CSE 591: GPU Programming

Memories: Constant and Texture

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Code examples from Shane Cook "CUDA Programming"

Constant Memory: Introduction

What is it?

- a *virtual* addressing of global memory
- no specially reserved constant memory space
- read-only

How can you use it?

- declare at compile time by __constant__ keyword (fastest)
- write at run time using *cudaCopyToSymbol()* before kernel invocation

How can it help you?

- it is cached and so enables single-cycle access when data is in cache
- can broadcast a single value to all the threads within a warp

Constant Memory Caching

Compute 1.x devices (pre-Fermi)

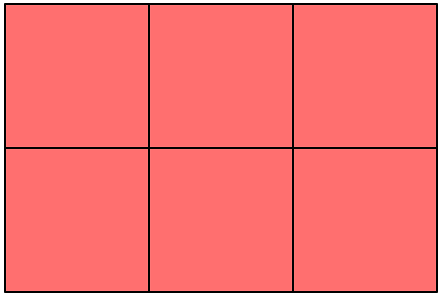
- per SM: 64K block with 8K cache size
- break program into 8K chunks to make best use of cache

Avoid irregular data accesses with bad locality

- not a good use of constant memory
- incurs global memory access overhead + cache write/access overhead

Break program into 64K sized tiles or even better, 8K tiles

- makes efficient use of cache



Constant Memory Caching

Compute 2.x devices

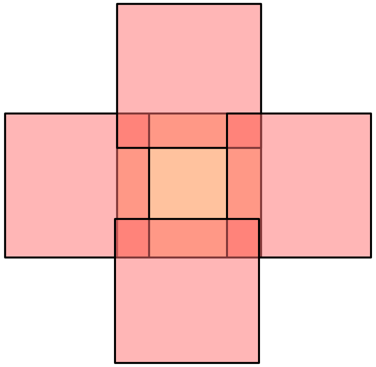
- here *any* constant section of data can be treated as constant memory
- use keyword *const* and access will go through the constant cache
- but it has to be non-thread → indexing must not include *threadIdx.x*

For per-thread acess

- need to declare with __constant__ at compile time
- or use *cudaCopyToSymbol()* before kernel invocation

One thing to keep in mind

- these devices also have L2 cache (much larger than constant cache)
- L2 cache might collect some information automatically
  example: boundary (halo) cells of
  tiles needed for processing other tiles
- might work quicker in some cases
- also saves memory



Constant Memory Broadcast

Also supported in L2 cache

Comes in handy when all threads require the same data item

- for example: rotation matrix in graphics
  convolution mask in image processing
- this item is provided in a single cycle to all the threads in the warp

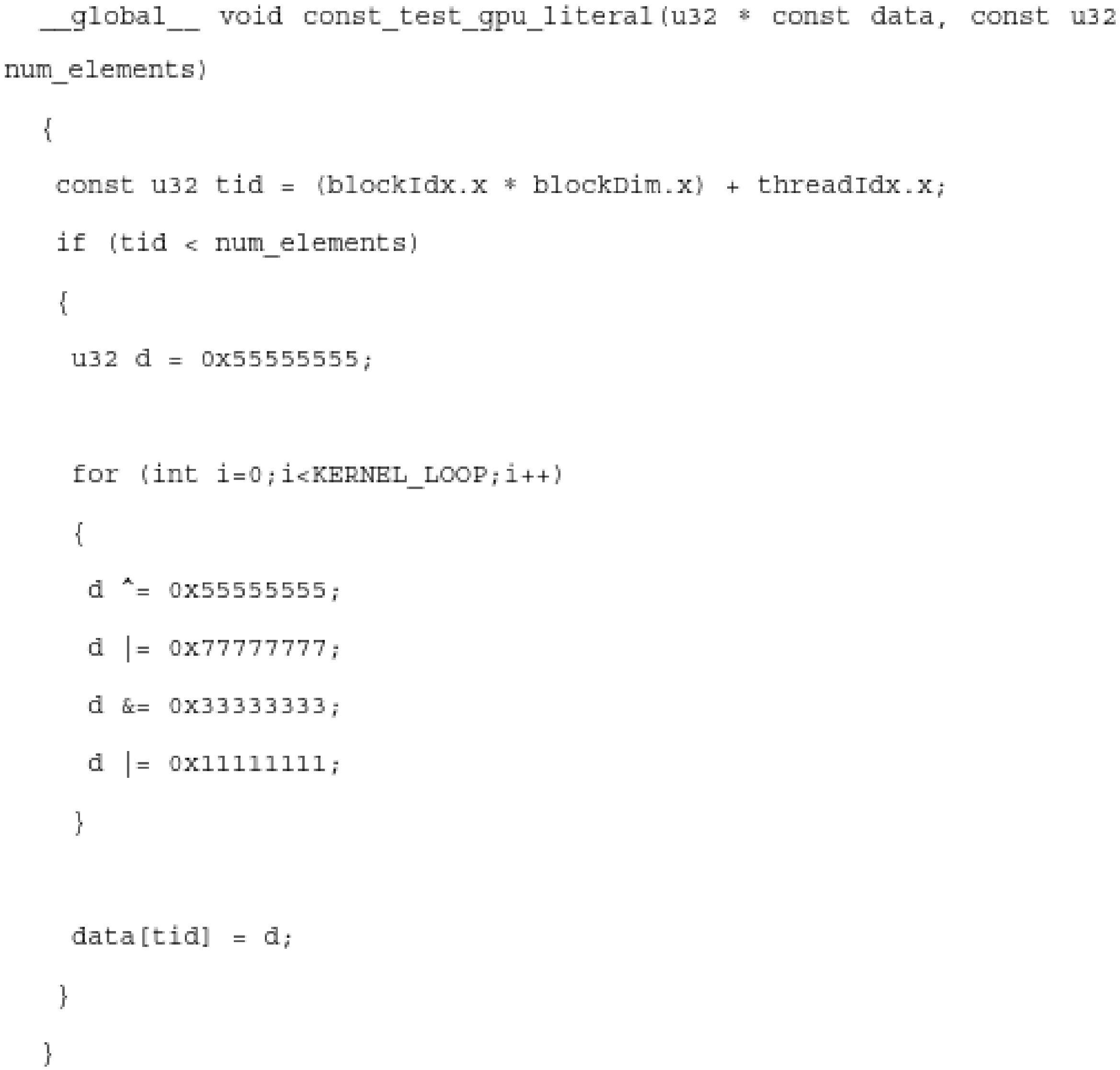
Be aware of literals

- will be wasteful to keep in constant memory
- rather use #define statement
- for example: #define PI 33.14159265359 (or more digits)
- or d += 676136.89
- speed is the same, but memory storage is different

For the following program

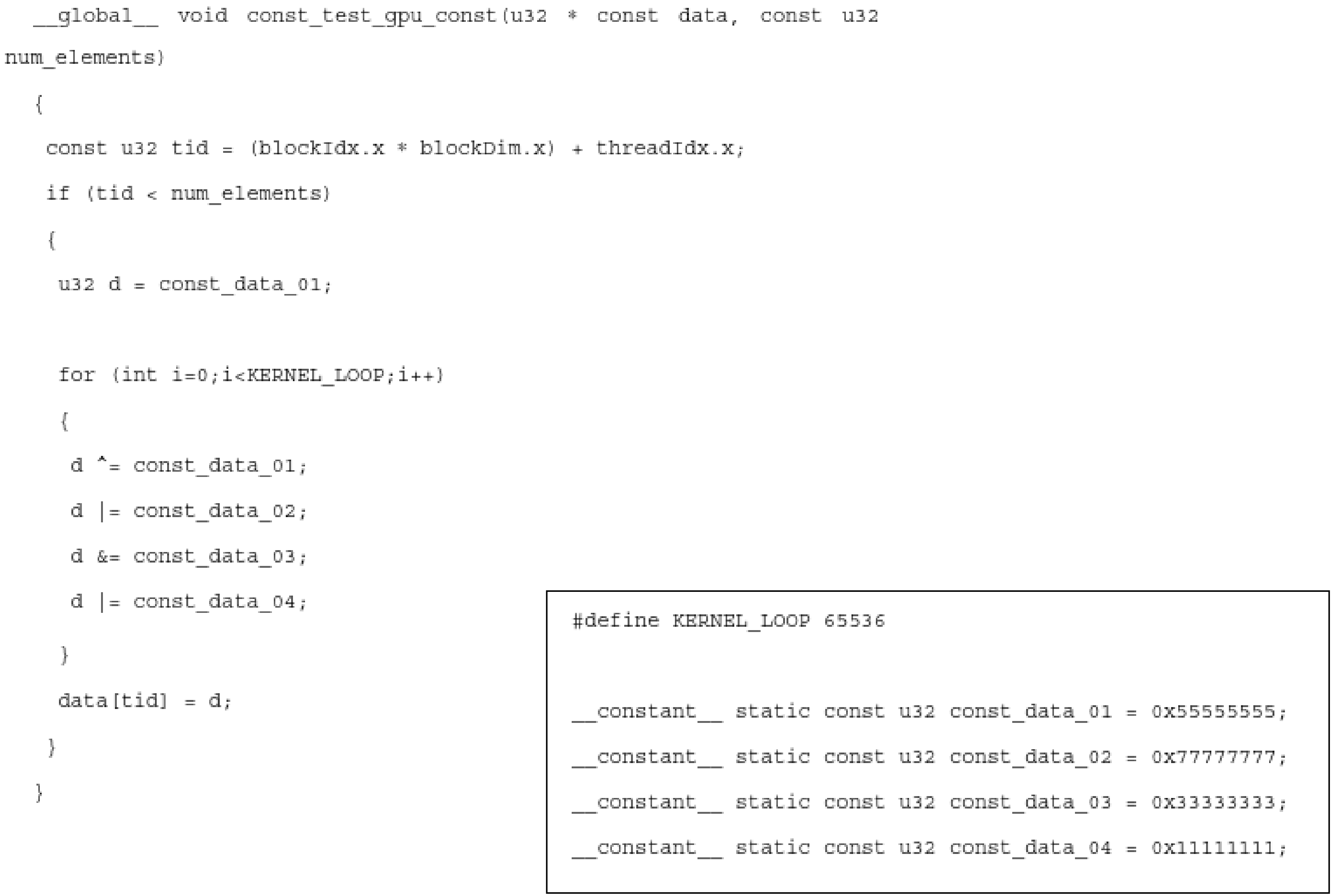
- &, |, and ^ are bitwise AND. OR, and XOR operators

Example Version 1: With Literals



```
  __global__ void const_test_gpu_literal(u32 * const data, const u32
num_elements)
  {
   const u32 tid = (blockIdx.x * blockDim.x) + threadIdx.x;
   if (tid < num_elements)
   {
    u32 d = 0x55555555;

    for (int i=0;i<KERNEL_LOOP;i++)
    {
     d ^= 0x55555555;
     d |= 0x77777777;
     d &= 0x33333333;
     d |= 0x11111111;
    }

    data[tid] = d;
   }
  }
```

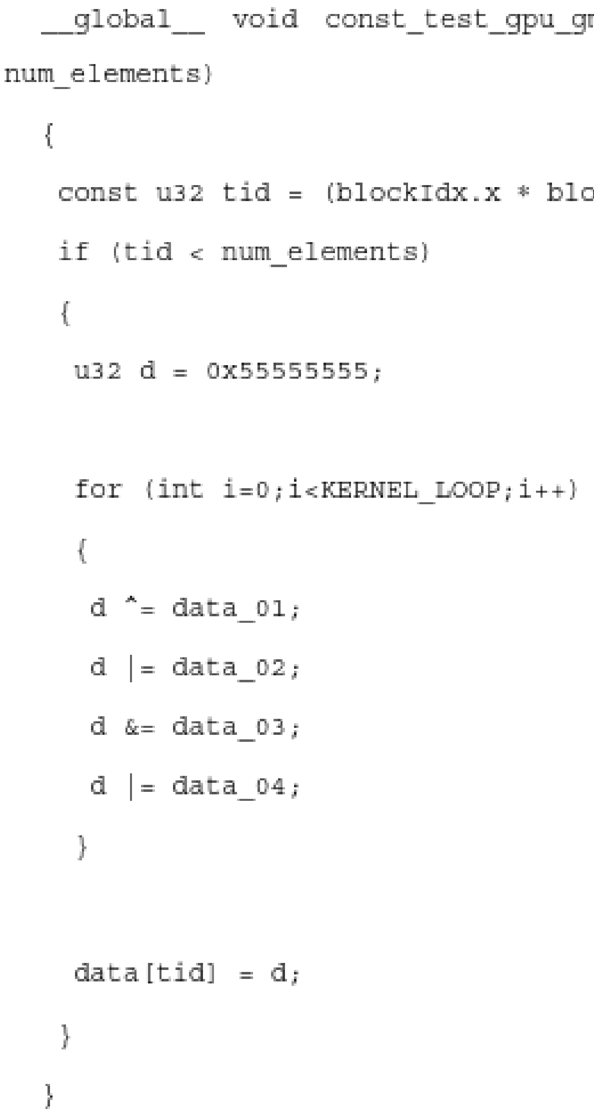
Example Version 2: With Constant Memory



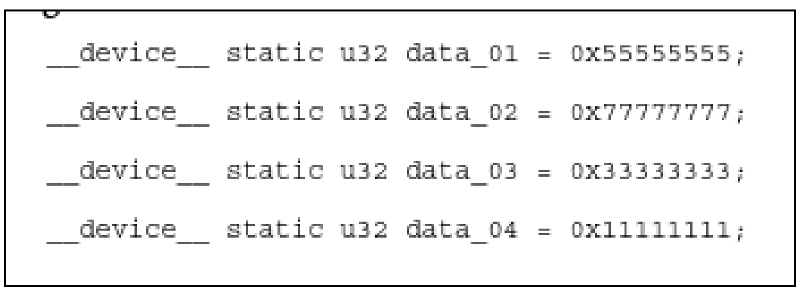
```
  __global__ void const_test_gpu_const(u32 * const data, const u32
num_elements)
  {
   const u32 tid = (blockIdx.x * blockDim.x) + threadIdx.x;
   if (tid < num_elements)
   {
    u32 d = const_data_01;

    for (int i=0;i<KERNEL_LOOP;i++)
    {
     d ^= const_data_01;
     d |= const_data_02;
     d &= const_data_03;
     d |= const_data_04;
    }
    data[tid] = d;
   }
  }
```

```
#define KERNEL_LOOP 65536

__constant__ static const u32 const_data_01 = 0x55555555;
__constant__ static const u32 const_data_02 = 0x77777777;
__constant__ static const u32 const_data_03 = 0x33333333;
__constant__ static const u32 const_data_04 = 0x11111111;
```

Example Version 3: With Global Memory



```
  __global__ void const_test_gpu_gmem(u32 * const data, const u32
num_elements)
  {
   const u32 tid = (blockIdx.x * blockDim.x) + threadIdx.x;
   if (tid < num_elements)
   {
    u32 d = 0x55555555;

    for (int i=0;i<KERNEL_LOOP;i++)
    {
     d ^= data_01;
     d |= data_02;
     d &= data_03;
     d |= data_04;
    }

    data[tid] = d;
   }
  }
```



```
__device__ static u32 data_01 = 0x55555555;
__device__ static u32 data_02 = 0x77777777;
__device__ static u32 data_03 = 0x33333333;
__device__ static u32 data_04 = 0x11111111;
```

Runtime Comparison (1)

Compare literal with constant memory

- only small differences, neck to neck race

```
  ID:3 GeForce GTX 460:Literal  version is faster by: 0.59ms (C=541.43ms,
L=542.02ms)
  ID:3 GeForce GTX 460:Literal  version is faster by: 0.17ms (C=541.20ms,
L=541.37ms)
  ID:3 GeForce GTX 460:Constant version is faster by: 0.45ms (C=542.29ms,
L=541.83ms)
  ID:3 GeForce GTX 460:Constant version is faster by: 0.27ms (C=542.17ms,
L=541.89ms)
  ID:3 GeForce GTX 460:Constant version is faster by: 1.17ms (C=543.55ms,
L=542.38ms)
  ID:3 GeForce GTX 460:Constant version is faster by: 0.24ms (C=542.92ms,
L=542.68ms)
```

Runtime Comparison (2)

Compare literal with global memory

Speedups:

- compute 1.1 hardware (9800GT): 40:1
- compute 1.3 hardware (GTX260): 3:1
- compute 2.0 hardware (GTX470):1.8:1
- compute 2.1 hardware (GTX460):1.6:1
- appears that even L2 devices can benefit from constant memory

Further Examination

It is interesting that constant and literal was equal speed

- shouldn’t constant be slower?

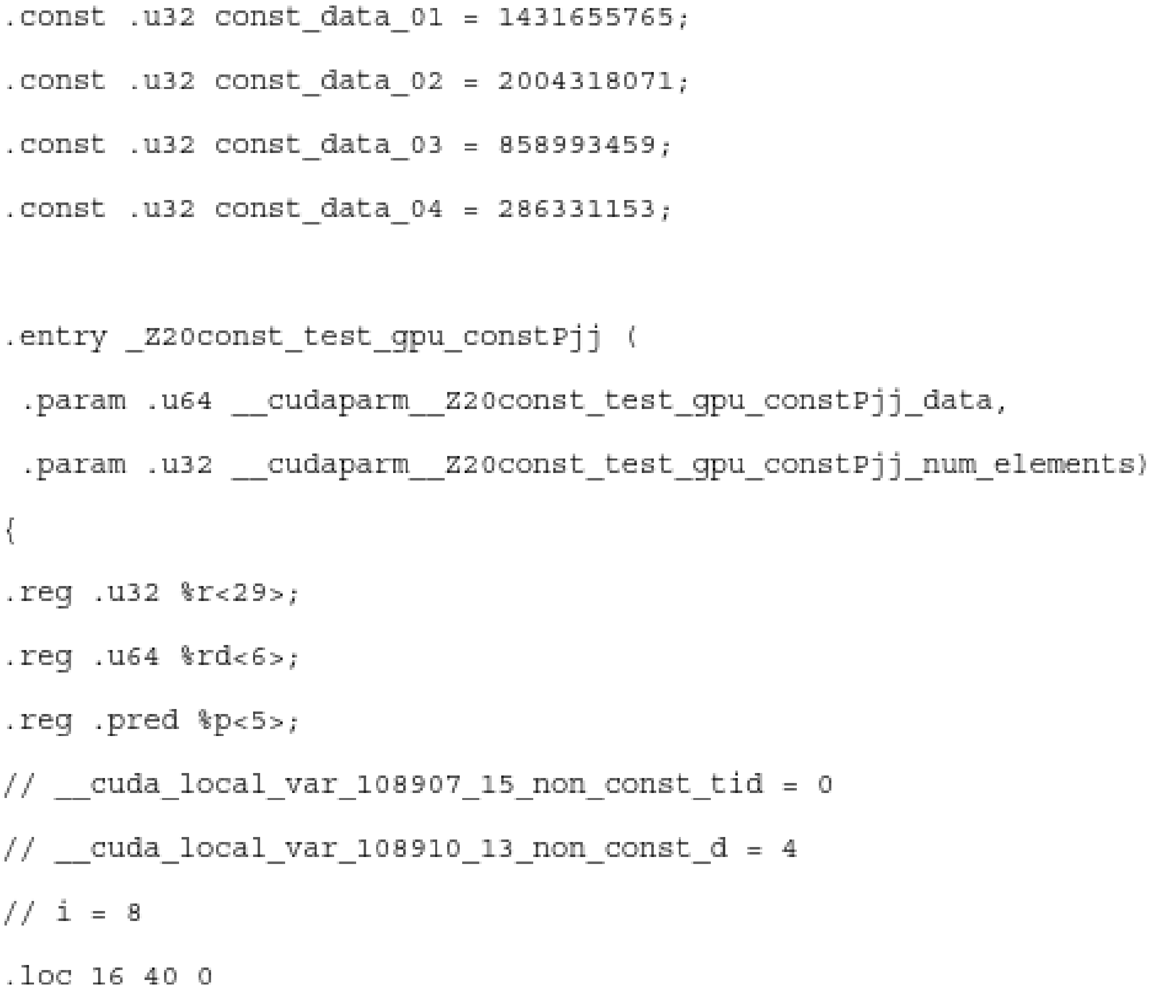
Also, it is interesting that global was slower for all hardware

- shouldn’t devices with L2 cache be better?

Have a look at PTX code

- it is a good habit to look at PTX code when something is unclear
- common practice among experience GPU programmers

PTX Code for Constant Kernel (1)

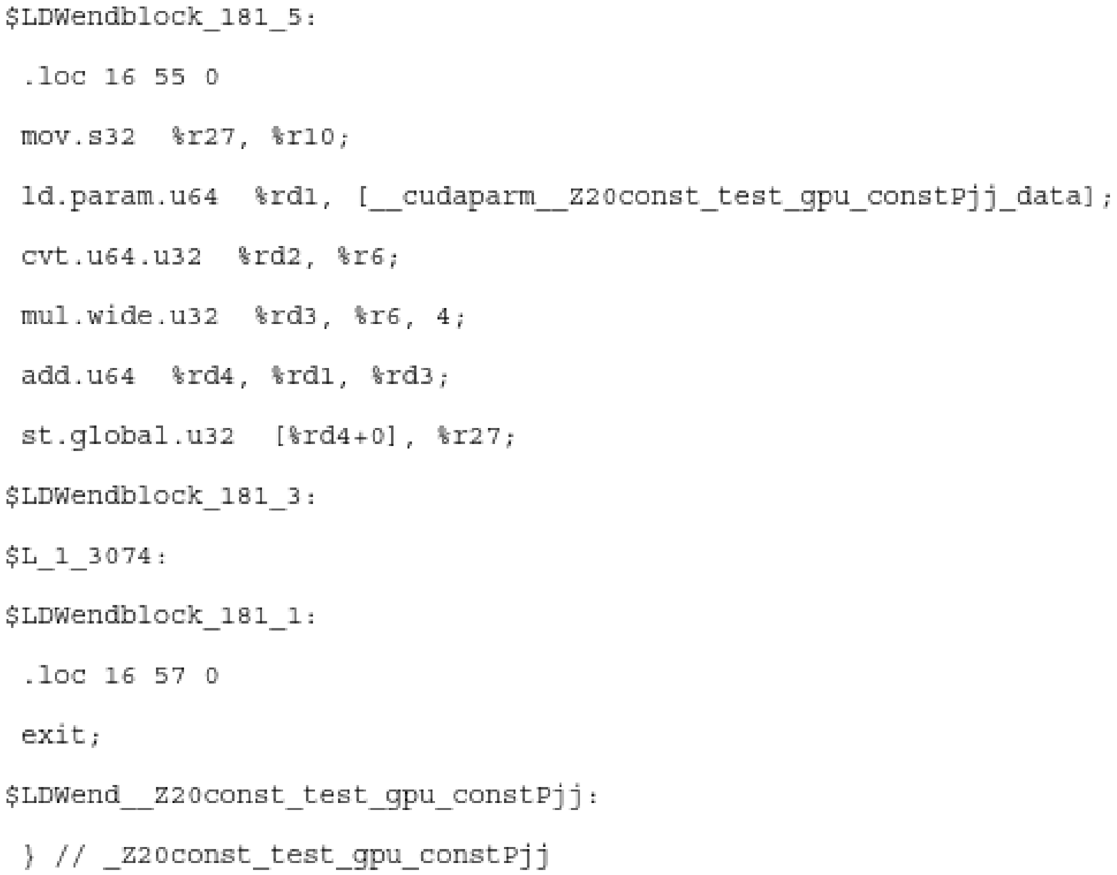


```
.const .u32 const_data_01 = 1431655765;
.const .u32 const_data_02 = 2004318071;
.const .u32 const_data_03 = 858993459;
.const .u32 const_data_04 = 286331153;

.entry _Z20const_test_gpu_constPjj (
 .param .u64 __cudaparm__Z20const_test_gpu_constPjj_data,
 .param .u32 __cudaparm__Z20const_test_gpu_constPjj_num_elements)
{
.reg .u32 %r<29>;
.reg .u64 %rd<6>;
.reg .pred %p<5>;
// __cuda_local_var_108907_15_non_const_tid = 0
// __cuda_local_var_108910_13_non_const_d = 4
// i = 8
.loc 16 40 0
```

```
$LDWbegin__Z20const_test_gpu_constPjj:
$LDWbeginblock_181_1:
 .loc 16 42 0
 mov.u32  %r1, %tid.x;
 mov.u32  %r2, %ctaid.x;
 mov.u32  %r3, %ntid.x;
 mul.lo.u32  %r4, %r2, %r3;
 add.u32  %r5, %r1, %r4;
 mov.s32  %r6, %r5;
 .loc 16 43 0
 ld.param.u32                                                  %r7,
[__cudaparm__Z20const_test_gpu_constPjj_num_elements];
 mov.s32  %r8, %r6;
 setp.le.u32  %p1, %r7, %r8;
 @%p1 bra  $L_1_3074;
$LDWbeginblock_181_3:
 .loc 16 45 0
 mov.u32  %r9, 1431655765;
 mov.s32  %r10, %r9;
$LDWbeginblock_181_5:
 .loc 16 47 0
 mov.s32  %r11, 0;
 mov.s32  %r12, %r11;
 mov.s32  %r13, %r12;
 mov.u32  %r14, 4095;
 setp.gt.s32  %p2, %r13, %r14;
 @%p2 bra  $L_1_3586;
```

```
$L_1_3330:
 .loc 16 49 0
 mov.s32  %r15, %r10;
 xor.b32  %r16, %r15, 1431655765;
 mov.s32  %r10, %r16;
 .loc 16 50 0
 mov.s32  %r17, %r10;
 or.b32  %r18, %r17, 2004318071;
 mov.s32  %r10, %r18;
 .loc 16 51 0
 mov.s32  %r19, %r10;
 and.b32  %r20, %r19, 858993459;
 mov.s32  %r10, %r20;
 .loc 16 52 0
 mov.s32  %r21, %r10;
 or.b32  %r22, %r21, 286331153;
 mov.s32  %r10, %r22;
 .loc 16 47 0
 mov.s32  %r23, %r12;
 add.s32  %r24, %r23, 1;
 mov.s32  %r12, %r24;
$Lt_1_1794:
 mov.s32  %r25, %r12;
 mov.u32  %r26, 4095;
 setp.le.s32  %p3, %r25, %r26;
 @%p3 bra  $L_1_3330;
$L_1_3586:
```

PTX Code for Constant Kernel (3)



```
$LDWendblock_181_5:
 .loc 16 55 0
 mov.s32  %r27, %r10;
 ld.param.u64  %rd1, [__cudaparm__Z20const_test_gpu_constPjj_data];
 cvt.u64.u32  %rd2, %r6;
 mul.wide.u32  %rd3, %r6, 4;
 add.u64  %rd4, %rd1, %rd3;
 st.global.u32  [%rd4+0], %r27;
$LDWendblock_181_3:
$L_1_3074:
$LDWendblock_181_1:
 .loc 16 57 0
 exit;
$LDWend__Z20const_test_gpu_constPjj:
 } // _Z20const_test_gpu_constPjj
```

Discussion of PTX Code

Compiler smartly converted constants into literals

- so the difference is hidden

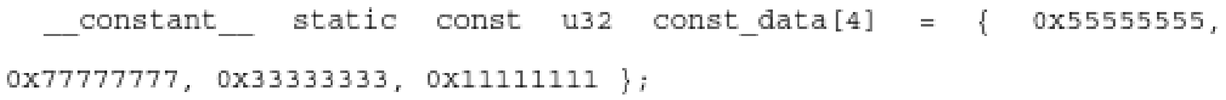
Let’s have a look at the global memory version

```
ld.global.u32  %r16, [data_01];

xor.b32  %r17, %r15, %r16;
```

- now an actual memory read occurs
- supported by L2 cache in new architectures

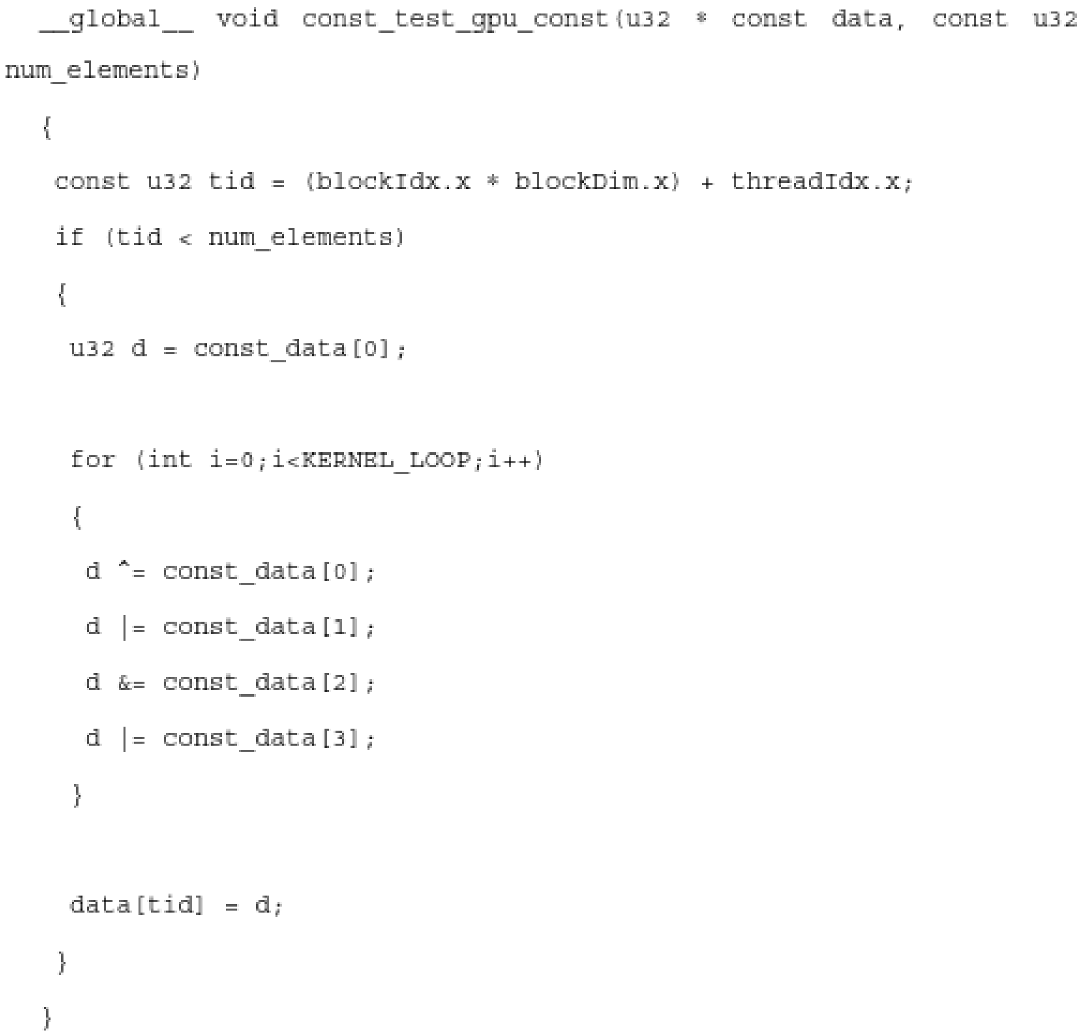
How can we really test the constant memory caching?

- declare the constant version as an array



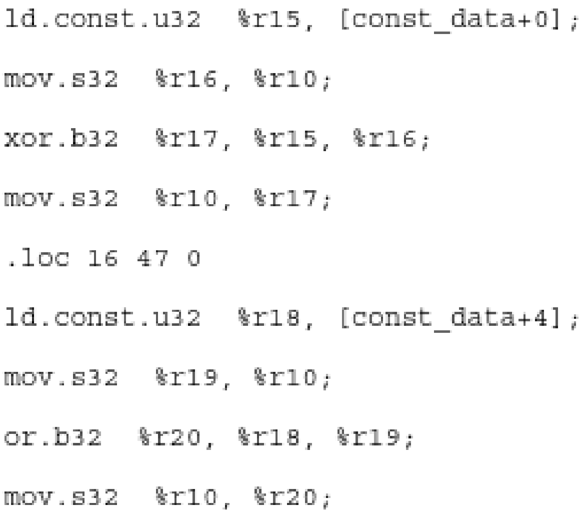
```
    __constant__  static  const  u32  const_data[4]  =  {  0x55555555,
0x77777777, 0x33333333, 0x11111111 };
```

Example Version 4: With Constant Memory (Array)



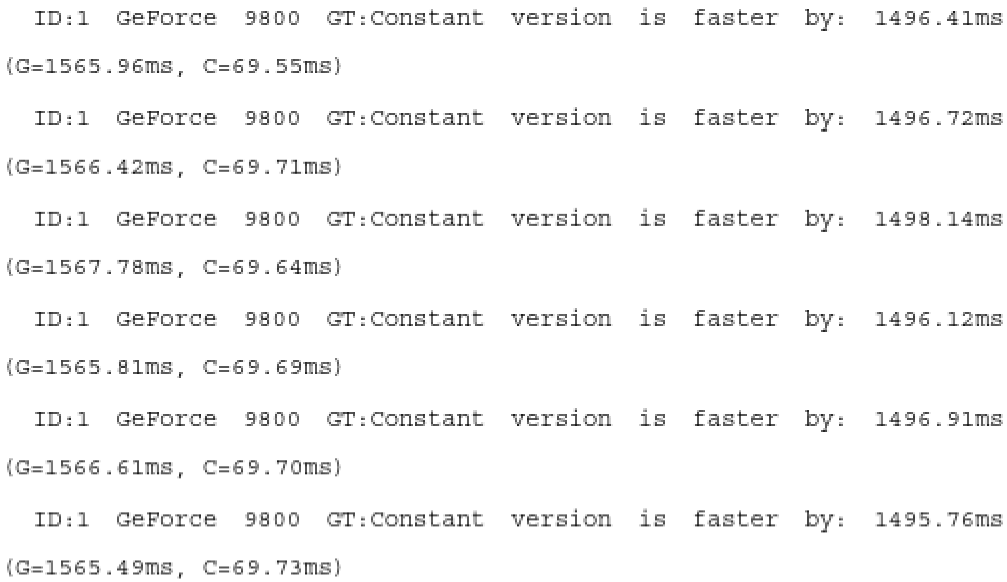
```
  __global__ void const_test_gpu_const(u32 * const data, const u32
num_elements)
  {
   const u32 tid = (blockIdx.x * blockDim.x) + threadIdx.x;
   if (tid < num_elements)
   {
    u32 d = const_data[0];

    for (int i=0;i<KERNEL_LOOP;i++)
    {
     d ^= const_data[0];
     d |= const_data[1];
     d &= const_data[2];
     d |= const_data[3];
    }

    data[tid] = d;
   }
  }
```

Discussion of PTX Code



```
ld.const.u32  %r15, [const_data+0];
mov.s32  %r16, %r10;
xor.b32  %r17, %r15, %r16;
mov.s32  %r10, %r17;
.loc 16 47 0
ld.const.u32  %r18, [const_data+4];
mov.s32  %r19, %r10;
or.b32  %r20, %r18, %r19;
mov.s32  %r10, %r20;
```

Discussion of PTX Code



```
  ID:1  GeForce  9800  GT:Constant  version  is  faster  by:  1496.41ms
(G=1565.96ms, C=69.55ms)
  ID:1  GeForce  9800  GT:Constant  version  is  faster  by:  1496.72ms
(G=1566.42ms, C=69.71ms)
  ID:1  GeForce  9800  GT:Constant  version  is  faster  by:  1498.14ms
(G=1567.78ms, C=69.64ms)
  ID:1  GeForce  9800  GT:Constant  version  is  faster  by:  1496.12ms
(G=1565.81ms, C=69.69ms)
  ID:1  GeForce  9800  GT:Constant  version  is  faster  by:  1496.91ms
(G=1566.61ms, C=69.70ms)
  ID:1  GeForce  9800  GT:Constant  version  is  faster  by:  1495.76ms
(G=1565.49ms, C=69.73ms)
```

without L2 cache the winner is constant memory

with L2 cache the winner is global memory

```
  ID:3 GeForce GTX 460:GMEM  version is faster by: 0.20ms (G=54.18ms,
C=54.38ms)
  ID:3 GeForce GTX 460:GMEM  version is faster by: 0.17ms (G=54.86ms,
C=55.03ms)
  ID:3 GeForce GTX 460:GMEM  version is faster by: 0.25ms (G=54.83ms,
C=55.07ms)
  ID:3 GeForce GTX 460:GMEM  version is faster by: 0.81ms (G=54.24ms,
C=55.05ms)
  ID:3 GeForce GTX 460:GMEM  version is faster by: 1.51ms (G=53.54ms,
C=55.05ms)
  ID:3 GeForce GTX 460:Constant version is faster by: 1.14ms (G=54.83ms,
C=53.69ms)
```

Lessons Learned

Always check out PTX code to get insight

Be creative to get the insight you want

- here we changed into an array although we did not need to
- applied the knowledge that arrays never become literals
- it can be a detective problem

Constant Memory Updates At Runtime

Recall

- constant memory is not really constant memory
- there is no dedicated special area of memory set aside
- the 64 K limit is exactly a 16-bit offset
- this allows very quick 16-bit addressing

Constant memory can be updated in chunks/tiles at run time

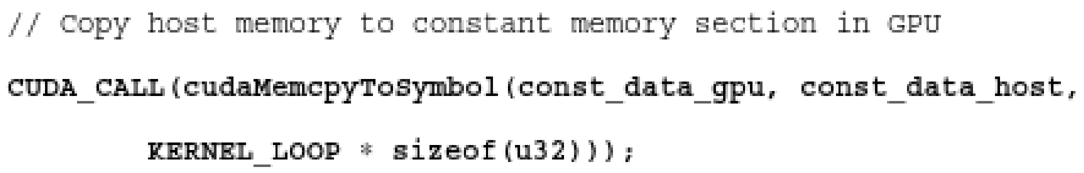
- of up to 64K at a time
- use *cudaCopyToSymbol()* API call
- but this can be expensive – do not do this in loops!

Update Example

Create some data on the host and use the API call

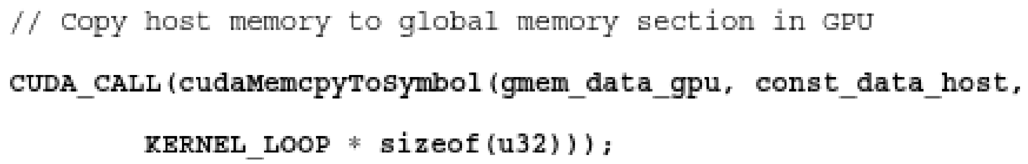
```
generate_rand_data(const_data_host);
```

- the constant memory case



```
// Copy host memory to constant memory section in GPU
CUDA_CALL(cudaMemcpyToSymbol(const_data_gpu, const_data_host,
        KERNEL_LOOP * sizeof(u32)));
```

- the global memory case



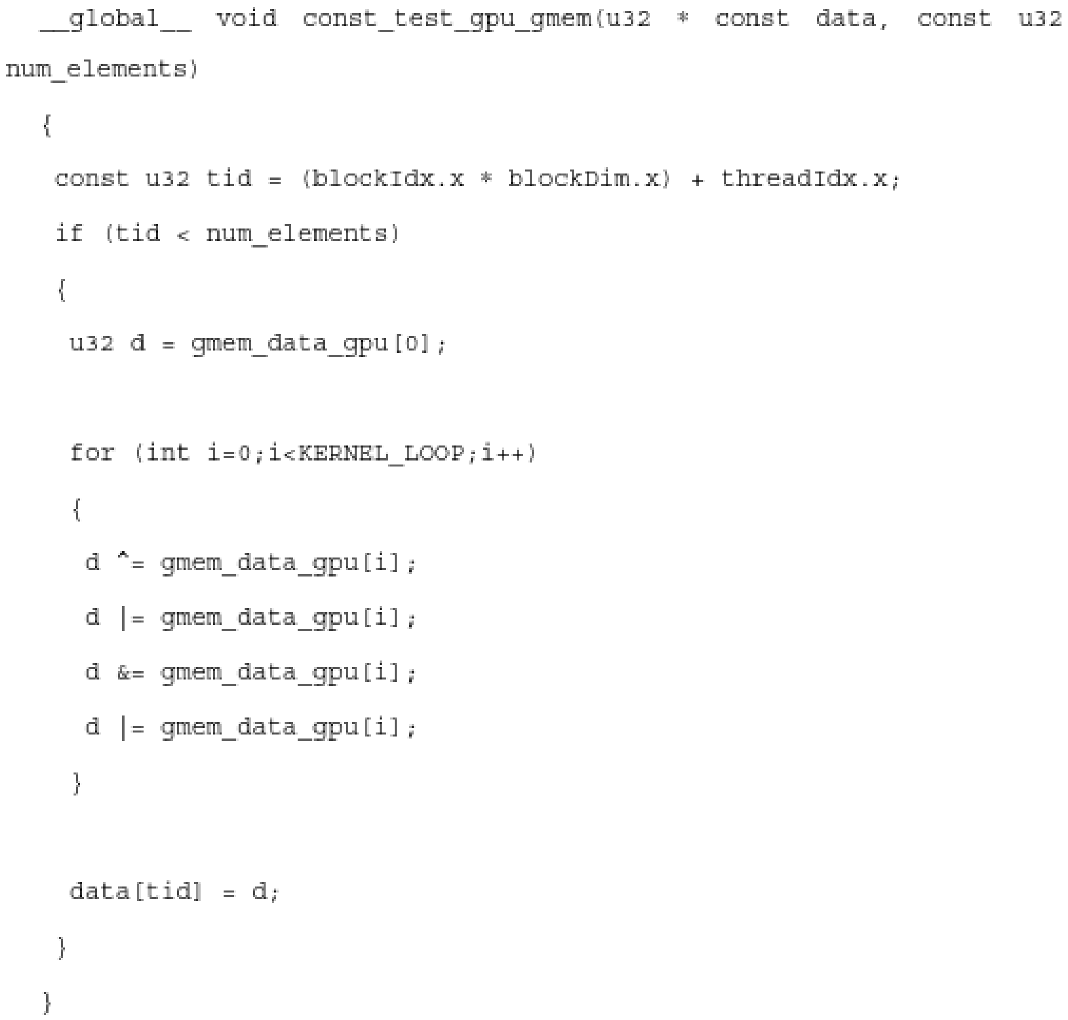
```
// Copy host memory to global memory section in GPU
CUDA_CALL(cudaMemcpyToSymbol(gmem_data_gpu, const_data_host,
        KERNEL_LOOP * sizeof(u32)));
```

For each case, launch the respective CUDA kernel

Update Example: Constant Memory

```
__global__ void const_test_gpu_const(u32 * const data, const u32 num_elements)
{
 const u32 tid = (blockIdx.x * blockDim.x) + threadIdx.x;
 if (tid < num_elements)
 {
  u32 d = const_data_gpu[0];

  for (int i=0;i<KERNEL_LOOP;i++)
  {
   d ^= const_data_gpu[i];
   d |= const_data_gpu[i];
   d &= const_data_gpu[i];
   d |= const_data_gpu[i];
  }

  data[tid] = d;
 }
}
```

Update Example: Global Memory



```
  __global__  void  const_test_gpu_gmem(u32  *  const  data,  const  u32
num_elements)
  {
   const u32 tid = (blockIdx.x * blockDim.x) + threadIdx.x;
   if (tid < num_elements)
   {
    u32 d = gmem_data_gpu[0];

    for (int i=0;i<KERNEL_LOOP;i++)
    {
     d ^= gmem_data_gpu[i];
     d |= gmem_data_gpu[i];
     d &= gmem_data_gpu[i];
     d |= gmem_data_gpu[i];
    }

    data[tid] = d;
   }
  }
```