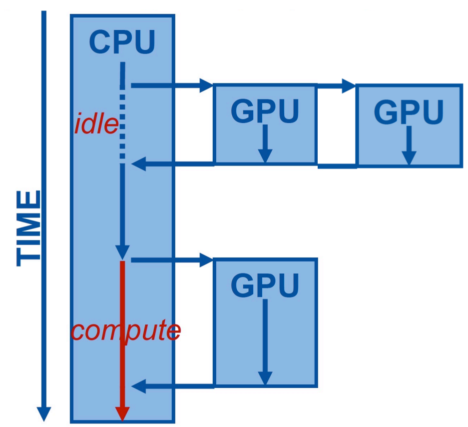
Synchronous offloading

- By default `target` constructs are synchronous
  - Host thread waits until the offloaded region is finished
  - Host thread is occupied while waiting
    - We risk that the CPU is idle while offloading
  - All transfers with the `map` clause are synchronous



Asynchronous offloading

- Asynchronous offloading allows
  - Simultaneous computing on host and device
  - Overlap of data transfers and computation
  - Overlap of data transfers in both directions
  - Simultaneous execution of several offload regions (if resources are available)



OpenMP offload syntax

- Syntax C/C++:

```
#pragma omp target nowait
#pragma omp taskwait
```

- The `nowait` clause overrides any synchronization that would otherwise occur at the end of a construct, including the `target` construct
- For constructs that generate a task, the `nowait` clause specifies that the task may be deferred
- The `taskwait` construct specifies a wait on the completion of child tasks of the current task

OpenMP offload syntax

- Syntax C/C++:

```
depend([depend-modifier,]depend-type : list)
```

- The `depend` clause enforces constraints on the scheduling of tasks or loop iterations
- A task cannot be executed until all its dependencies from predecessor tasks are completed

Not currently fully supported for target constucts in `nvc++`

- `depend-modifier`: out-of-scope for 02614

OpenMP offload syntax

Not currently supported in `nvc++`

- `dependence-type` can be
  - `in`
    - Task will depend on all previously generated sibling tasks that reference the list-item in an `out` or `inout` dependence
  - `out/inout`
    - Task will depend on all previously generated sibling tasks that reference the list-item in an `in`, `out` or `inout` dependence
  - ~~`inoutset/mutexinoutset`~~
    - Specifies a set of tasks that depend in the same list-item and can be executed in any order possibly with mutual exclusion
  - ~~`depobj`~~
    - Task dependences are derived from the dependences represented by the depend objects (user-computed)

Asynchronous offloading

- Simultaneous computing on host and device

```
#pragma omp target map(...) nowait depend(out: gpu_data)
/* do work on device -> gpu_data */

#pragma omp task nowait depend(out: cpu_data)
/* do work on host -> cpu_data */

#pragma omp task depend(in: cpu_data) depend(in: gpu_data)
/* combined work on host */

#pragma omp taskwait // wait for all tasks
```

Asynchronous offloading

- Example – vector addition v1

In order to make compute time longer – do not do this!

```
void vecadd(double *a, double *b, double *c)
{
    #pragma omp target teams distribute parallel for \
        num_teams(N) thread_limit(1)                  \
        map(to: a[0:N], b[0:N]) map(from: c[0:N])
    for (int i = 0; i < N; i++)
        c[i] = a[i] + b[i];
}
```

Asynchronous offloading

- Example – vector addition v1

In order to make compute time longer – do not do this!

```
void vecadd(double *a, double *b, double *c)
{
    #pragma omp target teams distribute parallel for \
        num_teams(N) thread_limit(1)                 \
        map(to: a[0:N], b[0:N]) map(from: c[0:N])
    for (int i = 0; i < N; i++)
        c[i] = a[i] + b[i];
}
```

main.cpp

```
#define N 1000000
double t, tmin = 1;
memset(c, 0, N * sizeof(double));
for (int n = 0; n < 100; ++n) {
    t = omp_get_wtime();
    vecadd(a, b, c);
    t = omp_get_wtime() - t;
    if (tmin > t) tmin = t;
}
check(c);
printf("Runtime: %f\n", tmin);
```

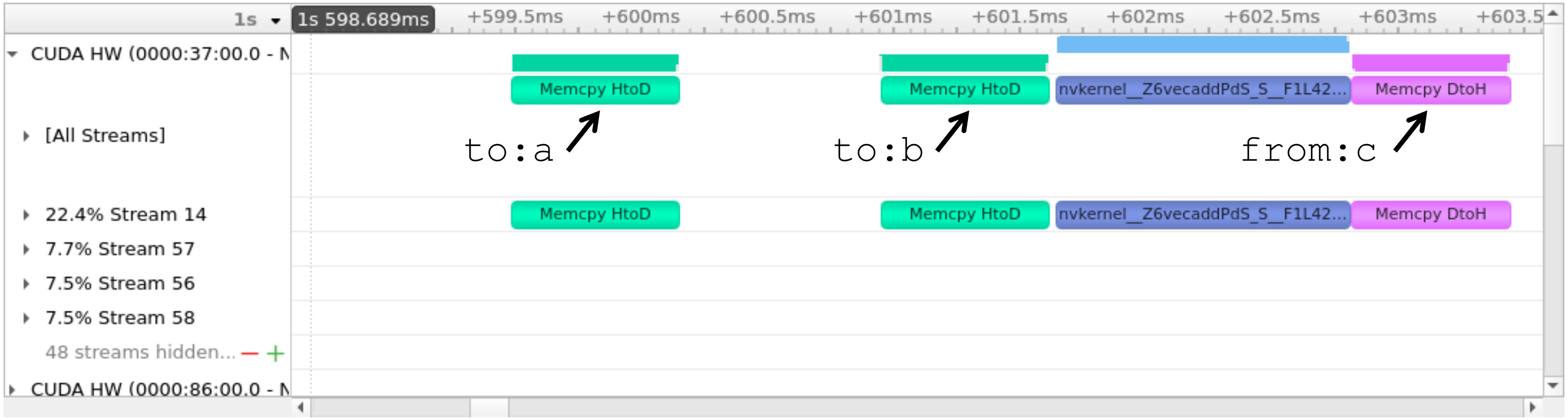
```
$ make && ./vecadd
Runtime: 0.006749
```

Version	v1
Time [ms]	6.75

Asynchronous offloading

- Example – vector addition v1

```
$ nsys profile ./vecadd
Runtime: 0.006700
Generating '/tmp/nsys-report-4b5d.qdstrm'
[1/1] [========================100%] report1.nsys-rep
```



Version	v1
Time [ms]	6.75

Asynchronous offloading

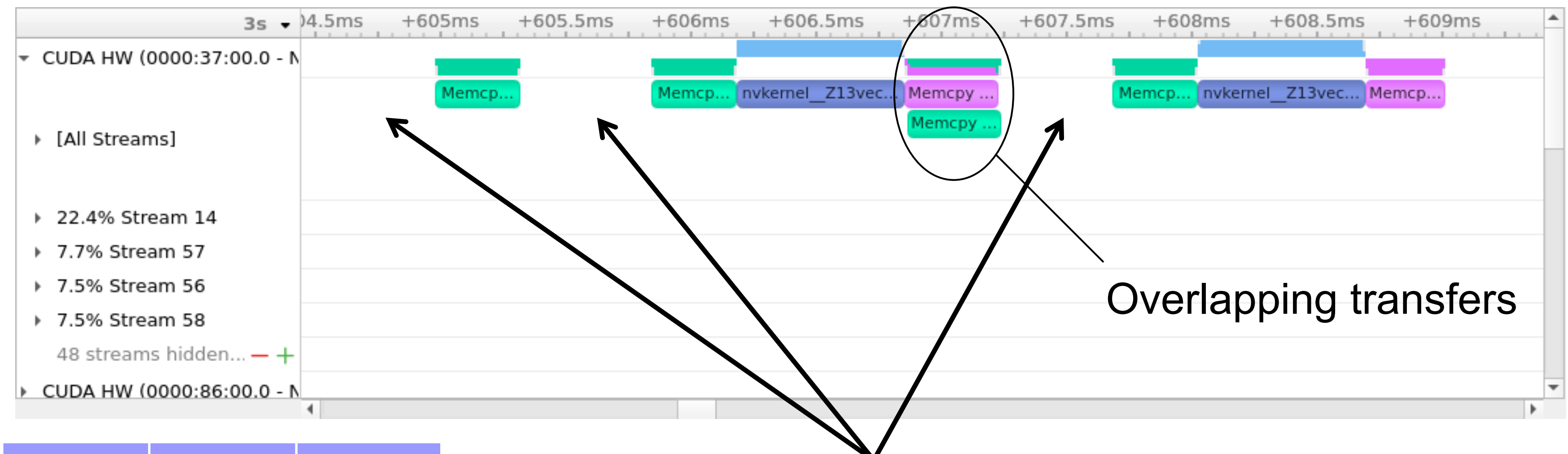
- Example – vector addition v2

```
void vecadd2(double *a, double *b, double *c)
{
    #pragma omp target teams distribute parallel for nowait \
        num_teams(N/2) thread_limit(1)                      \
        map(to: a[0:N/2], b[0:N/2]) map(from: c[0:N/2])
    for (int i = 0; i < N/2; i++)
        c[i] = a[i] + b[i];

    #pragma omp target teams distribute parallel for nowait \
        num_teams(N/2) thread_limit(1)                      \
        map(to: a[N/2:N/2], b[N/2:N/2]) map(from: c[N/2:N/2])
    for (int i = N/2; i < N; i++)
        c[i] = a[i] + b[i];

    #pragma omp taskwait
}
```

Asynchronous offloading

- Example – vector addition v2

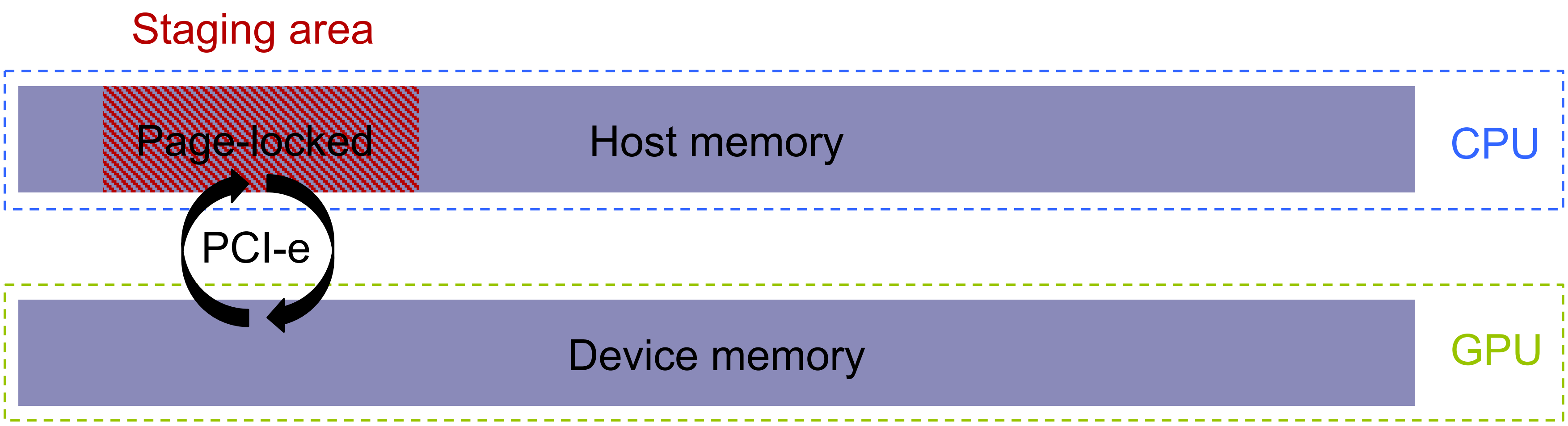
```
$ nsys profile ./vecadd2
Runtime: 0.005060
Generating '/tmp/nsys-report-7242.qdstrm'
[1/1] [========================100%] report2.nsys-rep
```



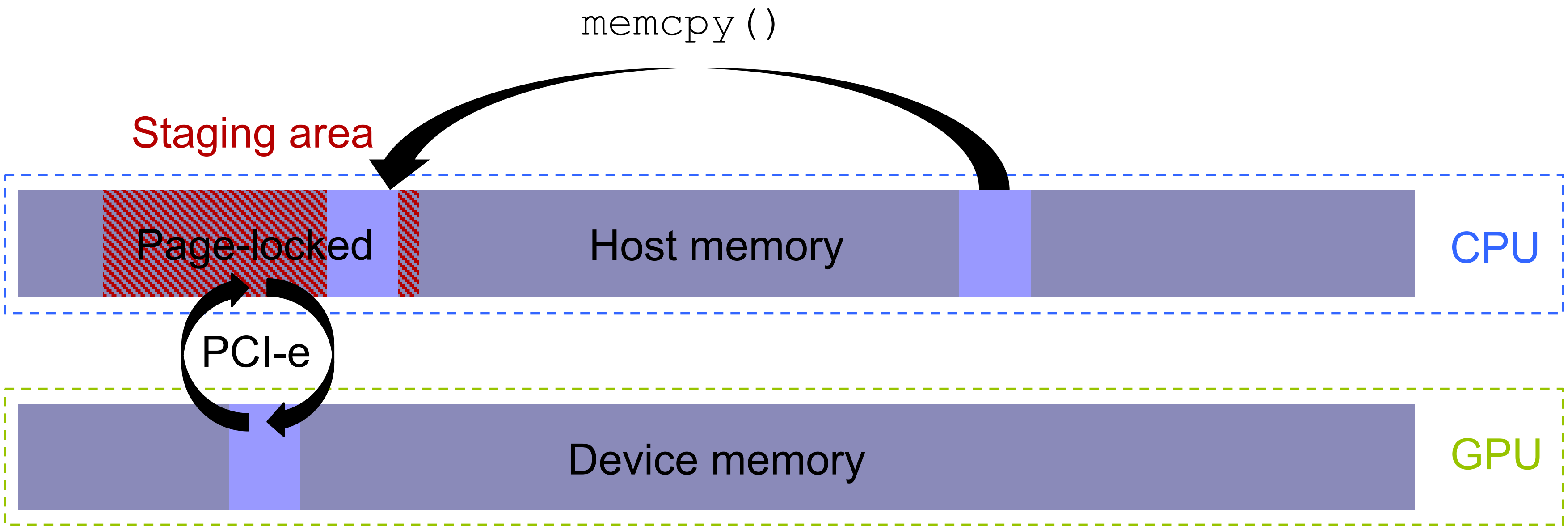
But what's going on here?

Version	v1	v2
Time [ms]	6.75	5.06

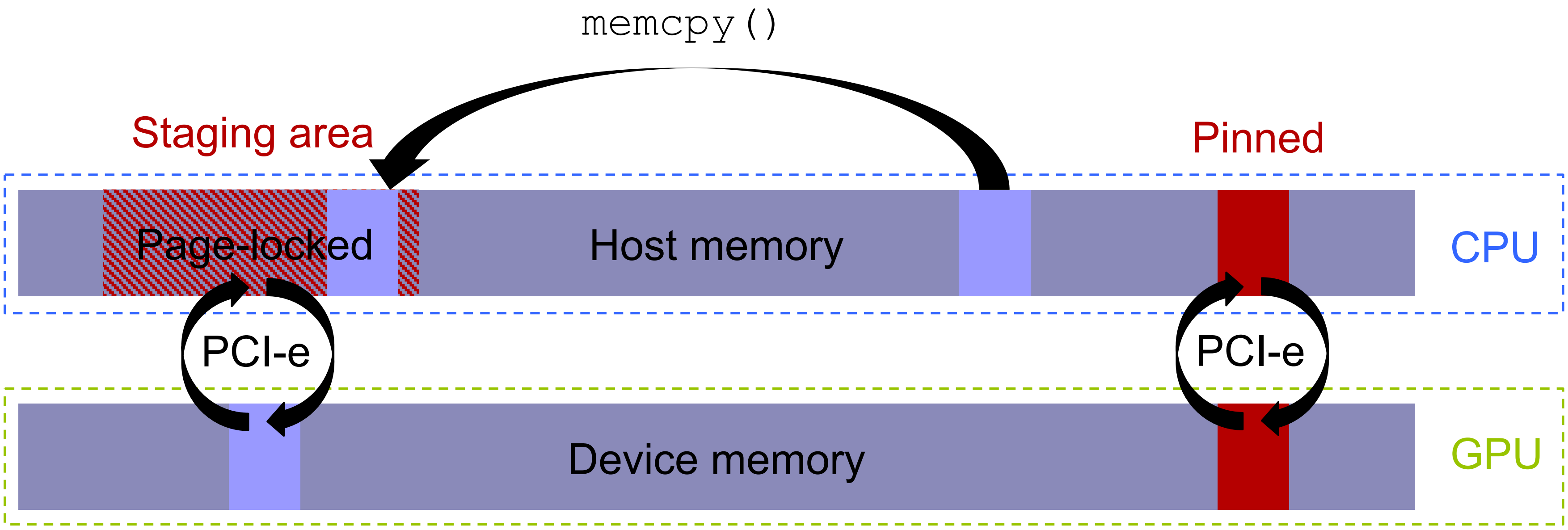
Pinned host memory



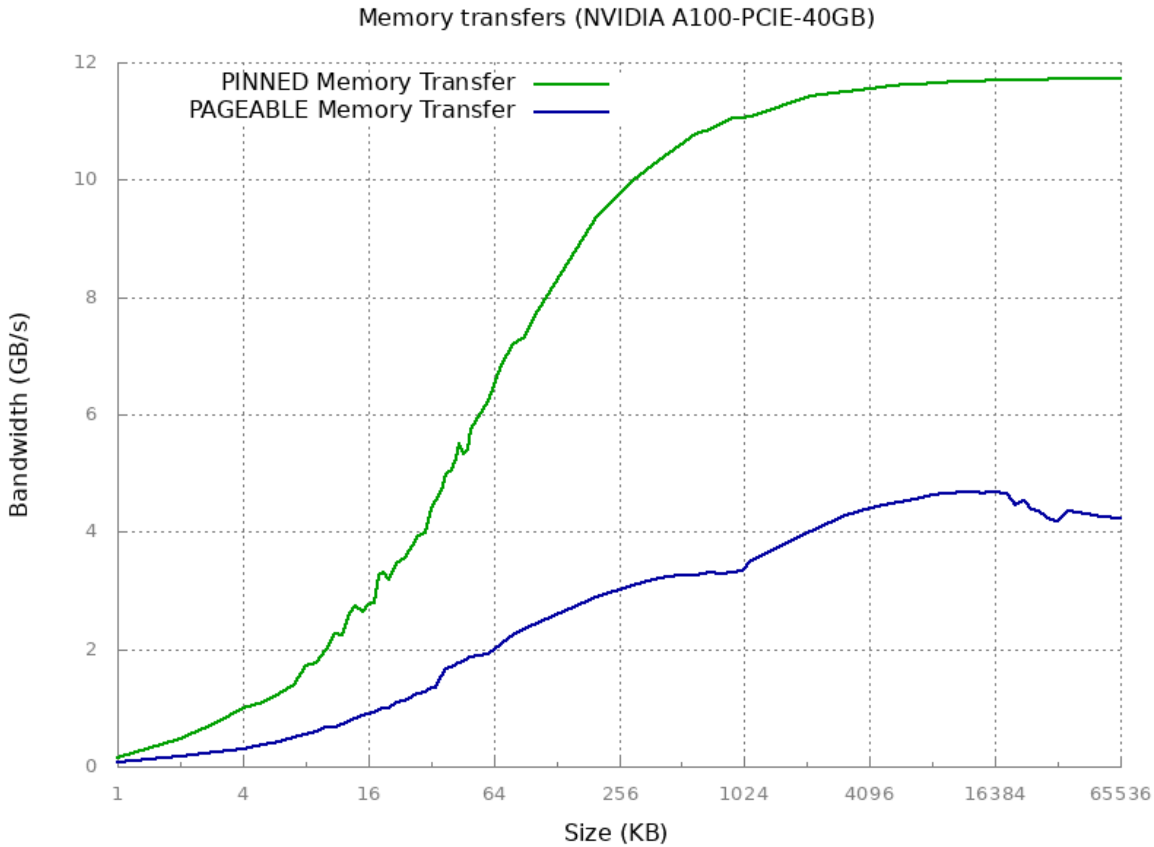
Pinned host memory



Pinned host memory



Pinned host memory



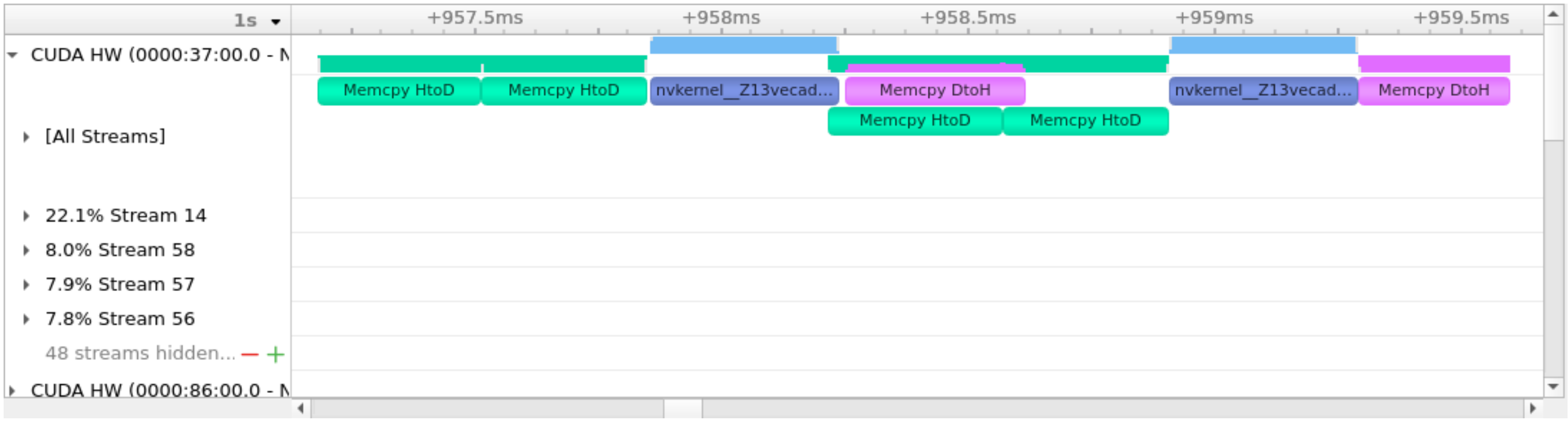
Use `nvc++` option
`-gpu=pinned`
vs.
`-gpu=nopinned`
(default)

- Drawback: The pinned allocation is much more expensive than a standard allocation with malloc

Asynchronous offloading

- Example – vector addition v2 pinned

```
$ nsys profile ./vecadd2_pinned
Runtime: 0.002053
Generating '/tmp/nsys-report-bc06.qdstrm'
[1/1] [========================100%] report3.nsys-rep
```



Version	v1	v2	v2 pin.
Time [ms]	6.75	5.06	2.05

Asynchronous offloading

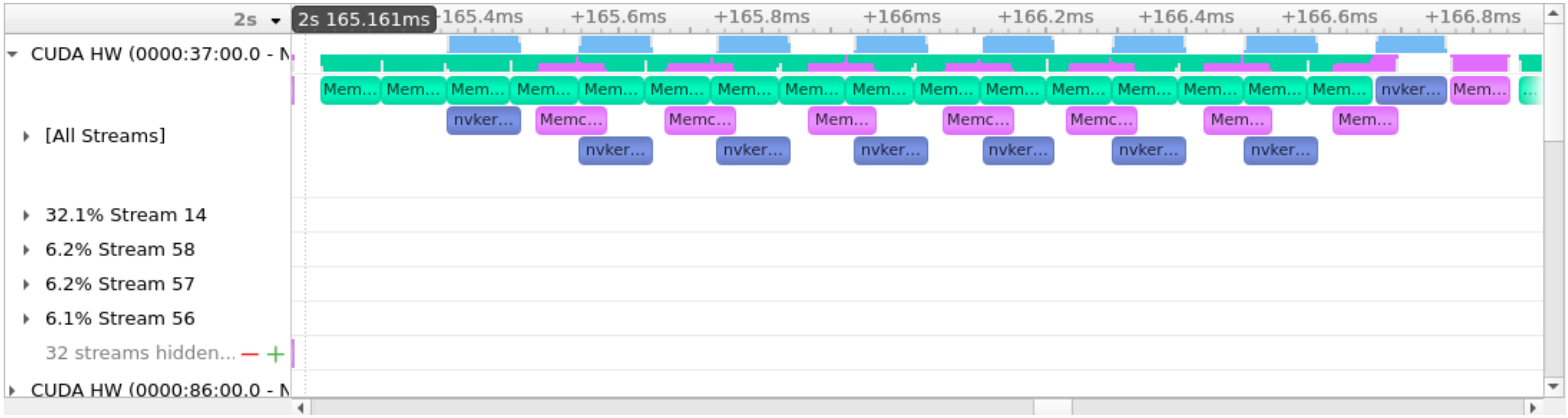
- Example – vector addition v3

```
void vecadd3(double *a, double *b, double *c)
{
    #define SPLITS 8

    for (int s = 0; s < SPLITS; ++s) {
        int length = N / SPLITS;
        int lower = s * length;
        #pragma omp target teams distribute parallel for nowait \
            num_teams(length) thread_limit(1)                  \
            map(to: a[lower:length], b[lower:length])          \
            map(from: c[lower:length])
        for (int i = lower; i < lower + length; i++)
            c[i] = a[i] + b[i];
    }
    #pragma omp taskwait
}
```

Asynchronous offloading

- Example – vector addition v3

```
$ nsys profile ./vecadd3_pinned
Runtime: 0.001716
Generating '/tmp/nsys-report-94aa.qdstrm'
[1/1] [========================100%] report4.nsys-rep
```



Version	v1	v2	v2 pin.	v3
Time [ms]	6.75	5.06	2.05	1.72

Asynchronous offloading

- Example – vector addition v3 alternative

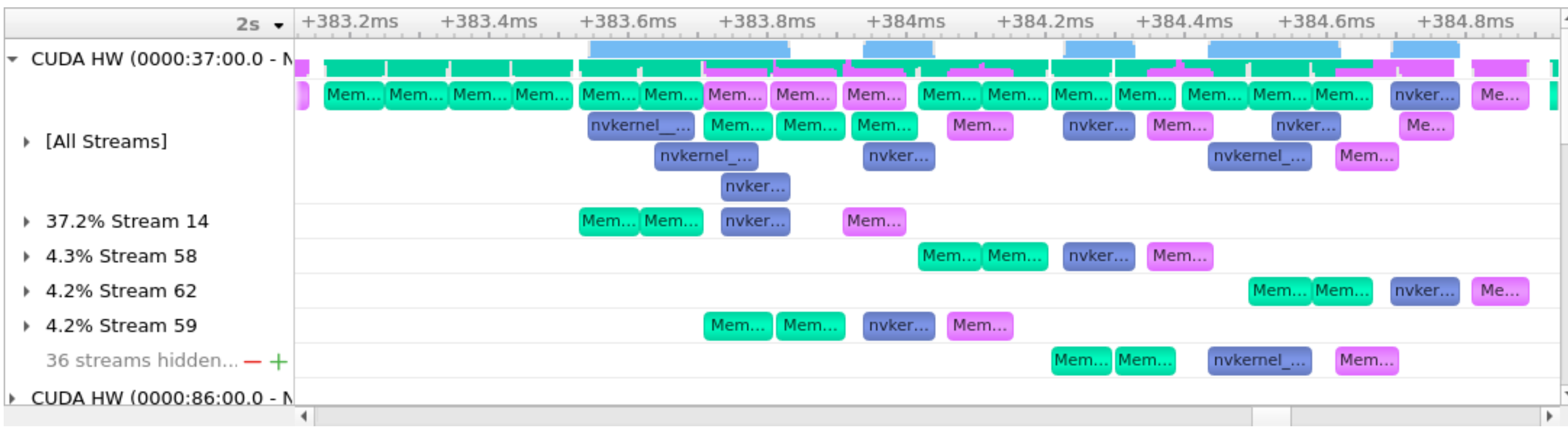
```
void vecadd3(double *a, double *b, double *c)
{
    #define SPLITS 8

    #pragma omp parallel for
    for (int s = 0; s < SPLITS; ++s) {
        int length = N / SPLITS;
        int lower = s * length;
        #pragma omp target teams distribute parallel for \
            num_teams(length) thread_limit(1)            \
            map(to: a[lower:length], b[lower:length])    \
            map(from: c[lower:length])
        for (int i = lower; i < lower + length; i++)
            c[i] = a[i] + b[i];
    }
}
```

OpenMP standard parallel threads as an alternative to `nowait`

Asynchronous offloading

- Example – vector addition alternative

```
$ nsys profile ./vecadd3alt_pinned
Runtime: 0.001852
Generating '/tmp/nsys-report-3a3d.qdstrm'
[1/1] [========================100%] report5.nsys-rep
```



Version	v1	v2	v2 pin.	v3	v3 alt.
Time [ms]	6.75	5.06	2.05	1.72	1.85

Multi-GPU

Multi-GPU systems

- Multi-GPU systems appear in several flavors

Server

NVIDIA Tesla K80

HPC Cluster (via MPI)

  - NVIDIA Tesla K80, while physically occupying a single expansion slot, will appear to OpenMP applications as two separate GPUs

Multi-GPU systems

- Using multiple GPUs within the same application can improve the performance
  - Splitting the task (extra level of parallelism)
  - Scales the peak performance
  - Scales the memory bandwidth
  - Does NOT always scale the PCI-e bandwidth!

Multi-GPU with OpenMP

- `omp_get_num_devices()`
  - Gets the number of available GPUs
- Clause `device()`
  - Selects the device on all `target` contructs

```
// Run independent offloads on each device
int numDevs = omp_get_num_devices();
for (int d = 0; d < numDevs; d++) {

    #pragma omp target nowait device(d)
    {
     ...
    }

}
```

Multi-GPU with OpenMP

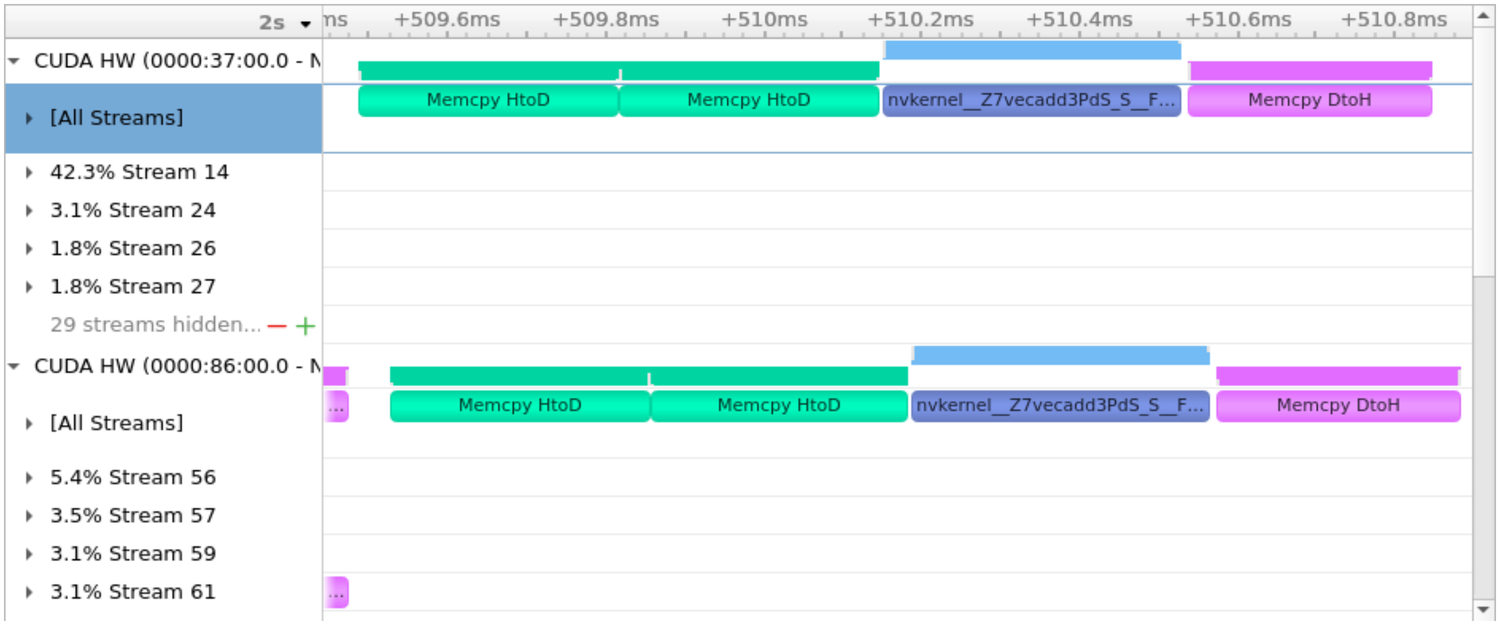
- Example using `device()` clause

```
void vecadd_multi(double *a, double *b, double *c)
{
    #pragma omp target teams distribute parallel for nowait \
        num_teams(N/2) thread_limit(1) device(0)             \
        map(to: a[0:N/2], b[0:N/2]) map(from: c[0:N/2])
    for (int i = 0; i < N/2; i++)
        c[i] = a[i] + b[i];

    #pragma omp target teams distribute parallel for nowait \
        num_teams(N/2) thread_limit(1) device(1)             \
        map(to: a[N/2:N/2], b[N/2:N/2]) map(from: c[N/2:N/2])
    for (int i = N/2; i < N; i++)
        c[i] = a[i] + b[i];

    #pragma omp taskwait
}
```

Multi-GPU with OpenMP

- Example using `device()` clause

```
$ nsys profile ./vecadd_multi
Runtime: 0.001564
Generating '/tmp/nsys-report-3ba8.qdstrm'
[1/1] [========================100%] report6.nsys-rep
```



Multi-GPU with OpenMP API

- `omp_set_default_device()`
  - Sets the device to run on
- `omp_get_default_device()`
  - Gets the current device

```c
// Allocate memory on two devices
double **a_d0, **a_d1, *data_d0, *data_d1;

omp_set_default_device(0);
a_d0 = malloc_2d_dev(N, N, &data_d0);
omp_set_default_device(1);
a_d1 = malloc_2d_dev(N, N, &data_d1);

... // clause: is_device_ptr(a_d0, a_d1)

omp_set_default_device(0);
free_2d_dev(a_d0, data_d0);
omp_set_default_device(1);
free_2d_dev(a_d1, data_d1);
```

```c
/* Routine for allocating two-dimensional
   array on the device */
double **malloc_2d_dev(int m, int n,
                       double **data)
{
    if (m <= 0 || n <= 0)
        return NULL;
    double **A =(double**)omp_target_alloc(
                 m*sizeof(double *),
                 omp_get_default_device());
    ...
}
```

Multi-GPU peer-to-peer access

- Trick: This is not currently part of OpenMP!
- Use `cudaDeviceEnablePeerAccess()` to get unidirectional peer access to other GPUs

```
// Enable peer-to-peer access and offload
cudaSetDevice(0);
cudaDeviceEnablePeerAccess(1, 0); // (dev 1, future flag)
cudaSetDevice(1);
cudaDeviceEnablePeerAccess(0, 0); // (dev 0, future flag)

#pragma omp target is_device_ptr(a_d0, a_d1) device(0)
{
  ... // both devices can access both arrays a_d0 and a_d1!
}
```

- Check peer access support with `deviceQuery`

End of lecture