GPU TECHNOLOGY CONFERENCE

ADVANCED OPENACC PROGRAMMING

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AGENDA

- OpenACC Review
- Optimizing OpenACC Loops
- Routines
- Update Directive
- Asynchronous Programming
- Multi-GPU Programming
- OpenACC Interoperability
- Atomic Directive
- Misc. Advice & Techniques
- Next Steps

OPENACC REVIEW

WHAT ARE COMPILER DIRECTIVES?

```
int main() {

  do_serial_stuff()


  for(int i=0; i < BIGN; i++)
  {
    …compute intensive work
  }

  do_more_serial_stuff();

}
```

Programmer inserts compiler hints.

Execution Begins on the CPU.

Compiler Generates GPU Code

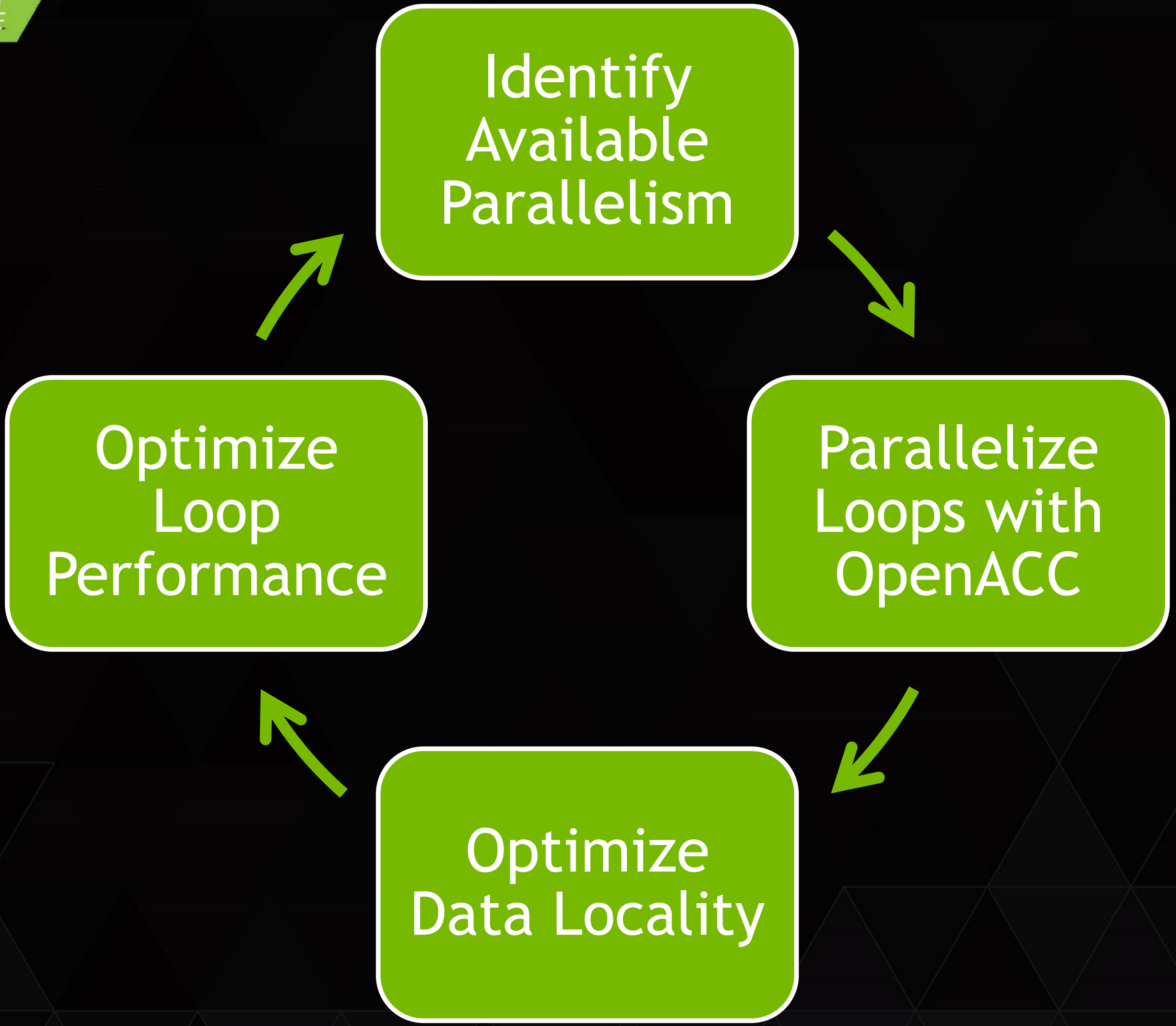
Data and Execution moves to the GPU.

Data and Execution returns to the CPU.

OPENACC: THE STANDARD FOR GPU DIRECTIVES

- **Simple:** Directives are the easy path to accelerate compute intensive applications
- **Open:** OpenACC is an open GPU directives standard, making GPU programming straightforward and portable across parallel and multi-core processors
- **Portable:** GPU Directives represent parallelism at a high level, allowing portability to a wide range of architectures with the same code.

OpenACC® DIRECTIVES FOR ACCELERATORS


Identify Available Parallelism
Parallelize Loops with OpenACC
Optimize Data Locality
Optimize Loop Performance

JACOBI ITERATION: C CODE

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


  for( int j = 1; j < n-1; j++) {
    for(int i = 1; i < m-1; i++) {

      Anew[j][i] = 0.25 * (A[j][i+1] + A[j][i-1] +
                           A[j-1][i] + A[j+1][i]);

      err = max(err, abs(Anew[j][i] - A[j][i]));
    }
  }


  for( int j = 1; j < n-1; j++) {
    for( int i = 1; i < m-1; i++ ) {
      A[j][i] = Anew[j][i];
    }
  }

  iter++;
}
```

- Iterate until converged
- Iterate across matrix elements
- Calculate new value from neighbors
- Compute max error for convergence
- Swap input/output arrays

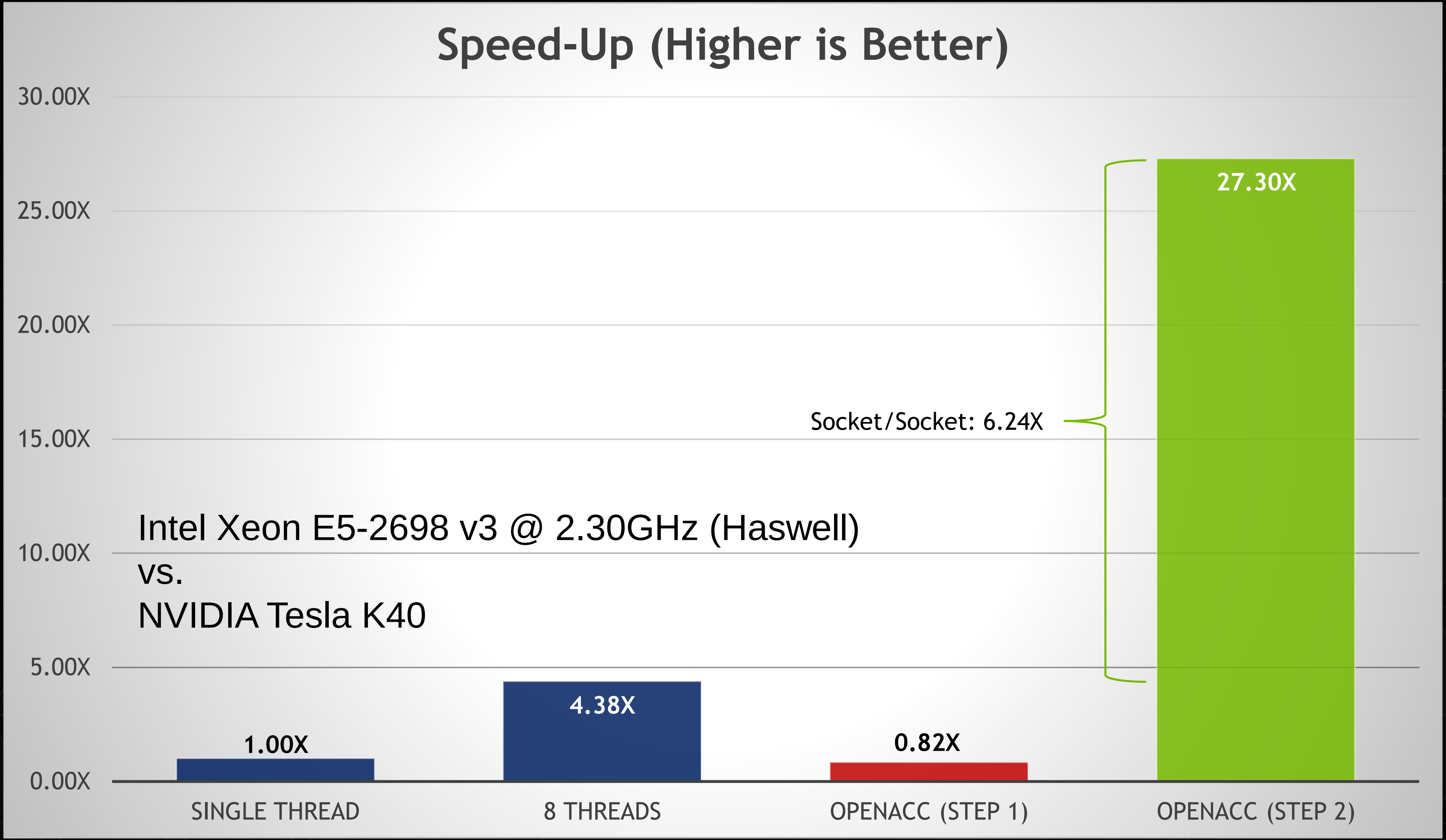
JACOBI: FINAL CODE

```
#pragma acc data copy(A) create(Anew)
while ( err > tol && iter < iter_max ) {
  err=0.0;

#pragma acc parallel loop reduction(max:err)
  for( int j = 1; j < n-1; j++) {
    for(int i = 1; i < m-1; i++) {

      Anew[j][i] = 0.25 * (A[j][i+1] + A[j][i-1] +
                           A[j-1][i] + A[j+1][i]);

      err = max(err, abs(Anew[j][i] - A[j][i]));
    }
  }

#pragma acc parallel loop
  for( int j = 1; j < n-1; j++) {
    for( int i = 1; i < m-1; i++ ) {
      A[j][i] = Anew[j][i];
    }
  }

  iter++;
}
```

◀ Optimized Data Locality

◀ Parallelized Loop

◀ Parallelized Loop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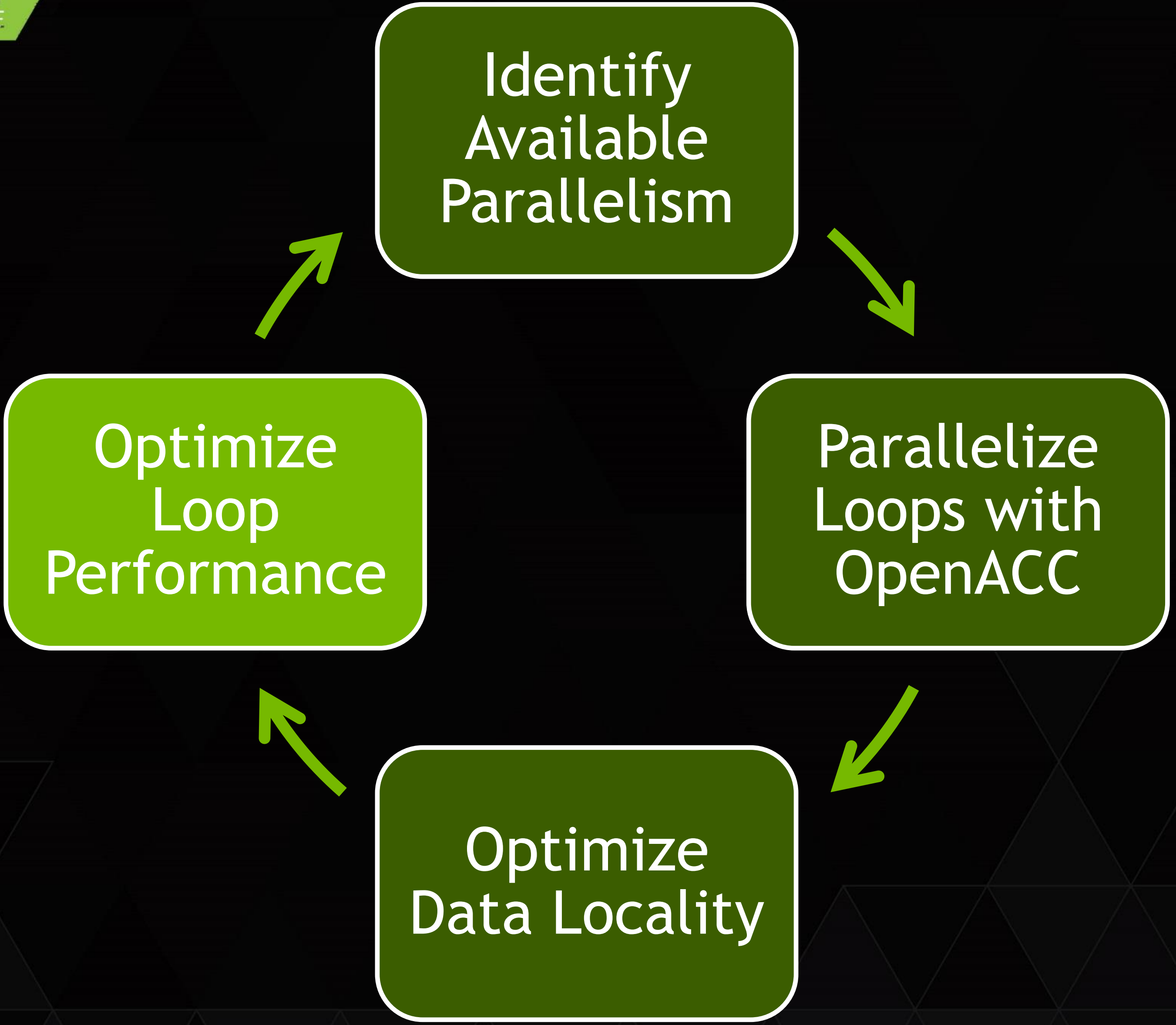
Speed-Up (Higher is Better)
30.00X
25.00X
20.00X
15.00X
10.00X
5.00X
0.00X
27.30X
Socket/Socket: 6.24X
Intel Xeon E5-2698 v3 @ 2.30GHz (Haswell)
vs.
NVIDIA Tesla K40
4.38X
1.00X
0.82X
SINGLE THREAD
8 THREADS
OPENACC (STEP 1)
OPENACC (STEP 2)


Identify Available Parallelism
Parallelize Loops with OpenACC
Optimize Data Locality
Optimize Loop Performance

SPARSE MATRIX/VECTOR PRODUCT

```
   do i=1,a%num_rows
      tmpsum = 0.0d0
      row_start = arow_offsets(i)
      row_end   = arow_offsets(i+1)-1
      do j=row_start,row_end
        acol = acols(j)
        acoef = acoefs(j)
        xcoef = x(acol)
        tmpsum = tmpsum + acoef*xcoef
      enddo
      y(i) = tmpsum
    enddo
```

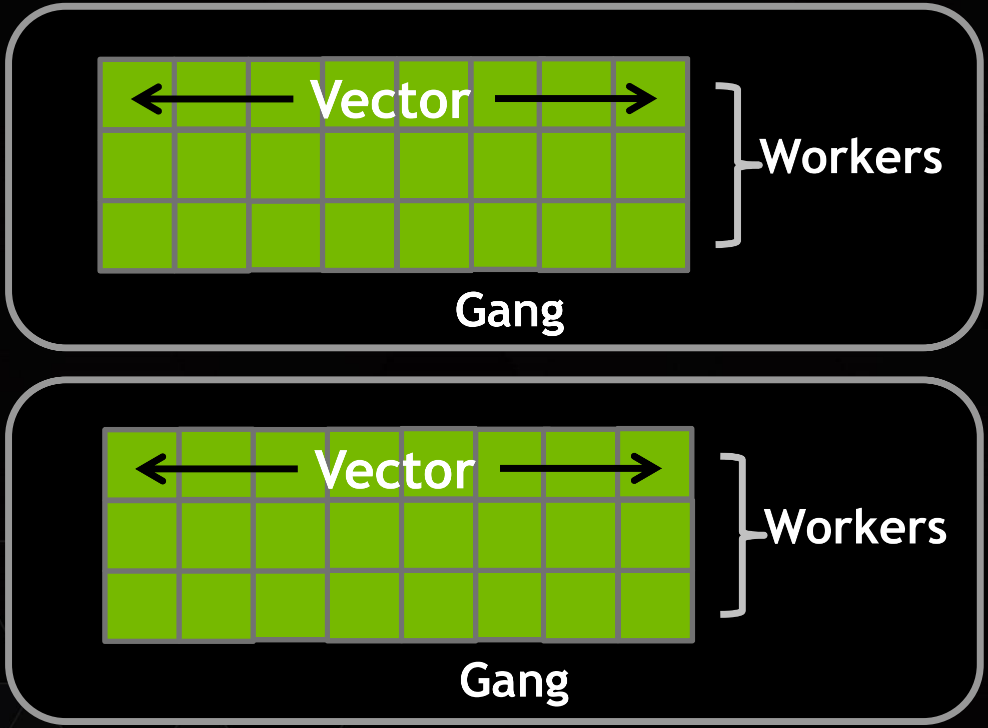
- Performs Mat/Vec product of sparse matrix
- Matrices are stored in a row-compressed format
- Parallelism per-row will vary, but is generally not very large

PARALLELIZED SPMV

```
106    !$acc parallel loop present(arow_offsets,acols,acoefs) &
107    !$acc& private(row_start,row_end,acol,acoef,xcoef) &
108    !$acc& reduction(+:tmpsum)
109    do i=1,a%num_rows
110      tmpsum = 0.0d0
111      row_start = arow_offsets(i)
112      row_end   = arow_offsets(i+1)-1
113      do j=row_start,row_end
114        acol = acols(j)
115        acoef = acoefs(j)
116        xcoef = x(acol)
117        tmpsum = tmpsum + acoef*xcoef
118      enddo
119      y(i) = tmpsum
120    enddo
```

- Data already on device
- Compiler has vectorized the loop at 113 and selected a vector length of 256
- Total application speed-up (including other accelerated routines): 1.08X

OPENACC: 3 LEVELS OF PARALLELISM



- *Vector* threads work in lockstep (SIMD/SIMT parallelism)
- *Workers* compute a vector
- *Gangs* have 1 or more workers and share resources (such as cache, the streaming multiprocessor, etc.)
- Multiple gangs work independently of each other

OPENACC GANG, WORKER, VECTOR CLAUSES

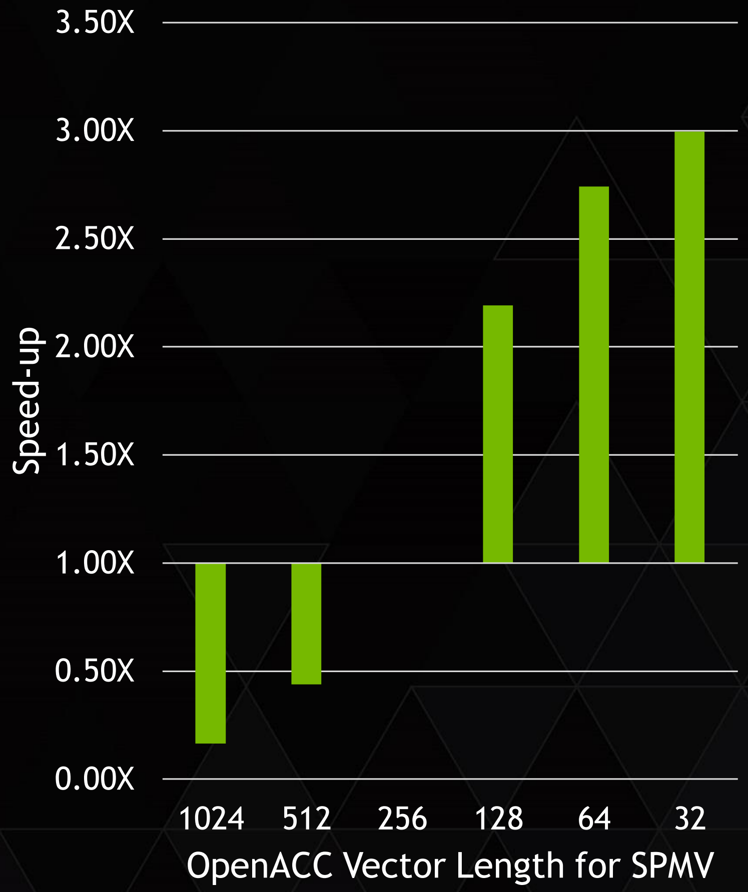
- gang, worker, and vector can be added to a loop clause
- A parallel region can only specify one of each gang, worker, vector
- Control the size using the following clauses on the parallel region
  - num_gangs(n), num_workers(n), vector_length(n)

```
#pragma acc kernels loop gang
for (int i = 0; i < n; ++i)
  #pragma acc loop vector(128)
  for (int j = 0; j < n; ++j)
   ...
```

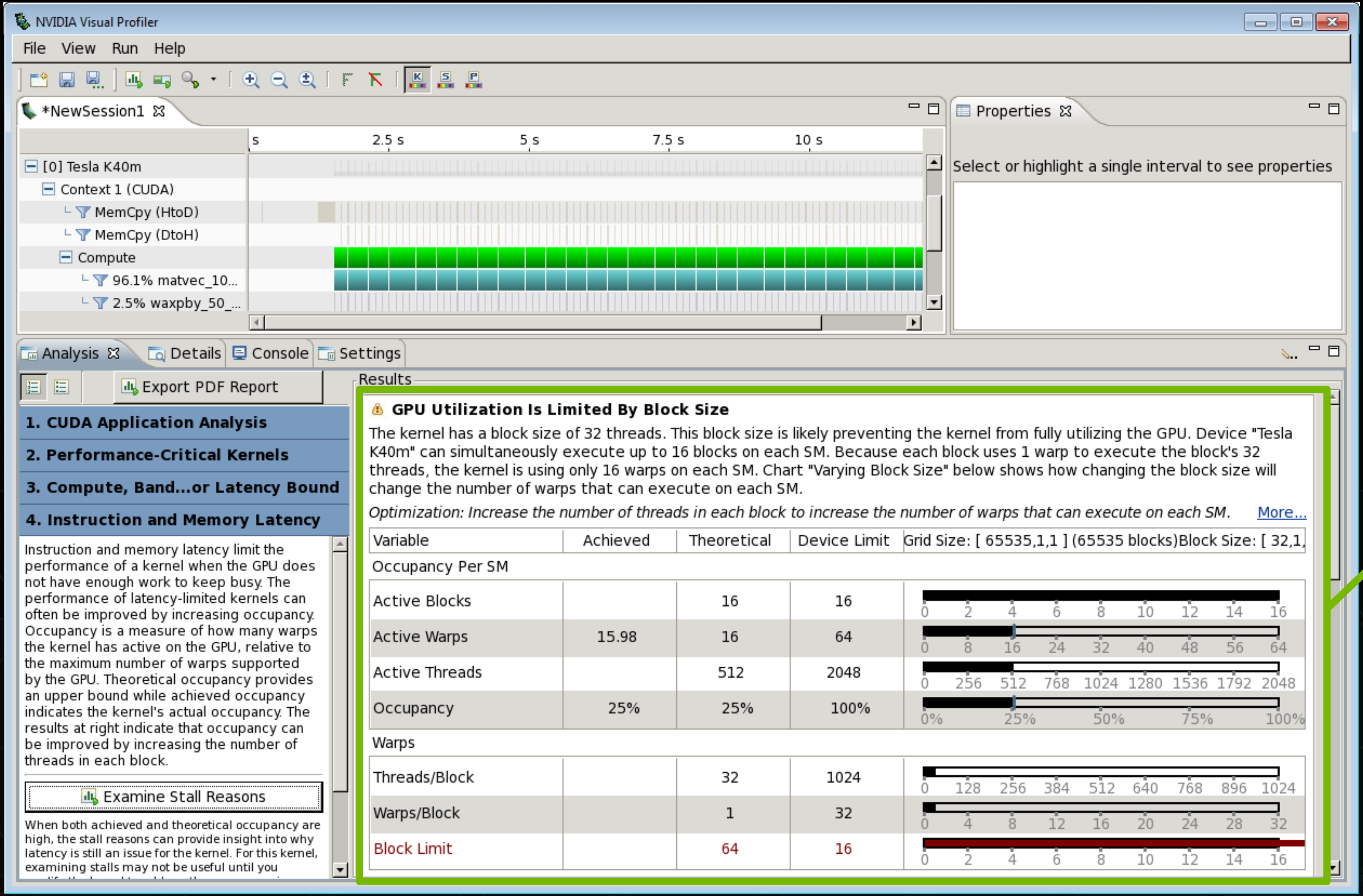
```
#pragma acc parallel vector_length(128)
#pragma acc loop gang
for (int i = 0; i < n; ++i)
  #pragma acc loop vector
  for (int j = 0; j < n; ++j)
     ...
```

OPTIMIZED SPMV VECTOR LENGTH

```
!$acc parallel loop present(arow_offsets,acols,acoefs) &
!$acc& private(row_start,row_end,acol,acoef,xcoef) &
!$acc& vector_length(32)
do i=1,a%num_rows
  tmpsum = 0.0d0
  row_start = arow_offsets(i)
  row_end   = arow_offsets(i+1)-1
  !$acc loop vector reduction(+:tmpsum)
  do j=row_start,row_end
    acol = acols(j)
    acoef = acoefs(j)
    xcoef = x(acol)
    tmpsum = tmpsum + acoef*xcoef
  enddo
  y(i) = tmpsum
enddo
```



PERFORMANCE LIMITER: OCCUPANCY



We need more threads!

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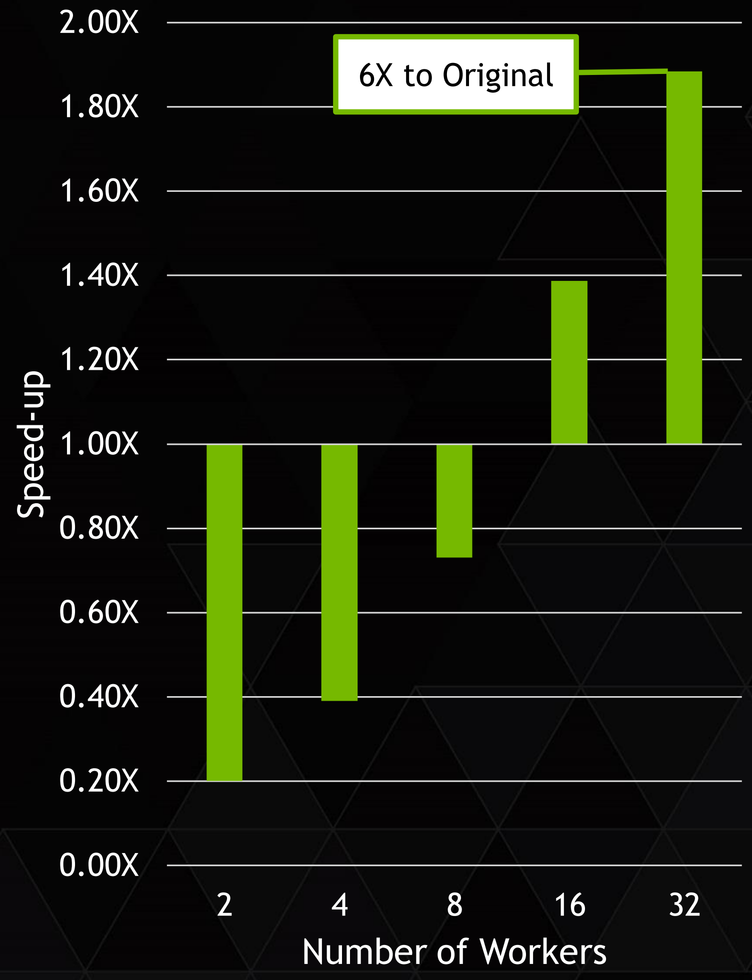
INCREASED PARALLELISM WITH WORKERS

```
!$acc parallel loop present(arow_offsets,acols,acoefs) &
!$acc& private(row_start,row_end,acol,acoef,xcoef) &
!$acc& gang worker vector_length(32) num_workers(32)
do i=1,a%num_rows
  tmpsum = 0.0d0
  row_start = arow_offsets(i)
  row_end   = arow_offsets(i+1)-1
  !$acc loop vector reduction(+:tmpsum)
  do j=row_start,row_end
    acol = acols(j)
    acoef = acoefs(j)
    xcoef = x(acol)
    tmpsum = tmpsum + acoef*xcoef
  enddo
  y(i) = tmpsum
enddo
```



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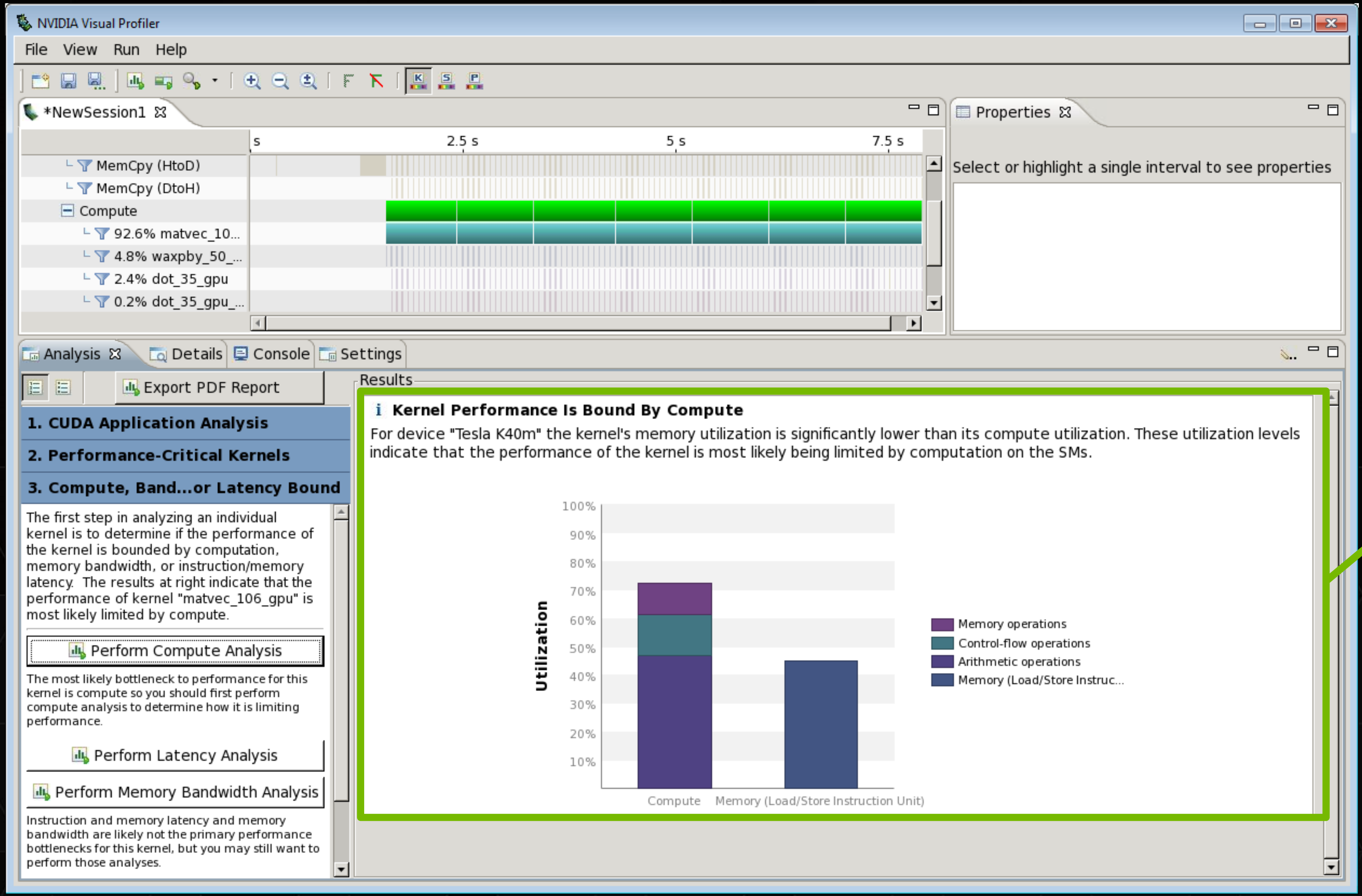
PERFORMANCE LIMITER: COMPUTE



Now we're compute bound

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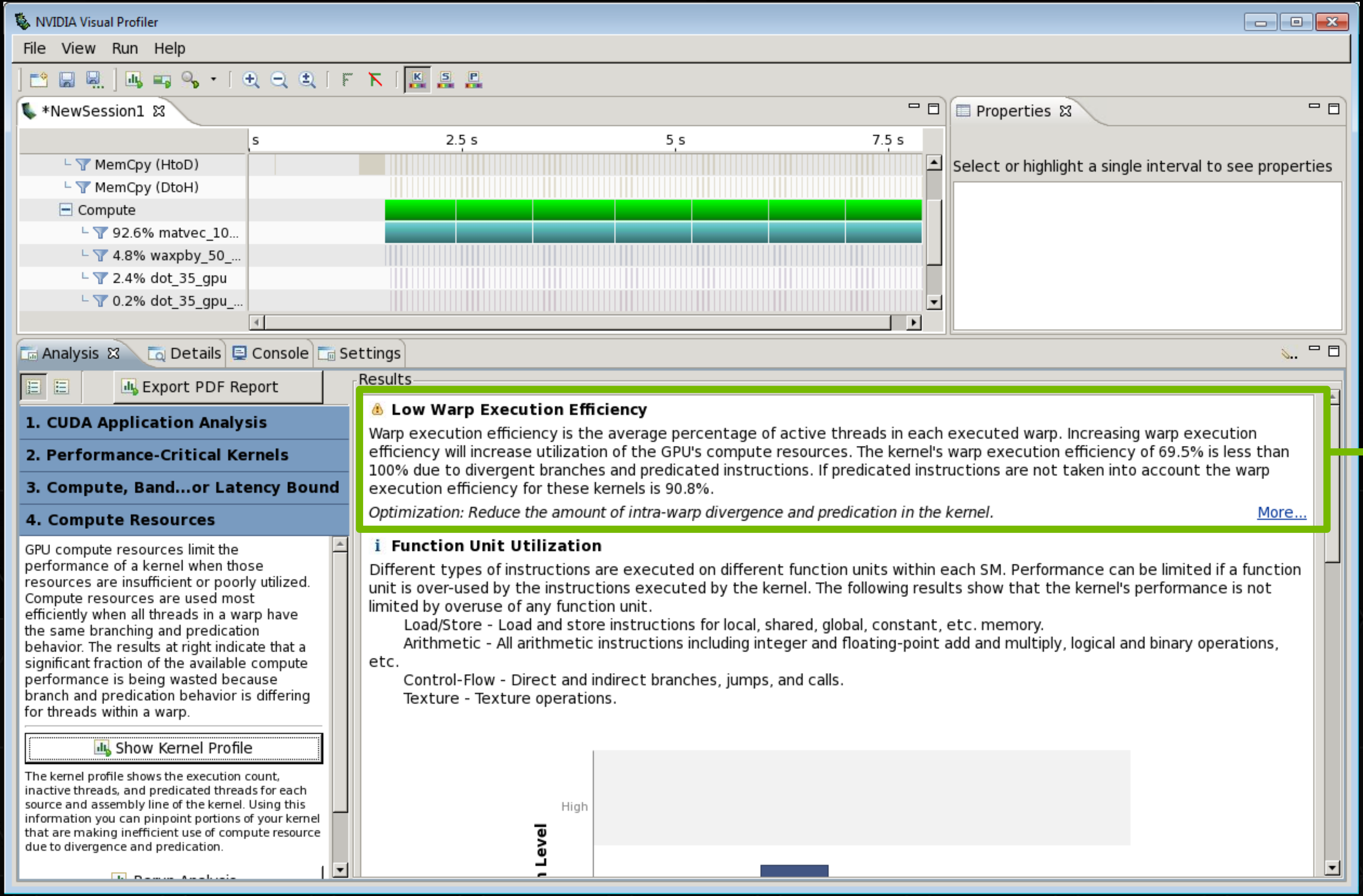
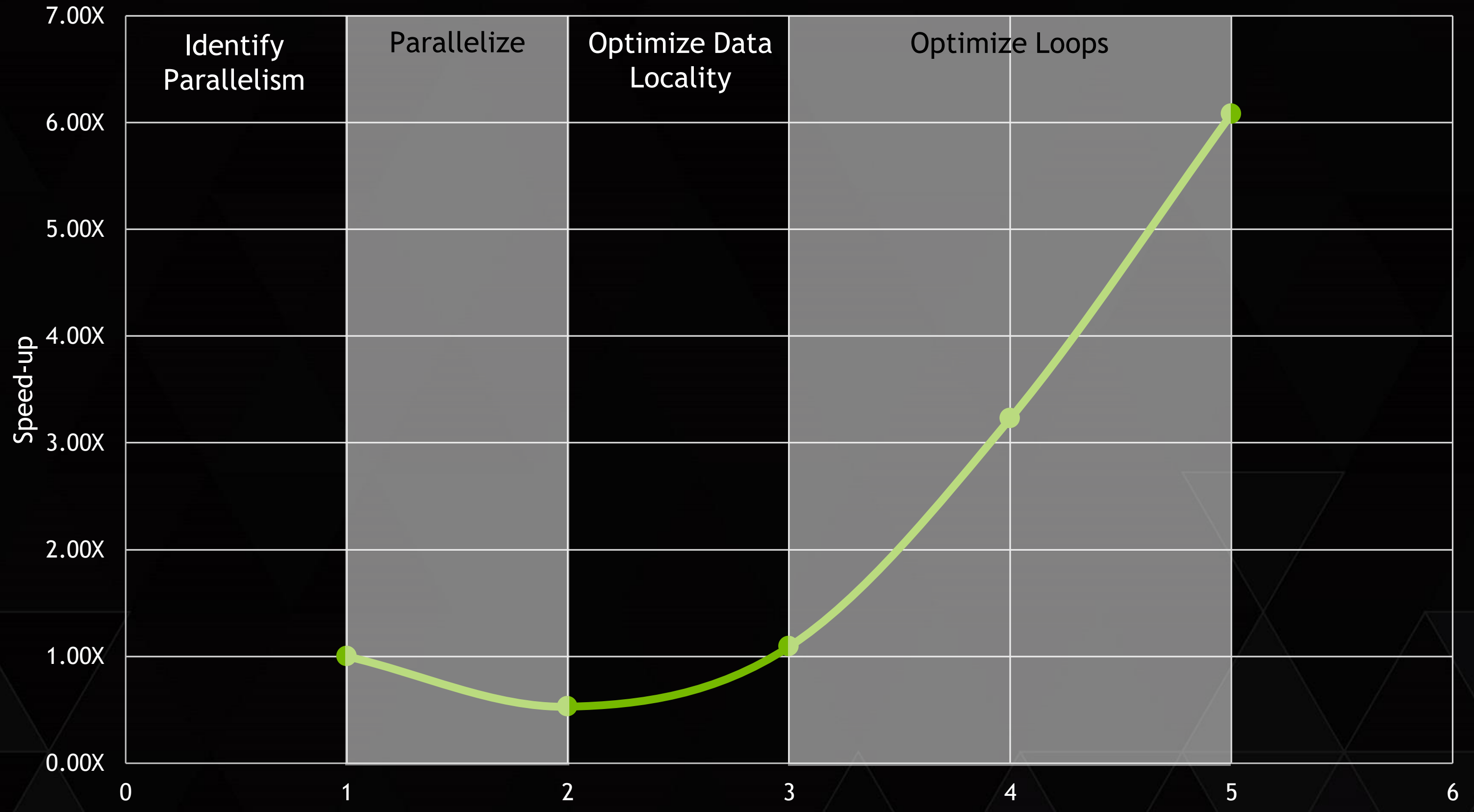
PERFORMANCE LIMITER: PARALLELISM



Really, we're limited by parallelism per-row.

SPEED-UP STEP BY STEP



OPENACC COLLAPSE CLAUSE

collapse(n): Transform the following *n* tightly nested loops into one, flattened loop.

- Useful when individual loops lack sufficient parallelism or more than 3 loops are nested (gang/worker/vector)

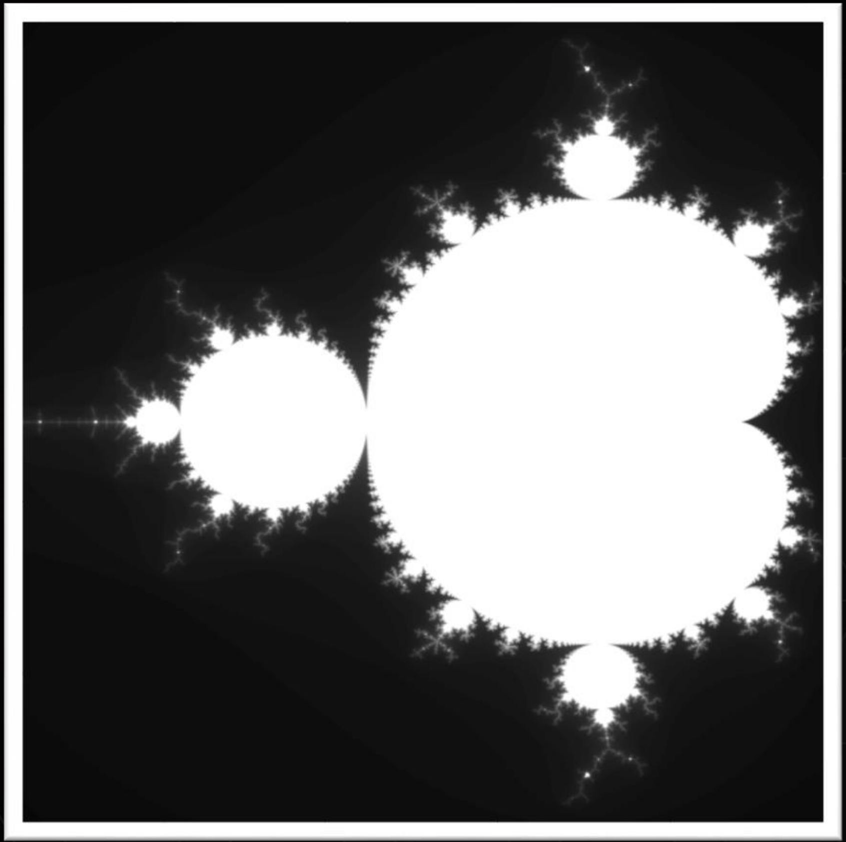
```
#pragma acc parallel
#pragma acc loop collapse(2)
for(int i=0; i<N; i++)
  for(int j=0; j<N; j++)
    ...
```

```
#pragma acc parallel
#pragma acc loop
for(int ij=0; ij<N*N; ij++)
    ...
```

Loops must be tightly nested

NEW CASE STUDY: MANDELBROT SET

- Application generates the image to the right.
- Each pixel in the image can be independently calculated.
- Skills Used:
  - Parallel Loop
  - Data Region
  - Update Directive
  - Asynchronous Pipelining



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MANDELBROT CODE

```
// Calculate value for a pixel
unsigned char mandelbrot(int Px, int Py) {
  double x0=xmin+Px*dx;   double y0=ymin+Py*dy;
  double x=0.0;   double y=0.0;
  for(int i=0;x*x+y*y<4.0 && i<MAX_ITERS;i++) {
    double xtemp=x*x-y*y+x0;
    y=2*x*y+y0;
    x=xtemp;
  }
  return (double)MAX_COLOR*i/MAX_ITERS;
}
 // Used in main()
 for(int y=0;y<HEIGHT;y++) {
    for(int x=0;x<WIDTH;x++) {
      image[y*WIDTH+x]=mandelbrot(x,y);
    }
  }
```

The mandelbrot() function calculates the color for each pixel.

Within main() there is a doubly-nested loop that calculates each pixel independently.

ROUTINES

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OPENACC ROUTINE DIRECTIVE

Specifies that the compiler should generate a device copy of the function/subroutine and what type of parallelism the routine contains.

Clauses:

- `gang/worker/vector/seq`
  - Specifies the level of parallelism contained in the routine.
- `bind`
  - Specifies an optional name for the routine, also supplied at call-site
- `no_host`
  - The routine will only be used on the device
- `device_type`
  - Specialize this routine for a particular device type.

MANDELBROT: ROUTINE DIRECTIVE

```
// mandelbrot.h
#pragma acc routine seq
unsigned char mandelbrot(int Px, int Py);

// Used in main()
#pragma acc parallel loop
for(int y=0;y<HEIGHT;y++) {
  for(int x=0;x<WIDTH;x++) {
    image[y*WIDTH+x]=mandelbrot(x,y);
  }
}
```

- At function source:
  - Function needs to be built for the GPU.
  - It will be called by each thread (sequentially)
- At call the compiler needs to know:
  - Function will be available on the GPU
  - It is a sequential routine

OPENACC ROUTINE: FORTRAN

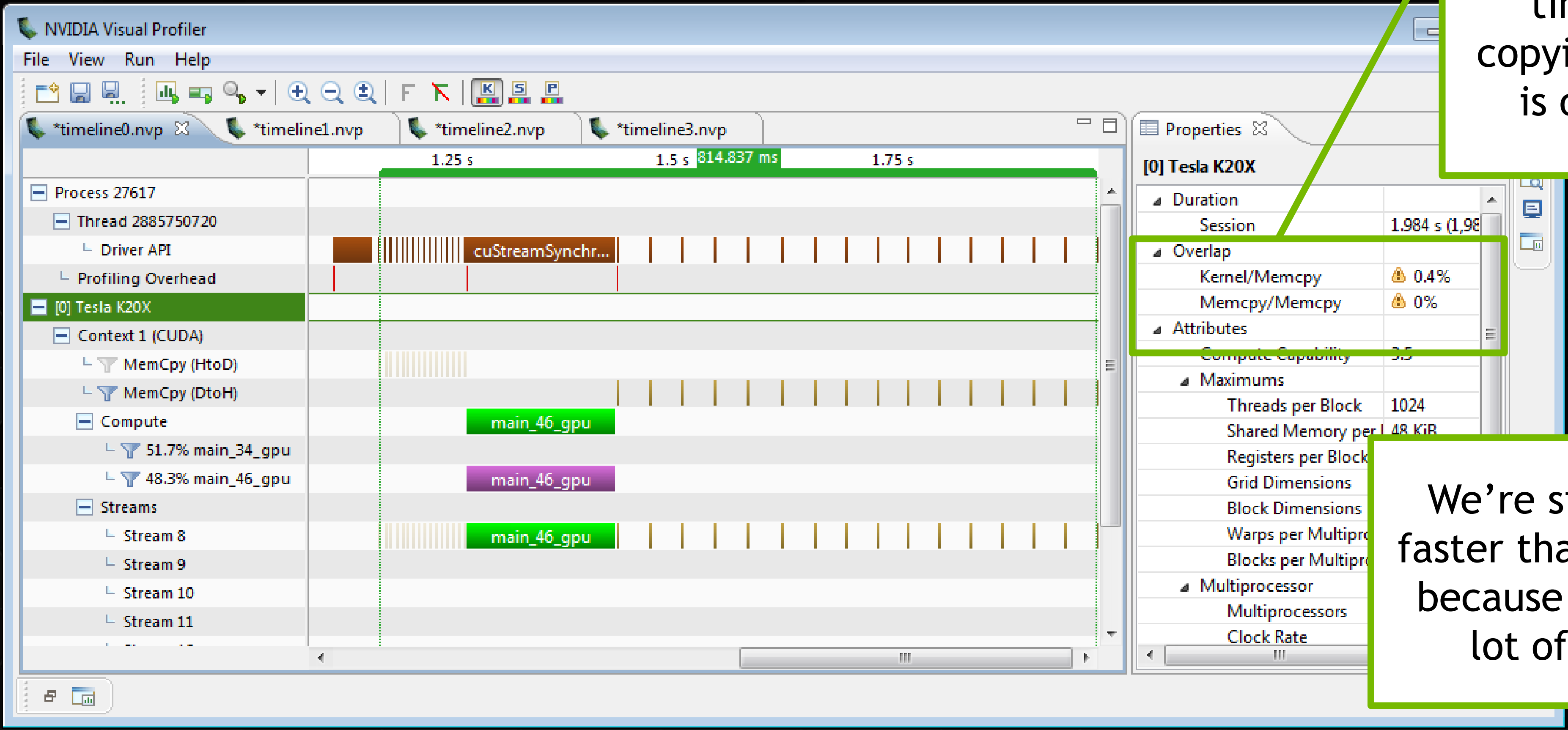
```
module mandelbrot_mod
  implicit none
  integer, parameter :: HEIGHT=16384
  integer, parameter :: WIDTH=16384
  integer, parameter :: MAXCOLORS = 255

contains
 real(8) function mandlebrot(px,py)
    implicit none
    !$acc routine(mandlebrot) seq
    ...
 end function mandlebrot

end module mandelbrot_mod
```

The **routine** directive may appear in a Fortran function or subroutine definition, or in an interface block.

The save attribute is not supported.

Nested acc routines require the routine directive within each nested routine.

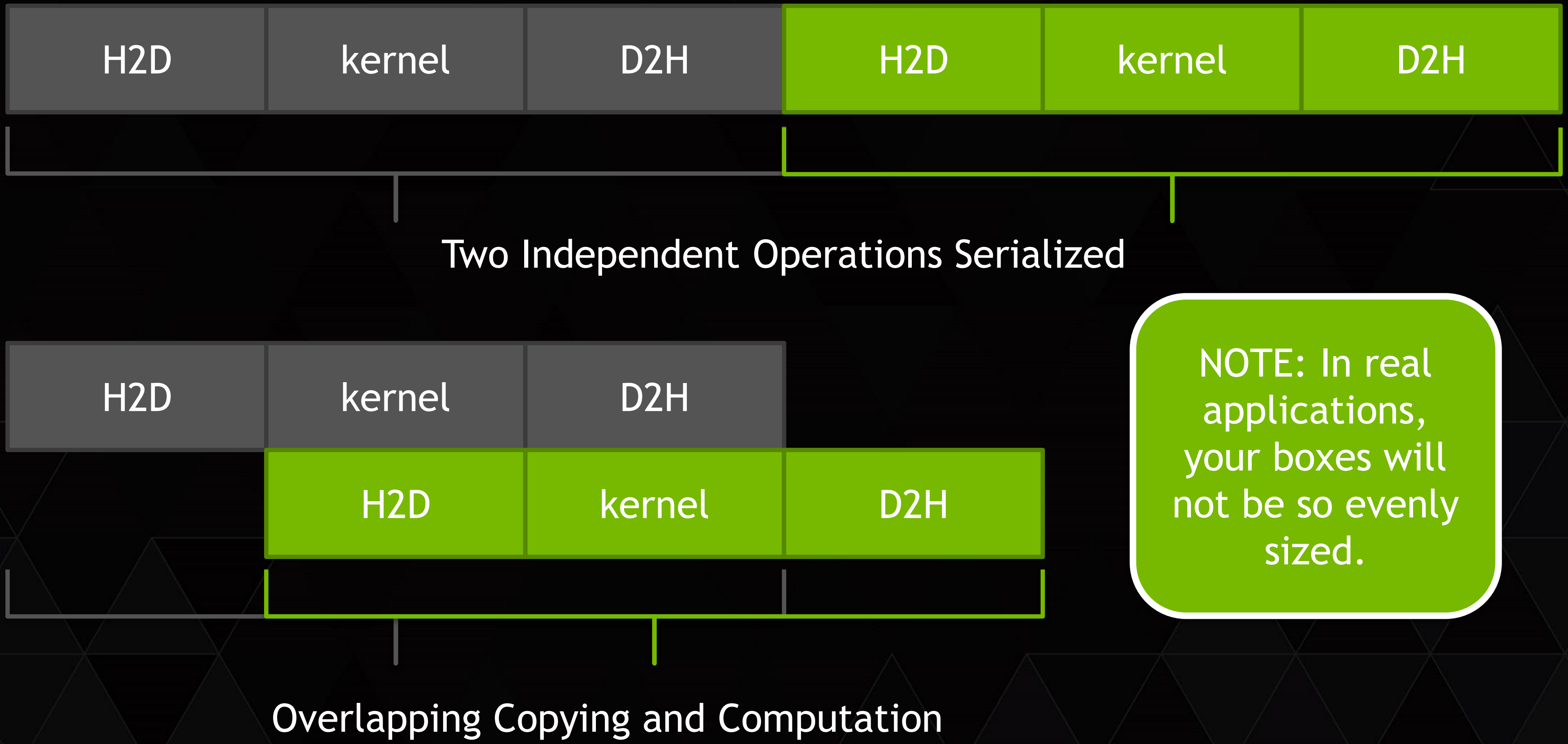
BASELINE PROFILE



Roughly 25% of our time is spent copying, none of it is overlapped.

We're still much faster than the CPU because there's a lot of work.

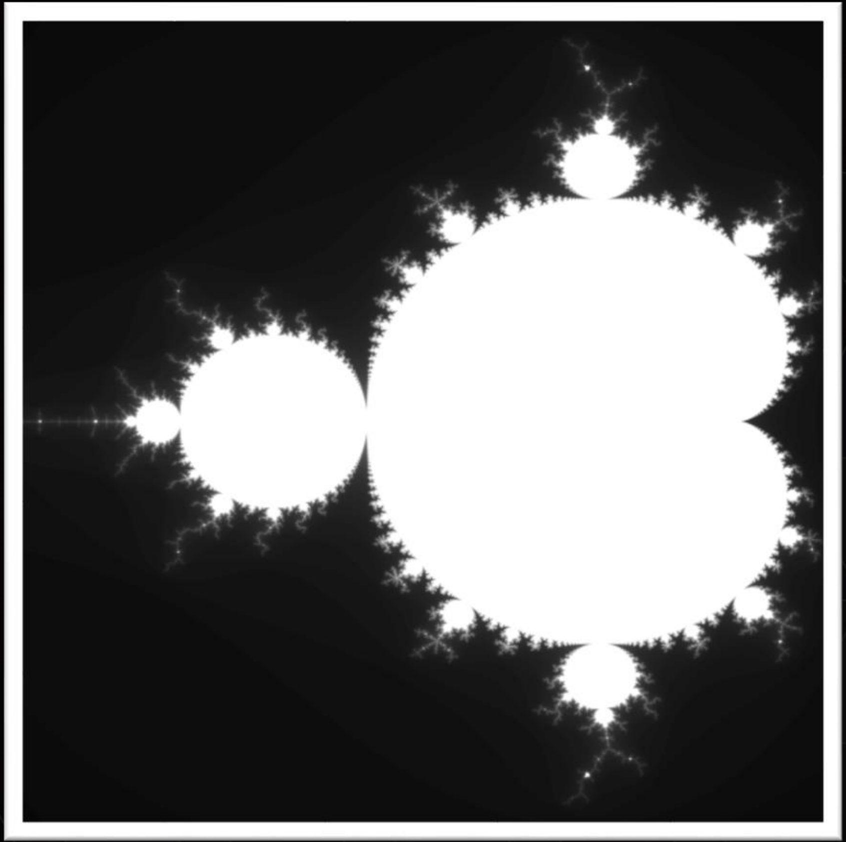
PIPELINING DATA TRANSFERS



NOTE: In real applications, your boxes will not be so evenly sized.

PIPELINING MANDELBROT SET

- We only have 1 kernel, so there's nothing to overlap.
- Since each pixel is independent, computation can be broken up
- Steps
  1. Break up computation into blocks along rows.
  2. Break up copies according to blocks
  3. Make both computation and copies asynchronous

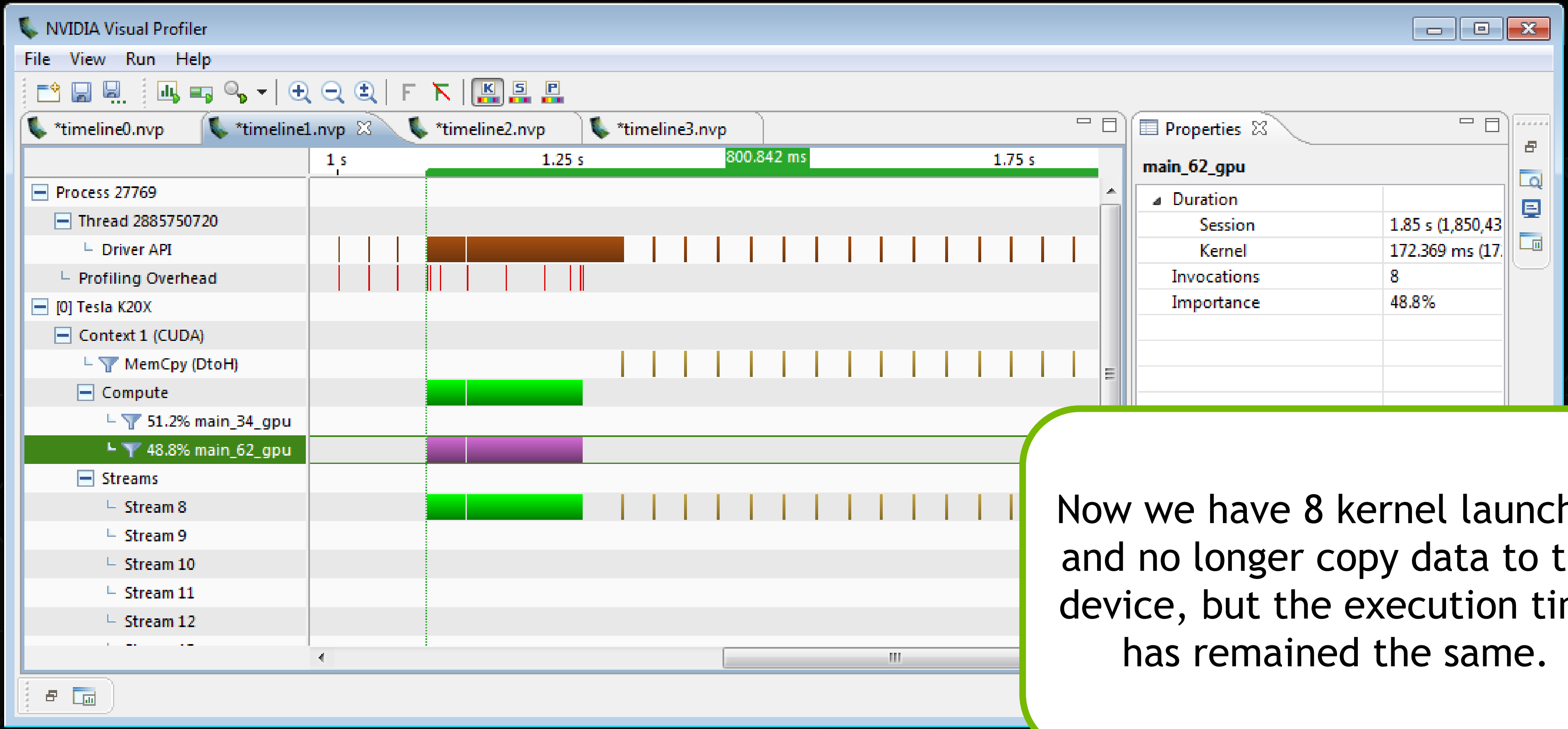


STEP 1: BLOCKING COMPUTATION

```
  numblocks = ( argc > 1 ) ? atoi(argv[1]) : 8;
  blocksize = HEIGHT / numblocks;
  printf("numblocks: %d, blocksize: %d\n",
numblocks, blocksize);

#pragma acc data copyout(image[:bytes])
  for(int block=0; block < numblocks; block++)
  {
    int ystart = block * blocksize;
    int yend   = ystart + blocksize;
#pragma acc parallel loop
    for(int y=ystart;y<yend;y++) {
      for(int x=0;x<WIDTH;x++) {
        image[y*WIDTH+x]=mandelbrot(x,y);
      }
    }
  }
```

- Add a loop over blocks
- Modify the existing row loop to only work within blocks
- Add data region around blocking loop to leave data local to the device.
- Check for correct results.
- NOTE: We don’t need to copy in the array, so make it an explicit copyout.

BLOCKING TIMELINE



Now we have 8 kernel launches and no longer copy data to the device, but the execution time has remained the same.

UPDATE DIRECTIVE

OPENACC DATA REGIONS REVIEW

```
#pragma acc data copyout(image[:bytes])
  for(int block=0; block < numblocks; block++)
  {
    int ystart = block * blocksize;
    int yend   = ystart + blocksize;
#pragma acc parallel loop
    for(int y=ystart;y<yend;y++) {
      for(int x=0;x<WIDTH;x++) {
        image[y*WIDTH+x]=mandelbrot(x,y);
      }
    }
  }
```

Data is shared within this region.

OPENACC UPDATE DIRECTIVE

Programmer specifies an array (or part of an array) that should be refreshed within a data region.

```
do_something_on_device()

!$acc update self(a)

do_something_on_host()

!$acc update device(a)
```

Copy "a" from GPU to CPU

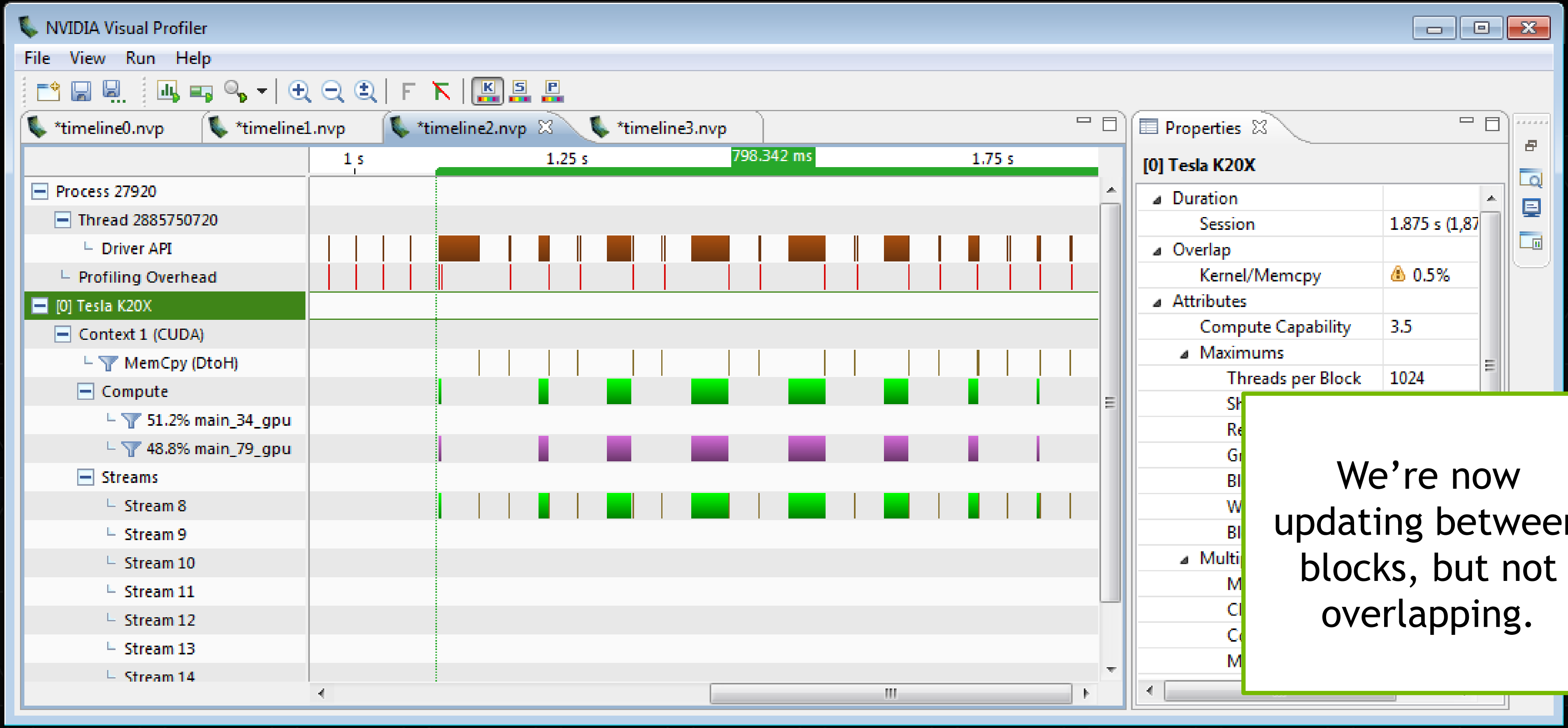
Copy "a" from CPU to GPU

STEP 2: COPY BY BLOCK

```
#pragma acc data create(image[:bytes])
  for(int block=0; block < numblocks; block++)
  {
    int ystart = block * blocksize;
    int yend   = ystart + blocksize;
#pragma acc parallel loop
    for(int y=ystart;y<yend;y++) {
      for(int x=0;x<WIDTH;x++) {
        image[y*WIDTH+x]=mandelbrot(x,y);
      }
    }
#pragma acc update
self(image[ystart*WIDTH:WIDTH*blocksize])
  }
```

- Change the data region to only create the array on the GPU
- Use an update directive to copy individual blocks back to the host when complete
- Check for correct results.

TIMELINE: UPDATING BY BLOCKS



We're now updating between blocks, but not overlapping.

ASYNCHRONOUS PROGRAMMING

OPENACC ASYNC AND WAIT

async(n): launches work asynchronously in queue *n*

wait(n): blocks host until all operations in queue *n* have completed

Can significantly reduce launch latency, enables pipelining and concurrent operations

```
#pragma acc parallel loop async(1)
...
#pragma acc parallel loop async(1)
for(int i=0; i<N; i++)
  ...
#pragma acc wait(1)
for(int i=0; i<N; i++)
```

If *n* is not specified, *async* will go into a default queue and *wait* will wait all previously queued work.

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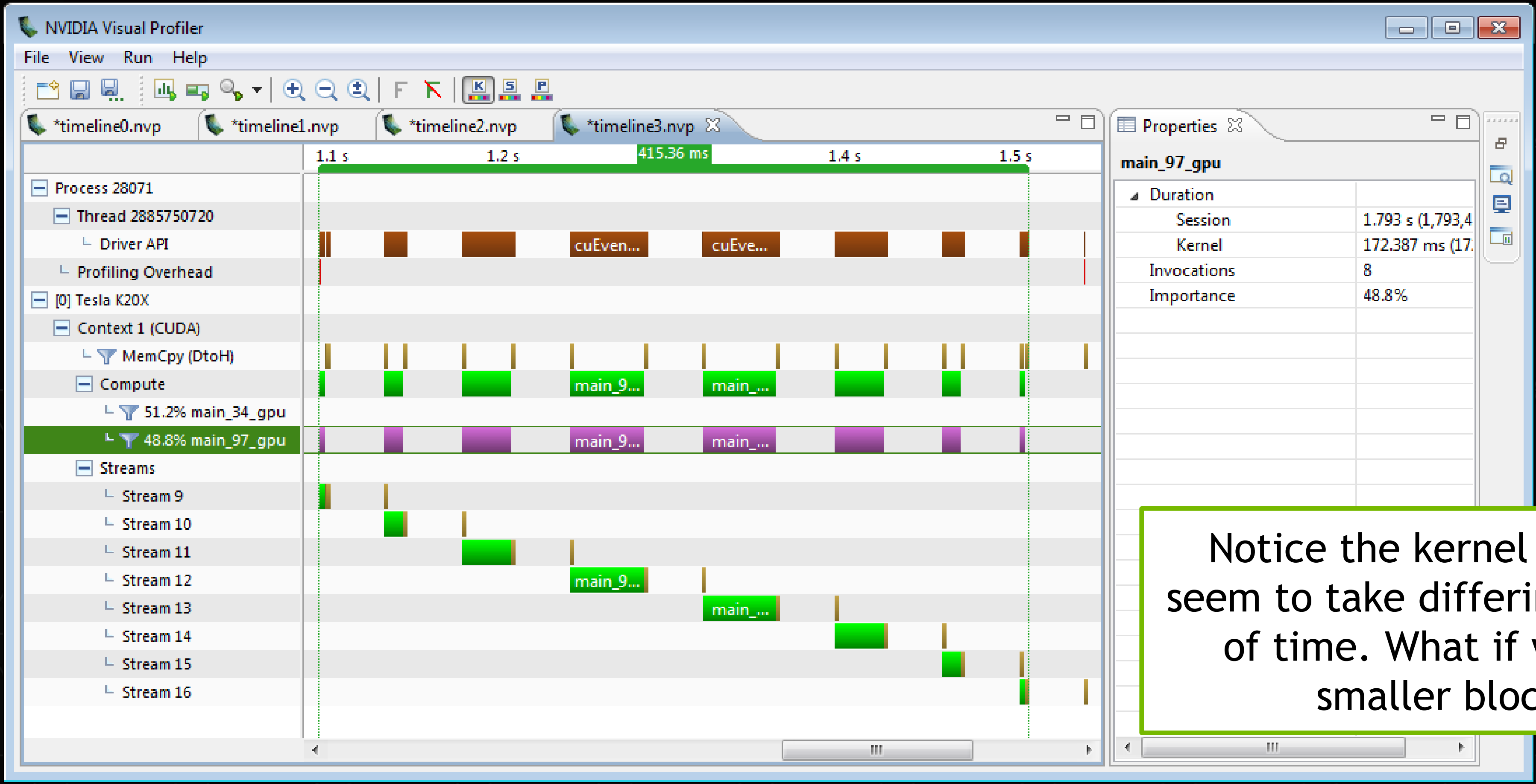
STEP 3: GO ASYNCHRONOUS

```
#pragma acc data create(image[:bytes])
  for(int block=0; block < numblocks; block++)
  {
    int ystart = block * blocksize;
    int yend   = ystart + blocksize;
#pragma acc parallel loop async(block)
    for(int y=ystart;y<yend;y++) {
      for(int x=0;x<WIDTH;x++) {
        image[y*WIDTH+x]=mandelbrot(x,y);
      }
    }
#pragma acc update self(image[ystart*WIDTH:WIDTH*blocksize]) async(block)
  }
#pragma acc wait
```

- Make each parallel region asynchronous by placing in different queues.
- Make each update asynchronous by placing in same stream as the parallel region on which it depends
- Synchronize for all to complete.
- Check for correct results.

TIMELINE: PIPELINING



Notice the kernel launches seem to take differing amounts of time. What if we tried smaller blocks?

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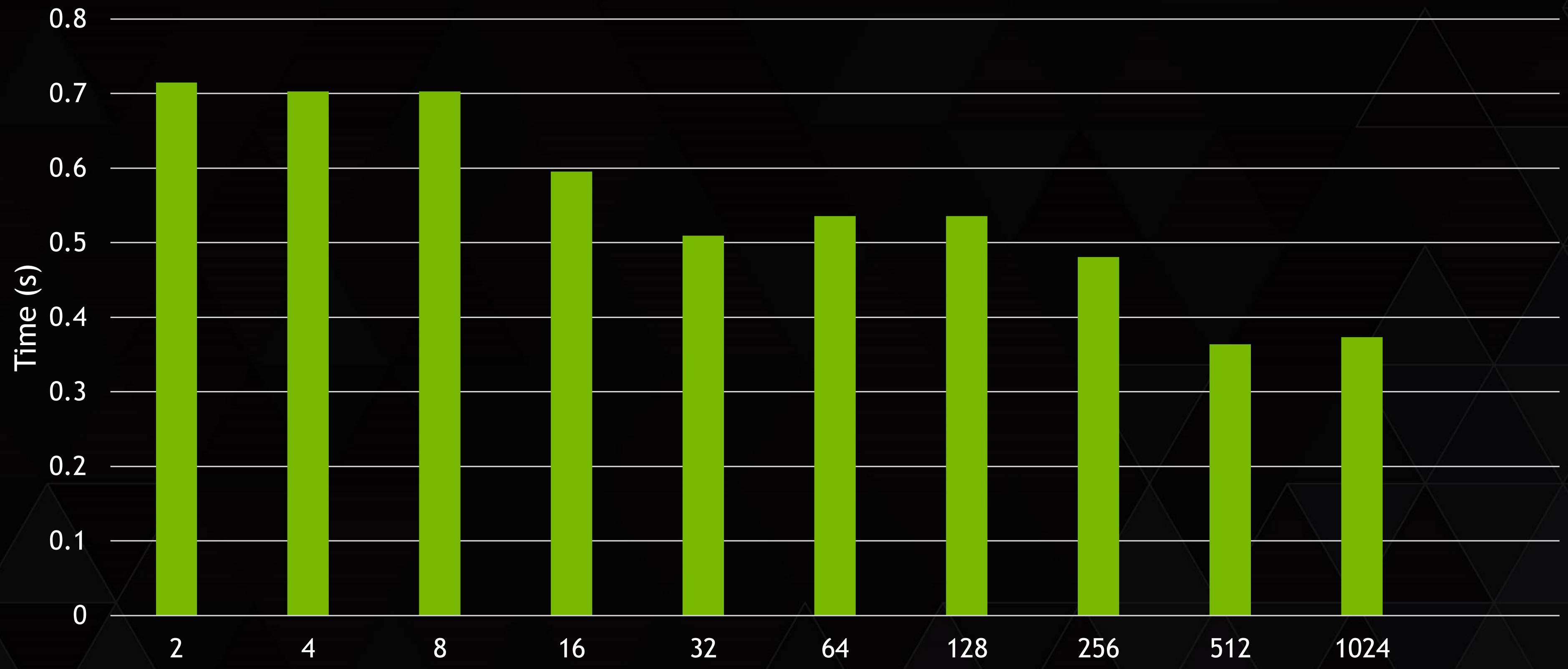
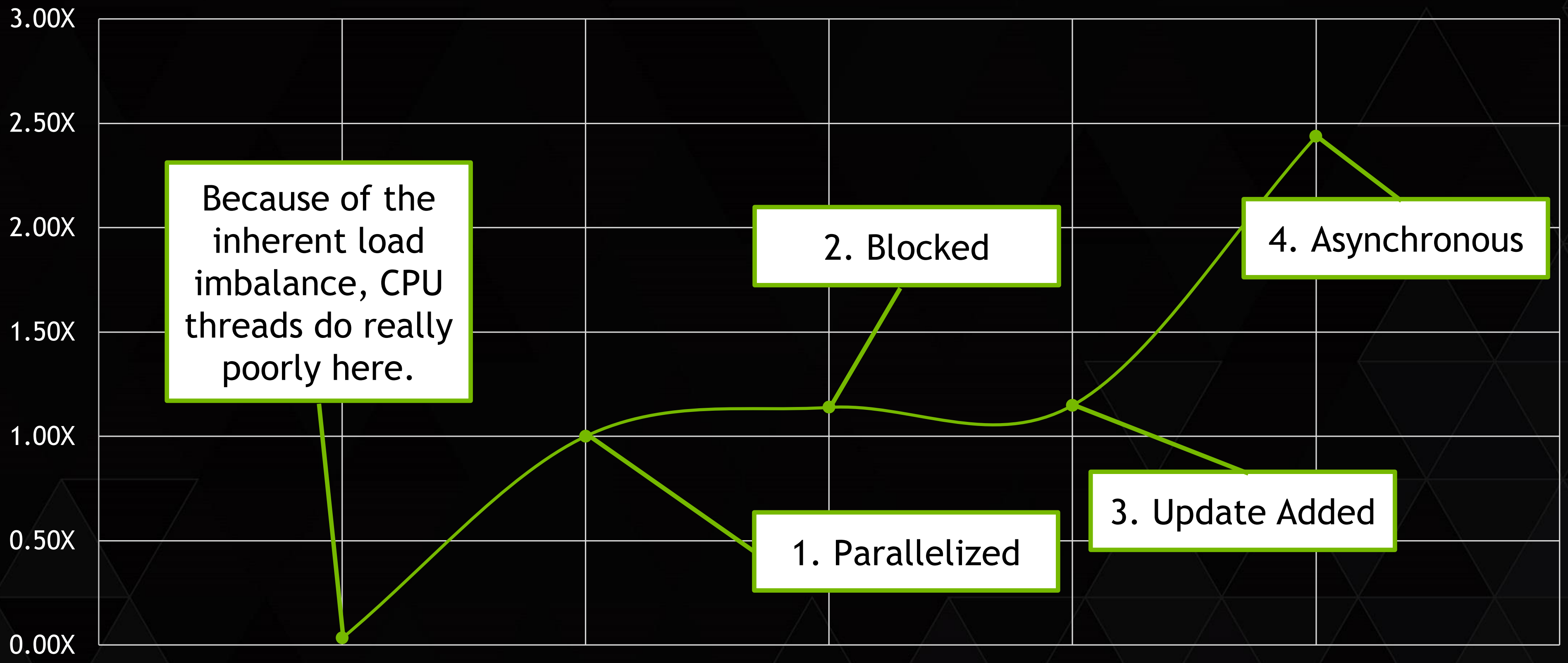
VARYING THE NUMBER OF BLOCKS



SPEED-UP STEP BY STEP



ASYNCHRONOUS TIPS

- Reuse streams, they're expensive to create
  - Pre-create them
  - Consider `async(block%2)` to re-use just 2 streams
- Don't forget to `wait`
- Test with 1 stream first

MULTI-GPU PROGRAMMING

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MULTI-GPU OPENACC

`acc_set_device_num(number, device_type)`

- Selects the device to use for all regions that follow

`acc_get_num_devices(device_type)`

- Queries how many devices are available of a given type

- Most often, one will set a device number once per CPU thread

MULTI-GPU MANDELBROT

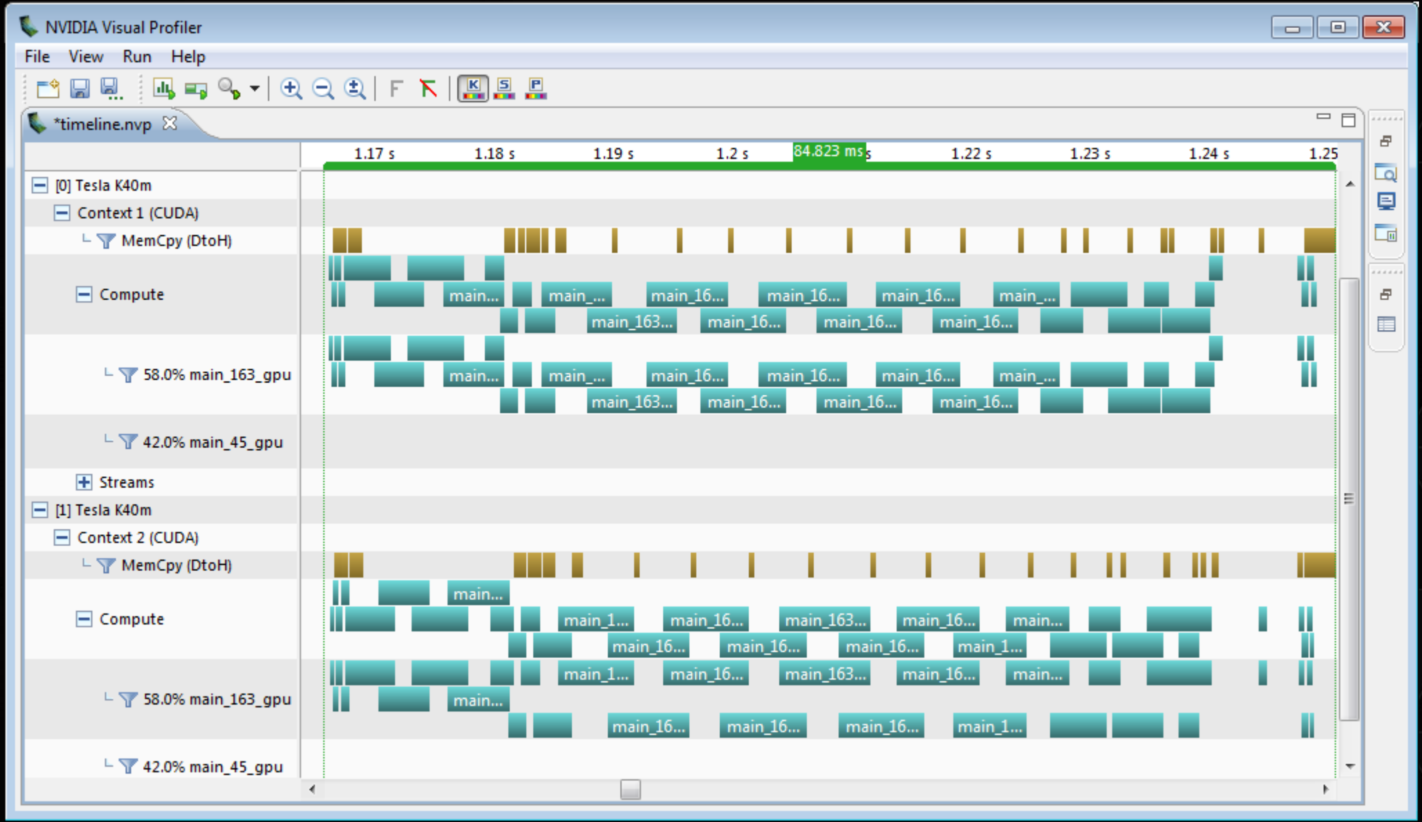
```
 for (int gpu=0; gpu < 2 ; gpu ++)
  {
    acc_set_device_num(gpu,acc_device_nvidia);
#pragma acc enter data create(image[:bytes])
  }

  for(int block=0; block < numblocks; block++)
  {
    int ystart = block * blocksize;
    int yend   = ystart + blocksize;
    acc_set_device_num(block%2,acc_device_nvidia);
#pragma acc parallel loop async(block)
    for(int y=ystart;y<yend;y++) {
      for(int x=0;x<WIDTH;x++) {
        image[y*WIDTH+x]=mandelbrot(x,y);
      }
    }
#pragma acc update self(image[ystart*WIDTH:WIDTH*blocksize]) async(block)
  }
  for (int gpu=0; gpu < 2 ; gpu ++)
  {
    acc_set_device_num(gpu,acc_device_nvidia);
#pragma acc wait
#pragma acc exit data delete(image)
  }
```

Allocate space on each device

Alternate devices per block

Clean up the devices

MULTI-GPU MANDELBROT PROFILE



OPENACC INTEROPERABILITY

OPENACC INTEROPERABILITY

OpenACC plays well with others.

- Add CUDA or accelerated libraries to an OpenACC application
- Add OpenACC to an existing accelerated application
- Share data between OpenACC and CUDA

OPENACC & CUDA STREAMS

OpenACC *suggests* two functions for interoperating with CUDA streams:

- `void* acc_get_cuda_stream( int async );`
- `int acc_set_cuda_stream( int async, void* stream );`

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OPENACC HOST_DATA DIRECTIVE

Exposes the *device* address of particular objects to the *host* code.

```
#pragma acc data copy(x,y)
{
// x and y are host pointers
#pragma acc host_data use_device(x,y)
{
 // x and y are device pointers
}
// x and y are host pointers
}
```

X and Y are device pointers here

HOST_DATA EXAMPLE

OpenACC Main

```
program main
  integer, parameter :: N = 2**20
  real, dimension(N) :: X, Y
  real               :: A = 2.0

  !$acc data
  ! Initialize X and Y
  ...

  !$acc host_data use_device(x,y)
  call saxpy(n, a, x, y)
  !$acc end host_data
  !$acc end data

end program
```

- It's possible to interoperate from C/C++ or Fortran.
- OpenACC manages the data and passes device pointers to CUDA.

CUDA C Kernel & Wrapper

```
__global__
void saxpy_kernel(int n, float a,
      float *x, float *y)
{
  int i = blockIdx.x*blockDim.x + threadIdx.x;
  if (i < n) y[i] = a*x[i] + y[i];
}

void saxpy(int n, float a, float *dx, float *dy)
{
  // Launch CUDA Kernel
  saxpy_kernel<<<4096,256>>>(N, 2.0, dx, dy);
}
```

- CUDA kernel launch wrapped in function expecting device arrays.
- Kernel is launch with arrays passed from OpenACC in main.

CUBLAS LIBRARY & OPENACC

OpenACC can interface with existing GPU-optimized libraries (from C/C++ or Fortran).

This includes…

- CUBLAS
- Libsci_acc
- CUFFT
- MAGMA
- CULA
- Thrust
- …

OpenACC Main Calling CUBLAS

```
int N = 1<<20;
float *x, *y
// Allocate & Initialize X & Y
...

cublasInit();

#pragma acc data copyin(x[0:N]) copy(y[0:N])
{
  #pragma acc host_data use_device(x,y)
  {
    // Perform SAXPY on 1M elements
    cublasSaxpy(N, 2.0, x, 1, y, 1);
  }
}

cublasShutdown();
```

GPU TECHNOLOGY CONFERENCE

OPENACC DEVICEPTR

The `deviceptr` clause informs the compiler that an object is already on the device, so no translation is necessary.

- Valid for `parallel`, `kernels`, and `data`

```
cudaMallocManaged((void*)&x,(size_t)n*sizeof(float));
cudaMallocManaged((void*)&y,(size_t)n*sizeof(float));
```

```
#pragma acc parallel loop deviceptr(x,y)
for(int i=0; i<n ; i++)
{
  y(i) = a*x(i)+y(i)
}
```

Do not translate x and y, they are already on the device.

DEVICEPTR EXAMPLE

OpenACC Kernels

```
void saxpy(int n, float a, float * restrict
x, float * restrict y)
{
#pragma acc kernels deviceptr(x[0:n],y[0:n])
  {
    for(int i=0; i<n; i++)
    {
      y[i] += 2.0*x[i];
    }
  }
}
```

By passing a device pointer to an OpenACC region, it's possible to add OpenACC to an existing CUDA code.

CUDA C Main

```
int main(int argc, char **argv)
{
  float *x, *y, tmp;
  int n = 1<<20, i;

  cudaMalloc((void*)&x,(size_t)n*sizeof(float));
  cudaMalloc((void*)&y,(size_t)n*sizeof(float));

  ...

  saxpy(n, 2.0, x, y);
  cudaMemcpy(&tmp,y,(size_t)sizeof(float),
             cudaMemcpyDeviceToHost);
  return 0;
}
```

Memory is managed via standard CUDA calls.

OPENACC & THRUST

Thrust (thrust.github.io) is a STL-like library for C++ on accelerators.

- High-level interface
- Host/Device container classes
- Common parallel algorithms

It's possible to cast Thrust vectors to device pointers for use with OpenACC

```
void saxpy(int n, float a, float * restrict
x, float * restrict y)
{
#pragma acc kernels deviceptr(x[0:n],y[0:n])
  {
    for(int i=0; i<n; i++)
    {
      y[i] += 2.0*x[i];
    }
  }
}
```

```
int N = 1<<20;
thrust::host_vector<float> x(N), y(N);
for(int i=0; i<N; i++)
{
  x[i] = 1.0f;
  y[i] = 0.0f;
}

// Copy to Device
thrust::device_vector<float> d_x = x;
thrust::device_vector<float> d_y = y;

saxpy(N,2.0, d_x.data().get(),
             d_y.data().get());

// Copy back to host
y = d_y;
```

CUDA DEVICE ROUTINES AND OPENACC

```
extern "C" __device__ void
f1dev( float* a, float* b, int i ){
  a[i] = .... b[i] .... ;
}
```

Even CUDA `__device__` functions can be called from OpenACC if declared with `acc routine`.

```
#pragma acc routine seq
extern "C" void f1dev( float*,
float* int );
...
#pragma acc parallel loop \
  present( a[0:n], b[0:n] )
for( int i = 0; i < n; ++i )
{
  f1dev( a, b, i );
}
```

OPENACC ACC_MAP_DATA FUNCTION

The `acc_map_data` (`acc_unmap_data`) maps (unmaps) an existing device allocation to an OpenACC variable.

```
cudaMalloc((void*)&x_d,(size_t)n*sizeof(float));
acc_map_data(x, x_d, n*sizeof(float));
cudaMalloc((void*)&y_d,(size_t)n*sizeof(float));
acc_map_data(y, y_d, n*sizeof(float));
```

Allocate device arrays with CUDA and *map* to OpenACC

```
#pragma acc parallel loop
for(int i=0; i<n ; i++)
{
  y(i) = a*x(i)+y(i)
}
```

Here x and y will reuse the memory of x_d and y_d

ATOMIC DIRECTIVE

OPENACC ATOMIC DIRECTIVE

atomic: subsequent block of code is performed atomically with respect to other threads on the accelerator

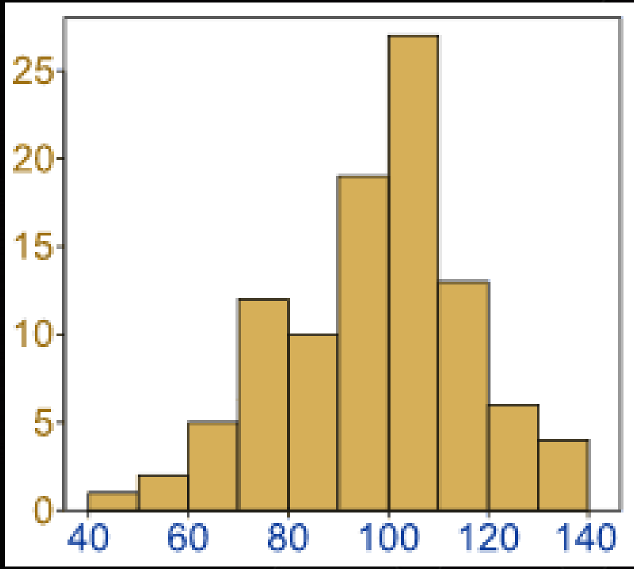
Clauses: read, write, update, capture

```
#pragma acc parallel loop
for(int i=0; i<N; i++) {
  #pragma acc atomic update
  a[i%100]++;
}
```

OPENACC ATOMIC: HISTOGRAM

```
#pragma acc data copyin(a[0:N]) copyout(h[0:HN])
for(int it=0;it<ITERS;it++)
{
  #pragma acc parallel loop
  for(int i=0;i<HN;i++)
    h[i]=0;

  #pragma acc parallel loop
  for(int i=0;i<N;i++) {
    #pragma acc atomic
    h[a[i]]+=1;
  }
}
```



MISC. ADVICE AND TECHNIQUES

WRITE PARALLELIZABLE LOOPS

Use countable loops
- C99: while->for
- Fortran: while->do

```
bool found=false;
while(!found && i<N) {
  if(a[i]==val) {
    found=true
    loc=i;
  }
  i++;
}
```

→

```
bool found=false;
for(int i=0;i<N;i++) {
  if(a[i]==val) {
    found=true
    loc=i;
  }
}
```

Avoid pointer arithmetic (use array syntax)

Write rectangular loops (compiler cannot parallelize triangular loops)

```
for(int i=0;i<N;i++) {
  for(int j=i;j<N;j++) {
    sum+=A[i][j];
  }
}
```

→

```
for(int i=0;i<N;i++) {
  for(int j=0;j<N;j++) {
    if(j>=i)
      sum+=A[i][j];
  }
}
```

C99: RESTRICT KEYWORD

- Declaration of intent given by the programmer to the compiler

    Applied to a pointer, e.g.

    ```
    float *restrict ptr
    ```

    Meaning: “for the lifetime of `ptr`, only it or a value directly derived from it (such as `ptr + 1`) will be used to access the object to which it points”*

- Parallelizing compilers often require `restrict` to determine independence
    - Otherwise the compiler can’t parallelize loops that access `ptr`
    - Note: if programmer violates the declaration, behavior is undefined

~~`float restrict *ptr`~~

`float *restrict ptr`

http://en.wikipedia.org/wiki/Restrict

INLINING

- When possible aggressively inline functions/routines
  - This is especially important for inner loop calculations
  - Inlined routines frequently perform better than acc routines because the compiler has more information.

```
#pragma acc routine seq
inline
int IDX(int row, int col, int LDA) {
  return row*LDA+col;
}
```

KERNEL FUSION

- Kernel calls are expensive
  - Each call can take over 10us in order to launch
  - It is often a good idea to combine loops of same trip counts containing very few lines of code
- Kernel Fusion (i.e. Loop fusion)
  - Join nearby kernels into a single kernel

```
#pragma acc parallel loop
  for (int i = 0; i < n; ++i) {
    a[i]=0;
}
#pragma acc parallel loop
  for (int i = 0; i < n; ++i) {
    b[i]=0;
}
```

→

```
#pragma acc parallel loop
  for (int i = 0; i < n; ++i) {
    a[i]=0;
    b[i]=0;
}
```

LOOP FISSION

- Loops that are exceptionally long may result in kernels that are resource-bound, resulting in low GPU occupancy.
- This is particularly true for outer parallel loops containing nested loops
- Caution: This may introduce temporaries.

```
#pragma acc parallel loop
for (int j = 0; j < m; ++j ) {
  for (int i = 0; i < n; ++i) {
    a[i]=0;
  }
  for (int i = 0; i < n; ++i) {
    b[i]=0;
  }
}
```

→

```
#pragma acc parallel loop
for (int j = 0; j < m; ++j )
  for (int i = 0; i < n; ++i) {
    a[i]=0;
  }
#pragma acc parallel loop
for (int j = 0; j < m; ++j )
  for (int i = 0; i < n; ++i) {
    b[i]=0;
  }
```

MEMORY COALESCING

- *Coalesced* access:
  - A group of 32 contiguous threads ("warp") accessing adjacent words
  - Few transactions and high utilization
- *Uncoalesced* access:
  - A warp of 32 threads accessing scattered words
  - Many transactions and low utilization
- For best performance the vector loop should access memory contiguously (stride-1)

COMPLEX DATA LAYOUTS

- OpenACC works best with flat arrays
- Some compilers handle complex types (structs, classes, derived types) better than others
  - Doesn't always work, particularly if members are dynamically allocated
  - Work around: Use local pointers to struct members (C99 & Fortran)

May work

```
#pragma acc parallel loop \
        copy(a, a.data[0:a.N])
for(i=0;i<a.N;i++)
  a.data[i]=0;
```

Generally Works

```
int N=a.N;
float *data=a.data;
#pragma acc parallel loop \
        copy(data[0:N])
for(i=0;i<N;i++)
  data[i]=0;
```

NEXT STEPS

NEXT STEPS

- Attend more OpenACC sessions at GTC (or go back and watch videos).

S5340	**OpenACC and C++: An Application Perspective**	**Fri 10:30**	**210C**
S5198	Panel on GPU Computing with OpenACC and OpenMP	Fri 11:00	210C

- Try an OpenACC self-paced lab.
- Get a free trial of the PGI Compiler (www.pgroup.com)
- Please remember to fill out your surveys.