GPU Profiling on Expanse
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EXPANSE
COMPUTING WITHOUT BOUNDARIES

SAN DIEGO SUPERCOMPUTER CENTER

NSF Award 1928224

Outline

- **nvprof**
  - Overview of options
  - Use CUDA SDK examples to illustrate profiling process
  - Import/export of profiles
  - Openacc example

- **Nsight Systems**
  - CLI and GUI options
  - Use CUDA SDK and vector addition examples to illustrate offline GUI use

- **Nsight Compute** – brief overview; currently disabled on Expanse

NVIDIA nvprof

- Command line tool that profiles CUDA related activities on both CPU and GPU.
- Console display of results OR can be saved for viewing using nvprof or nvvp (Visual Profiler).
- **CUDA options:** related to events, metrics, kernels, memory, source level analysis, and dependency analysis.
- **CPU Options:** related to frequency, depth, mode, scope, openacc, and openmp.
- **Print and IO Options:** related to demangling, summary, import/export of profiles, log files.
- Detailed options in nvprof documentation:
  - https://docs.nvidia.com/cuda/profiler-users-guide/index.html#nvprof-overview

NVIDIA nvprof: Query events, metrics

[mahidhar@exp-14-59 ~]$ nvprof --query-metrics
Available Metrics:
Name Description
Device 0 (Tesla V100-SXM2-32GB):
inst_per_warp: Average number of instructions executed by each warp
branch_efficiency: Ratio of branch instruction to sum of branch and divergent branch instruction

warp_execution_efficiency: Ratio of the average active threads per warp to the maximum number of threads per warp supported on a multiprocessor

warp_nonpred_execution_efficiency: Ratio of the average active threads per warp executing non-predicated instructions to the maximum number of threads per warp supported on a multiprocessor

inst_replay_overhead: Average number of replays for each instruction executed

…
…

[mahidhar@exp-14-59 ~]$ nvprof --query-events | more
Available Events:
Name Description
Device 0 (Tesla V100-SXM2-32GB):
Domain domain_a:
active_cycles_pm: Number of cycles a multiprocessor has at least one active warp.
active_warps_pm: Accumulated number of active warps per cycle. For every cycle it increments by the nu
mber of active warps in the cycle which can be in the range 0 to 64.
shared_ld_transactions: Number of transactions for shared load accesses. Maximum transaction size in volta is
128 bytes, any warp accessing more than 128 bytes will cause multiple transactions for a shared load instruction. This
also includes extra transactions caused by shared bank conflicts.
shared_st_transactions: Number of transactions for shared store accesses. Maximum transaction size in volta is 128 bytes, any warp accessing more than 128 bytes will cause multiple transactions for a shared store instruction. This also includes extra transactions caused by shared bank conflicts.
…
…

NVIDIA nvprof:Simple Example

```
[mahidhar@exp-14-59 matrixMul]$ nvprof ./matrixMul
[Matrix Multiply Using CUDA] - Starting...
==29356== NVPROF is profiling process 29356, command: ./matrixMul

GPU Device 0: "Volta" with compute capability 7.0

MatrixA(320,320), MatrixB(640,320)
Computing result using CUDA Kernel...
done
Performance= 2764.50 GFlop/s, Time= 0.047 msec, Size= 131072000 Ops, WorkgroupSize=
1024 threads/block
Checking computed result for correctness: Result = PASS

NOTE: The CUDA Samples are not meant for performancemeasurements. Results may vary
when GPU Boost is enabled.
==29356== Profiling application: ./matrixMul
==29356== Profiling result:
            Type  Time(%)      Time     Calls       Avg       Min       Max  Name
 GPU activities:   98.80%  13.986ms       301  46.465us  46.175us  47.263us  void
MatrixMulCUDA<int=32>(float*, float*, float*, int, int)
                    0.75%  105.98us         2  52.991us  36.831us  69.151us  [CUDA memcpy HtoD]
                    0.45%  63.392us         1  63.392us  63.392us  63.392us  [CUDA memcpy DtoH]
      API calls:   89.03%  175.52ms         3  58.507ms  2.3030us  175.52ms  cudaMalloc
                    6.55%  12.911ms         1  12.911ms  12.911ms  12.911ms  cudaEventSynchronize
                    1.99%  3.9151ms         4  978.78us  857.05us  1.0630ms  cuDeviceTotalMem
                    0.70%  1.3831ms       301  4.5950us  3.4940us  170.29us  cudaLaunchKernel
                    0.50%  988.44us       388  2.5470us     112ns  116.15us  cuDeviceGetAttribute
                    0.49%  974.78us         3  324.93us  172.52us  552.90us  cudaMemcpyAsync
                    0.22%  431.51us        22  19.614us     311ns  115.63us  cudaDeviceGetAttribute
                    0.17%  340.11us         1  340.11us  340.11us  340.11us  cudaGetDeviceCount
                    0.10%  199.36us         1  199.36us  199.36us  199.36us  cudaSetDevice
                    0.07%  145.48us         3  48.492us  3.0960us  130.70us  cudaFree
                    0.07%  143.04us         2  71.520us     612ns  142.43us  cudaEventCreate
                    0.05%  104.37us         4  26.091us  21.334us  37.046us  cuDeviceGetName
                    0.02%  48.915us         2  24.457us  3.0980us  45.817us  cudaStreamSynchronize
                    0.01%  12.254us         4  3.0630us  2.0060us  4.9760us  cuDeviceGetPCIBusId
                    0.00%  8.5450us         1  8.5450us  8.5450us  8.5450us  cudaStreamCreateWithFlags
                    0.00%  6.4310us         3  2.1430us     465ns  4.2790us  cuDeviceGetCount
                    0.00%  6.3390us         2  3.1690us  2.2410us  4.0980us  cudaEventRecord
                    0.00%  2.5880us         1  2.5880us  2.5880us  2.5880us  cudaEventElapsedTime
                    0.00%  2.1770us         2  1.0880us     435ns  1.7420us  cudaEventDestroy
                    0.00%  1.6600us         8     207ns     106ns     759ns  cuDeviceGet
                    0.00%     682ns         4     170ns     143ns     227ns  cuDeviceGetUuid
```

NVIDIA nvprof – Examples on Expanse

- Copy CUDA examples:

cp -r /cm/shared/apps/cuda10.2/sdk/10.2.89 $HOME/examples

- Setup profiling environment:

module load cuda10.2/toolkit

module load cuda10.2/profiler

- Compile some cases:

cd $HOME/examples/0_Simple/matrixMul

make

cd $HOME/examples/7_CUDALibraries/cuSolverSp_LinearSolver

make

NVIDIA nvprof

- Get interactive access to a GPU node for 15 minutes:

srun --pty --nodes=1 --ntasks-per-node=1 --cpus-per-task=10 -p gpu-shared --gpus=1 -A XYZ123 -t 00:15:00 --wait 0 /bin/bash

module reset; module load cuda10.2/toolkit cuda10.2/profiler

- Get timeline of activities on GPU in chronological order:

nvprof --print-gpu-trace ./cuSolverSp_LinearSolver

- Get timeline of all CUDA runtime, driver API calls invoked on the host in chronological order:

nvprof --print-api-trace ./cuSolverSp_LinearSolver

- Collect info on selected events, metrics:

nvprof --events warps_launched,active_warps_pm,inst_issued0 --metrics flop_count_sp ./cuSolverSp_LinearSolver

(***Last one needs permissions to be set up – we are working on this***)

NVIDIA nvprof : Sample output (**--print-gpu-trace**)

```
==33124== Profiling application: ./cuSolverSp_LinearSolver
==33124== Profiling result:
   Start  Duration            Grid Size      Block Size     Regs*    SSMem*    DSMem*      Size  Throughput  SrcMemType
 DstMemType           Device   Context    Stream  Name
1.00716s  1.5680us                    -               -         -         -         -      112B  68.120MB/s    Pageable
     Device  Tesla V100-SXM2         1         7  [CUDA memcpy HtoD]
1.73374s  5.0240us                    -               -         -         -         -  39.066KB  7.4157GB/s    Pageable
     Device  Tesla V100-SXM2         1        14  [CUDA memcpy HtoD]
1.73379s  19.200us                    -               -         -         -         -  193.75KB  9.6237GB/s    Pageable
     Device  Tesla V100-SXM2         1        14  [CUDA memcpy HtoD]
1.73387s  36.800us                    -               -         -         -         -  387.50KB  10.042GB/s    Pageable
     Device  Tesla V100-SXM2         1        14  [CUDA memcpy HtoD]
1.73392s  5.0240us                    -               -         -         -         -  39.066KB  7.4157GB/s    Pageable
     Device  Tesla V100-SXM2         1        14  [CUDA memcpy HtoD]
1.73393s  18.560us                    -               -         -         -         -  193.75KB  9.9555GB/s    Pageable
     Device  Tesla V100-SXM2         1        14  [CUDA memcpy HtoD]
1.73401s  34.880us                    -               -         -         -         -  387.50KB  10.595GB/s    Pageable
     Device  Tesla V100-SXM2         1        14  [CUDA memcpy HtoD]
1.73405s  9.1200us                    -               -         -         -         -  78.125KB  8.1695GB/s    Pageable
     Device  Tesla V100-SXM2         1        14  [CUDA memcpy HtoD]
1.73407s  8.9590us                    -               -         -         -         -  78.125KB  8.3163GB/s    Pageable
     Device  Tesla V100-SXM2         1        14  [CUDA memcpy HtoD]
1.73409s  4.9920us                    -               -         -         -         -  39.063KB  7.4625GB/s    Pageable
     Device  Tesla V100-SXM2         1        14  [CUDA memcpy HtoD]
```

NVIDIA nvprof : Sample output (**--print-gpu-trace**)

```
1.91607s  1.3440us                    -               -         -         -         -        4B  2.8383MB/s      Device
   Pageable  Tesla V100-SXM2         1        14  [CUDA memcpy DtoH]
1.91609s  1.0880us                    -               -         -         -         -  39.063KB  34.240GB/s      Device
     Device  Tesla V100-SXM2         1        14  [CUDA memcpy DtoD]
1.91609s  1.0880us                    -               -         -         -         -  39.063KB  34.240GB/s      Device
     Device  Tesla V100-SXM2         1        14  [CUDA memcpy DtoD]
1.91610s  1.0880us                    -               -         -         -         -  39.063KB  34.240GB/s      Device
     Device  Tesla V100-SXM2         1        14  [CUDA memcpy DtoD]
1.91638s  12.064us           (7814 1 1)       (128 1 1)        16        0B        0B         -           -           -
         -  Tesla V100-SXM2         1        14  void set_identy<int=128>(int, int*) [634]
1.91640s  7.4240us           (2560 1 1)        (64 1 1)        16        0B        0B         -           -           -
         -  Tesla V100-SXM2         1        14  void convert_CsrToCoo_kernel<int=0>(int const *, int, int, int*) [638]
1.91642s  16.672us                    -               -         -         -         -  3.8151MB  223.47GB/s      Device
     Device  Tesla V100-SXM2         1        14  [CUDA memcpy DtoD]
1.91643s  12.160us           (7814 1 1)       (128 1 1)        16        0B        0B         -           -           -
         -  Tesla V100-SXM2         1        14  void set_identy<int=128>(int, int*) [641]
1.91645s  1.2800us                    -               -         -         -         -      132B  98.348MB/s      Device
         -  Tesla V100-SXM2         1        14  [CUDA memset]
1.91645s  19.488us            (977 1 1)       (256 1 1)        38  8.5000KB        0B         -           -           -
         -  Tesla V100-SXM2         1        14  void stable_sort_by_key_local_core<int=256, int=4>(int, int, int*, int
*, int*, int*) [644]
```

NVIDIA nvprof

- System profiling: Low frequency sampling of the power, clock, and thermal behavior of GPU

nvprof --print-gpu-trace --system-profiling on ./cuSolverSp_LinearSolver

- Dependency analysis:

nvprof --dependency-analysis ./cuSolverSp_LinearSolver

- OpenACC profiling: (copy over /cm/shared/examples/sdsc/openacc)

nvprof ./laplace2d.openacc.exe

nvprof --print-openacc-summary ./laplace2d.openacc.exe

nvprof --print-openacc-trace ./laplace2d.openacc.exe

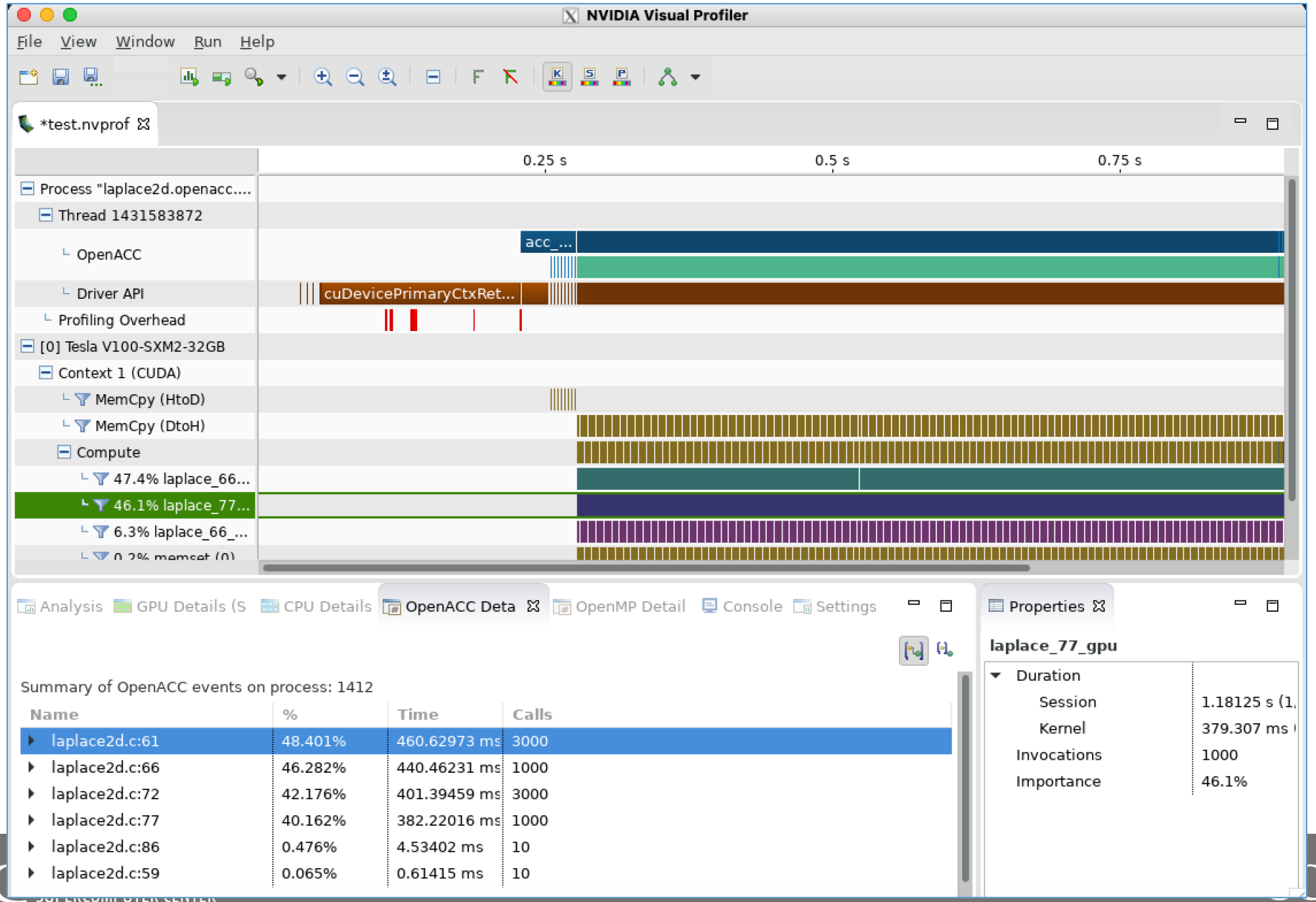
- Export to file that can be opened with nvvp

nvprof --export-profile test.nvprof --print-openacc-trace ./laplace2d.openacc.exe

NVIDIA nvprof : Sample output (**--system-profiling on --**)

```
     Device  Tesla V100-SXM2         1        14                    -  [CUDA memcpy HtoD]
1.40207s  34.911us                    -         -         -         -         -  387.50KB  10.585GB/s    Pageable
     Device  Tesla V100-SXM2         1        14                    -  [CUDA memcpy HtoD]
1.40211s  9.1200us                    -         -         -         -         -  78.125KB  8.1695GB/s    Pageable
     Device  Tesla V100-SXM2         1        14                    -  [CUDA memcpy HtoD]
1.40213s  8.8320us                    -         -         -         -         -  78.125KB  8.4359GB/s    Pageable
     Device  Tesla V100-SXM2         1        14                    -  [CUDA memcpy HtoD]
1.40215s  5.0240us                    -         -         -         -         -  39.063KB  7.4150GB/s    Pageable
     Device  Tesla V100-SXM2         1        14                    -  [CUDA memcpy HtoD]
1.42622s         -                    -         -         -         -         -         -         -           -
          -  Tesla V100-SXM2         -         -                   40  [Temperature (C)]
1.42709s         -                    -         -         -         -         -         -         -           -
          -  Tesla V100-SXM2         -         -       66539/300000  [Power/Limit (mW)]
1.45259s         -                    -         -         -         -         -         -         -           -
          -  Tesla V100-SXM2         -         -         1530/877  [SM/Memory Clock (MHz)]
1.45261s         -                    -         -         -         -         -         -         -           -
          -  Tesla V100-SXM2         -         -                   40  [Temperature (C)]
1.45346s         -                    -         -         -         -         -         -         -           -
          -  Tesla V100-SXM2         -         -       66539/300000  [Power/Limit (mW)]
1.50360s         -                    -         -         -         -         -         -         -           -
          -  Tesla V100-SXM2         -         -                   40  [Temperature (C)]
1.50449s         -                    -         -         -         -         -         -         -           -
          -  Tesla V100-SXM2         -         -       66539/300000  [Power/Limit (mW)]
1.55497s         -                    -         -         -         -         -         -         -           -
```

Reading nvprof result from nvvp



Nsight Systems

- Systemwide performance tool, profile combines info from both CPU and GPU.
- Gives a full system view of the code execution and helps identify bottlenecks at all levels. Examples:
  - GPU starvation
  - unnecessary GPU synchronization
  - insufficient CPU parallelizing
  - memory access/data movement inefficiencies
- Can run in both command line (CLI) and graphical (GUI) mode.
- CLI based runs can export report files that can viewed on client machines.

Nsight Systems

- Several tracing options. Examples: cublas, cuda, cudnn, nvtx, opengl, openacc, openmp, osrt, and mpi.
- OpenMPI and MPICH options.
- CUDA and OS runtime backtrace options.
- Sample screenshots available at:

https://docs.nvidia.com/nsight-systems/UserGuide/index.html

- **Currently on Expanse there are some limitations in place due to security reasons.**
- **Recommend downloading a copy on your desktop/laptop (need developer registration with NVIDIA) if you want to use GUI.**

Nsight Systems: Simple Profiling Example

- Get interactive access on a GPU node:

srun --pty --nodes=1 --ntasks-per-node=1 --cpus-per-task=10 -p gpu-shared --gpus=1 -A XYZ123 -t 00:15:00 --wait 0 /bin/bash

- Set up profiling environment:

module reset

module load cuda10.2/toolkit

export PATH=/cm/shared/examples/sdsc/nsight/v2020.5/bin:$PATH

- Profile with cli and write to baseline report file:

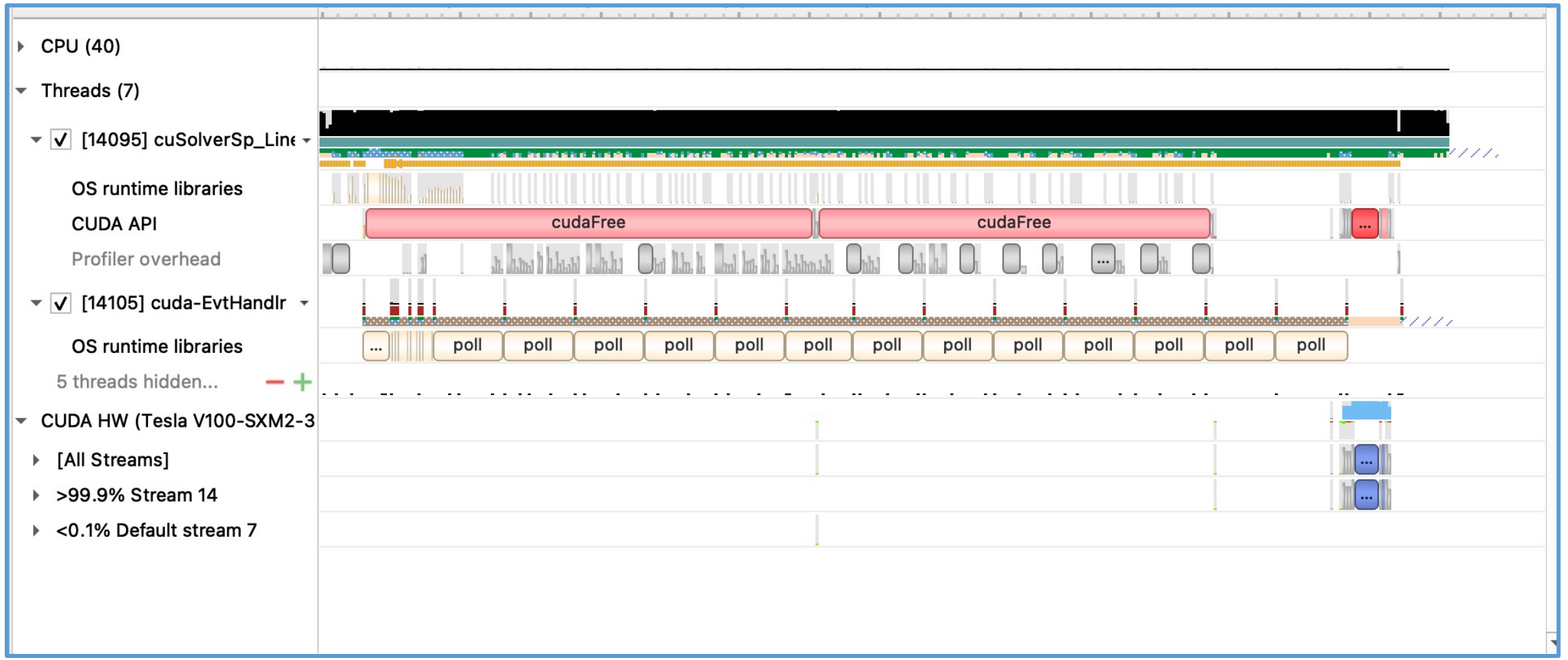
nsys profile -t cuda,osrt -o baseline -w true ./cuSolverSp_LinearSolver

Nsight Systems: Simple Profiling Example

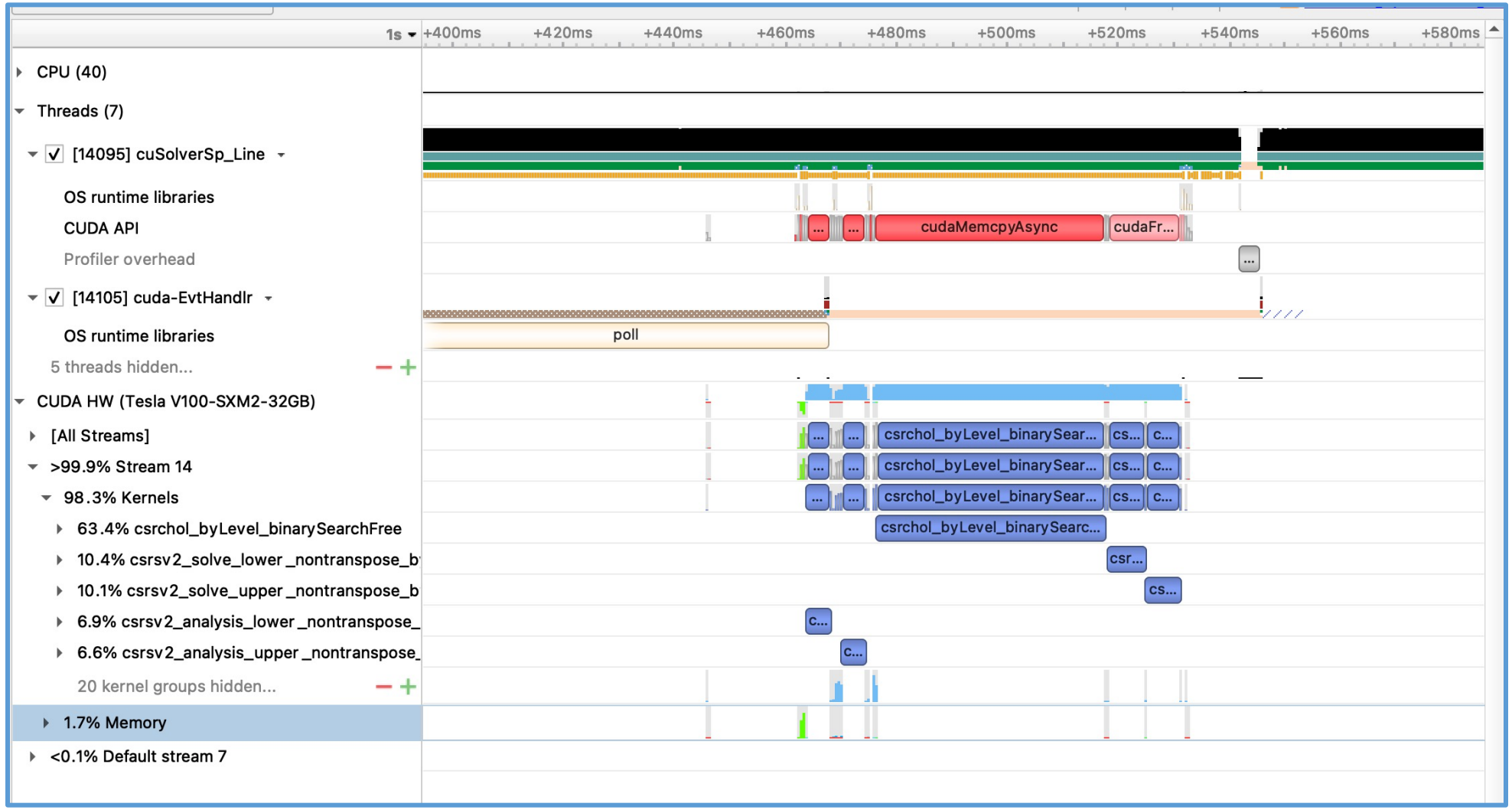
```
[mahidhar_test@exp-1-57 cuSolverSp_LinearSolver]$ nsys profile -t cuda,osrt -o baseline
-w true ./cuSolverSp_LinearSolver

Collecting data...
GPU Device 0: "Volta" with compute capability 7.0

Using default input file [./lap2D_5pt_n100.mtx]
step 1: read matrix market format
sparse matrix A is 10000 x 10000 with 49600 nonzeros, base=1
step 2: reorder the matrix A to minimize zero fill-in
      if the user choose a reordering by -P=symrcm, -P=symamd or -P=metis
step 2.1: no reordering is chosen, Q = 0:n-1
step 2.2: B = A(Q,Q)
step 3: b(j) = 1 + j/n
step 4: prepare data on device
step 5: solve A*x = b on CPU
step 6: evaluate residual r = b - A*x (result on CPU)
(CPU) |b - A*x| = 5.456968E-12
(CPU) |A| = 8.000000E+00
(CPU) |x| = 1.136492E+03
(CPU) |b| = 1.999900E+00
(CPU) |b - A*x|/(|A|*|x| + |b|) = 6.000667E-16
step 7: solve A*x = b on GPU
```

```
step 8: evaluate residual r = b - A*x (result on GPU)
(GPU) |b - A*x| = 1.818989E-12
(GPU) |A| = 8.000000E+00
(GPU) |x| = 1.136492E+03
(GPU) |b| = 1.999900E+00
(GPU) |b - A*x|/(|A|*|x| + |b|) = 2.000222E-16
timing chol: CPU =   0.162645 sec , GPU =   0.086416 sec

show last 10 elements of solution vector (GPU)
consistent result for different reordering and solver
x[9990] = 3.000016E+01
x[9991] = 2.807343E+01
x[9992] = 2.601354E+01
x[9993] = 2.380285E+01
x[9994] = 2.141866E+01
x[9995] = 1.883070E+01
x[9996] = 1.599668E+01
x[9997] = 1.285365E+01
x[9998] = 9.299423E+00
x[9999] = 5.147265E+00
Processing events...
Saving temporary "/tmp/nsys-report-940c-3a9e-7049-6092.qdstrm" file to disk...

Creating final output files...
Processing [==========================================================100%]
Saved report file to "/tmp/nsys-report-940c-3a9e-7049-6092.qdrep"
Unable to create output file
/home/mahidhar_test/examples/7_CUDALibraries/cuSolverSp_LinearSolver/baseline.qdrep : File
exists
Use `--force-overwrite true` to override existing files.
Please manually fetch report file(s) from:
* /tmp/nsys-report-940c-3a9e-7049-6092.qdrep
```

Nsight Systems: Simple Profiling Example



Nsight Systems: Simple Profiling Example (zoomed)



Simple Profiling Example: nvprof comparison

```
==37294== Profiling application: ./cuSolverSp_LinearSolver
==37294== Profiling result:
            Type  Time(%)      Time     Calls       Avg       Min       Max  Name
 GPU activities:   62.46%  41.322ms         1  41.322ms  41.322ms  41.322ms  void csrchol_byLevel_binarySearchFree<doubl
e, double, int=5, int=3>(int, double*, int const *, int const *, int*, int*, int*, int*, int*, int*, int*, int)
                  10.05%  6.6484ms         1  6.6484ms  6.6484ms  6.6484ms  void csrsv2_solve_lower_nontranspose_byLeve
l_kernel<double, int=5, int=3>(int, int, double const *, int const *, int const *, double const *, double*, int*, int*,
double const *, double, int, int*, double*, int*, int)
                   9.92%  6.5622ms         1  6.5622ms  6.5622ms  6.5622ms  void csrsv2_solve_upper_nontranspose_byLeve
l_kernel<double, int=5, int=3>(int, int, double const *, int const *, int const *, double const *, double*, int*, int*,
double const *, double, int, int*, double*, int*, int)
                   6.75%  4.4672ms         1  4.4672ms  4.4672ms  4.4672ms  void csrsv2_analysis_lower_nontranspose_ker
nel<int=5, int=3>(int, int const *, int const *, int*, int, int*, int*, int*, int)
                   6.54%  4.3247ms         1  4.3247ms  4.3247ms  4.3247ms  void csrsv2_analysis_upper_nontranspose_ker
nel<int=5, int=3>(int, int const *, int const *, int*, int, int*, int*, int*, int)
                   1.28%  848.86us        26  32.648us  1.2160us  625.12us  [CUDA memcpy HtoD]
                   0.98%  650.01us         2  325.01us  1.3440us  648.67us  void pegasus_Imemset<int=128>(int, int, int
*)
                   0.53%  352.77us        14  25.197us  24.576us  26.304us  void stable_sort_by_key_merge_core<int=256,
 int=4>(int, int*, int*, int*, int*, int*, int*)
                   0.38%  251.45us        14  17.960us  16.576us  19.840us  void stable_sort_by_key_local_core<int=256,
 int=4>(int, int, int*, int*, int*, int*)
                   0.22%  143.17us        30  4.7720us  4.6080us  5.9200us  void stable_sort_by_key_domino_phase1<int=2
56, int=4>(int, int, int, int*, int*, int*, int*, int*, int*)
```

Nsight Systems: Example illustrating process

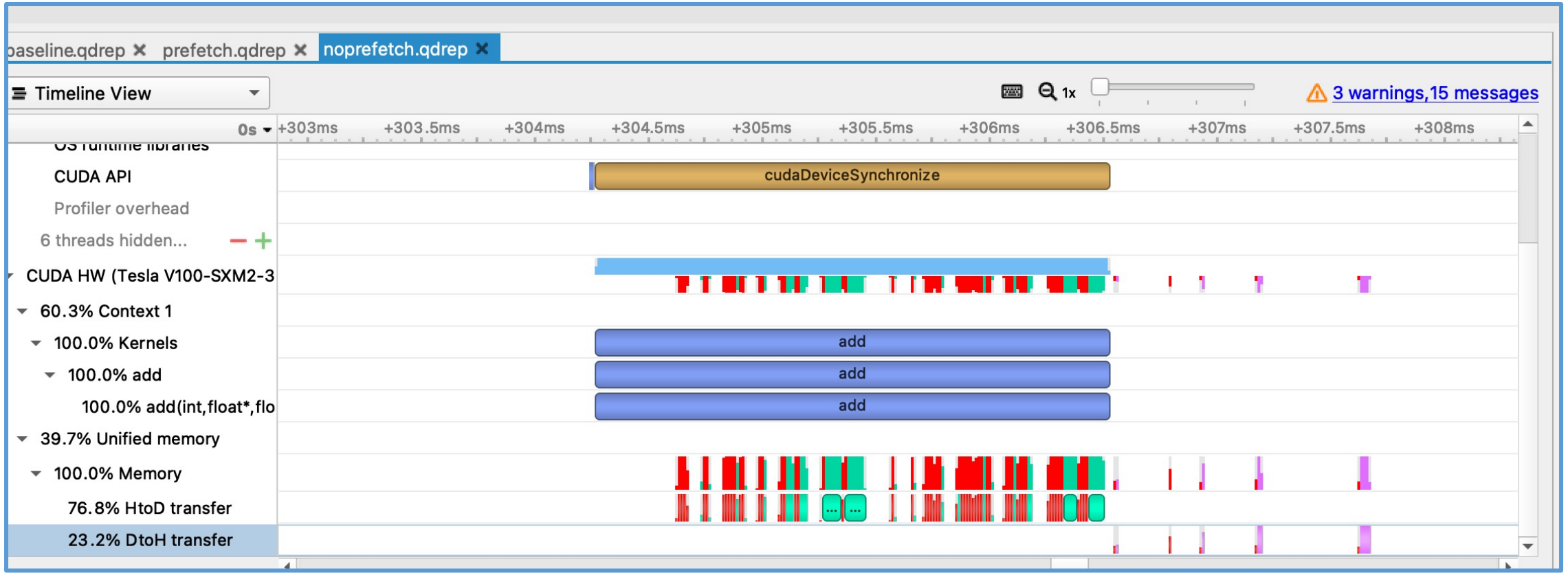
- **Reference:**

https://developer.nvidia.com/blog/transitioning-nsight-systems-nvidia-visual-profiler-nvprof/

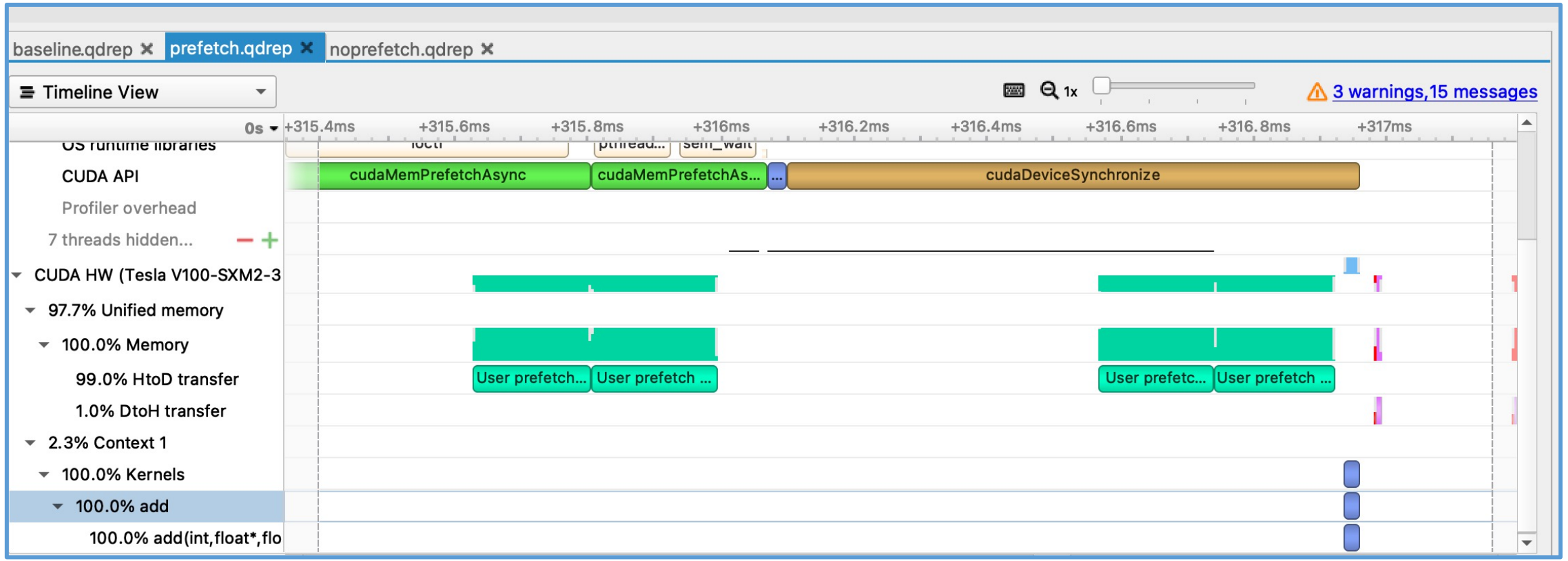
- Sample code (in link above) uses unified memory data movement and does vector addition.

- Two approaches for the data movement are considered – with and without prefetch. We can run these on Expanse and look at the profiles.

Nsight Systems: Example w/ no prefetch



Nsight Systems: Example w/ prefetch



Nsight Compute

- Interactive kernel profiler for CUDA applications. Part of CUDA toolkit
- Both graphical user interface and command line options.
- Features include:
  - Compare performance metrics between baselines and the current run,
  - CUDA Task Graph Profiling
  - Source code correlation
  - Roofline Analysis to visualize performance headroom
- Currently disabled on Expanse and Comet (restricted permissions due to security reasons)

Good example of optimization workflow here:

https://developer.nvidia.com/blog/analysis-driven-optimization-preparing-for-analysis-with-nvidia-nsight-compute-part-1/

Summary

- Several command line and GUI based options available for profiling
- Some features limited by permissions restrictions (security considerations). Will be enabled in the future if nodes are exclusive access and with a feature request in SLURM.
- **nvprof** is the simplest profiling tool – command line approach with many different events, metrics options. CUDA/OpenACC codes can be easily profiled.
- **Nsight Systems** offers both CLI and GUI options to do system level profiling (both CPU and GPU components covered).
- **Nsight Compute** is a powerful Interactive kernel profiler for CUDA applications. C*urrently disabled on Expanse, will be opened in the future.*