GPU TECHNOLOGY CONFERENCE

CUDA OPTIMIZATION WITH NVIDIA NSIGHT™ ECLIPSE EDITION

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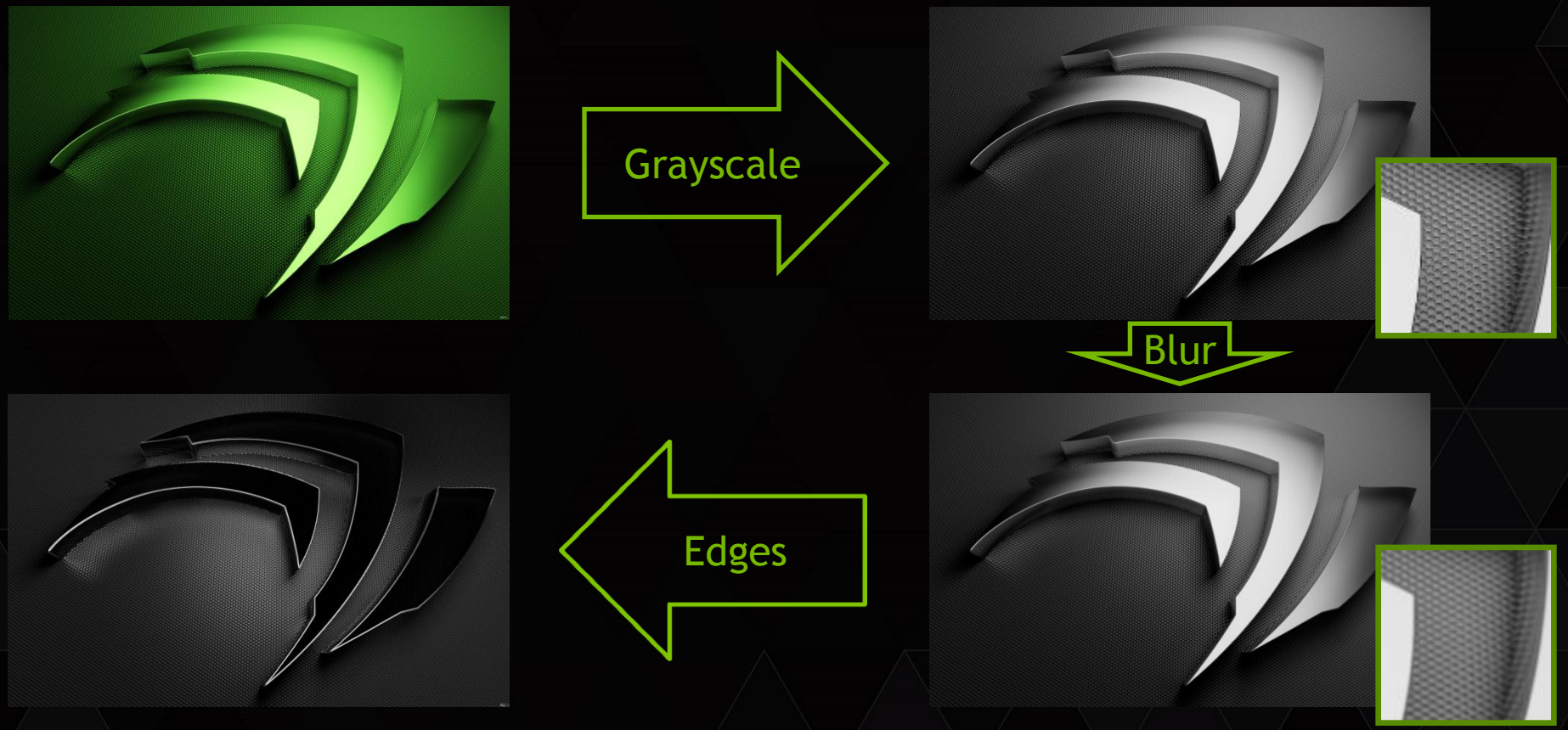
WHAT YOU WILL LEARN

- An iterative method to optimize your GPU code
- A way to conduct that method with NVIDIA Nsight EE
- Companion Code: https://github.com/chmaruni/nsight-gtc2015

INTRODUCING THE APPLICATION



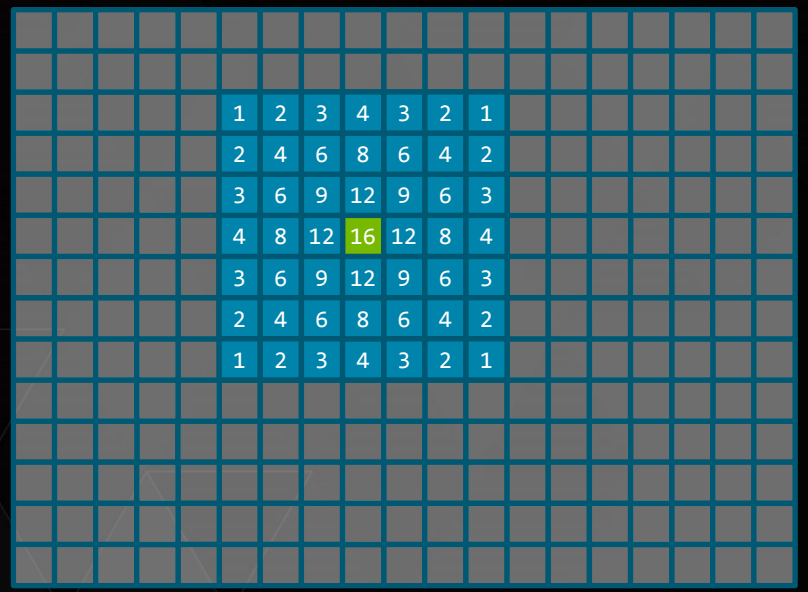
INTRODUCING THE APPLICATION

- Grayscale Conversion

```
// r, g, b: Red, green, blue components of the pixel p
foreach pixel p:
  p = 0.298839f*r + 0.586811f*g + 0.114350f*b;
```

INTRODUCING THE APPLICATION

- Blur: 7x7 Gaussian Filter




```
foreach pixel p:
  p = weighted sum of p and its 48 neighbors
```

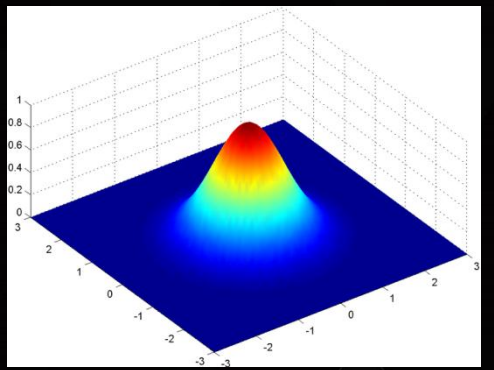
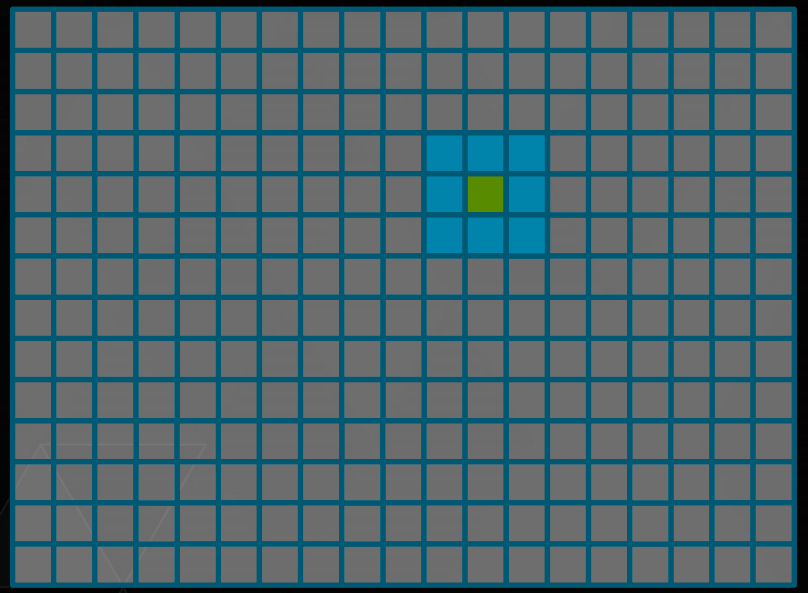


Image from Wikipedia

INTRODUCING THE APPLICATION

- Edges: 3x3 Sobel Filters



```
foreach pixel p:
  Gx = weighted sum of p and its 8 neighbors
  Gy = weighted sum of p and its 8 neighbors
  p  = sqrt(Gx + Gy)
```

Weights for Gx:

-1	0	1
-2	0	2
-1	0	1

Weights for Gy:

1	2	1
0	0	0
-1	-2	-1

ENVIRONMENT

- NVIDIA Tesla K40m
  - GK110B
  - SM3.5
  - ECC off
  - 3004 MHz memory clock, 875 MHz SM clock
- NVIDIA CUDA 7.0 release candidate

- Similar results are obtained on Windows

PERFORMANCE OPTIMIZATION CYCLE

1. Profile Application

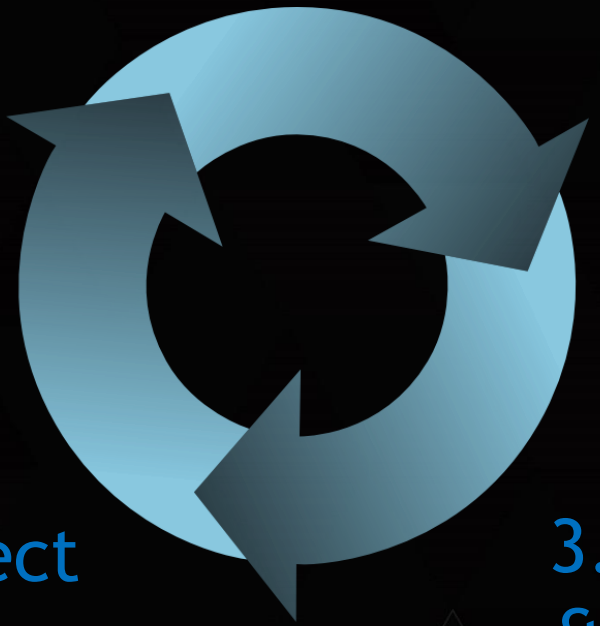
2. Identify Performance Limiter

3. Analyze Profile & Find Indicators

4. Reflect

4b. Build Knowledge

5. Change and Test Code



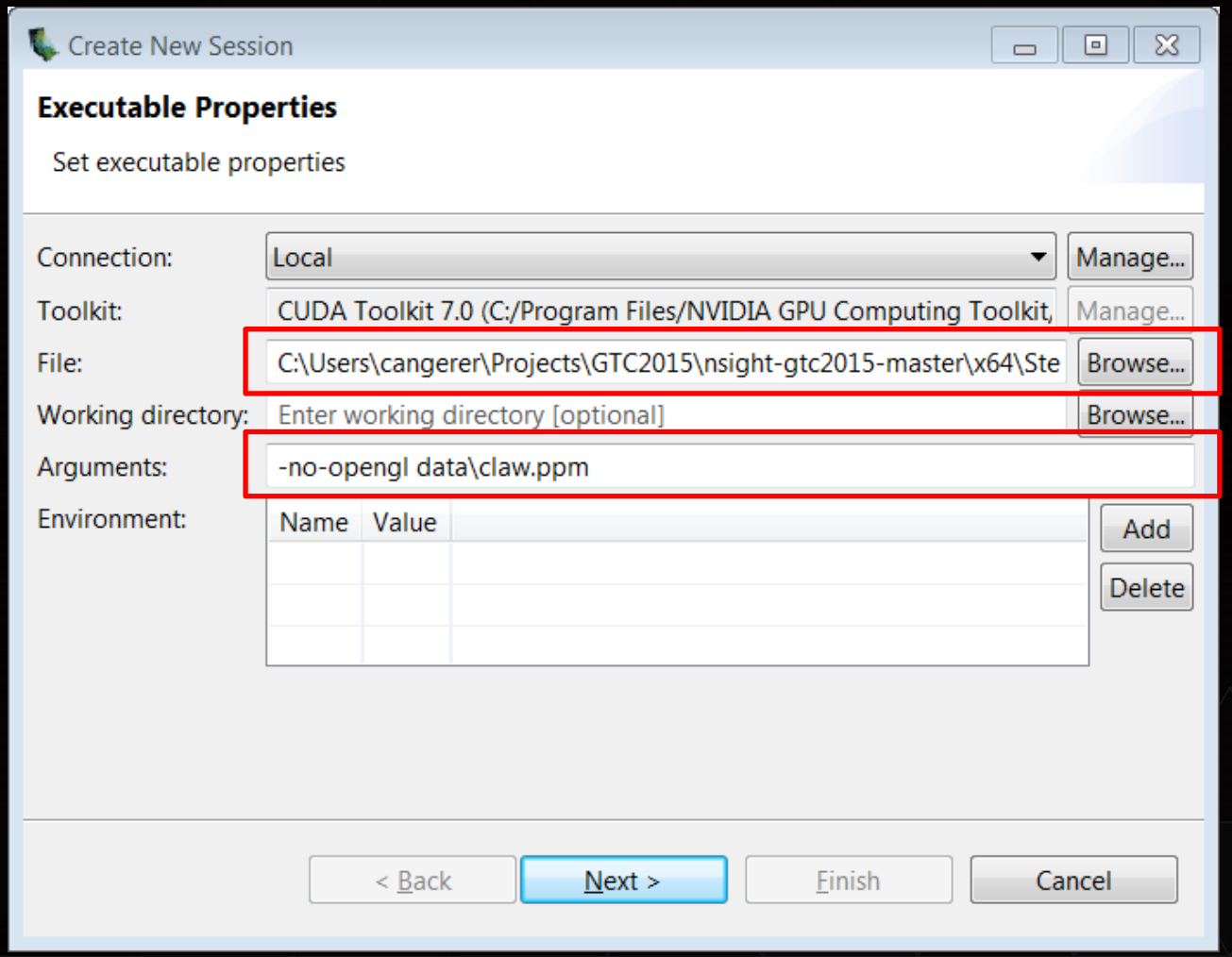
Chameleon from http://www.vectorportal.com, Creative Commons

PREREQUISITES

- Basic understanding of the GPU Memory Hierarchy
  - Global Memory (slow, generous)
  - Shared Memory (fast, limited)
  - Registers (very fast, very limited)
  - (Texture Cache)
- Basic understanding of the CUDA execution model
  - Grid 1D/2D/3D
  - Block 1D/2D/3D
  - Warp-synchronous execution (32 threads per warp)

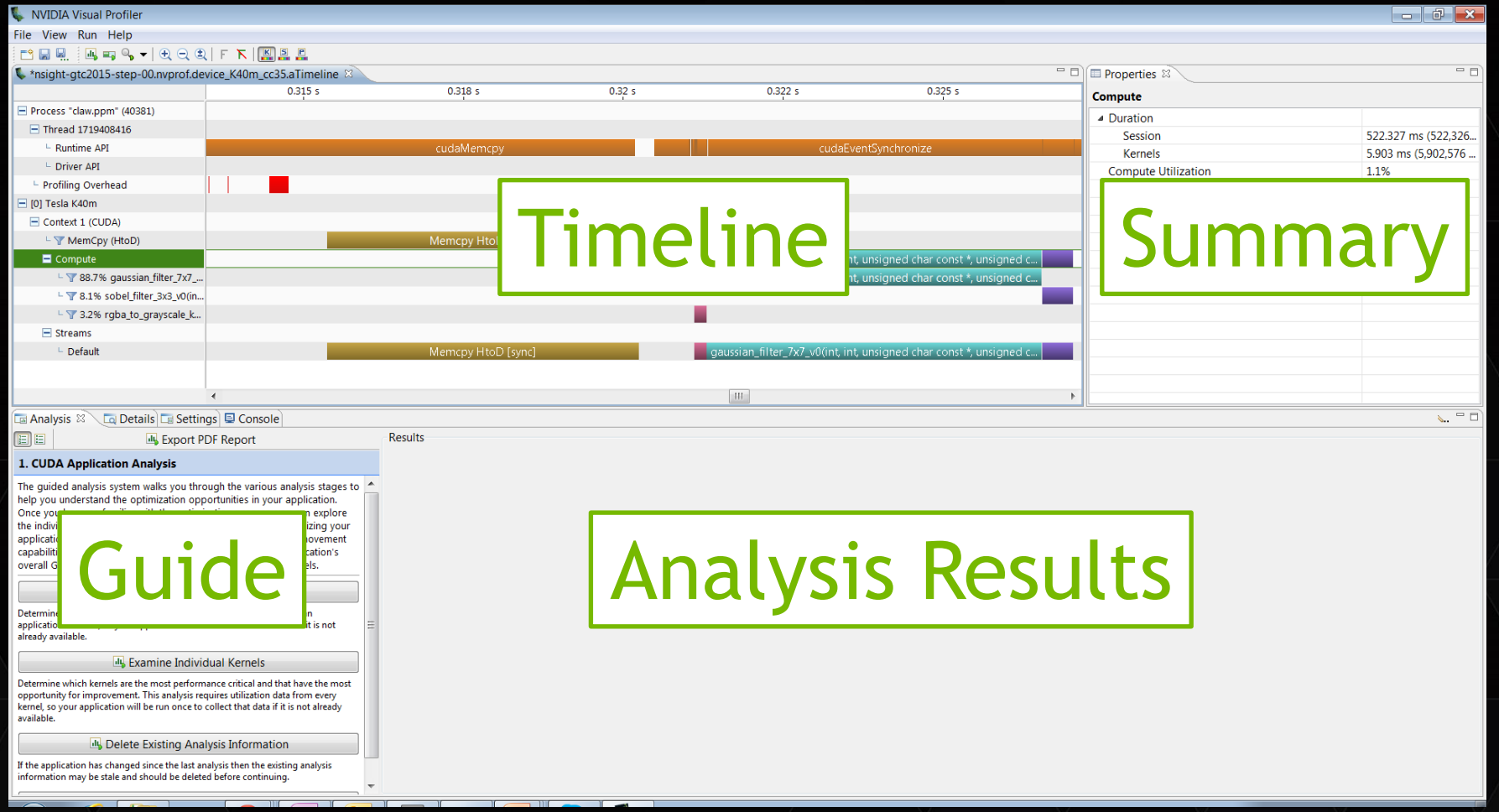
ITERATION 1

CREATE A NEW NVVP SESSION

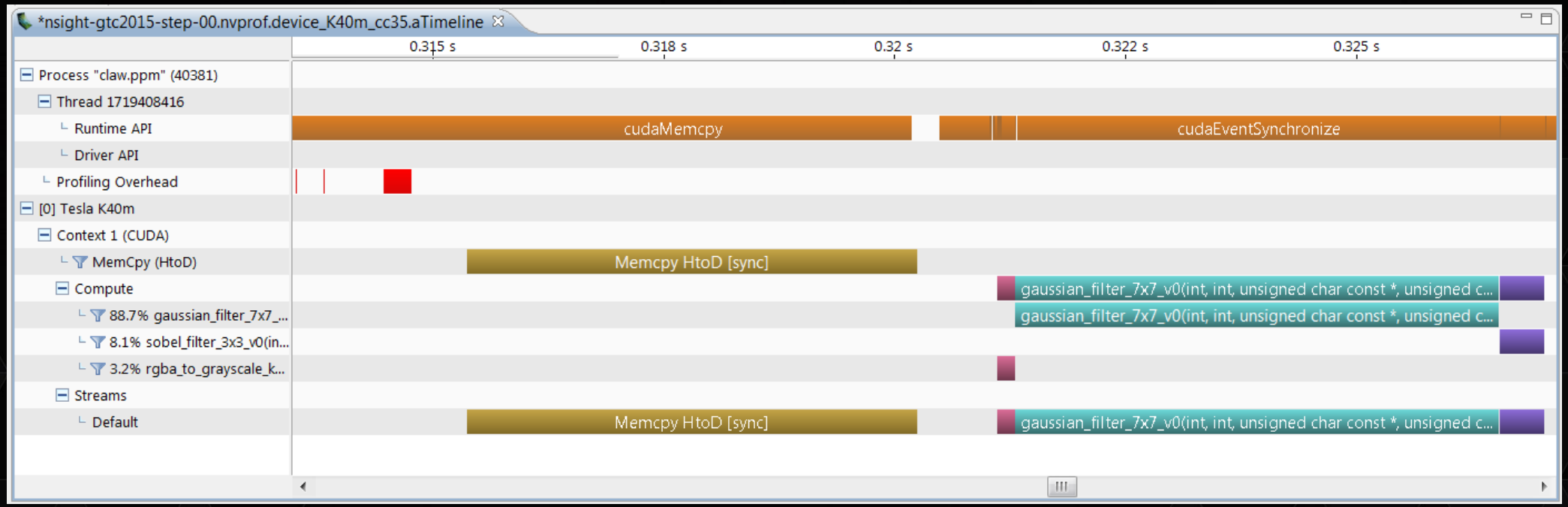


GPU TECHNOLOGY CONFERENCE

THE PROFILER WINDOW

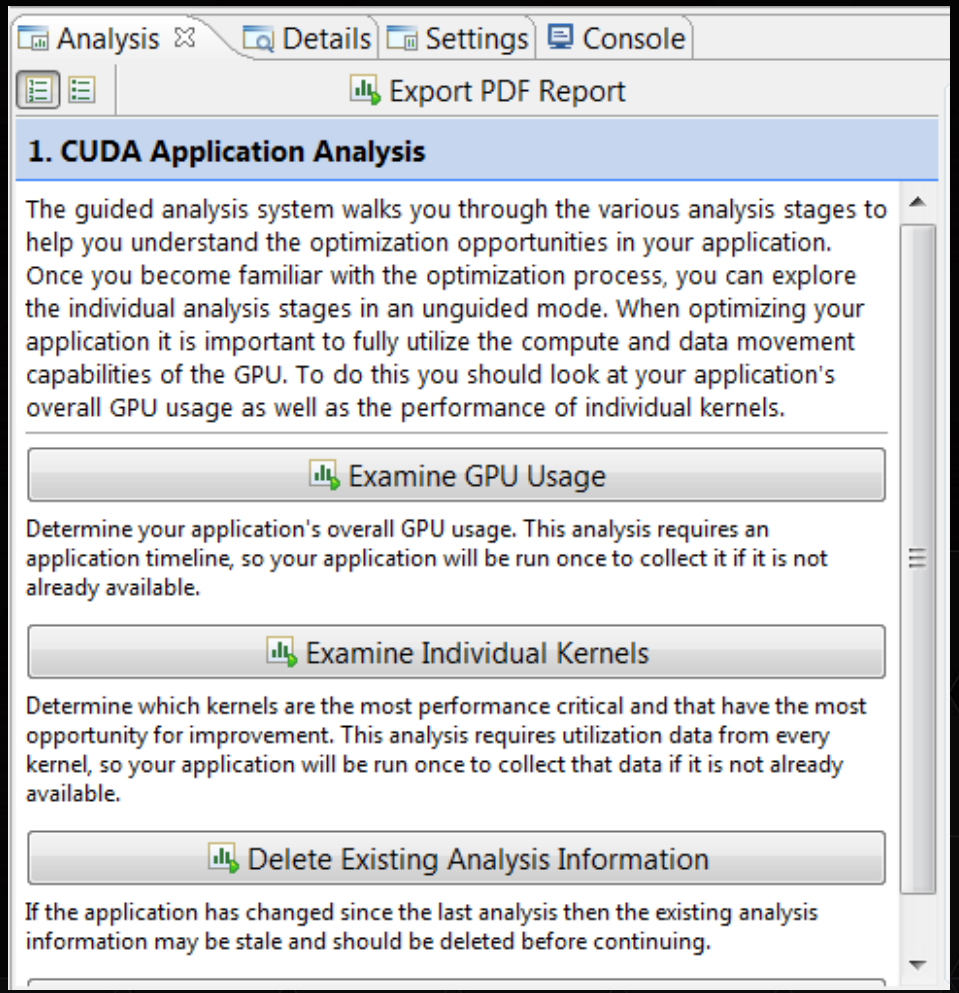


TIMELINE



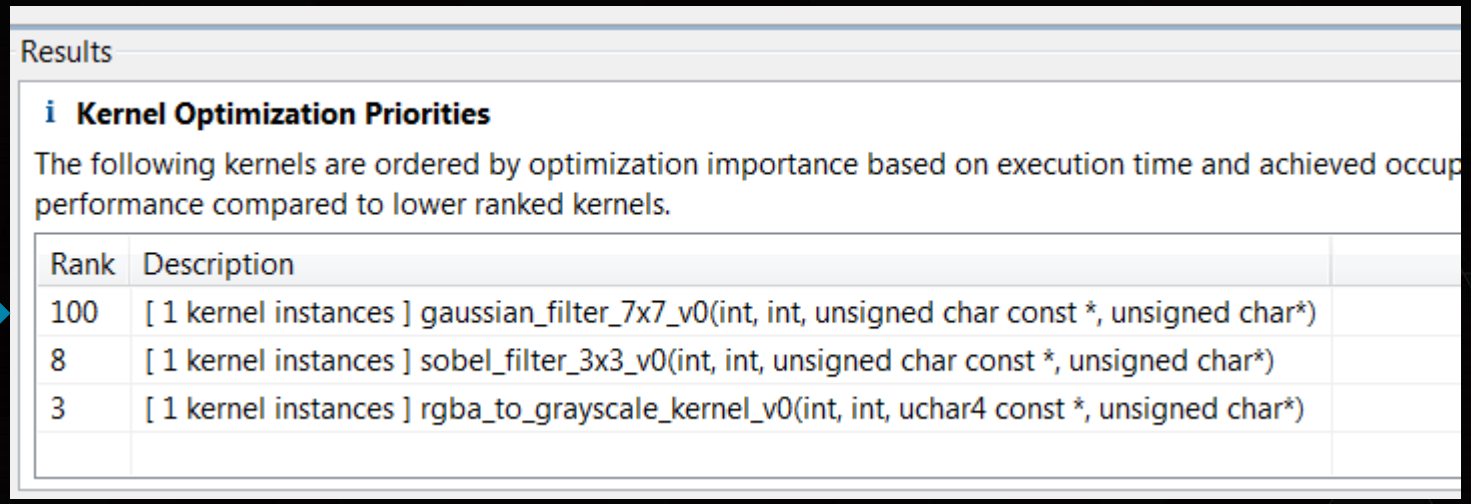
EXAMINE INDIVIDUAL KERNELS
(GUIDED ANALYSIS)

Launch



IDENTIFY HOTSPOT

Hotspot



Results

Kernel Optimization Priorities

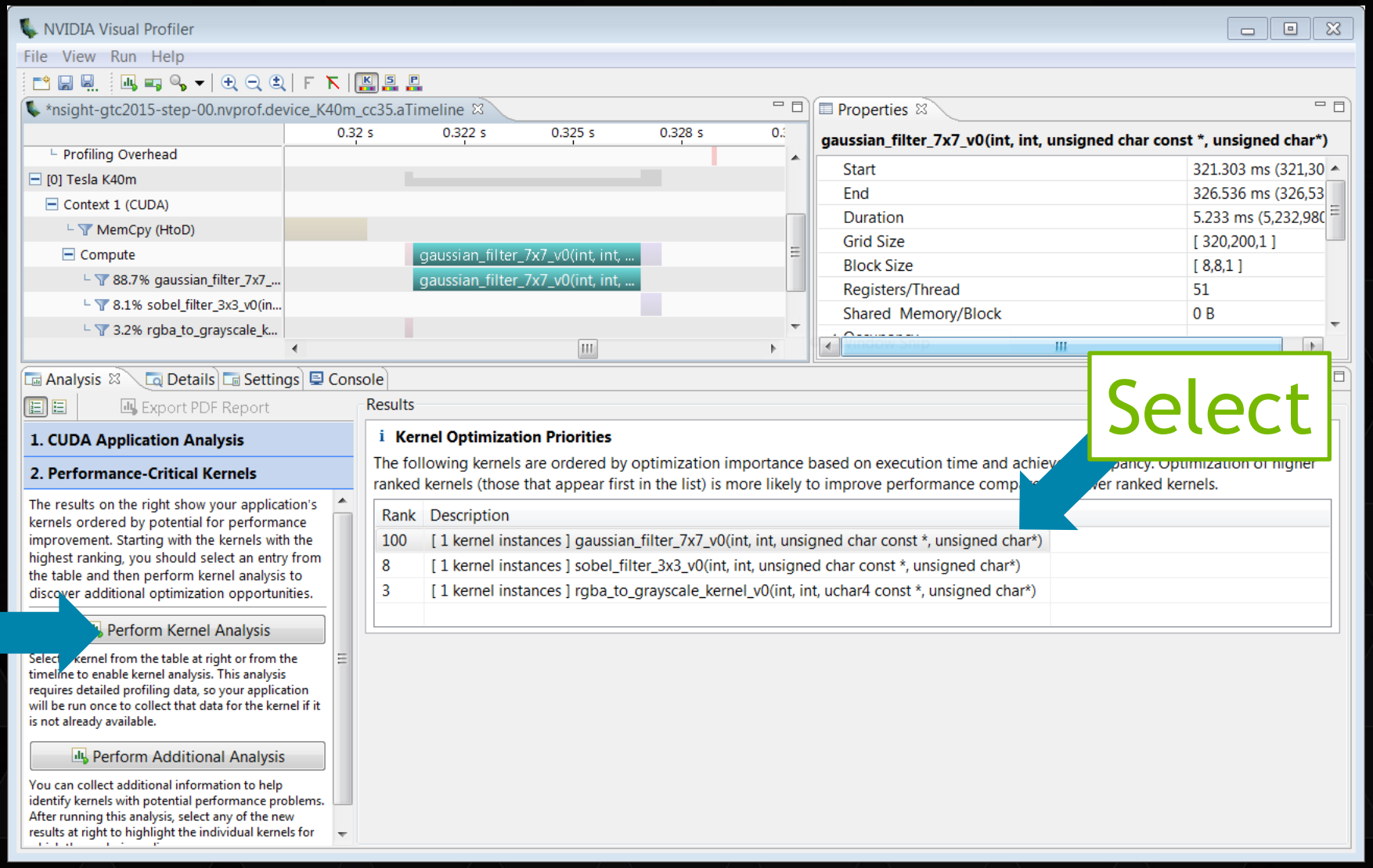
The following kernels are ordered by optimization importance based on execution time and achieved occup
performance compared to lower ranked kernels.

Rank	Description
100	[1 kernel instances] gaussian_filter_7x7_v0(int, int, unsigned char const *, unsigned char*)
8	[1 kernel instances] sobel_filter_3x3_v0(int, int, unsigned char const *, unsigned char*)
3	[1 kernel instances] rgba_to_grayscale_kernel_v0(int, int, uchar4 const *, unsigned char*)

- Identify the hotspot: gaussian_filter_7x7_v0()

Kernel	Time	Speedup
Original Version	5.233ms	1.00x

PERFORM KERNEL ANALYSIS



Launch

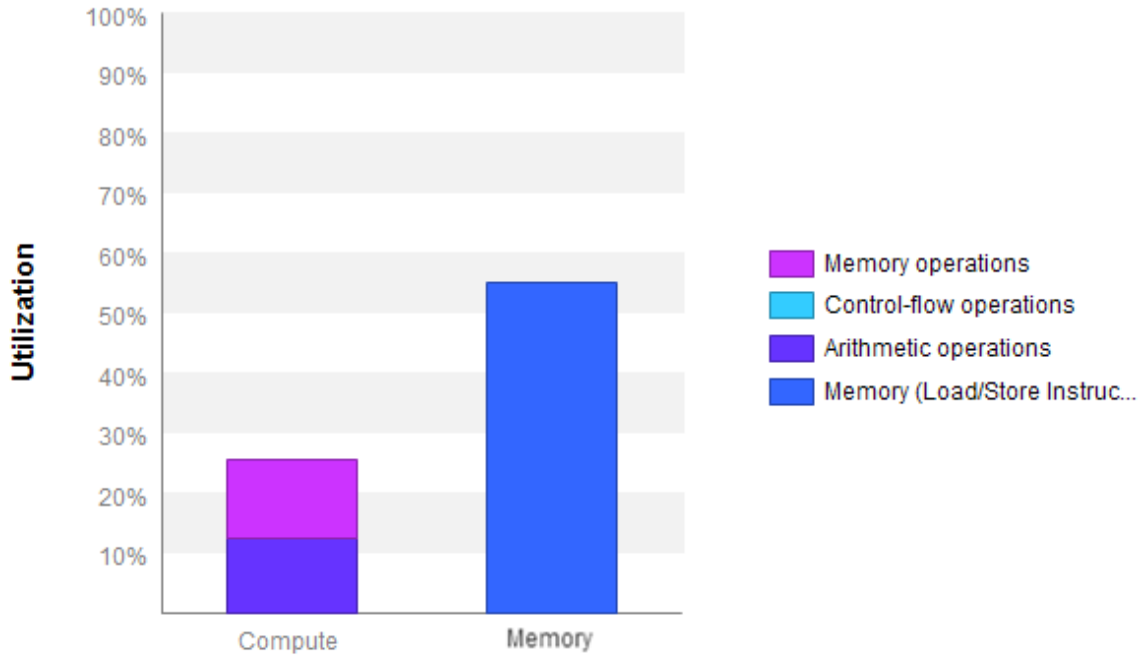
Select

IDENTIFY PERFORMANCE LIMITER

Results

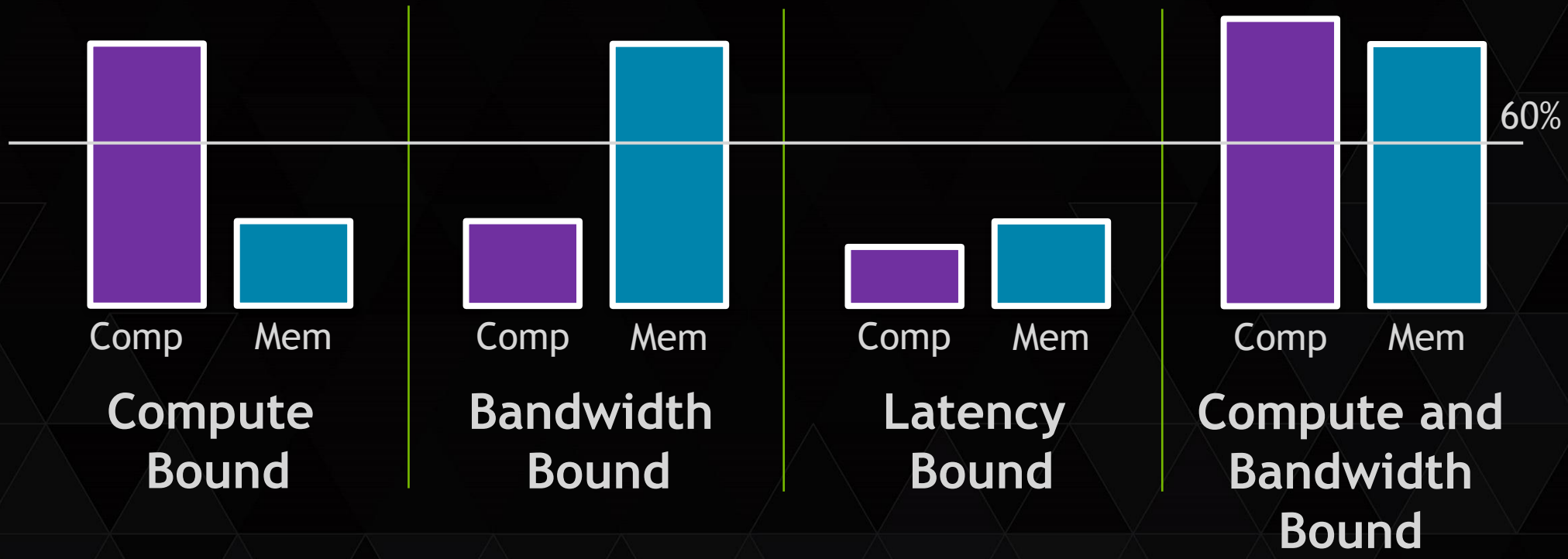
Kernel Performance Is Bound By Instruction And Memory Latency

This kernel exhibits low compute throughput and memory bandwidth utilization relative to the peak performance of "Tesla K40m". These utilization levels indicate that the performance of the kernel is most likely limited by the latency of arithmetic or memory operations. Achieved compute throughput and/or memory bandwidth below 60% of peak typically indicates latency issues.



PERFORMANCE LIMITER CATEGORIES

- Memory Utilization vs Compute Utilization
- Four possible combinations:



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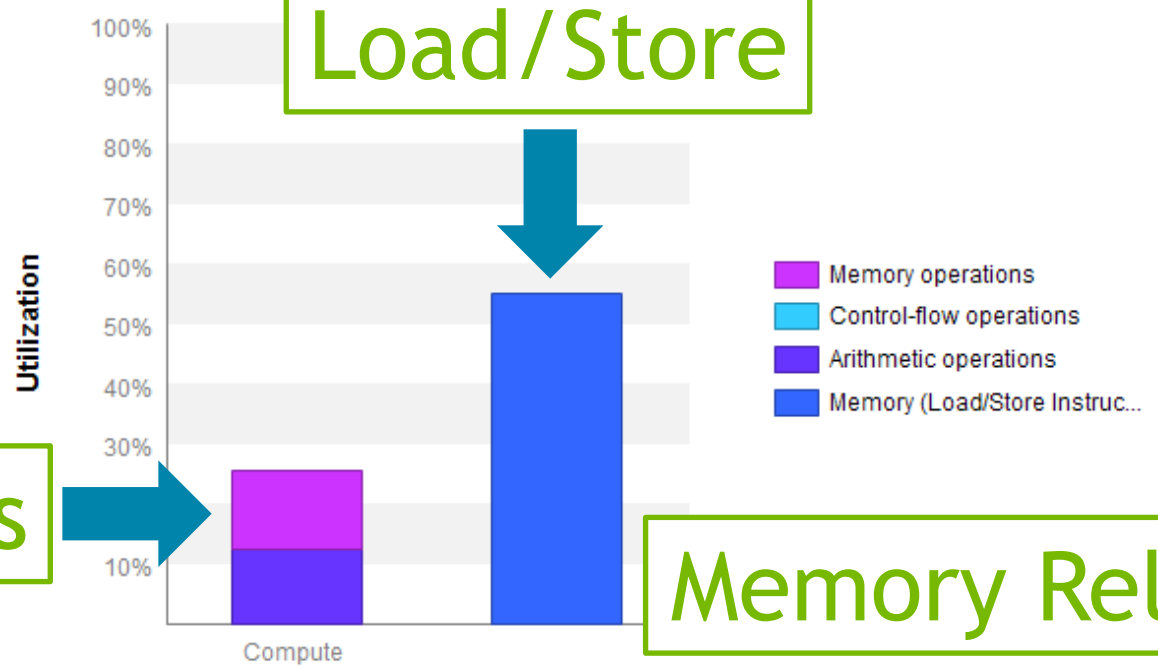


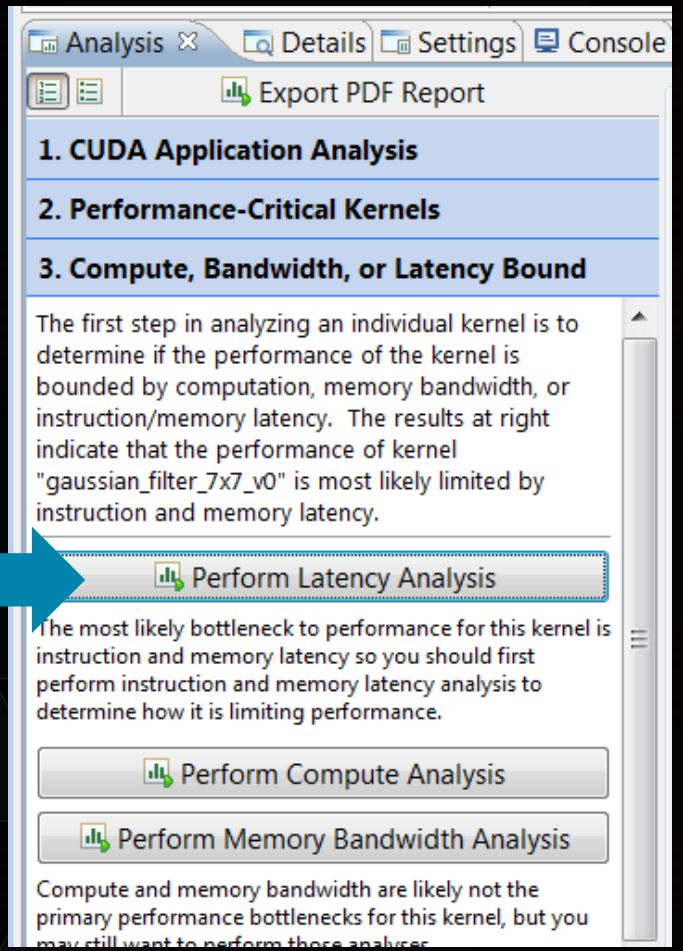
Load/Store

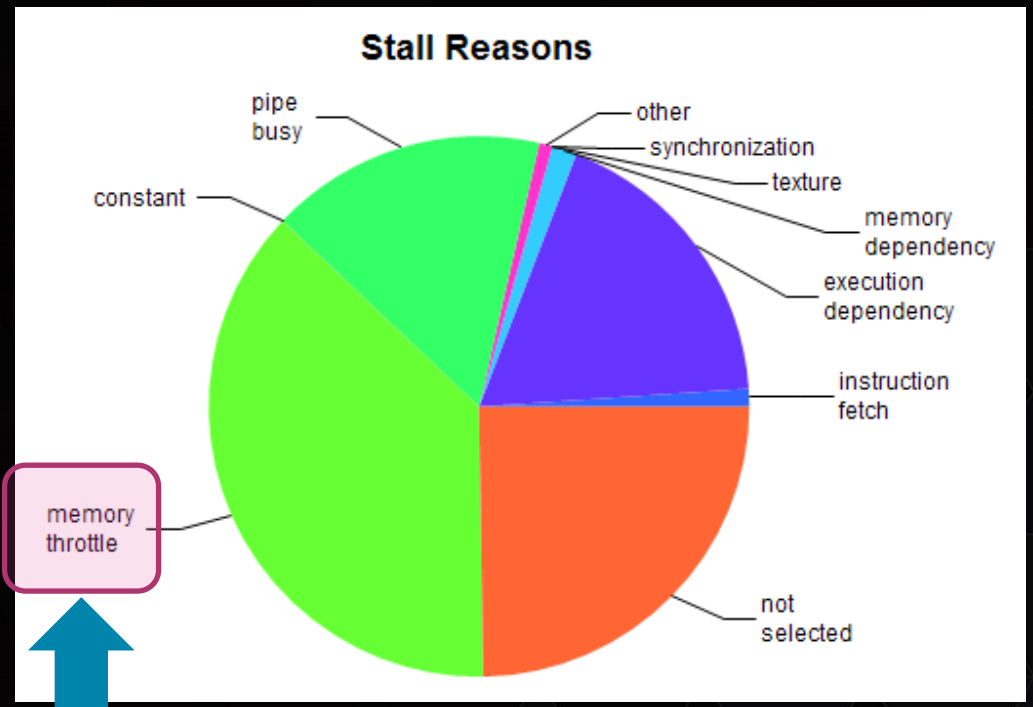
Memory Ops

Memory Related Issues?

LOOKING FOR INDICATORS

Launch

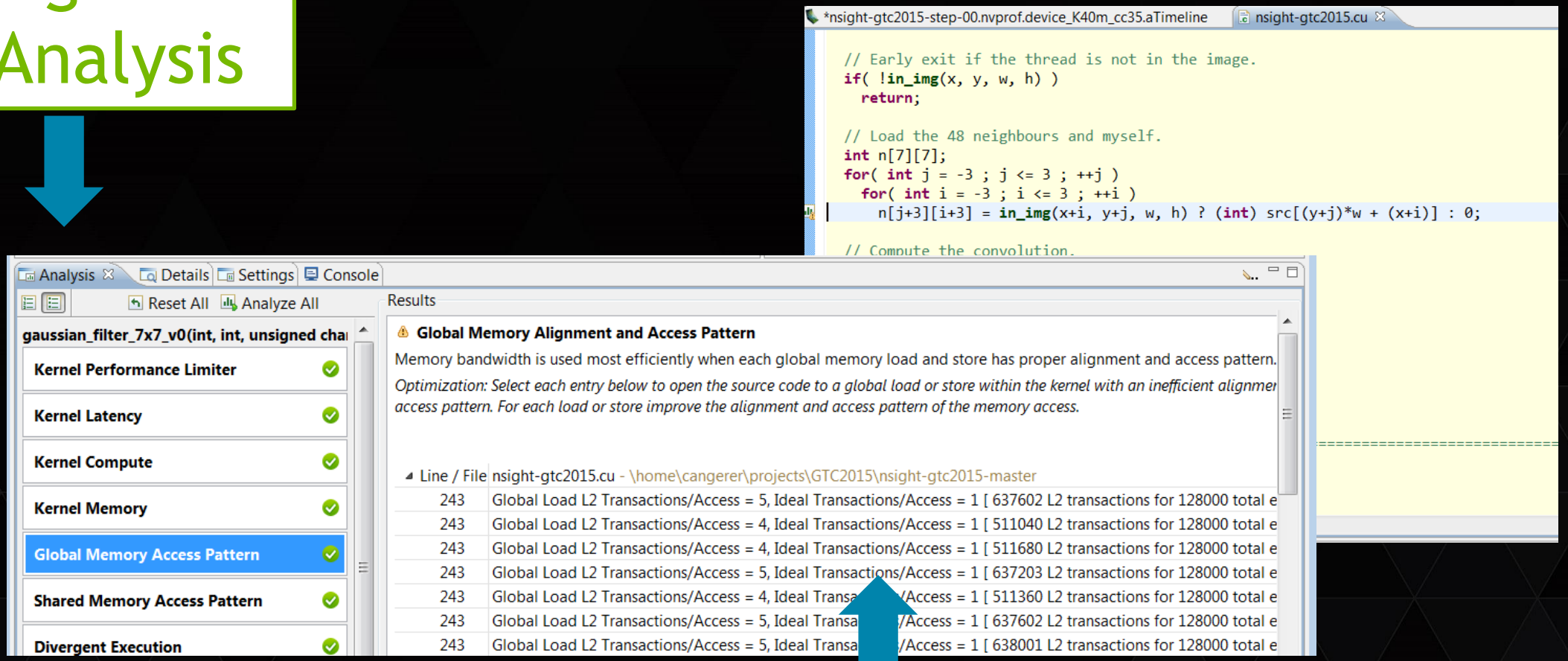




Large number of memory operations stalling LSU

LOOKING FOR MORE INDICATORS

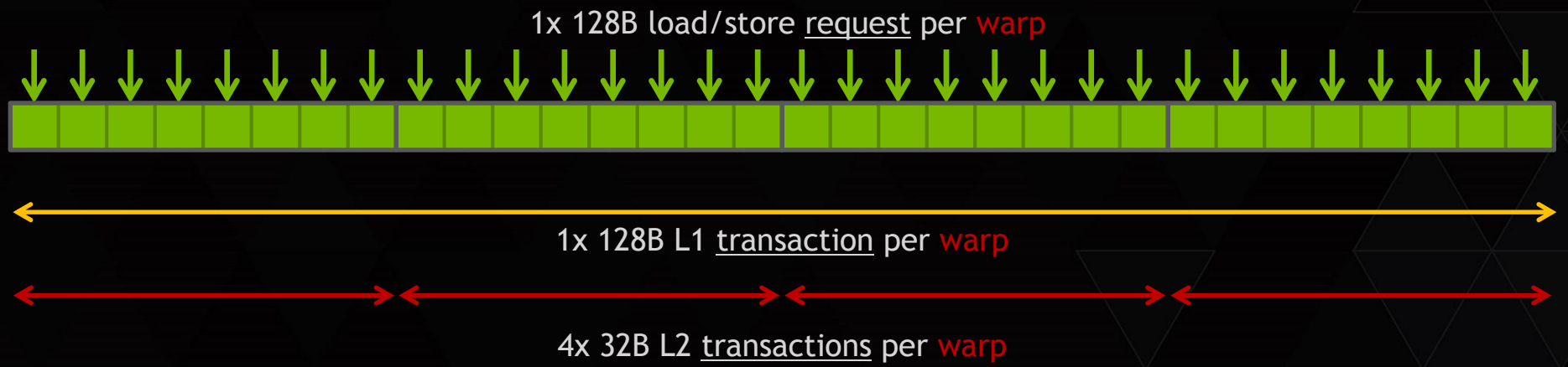
Unguided Analysis



4-5 Global Load/Store Transactions per 1 Request

MEMORY TRANSACTIONS: BEST CASE

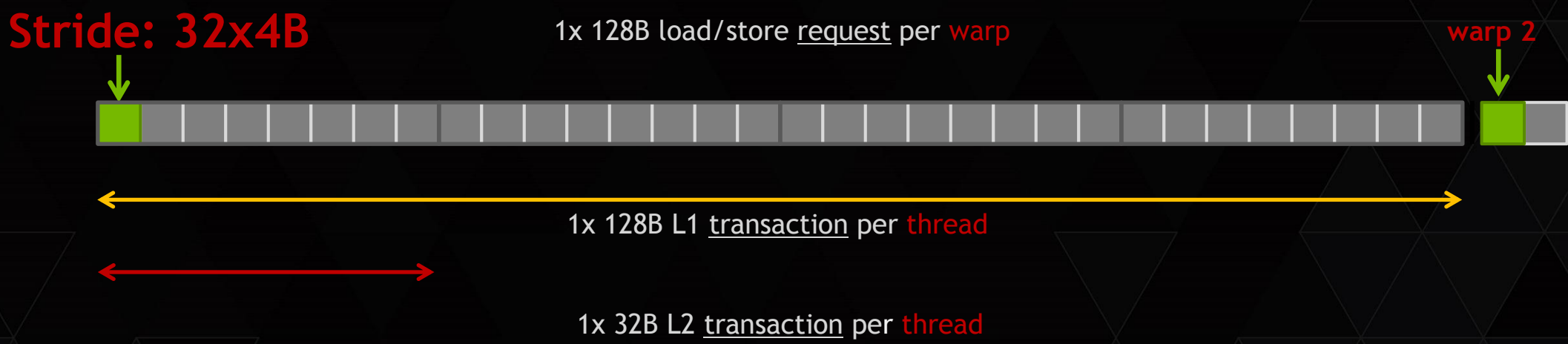
- A warp issues 32x4B aligned and consecutive load/store request
- Threads read different elements of the same 128B segment



- 1x L1 transaction: 128B needed / 128B transferred
- 4x L2 transactions: 128B needed / 128B transferred

MEMORY TRANSACTIONS: WORST CASE

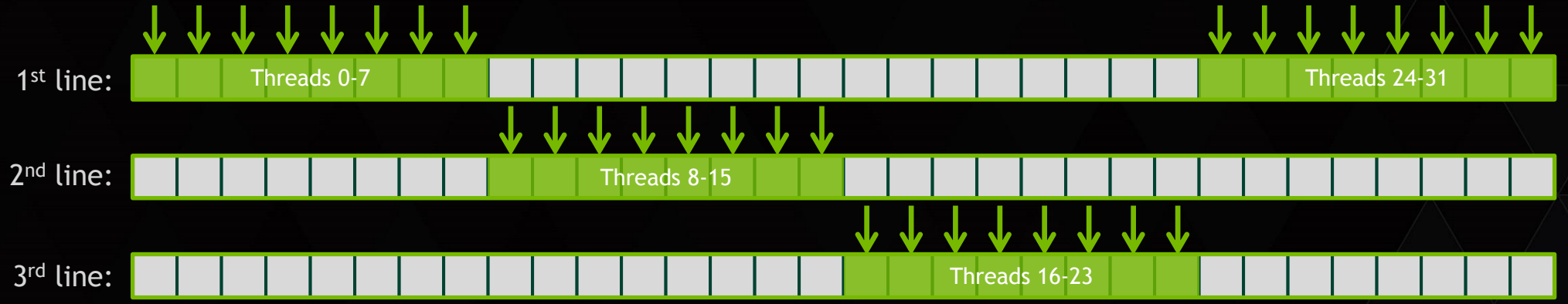
- Threads in a warp read/write 4B words, 128B between words
- Each thread reads the first 4B of a 128B segment



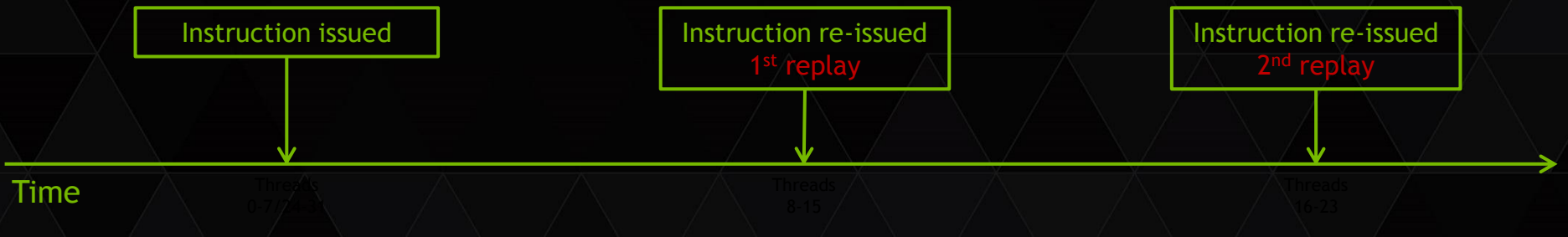
- 32x L1 transactions: 128B needed / 32x 128B transferred
- 32x L2 transactions: 128B needed / 32x 32B transferred

TRANSACTIONS AND REPLAYS

- A warp reads from addresses spanning 3 lines of 128B

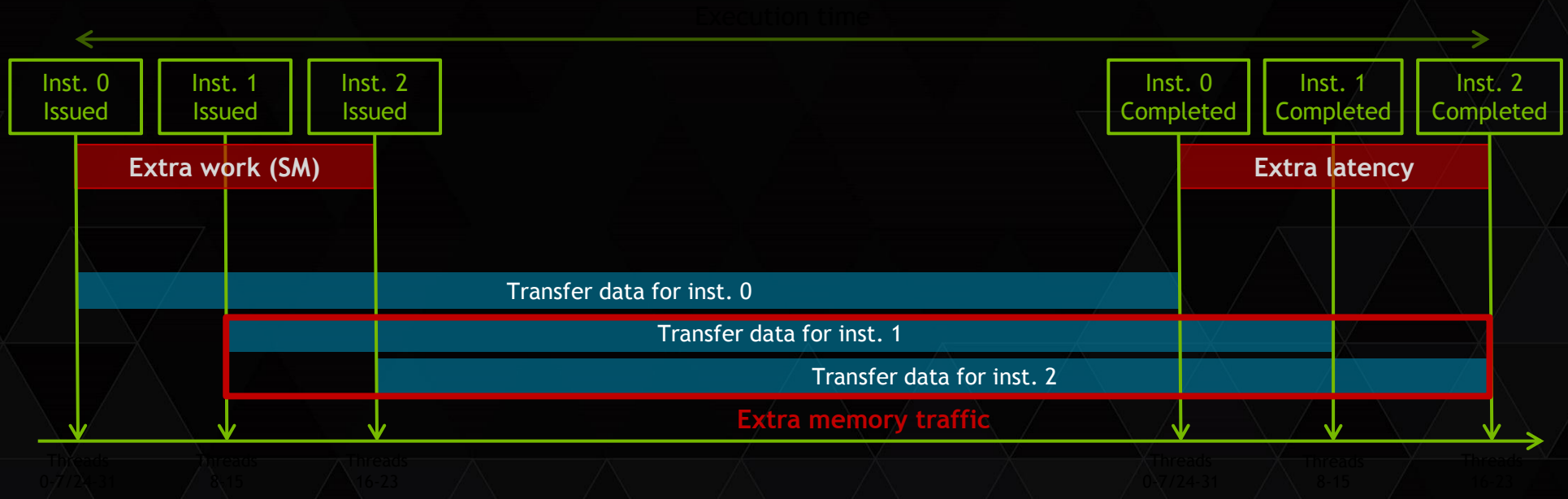


- 1 instr. executed and 2 replays = 1 request and 3 transactions



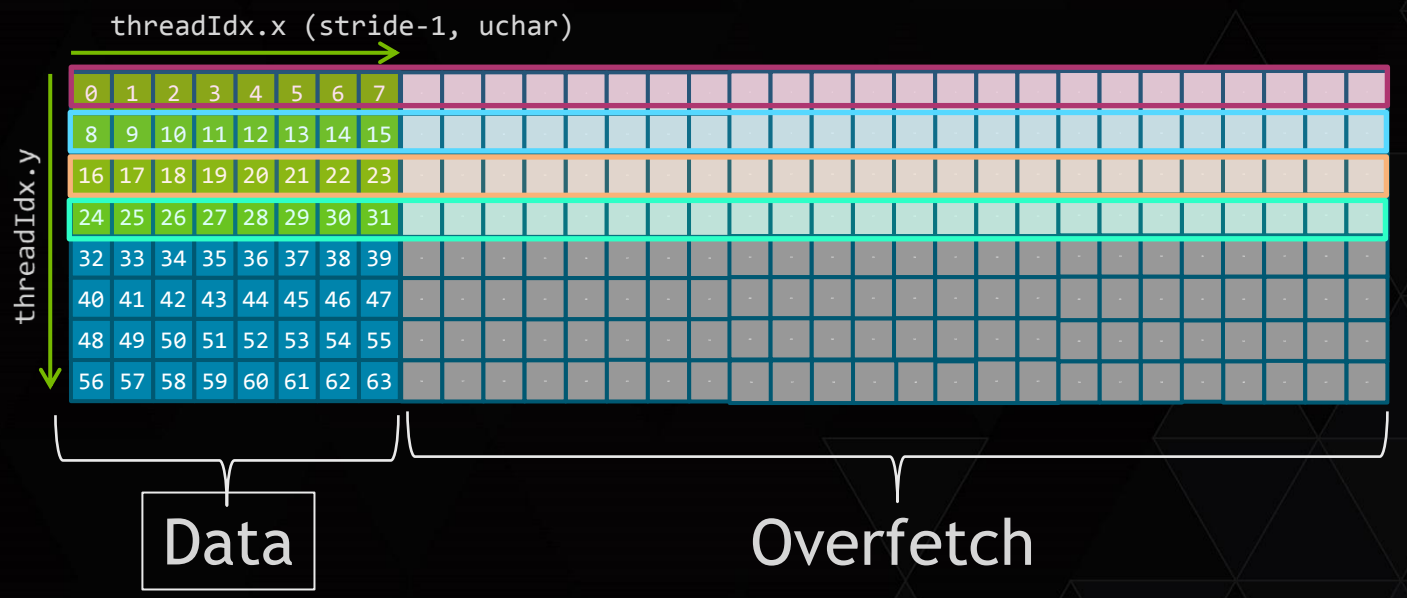
TRANSACTIONS AND REPLAYS

- With replays, requests take more time and use more resources
  - More instructions issued
  - More memory traffic
  - Increased execution time

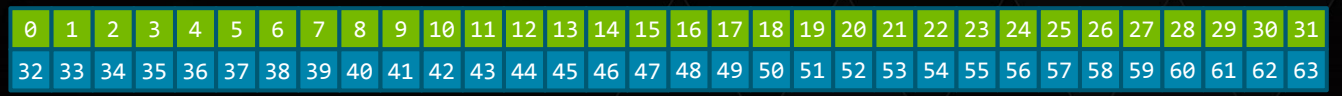


CHANGING THE BLOCK LAYOUT

- Our blocks are 8x8



- We should use blocks of size 32x2



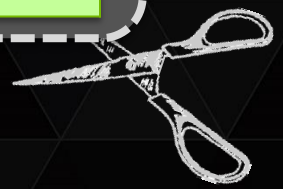
IMPROVED MEMORY ACCESS

- Blocks of size 32x2
- Memory is used more efficiently

Kernel	Time	Speedup
Original Version	5.233ms	1.00x
Better Memory Accesses	1.589ms	3.29x

PERF-OPT QUICK REFERENCE CARD

Category:	Latency Bound - Coalescing
Problem:	Memory is accessed inefficiently => high latency
Goal:	Reduce #transactions/request to reduce latency
Indicators:	Low global load/store efficiency, High #transactions/#request compared to ideal
Strategy:	Improve memory coalescing by: • Cooperative loading inside a block • Change block layout • Aligning data • Changing data layout to improve locality



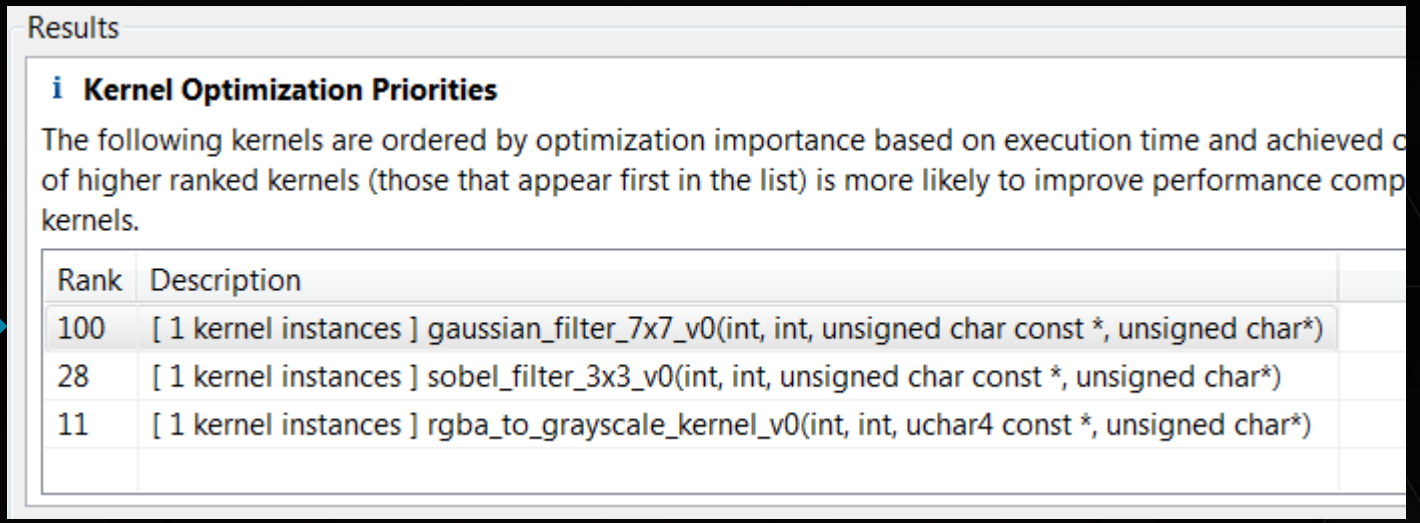
PERF-OPT QUICK REFERENCE CARD

Category:	Bandwidth Bound - Coalescing
Problem:	Too much unused data clogging memory system
Goal:	Reduce traffic, move more useful data per request
Indicators:	Low global load/store efficiency, High #transactions/#request compared to ideal
Strategy:	Improve memory coalescing by: • Cooperative loading inside a block • Change block layout • Aligning data • Changing data layout to improve locality

ITERATION 2

IDENTIFY HOTSPOT

Hotspot



Results

Kernel Optimization Priorities

The following kernels are ordered by optimization importance based on execution time and achieved o
of higher ranked kernels (those that appear first in the list) is more likely to improve performance comp
kernels.

Rank	Description
100	[1 kernel instances] gaussian_filter_7x7_v0(int, int, unsigned char const *, unsigned char*)
28	[1 kernel instances] sobel_filter_3x3_v0(int, int, unsigned char const *, unsigned char*)
11	[1 kernel instances] rgba_to_grayscale_kernel_v0(int, int, uchar4 const *, unsigned char*)

- gaussian_filter_7x7_v0() still the hotspot

Kernel	Time	Speedup
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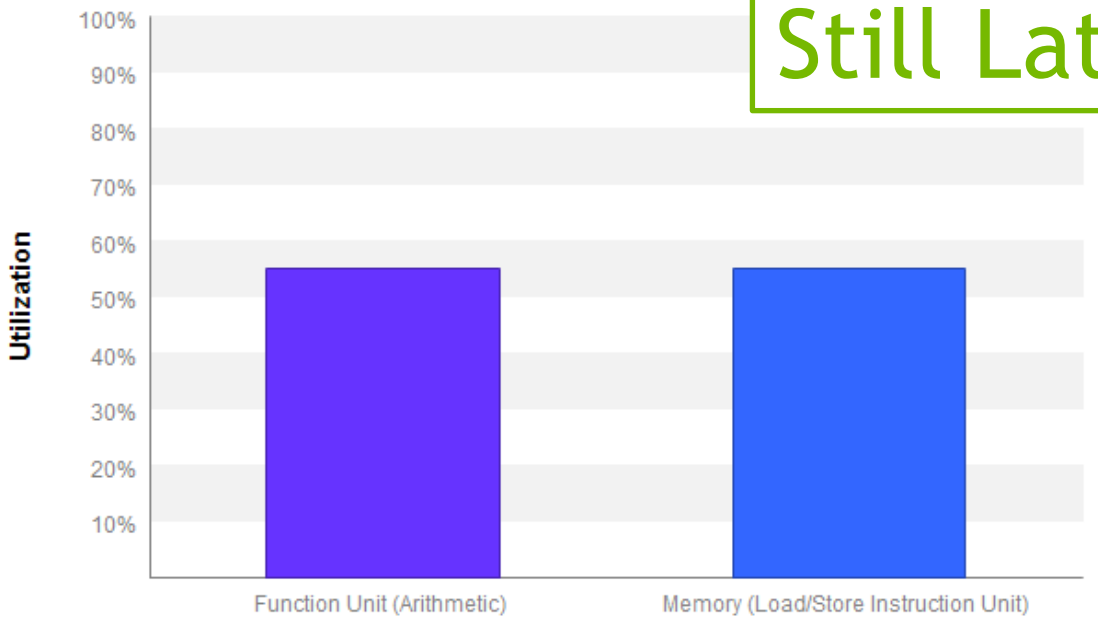
Better Memory Accesses	1.589ms	3.29x

IDENTIFY PERFORMANCE LIMITER

Results

Kernel Performance Is Bound By Instruction And Memory Latency

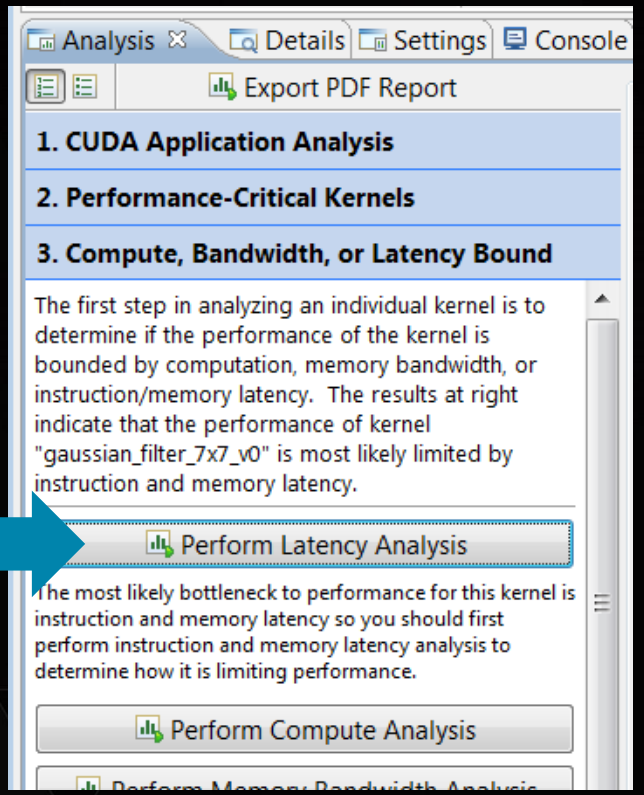
This kernel exhibits low compute throughput and memory bandwidth utilization relative to the peak performance of "Tesla K40m". These utilization levels indicate that the performance of the kernel is most likely limited by the latency of arithmetic or memory operations. Achieved compute throughput and/or memory bandwidth below 60% of peak typically indicates latency issues.



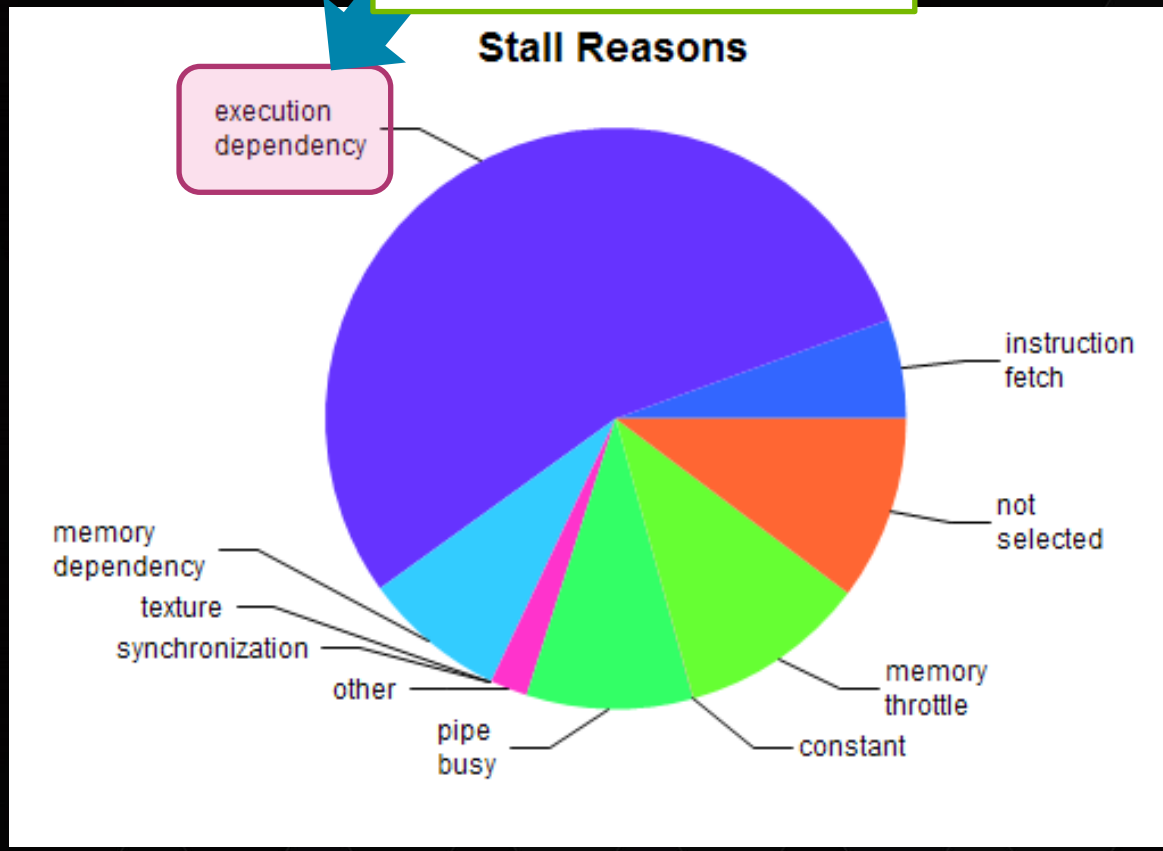
Still Latency Bound

LOOKING FOR INDICATORS

A lot of idle time



Launch



- Not enough work inside a thread to hide latency?

STALL REASONS: EXECUTION DEPENDENCY

```
a = b + c; // ADD

d = a + e; // ADD
```

```
a = b[i];  // LOAD

d = a + e; // ADD
```

- Memory accesses may influence execution dependencies
  - Global accesses create longer dependencies than shared accesses
  - Read-only/texture dependencies are counted in Texture
- Instruction level parallelism can reduce dependencies

```
a = b + c;  // Independent ADDs
d = e + f;
```

ILP AND MEMORY ACCESSES

No ILP

```
float a = 0.0f;
for( int i = 0 ; i < N ; ++i )
  a += logf(b[i]);
```

```
c = b[0]
a += logf(c)
c = b[1]
a += logf(c)
c = b[2]
a += logf(c)
c = b[3]
a += logf(c)
```

2-way ILP (with loop unrolling)

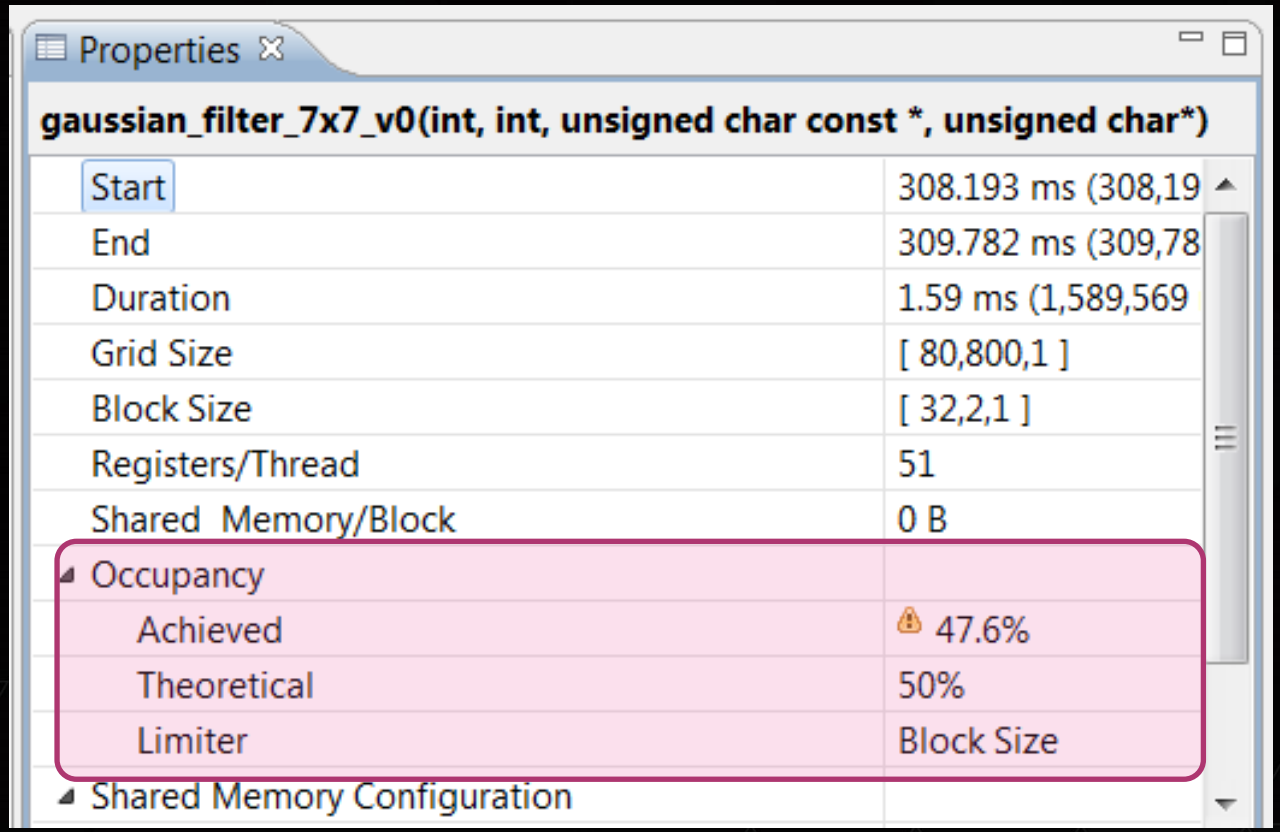
```
float a, a0 = 0.0f, a1 = 0.0f;
for( int i = 0 ; i < N ; i += 2 )
{
  a0 += logf(b[i]);
  a1 += logf(b[i+1]);
}
a = a0 + a1
```

```
c0 = b[0]
a0 += logf(c0)
c0 = b[2]
a0 += logf(c0)
...
a = a0 + a1
```

```
c1 = b[1]
a1 += logf(c1)
c1 = b[3]
a1 += logf(c1)
```

- #pragma unroll is useful to extract ILP
- Manually rewrite code if not a simple loop

LOOKING FOR MORE INDICATORS



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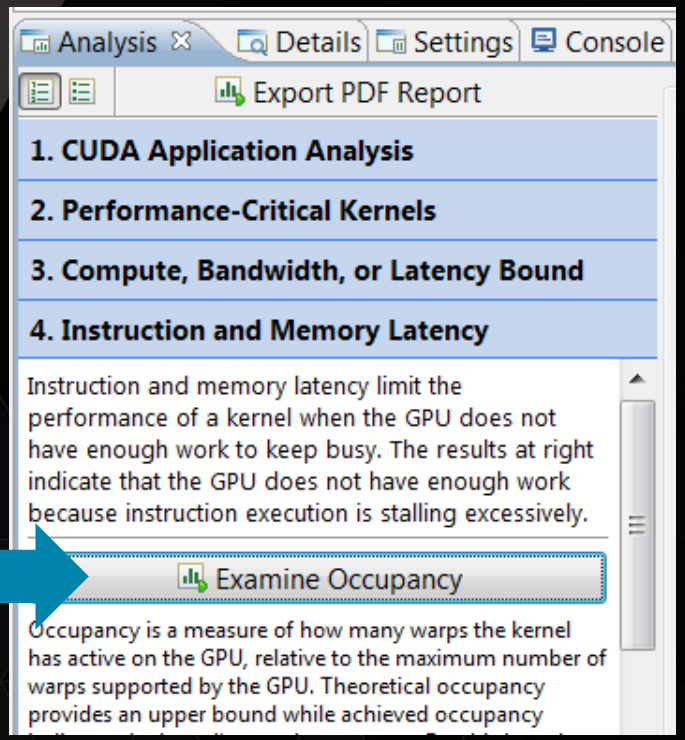
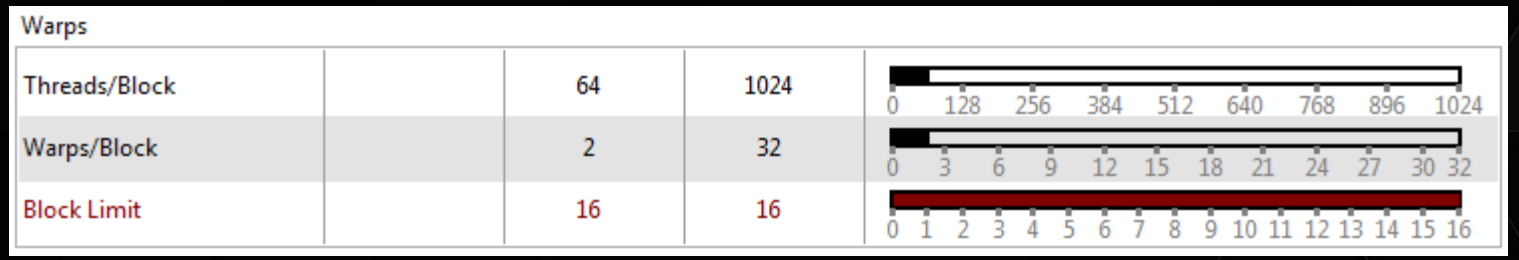
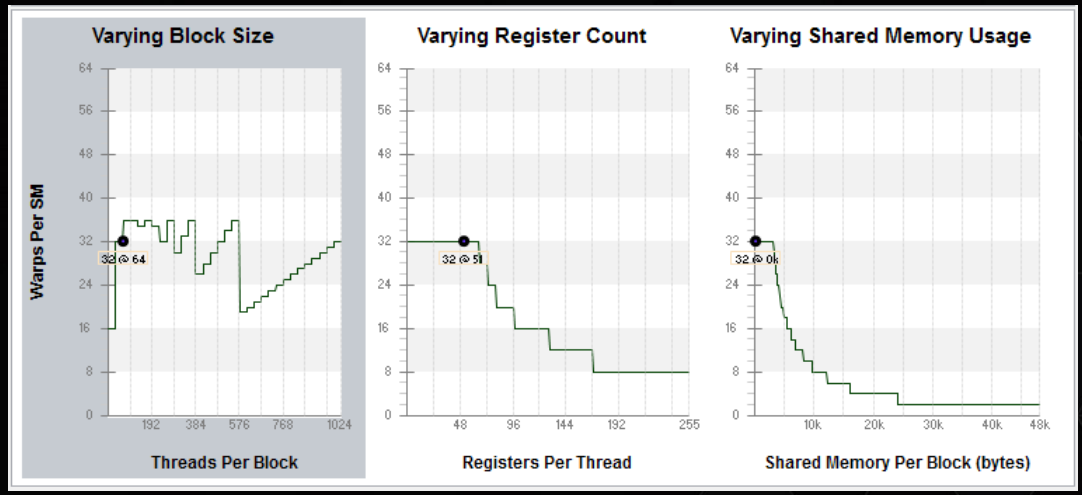






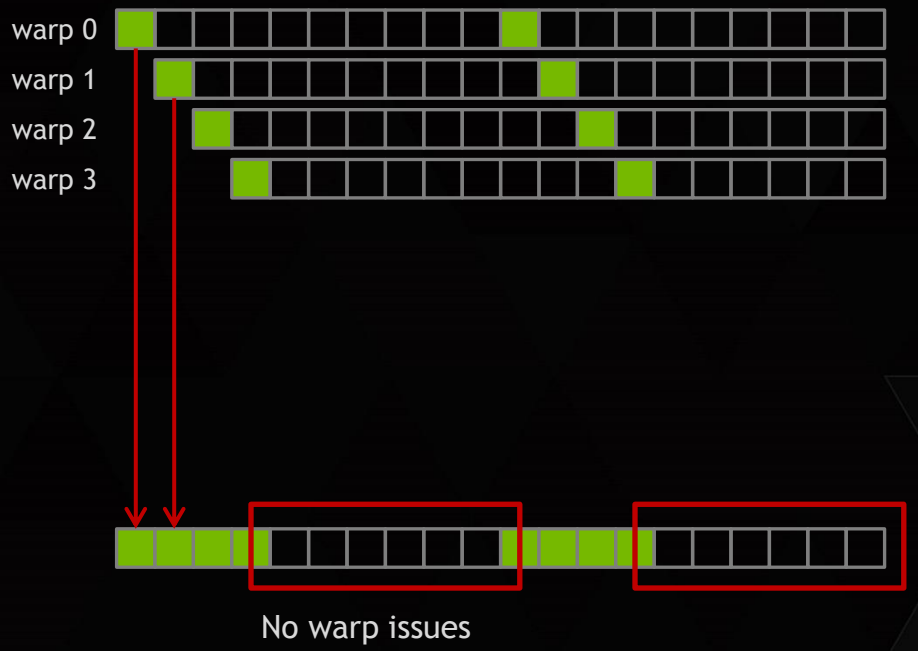
- Not enough active warps to hide latencies?

LATENCY

- GPUs cover latencies by having a lot of work in flight

LATENCY: LACK OF OCCUPANCY

- Not enough active warps



- The schedulers cannot find eligible warps at every cycle

IMPROVED OCCUPANCY

- Bigger blocks of size 32x4
- Increases achieved occupancy slightly (from 47.6% to 52.4%)

Kernel	Time	Speedup
Original Version	5.233ms	1.00x
Better Memory Accesses	1.589ms	3.29x
Higher Occupancy	1.562ms	3.35x

PERF-OPT QUICK REFERENCE CARD

Category:	Latency Bound - Occupancy
Problem:	Latency is exposed due to low occupancy
Goal:	**Hide** latency behind more parallel work
Indicators:	Occupancy low (< 60%) Execution Dependency High
Strategy:	Increase occupancy by: • Varying block size • Varying shared memory usage • Varying register count

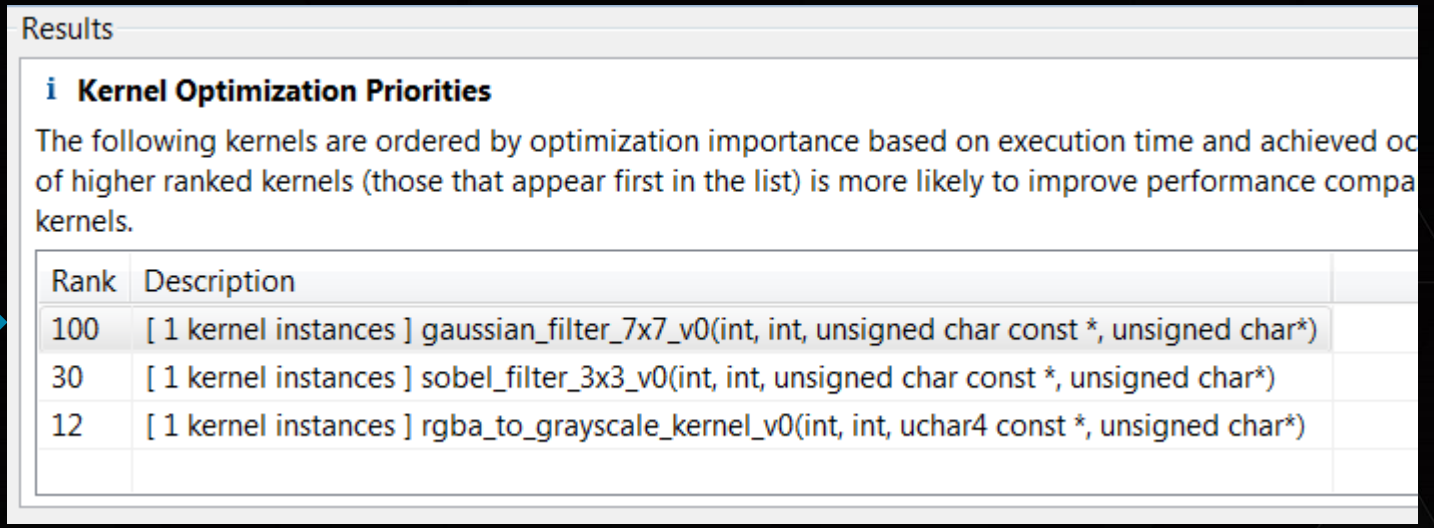
PERF-OPT QUICK REFERENCE CARD

Category:	Latency Bound - Instruction Level Parallelism
Problem:	Not enough independent work per thread
Goal:	Do more parallel work inside single threads
Indicators:	High execution dependency, increasing occupancy has no/little positive effect, still registers available
Strategy:	• Unroll loops (#pragma unroll) • Refactor threads to compute n output values at the same time (code duplication)

ITERATION 3

IDENTIFY HOTSPOT

Hotspot



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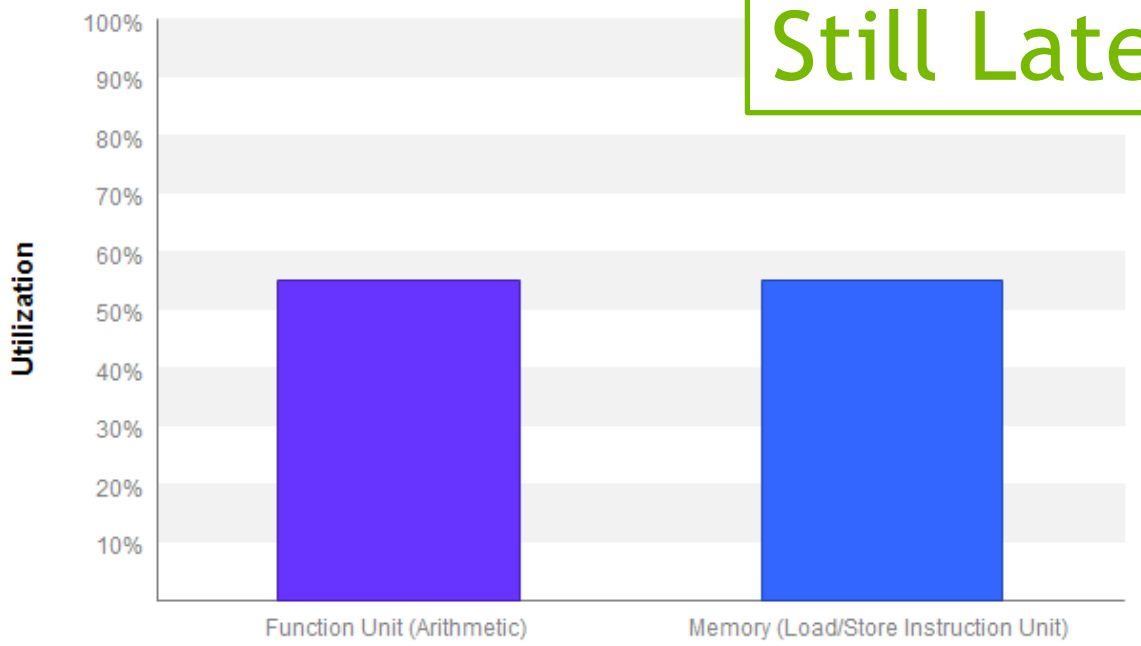
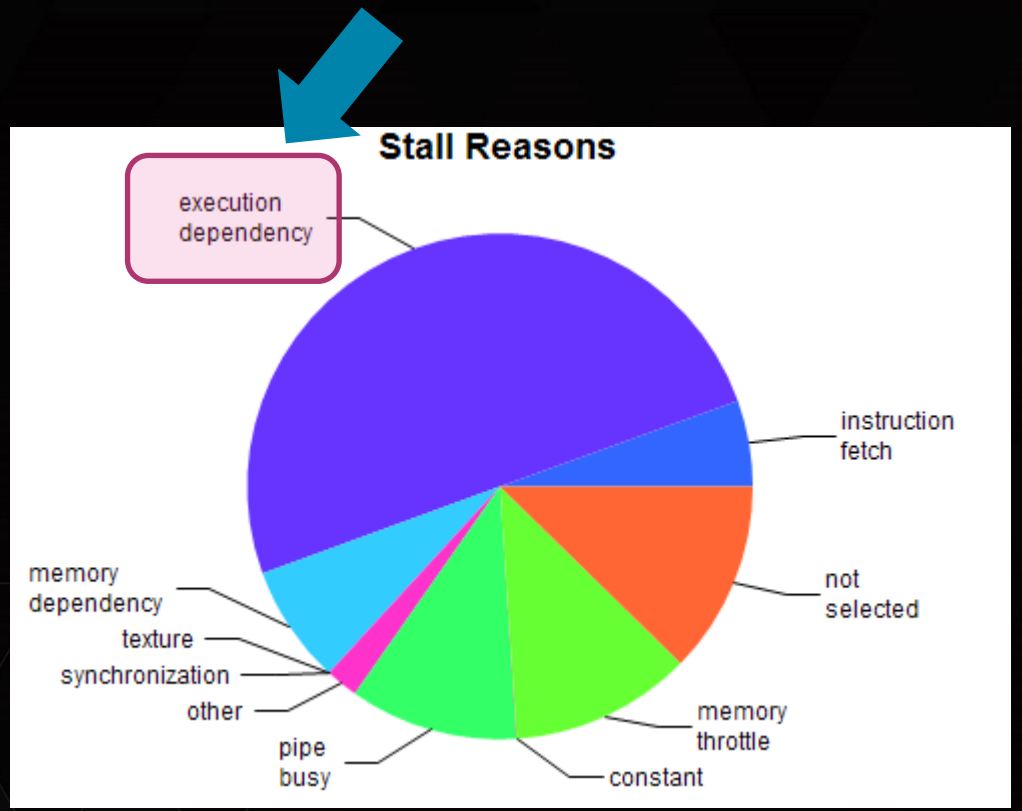


Still Latency Bound

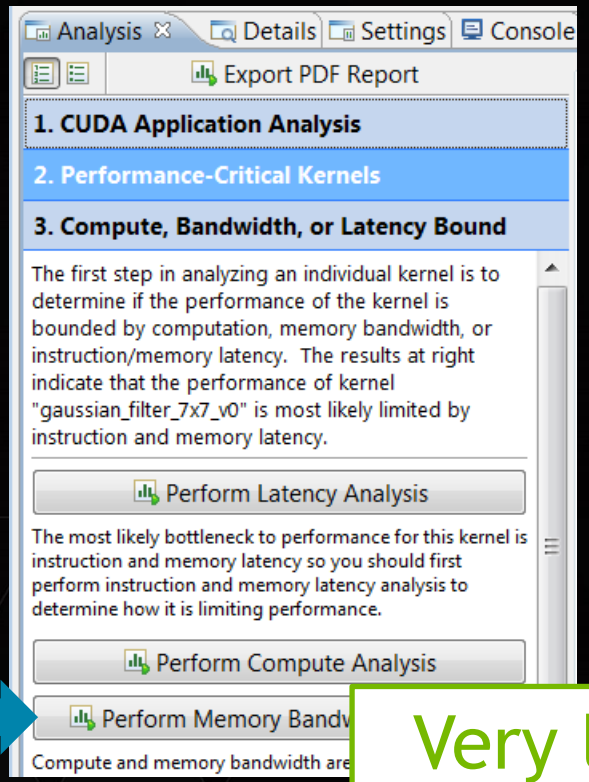
LOOKING FOR INDICATORS

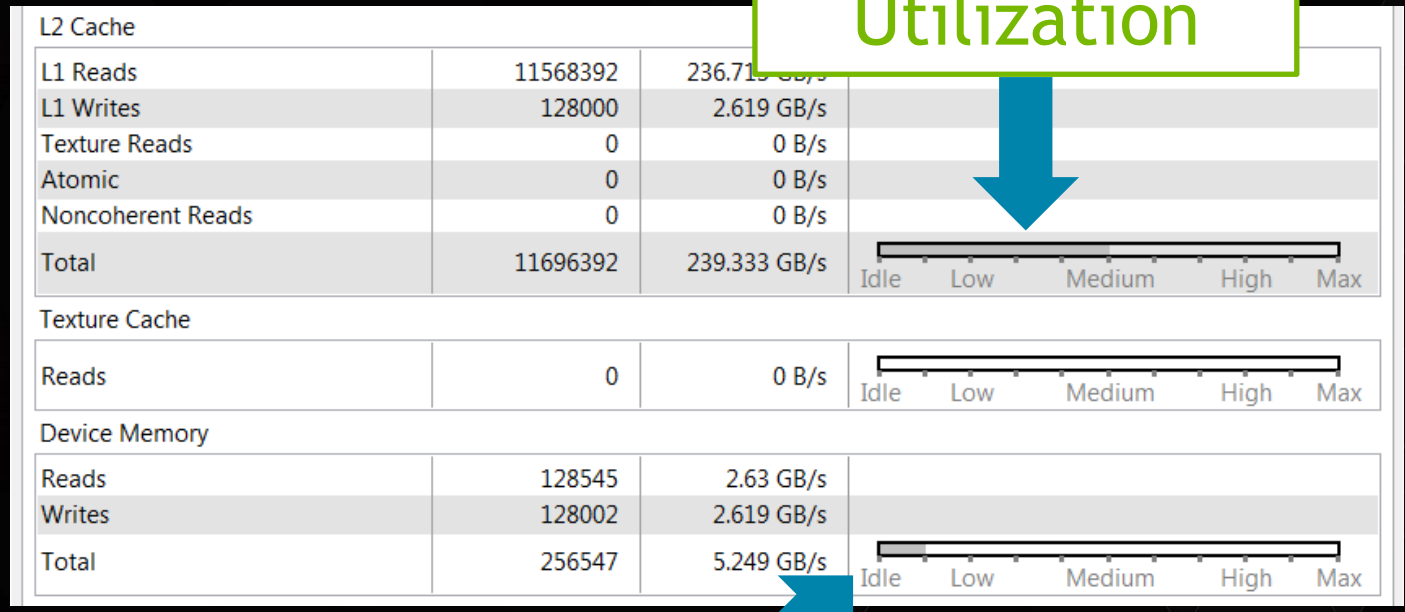


Still high execution dependency, but occupancy OK

LOOKING FOR MORE INDICATORS

Medium L2 Bandwidth Utilization



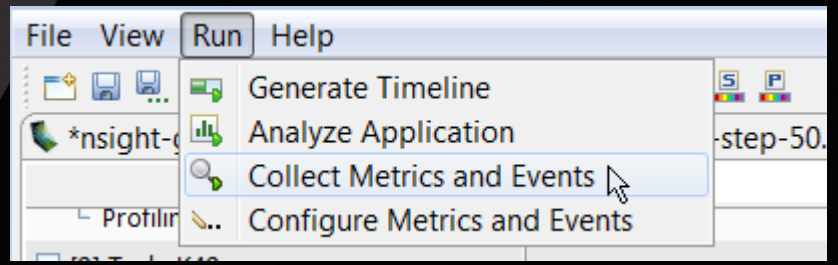


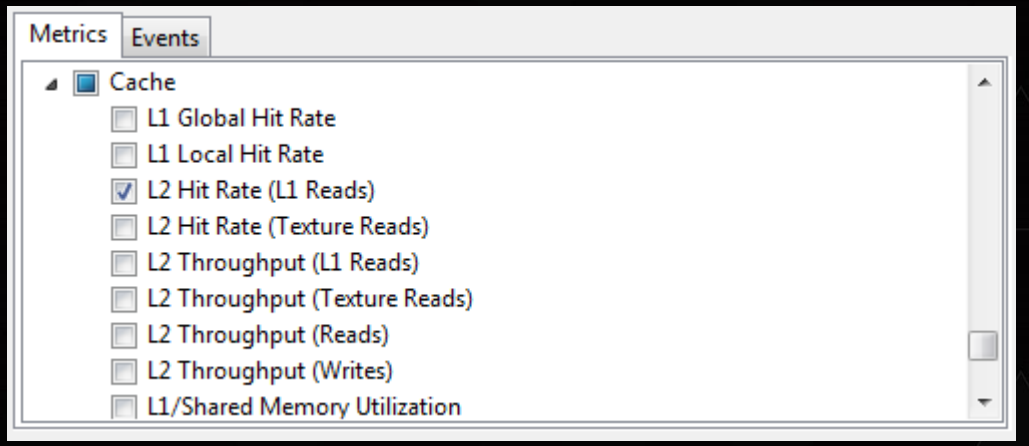
Launch

Very low device memory bandwidth utilization

Is our working set mostly in L2$?

CHECKING L2 HIT RATE: 98.9%



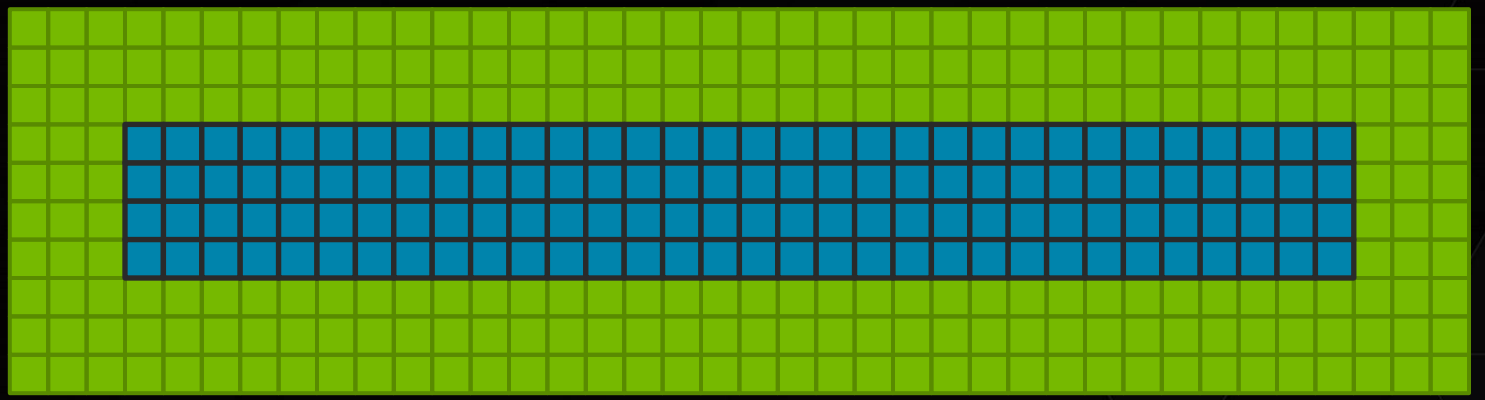


Name	Duration	L2 Hit Rate (L1 Reads)
gaussian_filter_7x7_v0(int, int, unsigned char const *, unsigned char*)	3.606 ms	98.9%

Our working set is mostly in L2$
Can we move it even closer?

SHARED MEMORY

- Adjacent pixels access similar neighbors in Gaussian Filter



- We should use shared memory to store those common pixels

```
__shared__ unsigned char smem_pixels[10][64];
```

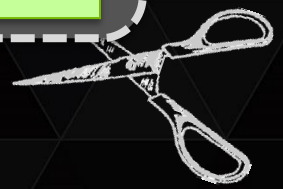
SHARED MEMORY

- Using shared memory for the Gaussian Filter
- Significant speedup, < 1ms

Kernel	Time	Speedup
Original Version	5.233ms	1.00x
Better Memory Accesses	1.589ms	3.29x
Higher Occupancy	1.562ms	3.35x
Shared Memory	0.911ms	5.74x

PERF-OPT QUICK REFERENCE CARD

Category:	Latency Bound - Shared Memory
Problem:	Long memory latencies are difficult to hide
Goal:	**Reduce** latency, move data to faster memory
Indicators:	Shared memory not occupancy limiter High L2 hit rate Data reuse between threads and small-ish working set
Strategy:	(Cooperatively) move data to: • Shared Memory • (or Registers) • (or Constant Memory) • (or Texture Cache)



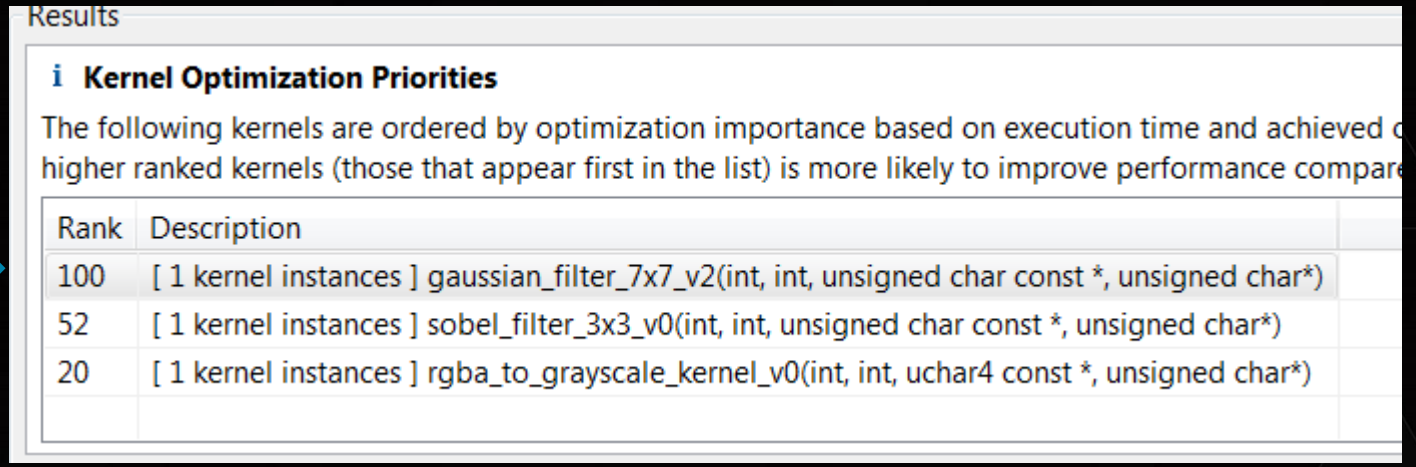
PERF-OPT QUICK REFERENCE CARD

Category:	Memory Bound – Shared Memory
Problem:	Too much data movement
Goal:	Reduce amount of data traffic to/from global mem
Indicators:	Higher than expected memory traffic to/from global memory Low arithmetic intensity of the kernel
Strategy:	(Cooperatively) move data closer to SM: • Shared Memory • (or Registers) • (or Constant Memory) • (or Texture Cache)

ITERATION 4

IDENTIFY HOTSPOT

Hotspot



- gaussian_filter_7x7_v0() still the hotspot

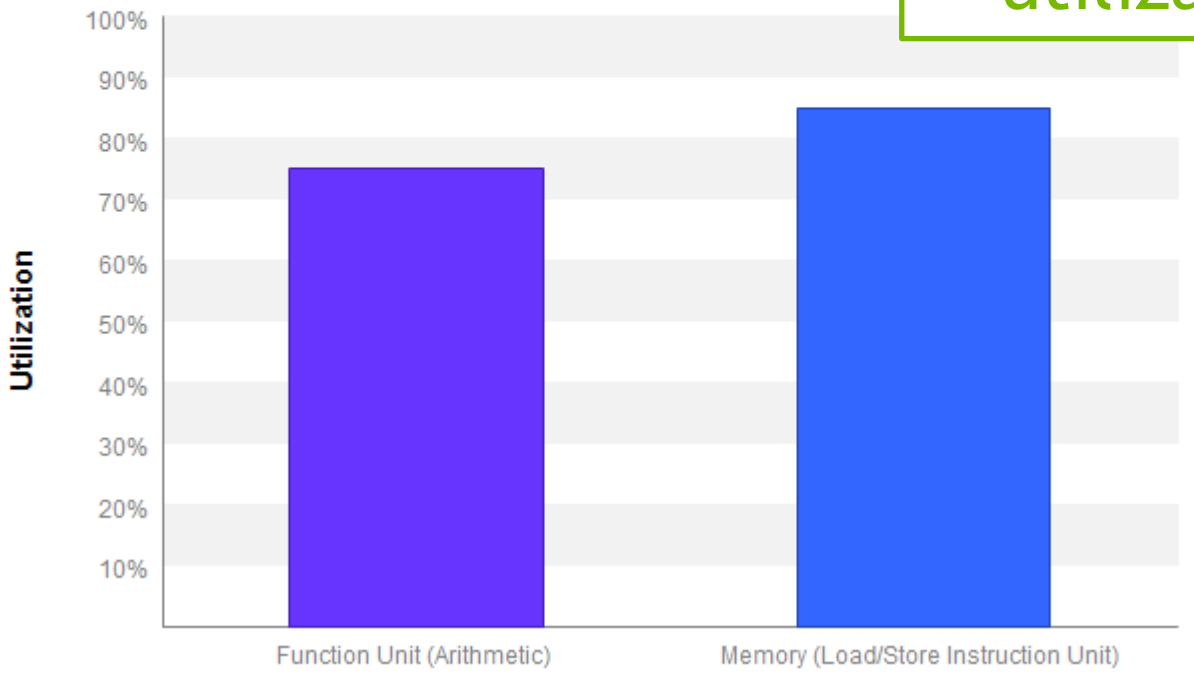
Kernel	Time	Speedup
Original Version	5.233ms	1.00x
Better Memory Accesses	1.589ms	3.29x
Higher Occupancy	1.562ms	3.35x
Shared Memory	0.911ms	5.74x

IDENTIFY PERFORMANCE LIMITER

Results

Kernel Performance Is Bound By Compute And Memory Bandwidth

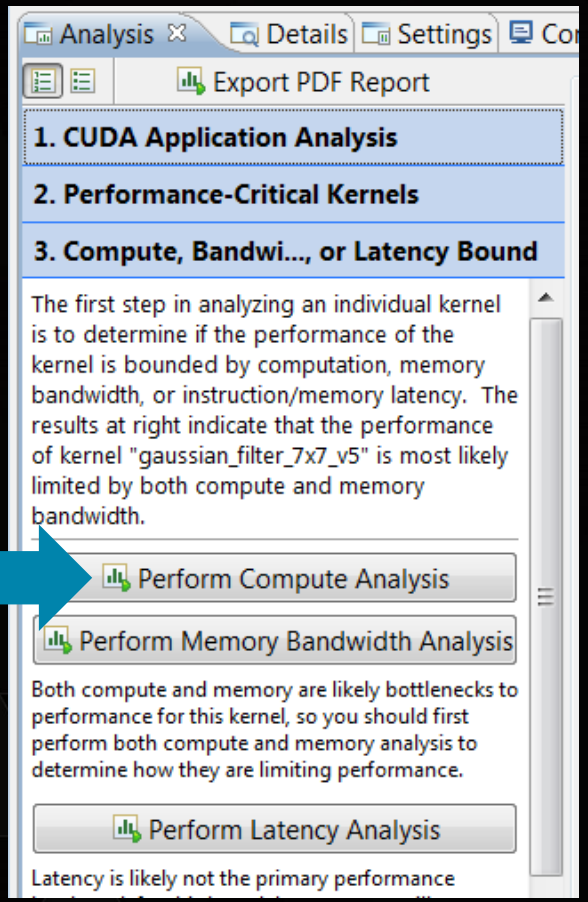
For device "Tesla K40m" compute and memory utilization are balanced. These utilizatio
good, but that additional performance improvement may be possible if either of both c
are increased.

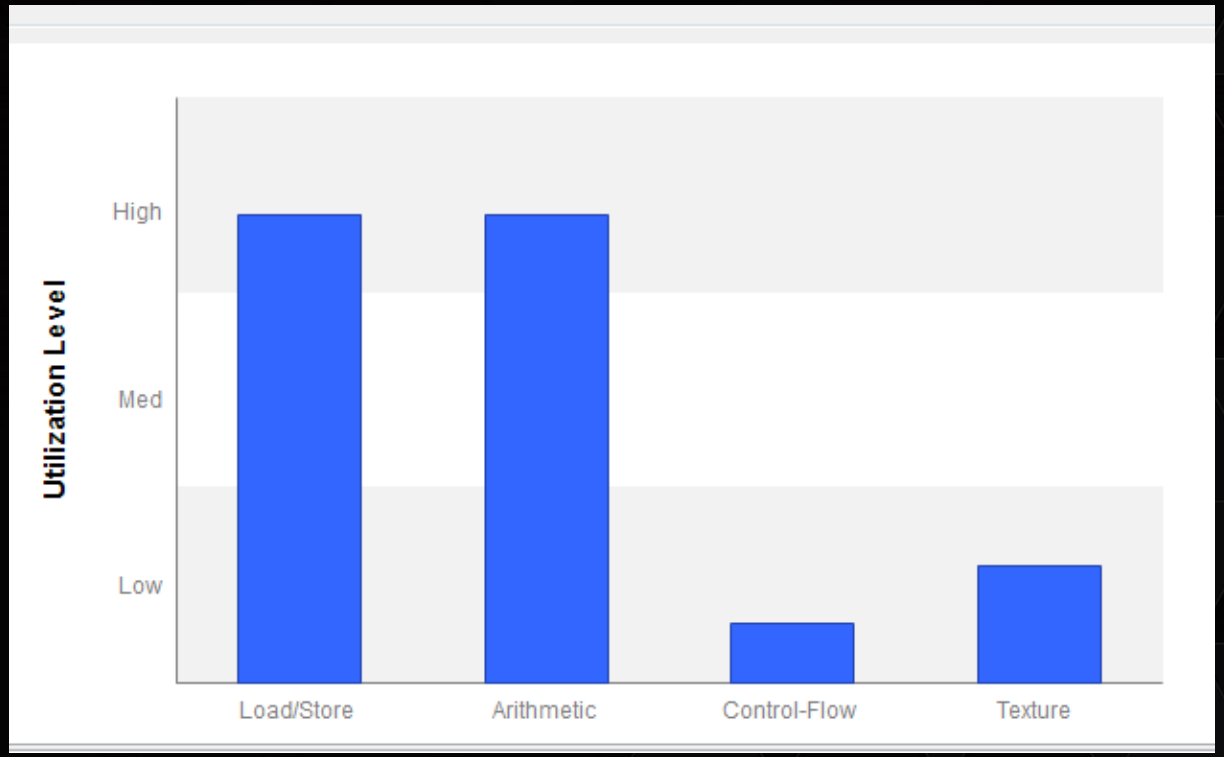


Aha!
Getting into the high utilization region

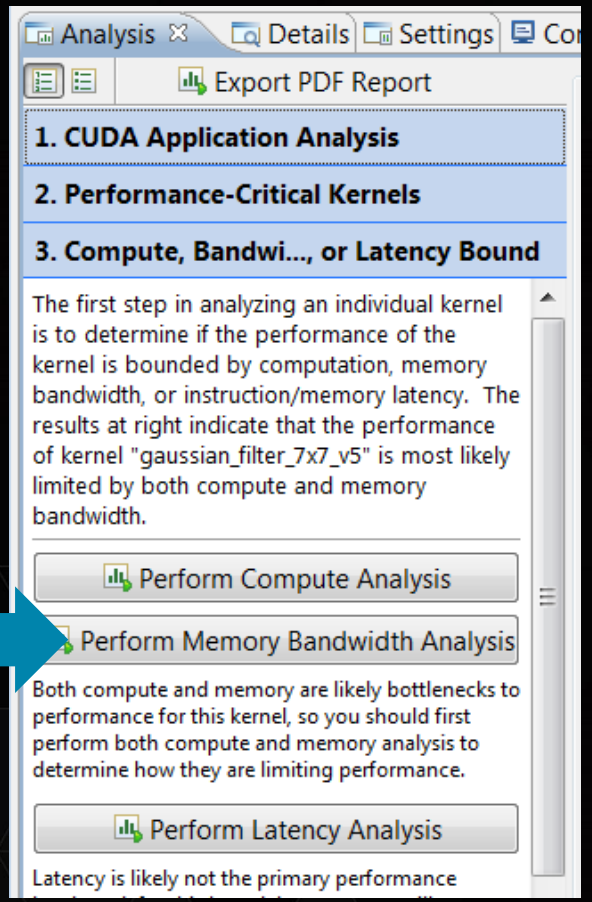
LOOKING FOR INDICATORS

Launch





LOOKING FOR MORE INDICATORS

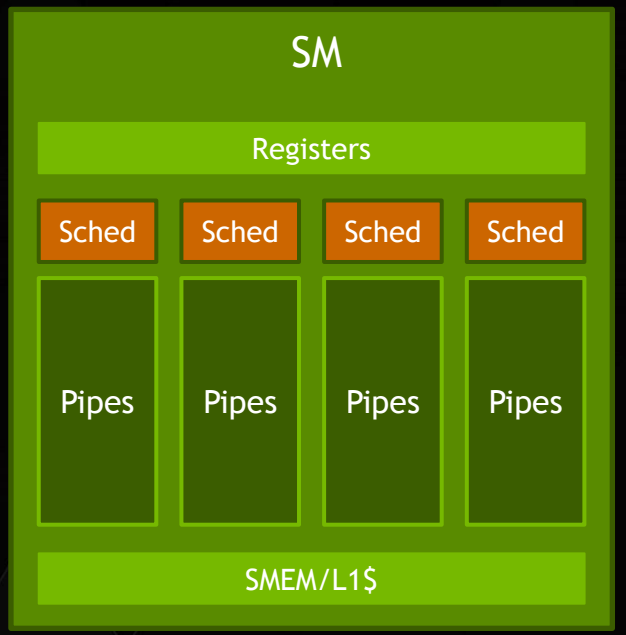


Results

	Transactions	Bandwidth	Utilization
L1/Shared Memory			
Local Loads	0	0 B/s	
Local Stores	0	0 B/s	
Shared Loads	2304000	1,439.543 GB/s	
Shared Stores	640000	399.873 GB/s	
Global Loads	0	0 B/s	
Global Stores	128000	9.997 GB/s	
Atomic	0	0 B/s	
L1/Shared Total	3072000	1,849.413 GB/s	Idle Low Medium High Ma
L2 Cache			
L1 Reads	0	0 B/s	
L1 Writes	128000	9.997 GB/s	
Texture Reads	757777	59.183 GB/s	
Atomic	0	0 B/s	
Noncoherent Reads	757778	59.183 GB/s	
Total	1643555	128.362 GB/s	Idle Low Medium High Ma
Texture Cache			

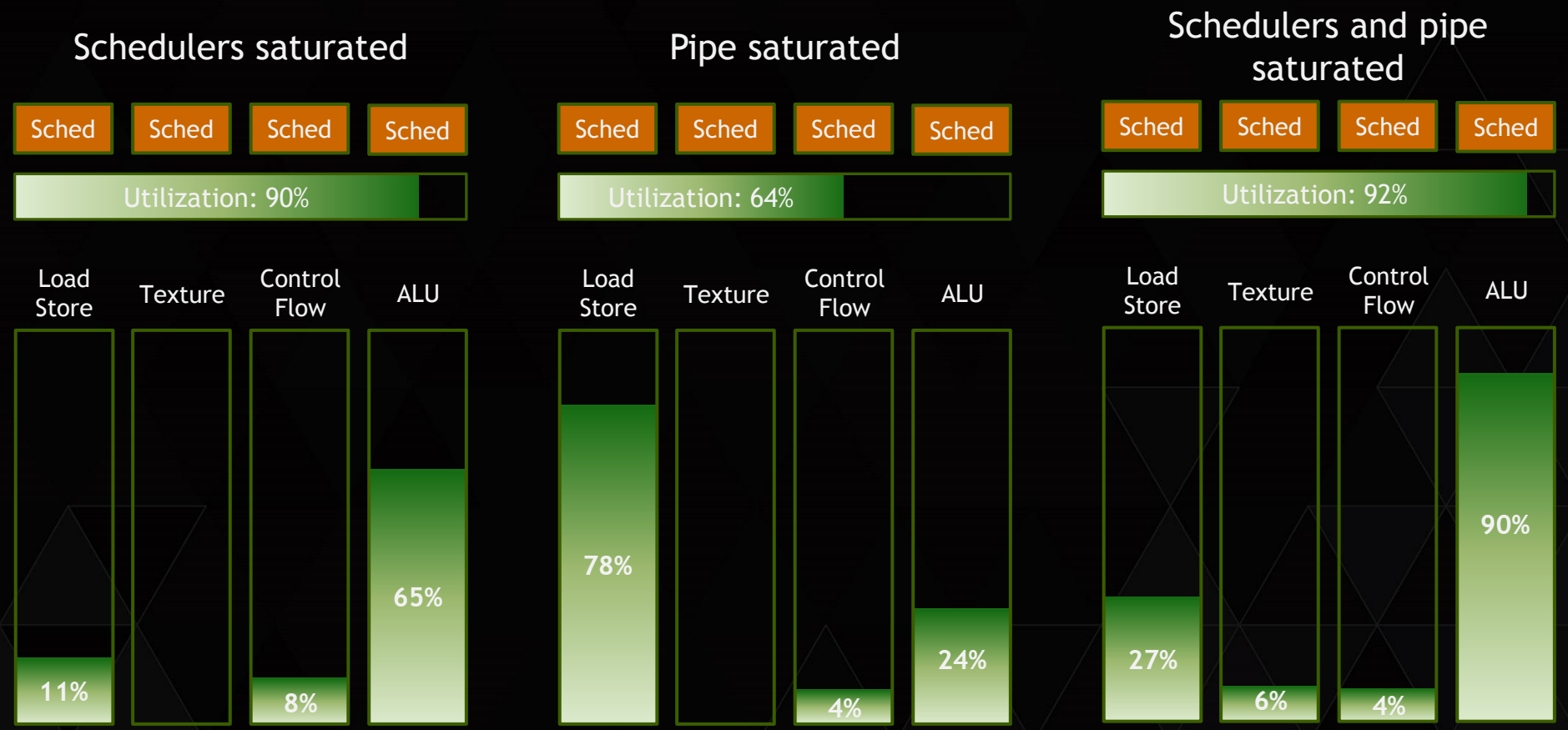
Load/Store Unit is really busy!
Can we reduce the load?

INSTRUCTION THROUGHPUT

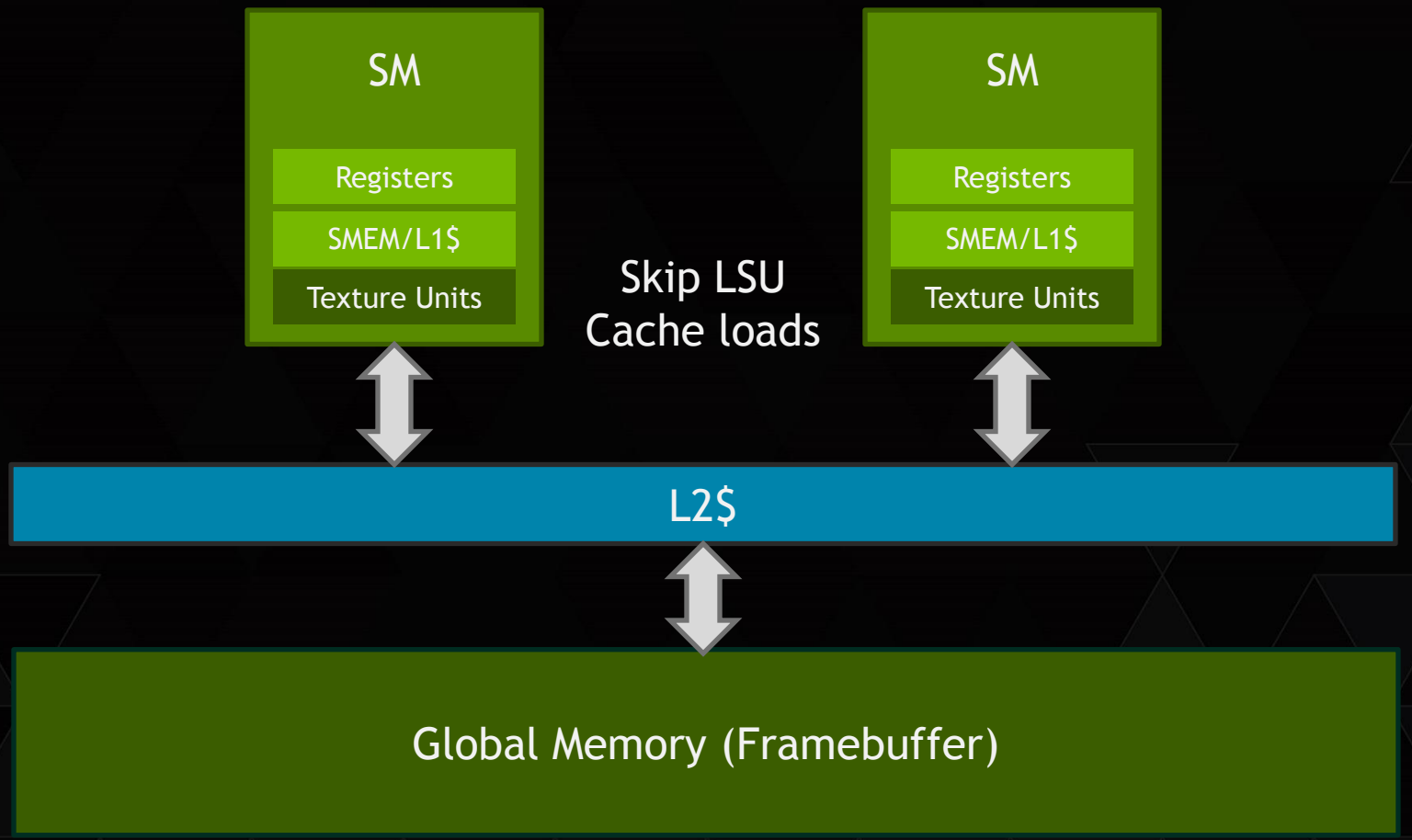


- Each SM has 4 schedulers (Kepler)
- Schedulers issue instructions to pipes
- A scheduler issues up to 2 instructions/cycle
  - Sustainable peak is 7 instructions/cycle per SM (not 4x2 = 8)
- A scheduler issues inst. from a single warp
- Cannot issue to a pipe if its issue slot is full

INSTRUCTION THROUGHPUT



READ-ONLY CACHE (TEXTURE UNITS)



READ-ONLY PATH

- Annotate read-only parameters with const __restrict

```
__global__ void gaussian_filter_7x7_v2(int w, int h, const uchar *__restrict src, uchar *dst)
```

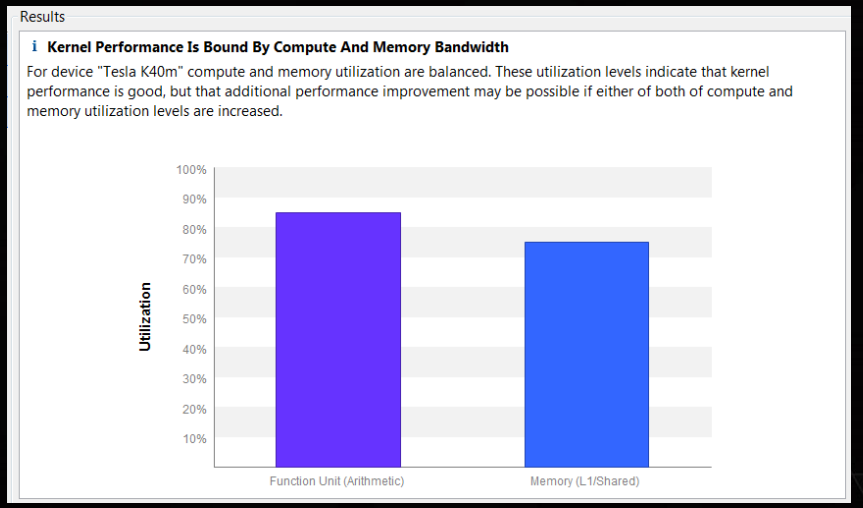
- The compiler generates LDG instructions: 0.808ms

Kernel	Time	Speedup
Original version	5.233ms	1.00x
Better memory accesses	1.589ms	3.29x
Higher Occupancy	1.562ms	3.35x
Shared memory	0.911ms	5.74x
Read-Only path	0.808ms	6.48x

PERF-OPT QUICK REFERENCE CARD

Category:	Latency Bound - Texture Cache
Problem:	Load/Store Unit becomes bottleneck
Goal:	Relieve Load/Store Unit from read-only data
Indicators:	High utilization of Load/Store Unit, pipe-busy stall reason, significant amount of read-only data
Strategy:	Load read-only data through Texture Units: • Annotate read-only pointers with const __restrict__ • Use __ldg() intrinsic

THE RESULT: 6.5X



- Looking much better
- Things to investigate next
  - Reduce computational intensity (separable filter)
  - Increase Instruction Level Parallelism (process two elements per thread)
- The sobel filter is starting to become the bottleneck

Results

Kernel Optimization Priorities

The following kernels are ordered by optimization importance based on execution time and achieved occu
of higher ranked kernels (those that appear first in the list) is more likely to improve performance compared
kernels.

Rank	Description
100	[1 kernel instances] sobel_filter_3x3_v0(int, int, unsigned char const *, unsigned char*)
88	[1 kernel instances] gaussian_filter_7x7_v4(int, int, unsigned char const *, unsigned char*)
39	[1 kernel instances] rgba_to_grayscale_kernel_v0(int, int, uchar4 const *, unsigned char*)

MORE IN OUR COMPANION CODE

Kernel	Time	Speedup
Original version	5.233ms	1.00x
Better memory accesses	1.589ms	3.29x
Higher Occupancy	1.562ms	3.35x
Shared memory	0.911ms	5.74x
Read-Only path	0.808ms	6.48x
Separable filter	0.481ms	10.88x
Process two pixels per thread (memory efficiency + ILP)	0.415ms	12.61x
Use 64-bit shared memory (remove bank conflicts)	0.403ms	12.99x
Use float instead of int (increase instruction throughput)	0.363ms	14.42x
Your next idea!!!		

Companion Code: https://github.com/chmaruni/nsight-gtc2015

SUMMARY

ITERATIVE OPTIMIZATION WITH NSIGHT EE

- Trace the Application
- Identify the Hotspot and Profile it
- Identify the Performance Limiter
  - Memory Bandwidth
  - Instruction Throughput
  - Latency
- Look for indicators
  - Take nvvp guided analysis as a starting point
  - But don’t follow it too closely
- Optimize the Code
- Iterate

REFERENCES

- Performance Optimization: Programming Guidelines and GPU Architecture Details Behind Them, GTC 2013
  - http://on-demand.gputechconf.com/gtc/2013/video/S3466-Performance-Optimization-Guidelines-GPU-Architecture-Details.mp4
  - http://on-demand.gputechconf.com/gtc/2013/presentations/S3466-Programming-Guidelines-GPU-Architecture.pdf
- CUDA Best Practices Guide
  - http://docs.nvidia.com/cuda/cuda-c-best-practices-guide/
- Parallel Forall devblog
  - http://devblogs.nvidia.com/parallelforall/
- Upcoming GTC 2015 Sessions:
  - S5655 CUDA Application Development Life Cycle with Nsight Eclipse Edition (Hands-on lab), Nikita Shulga, Thursday 2pm
  - S5353+S5376 Memory Bandwidth Bootcamp (and Beyond), Tony Scudiero, Thursday 3:30pm and 5pm

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