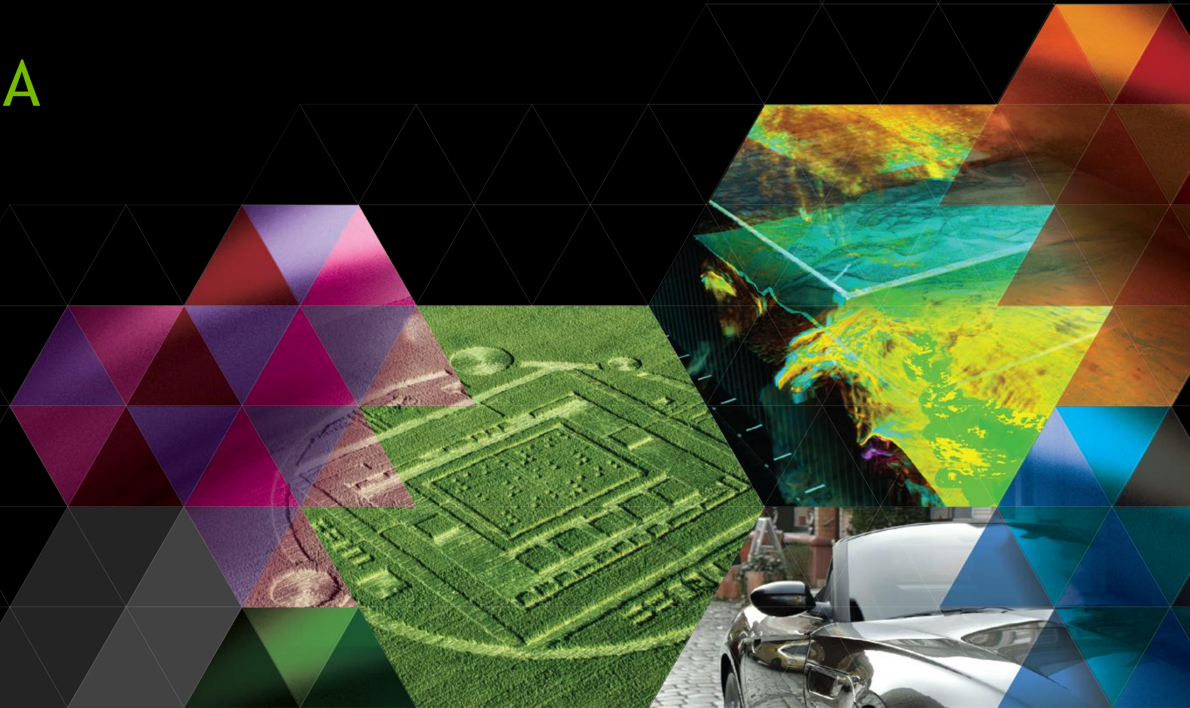
GPU TECHNOLOGY CONFERENCE

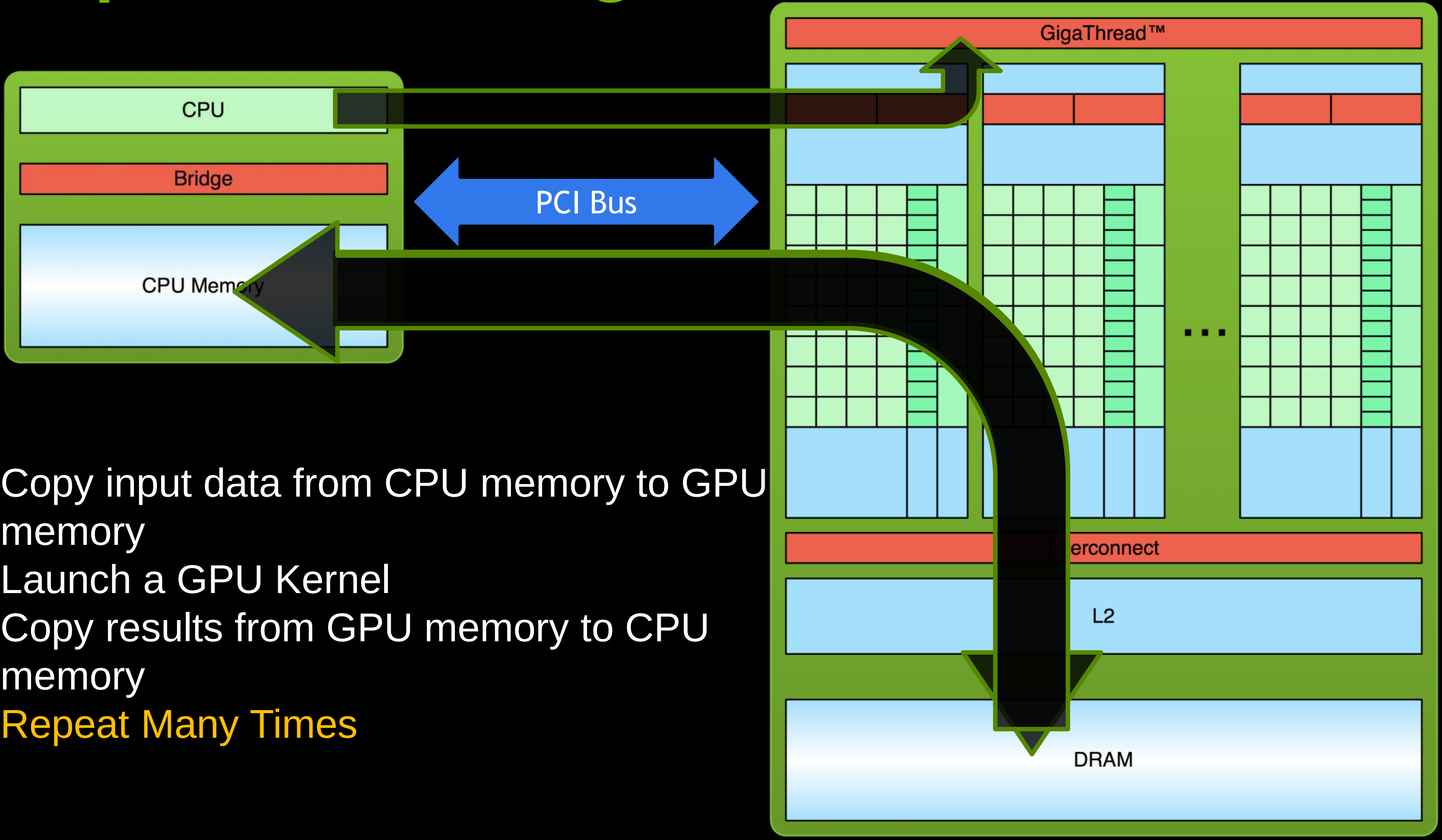
CUDA STREAMS

BEST PRACTICES AND COMMON PITFALLS

Justin Luitjens - NVIDIA



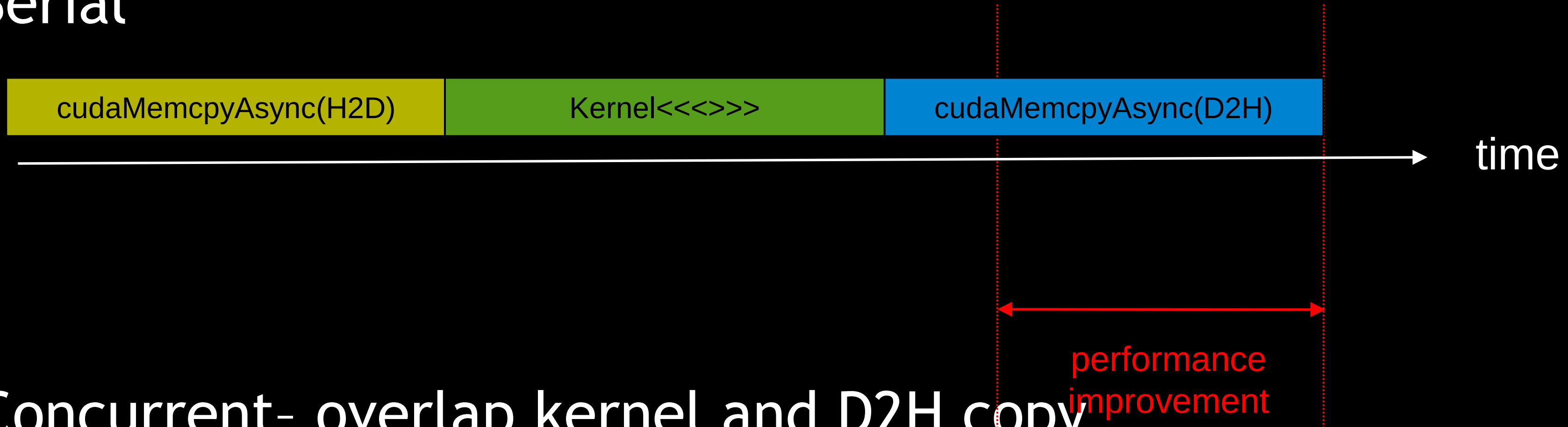
Simple Processing Flow



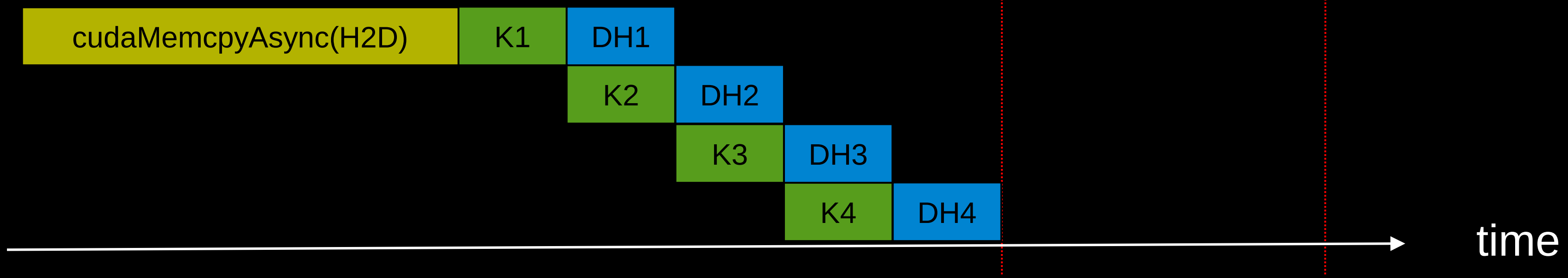
1. Copy input data from CPU memory to GPU memory
2. Launch a GPU Kernel
3. Copy results from GPU memory to CPU memory
4. Repeat Many Times

CONCURRENCY THROUGH PIPELINING

- Serial



- Concurrent– overlap kernel and D2H copy



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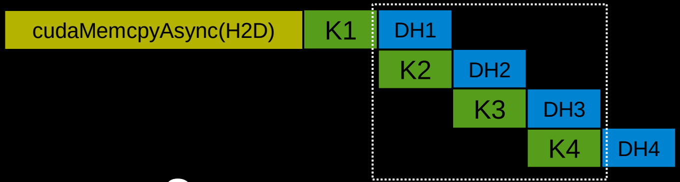
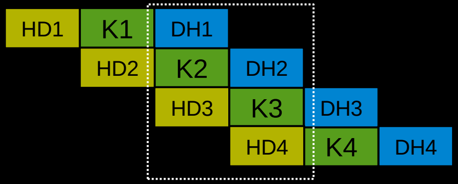
CONCURRENCY THROUGH PIPELINING

- Serial (1x)

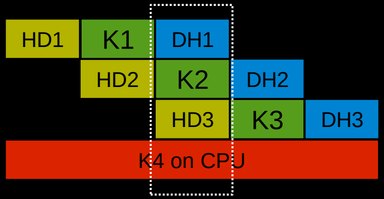
- 2-way concurrency (up to 2x)



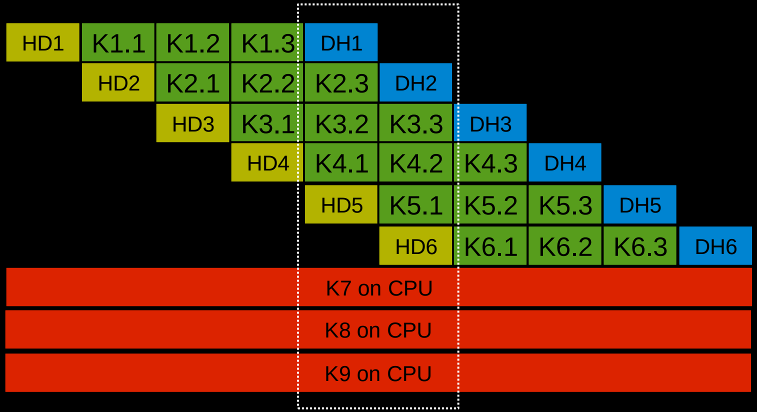
- 3-way concurrency (up to 3x)



- **4-way concurrency** (3x+)



- **4+ way concurrency**

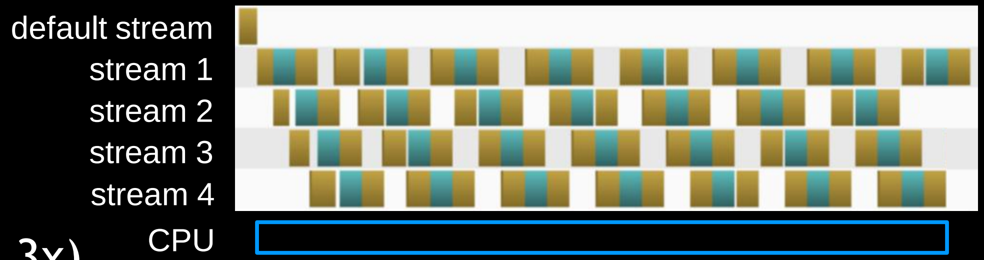


EXAMPLE – TILED DGEMM

- CPU (dual 6 core SandyBridge E5-2667 @2.9 Ghz, MKL)
  - 222 Gflop/s
- GPU (K20X)
  - Serial: 519 Gflop/s (2.3x)
  - 2-way: 663 Gflop/s (3x)
  - 3-way: 990 Gflop/s (4x)
- GPU + CPU
  - 4-way con.: 1180 Gflop/s (5.3x)
- Obtain maximum performance by leveraging concurrency
- All PCI-E traffic is hidden
  - Effectively removes device memory size limitations!

DGEMM: m=n=16384, k=1408

Nvidia Visual Profiler (nvvp)



Enabling Concurrency with MPS

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MULTI-PROCESS SERVICE (MPS)

- Background:
  - Each process has a unique context.
  - Only a single context can be active on a device at a time.
  - Multiple processes (e.g. MPI) on a single GPU could not operate concurrently
- MPS: Software layer that sits between the driver and your application.
  - Routes all CUDA calls through a single context
  - Multiple processes can execute concurrently

MULTI-PROCESS SERVICE (CONT)

- Advantages:
  - Oversubscribe MPI processes and concurrency occurs automatically
    - E.g. 1 MPI process per core sharing a single GPU
  - Simple and natural path to acceleration (especially if your application is MPI ready)
- Disadvantage:
  - MPS adds extra launch latency
  - Not supported on older hardware (Kepler and newer)
  - Linux Only

ENABLING CONCURRENCY WITH STREAMS

SYNCHRONICITY IN CUDA

- All CUDA calls are either synchronous or asynchronous w.r.t the host
  - Synchronous: enqueue work and wait for completion
  - Asynchronous: enqueue work and return immediately
- Kernel Launches are asynchronous Automatic overlap with host

CUDA STREAMS

- A stream is a queue of device work
  - The host places work in the queue and continues on immediately
  - Device schedules work from streams when resources are free
- CUDA operations are placed within a stream
  - e.g. Kernel launches, memory copies
- Operations within the same stream are ordered (FIFO) and cannot overlap
- Operations in different streams are unordered and can overlap

MANAGING STREAMS

- `cudaStream_t stream;`
  - Declares a stream handle
- `cudaStreamCreate(&stream);`
  - Allocates a stream
- `cudaStreamDestroy(stream);`
  - Deallocates a stream
  - Synchronizes host until work in stream has completed

PLACING WORK INTO A STREAM

- Stream is the 4th launch parameter
  - kernel<<< blocks , threads, smem, stream>>>();
- Stream is passed into some API calls
  - cudaMemcpyAsync(dst, src, size, dir, stream);

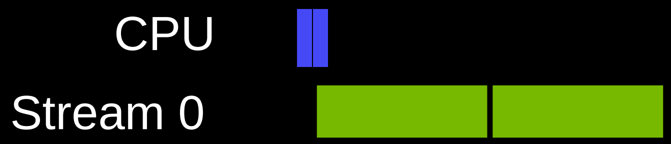
DEFAULT STREAM

- Unless otherwise specified all calls are placed into a default stream
  - Often referred to as “Stream 0”
- Stream 0 has special synchronization rules
  - Synchronous with all streams
    - Operations in stream 0 cannot overlap other streams
- Exception: Streams with non-blocking flag set
  - `cudaStreamCreateWithFlags(&stream,cudaStreamNonBlocking)`
  - Use to get concurrency with libraries out of your control (e.g. MPI)

KERNEL CONCURRENCY

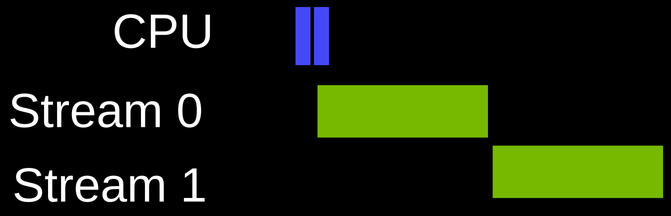
- Assume foo only utilizes 50% of the GPU
- Default stream

```
foo<<<blocks,threads>>>();
foo<<<blocks,threads>>>();
```



- Default & user streams

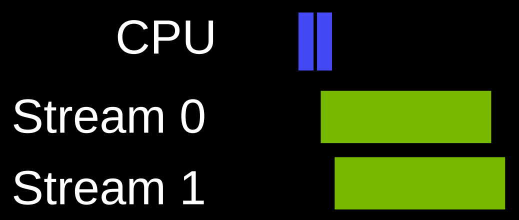
```
cudaStream_t stream1;
cudaStreamCreate(&stream1);
foo<<<blocks,threads>>>();
foo<<<blocks,threads,0,stream1>>>();
cudaStreamDestroy(stream1);
```



KERNEL CONCURRENCY

- Assume foo only utilizes 50% of the GPU
- Default & user streams

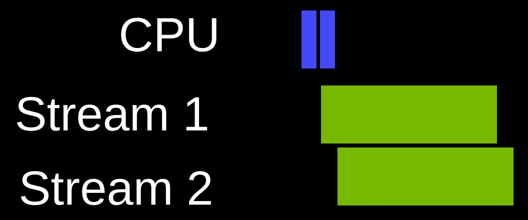
```
cudaStream_t stream1;
cudaStreamCreateWithFlags(&stream1,cudaStreamNonBlocking);
foo<<<blocks,threads>>>();
foo<<<blocks,threads,0,stream1>>>();
cudaStreamDestroy(stream1);
```



KERNEL CONCURRENCY

- Assume foo only utilizes 50% of the GPU
  User streams

```
cudaStream_t stream1, stream2;
cudaStreamCreate(&stream1);
cudaStreamCreate(&stream2);
foo<<<blocks,threads,0,stream1>>>();
foo<<<blocks,threads,0,stream2>>>();
cudaStreamDestroy(stream1);
cudaStreamDestroy(stream2);
```



REVIEW

- The host is automatically asynchronous with kernel launches
- Use streams to control asynchronous behavior
  - Ordered within a stream (FIFO)
  - Unordered with other streams
  - Default stream is synchronous with all streams.

Concurrent Memory Copies

CONCURRENT MEMORY COPIES

- First we must review CUDA memory

THREE TYPES OF MEMORY

- Device Memory
  - Allocated using cudaMalloc
  - Cannot be paged
- Pageable Host Memory
  - Default allocation (e.g. malloc, calloc, new, etc)
  - Can be paged in and out by the OS
- Pinned (Page-Locked) Host Memory
  - Allocated using special allocators
  - Cannot be paged out by the OS

ALLOCATING PINNED MEMORY

- `cudaMallocHost(...) / cudaHostAlloc(...)`
  - Allocate/Free pinned memory on the host
  - Replaces malloc/free/new
- `cudaFreeHost(...)`
  - Frees memory allocated by cudaMallocHost or cudaHostAlloc
- `cudaHostRegister(...) / cudaHostUnregister(...)`
  - Pins/Unpins pagable memory (making it pinned memory)
  - Slow so don't do often
- Why pin memory?
  - Pagable memory is transferred using the host CPU
  - Pinned memory is transferred using the DMA engines
    - Frees the CPU for asynchronous execution
    - Achieves a higher percent of peak bandwidth

CONCURRENT MEMORY COPIES

- `cudaMemcpy(...)`
  - Places transfer into default stream
  - Synchronous: Must complete prior to returning
- `cudaMemcpyAsync(..., &stream)`
  - Places transfer into stream and returns immediately
- To achieve concurrency
  - Transfers must be in a non-default stream
  - Must use async copies
  - 1 transfer per direction at a time
  - Memory on the host must be pinned

PAGED MEMORY EXAMPLE

```
int *h_ptr, *d_ptr;

h_ptr=malloc(bytes);
cudaMalloc(&d_ptr,bytes);

cudaMemcpy(d_ptr,h_ptr,bytes,cudaMemcpyHostToDevice);

free(h_ptr);
cudaFree(d_ptr);
```

PINNED MEMORY: EXAMPLE 1

```
int *h_ptr, *d_ptr;

cudaMallocHost(&h_ptr,bytes);
cudaMalloc(&d_ptr,bytes);

cudaMemcpy(d_ptr,h_ptr,bytes,cudaMemcpyHostToDevice);

cudaFreeHost(h_ptr);
cudaFree(d_ptr);
```

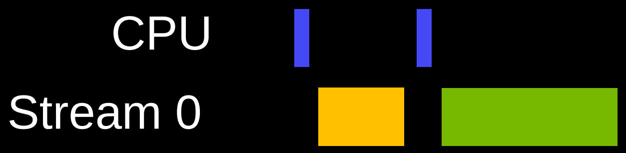
PINNED MEMORY: EXAMPLE 2

```
int *h_ptr, *d_ptr;

h_ptr=malloc(bytes);
cudaHostRegister(h_ptr,bytes,0);
cudaMalloc(&d_ptr,bytes);

cudaMemcpy(d_ptr,h_ptr,bytes,cudaMemcpyHostToDevice);

cudaHostUnregister(h_ptr);
free(h_ptr);
cudaFree(d_ptr);
```

CONCURRENCY EXAMPLES

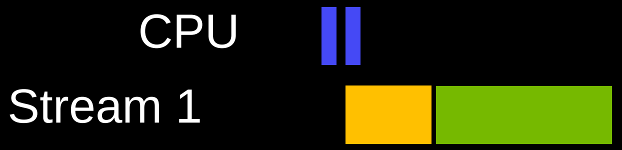
Synchronous

```
cudaMemcpy(...);
foo<<<...>>>();
```



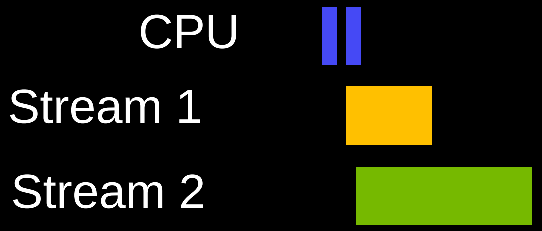
Asynchronous Same Stream

```
cudaMemcpyAsync(...,stream1);
foo<<<...,stream1>>>();
```



Asynchronous Different Streams

```
cudaMemcpyAsync(...,stream1);
foo<<<...,stream2>>>();
```



REVIEW

- Memory copies can execute concurrently if (and only if)
  - The memory copy is in a different non-default stream
  - The copy uses pinned memory on the host
  - The asynchronous API is called
  - There isn't another memory copy occurring in the same direction at the same time.

Synchronization

SYNCHRONIZATION APIS

- Synchronize everything
  - cudaDeviceSynchronize()
    - Blocks host until all issued CUDA calls are complete
- Synchronize host w.r.t. a specific stream
  - cudaStreamSynchronize (stream)
    - Blocks host until all issued CUDA calls in stream are complete
- Synchronize host or devices using events

More Synchronization

Less Synchronization

CUDA EVENTS

- Provide a mechanism to signal when operations have occurred in a stream
  - Useful for profiling and synchronization
- Events have a boolean state:
  - Occurred
  - Not Occurred
  - Important: Default state = occurred

MANAGING EVENTS

- `cudaEventCreate(&event)`
  - Creates an event
- `cudaEventDestroy(&event)`
  - Destroys an event
- `cudaEventCreateWithFlags(&ev, cudaEventDisableTiming)`
  - Disables timing to increase performance and avoid synchronization issues
- `cudaEventRecord(&event, stream)`
  - Set the event state to not occurred
  - Enqueue the event into a stream
  - Event state is set to occurred when it reaches the front of the stream

SYNCHRONIZATION USING EVENTS

- Synchronize using events
  - cudaEventQuery (event)
    - Returns CUDA_SUCCESS if an event has occurred
  - cudaEventSynchronize (event)
    - Blocks host until stream completes all outstanding calls
  - cudaStreamWaitEvent (stream, event)
    - Blocks stream until event occurs
    - Only blocks launches after this call
    - Does not block the host!
- Common multi-threading mistake:
  - Calling cudaEventSynchronize before cudaEventRecord

CUDA_LAUNCH_BLOCKING

- Environment variable which forces sychronization
  - export CUDA_LAUNCH_BLOCKING=1
  - All CUDA operations are synchronous w.r.t the host
- Useful for debugging race conditions
  - If it runs successfully with CUDA_LAUNCH_BLOCKING set but doesn’t without you have a race condition.

REVIEW

- Synchronization with the host can be accomplished via
  - cudaDeviceSynchronize()
  - cudaStreamSynchronize(stream)
  - cudaEventSynchronize(event)
- Synchronization between streams can be accomplished with
  - cudaStreamWaitEvent(stream,event)
- Use CUDA_LAUNCH_BLOCKING to identify race conditions

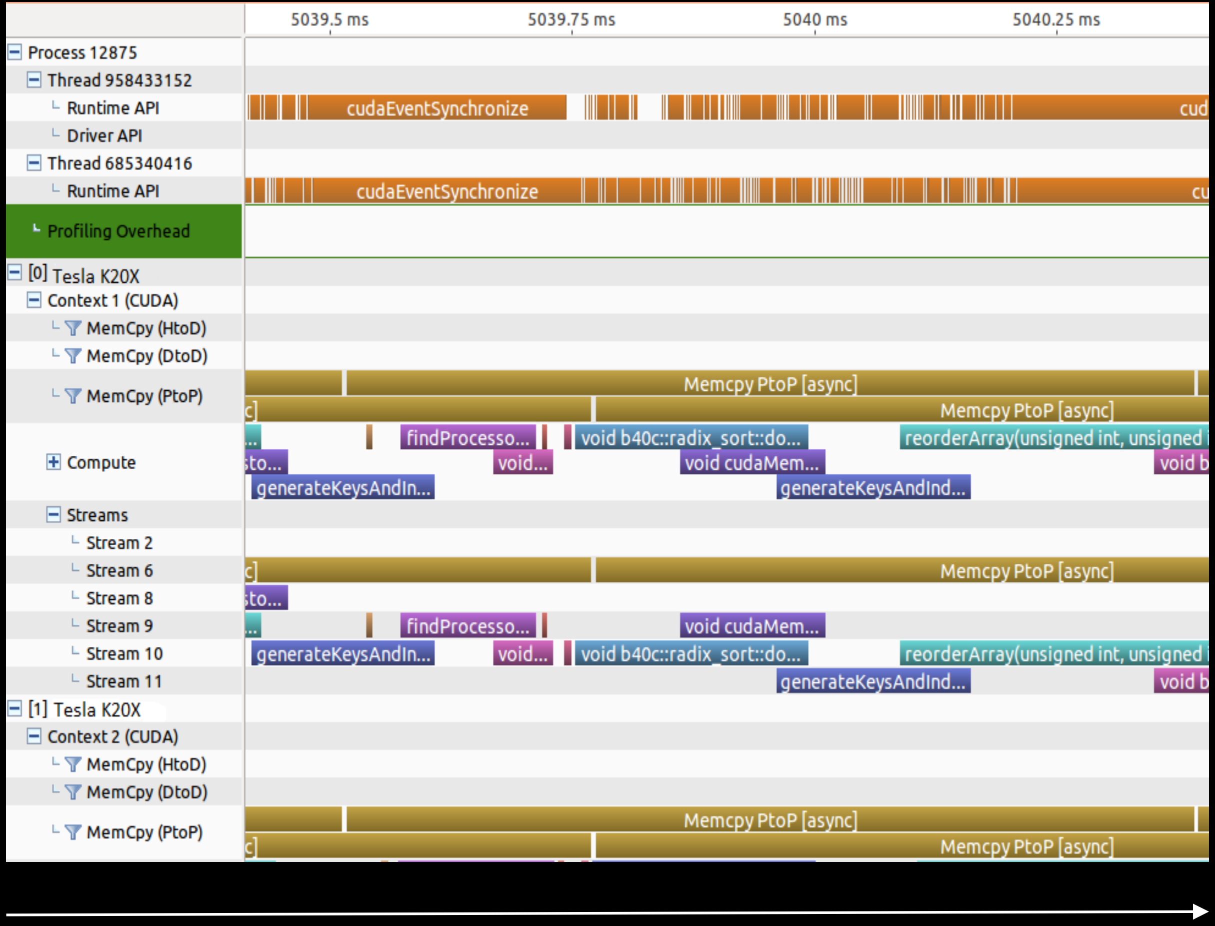
Streaming Performance

PROFILING TOOLS

- Windows
  - Nsight Visual Studio Edition
  - NVIDIA Visual Profiler
- Linux, Mac
  - Nsight Eclipse Edition
  - NVIDIA Visual Profiler
  - nvprof

NVVP PROFILER TIMELINE

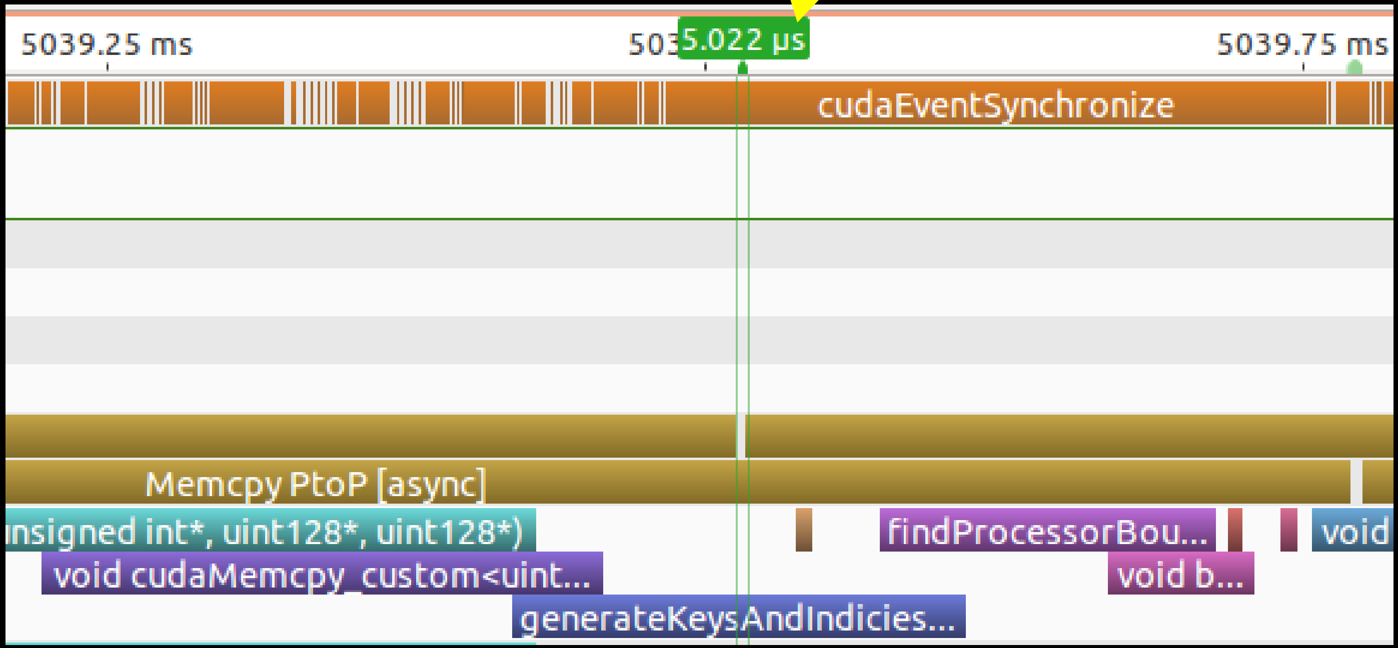
- Host API Calls
- Multi-threaded
- Multi-GPU
- Multi-process
- Kernels
- Memory copies
- Streams



time

OPTIMAL TIMELINE

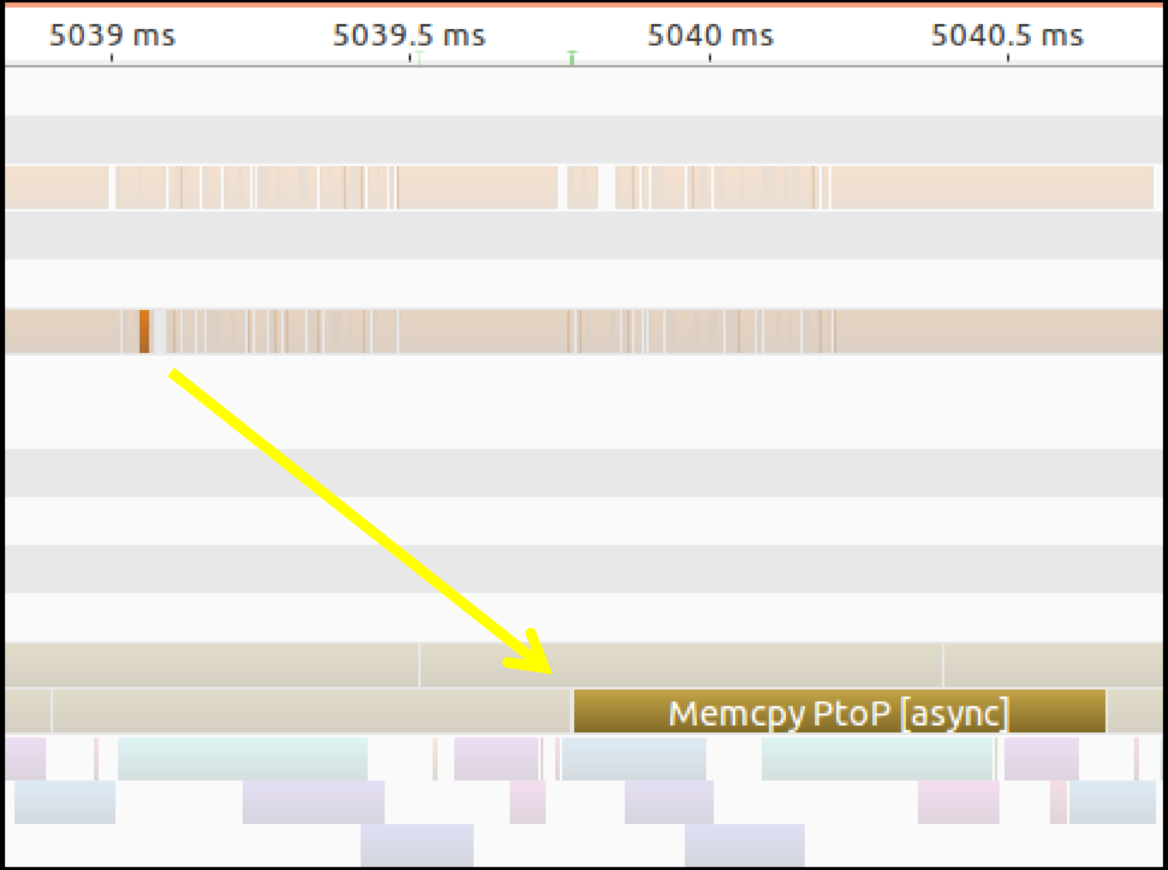
Less than 10 us idle time between successive operations



Concurrent Operations

OPTIMAL TIMELINE

Host is running ahead of the device >30 us



COMMON STREAMING PROBLEMS

COMMON STREAMING PROBLEMS

- The following is an attempt to demonstrate the most common streaming issues I’ve seen in customers applications
- They are loosely ordered according to how common they are

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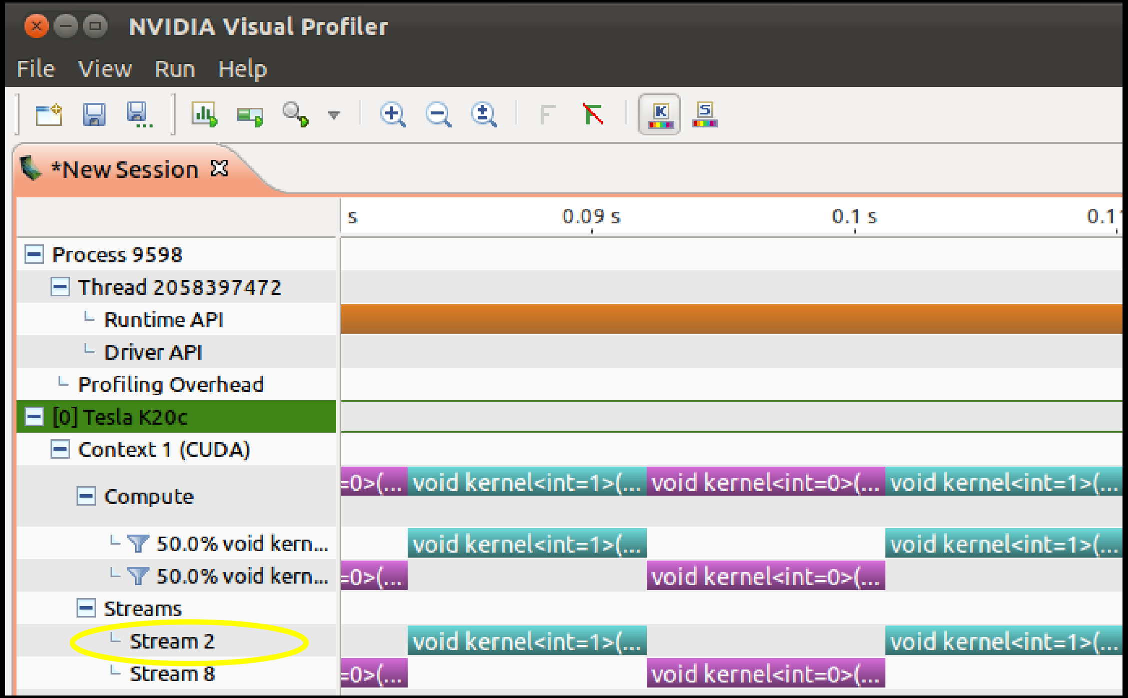
CASE STUDY 1-A

```
for(int i=0;i<repeat;i++)
{
  kernel<<<1,1,0,stream1>>>();
  kernel<<<1,1>>>();
}
```



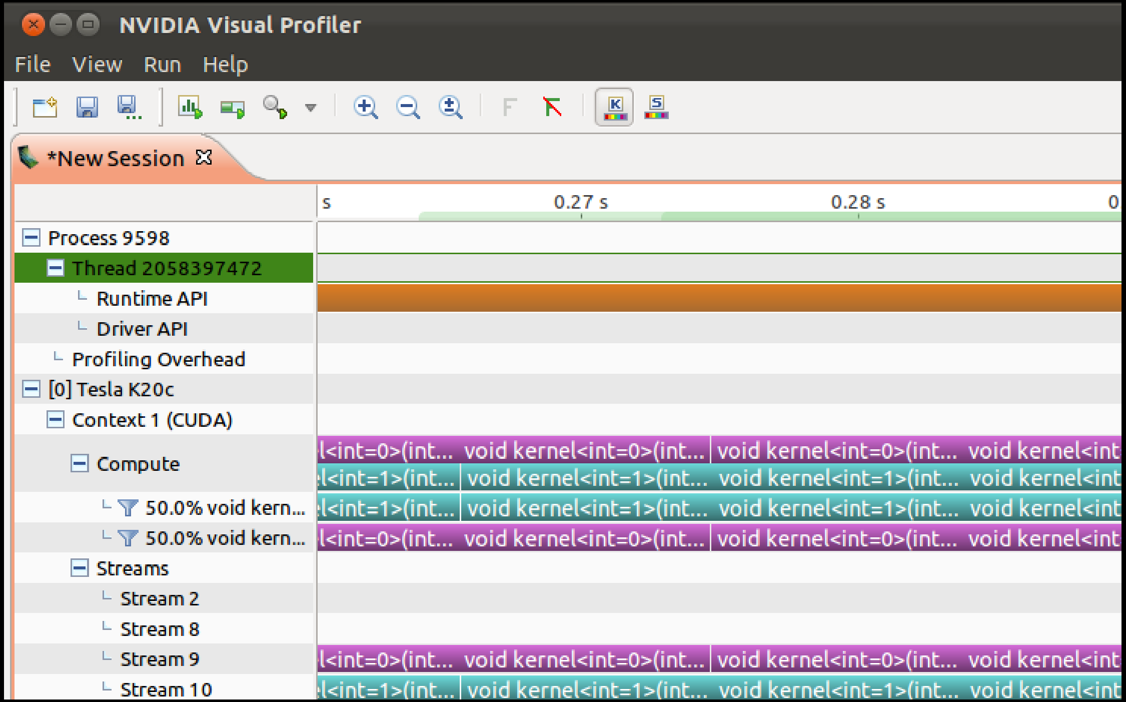
Problem:

One kernel is in the default stream

Stream 2 is the default stream

CASE STUDY 1-A

```
for(int i=0;i<repeat;i++) {
  kernel<<<1,1,0,stream1>>>();
  kernel<<<1,1,0,stream2>>>();
}
```



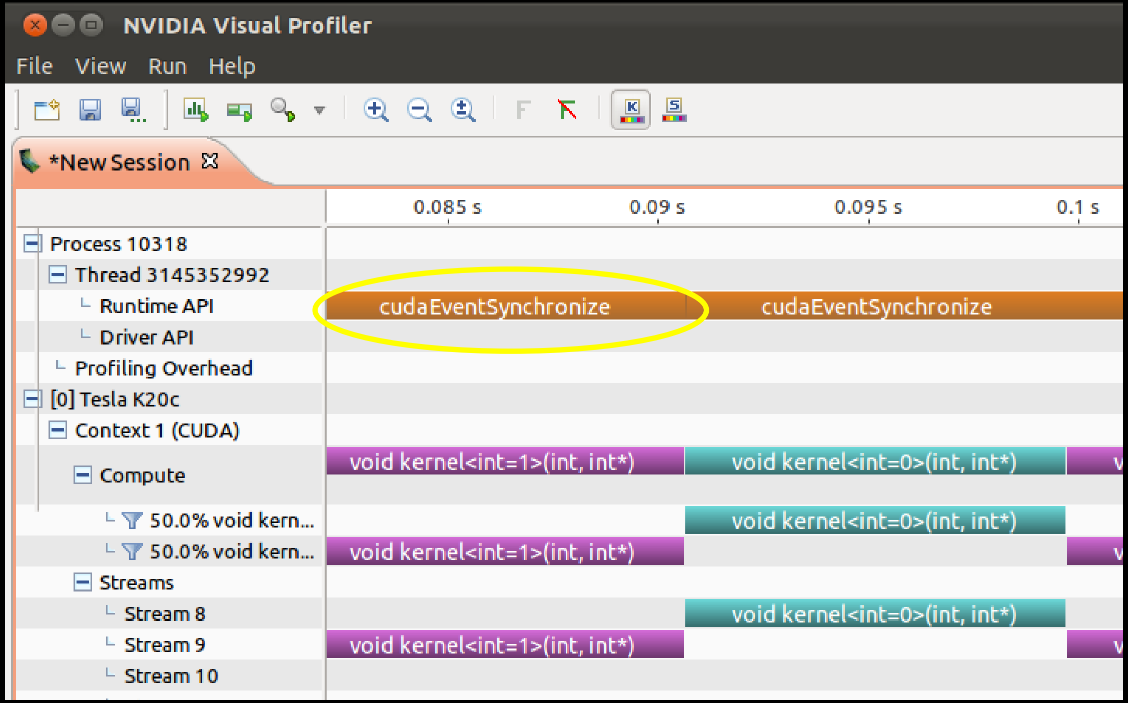
Solution:

Place each kernel in its own stream

CASE STUDY 1-B

```
for(int i=0;i<repeat;i++) {
  kernel<<<1,1,0,stream1>>>();
  cudaEventRecord(event1);
  kernel<<<1,1,0,stream2>>>();
  cudaEventRecord(event2);

  cudaEventSynchronize(event1);
  cudaEventSynchronize(event2);
}
```

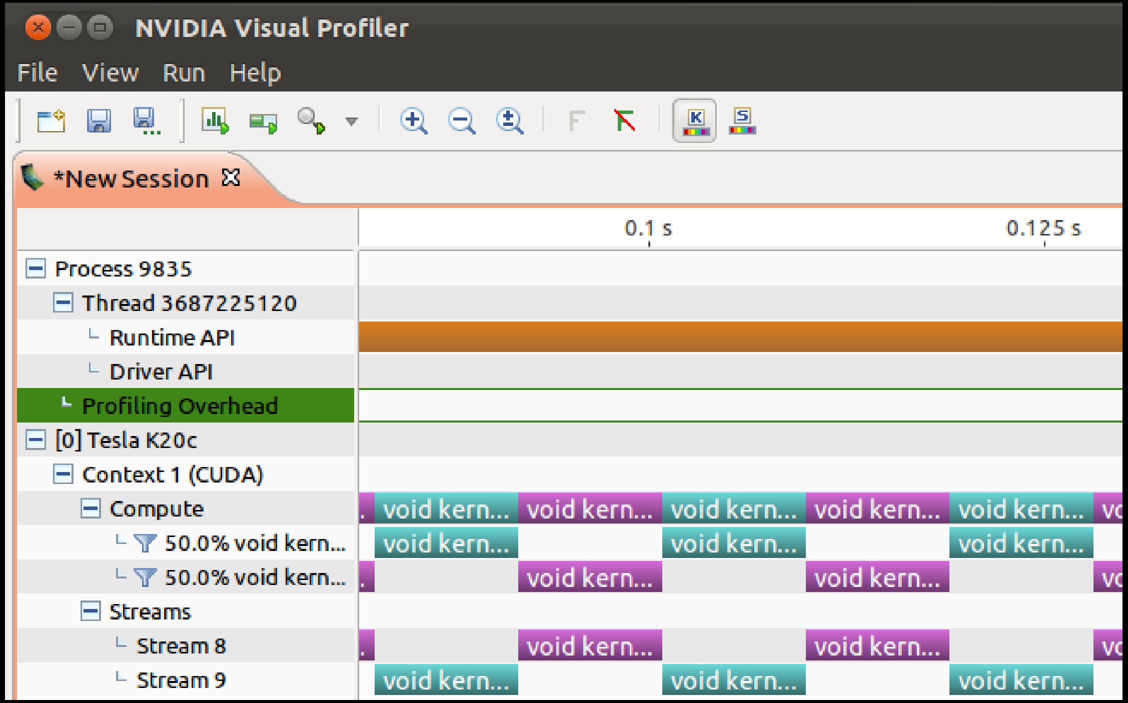


Are events causing the problem?

CASE STUDY 1-B

```
for(int i=0;i<repeat;i++) {
  kernel<<<1,1,0,stream1>>>();
  cudaEventRecord(event1);
  kernel<<<1,1,0,stream2>>>();
  cudaEventRecord(event2);

  cudaEventSynchronize(event1);
  cudaEventSynchronize(event2);
}
```



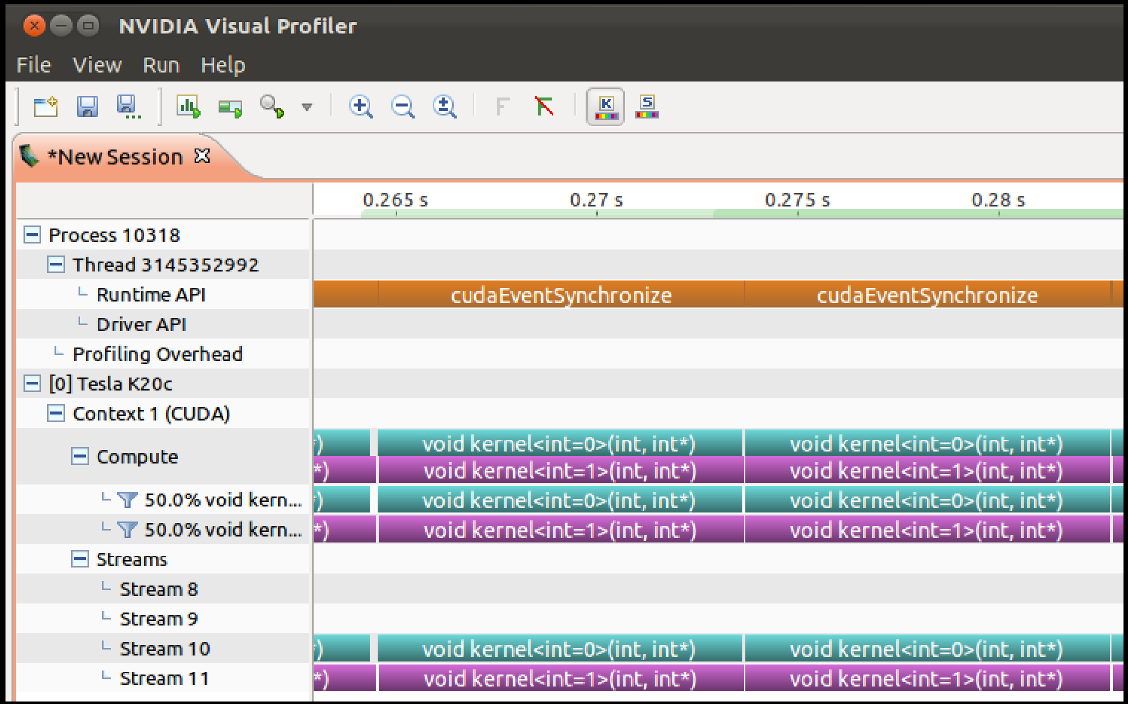
Problem:

cudaEventRecord by without a stream goes into the default stream

CASE STUDY 1-B

```
for(int i=0;i<repeat;i++) {
  kernel<<<1,1,0,stream1>>>();
  cudaEventRecord(event1,stream1);
  kernel<<<1,1,0,stream2>>>();
  cudaEventRecord(event2,stream2);

  cudaEventSynchronize(event1);
  cudaEventSynchronize(event2);
}
```



Solution:

Record events into non-default streams

PROBLEM 1: USING THE DEFAULT STREAM

- Symptoms
  - One stream will not overlap other streams
    - In Cuda 5.0 stream 2 = default stream
  - Search for cudaEventRecord(event) , cudaMemcpyAsync(), etc.
    - If stream is not specified it is placed into the default stream
  - Search for kernel launches in the default stream
    - <<<a,b>>>
- Solutions
  - Move work into a non-default stream
  - cudaEventRecord(event,stream), cudaMemcpyAsync(…,stream)
  - Alternative: Allocate other streams as non-blocking streams

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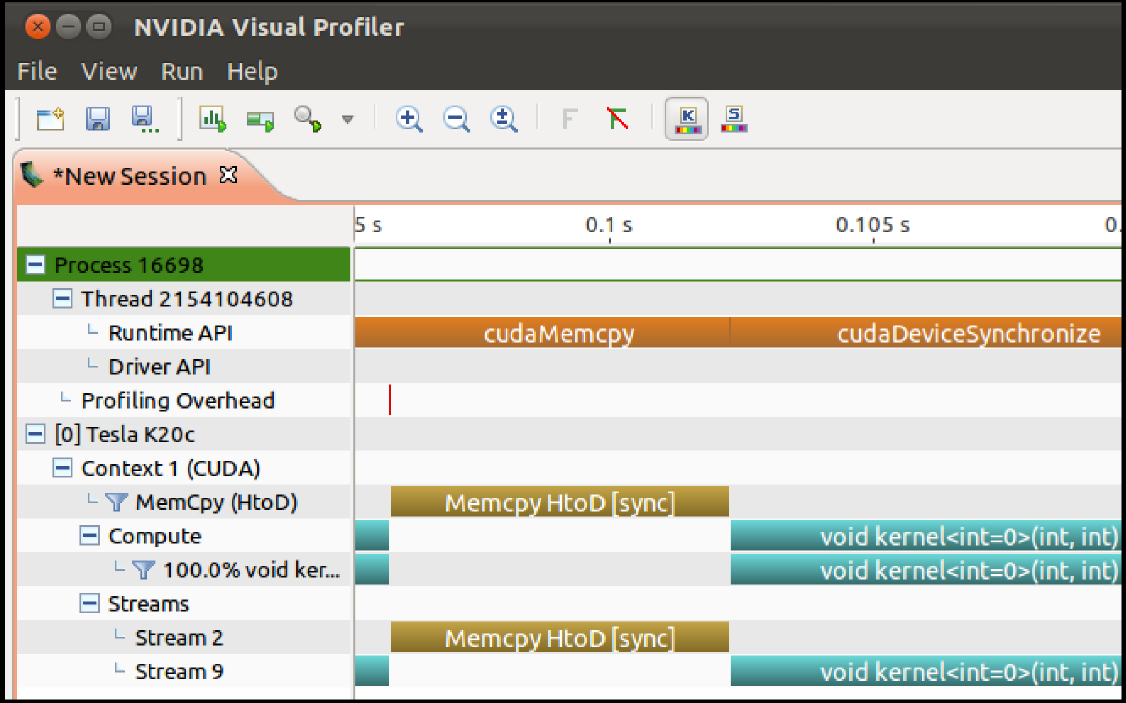
CASE STUDY 2-A

```
for(int i=0;i<repeat;i++) {
  cudaMemcpy(d_ptr,h_ptr,bytes, cudaMemcpyHostToDevice);
  kernel<<<1,1,0,stream2>>>();
  cudaDeviceSynchronize();
}
```



Problem:

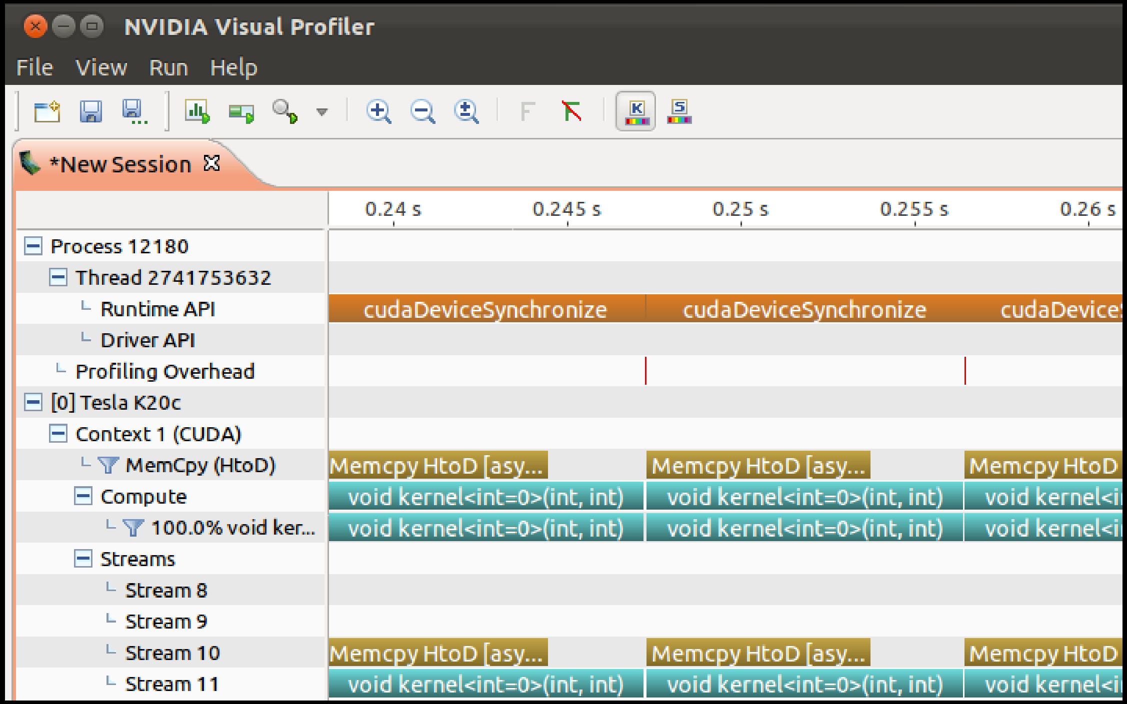
Memory copy is synchronous

CASE STUDY 2-A

```
for(int i=0;i<repeat;i++) {
  cudaMemcpyAsync(d_ptr,h_ptr,bytes, cudaMemcpyHostToDevice, stream1);
  kernel<<<1,1,0,stream2>>>();
  cudaDeviceSynchronize();
}
```

Solution:

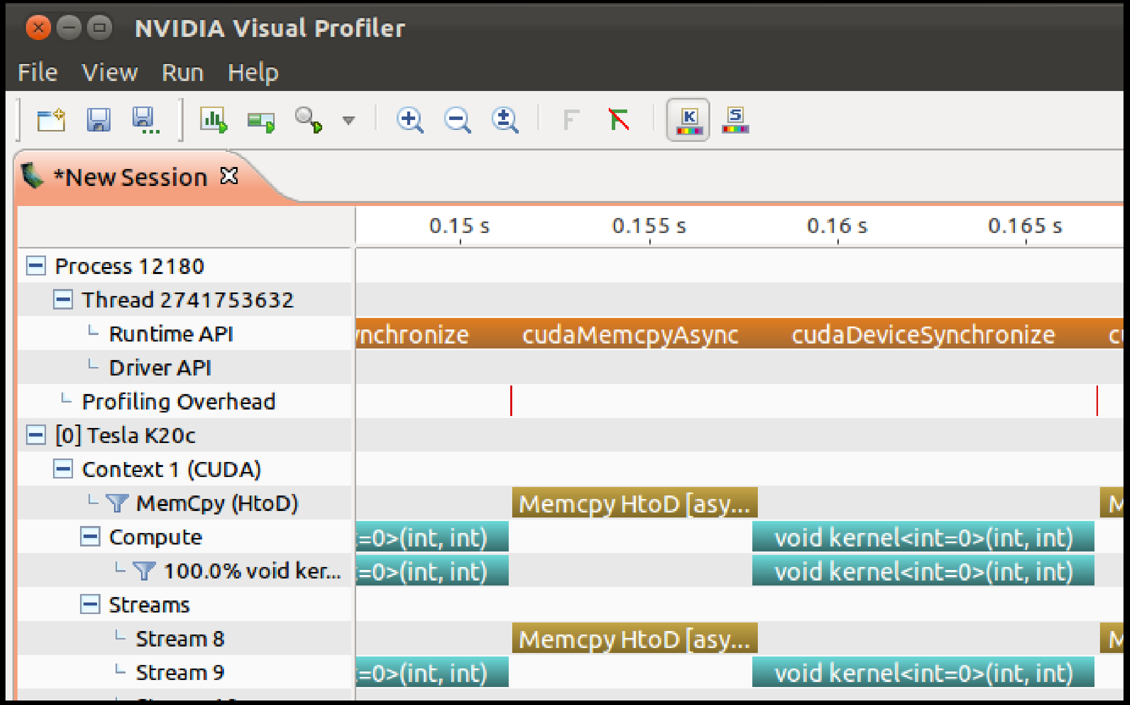
Use asynchronous API



CASE STUDY 2-B

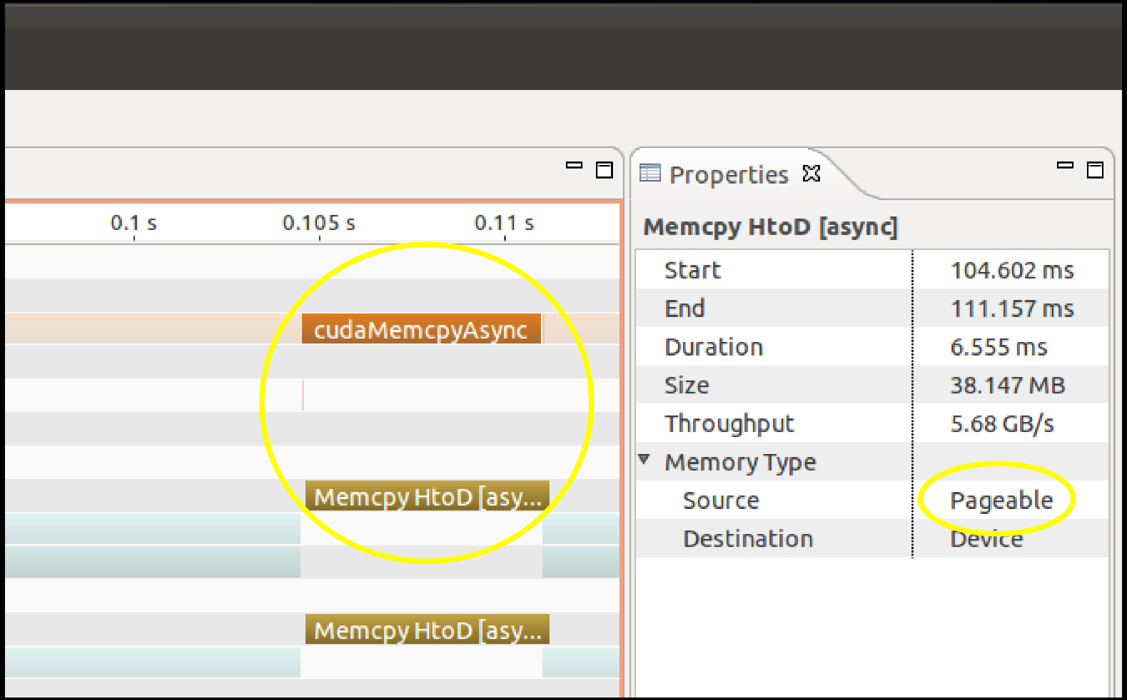
```
for(int i=0;i<repeat;i++) {
  cudaMemcpyAsync(d_ptr,h_ptr,bytes, cudaMemcpyHostToDevice, stream1);
  kernel<<<1,1,0,stream2>>>();
  cudaDeviceSynchronize();
}
```

Problem: ??



CASE STUDY 2-B

```
for(int i=0;i<repeat;i++) {
  cudaMemcpyAsync(d_ptr,h_ptr,bytes, cudaMemcpyHostToDevice, stream1);
  kernel<<<1,1,0,stream2>>>();
  cudaDeviceSynchronize();
}
```

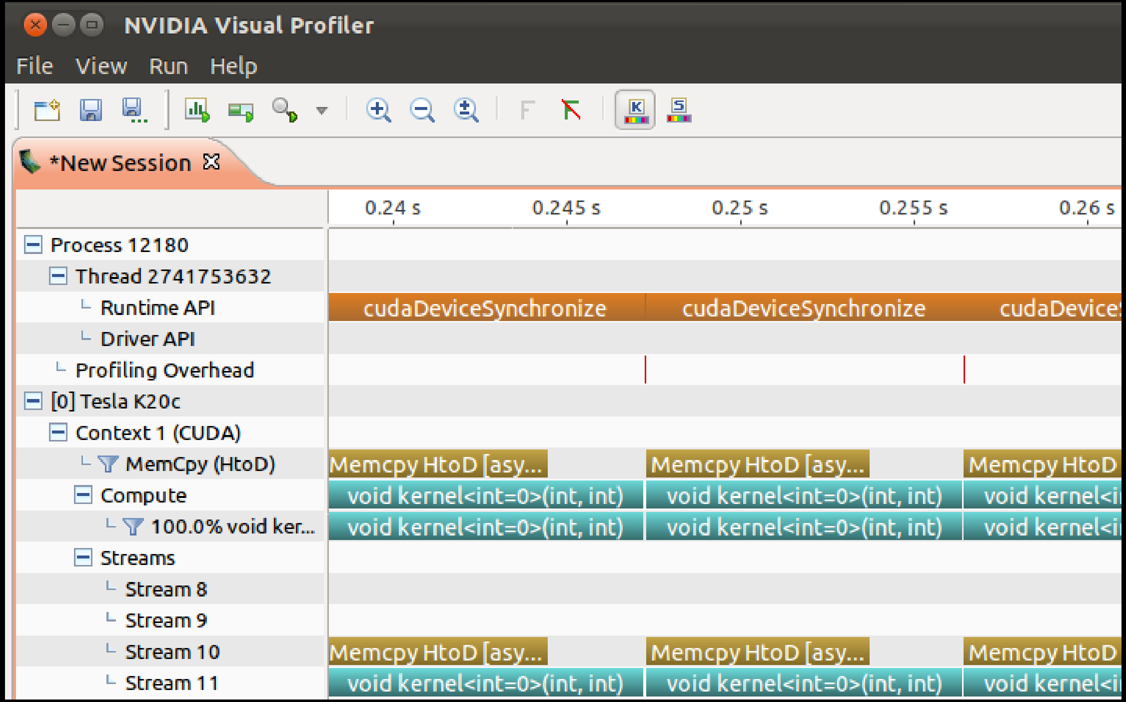


Host doesn’t get ahead

Cuda 5.5 reports “Pageable” type

CASE STUDY 2-B

```
cudaHostRegister(h_ptr,bytes,0);
for(int i=0;i<repeat;i++) {
  cudaMemcpyAsync(d_ptr,h_ptr,bytes, cudaMemcpyHostToDevice, stream1);
  kernel<<<1,1,0,stream2>>>();
  cudaDeviceSynchronize();
}
cudaHostUnregister(h_ptr);
```



Solution:

Pin host memory using cudaHostRegister or cudaMallocHost

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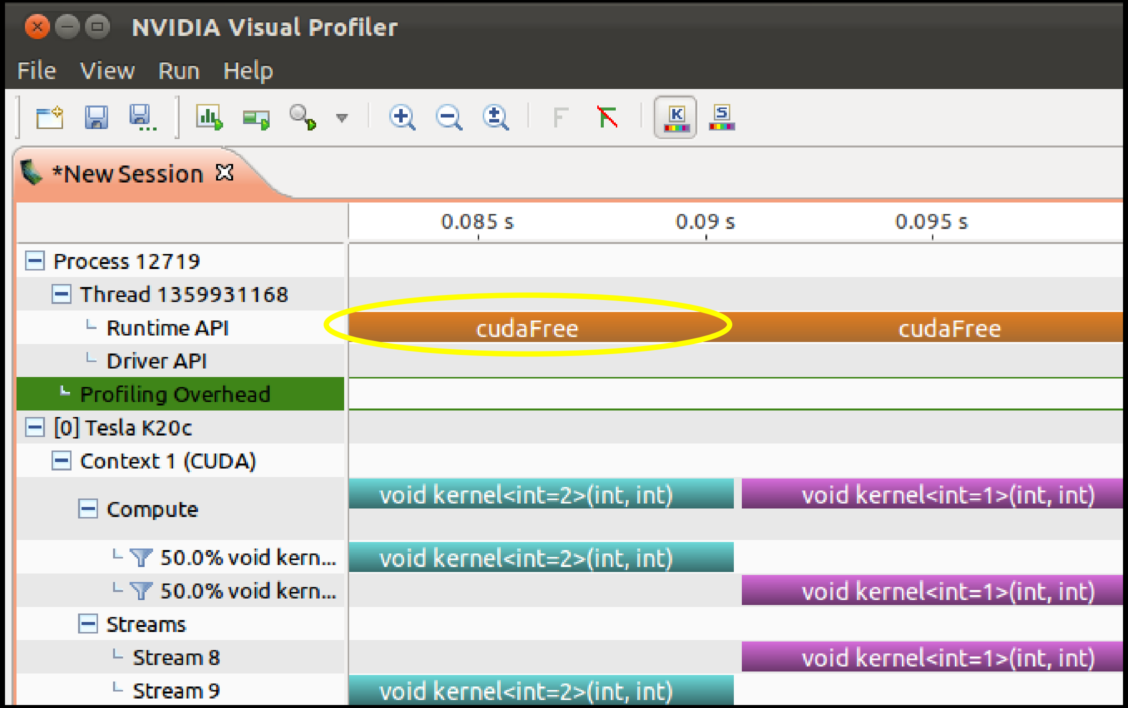
PROBLEM 2: MEMORY TRANSFERS ISSUES

- Symptoms
  - Memory copies do not overlap
  - Host spends excessive time in memory copy API
  - Cuda reports "Pageable" memory (Cuda 5.5+)
- Solutions
  - Use asynchronous memory copies
  - Use pinned memory for host memory
    - cudaMallocHost or cudaHostRegister

CASE STUDY 3

```
void launchwork(cudaStream_t stream) {
  int *mem;
  cudaMalloc(&mem,bytes);
  kernel<<<1,1,0,stream>>>(mem);
  cudaFree(mem);
}
...

  for(int i=0;i<repeat;i++) {
    launchwork(stream1);
    launchwork(stream2);
  }
```



Host blocked in allocation/free

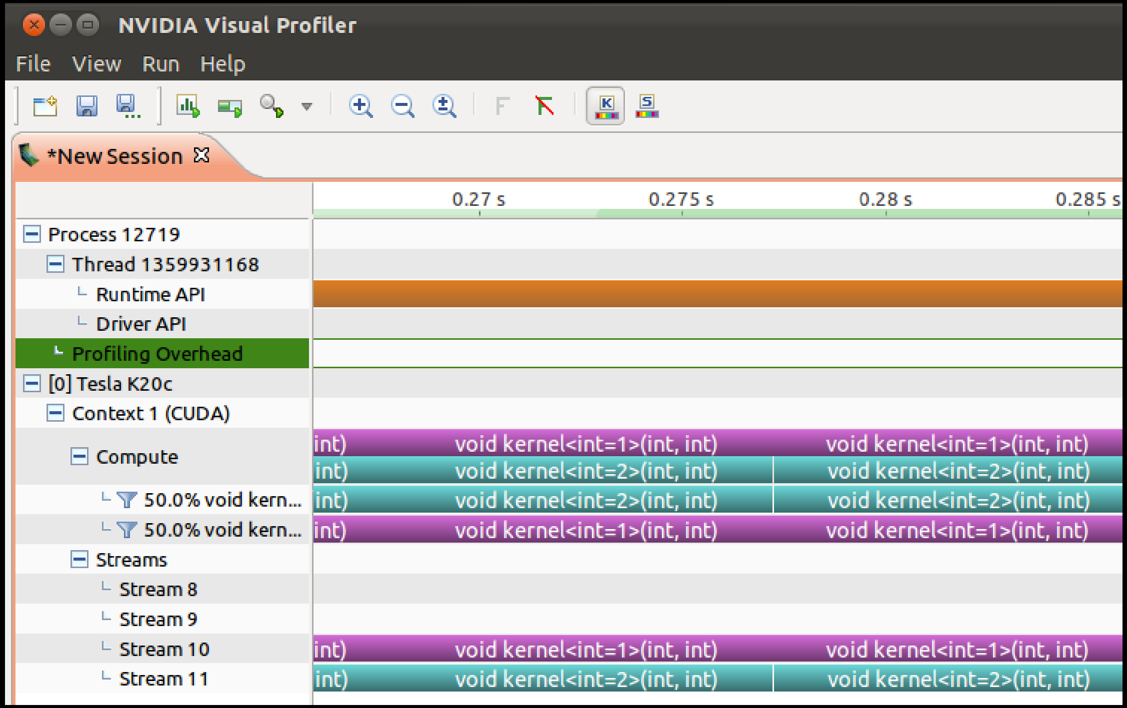
Problem:

Allocation & deallocation synchronize the device

CASE STUDY 3

```
void launchwork(cudaStream_t stream, int *mem) {
  kernel<<<1,1,0,stream>>>(mem);
}
...

  for(int i=0;i<repeat;i++) {
    launchwork<1>(stream1,mem1);
    launchwork<2>(stream2,mem2);
  }
```



Solution:

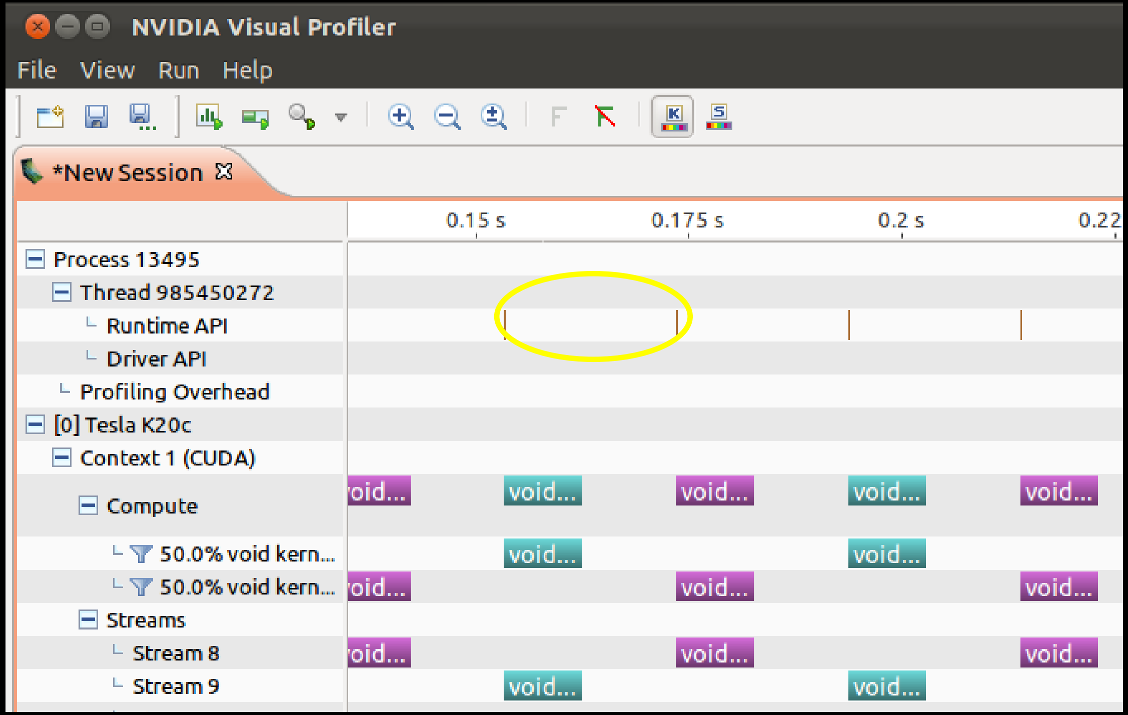
Reuse cuda memory and objects including streams and events

PROBLEM 3: IMPLICIT SYNCHRONIZATION

- Symptoms
  - Host does not get ahead
  - Host shows excessive time in certain API calls
    - cudaMalloc, cudaFree, cudaEventCreate, cudaEventDestroy, cudaStreamCreate, cudaStreamCreate, cudaHostRegister, cudaHostUnregister, cudaFuncSetCacheConfig
- Solution:
  - Reuse memory and data structures

CASE STUDY 4

```
for(int i=0;i<repeat;i++)
{
  hostwork();
  kernel<<<1,1,0,stream1>>>();
  hostwork();
  kernel<<<1,1,0,stream2>>>();
}
```



Problem:

Host is limiting performance

Host is outside of API calls

PROBLEM 4: LIMITED BY HOST

- Symptoms
  - Host is outside of cuda APIs
  - Large gaps in timeline where the host and device are empty
- Solution
  - Move more work to the GPU
  - Multi-thread host code

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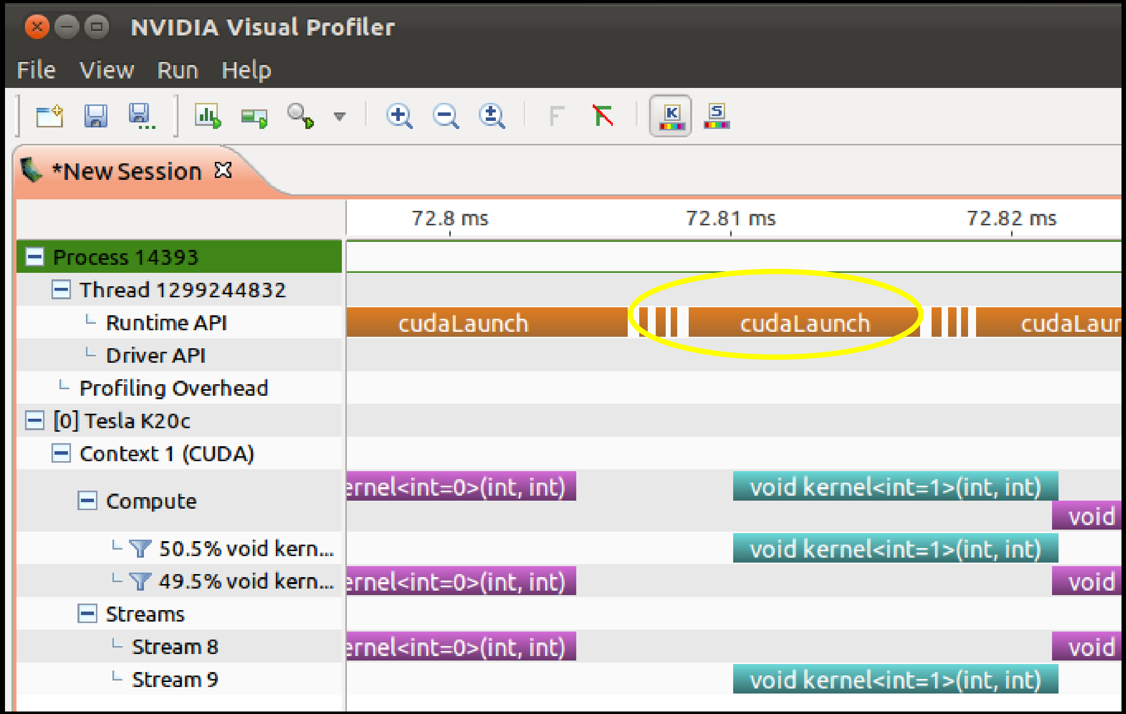
CASE STUDY 5

```
for(int i=0;i<repeat;i++)
{
  kernel<<<1,1,0,stream1>>>();
  kernel<<<1,1,0,stream2>>>();
}
```



Host is in cudaLaunch or other APIs

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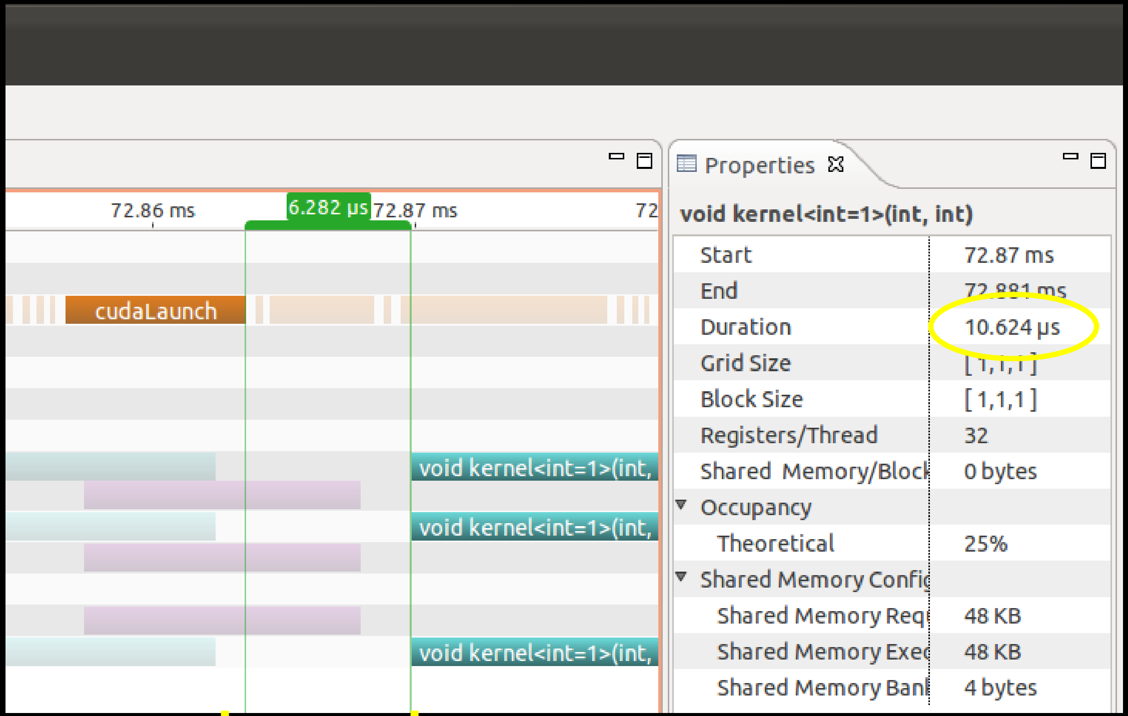
CASE STUDY 5

```
for(int i=0;i<repeat;i++)
{
  kernel<<<1,1,0,stream1>>>();
  kernel<<<1,1,0,stream2>>>();
}
```



Problem:

Not enough work to cover launch overhead

Host is not far ahead

Kernel runtime is short (<30us)

PROBLEM 5: LIMITED BY LAUNCH OVERHEAD

- Symptoms
  - Host does not get ahead
  - Kernels are short <30 us
  - Time between successive kernels is >10 us
- Solutions
  - Make longer running kernels
    - Fuse nearby kernels together
    - Batch work within a single kernel
    - Solve larger problems

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PROBLEM 6: EXCESSIVE SYNCHRONIZATION

- Symptoms
  - Host does not get ahead
  - Large gaps of idle time in timeline
  - Host shows synchronization API calls
- Solutions
  - Use events to limit the amount of synchronization
  - Use cudaStreamWaitEvent to prevent host synchronization
  - Use cudaEventSynchronize

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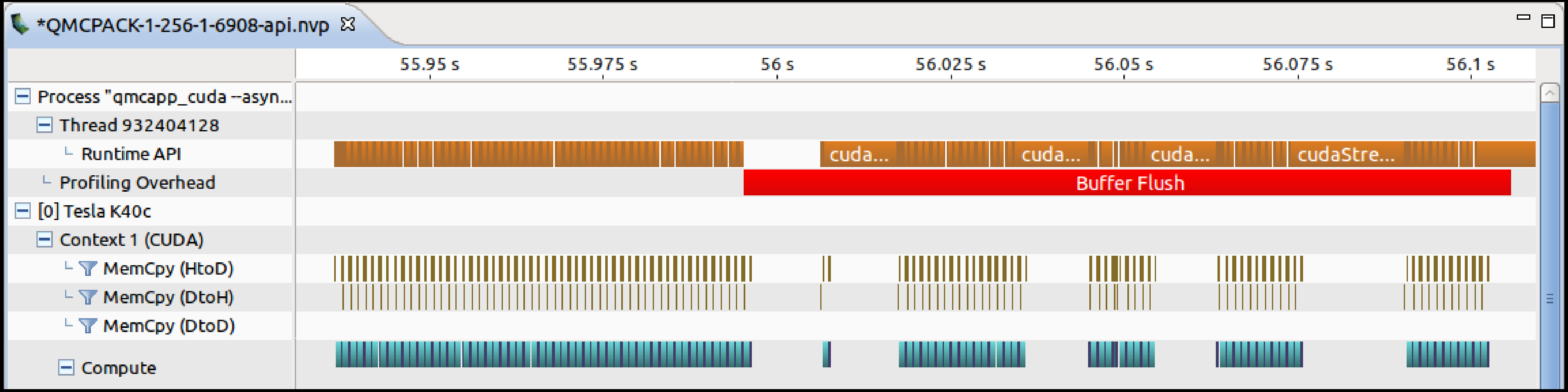
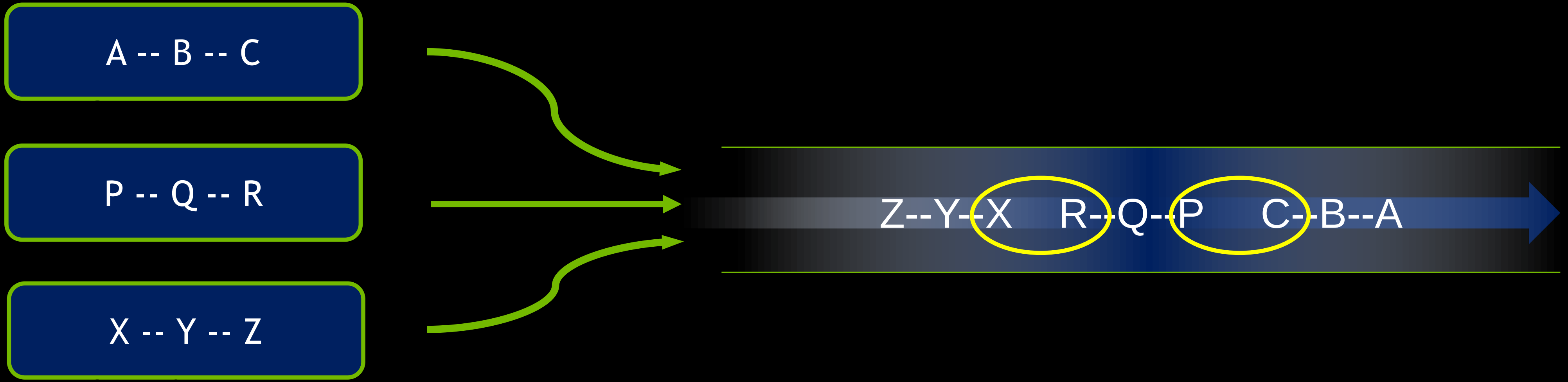
PROBLEM 7: PROFILER OVERHEAD



- Symptoms: Large gaps in timeline, Timeline shows profiler overhead
- Real code likely does not have the same problem
- Solution: Avoid cudaDeviceSynchronize() & cudaStreamSynchronize()

```
cudaEventRecord(event,stream);
cudaEventSynchronize(event);
```

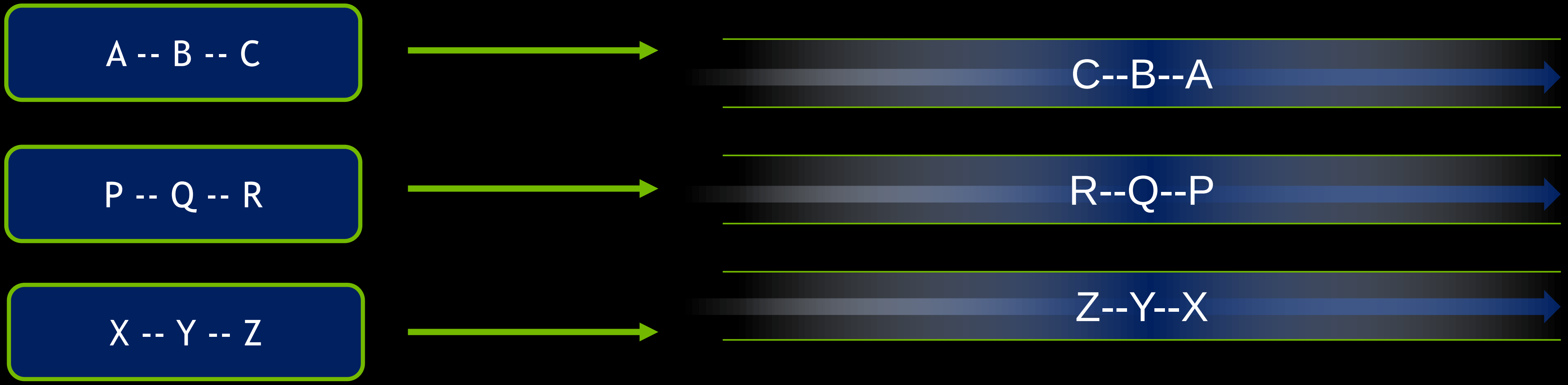
FERMI CONCURRENCY



Fermi allows 16-way concurrency

- But CUDA streams multiplex into a single queue
- Issue order matters for concurrency
- For more info see the streams webinar
  - https://developer.nvidia.com/gpu-computing-webinars

KEPLER IMPROVED CONCURRENCY



Kepler allows 32-way concurrency

- One work queue per stream
- Concurrency at full-stream level
- No inter-stream dependencies

REVIEW

- Common Streaming Problems
  1. Using the default stream
  2. Memory transfer issues
  3. Implicit synchronization
  4. Limited by host throughput
  5. Limited by launch overhead
  6. Excessive synchronization
  7. Profiler overhead
  8. False serialization on Fermi

ADVANCED STREAMING TOPICS

STREAM CALLBACKS

- Cuda 5.0 now allows you to add stream callbacks (K20 or newer)
  - Useful for launching work on the host when something has completed

```
void CUDART_CB MyCallback(void *data){
   ...
}
...
  MyKernel<<<100, 512, 0, stream>>>();
  cudaStreamAddCallback(stream, MyCallback, (void*)i, 0);
```

- Callbacks are processed by a driver thread
  - The same thread processes all callbacks
  - You can use this thread to signal other threads

PRIORITY STREAMS

- You can give streams priority
  - High priority streams will preempt lower priority streams.
    - Currently executing blocks will complete but new blocks will only be scheduled after higher priority work has been scheduled.
- Query available priorities:
  - cudaDeviceGetStreamPriorityRange(&low, &high)
  - Kepler: low: -1, high: 0
  - Lower number is higher priority
- Create using special API:
  - cudaStreamCreateWithPriority(&stream, flags, priority)
- Cuda 5.5+

REVIEW

- Enabling concurrency is vital to achieving peak performance
- Use MPS+MPI to get concurrency automatically
- Or use streams to add concurrency
  - Watch out for common mistakes
    - Using stream 0
    - Synchronous memory copies
    - Not using pinned memory
    - Overuse of synchronization primitives