CUDA Asynchronous Memory Usage and Execution

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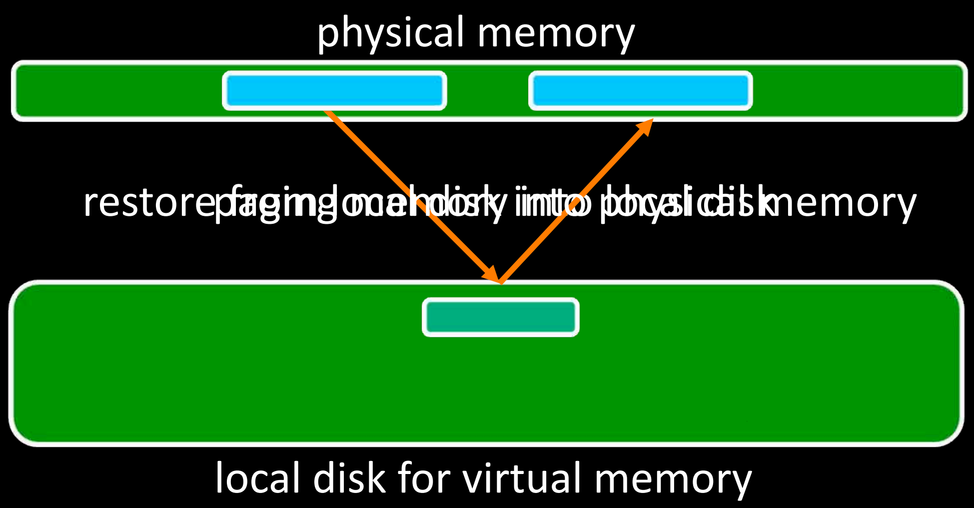
Page-Locked Memory

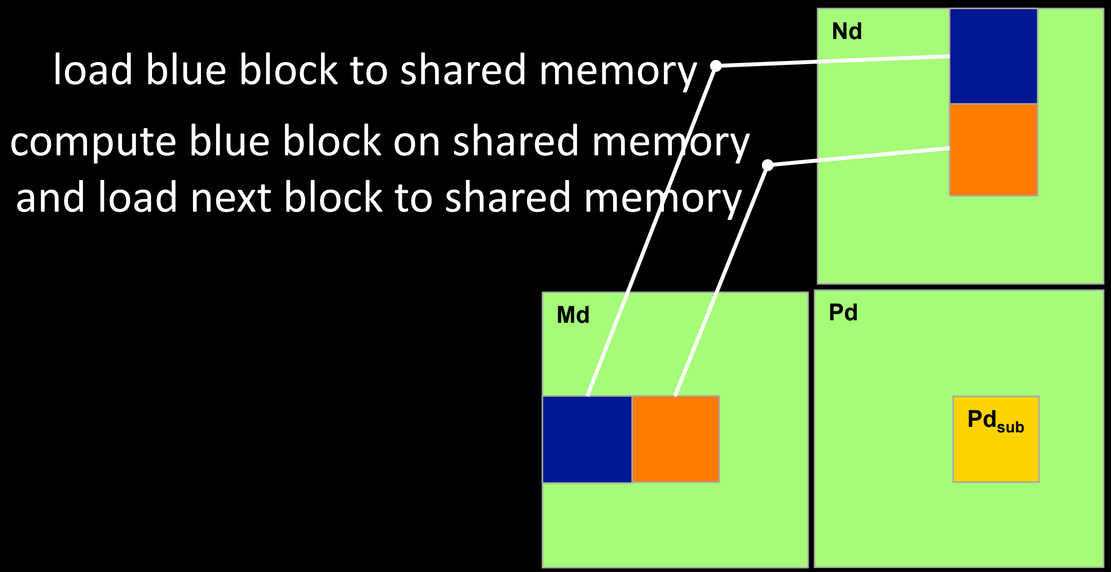
Page-Locked Memory

- Regular pageable and page-locked or pinned host memory
  - use too much page-locked memory reduces system performance



Page-Locked Memory

- Regular pageable and page-locked or pinned host memory
  - copy between page-locked memory and device memory can be performed concurrently with kernel execution for some devices



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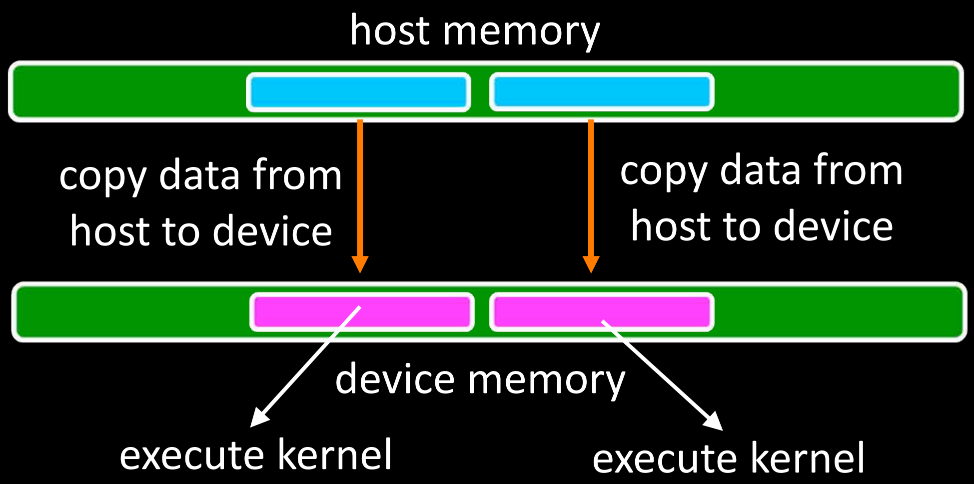
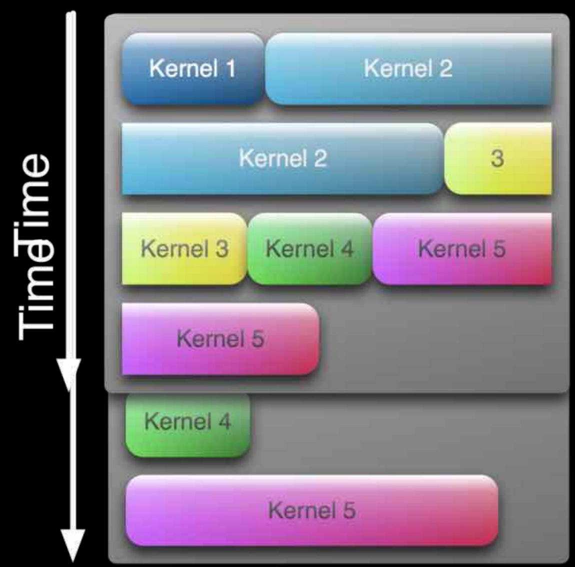


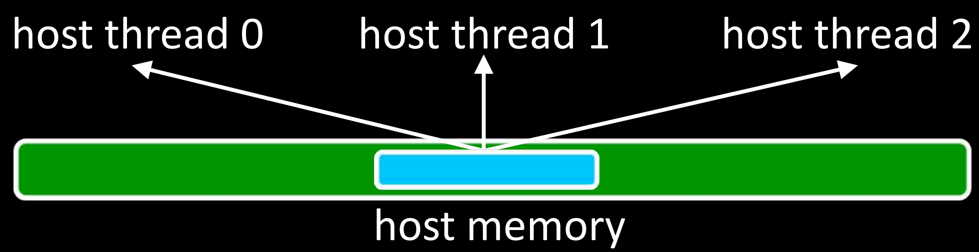
Page-Locked Memory

- Regular pageable and page-locked or pinned host memory
  - use page-locked host memory can support executing more than one device kernel concurrently for compute capability 2.0 hardware



Page-Locked Memory

- Portable memory
  - the block of page-locked memory is only available for the thread that allocates it by the default setting, use portable memory flag to share the page-locked memory with other threads



Page-Locked Memory

- How to allocate portable memory?

```
float* pointer;

//allocate host page-locked write-combining memory
cudaHostAlloc((void**)&pointer,bytes,cudaHostAllocPortable);

//free allocated memory space
cudaFreeHost(pointer);
```

Page-Locked Memory

- Write-Combining memory

  - page-locked memory is allocated as cacheable by default
  - page-locked memory can be allocated as write-combining memory by using special flag, which frees up L1 and L2 cache resource usage

- Advantage and disadvantage

  - write-combining memory is not snooped during transfers across bus, which can improve transfer performance by up to 40%
  - reading from write-combining memory from host is slow, which should in general be used for memory that the host only write to

Page-Locked Memory

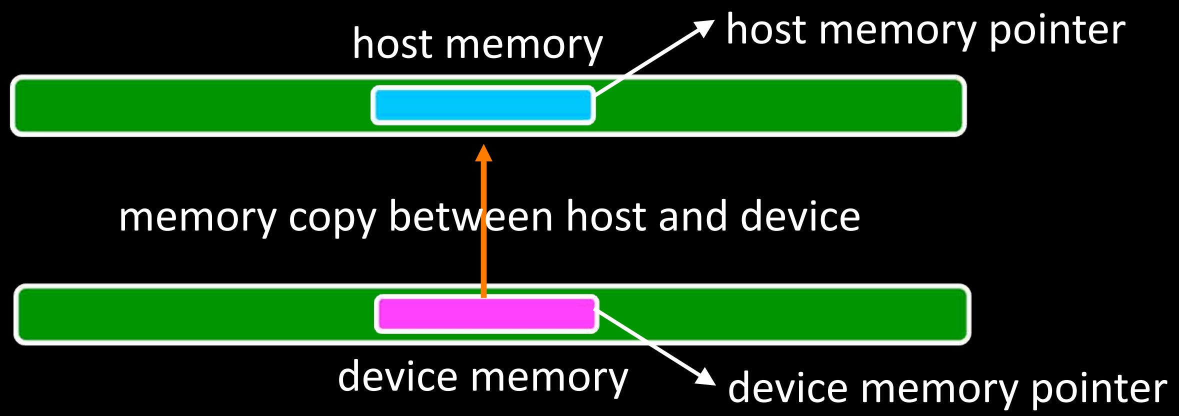
- How to allocate write-combining memory?

```
float* pointer;

//allocate host page-locked write-combining memory
cudaHostAlloc((void**)
   &pointer,bytes,cudaHostAllocWriteCombined);

//free allocated memory space
cudaFreeHost(pointer);
```

1 GB data size	normal	write-combining
host to device	0.533522	0.338092
device to host	0.591750	0.320989

Page-Locked Memory

- Mapped memory
  - the page-locked host memory can be mapped into the address space of the device by passing special flag to allocate memory



Page-Locked Memory

- Mapped memory
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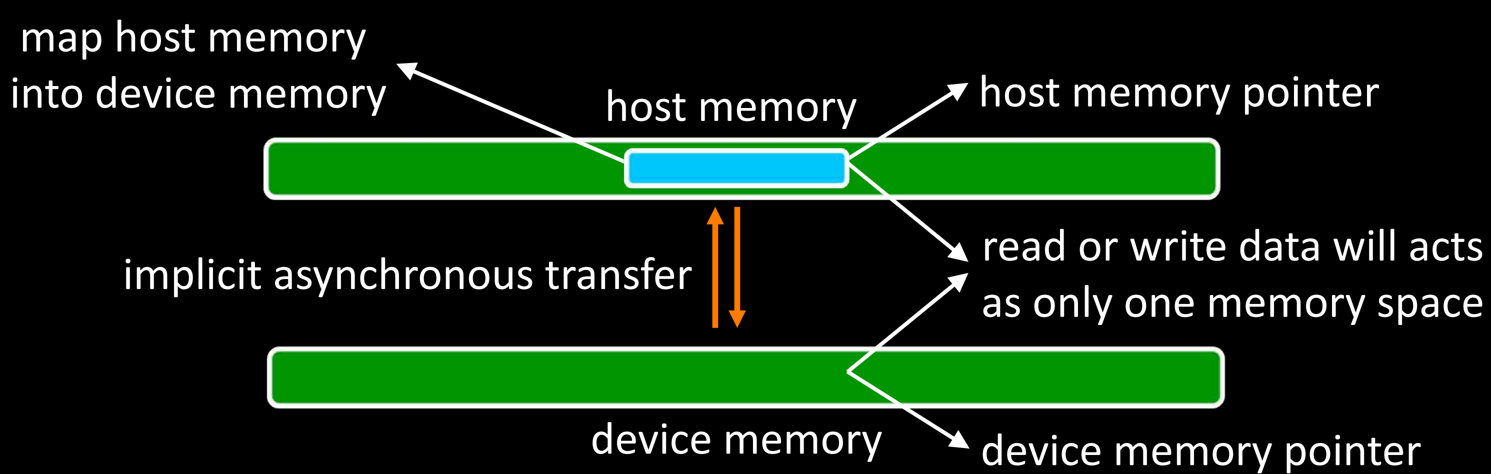


Page-Locked Memory

- How to allocate mapped memory?

```
float* pointer;

//allocate host page-locked write-combining memory
cudaHostAlloc((void**)&pointer,bytes,cudaHostAllocMapped);

//free allocated memory space
cudaFreeHost(pointer);
```

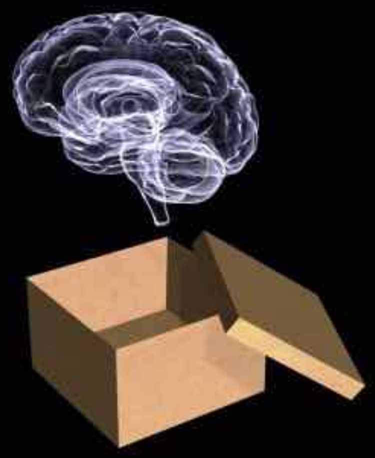
Page-Locked Memory

- Check the hardware is support or not?
  - check the hardware properties to ensure it is available for mapping host page-locked memory with device memory

```
cudaDeviceProp deviceprop;

//query the device hardwared properties
//the structure records all device properties
cudaGetDeviceProperties(&deviceprop,0);

//check the map memory is available or not
if(!deviceprop.canMapHostMemory)
printf("cudaError:cannot map host to devicmemory\n");
```

Page-Locked Memory

- What is the property structure contents?



Mapped Memory

```
#define size 1048576

int main(int argc,char** argv)
{
   int loop;

   float residual;

   float *h_a, *d_a;
   float *h_b, *d_b;
   float *h_c, *d_c;

   cudaDeviceProp deviceprop;

   //query the device hardwared properties
   //the structure records all device properties
   cudaGetDeviceProperties(&deviceprop,0);

   //check the map memory is available or not
   if(!deviceprop.canMapHostMemory)
   printf("cudaError:cannot map host to device memory\n");
```

Mapped Memory

```
//this flag must be set in order to allocate pinned
//host memory that is accessible to the device
cudaSetDeviceFlags(cudaDeviceMapHost);

//allocate host page-locked and accessible to the device memory
//maps the memory allocation on host into cuda device address
cudaHostAlloc((void**)&h_a,sizeof(float)*size,cudaHostAllocMapped);
cudaHostAlloc((void**)&h_b,sizeof(float)*size,cudaHostAllocMapped);
cudaHostAlloc((void**)&h_c,sizeof(float)*size,cudaHostAllocMapped);

//initialize host vectors
for(loop=0;loop<size;loop++)
{
   h_a[loop]=(float)rand()/(RAND_MAX-1);
   h_b[loop]=(float)rand()/(RAND_MAX-1);
}

//pass back the device pointer and map with host
cudaHostGetDevicePointer((void**)&d_a,(void*)h_a,0);
cudaHostGetDevicePointer((void**)&d_b,(void*)h_b,0);
cudaHostGetDevicePointer((void**)&d_c,(void*)h_c,0);
```

Mapped Memory

```
    //execute device kenel for vector addtion
    vectorAdd<<<(int)ceil((float)size/256),256s>>>(d_a,d_b,d_c,size);
    cudaThreadSynchronize();

    //check the result residual value
    for(loop=0,residual=0.0;loop<size;loop++)
    residual=residual+(h_a[loop]+h_b[loop]-h_c[loop]);

    printf("residual value is %f\n",residual);

    //free the memory space which must have been returnedd
    //by a previous call to cudaMallocHost or cudaHostAlloc
    cudaFreeHost(h_a);
    cudaFreeHost(h_b);
    cudaFreeHost(h_c);

    //catch and check cuda error message
    if((error=cudaGetLastError())!=cudaSuccess)
    printf("cudaError:%s\n",cudaGetErrorString(error));

    return 0;
}
```

Mapped Memory

```
__global__ void vectorAdd(float* da,float* db,float* dc,int size)
{
   int index;

   //calculate each thread global index
   index=blockIdx.x*blockDim.x+threadIdx.x;

   if(index<size)
   //each thread computer one component
   dc[index]=da[index]+db[index];

   return;
}
```

Page-Locked Memory

- Several advantages

  - there is no need to allocate a block in device memory and copy data between this block and block in host memory, the data transfers are implicitly performed as needed by the kernel

  - there is no need to use streams to overlap data transfers with kernel execution, the kernel-originated data transfers overlap with kernel execution automatically

  - mapped memory is able to exploit he full duplex of the PCI express bus by reading and writing at the same time, since memory copy only move data in one direction, half duplex

Page-Locked Memory

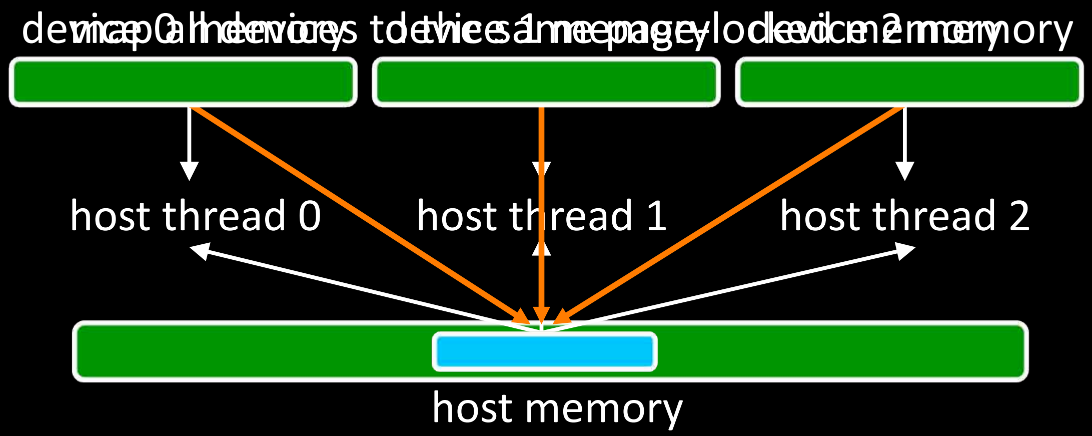
- Several disadvantages

  - the page-locked memory is shared with host and device, any application must avoid write on the both side simultaneously

  - the atomic functions operating on mapped page-locked memory are not atomic from the point of view of the host or other devices

Page-Locked Memory

- Portable and mapped memory
  - the page-locked host memory can be allocated as both portable and mapped memory, such that each host thread can map the same page-locked memory into different device address



Page-Locked Memory

- Integrated system

  - the mapped page-locked memory is very suitable on integrated system that utilize the a part of host memory as device memory
  - check the integrated field on cuda device properties structure

  - mapped memory is faster, if data only read from or write to global memory once, the coalescing is even more important with mapped memory in order to reduce the data transfer times

Asynchronous Execution

Asynchronous Execution

- Asynchronous execution

  - some functions are supported asynchronous launching in order to facilitate concurrent execution between host and device resource
  - control is returned to the host thread before the work is finished

transfer data between host and device
perform some device kernels
perform some host functions

overlapping

Asynchronous Execution

- Asynchronous execution

  - some functions are supported asynchronous launching in order to facilitate concurrent execution between host and device resource
  - control is returned to the host thread before the work is finished

perform device kernel launch

```
kernel<<<blocknum,blocksize,0,stream>>>(…)
```

perform data transfer between host and device
perform data transfer between device and device

```
cudaMemcpyAsync(destination,source,bytes,direction,stream);
```

perform global memory set

Asynchronous Execution

```
#define size 1048576

int main(int argc,char** argv)
{
   int loop;
   int bytes;

   float *h_a, *d_a;
   float *h_b, *d_b;
   float *h_c, *d_c;

   //allocate host page-locked memory
   cudaMallocHost((void**)&h_a,sizeof(float)*size);
   cudaMallocHost((void**)&h_b,sizeof(float)*size);
   cudaMallocHost((void**)&h_c,sizeof(float)*size);

   //allocate device global memory
   cudaMalloc((void**)&d_a,sizeof(float)*size);
   cudaMalloc((void**)&d_b,sizeof(float)*size);
   cudaMalloc((void**)&d_c,sizeof(float)*size);
```

Asynchronous Execution

```
cudaEvent_t stop;
cudaEvent_t start;

//create an event object which is used to
//record device execution elasped time
cudaCreateEvent(&stop);
cudaCreateEvent(&start);

//initialize host vectors
for(loop=0;loop<size;loop)
{
   h_a[loop]=(float)rand()/(RAND_MAX-1);;
   h_b[loop]=(float)rand()/(RAND_MAX-1);;
}
```

Asynchronous Execution

```
bytes=sizeof(float)*size;

//set time event recorder
cudaEventRecord(start,0);

//copy data from host to device memory asynchronously
cudaMemcpyAsync(d_a,h_a,bytes,cudaMemcpyHostToDevice,0);
cudaMemcpyAsync(d_b,h_b,bytes,cudaMemcpyHostToDevice,0);

//execute device kernel asynchronously
vectorAdd<<<(int)ceil((float)size/256,256,0,0)>>>(d_a,d_,d_c,size);

//copy data from device to host memory asynchronously
cudaMemcpyAsync(h_c,d_c,bytes,cudaMemcpyDeviceToHost,0);

//set time event recorder
cudaEventRecord(stop,0);
```

Asynchronous Execution

```
counter=0;

//increase the counter before the queried
//cuda event has actually been finished
while(cudaEventQuery(stop)==cudaErrorNotReady)
counter=counter+1;

//calculate device execution elapsed time
cudaEventElapsedTime(&elapsed,start,stop);

//check the result residual value
for(loop=0,residual=0.0;loop<size;loop++)
residual=residual+(h_c[loop]-h_a[loop]-h_b[loop]);

printf("counter:%d\n",counter);
printf("residual:%f\n",residual);
```

Asynchronous Execution

```
    //free the memory space which must have been returnedd
    //by a previous call to cudaMallocHost or cudaHostAlloc
    cudaFreeHost(h_a);
    cudaFreeHost(h_b);
    cudaFreeHost(h_c);

    //free the device memory space
    cudaFree(d_a);
    cudaFree(d_b);
    cudaFree(d_c);

    //free the cuda event object
    cudaEventDestroy(stop);
    cudaEventDestroy(start);

    //catch and check cuda error message
    if((error=cudaGetLastError())!=cudaSuccess)
    printf("cudaError:%s\n",cudaGetErrorString(error));

    return 0;
}
```

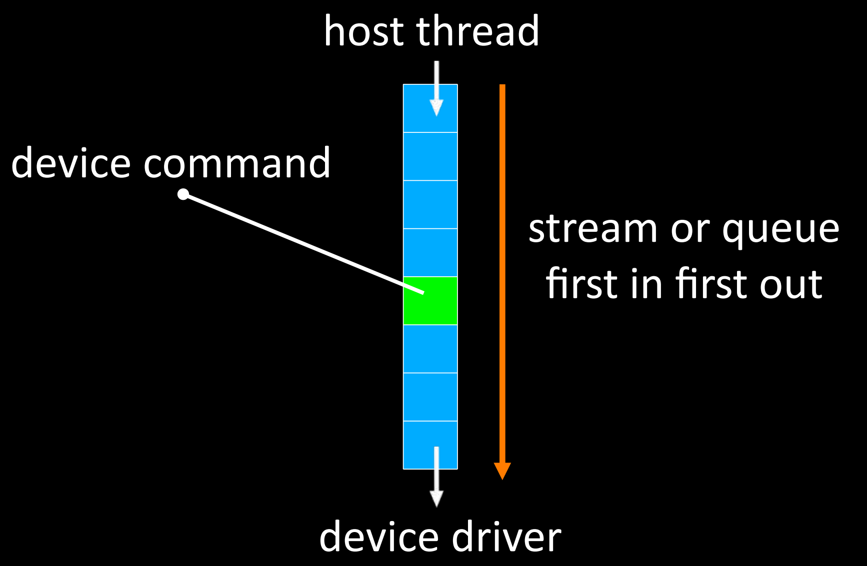
Asynchronous Execution

```
__global__ void vectorAdd(float* da,float* db,float* dc,int size)
{
   int index;

   //calculate each thread global index
   index=blockIdx.x*blockDim.x+threadIdx.x;

   if(index<size)
   //each thread computer one component
   dc[index]=da[index]+db[index];

   return;
}
```

Stream

Stream

- Stream
  - applications manage concurrency through stream
  - a stream is a sequence of commands that execute in order
  - all device requests made from the host code are put into a queues



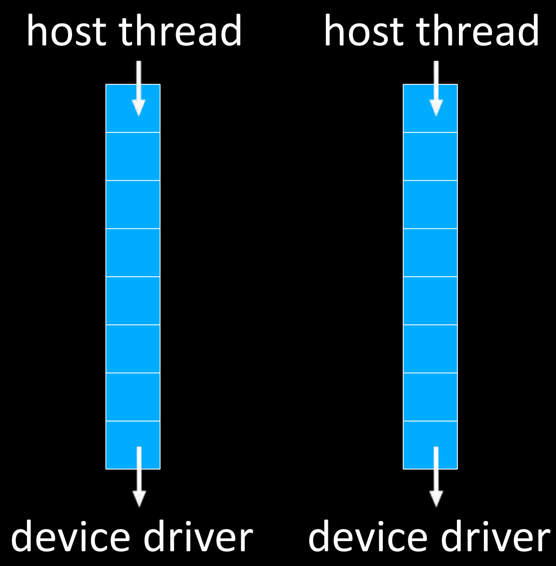
Stream

- How to create a stream?

```
cudaStream_t stream;

//create an asynchronous new stream
cudaStreamCreate(&stream);

//destroy stream
cudaStreamDestroy(stream);
```

Stream

- Stream
  - different streams may execute their commands or host requests out of order with respect to one another or concurrently, but the same stream is still a sequence of commands that execute in order



Stream

```
#define snum 10
#define size 1048576

int main(int argc,char** argv)
{
   int loop;
   int bytes;

   float *h_a, *d_a;
   float *h_b, *d_b;
   float *h_c, *d_c;

   cudaStream_t stream[snum];

   //create new asynchronous stream
   //which acts as device work queue
   for(loop=0;loop<snum;loop++)
   cudaStreamCreate(stream+loop);
```

Stream

```
//allocate host page-locked memory
cudaMallocHost((void**)&h_a,sizeof(float)*size*snum);
cudaMallocHost((void**)&h_b,sizeof(float)*size*snum);
cudaMallocHost((void**)&h_c,sizeof(float)*size*snum);

//allocate device global memory
cudaMalloc((void**)&d_a,sizeof(float)*size*snum);
cudaMalloc((void**)&d_b,sizeof(float)*size*snum);
cudaMalloc((void**)&d_c,sizeof(float)*size*snum);

//initialize host vectors
for(loop=0;loop<size*snum;loop++)
{
   h_a[loop]=(float)rand()/(RAND_MAX-1);;
   h_b[loop]=(float)rand()/(RAND_MAX-1);;
}
```

Stream

```
//put all the works into default stream
//executes all works by using noly one stream
for(loop=0;loop<snum;loop++)
{
   bytes=sizeof(float)*size;

   sp1=h_a+loop*size; dp1=d_a+loop*size;
   sp2=h_b+loop*size; dp2=d_b+loop*size;
   sp3=d_c+loop*size; dp3=h_c+loop*size;

   //copy data from host to device memory asynchronously
   cudaMemcpyAsync(dp1,sp1,bytes,cudaMemcpyHostToDevice,0);
   cudaMemcpyAsync(dp2,sp2,bytes,cudaMemcpyHostToDevice,0);

   //execute device kernel asynchronously
   kernel<<<blocknum,blocksize,0,0>>>(d_a,d_b,d_c,size);

   //copy data from device to host memory asynchronously
   cudaMemcpyAsync(dp3,sp3,bytes,cudaMemcpyDeviceToHost,0);
}

//wait until the stream is finished
cudaThreadSynchronize();
```

Stream

```
//put all the works into different asynchronous streams
//each stream only executes three copies and one kernel
for(loop=0;loop<snum;loop++)
{
   bytes=sizeof(float)*size;

   sp1=h_a+loop*size; dp1=d_a+loop*size;
   sp2=h_b+loop*size; dp2=d_b+loop*size;
   sp3=d_c+loop*size; dp3=h_c+loop*size;

   //copy data from host to device memory asynchronously
   cudaMemcpyAsync(dp1,sp1,bytes,cudaMemcpyHostToDevice,stream[loop]);
   cudaMemcpyAsync(dp2,sp2,bytes,cudaMemcpyHostToDevice,stream[loop]);

   //execute device kernel asynchronously
   kernel<<<blocknum,blocksize,0,stream[loop]>>>(d_a,d_b,d_c,size);

   //copy data from device to host memory asynchronously
   cudaMemcpyAsync(dp3,sp3,bytes,cudaMemcpyDeviceToHost,stream[loop]);
}

//wait until all stream are finished
cudaThreadSynchronize();
```

Stream

```
    //free the memory space which must have been returnedd
    //by a previous call to cudaMallocHost or cudaHostAlloc
    cudaFreeHost(h_a);
    cudaFreeHost(h_b);
    cudaFreeHost(h_c);

    //free the device memory space
    cudaFree(d_a);
    cudaFree(d_b);
    cudaFree(d_c);

    //free the asynchronous streams
    for(loop=0;loop<snum;loop++)
    cudaStreamDestroy(stream[loop]);

    return 0;
}
```

Stream

```
__global__ void vectorAdd(float* da,float* db,float* dc,int size)
{
   int loop;
   int index;

   volatile float temp1;
   volatile float temp2;

   //calculate each thread global index
   index=blockIdx.x*blockDim.x+threadIdx.x;

   if(index<size)
   for(loop=0;loop<iteration;loop++)
   {
      temp1=da[index];
      temp2=db[index];
      dc[index]=temp1+temp2;
   }

   return;
}
```

Stream

- How about the performance ?

	Fermi C2050	Tesla C1060
single stream	64.096382	180.179825
multiple stream	31.996338	166.010757

Stream

- Stream controlling

  `cudaThreadSynchronize()`

  called in the end to make sure all streams are finished before preceding further, it forces the runtime to wait until all device tasks or commands in all asynchronous streams have completed

  `cudaStreamSynchronize()`

  force the runtime to wait until all preceding device tasks or host commands in one specific stream have completed

  `cudaStreamQuery()`

  provide applications with a way to know if all preceding device tasks or host commands in a stream have completed

Stream

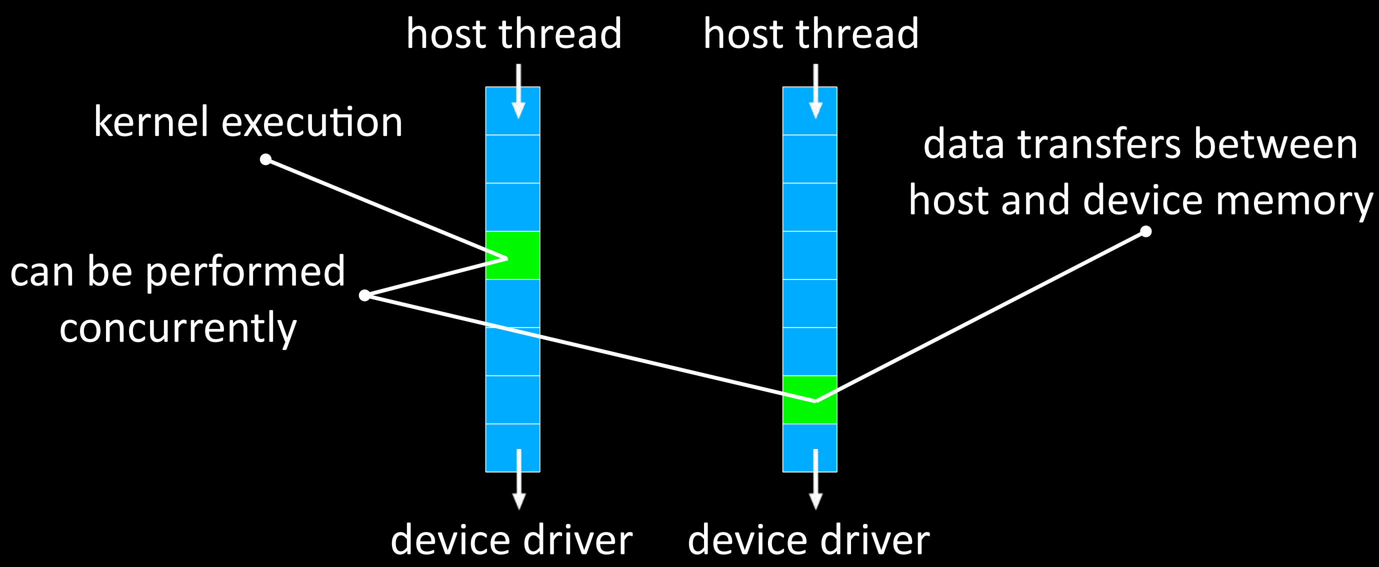
- Stream controlling

  `cudaStreamDestroy()`

  wait for all preceding tasks in the give stream to complete before destroying the stream and returning control to the host thread, which is blocked until the stream finished all commands or tasks

Stream

- Overlap of data transfer and kernel execution
  transfer data between host page-locked memory and device memory and kernel execution can be performed concurrently



Stream

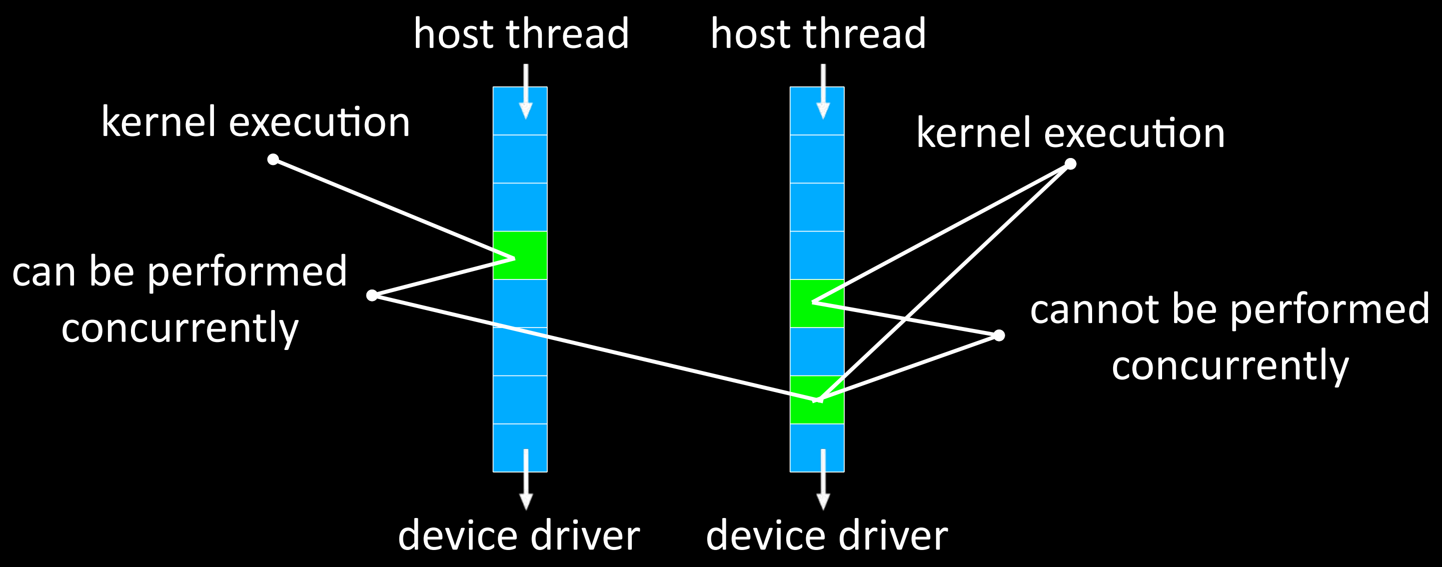
- Overlap of data transfer and kernel execution
  transfer data between host page-locked memory and device memory and kernel execution can be performed concurrently

  any application may query the hardware capability by calling the device manage function and checking the property flag

```
cudaDeviceProp deviceprop;

//query the device hardwared properties
//the structure records all device properties
cudaGetDeviceProperties(&deviceprop,0);

//check the overlapping is available or not
if(!deviceprop.deviceOverlap)
printf("cudaError:cannot overlap kernel and transfer\n");
```

Stream

- Concurrent kernel execution
  some hardware can execute multiple kernels concurrently



Stream

- Concurrent kernel execution
  some hardware can execute multiple kernels concurrently

  any application may query the hardware capability by calling the device manage function and checking the property flag

```
cudaDeviceProp deviceprop;

//query the device hardwared properties
//the structure records all device properties
cudaGetDeviceProperties(&deviceprop,0);

//check the concurent kernels is available or not
if(!deviceprop.concurrentKernels)
printf("cudaError:cannot use concurrent kernels\n");
```

Stream

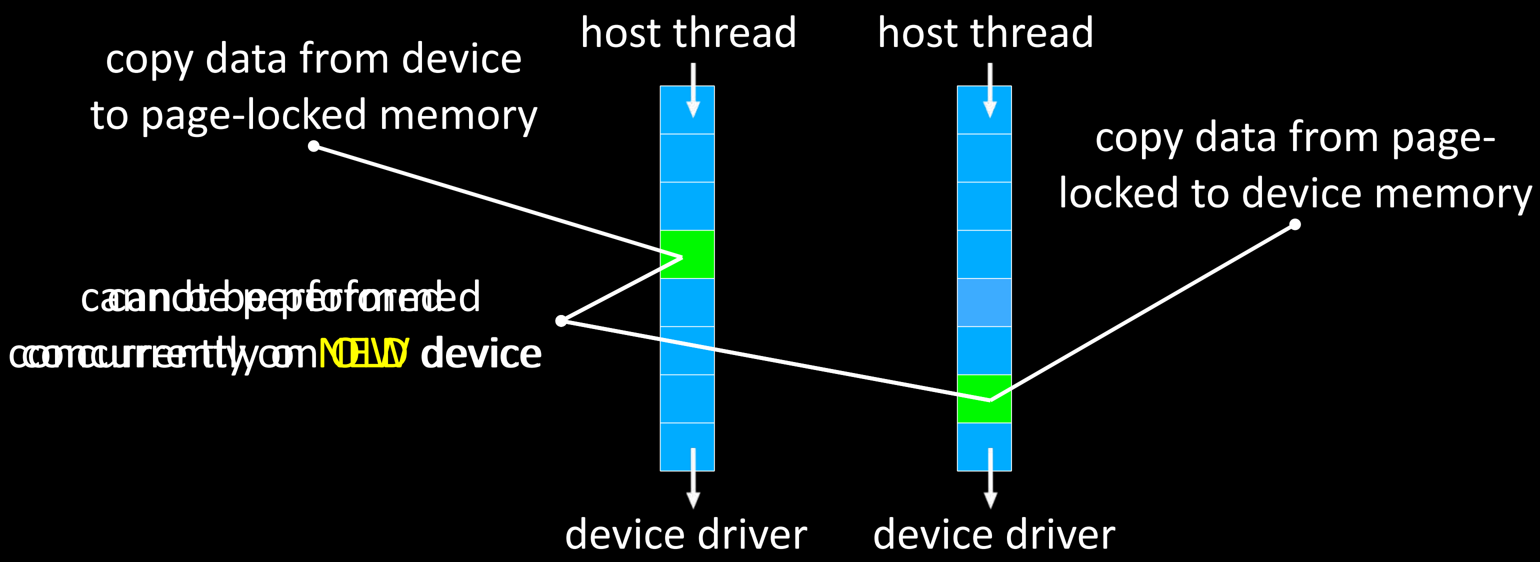
- Concurrent kernel execution
  some hardware can execute multiple kernels concurrently

  any application may query the hardware capability by calling the device manage function and checking the property flag

  the kernels that may use many textures or registers or shared memory are less likely to execute with other kernels concurrently

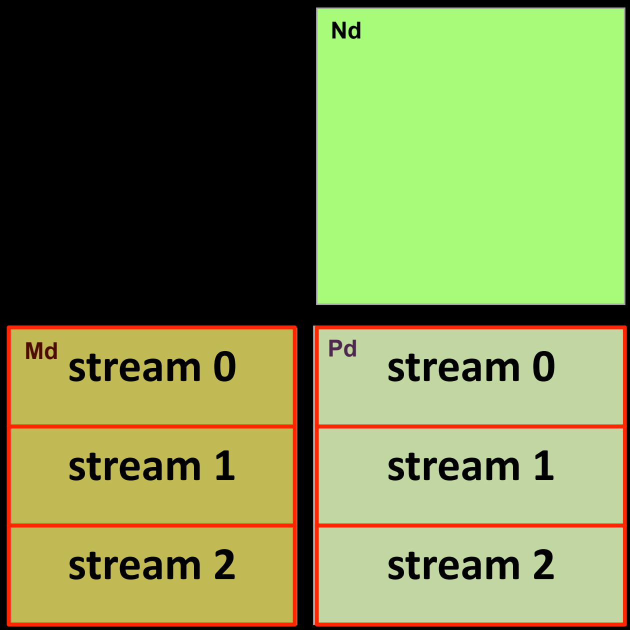
Stream

- Concurrent data transfer
  some devices can perform copy data from page-locked memory to device memory with copy data from device memory to host page-locked memory concurrently



Stream

- Streams on the matrix-matrix multiplication



Event

Event

- Event
  the runtime provides a ways to closely monitor the device progress by letting the program record events at any point in the program

```
cudaEvent_t event1;
cudaEvent_t event2;

//create and initialize event
cudaEventCreate(&event1);
cudaEventCreate(&event2);

//insert event recorder into stream
cudaEventRecord(event1,stream);
cudaEventRecord(event2,stream);

//destroy created event recorder
cudaEventDestroy(event1);
cudaEventDestroy(event2);
```

Event

- Event

  `cudaEventSynchronize()`

  this function blocks until the event has actually been recorded , since the event recorder is an asynchronous method

  `cudaEventQuery()`

  provide any applications with a way to know if one specific event recorder in the stream have completed , which returns cudaSuccess

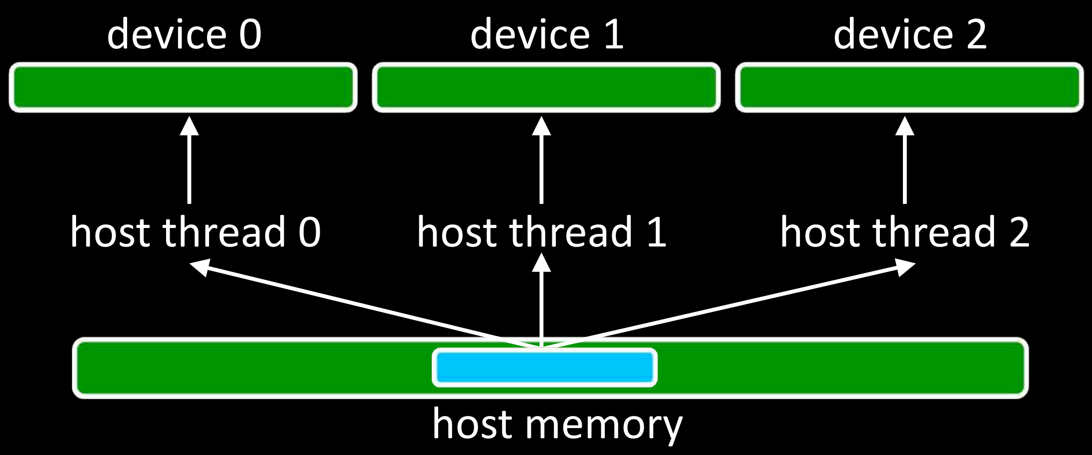
Multi-GPU

Multi-GPU

- GPU can not share global memory
  - one GPU can not access another GPUs memory directly
  - application code is responsible for moving data between GPUs

Multi-GPU

- A host thread can maintain one context at a time
  - need as many host threads as GPUs to maintain all device
  - multiple host threads can establish context with the same GPU
    hardware diver handles time-sharing and resource partitioning



Multi-GPU

- Device management calls

  `cudaGetDeviceCount()`

  returns the number of devices on the current system with compute capability greater or equal to 1.0, that are available for execution

  `cudaSetDevice()`

  set the specific device on which the active host thread executes the device code. If the host thread has already initialized he cuda runtime by calling non-device management runtime functions, returns error

  must be called prior to context creation, fails if the context has already been established, one can forces the context creation with cudaFree(0)

  `cudaGetDevice()`

  returns the device on which the active host thread executes the code

Multi-GPU

- Device management calls

  `cudaThreadExit()`

  explicitly clean up all runtime-related resource associated with the calling host thread, any subsequent calls reinitializes the runtime, this function is implicitly called on the host thread exit

  `cudaGetDeviceProperties()`

  returns the properties of one specific device, this is useful when a system contains different devices in order to choose best devices

- Reference
  - Mark Harris http://www.markmark.net/
  - Wei-Chao Chen http://www.cs.unc.edu/~ciao/
  - Wen-Mei Hwu http://impact.crhc.illinois.edu/people/current/hwu.php