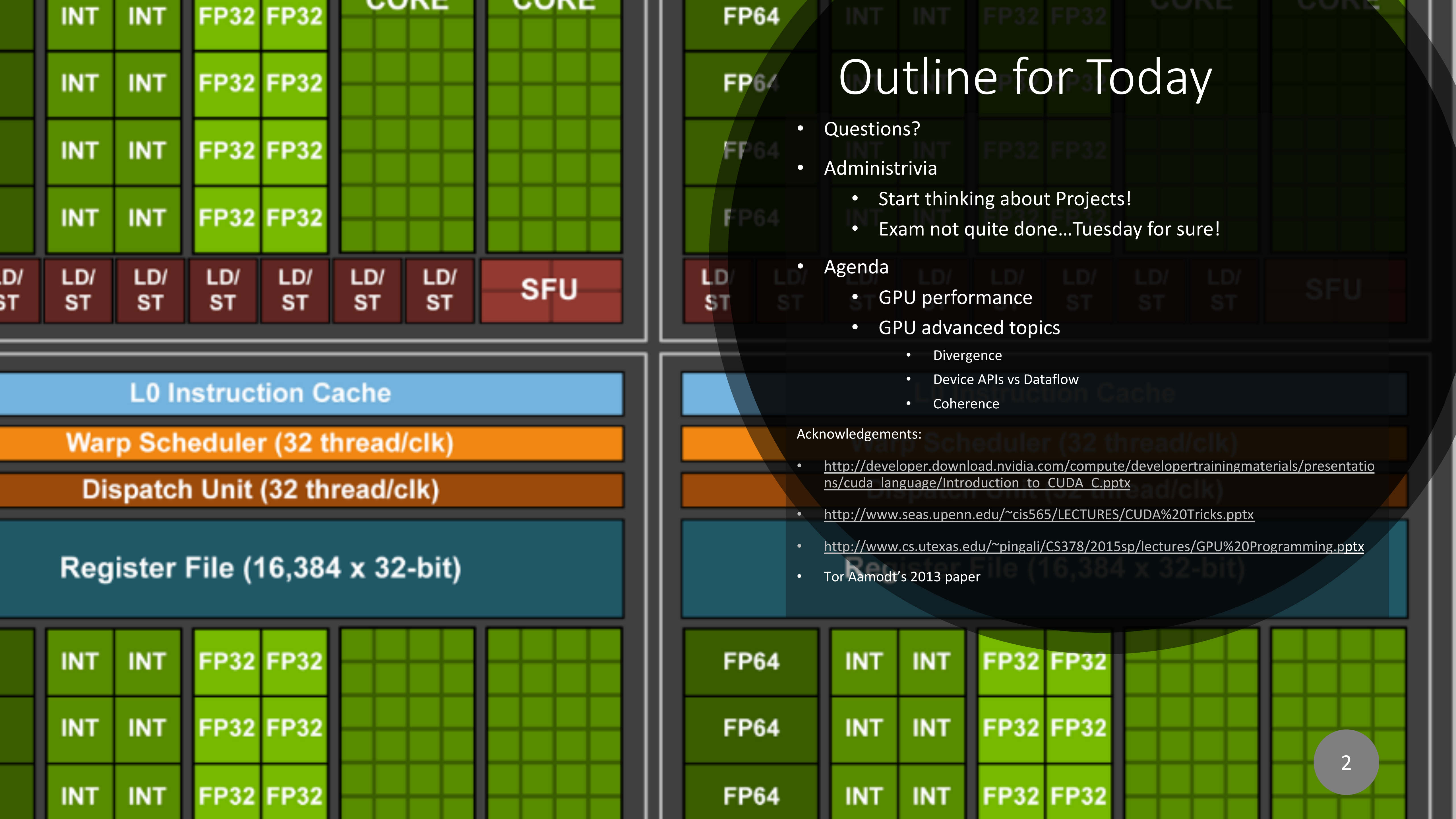
GPUs going once…
GPUs going twice…
you get the idea

Chris Rossbach

cs378


CORE
CORE
INT
FP32
FP64
LD/ ST
SFU
L0 Instruction Cache
Warp Scheduler (32 thread/clk)
Dispatch Unit (32 thread/clk)
Register File (16,384 x 32-bit)

Outline for Today

- Questions?
- Administrivia
  - Start thinking about Projects!
  - Exam not quite done…Tuesday for sure!
- Agenda
  - GPU performance
  - GPU advanced topics
    - Divergence
    - Device APIs vs Dataflow
    - Coherence

Acknowledgements:

- http://developer.download.nvidia.com/compute/developertrainingmaterials/presentations/cuda_language/Introduction_to_CUDA_C.pptx
- http://www.seas.upenn.edu/~cis565/LECTURES/CUDA%20Tricks.pptx
- http://www.cs.utexas.edu/~pingali/CS378/2015sp/lectures/GPU%20Programming.pptx
- Tor Aamodt’s 2013 paper

Faux Quiz Questions

- How is occupancy defined (in CUDA nomenclature)?
- What’s the difference between a block scheduler (e.g. Giga-Thread Engine) and a warp scheduler?
- Modern CUDA supports UVM to eliminate the need for cudaMalloc and cudaMemcpy*. Under what conditions might you want to use or not use it and why?
- What is control flow divergence? How does it impact performance?
- What is a bank conflict?
- What is work efficiency?
- What is the difference between a thread block scheduler and a warp scheduler?
- How are atomics implemented in modern GPU hardware?
- How is __shared__ memory implemented by modern GPU hardware?
- Why is __shared__ memory necessary if GPUs have an L1 cache? When will an L1 cache provide all the benefit of __shared__ memory and when will it not?
- Is cudaDeviceSynchronize still necessary after copyback if I have just one CUDA stream?

How many threads/blocks?

```
    // Copy inputs to device
    cudaMemcpy(d_a, a, size, cudaMemcpyHostToDevice);
    cudaMemcpy(d_b, b, size, cudaMemcpyHostToDevice);

    // Launch add() kernel on GPU
    add<<<N/THREADS_PER_BLOCK, THREADS_PER_BLOCK>>>(d_a, d_b, d_c);

    // Copy result back to host
    cudaMemcpy(c, d_c, size, cudaMemcpyDeviceToHost);

    // Cleanup
    free(a); free(b); free(c);
    cudaFree(d_a); cudaFree(d_b); cudaFree(d_c);
    return 0;
}
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- Usually things are correct if grid*block dims >= input size
- Getting good performance is another matter

Review: Internals

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__host__
void vecAdd()
{
  dim3 DimGrid = (ceil(n/256,1,1);
  dim3 DimBlock = (256,1,1);
  addKernel<<<DGrid,DBlock>>>(A_d,B_d,C_d,n);
}
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__global__
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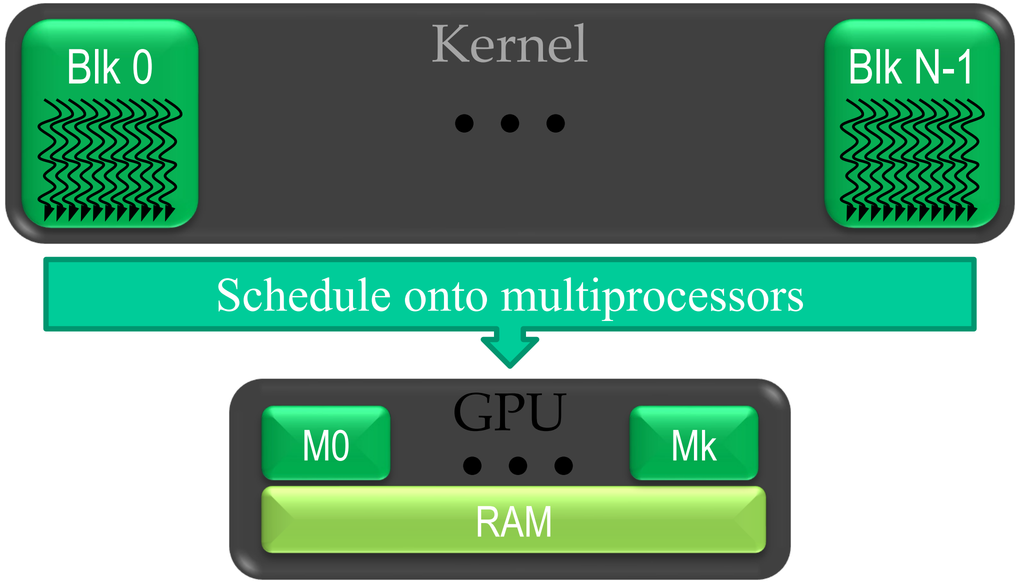

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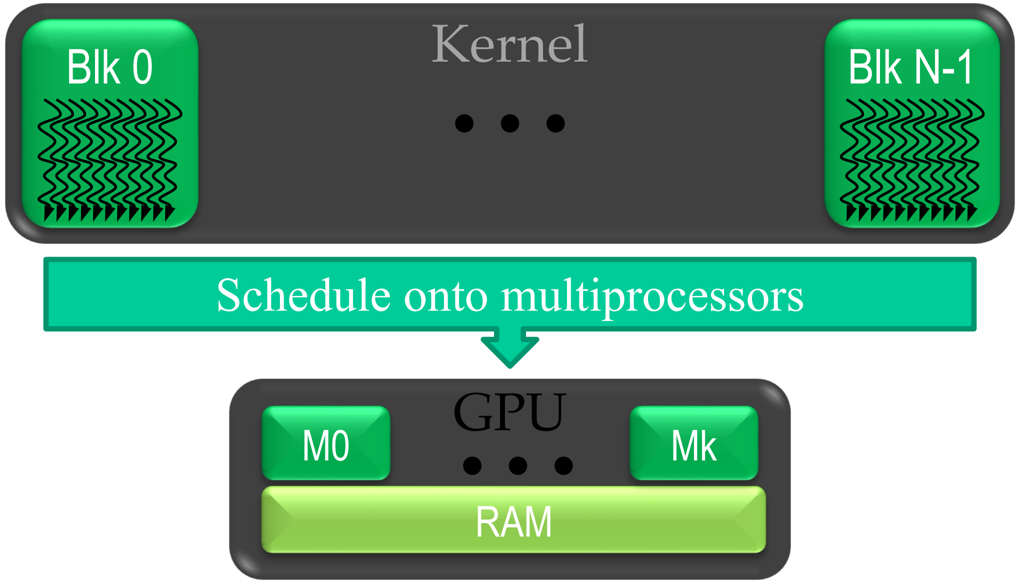

Kernel

Blk 0

• • •

Blk N-1

Schedule onto multiprocessors

GPU

M0

• • •

Mk

RAM

How are threads scheduled?

Thread Blocks, Warps, Scheduling

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Suppose one TB (threadblock) has 64 threads (2 warps)

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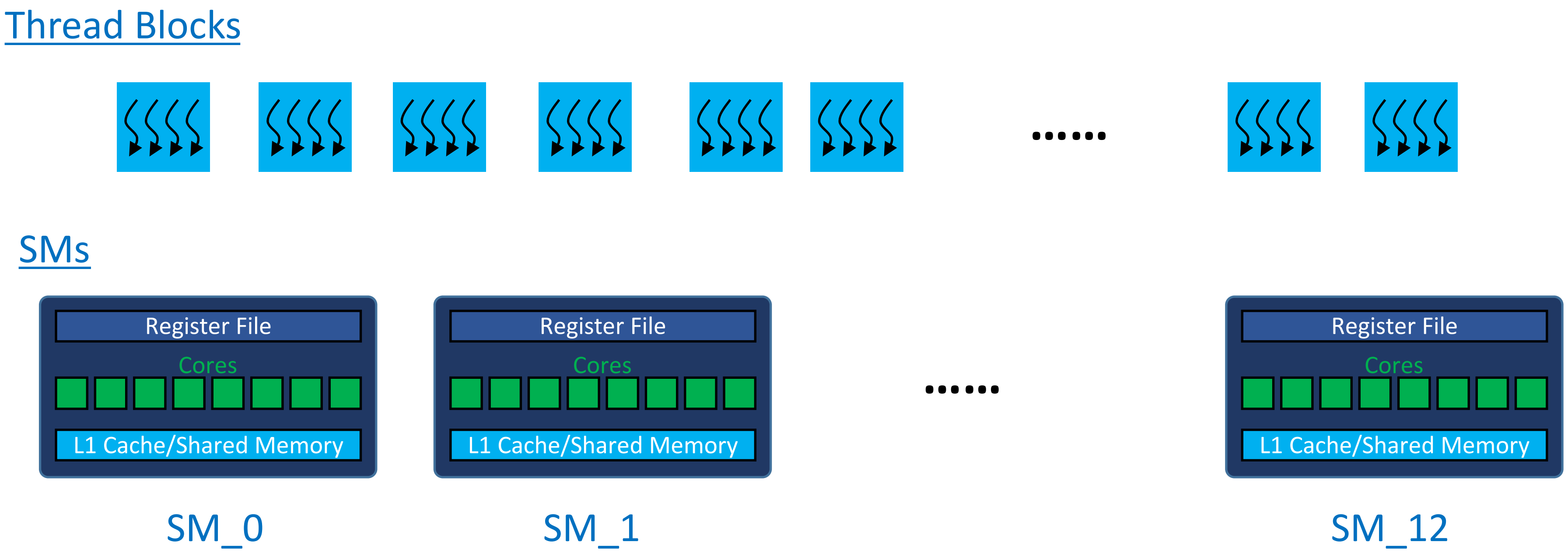

- SMs split blocks into warps
- Unit of HW scheduling for SM
- 32 threads each

Thread Blocks, Warps, Scheduling

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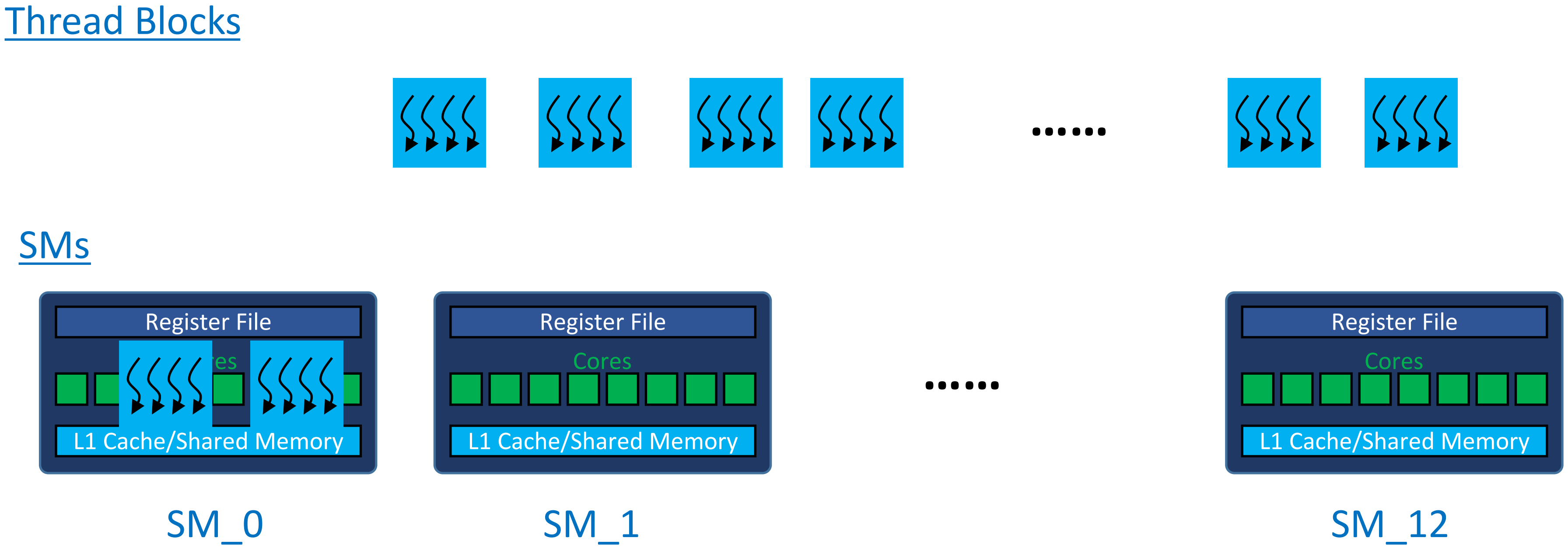

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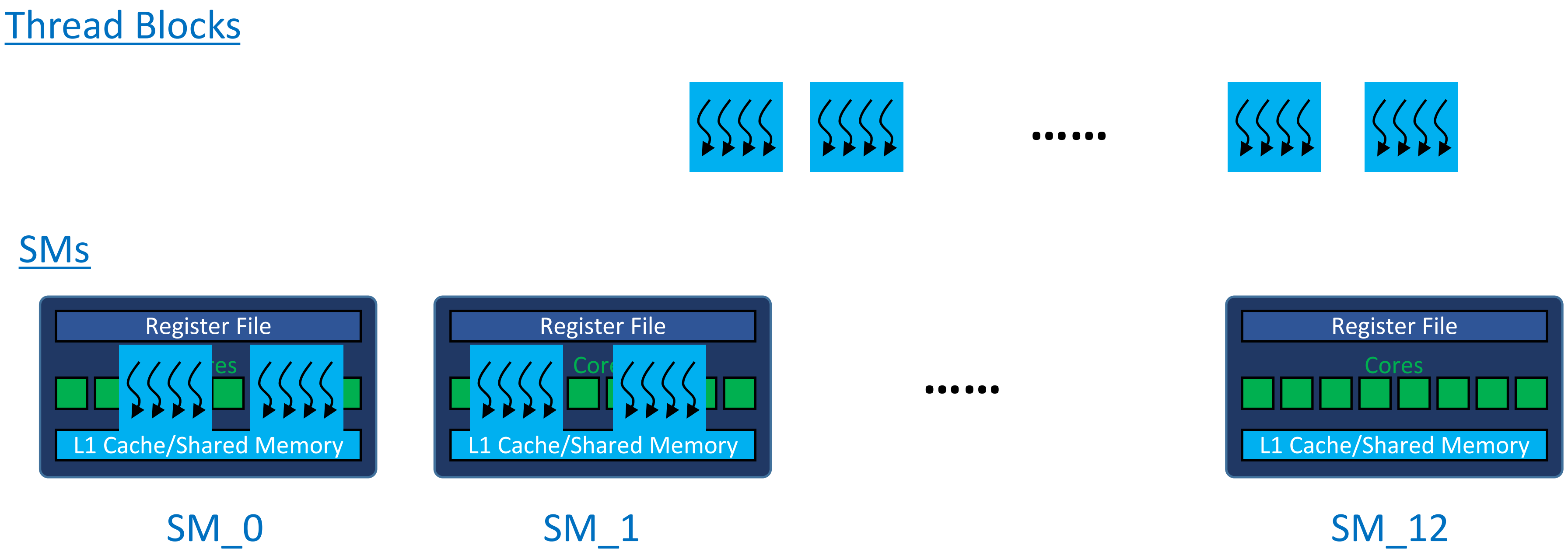

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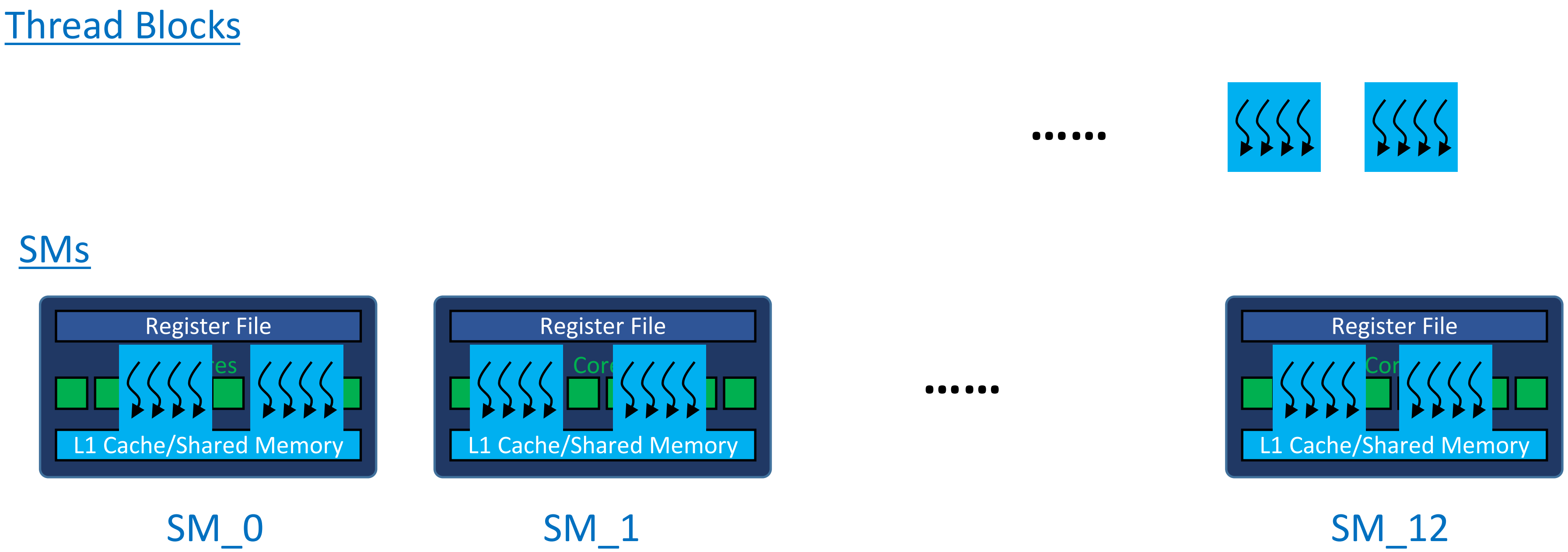

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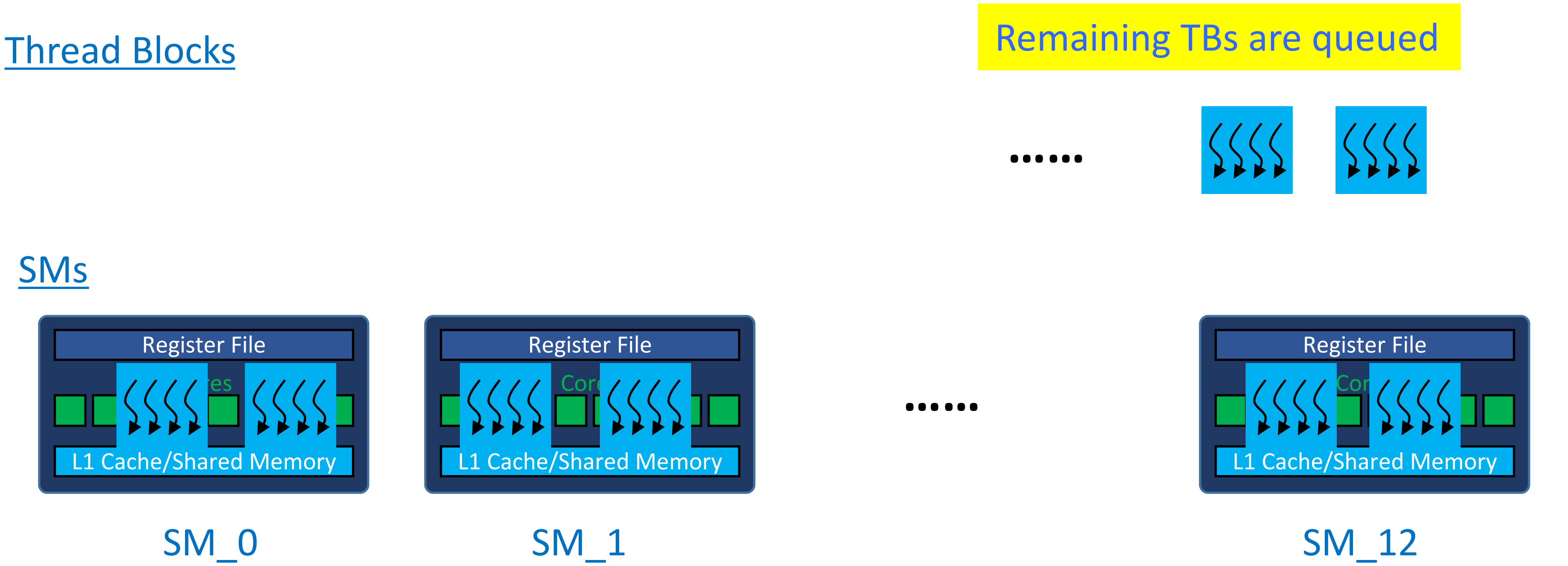

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PCI Express 3.0 Host Interface
GigaThread Engine
GPC
TPC
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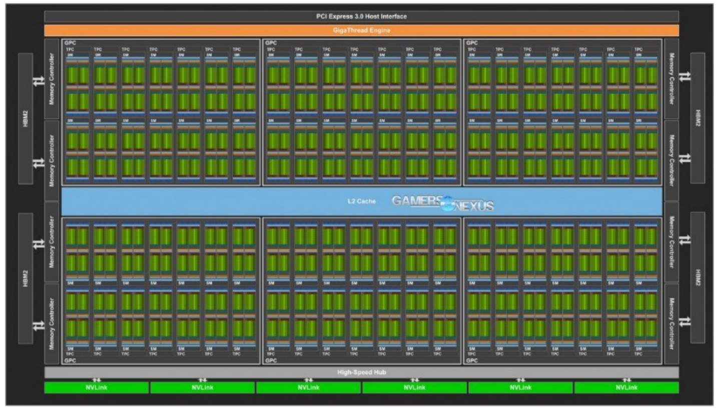
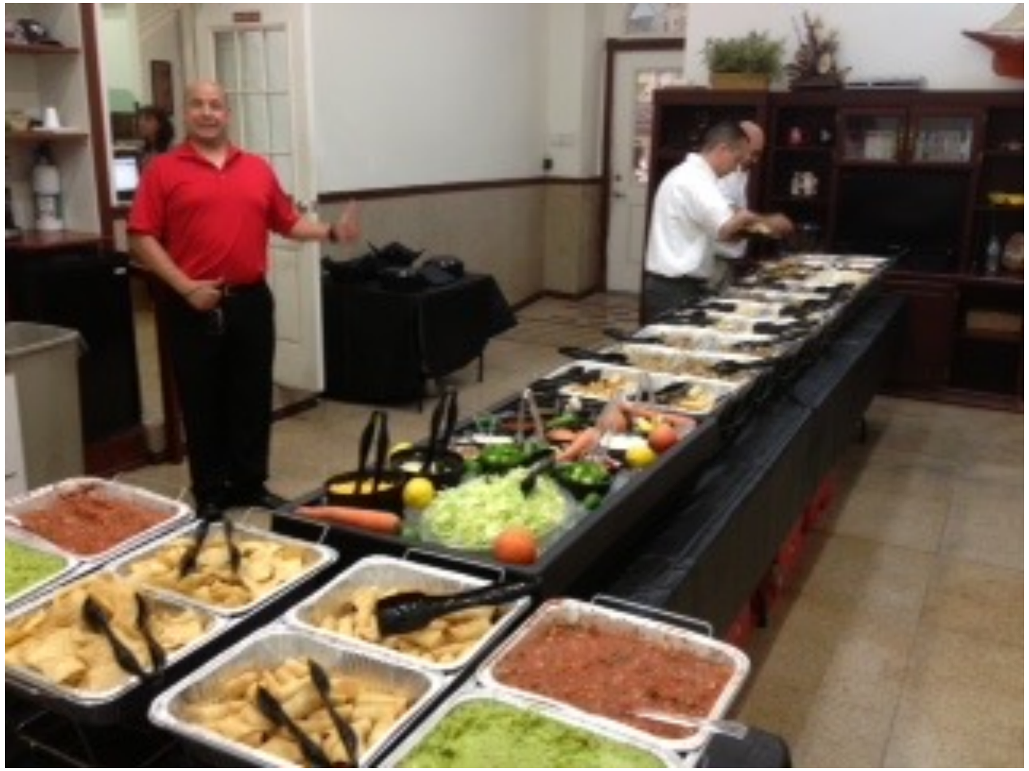


A Taco Bar



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- Where is the parallelism here?

GPU: a multi-lane Taco Bar

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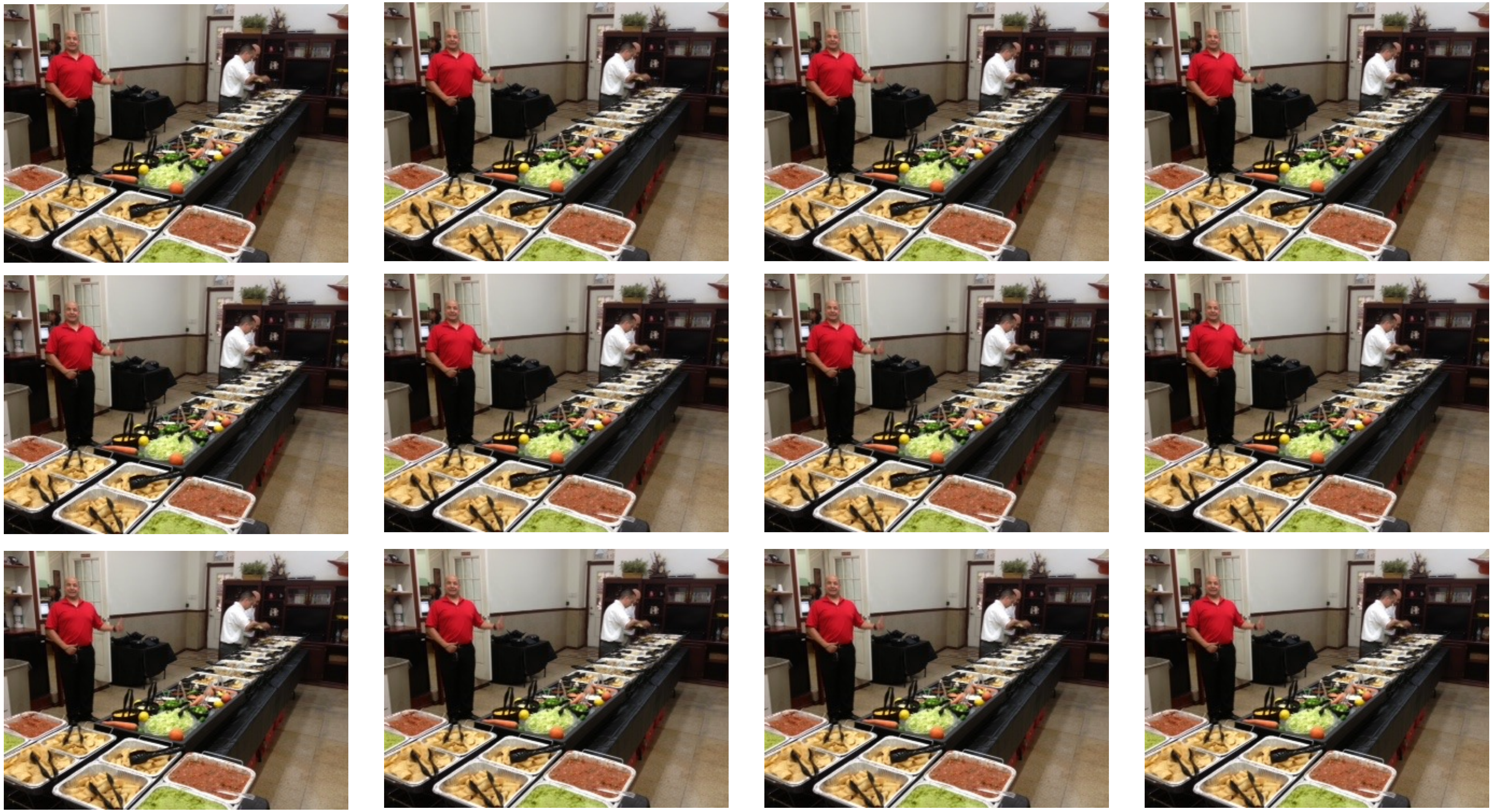

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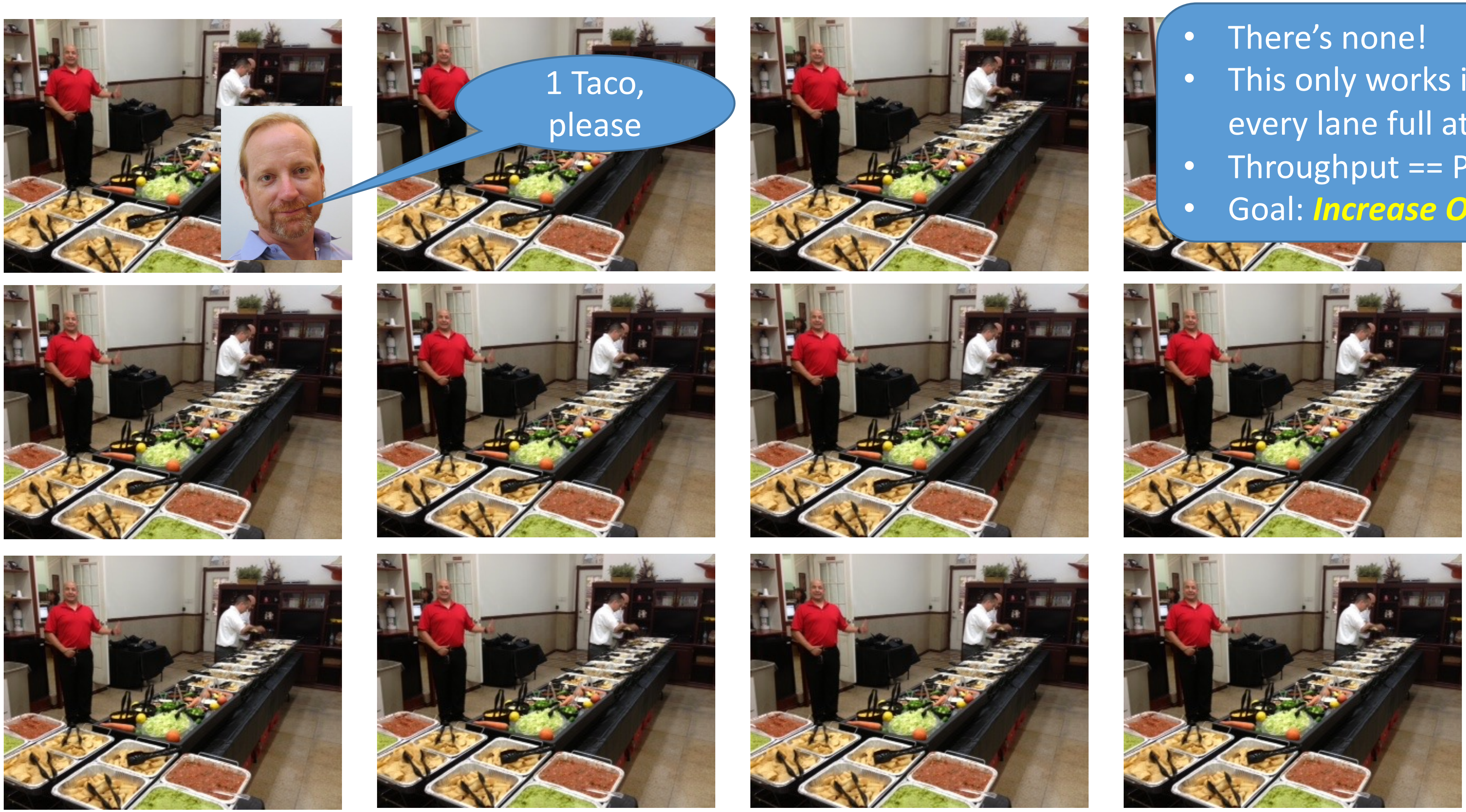

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- This only works if you can keep every lane full at every step
- Throughput == Performance
- Goal: ***Increase Occupancy!***

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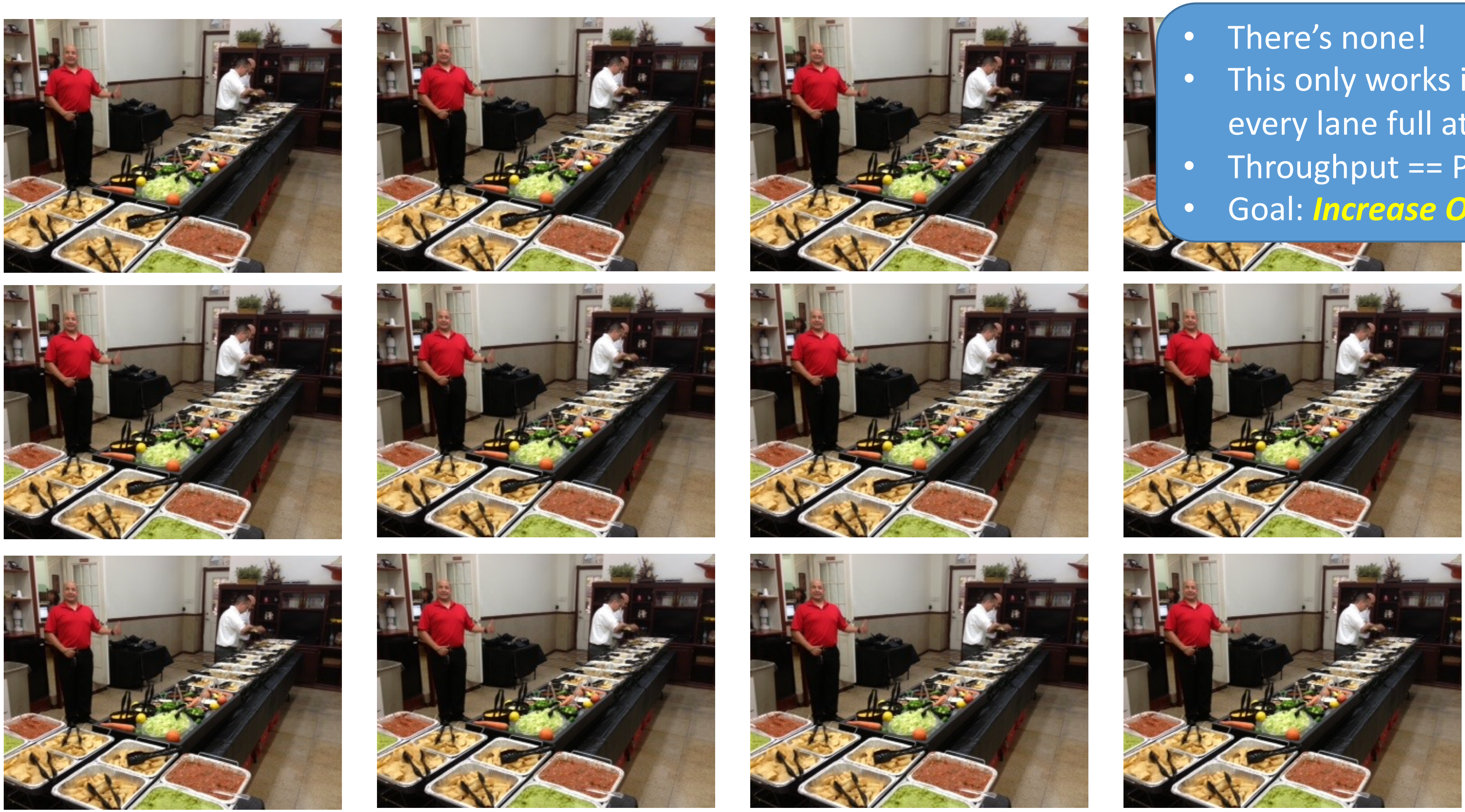

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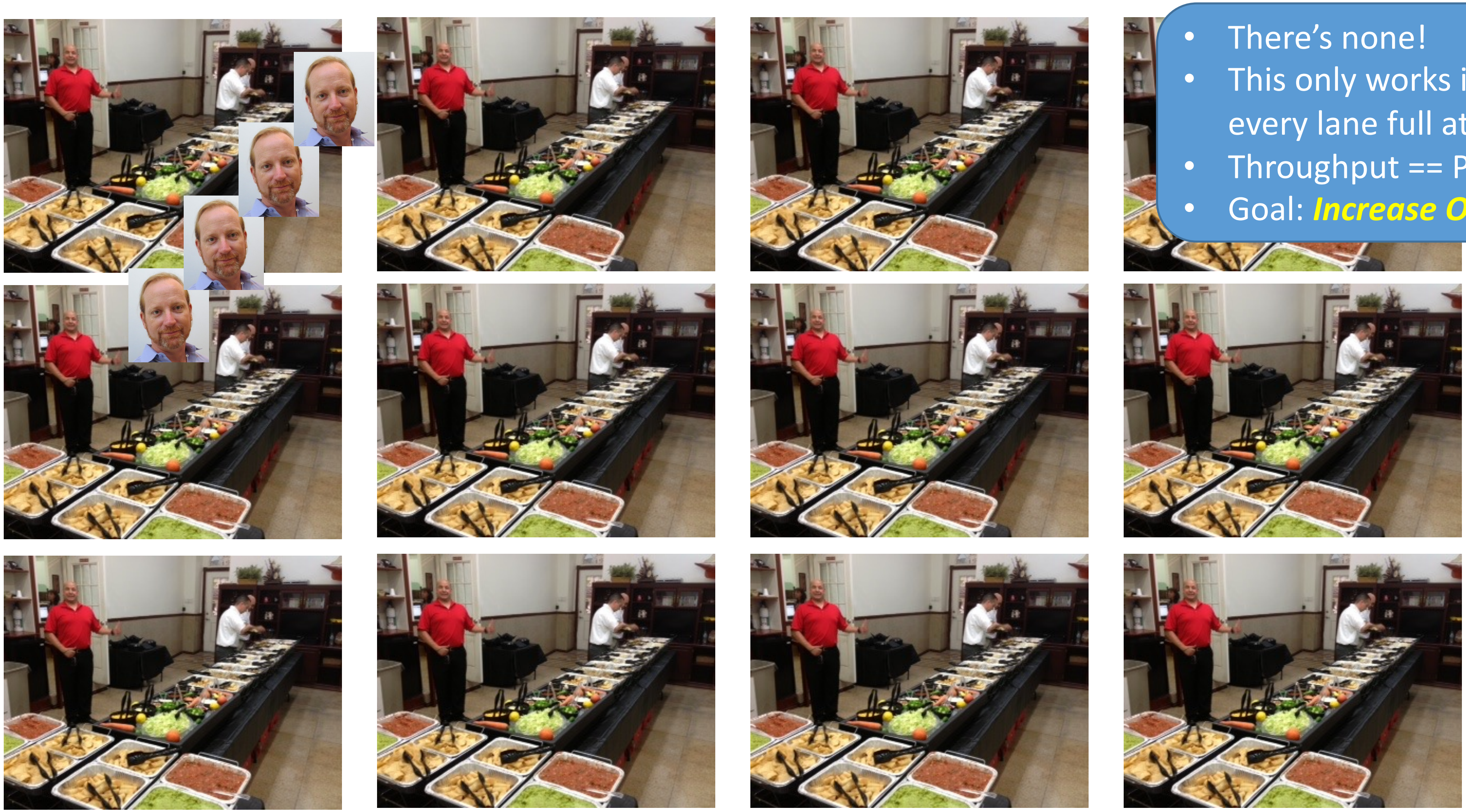

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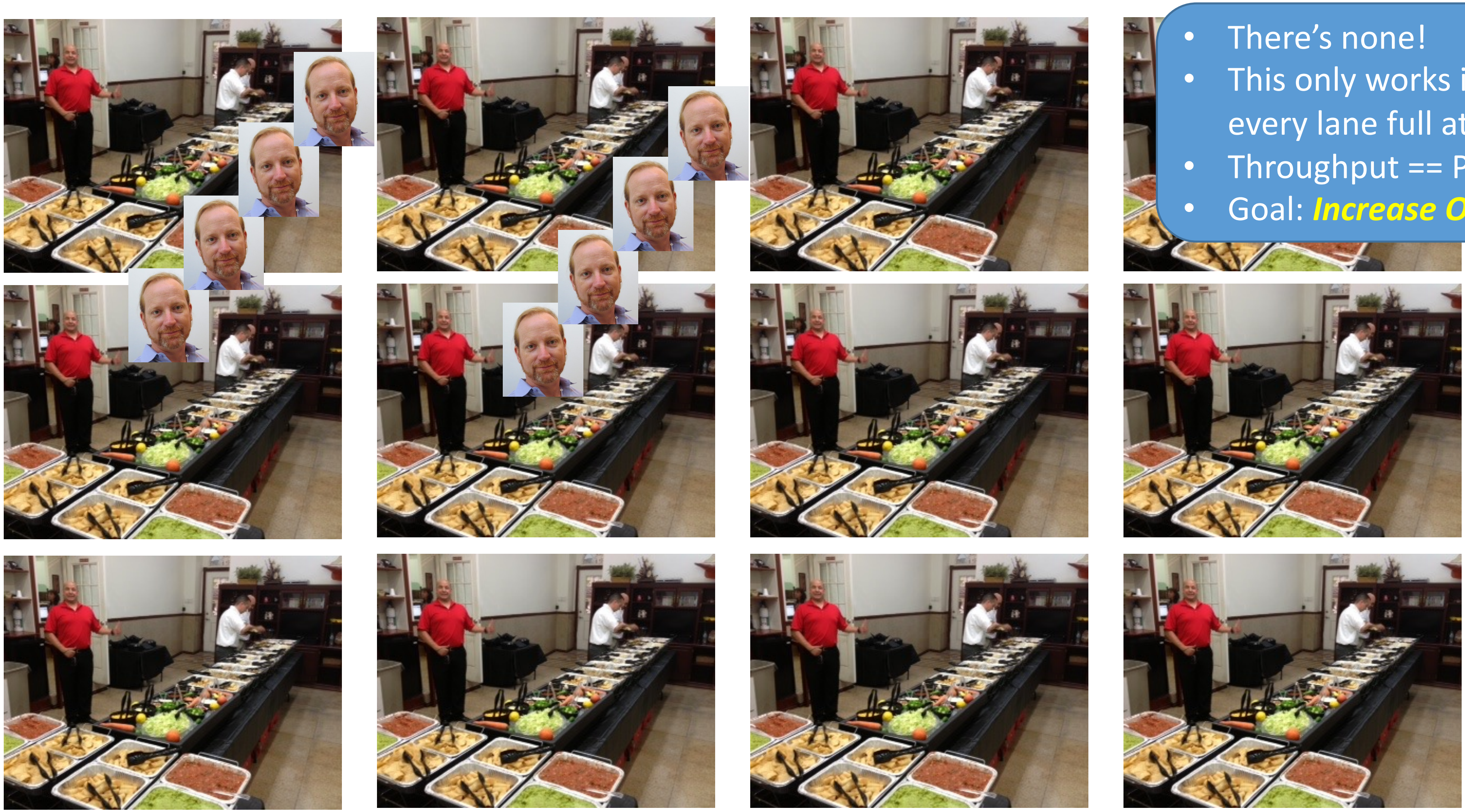

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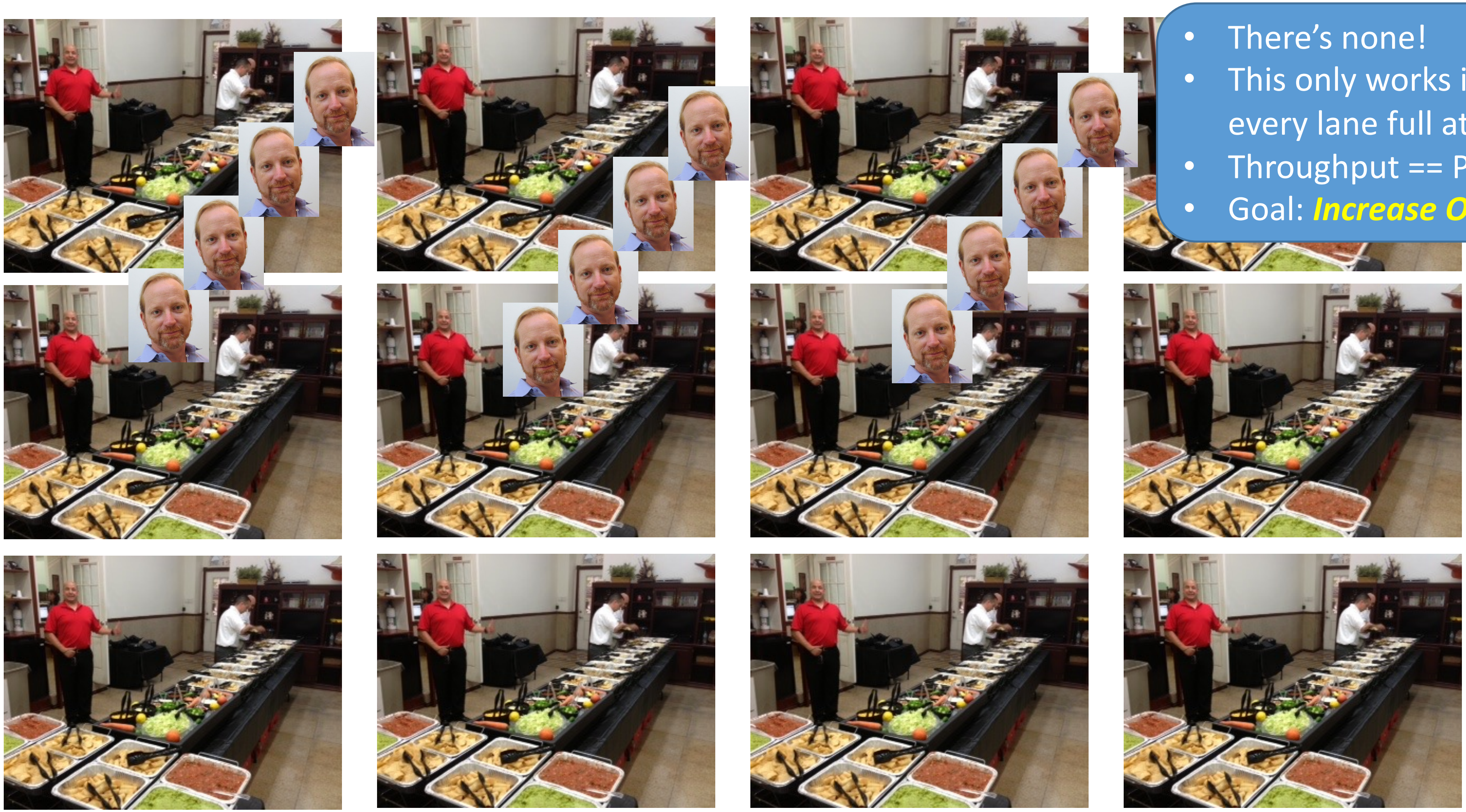

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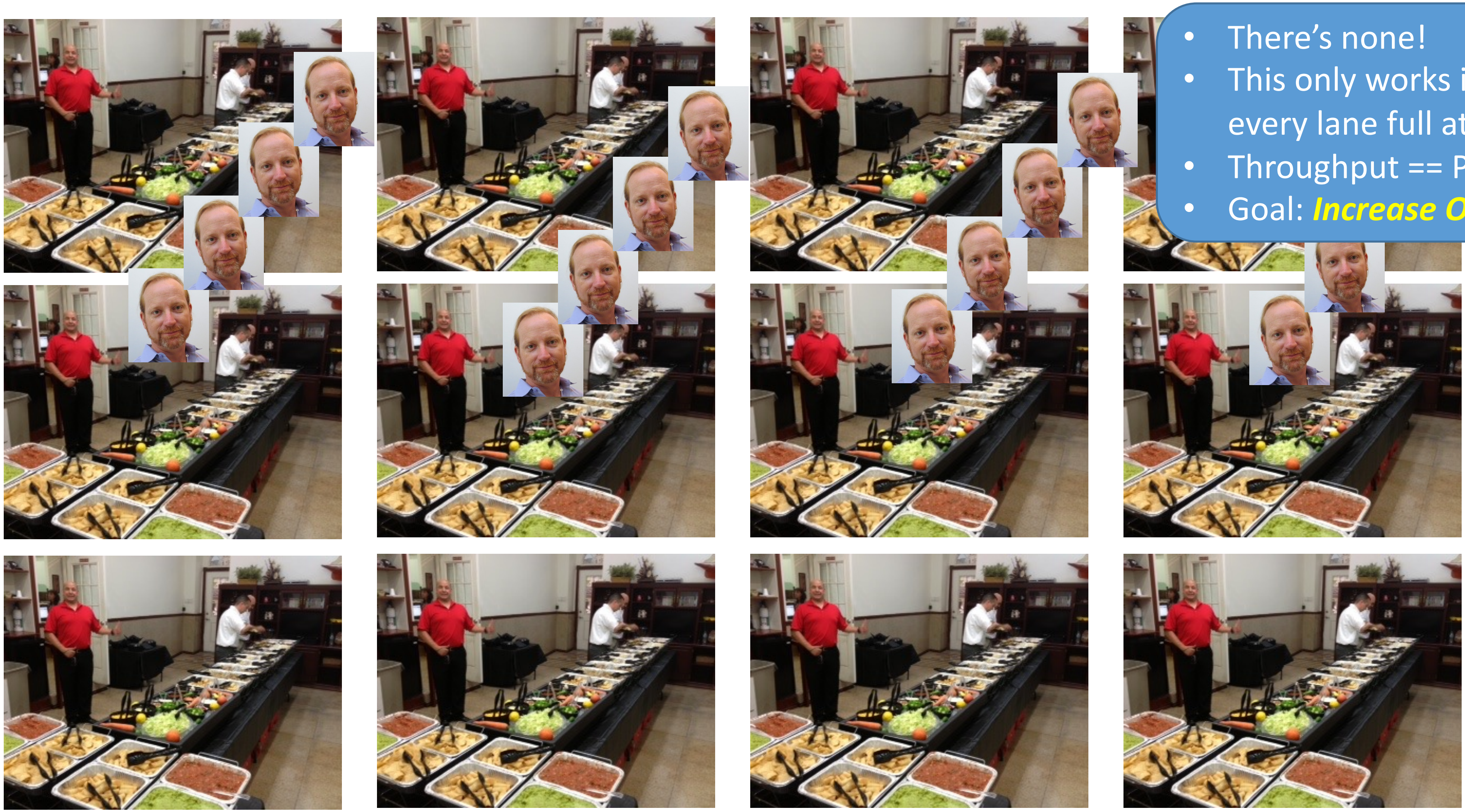

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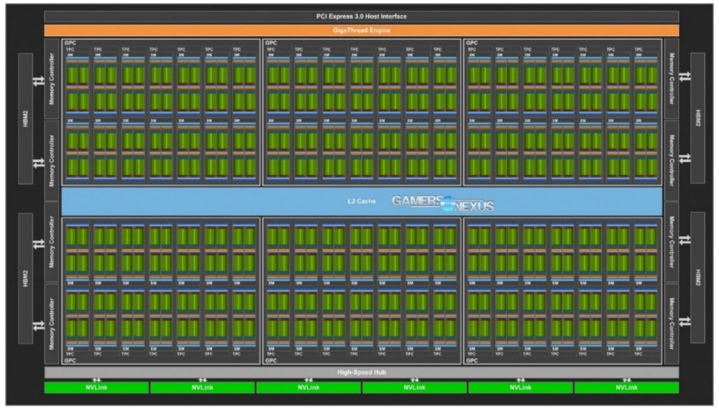

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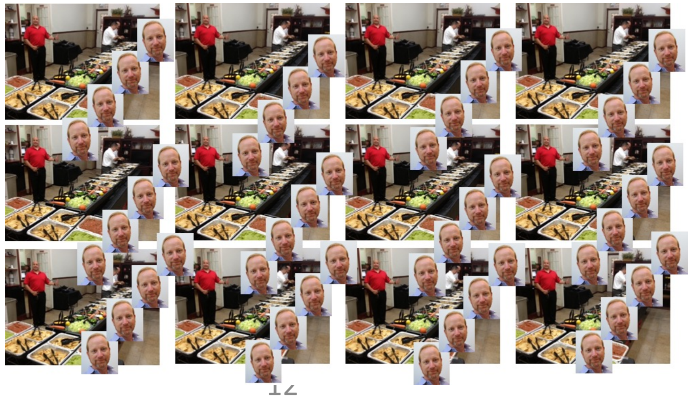

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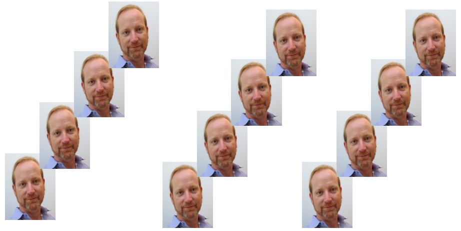

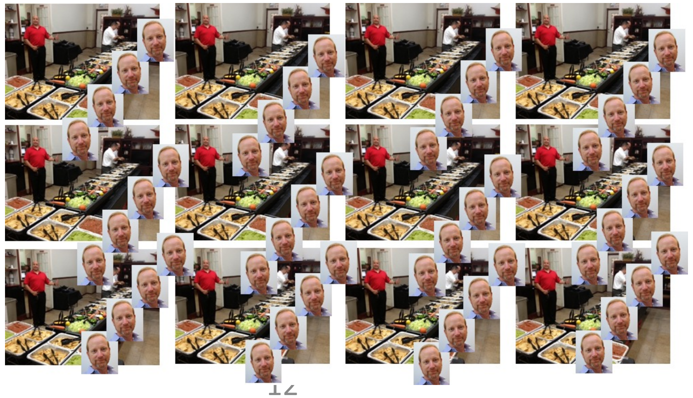

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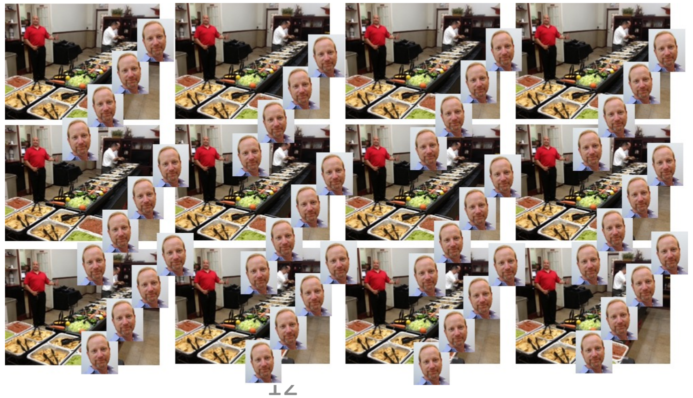

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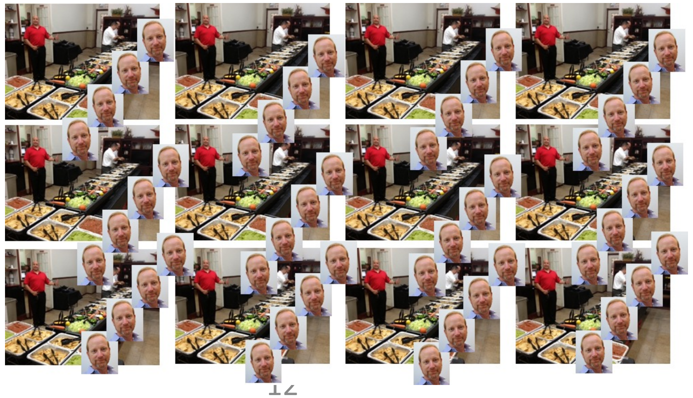

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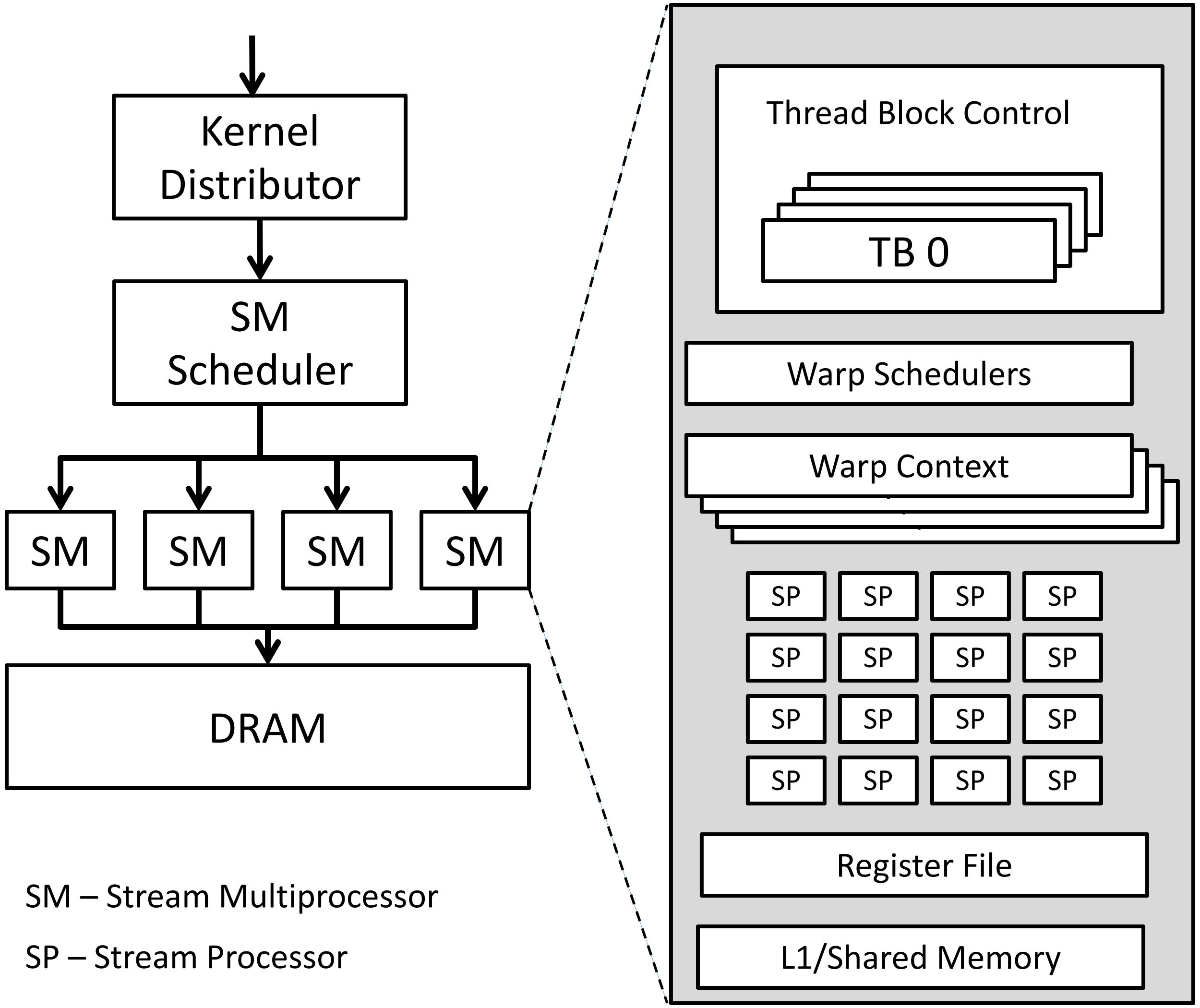
Hardware Resources Are Finite



SM – Stream Multiprocessor

SP – Stream Processor

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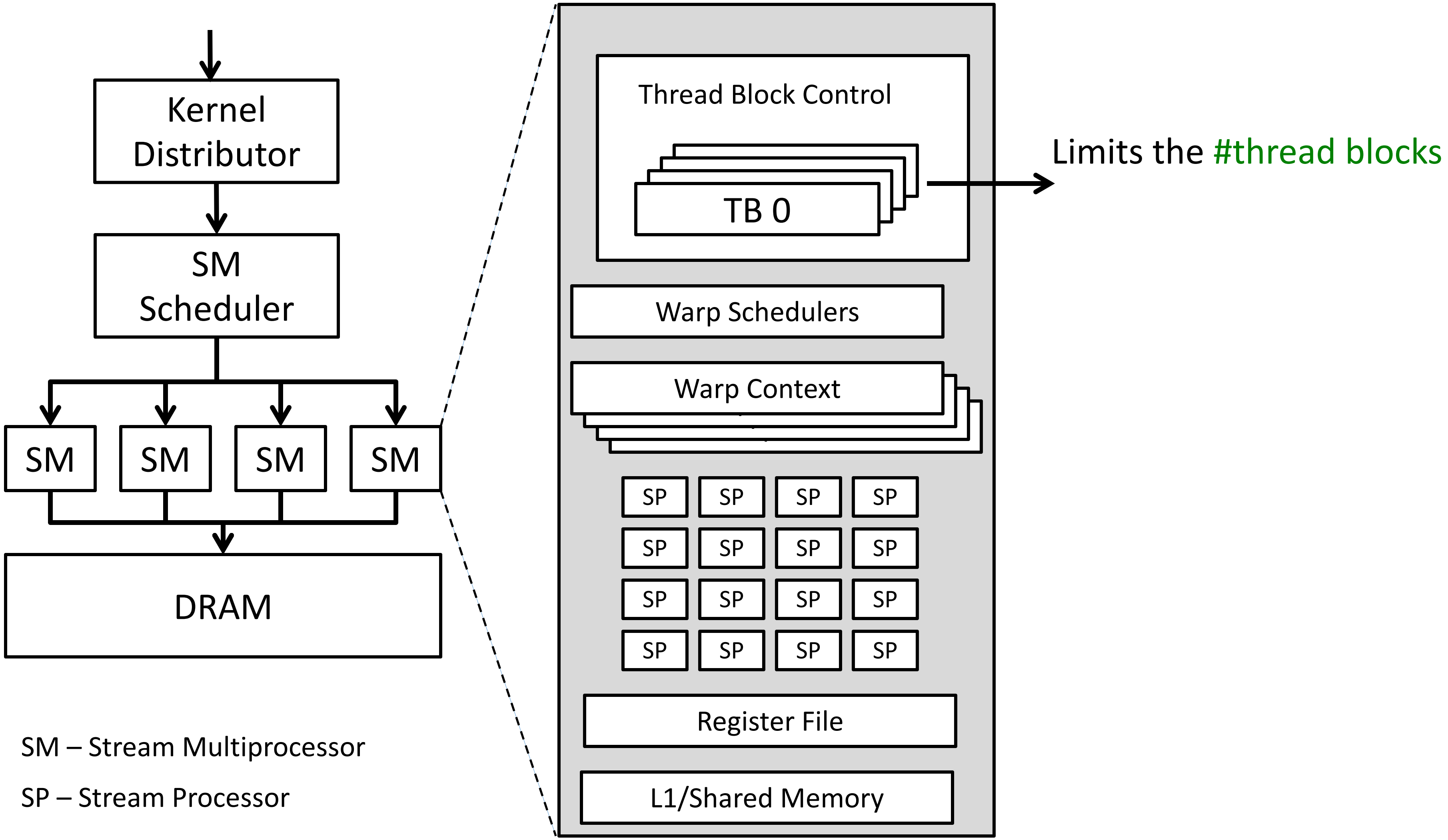

Limits the #thread blocks

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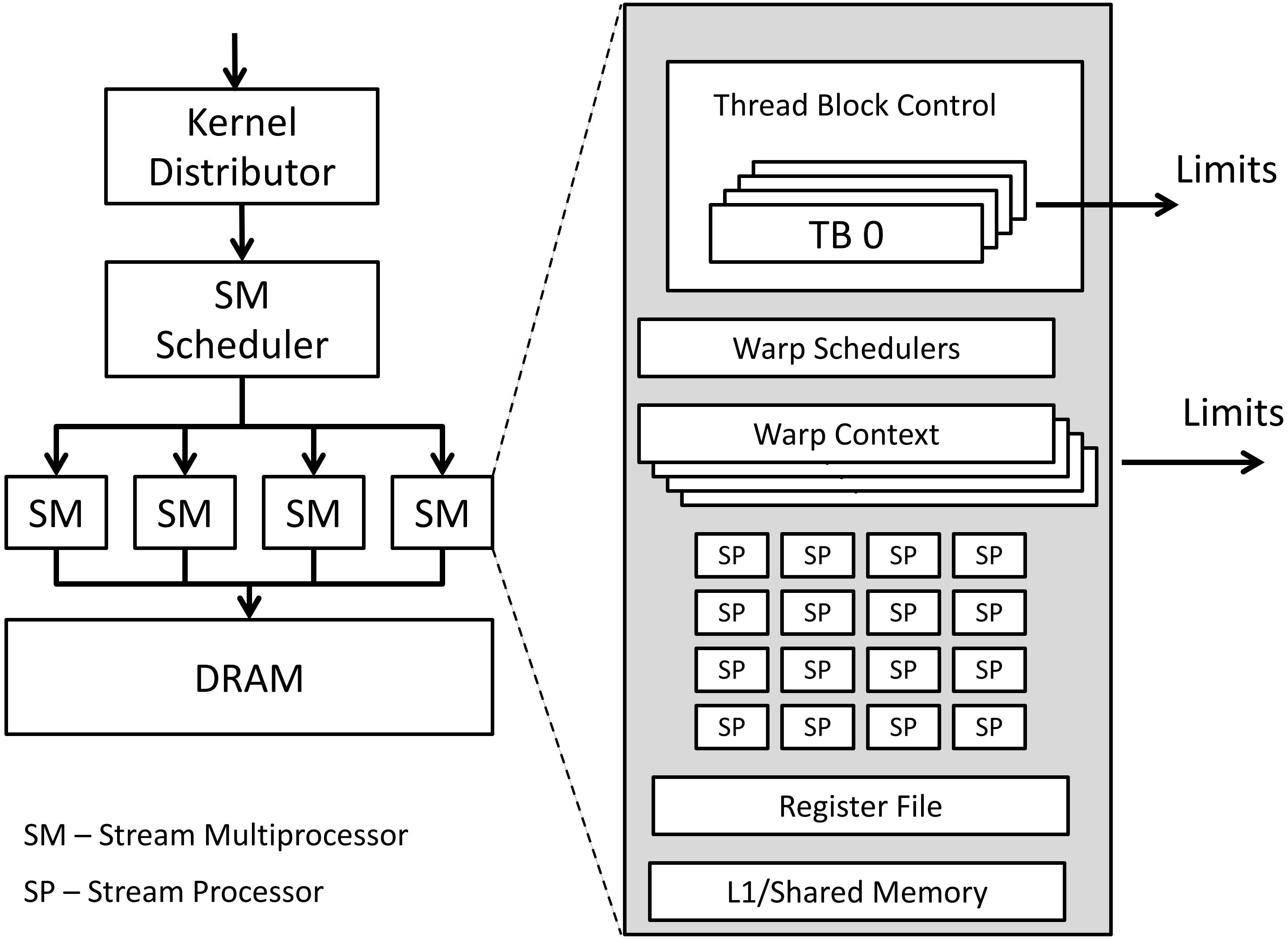

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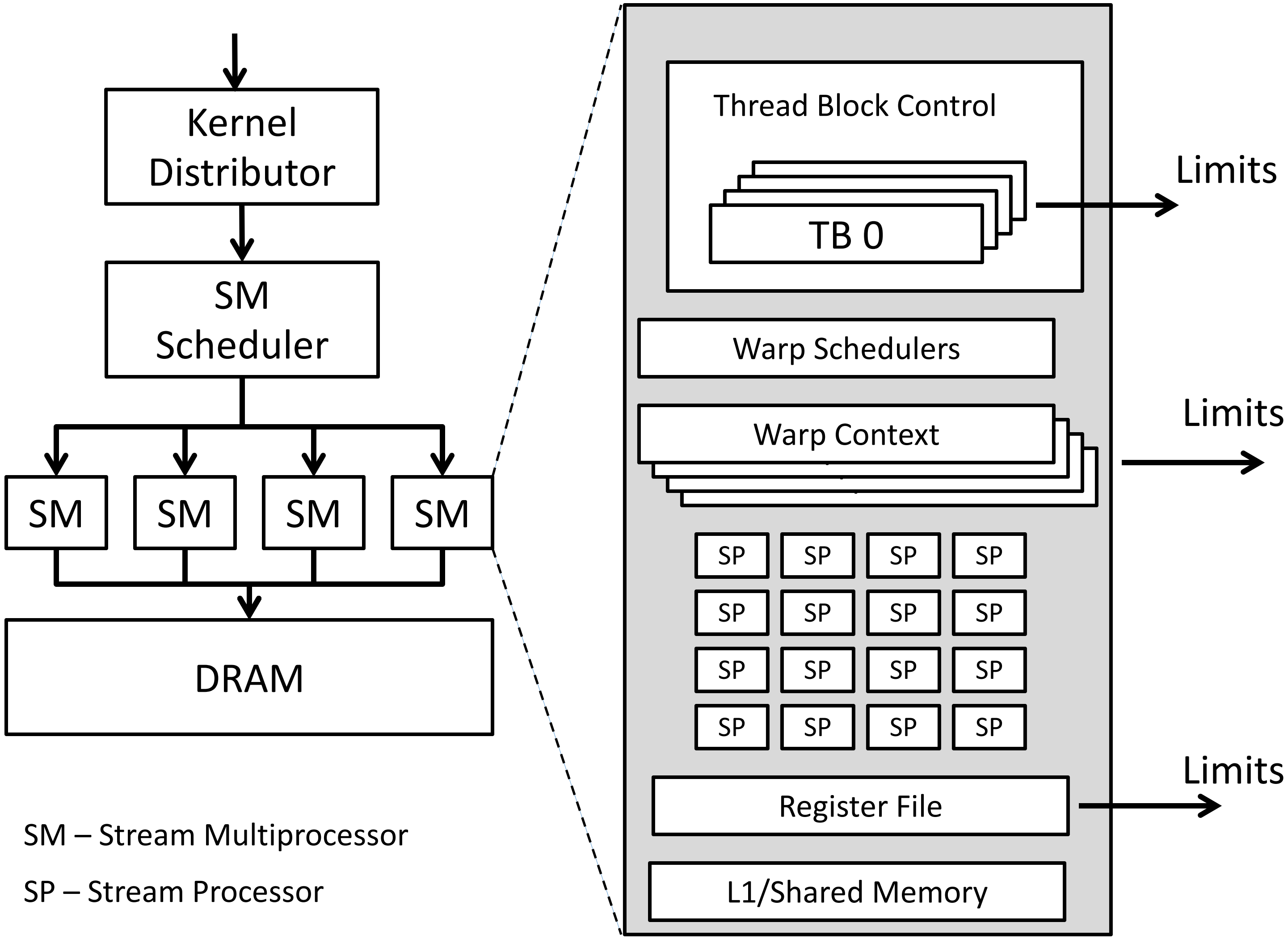

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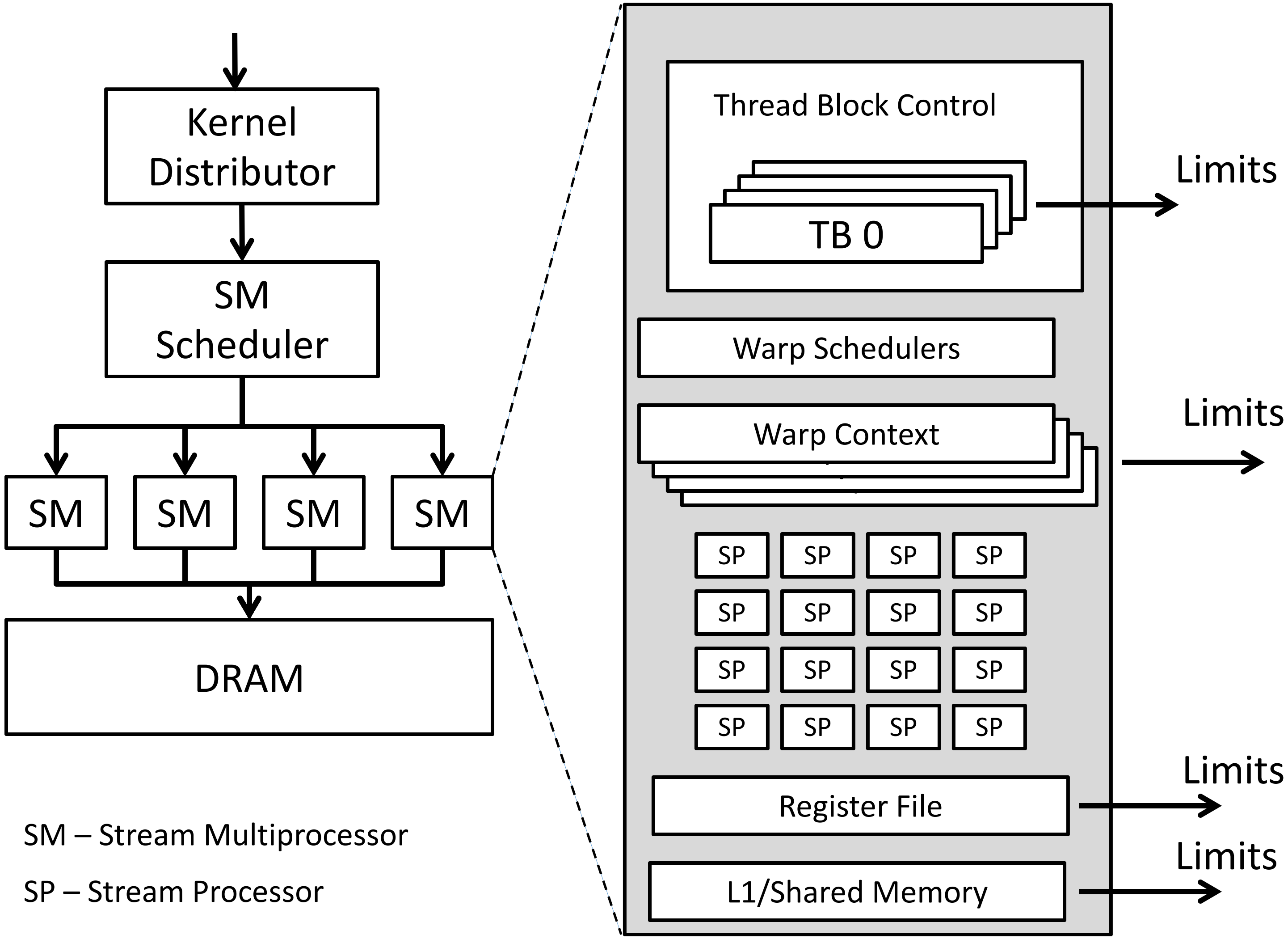

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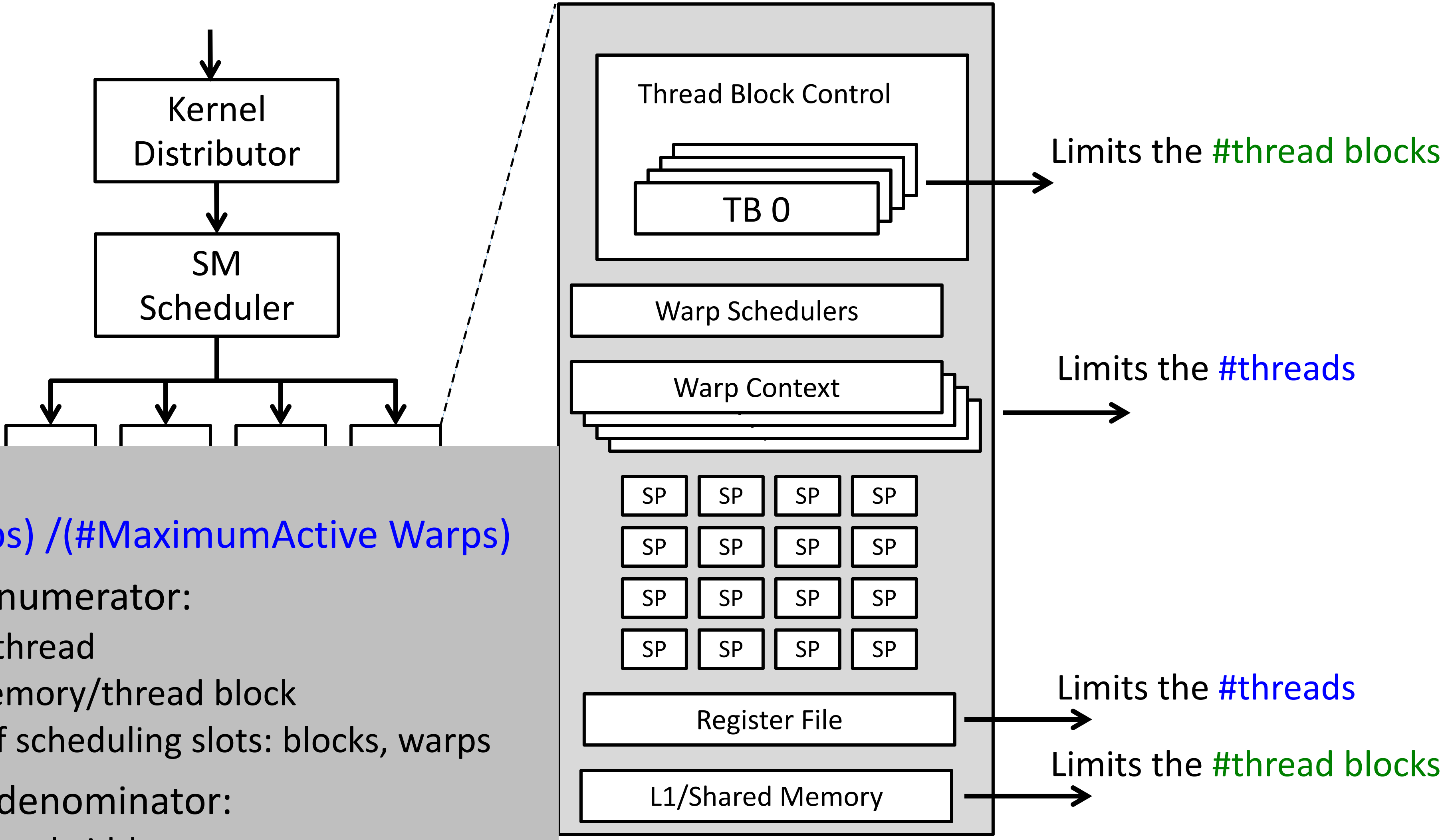

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Occupancy:

- (#Active Warps) /(#MaximumActive Warps)
- Limits on the numerator:
  - Registers/thread
  - Shared memory/thread block
  - Number of scheduling slots: blocks, warps
- Limits on the denominator:
  - Memory bandwidth
  - Scheduler slots

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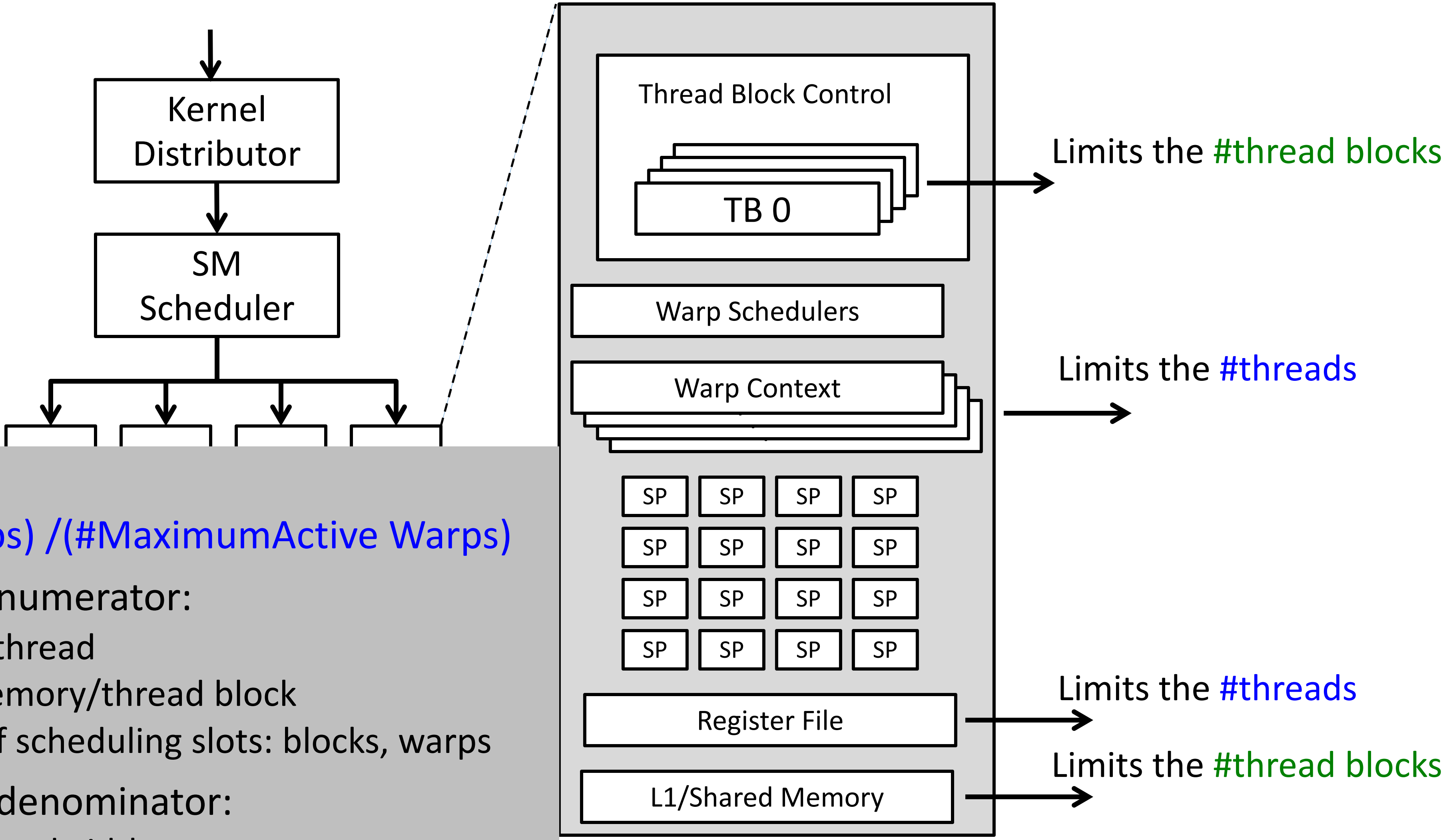

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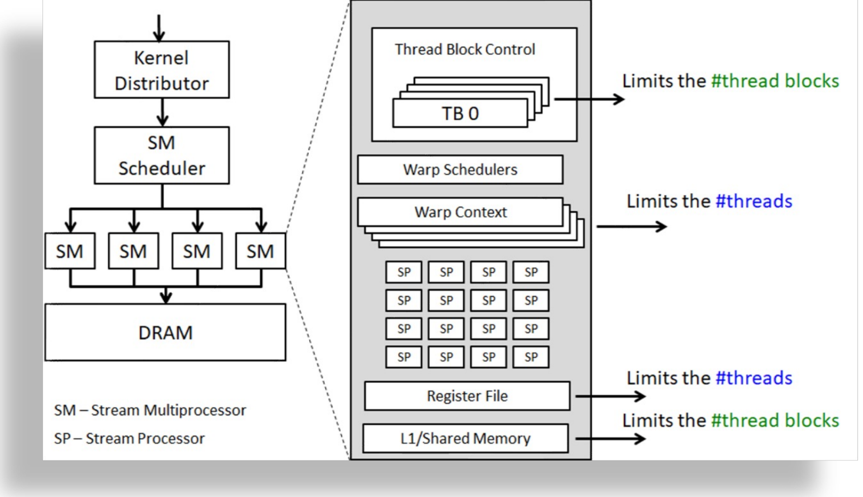
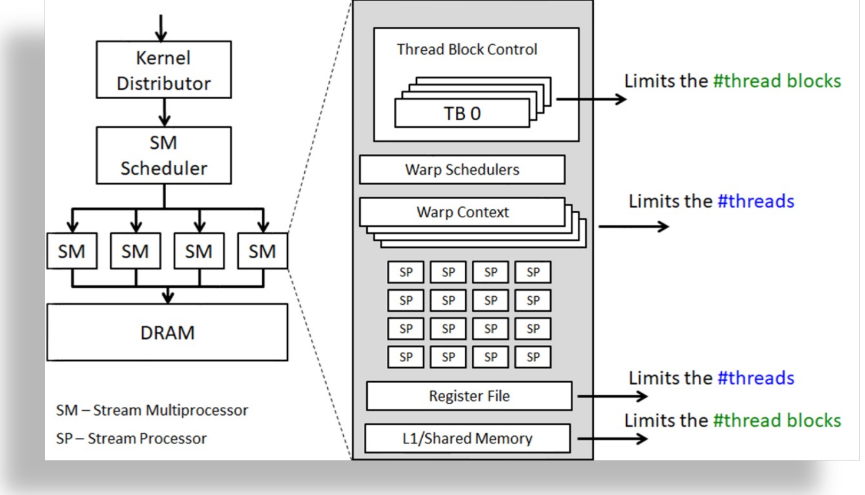
What is the performance impact of varying kernel resource demands?

Impact of Thread Block Size



Impact of Thread Block Size

Example: v100:



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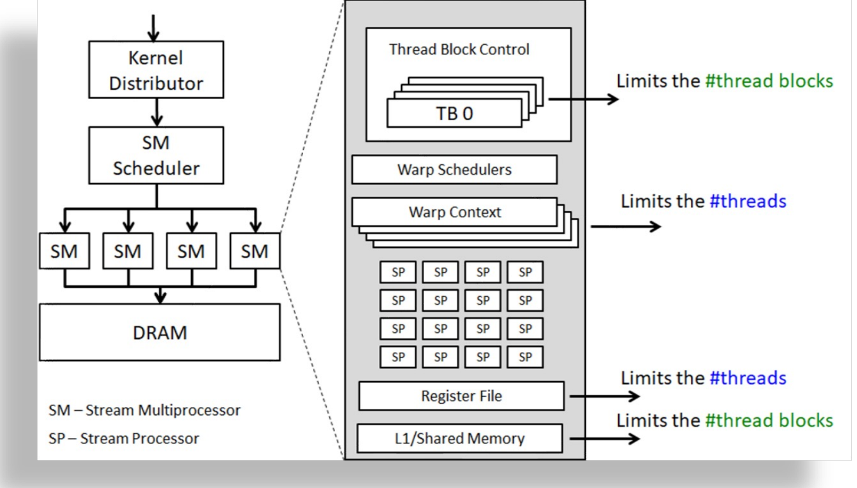


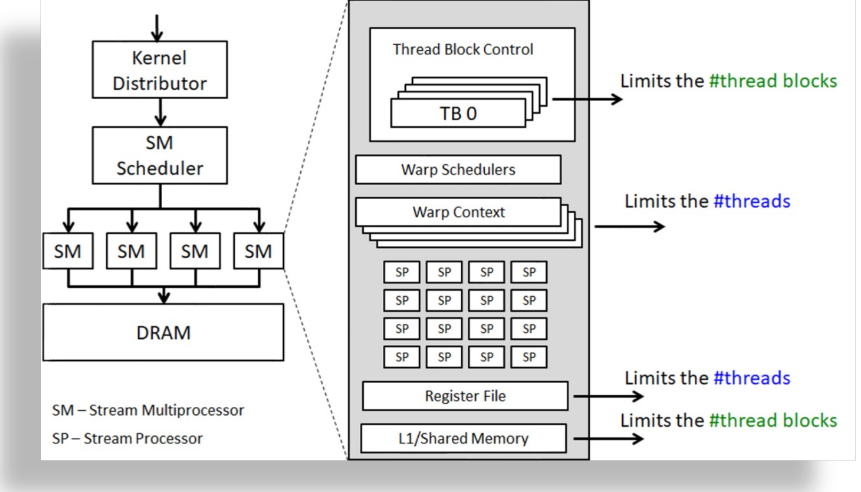
Example: v100:

- max active warps/SM == 64 (limit: warp context)

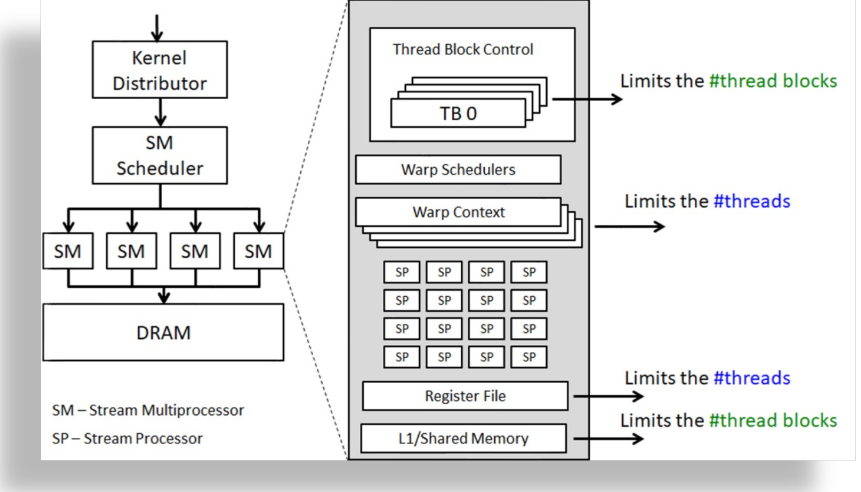
Impact of Thread Block Size

Example: v100:

- max active warps/SM == 64 (limit: warp context)
- max active blocks/SM == 32 (limit: block control)



Impact of Thread Block Size



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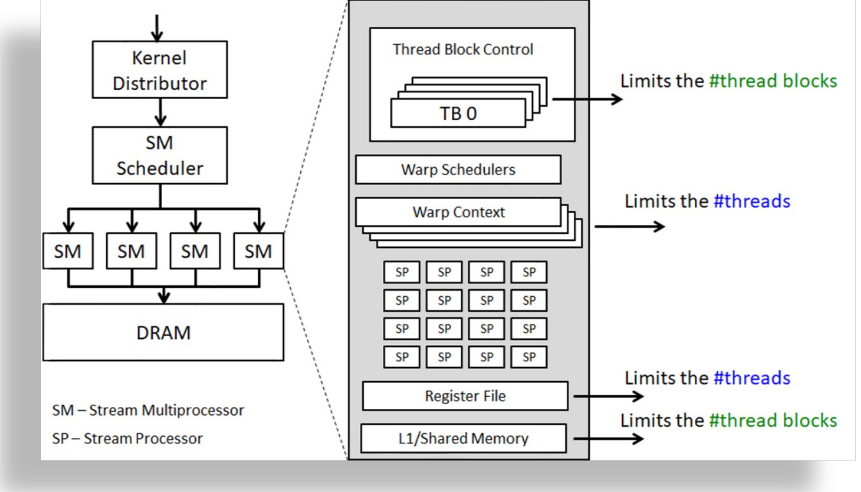

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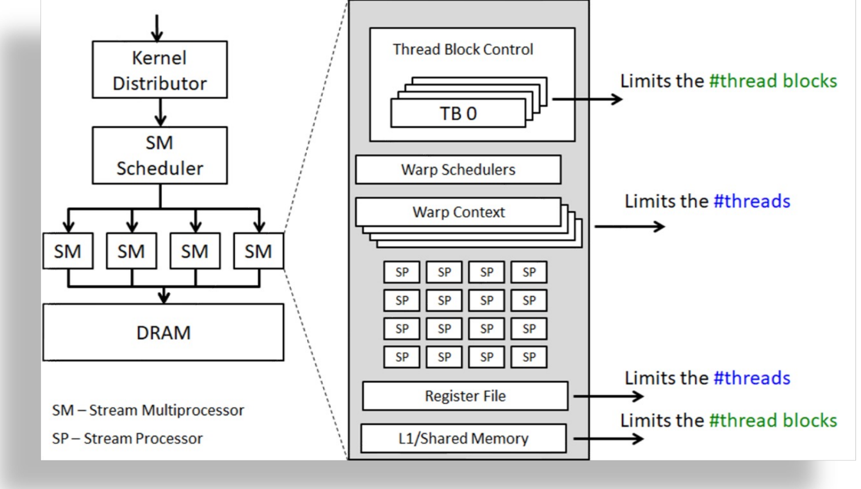

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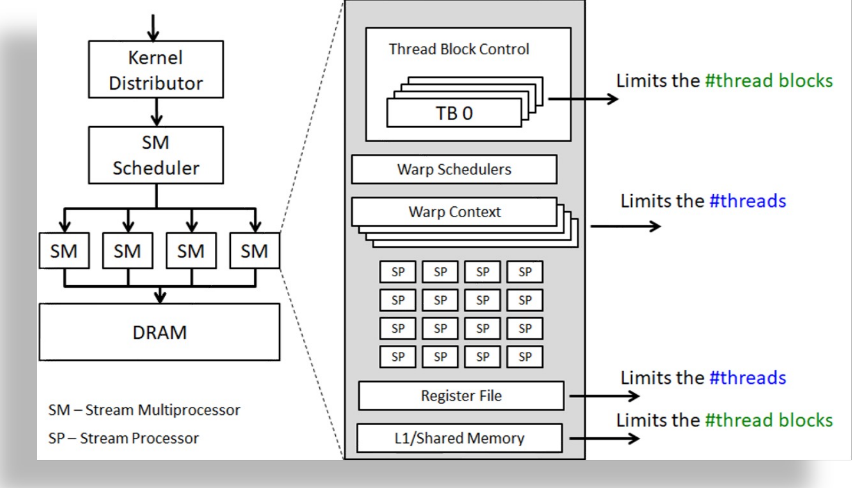

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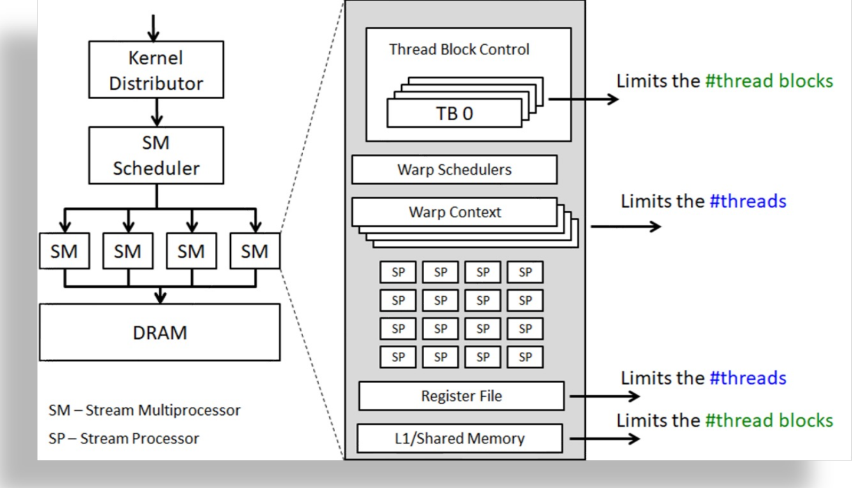

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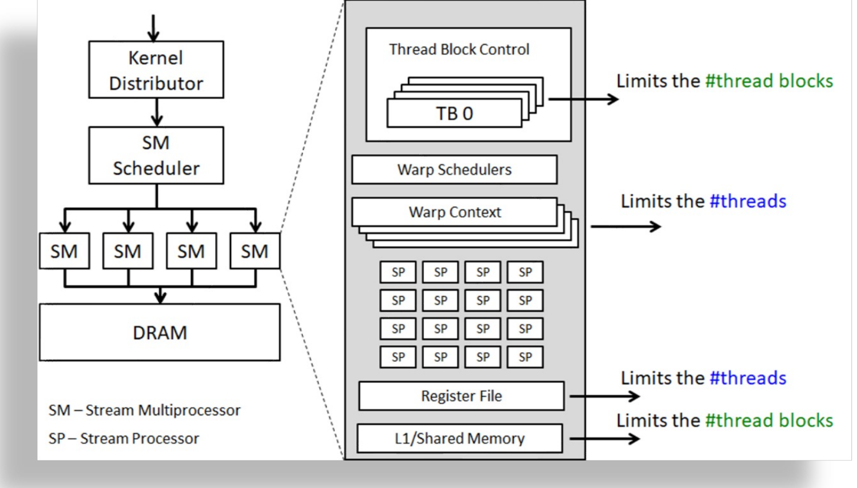

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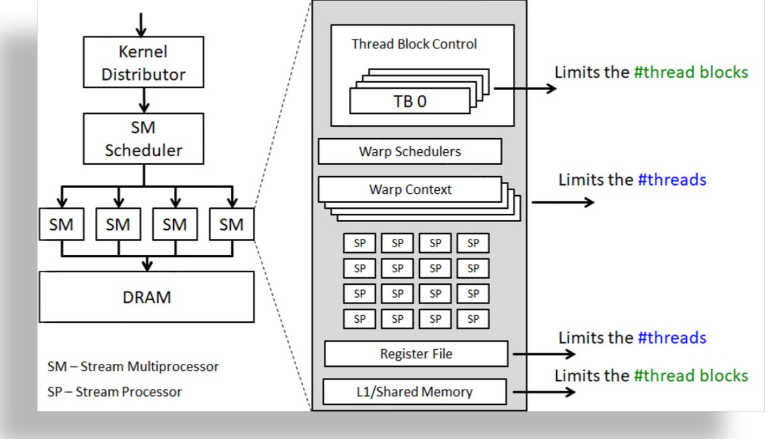
- To maximize utilization, thread block size should balance
  - Limits on active thread blocks vs.
  - Limits on active warps

Impact of #Registers Per Thread



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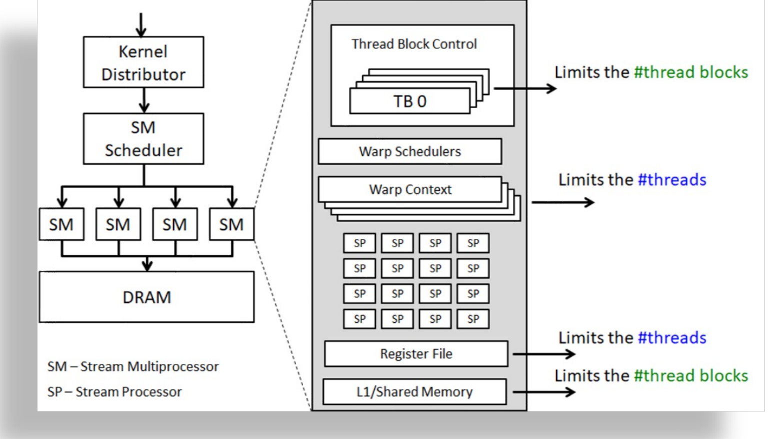
Registers/thread can limit number of active threads!



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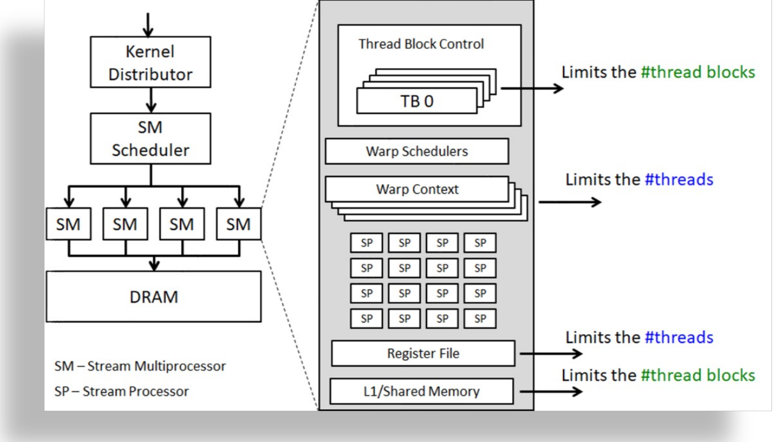

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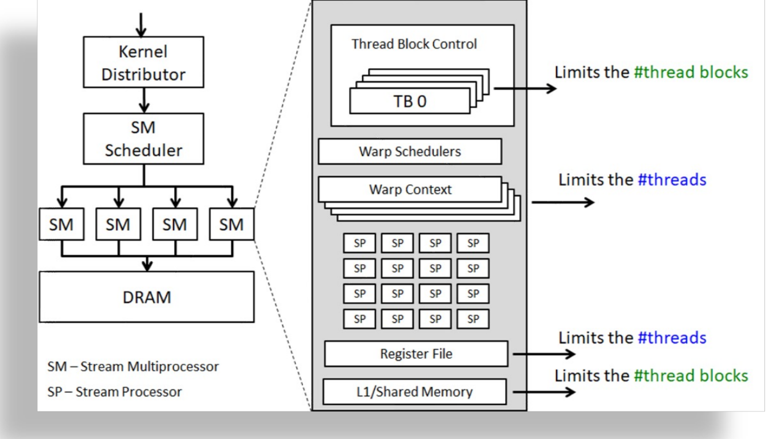

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- Registers per thread max: 255

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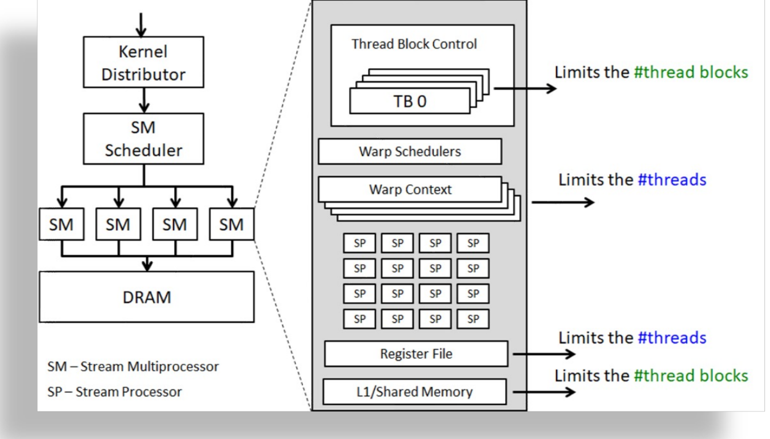

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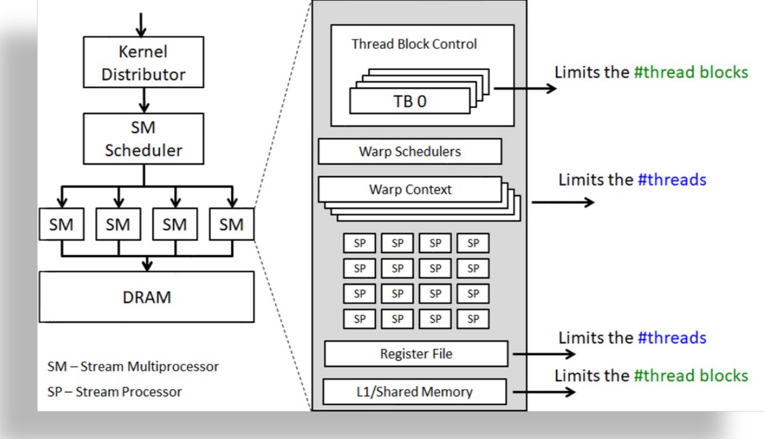

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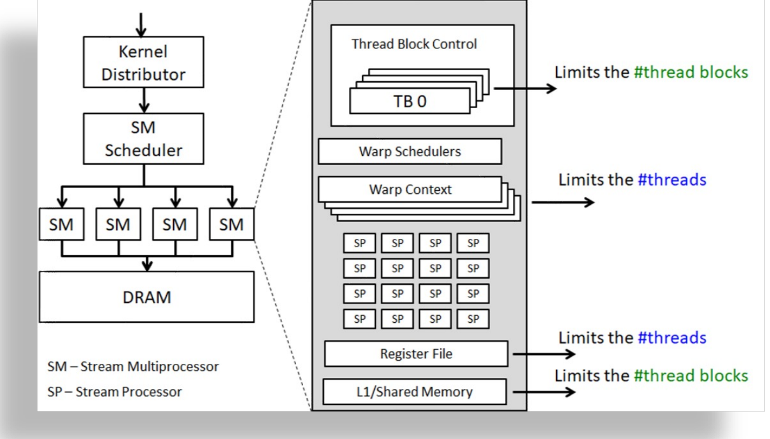

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- Thus, A TB requires 8192 registers for a maximum of 8 thread blocks per SM
  - Uses all 2048 thread slots (8 blocks * 256 threads/block)
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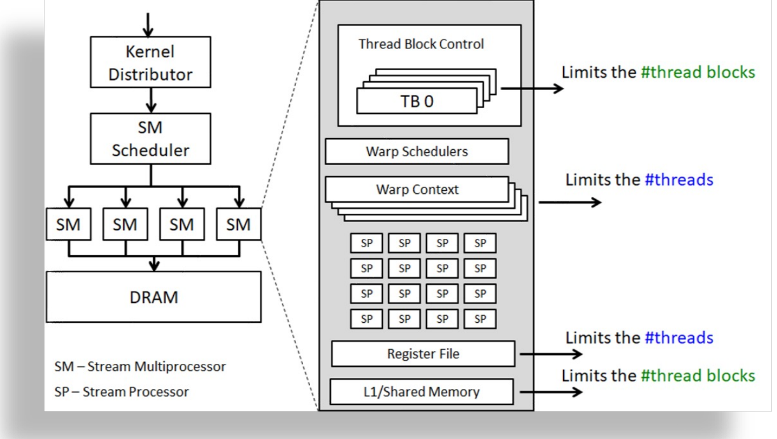

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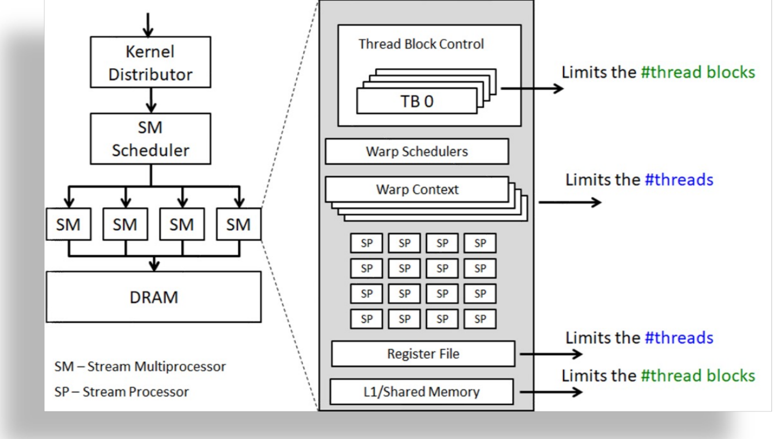

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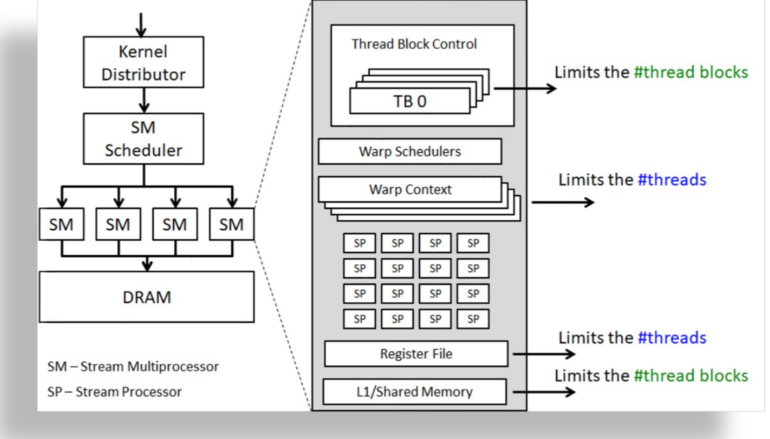

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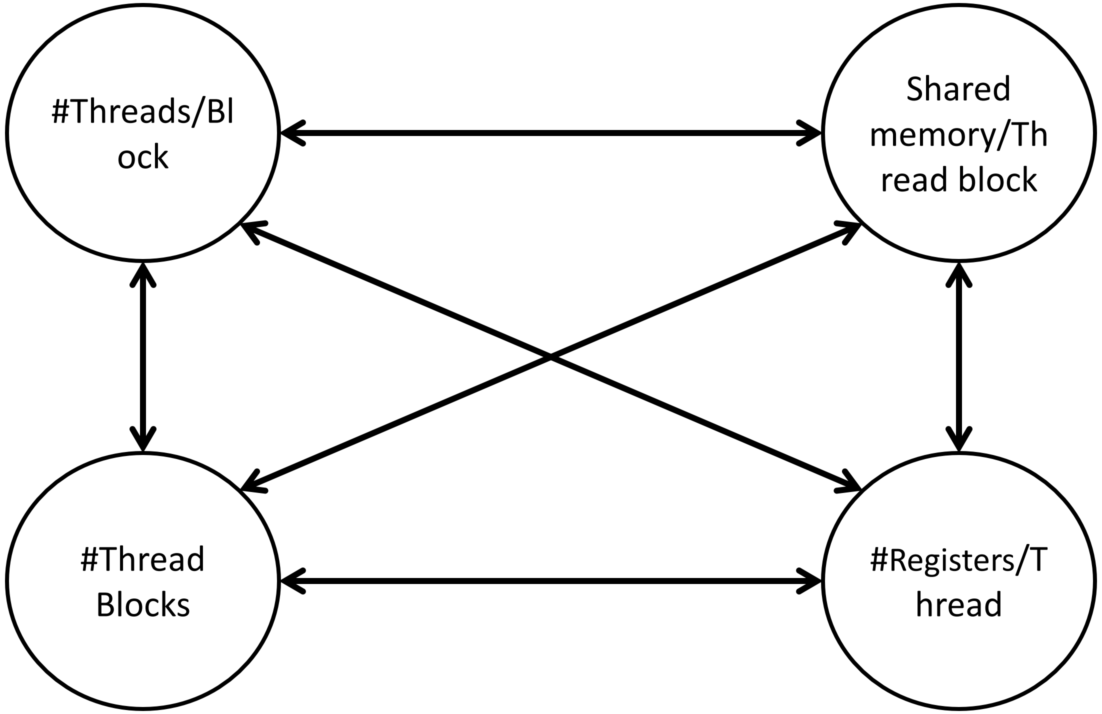
  - *FULLY Occupied!*
- What is the impact of increasing number of registers by 2?
  - Recall: granularity of management is a thread block!
  - Loss of concurrency of 256 threads!
  - *34 regs/thread * 256 threads/block * 7 blocks/SM = 60k registers,*
  - *8 blocks would over-subscribe register file*
  - *Occupancy drops to .875!*

Impact of Shared Memory

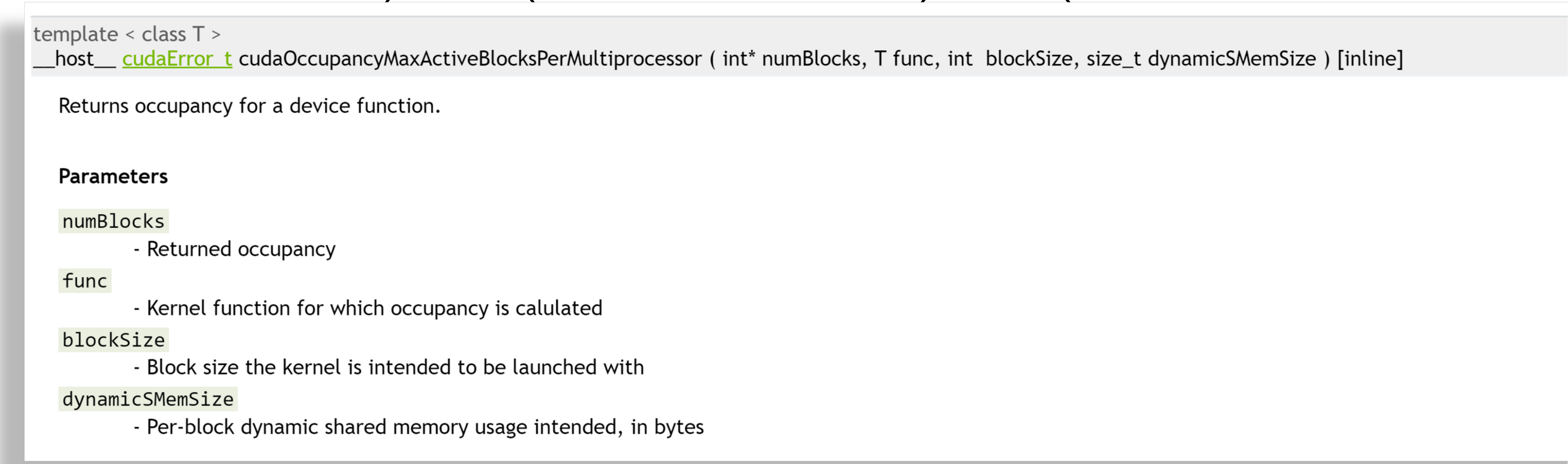
- Shared memory is allocated per thread block
  - Can limit the number of thread blocks executing concurrently per SM
  - Shared mem/block * # blocks <= total shared mem per SM
- gridDim and blockDim parameters impact demand for
  - shared memory
  - number of thread slots
  - number of thread block slots

Balance



- Navigate the tradeoffs
  - maximize core utilization and memory bandwidth utilization
  - Device-specific
- Goal: Increase occupancy until one or the other is saturated

Balance



template < class T >
__host__ cudaError_t cudaOccupancyMaxActiveBlocksPerMultiprocessor (int* numBlocks, T func, int blockSize, size_t dynamicSMemSize) [inline]

Returns occupancy for a device function.

Parameters

`numBlocks`
- Returned occupancy

`func`
- Kernel function for which occupancy is calulated

`blockSize`
- Block size the kernel is intended to be launched with

`dynamicSMemSize`
- Per-block dynamic shared memory usage intended, in bytes

- Navigate the tradeoffs
  - maximize core utilization and memory bandwidth utilization
  - Device-specific
- Goal: Increase occupancy until one or the other is saturated

Parallel Memory Accesses

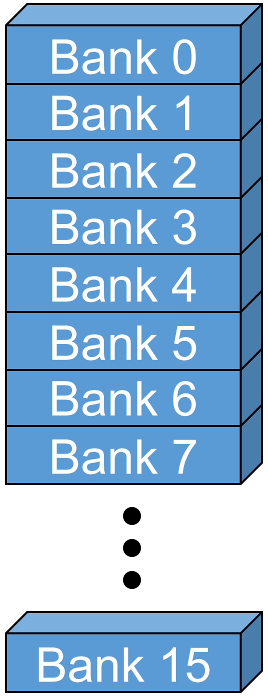
- Coalesced main memory access (16/32x faster)
  - HW combines multiple warp memory accesses into a single coalesced access
- Bank-conflict-free shared memory access (16/32)
  - No alignment or contiguity requirements
    - CC 2.x+3.0 : 32 different banks + 1-word broadcast each

Parallel Memory Architecture

- In a parallel machine, many threads access memory
  - Therefore, memory is divided into banks
  - Essential to achieve high bandwidth

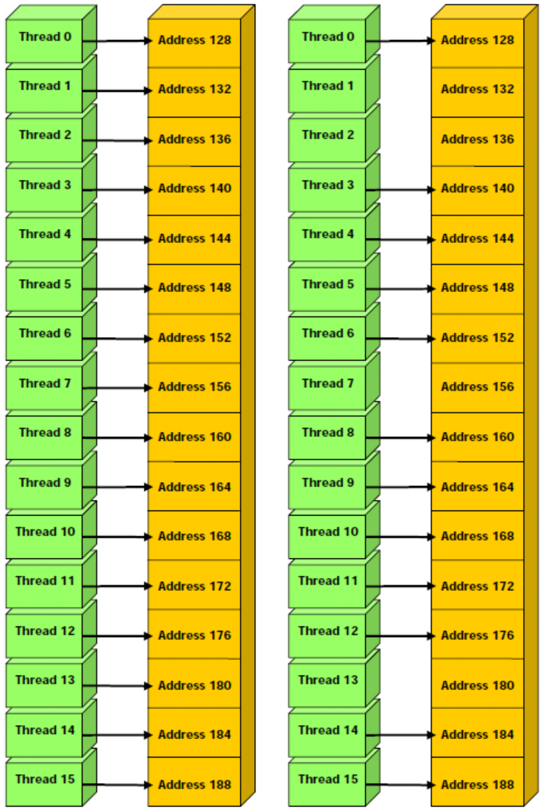
- Each bank can service one address per cycle
  - A memory can service as many simultaneous accesses as it has banks

- Multiple simultaneous accesses to a bank result in a bank conflict
  - Conflicting accesses are serialized



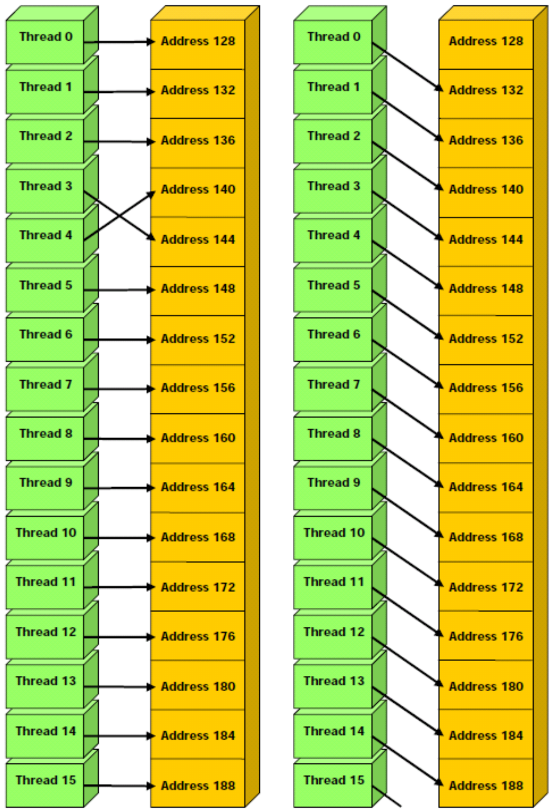
Coalesced Main Memory Accesses

single coalesced access



NVIDIA

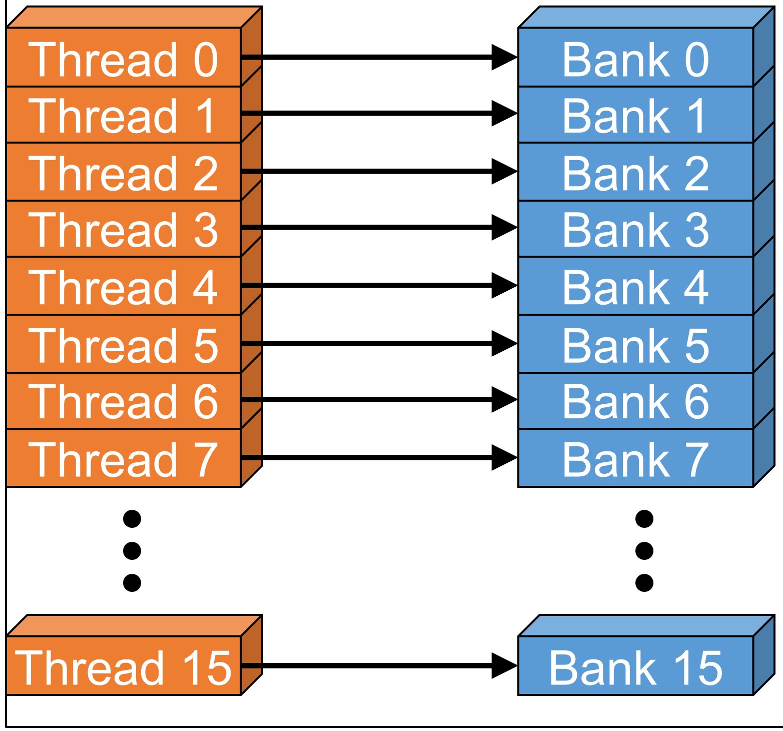
one and two coalesced accesses*



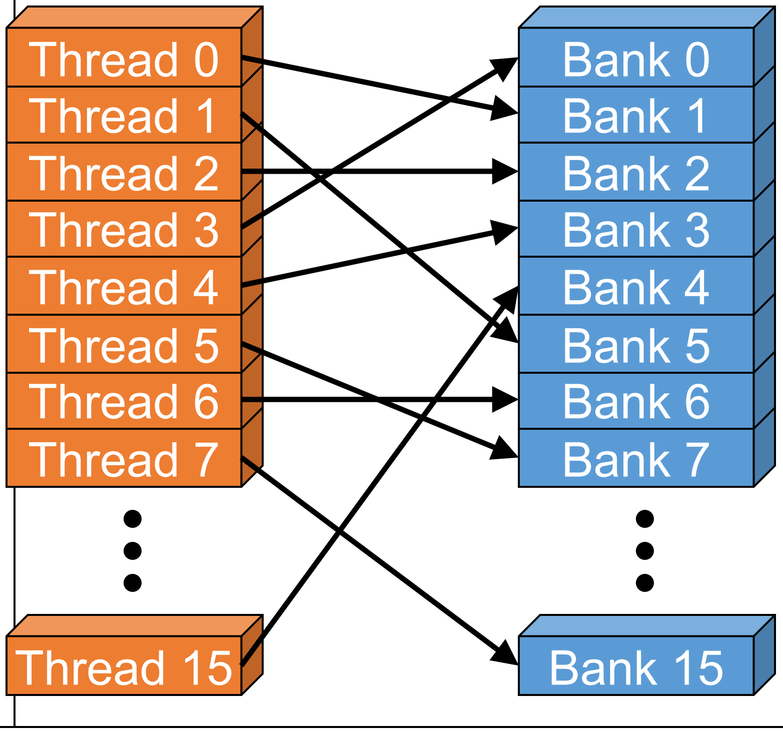
NVIDIA

Bank Addressing Examples

- No Bank Conflicts
  - Linear addressing stride == 1

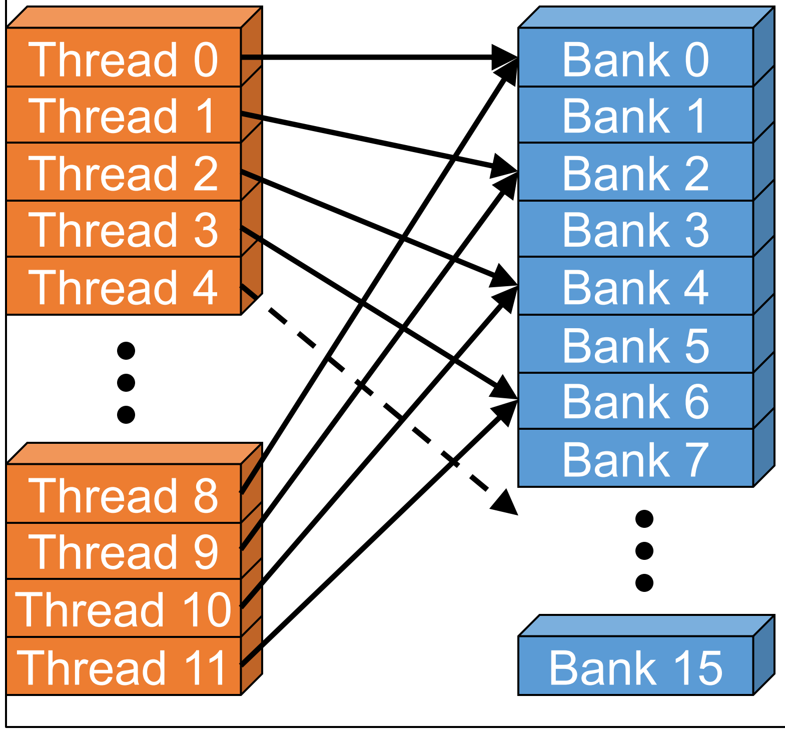


- No Bank Conflicts
  - Random 1:1 Permutation



Bank Addressing Examples

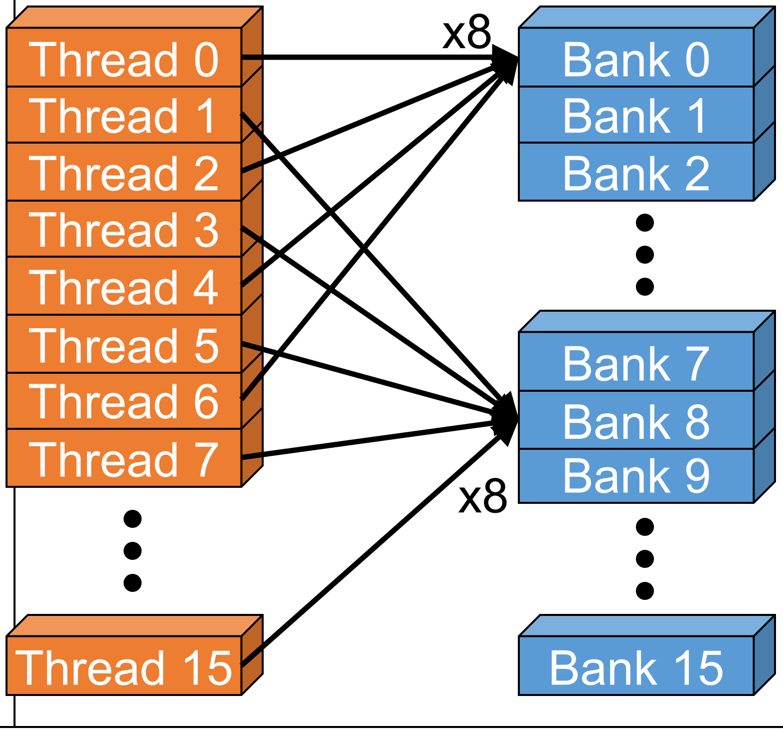
- 2-way Bank Conflicts
  - Linear addressing stride == 2



Thread 0
Thread 1
Thread 2
Thread 3
Thread 4
Thread 8
Thread 9
Thread 10
Thread 11

Bank 0
Bank 1
Bank 2
Bank 3
Bank 4
Bank 5
Bank 6
Bank 7
Bank 15

- 8-way Bank Conflicts
  - Linear addressing stride == 8



Thread 0
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Thread 2
Thread 3
Thread 4
Thread 5
Thread 6
Thread 7
Thread 15

x8

Bank 0
Bank 1
Bank 2
Bank 7
Bank 8
Bank 9
Bank 15

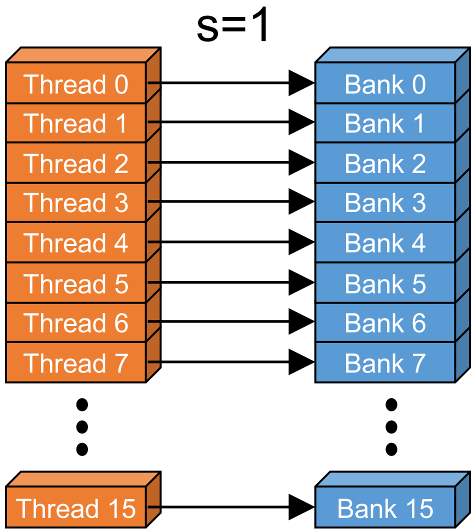
x8

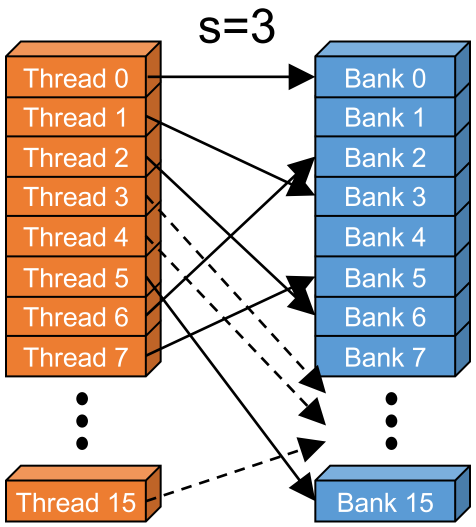
Linear Addressing

- Given:

```
__shared__ float shared[256];
float foo =
  shared[baseIndex + s *
   threadIdx.x];
```

- This is only bank-conflict-free if s shares no common factors with the number of banks
  - 16 on G80, so s must be odd





GPU Atomics & Divergence

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Race conditions –

- Traditional locks: avoid!
- How do we synchronize?

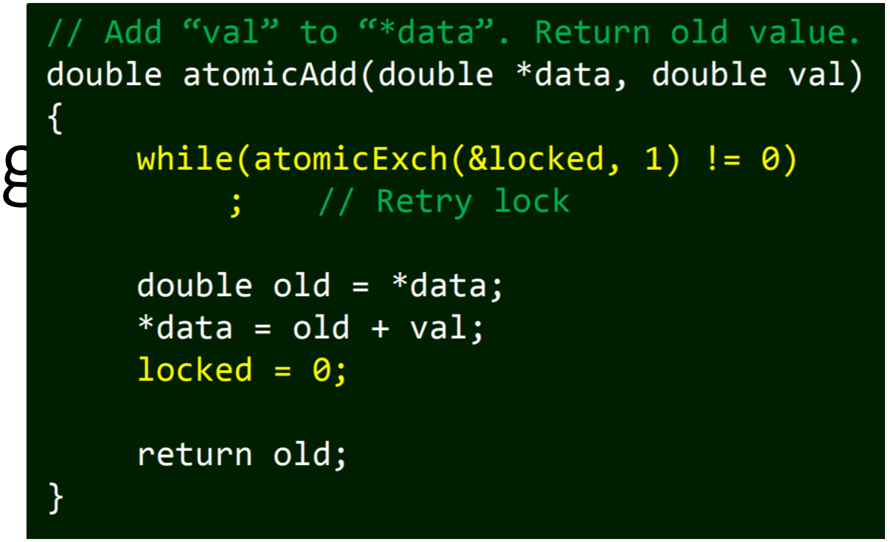
Read-Modify-Write – atomic

```
atomicAdd()                 atomicInc()
atomicSub()                 atomicDec()
atomicMin()                 atomicExch()
atomicMax()                 atomicCAS()
```

Implemented as write-through to L2

- “Fire-and-forget”

GPU Atomics & Diverg



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// Add "val" to "*data". Return old value.
double atomicAdd(double *data, double val)
{
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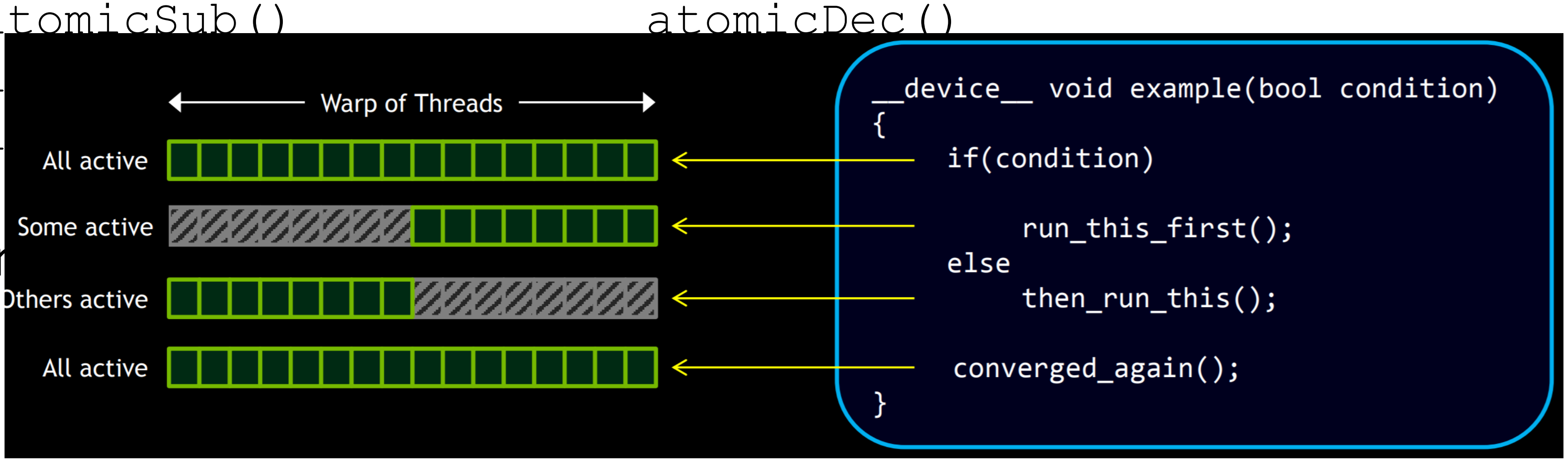

```
__device__ void example(bool condition)
{
    if(condition)

        run_this_first();
    else
        then_run_this();

    converged_again();
}
```

Ir

•

GPU Atomics & Diverg

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Im

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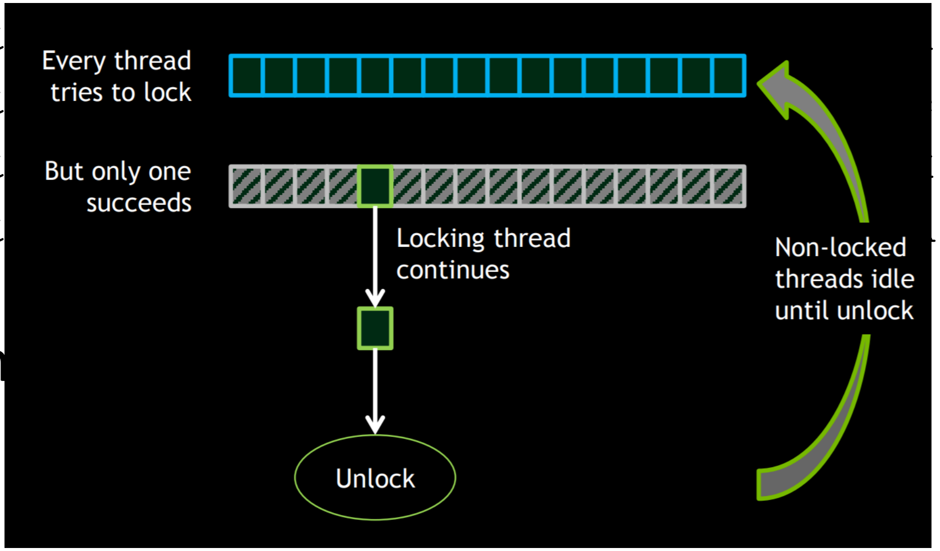
Every thread tries to lock
But only one succeeds
Locking thread continues
Non-locked threads idle until unlock
Unlock

GPU Atomics & Diverg

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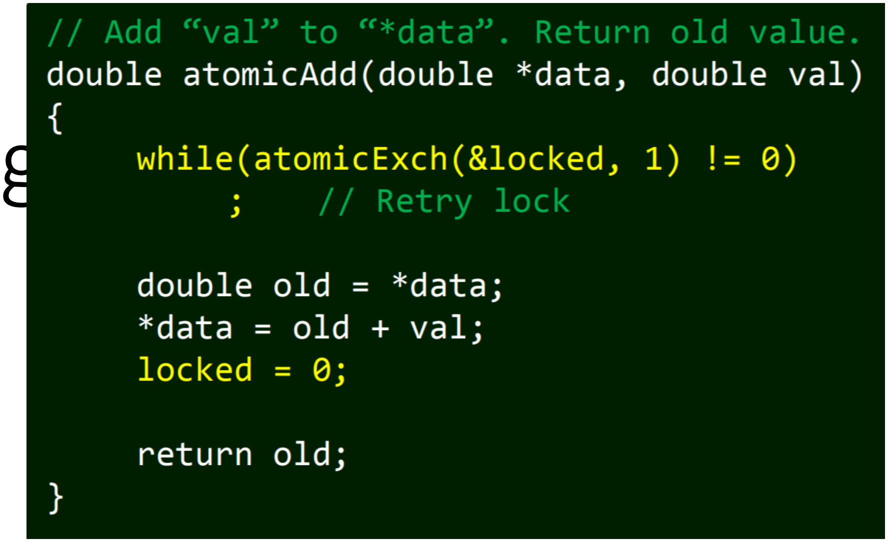

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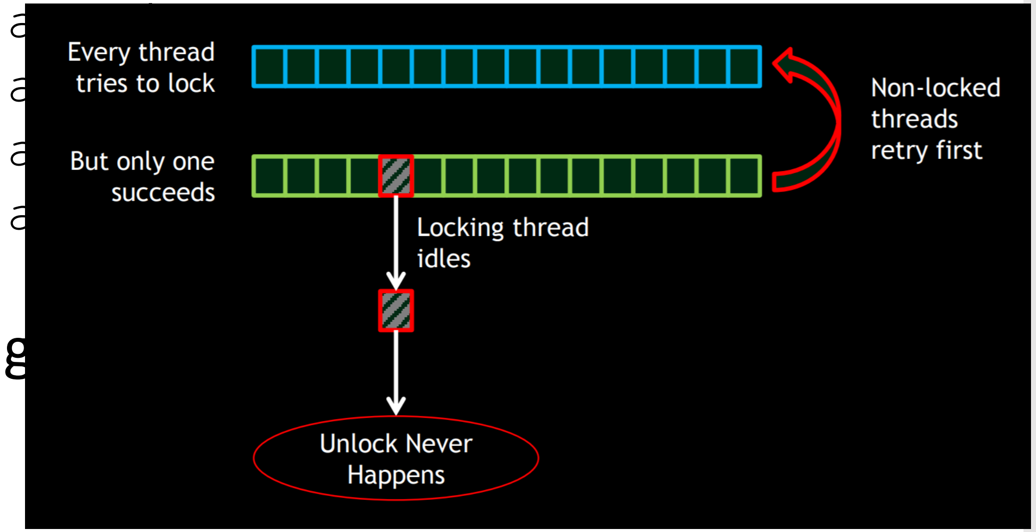

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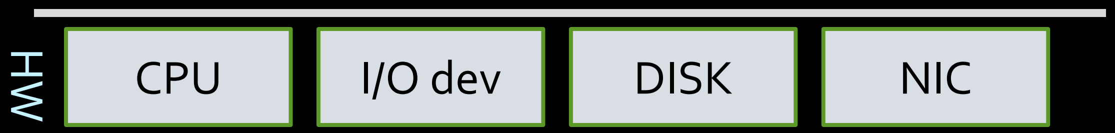
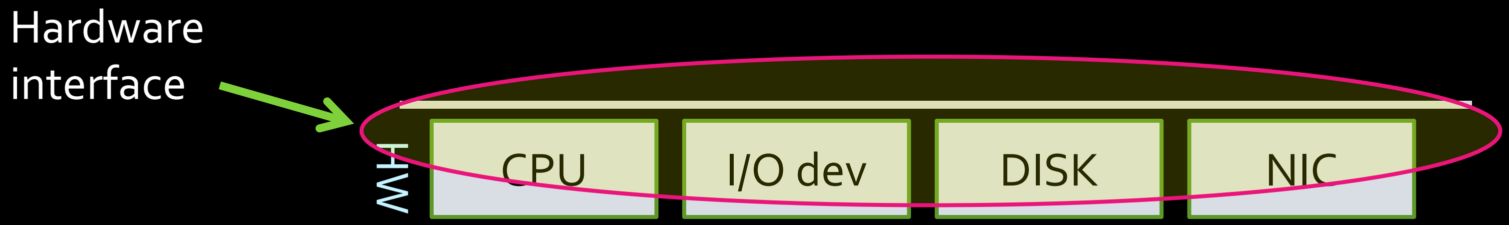
Advanced Topic: GPU Programming Models

Layered abstractions



Layered abstractions



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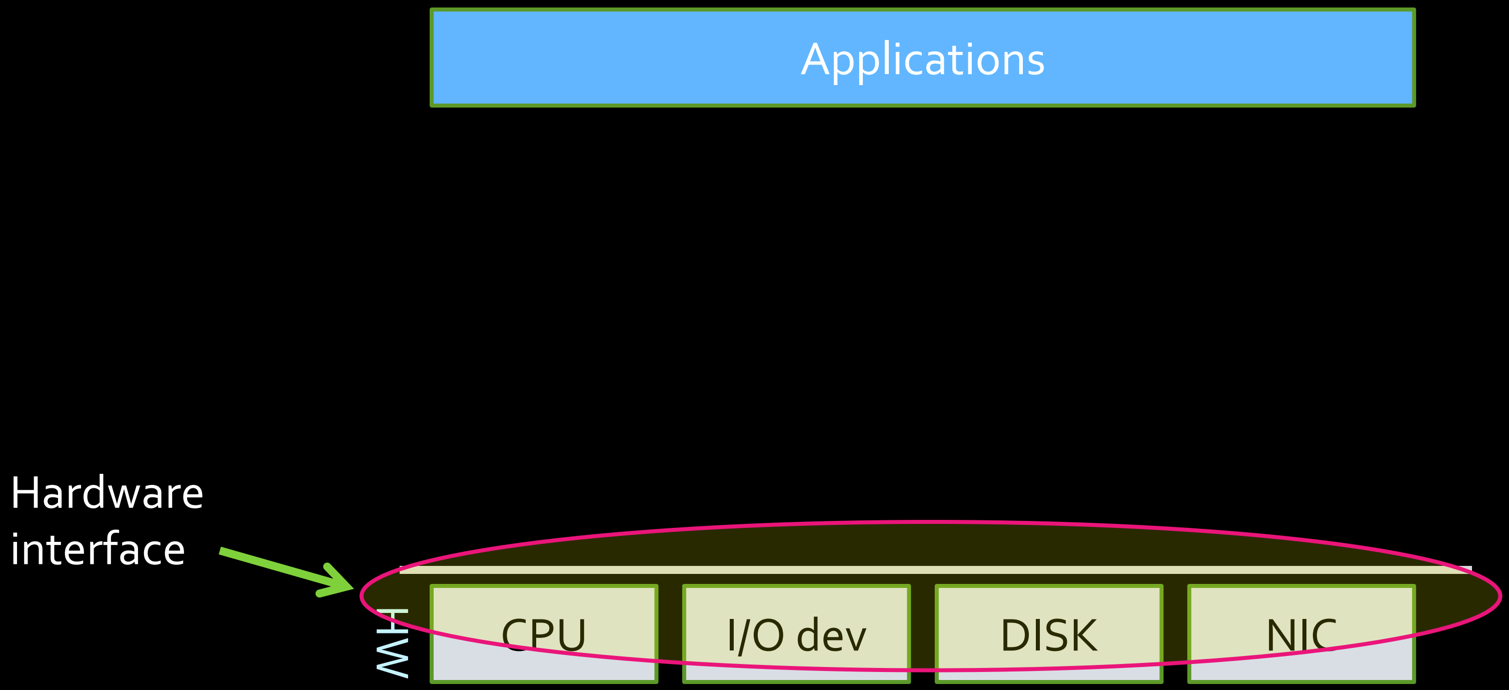


Applications

Hardware interface

HW

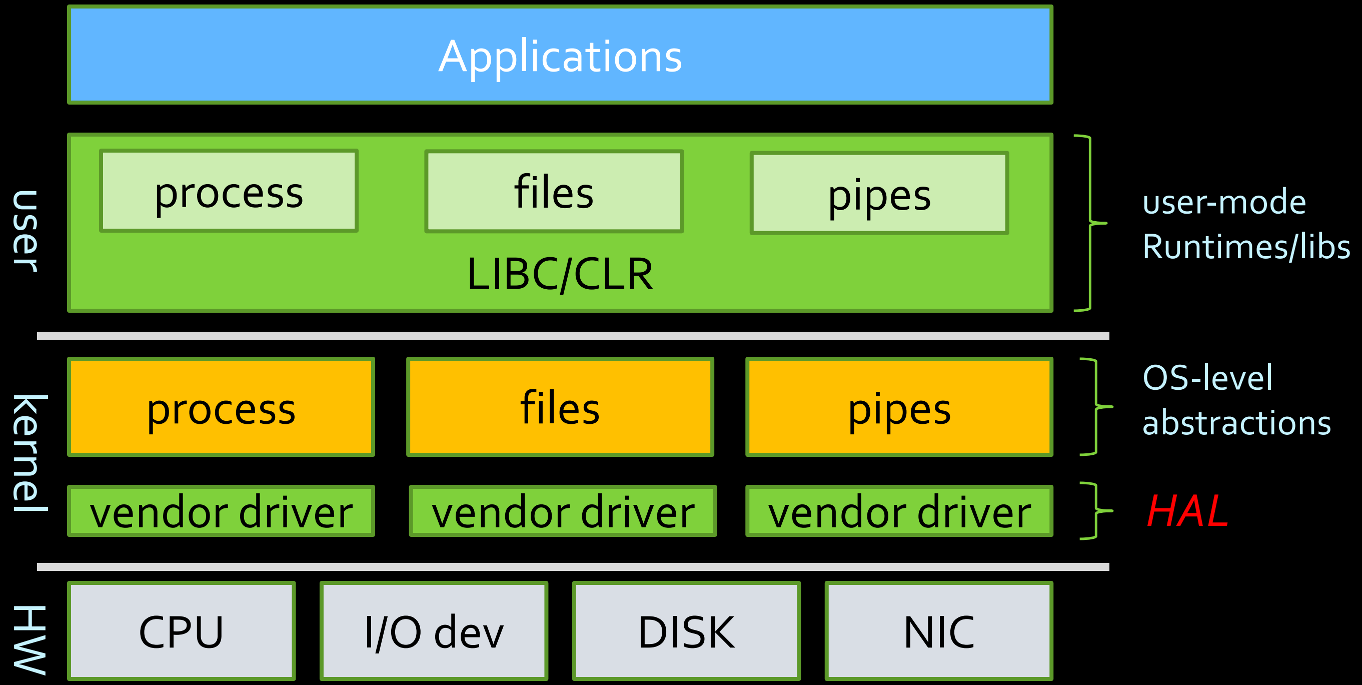
CPU

I/O dev

DISK

NIC

Layered abstractions



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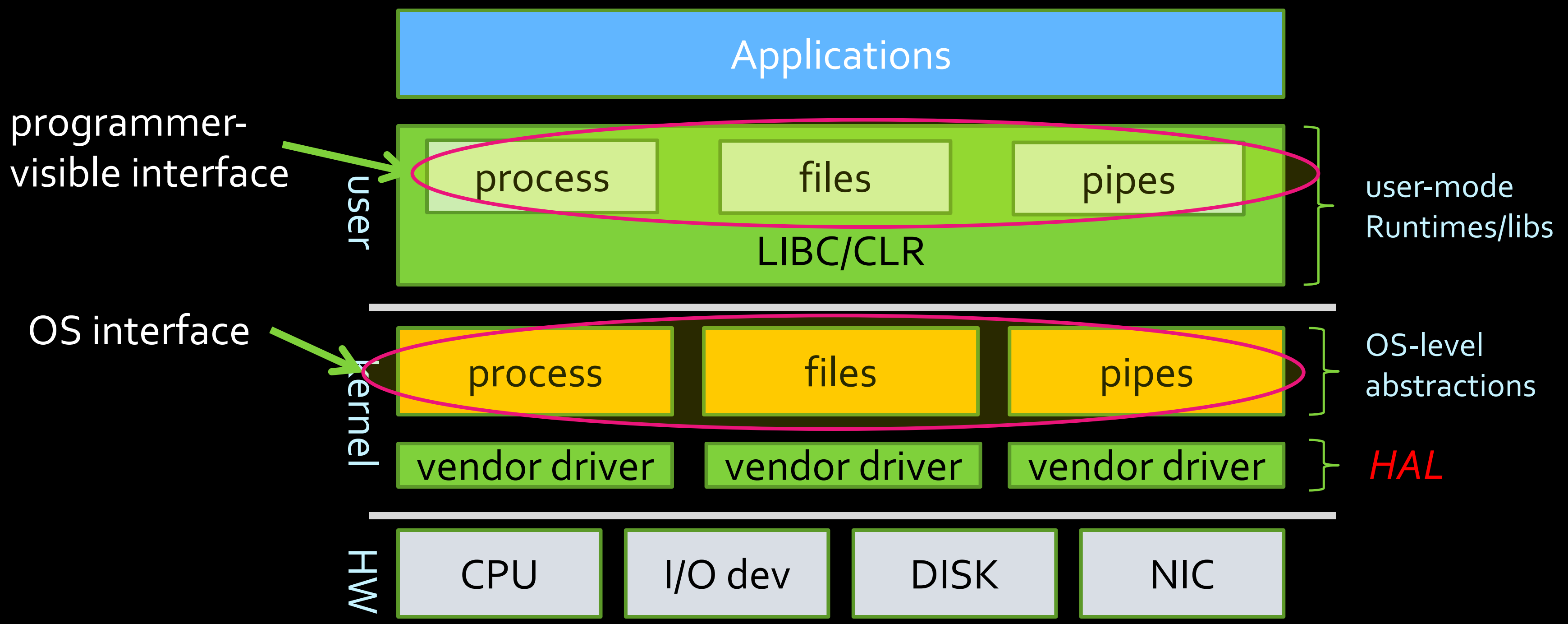
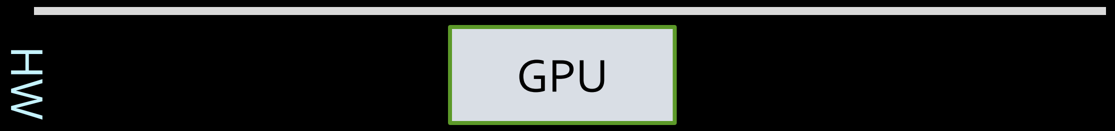
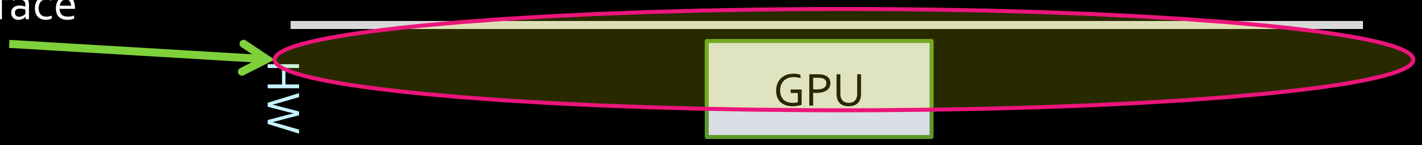


** 1:1 correspondence between OS-level and user-level abstractions*
** Diverse HW support enabled HAL*

GPU abstractions

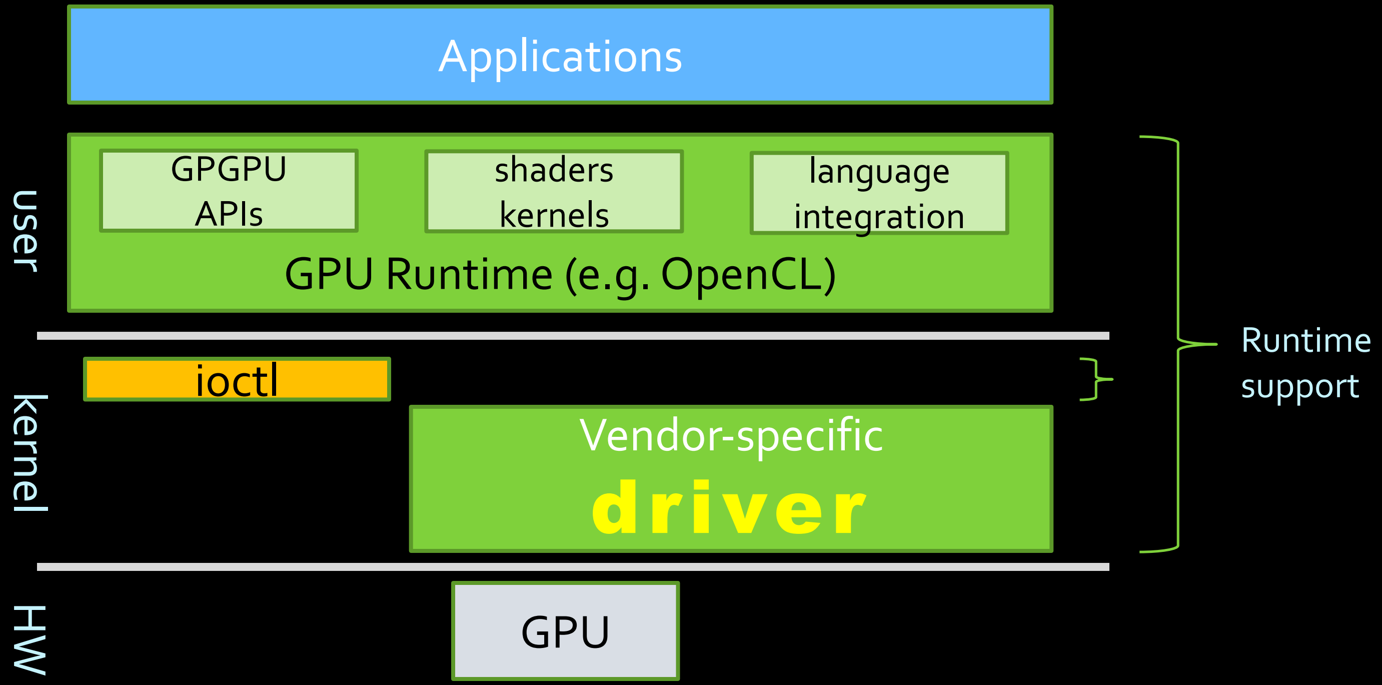


GPU abstractions



Hardware interface

GPU abstractions



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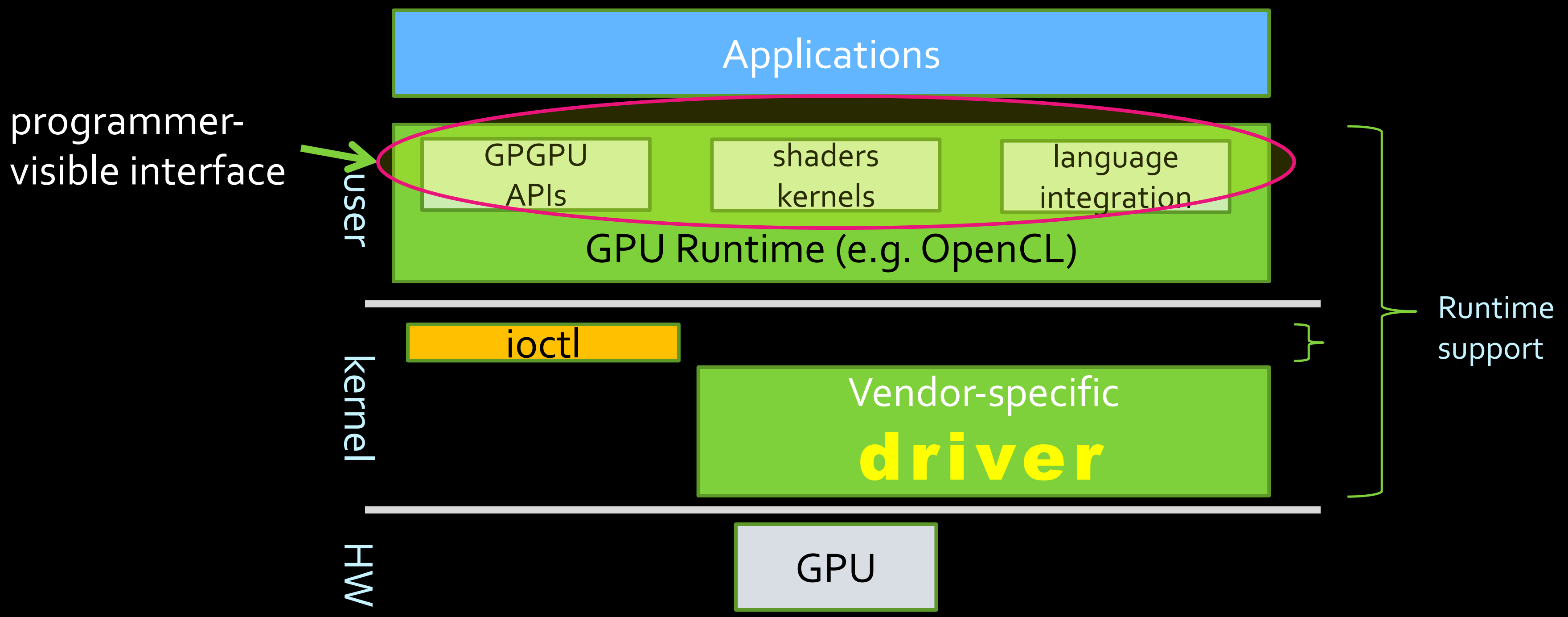

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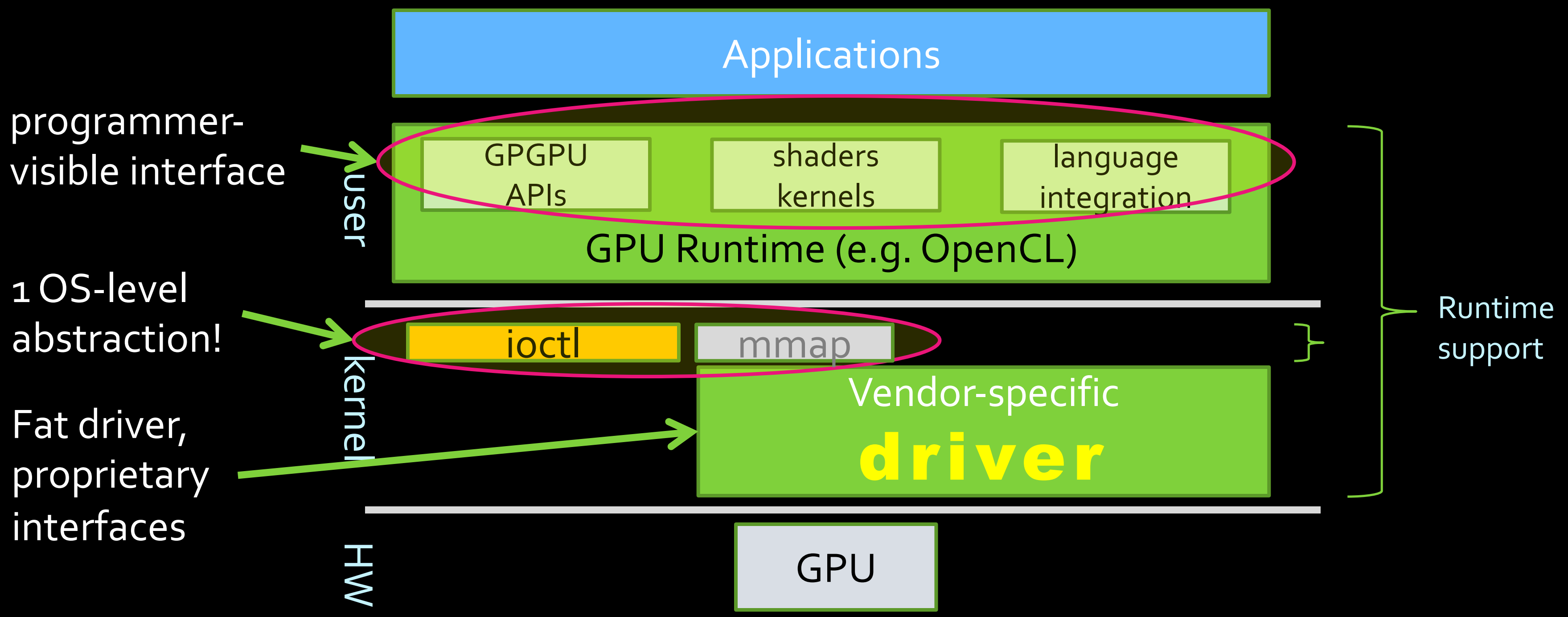
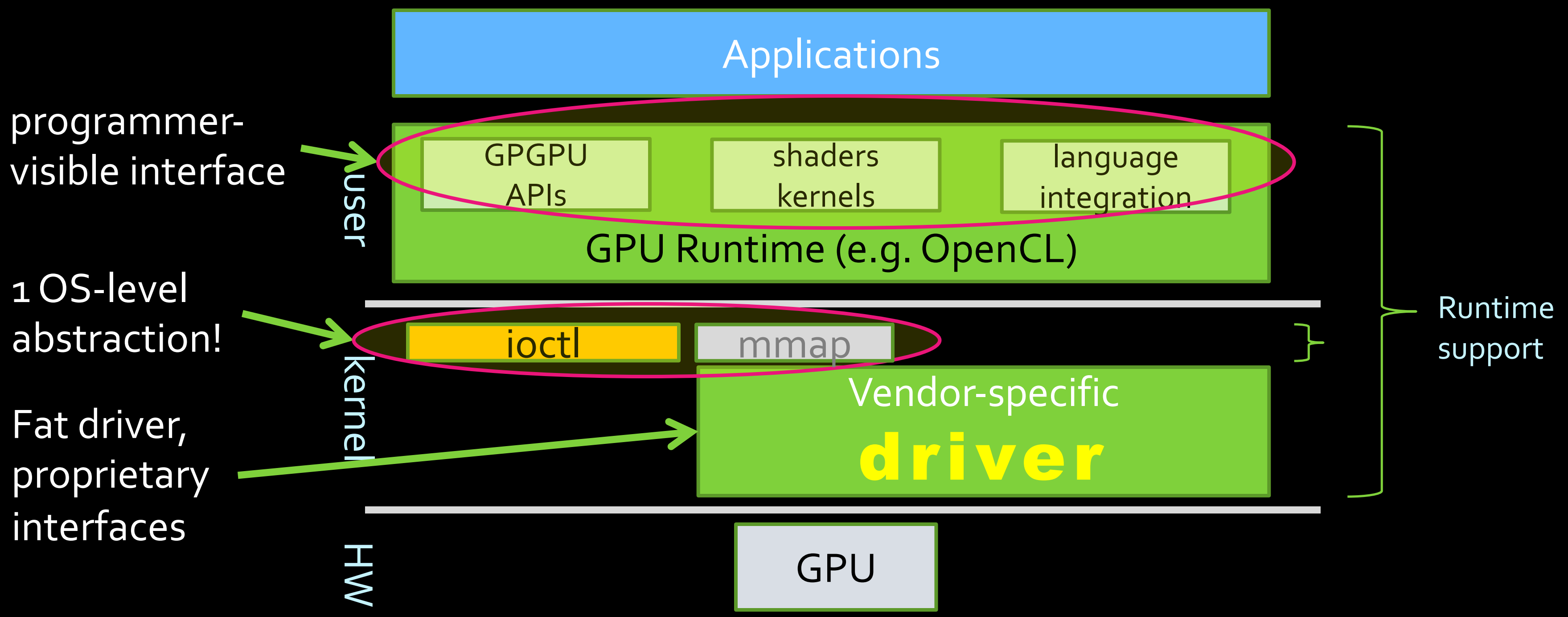


programmer-visible interface

1 OS-level abstraction!

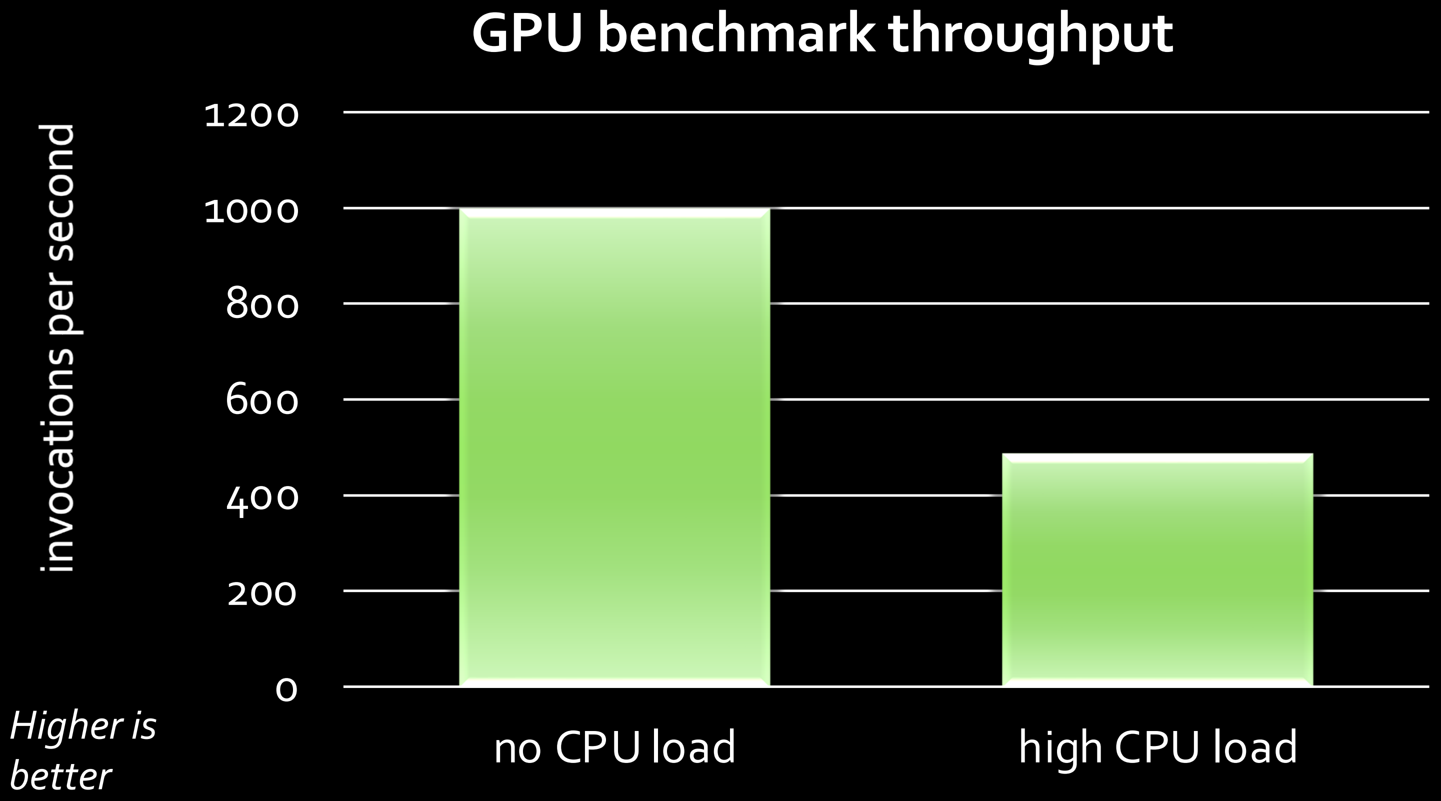
Fat driver, proprietary interfaces

GPU abstractions



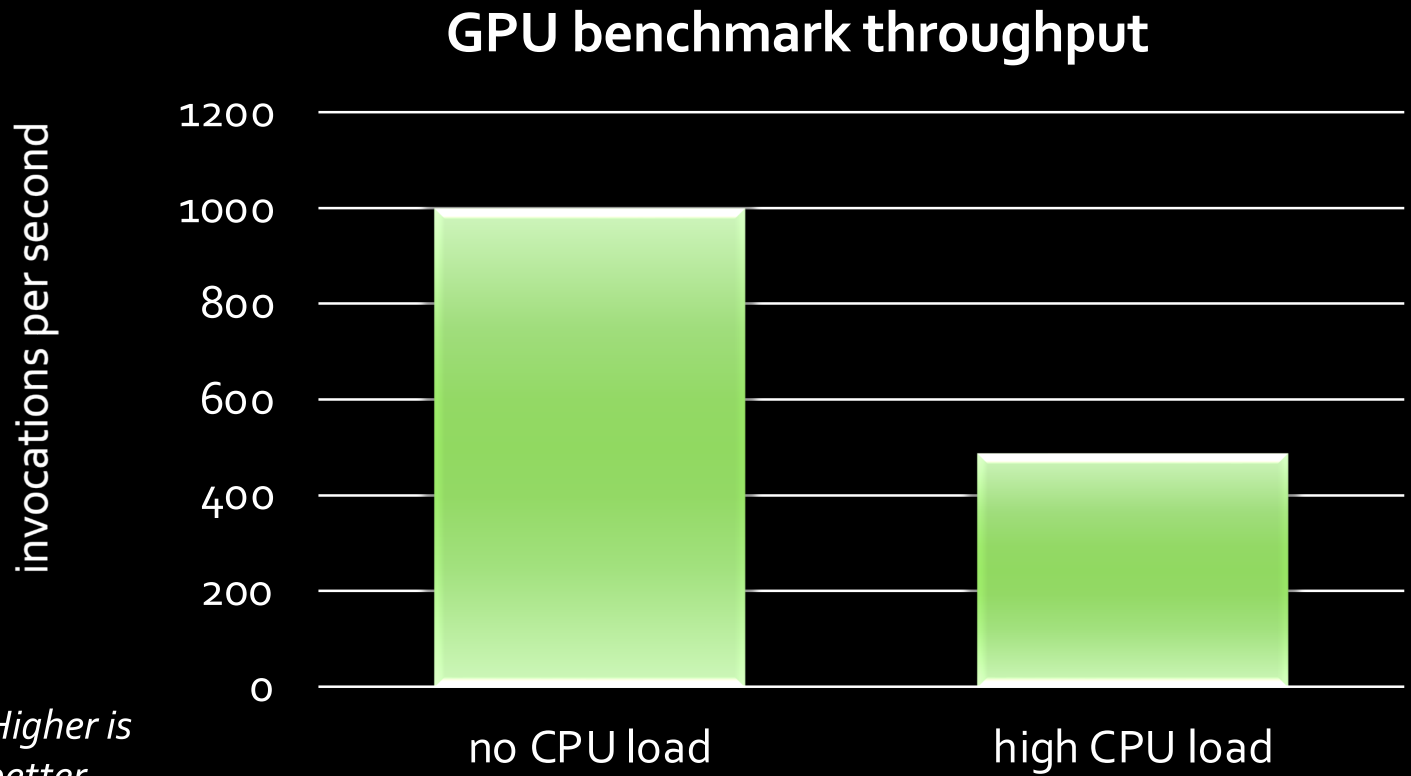
1. No kernel-facing API
2. OS resource-management limited
3. *Poor composability*

No OS support → No isolation



- Image-convolution in CUDA
- Windows 7 x64 8GB RAM
- Intel Core 2 Quad 2.66GHz
- nVidia GeForce GT230

No OS support → No isolation

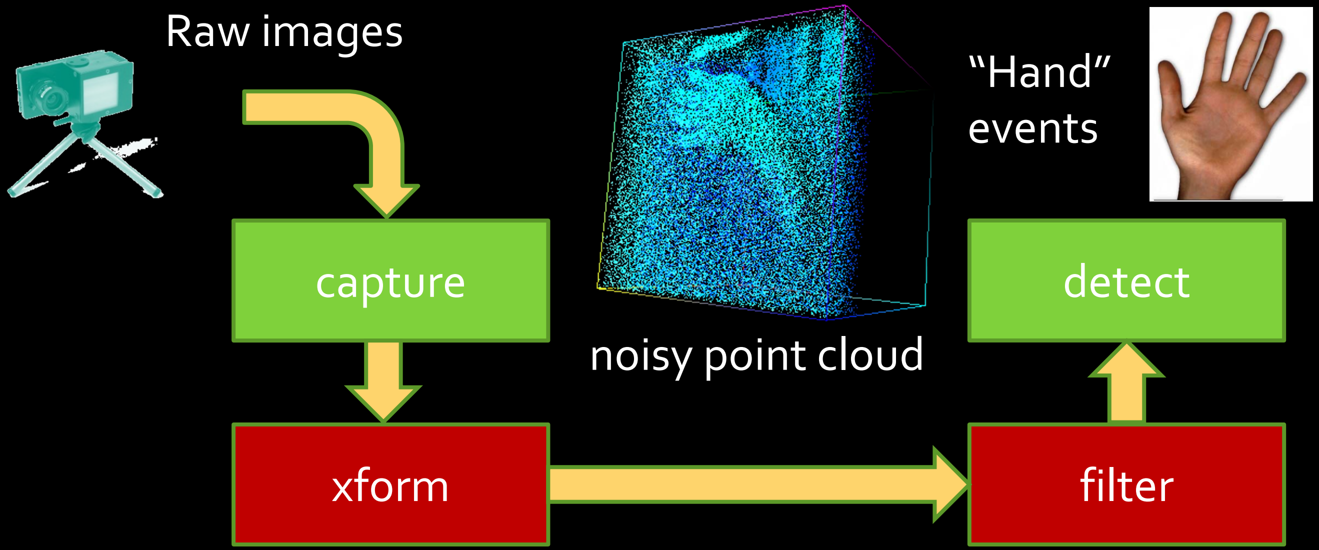


Higher is better

CPU+GPU schedulers not integrated!
...other pathologies abundant

ge-convolution in CUDA
dows 7 x64 8GB RAM
l Core 2 Quad 2.66GHz
dia GeForce GT230

Composition: Gestural Interface



Raw images

capture

xform

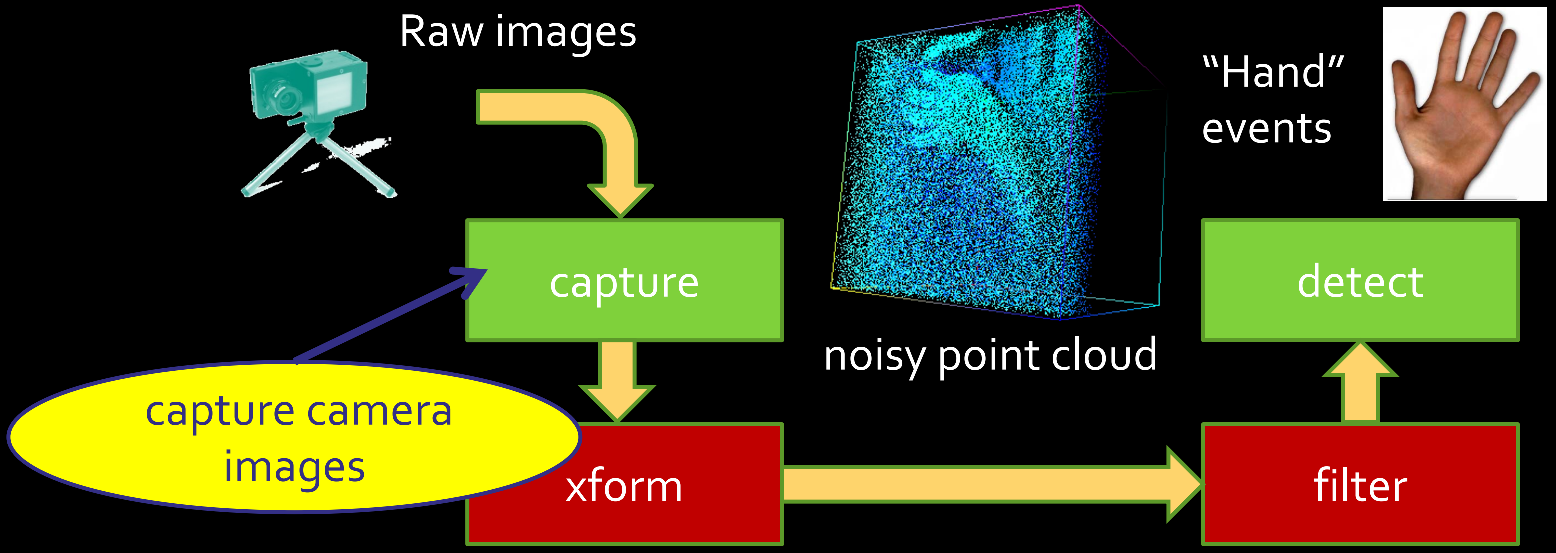
noisy point cloud

filter

detect

“Hand” events

Composition: Gestural Interface



Raw images

capture

noisy point cloud

"Hand" events

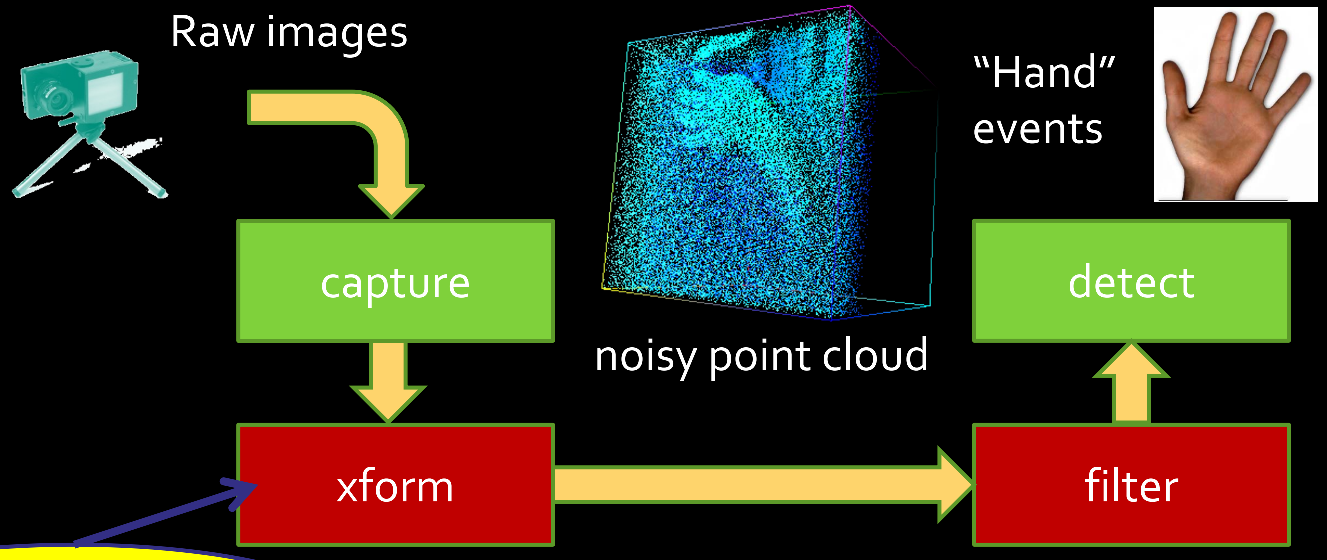
detect

xform

filter

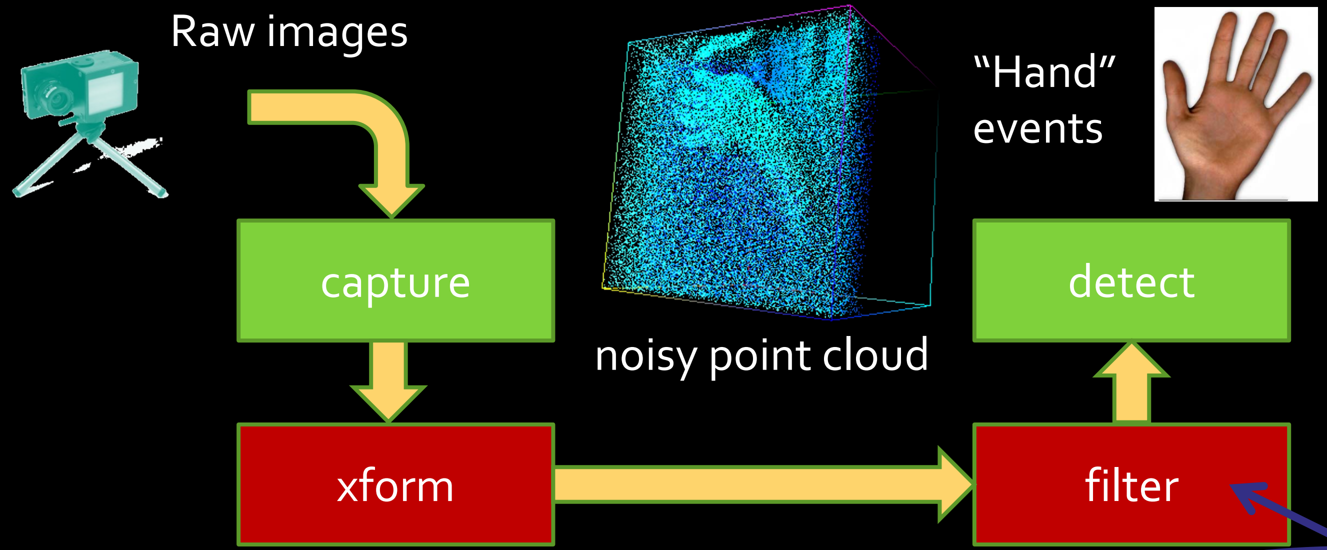
capture camera images

Composition: Gestural Interface



geometric
transformation

Composition: Gestural Interface



Raw images

capture

xform

noisy point cloud

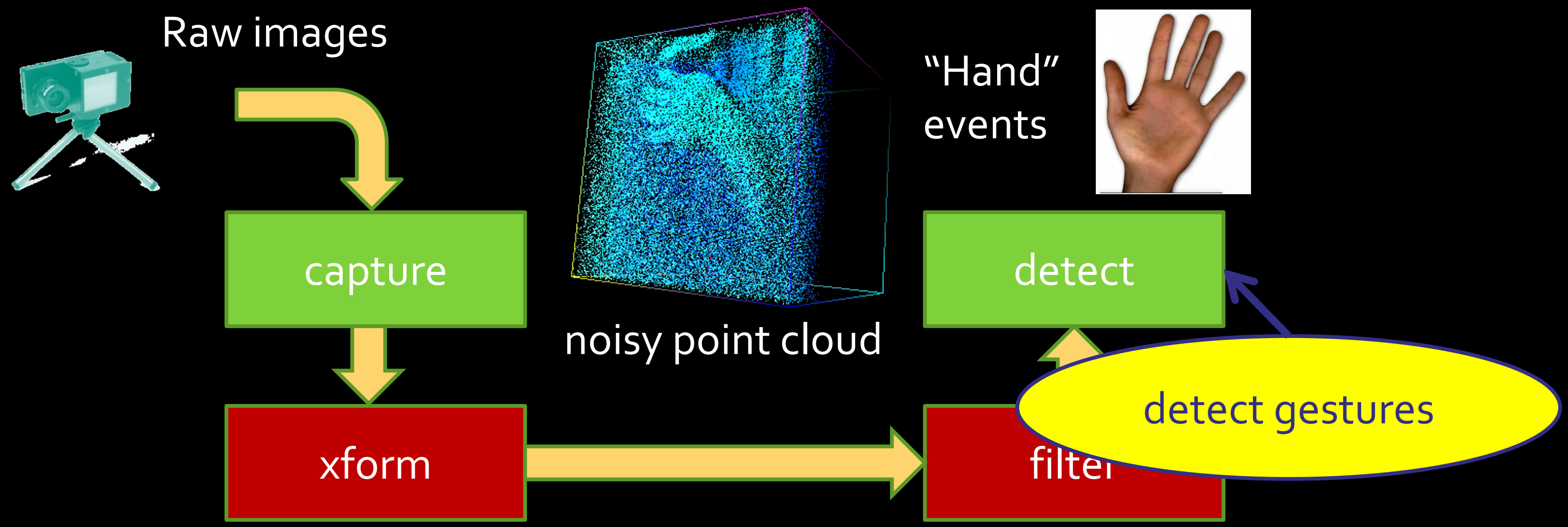
filter

detect

"Hand" events

noise filtering

Composition: Gestural Interface



Raw images

capture

xform

noisy point cloud

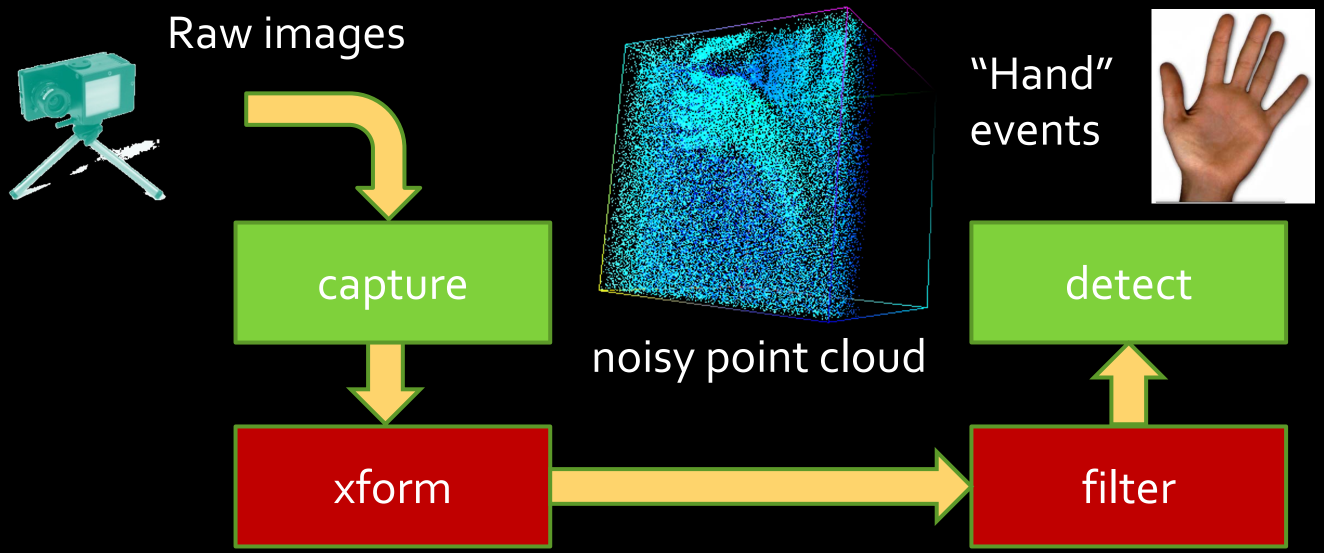
filter

detect

“Hand” events

detect gestures

Composition: Gestural Interface



Raw images

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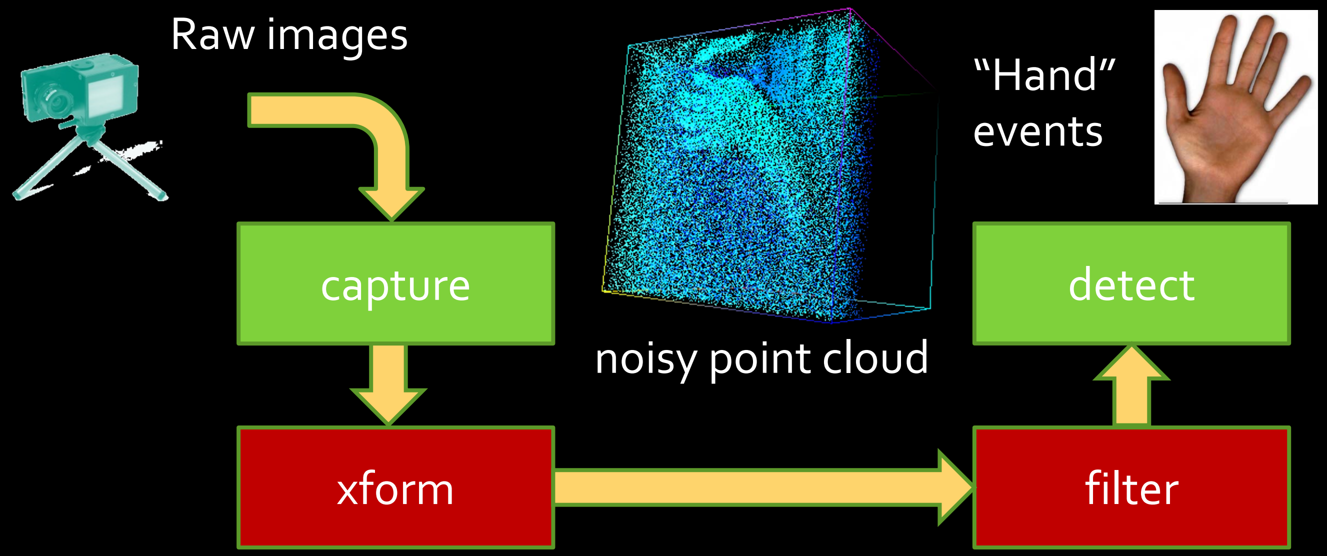
Composition: Gestural Interface



- Requires OS mediation
- High data rates
- Abundant data parallelism

…use GPUs!

What We'd Like To Do

```
#> capture | xform | filter | detect &
```

- Modular design
  - flexibility, reuse
- Utilize heterogeneous hardware
  - Data-parallel components → GPU
  - Sequential components → CPU
- Using OS provided tools
  - processes, pipes

What We’d Like To Do

```
#> capture | xform | filter | detect &
     CPU       GPU      GPU      CPU
```

- Modular design
  - flexibility, reuse
- Utilize heterogeneous hardware
  - Data-parallel components → GPU
  - Sequential components → CPU
- Using OS provided tools
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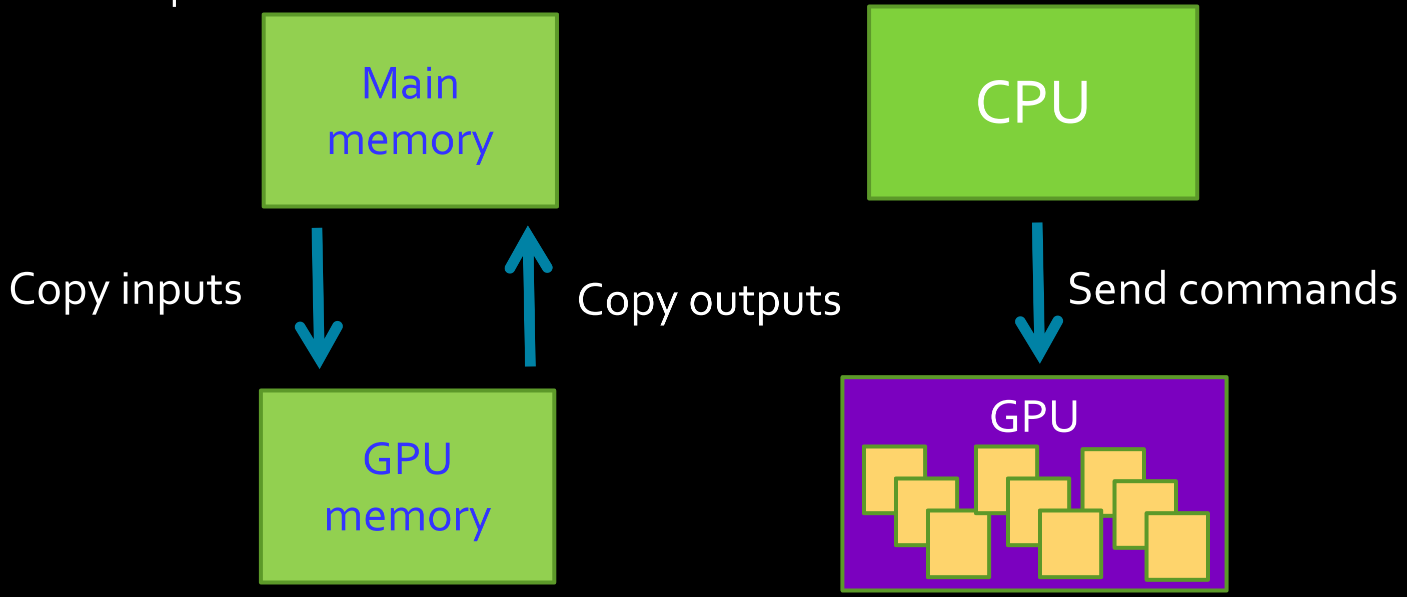
GPU Execution model

- GPUs cannot run OS:
  - different ISA
  - Memories have different coherence guarantees
    - **(disjoint, or require fence instructions)**
- Host CPU must "manage" GPU execution
  - Program inputs explicitly transferred/bound at runtime
  - Device buffers pre-allocated



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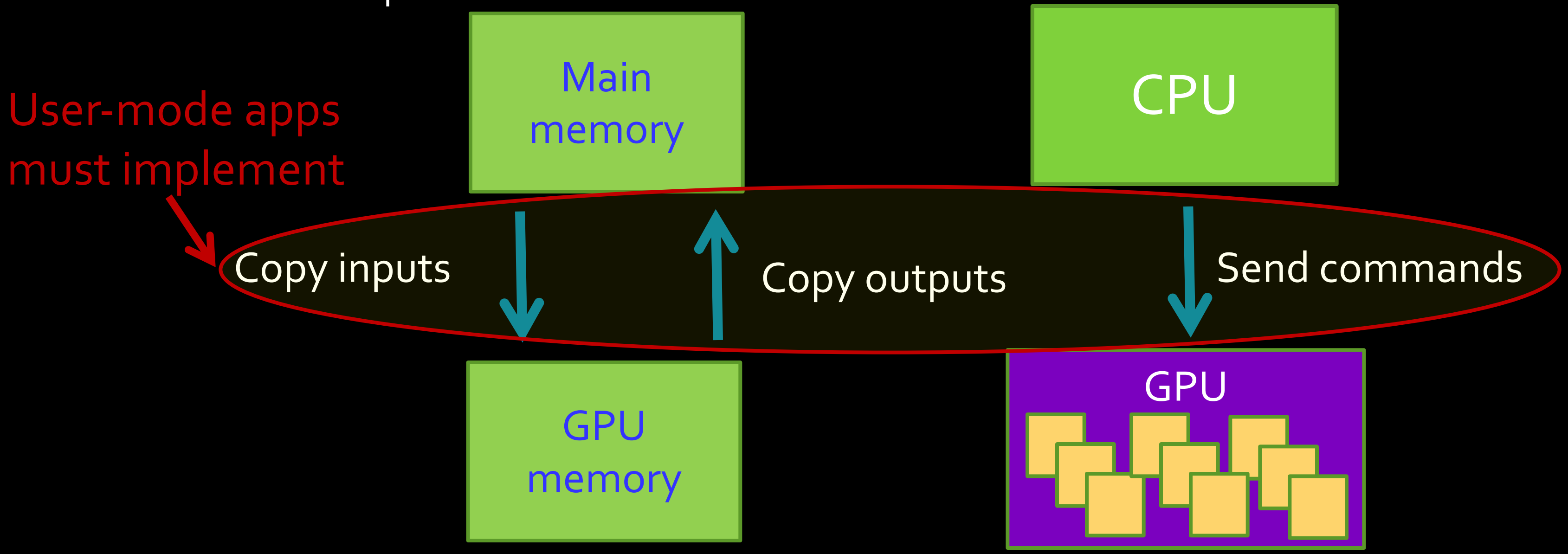
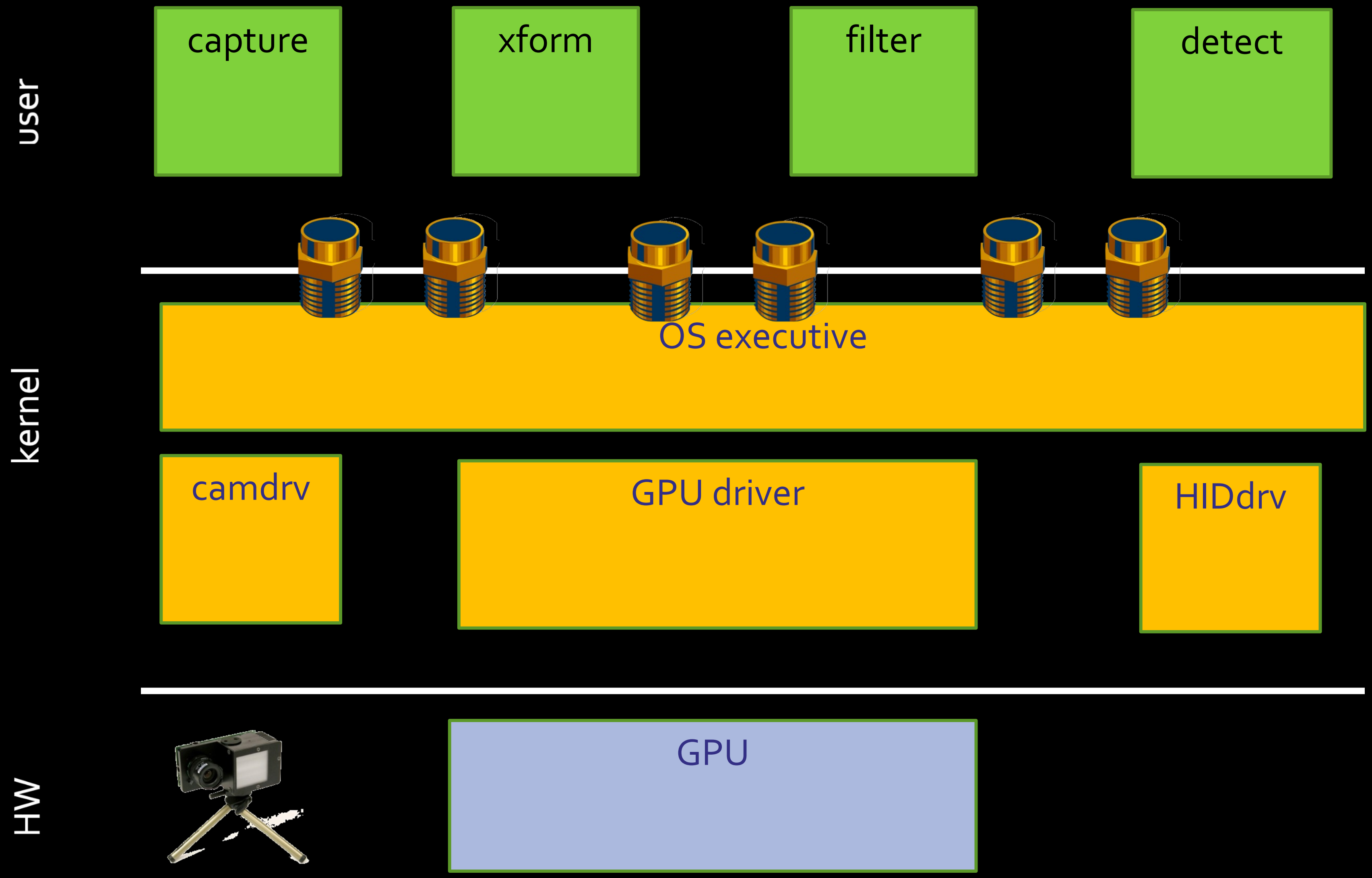


Data migration

```
#> capture | xform | filter | detect &
```



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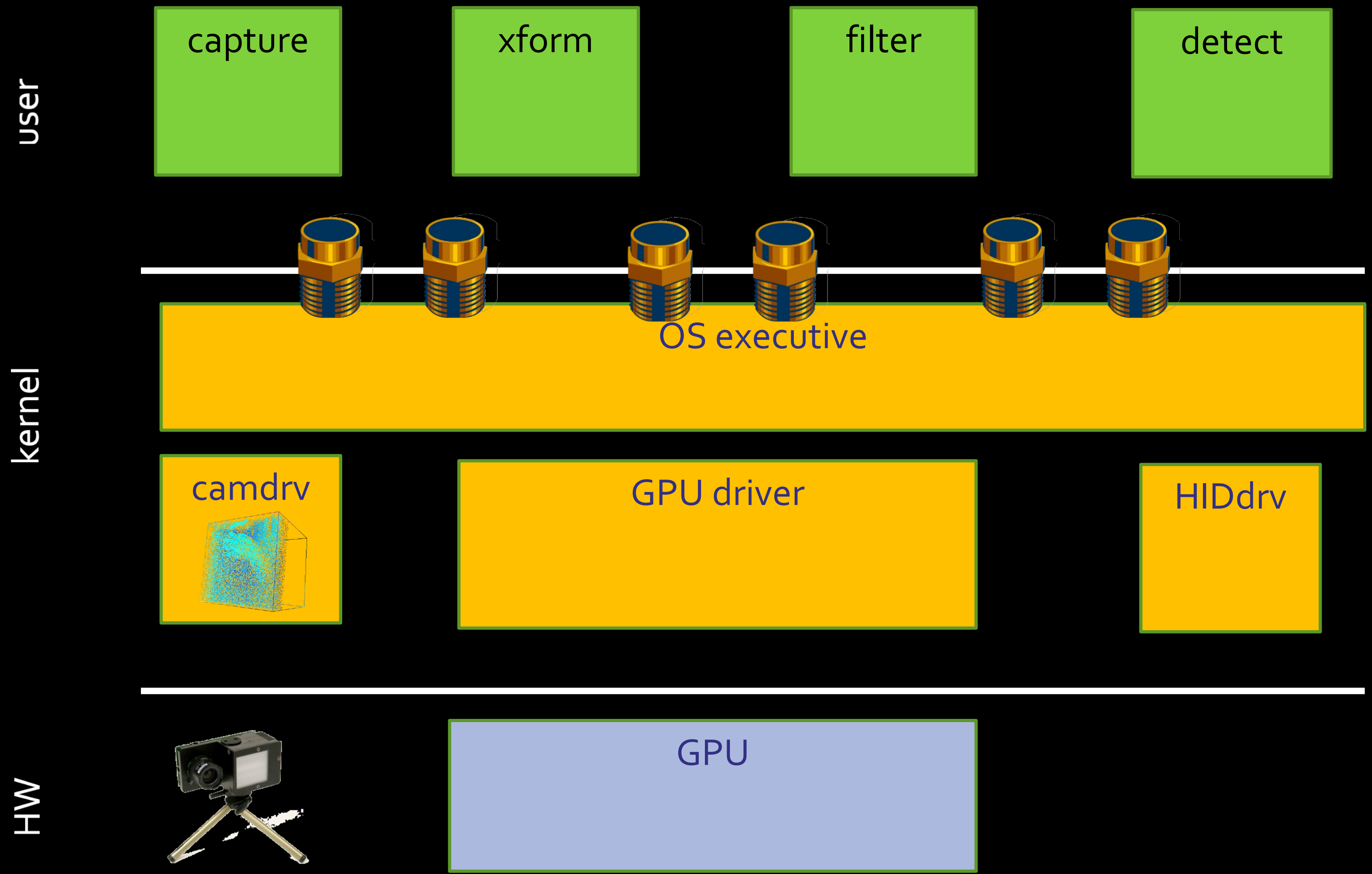

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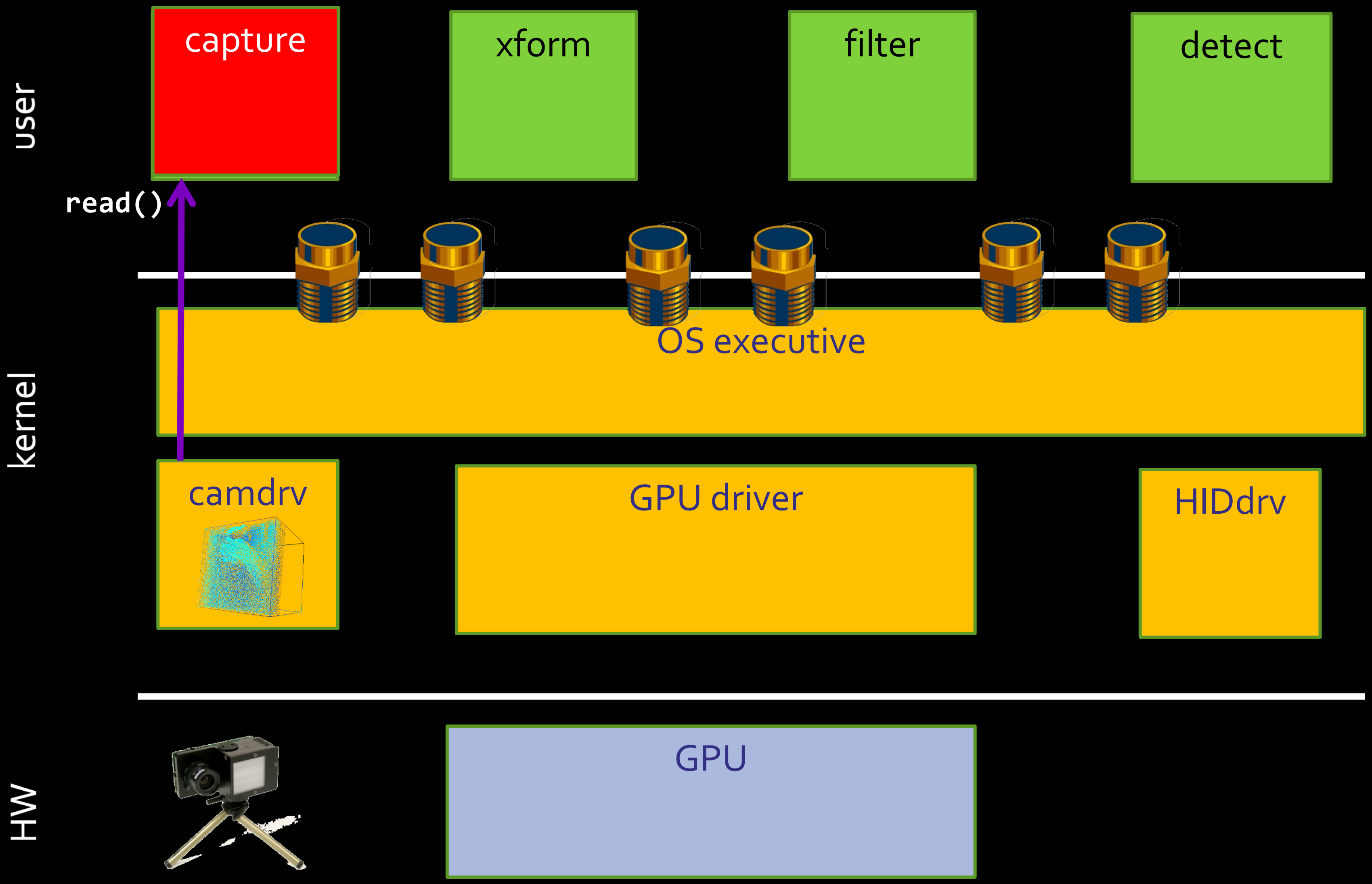

10/11/23

Data migration

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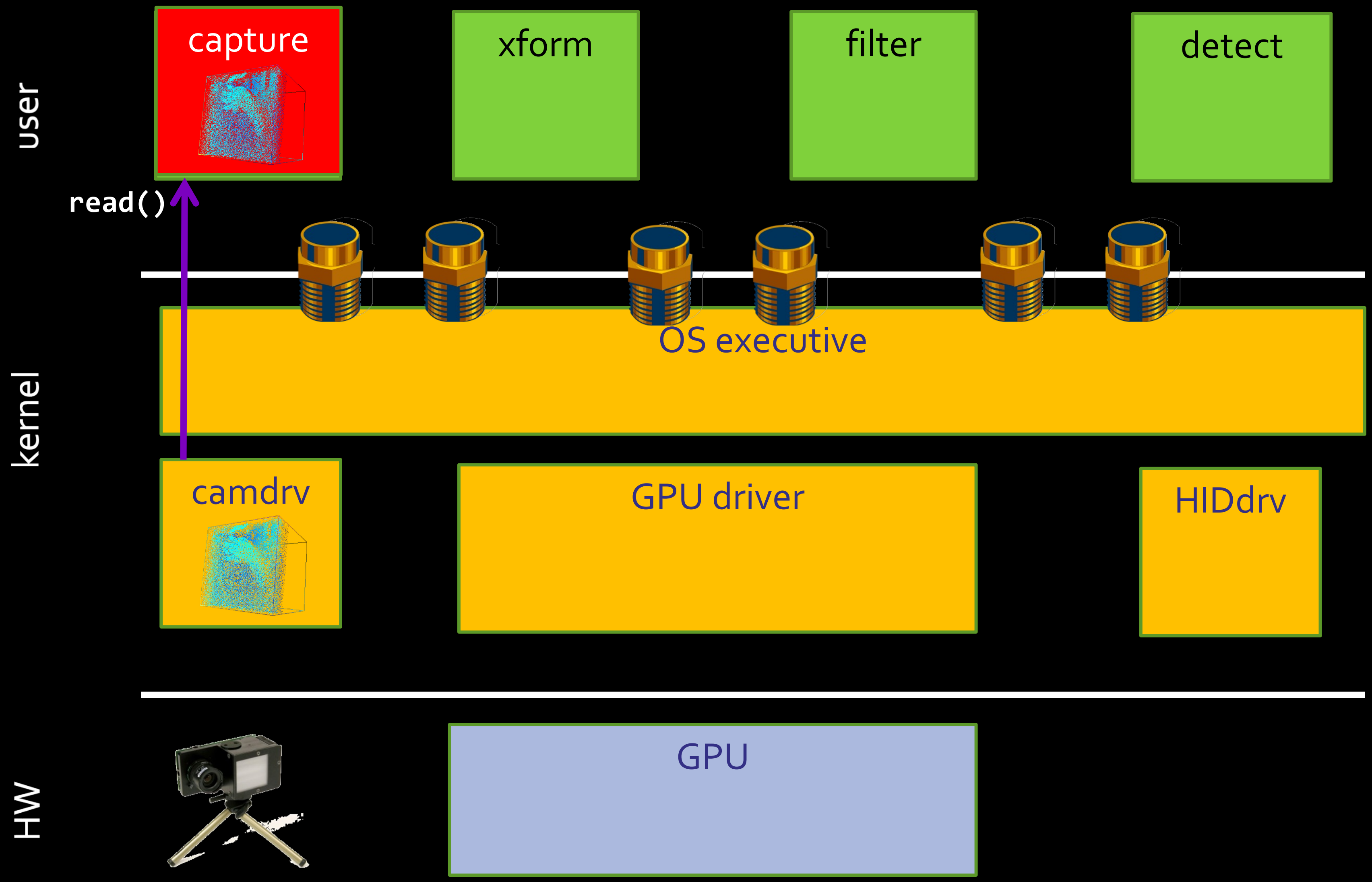

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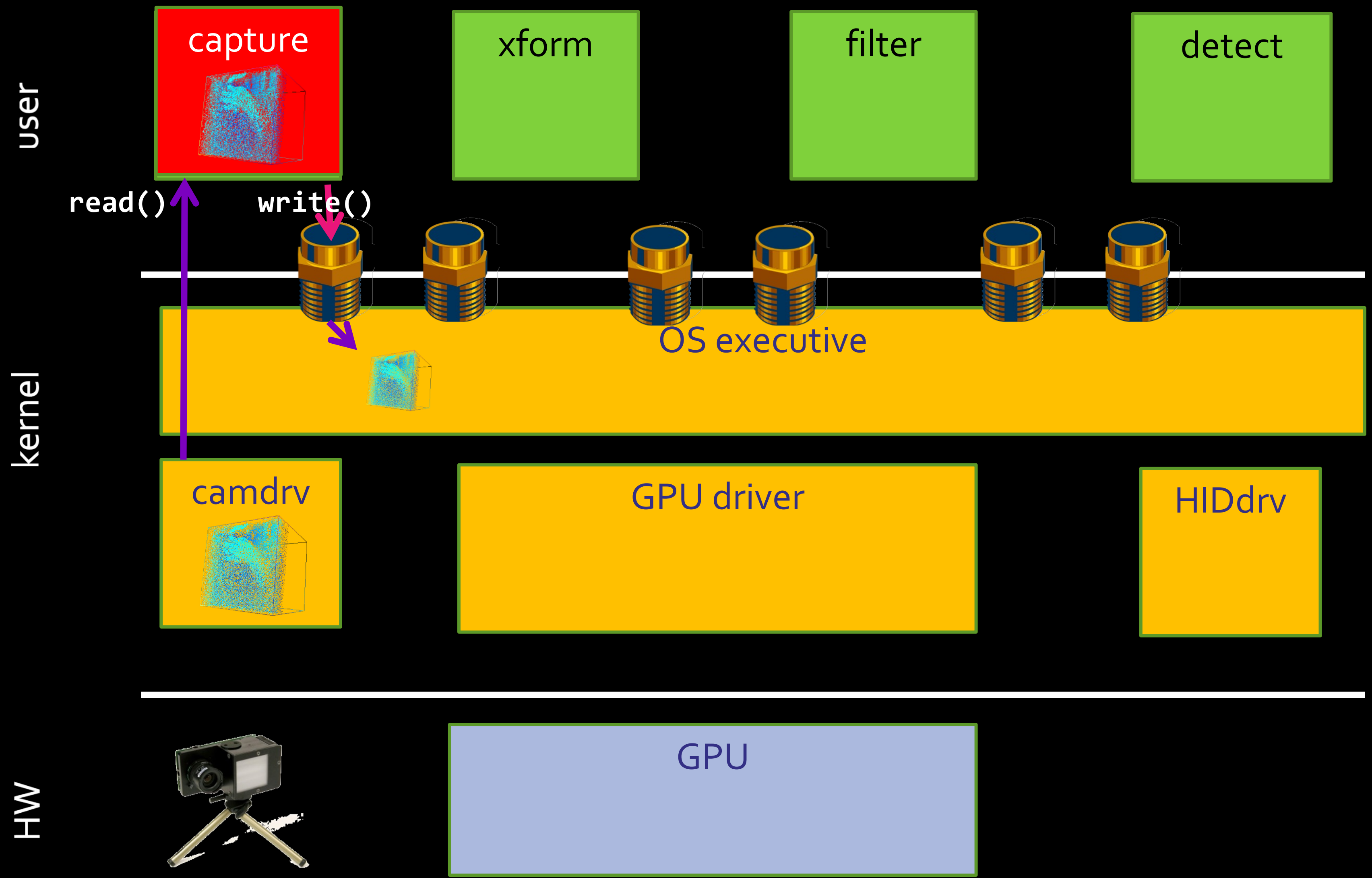

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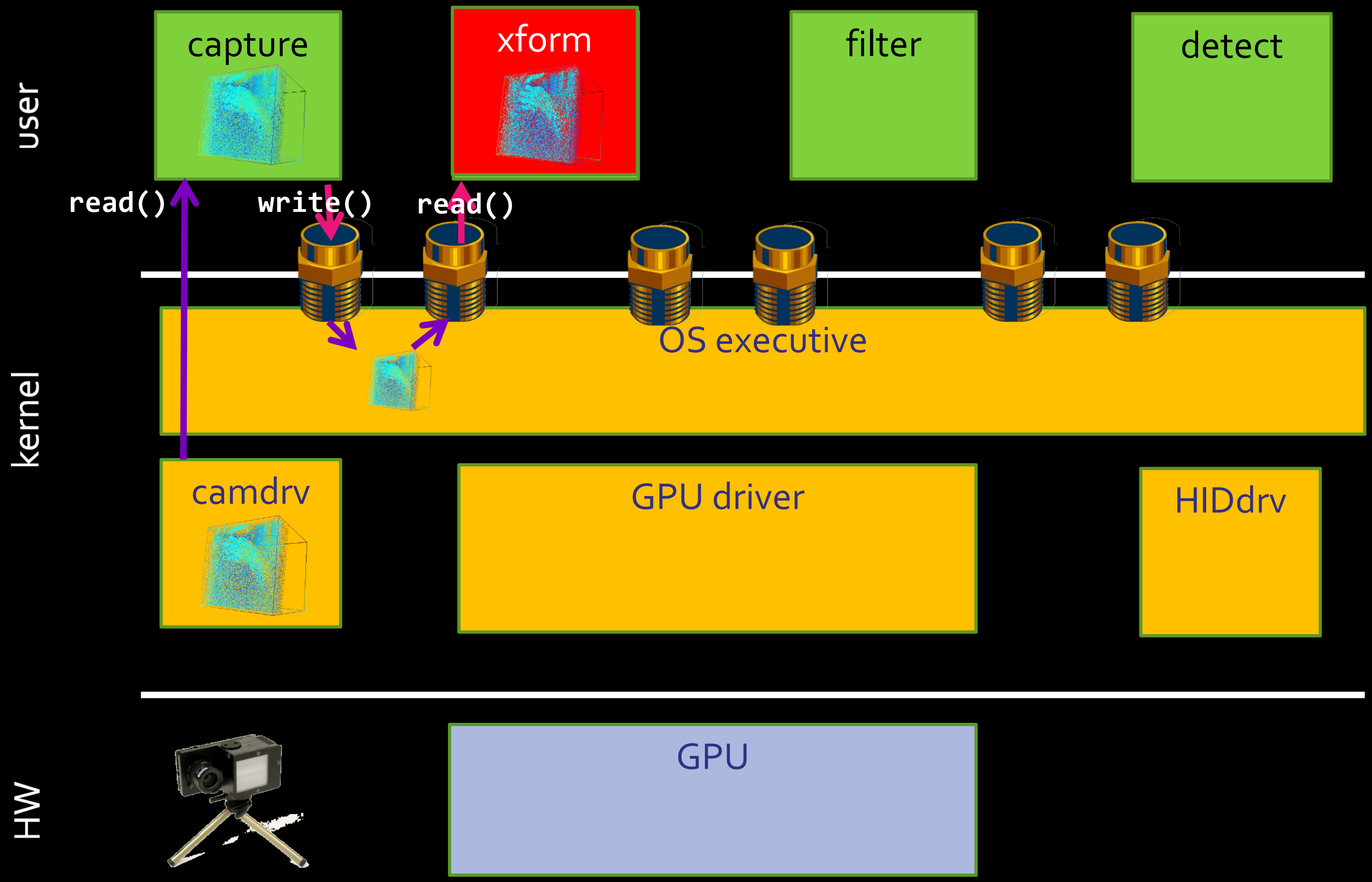

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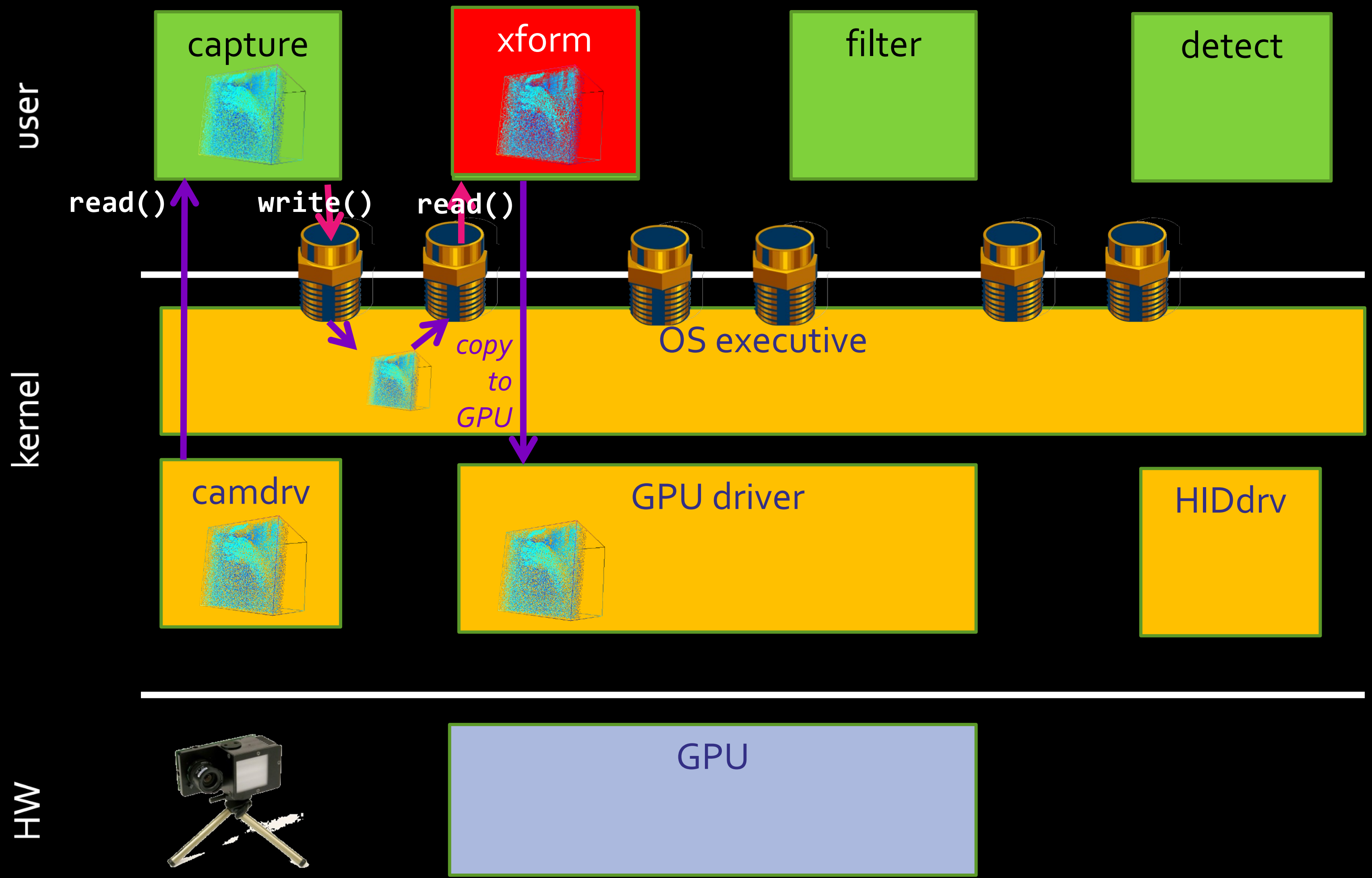

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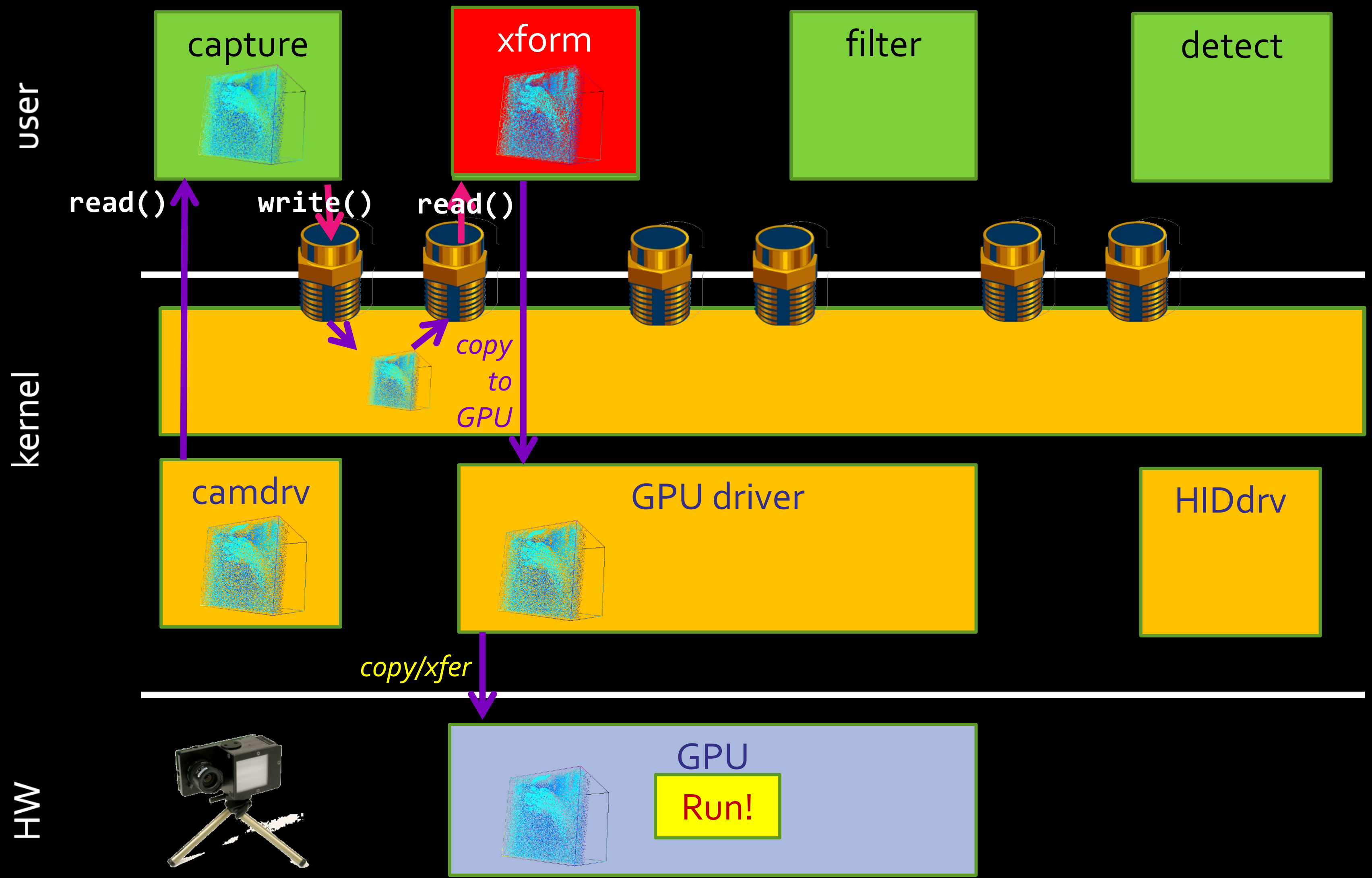

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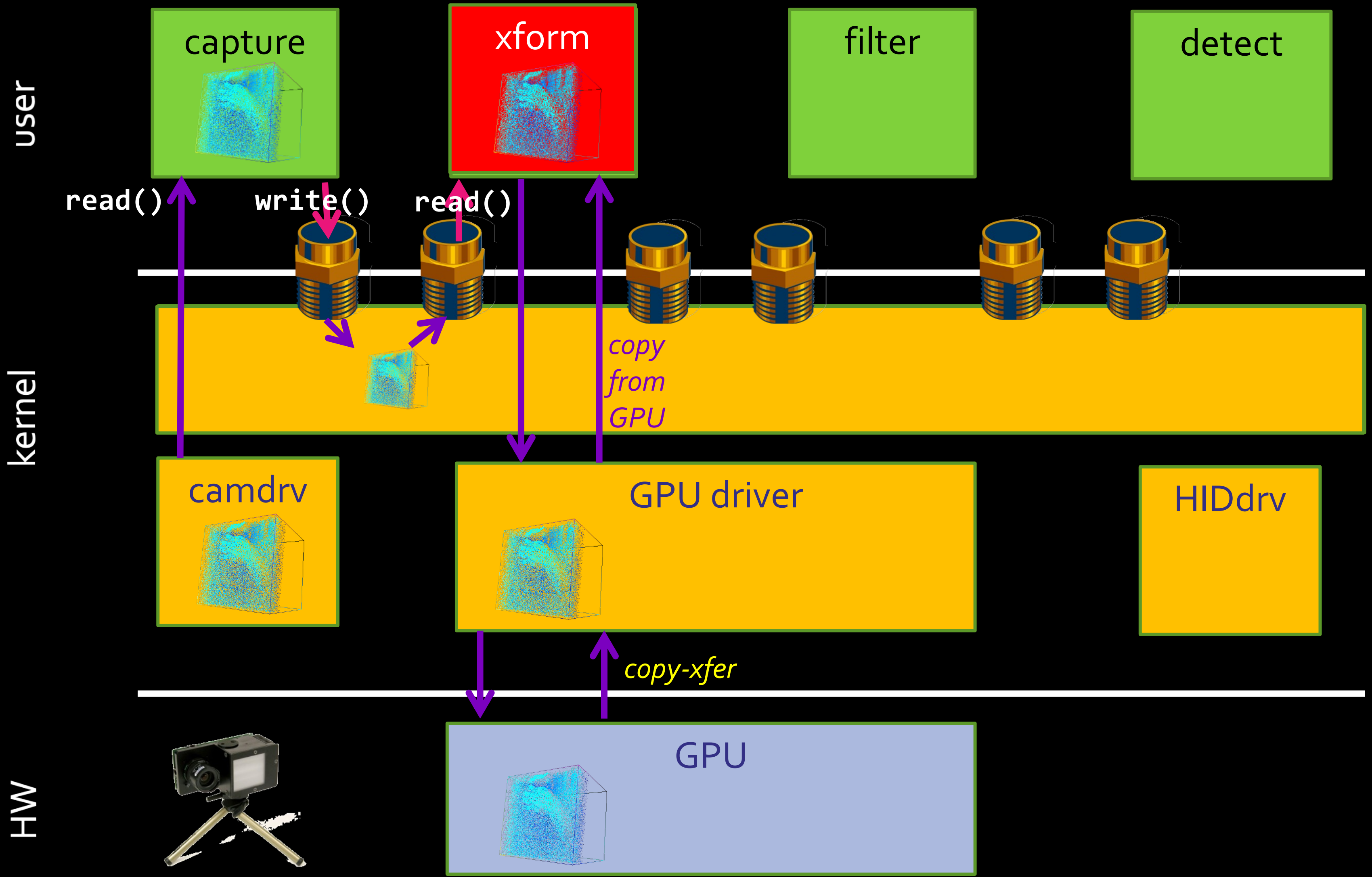

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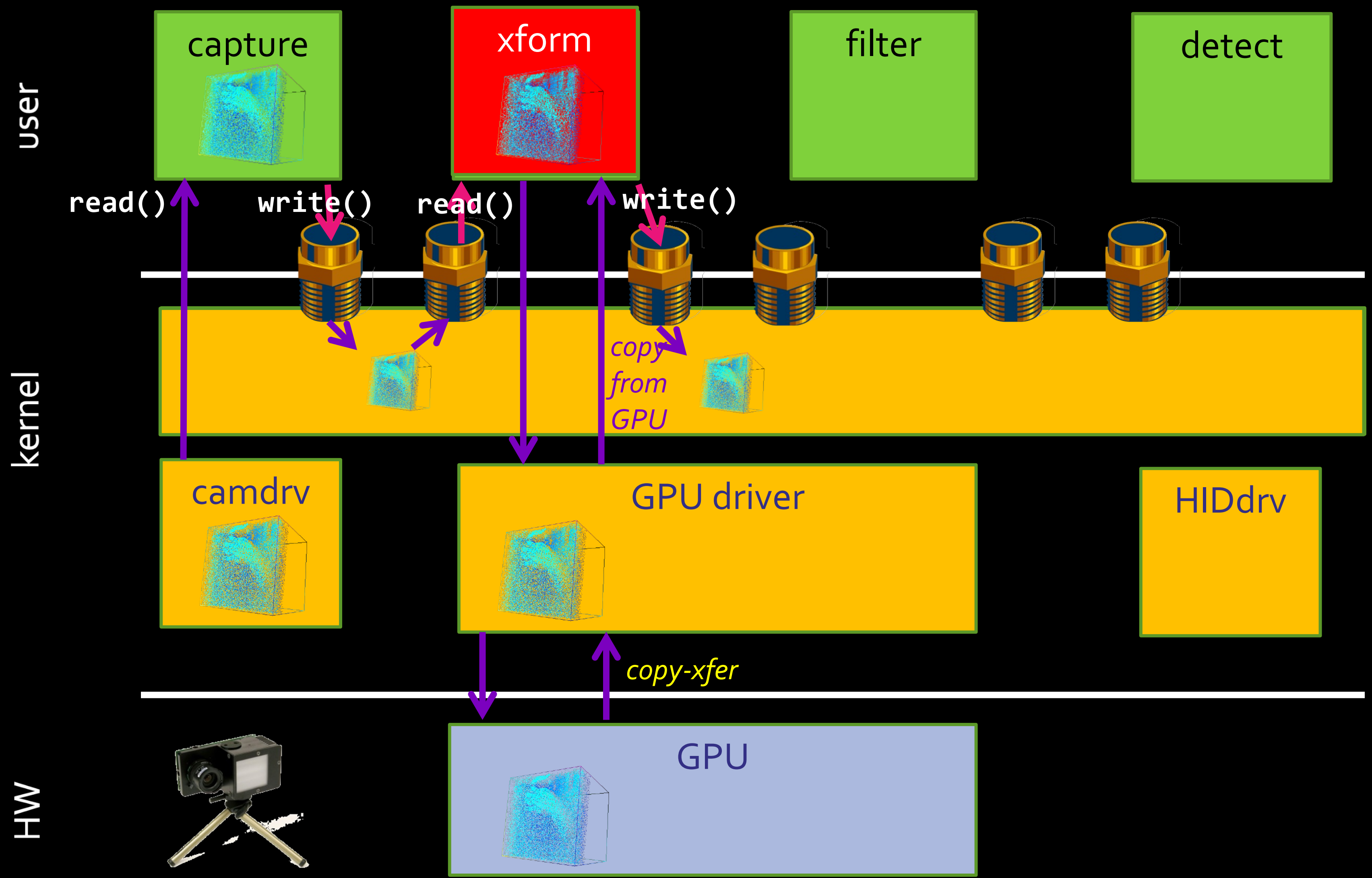

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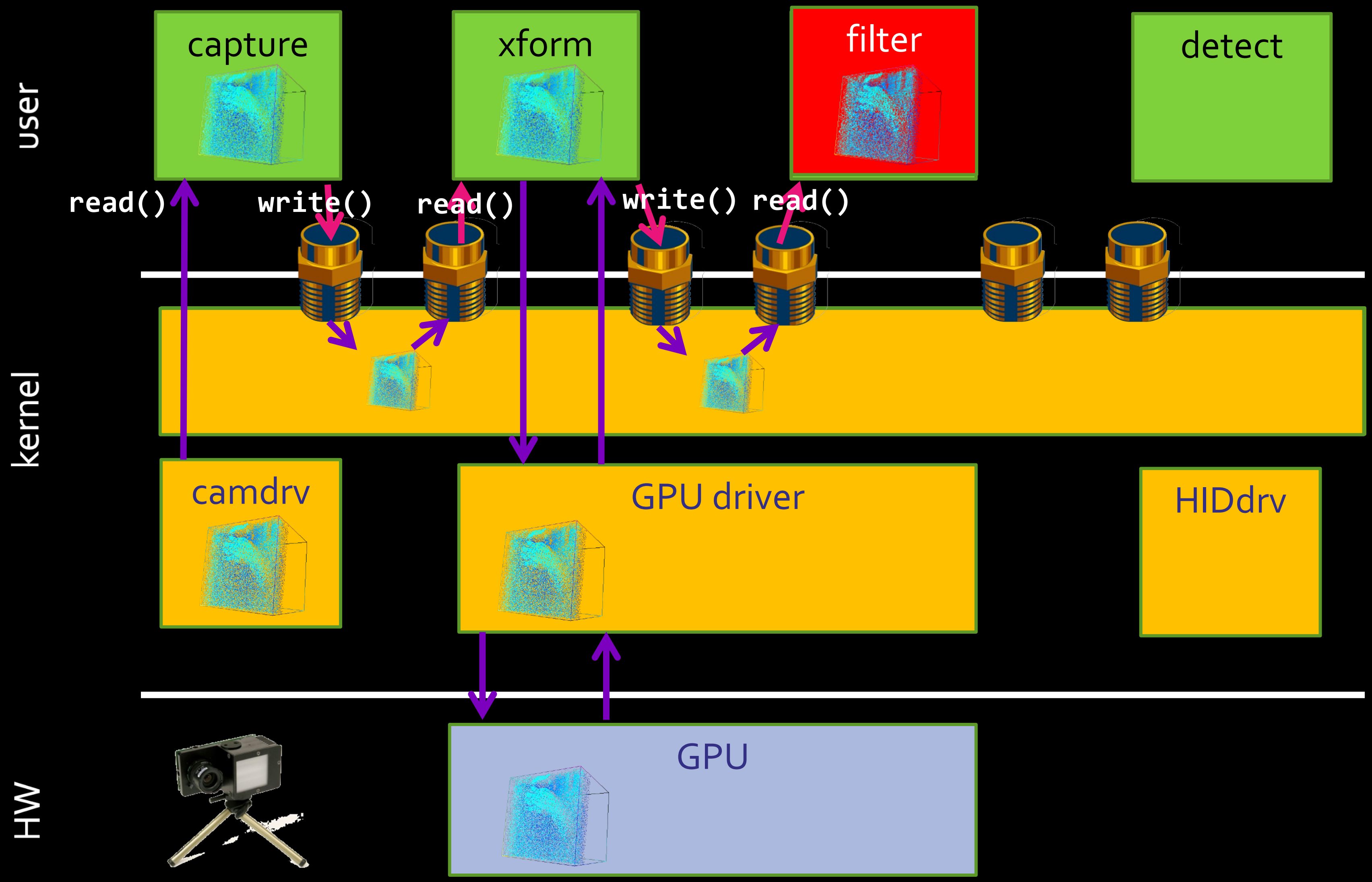

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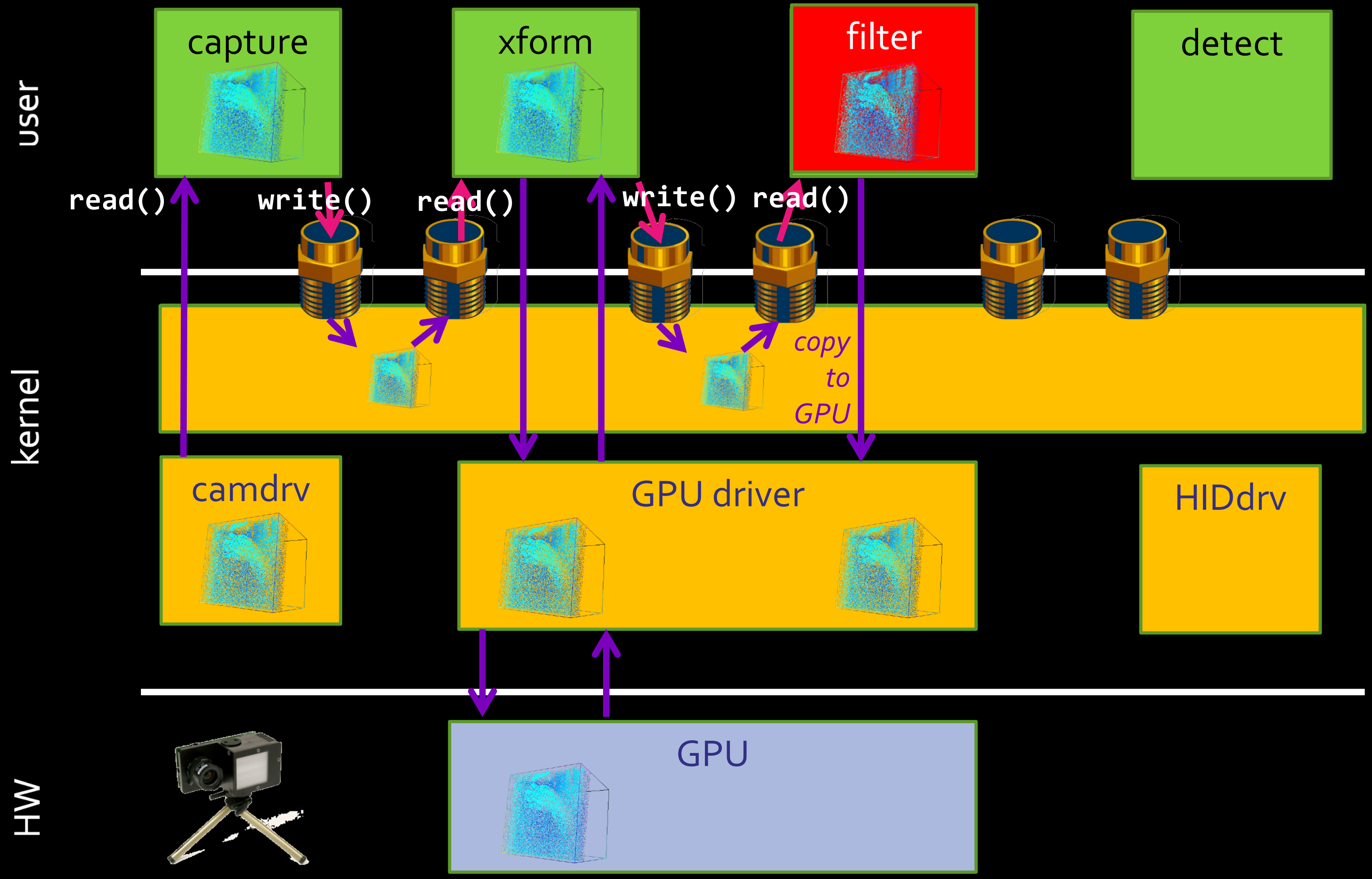

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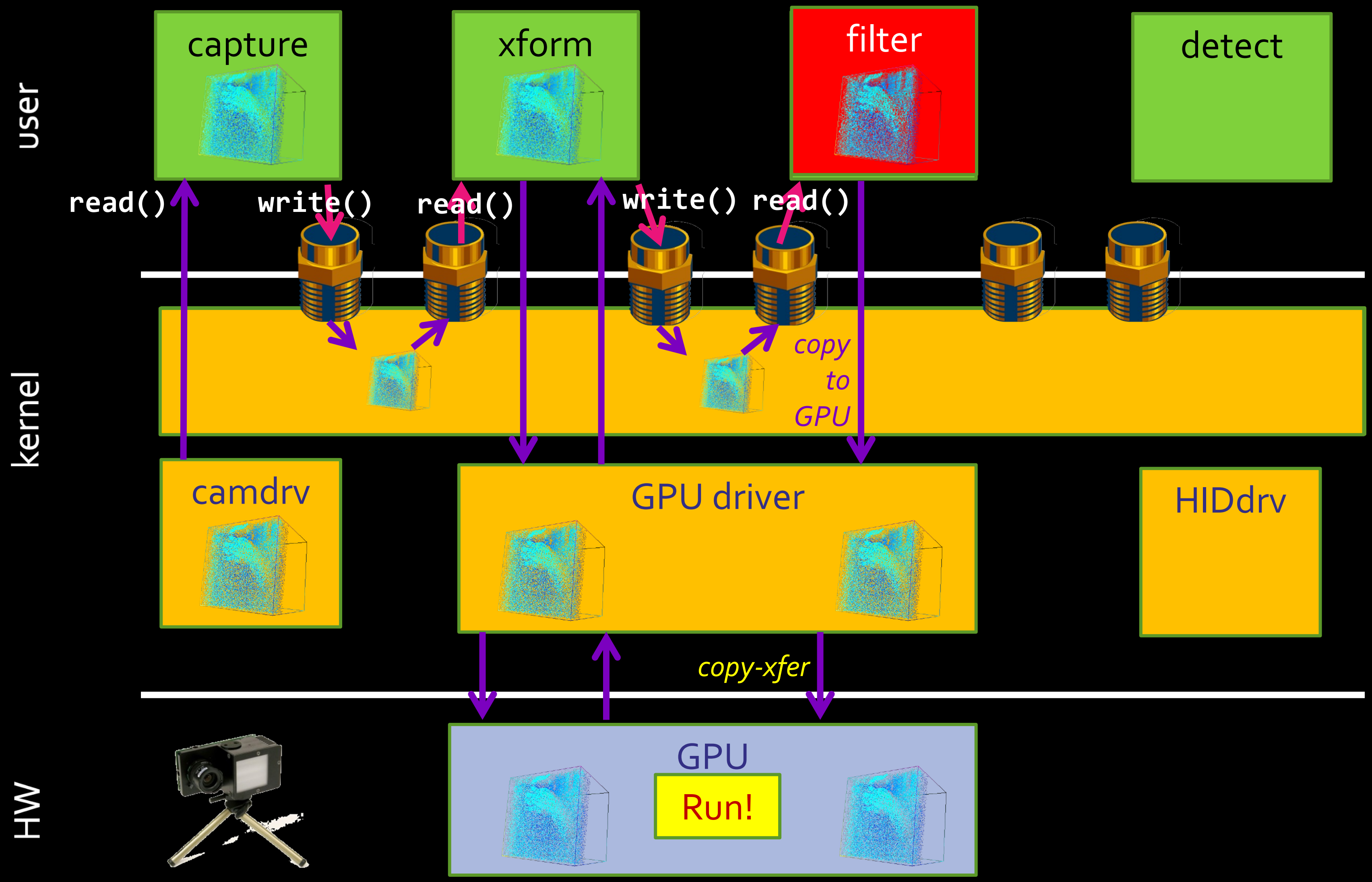

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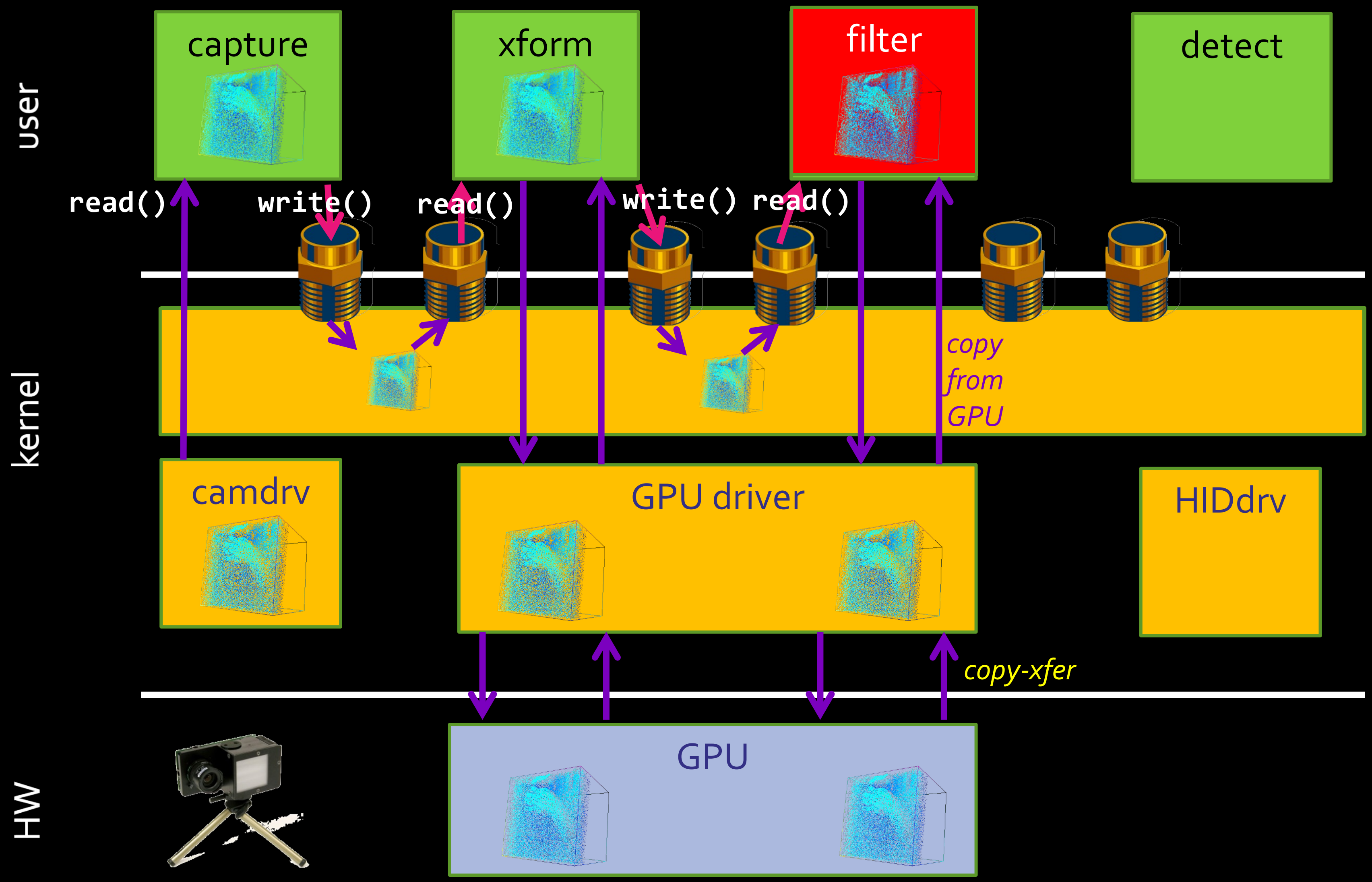

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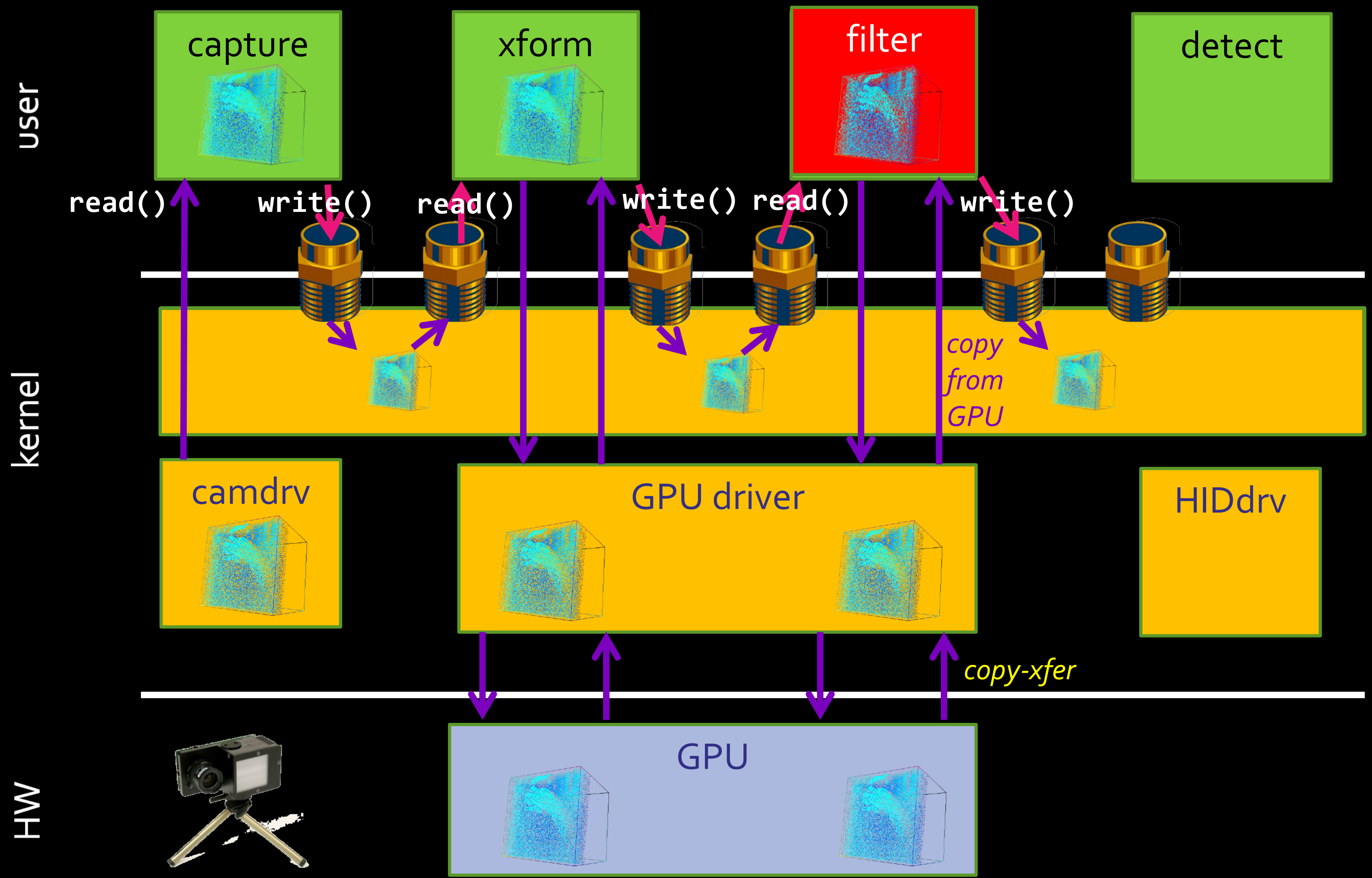

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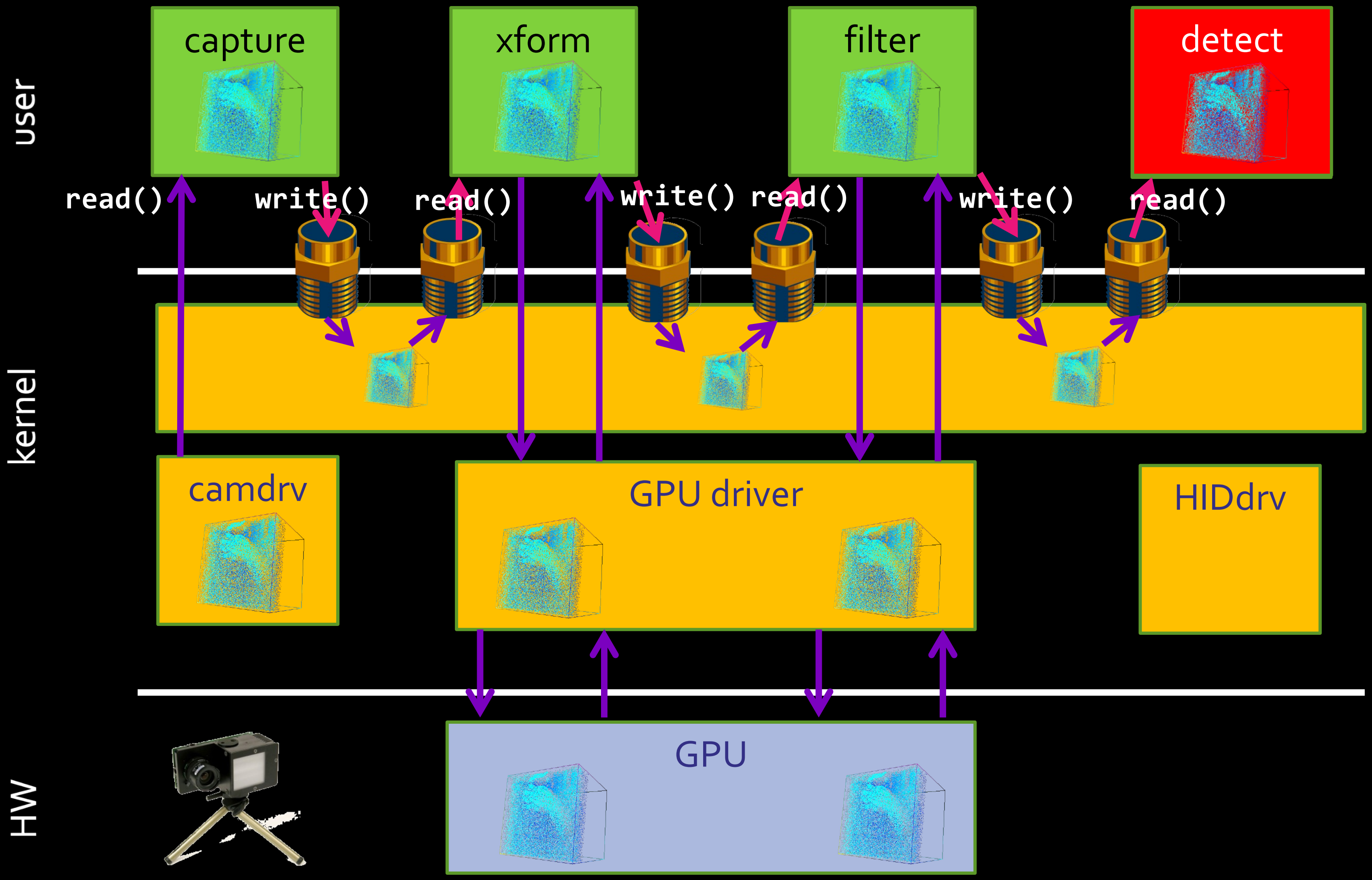

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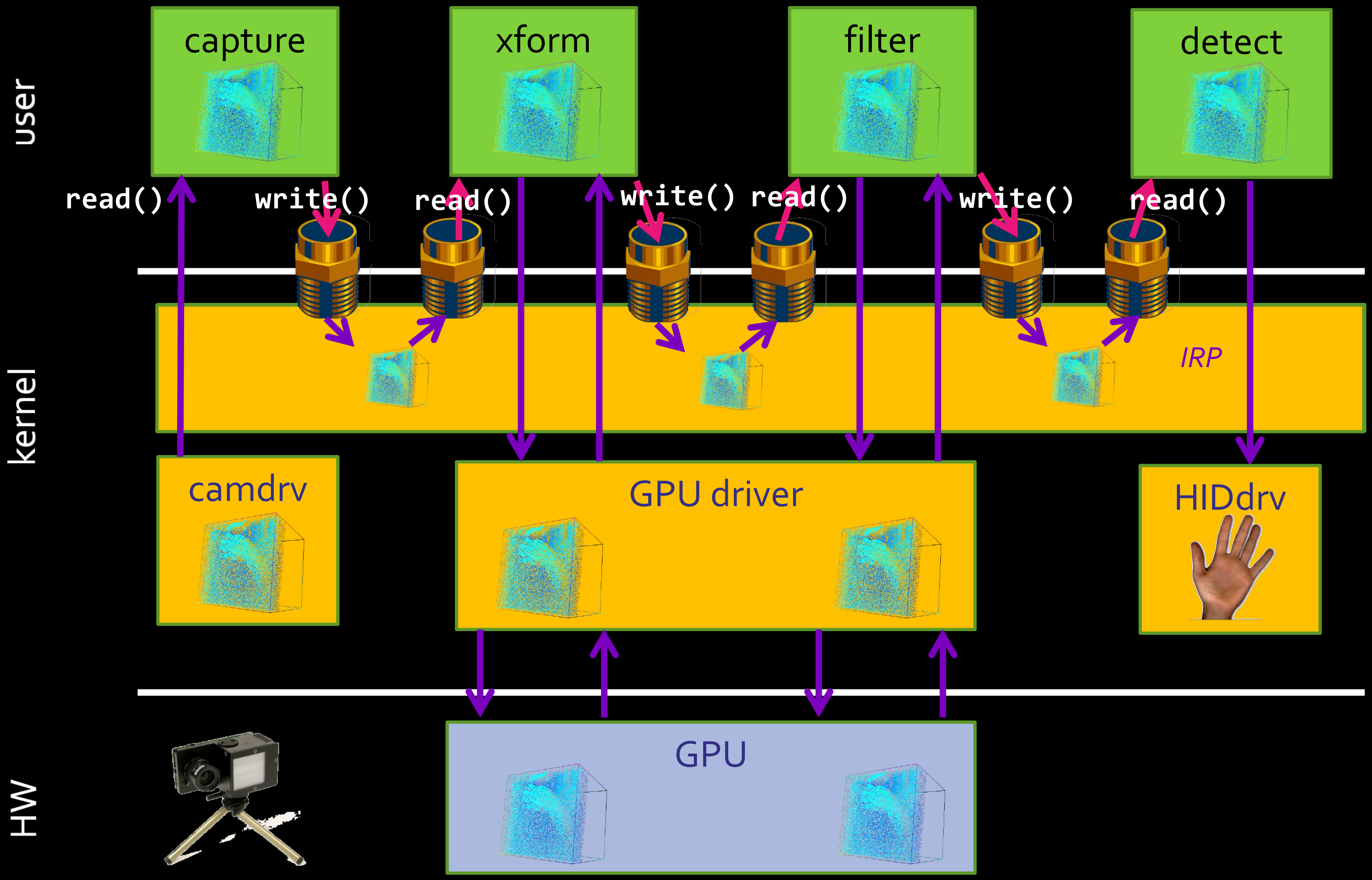

Device-centric APIs considered harmful

```
Matrix
gemm(Matrix A, Matrix B) {
    copyToGPU(A);
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    invokeGPU();
    Matrix C = new Matrix();
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}
```

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What happens if I want the following?
Matrix D = A x B x C

Composed matrix multiplication

```
Matrix
AxBxC(Matrix A, B, C) {
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}
```

AxB copied from GPU memory…

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```

…only to be copied right back!

What if I have many GPUs?

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Matrix
gemm(Matrix A, Matrix B) {
   copyToGPU(A);
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What if I have many GPUs?

```
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gemm(GPU dev,Matrix A, Matrix B) {
    copyToGPU(dev, A);
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Composition with many GPUs

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}
```

Composition with many GPUs

Rats…now I can only use 1 GPU. *How to partition computation?*

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Composition with many GPUs

This will never be manageable for *many* GPUs. *Programmer implements scheduling using static view!*

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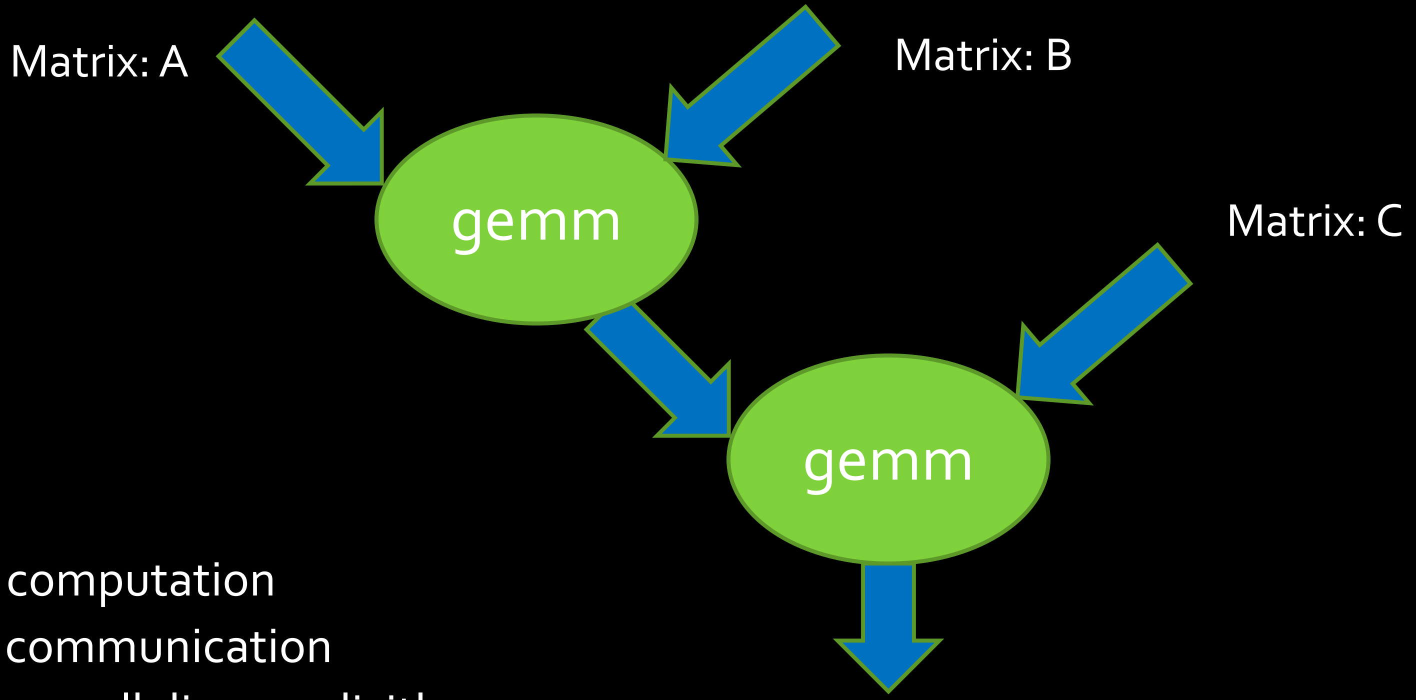
```

Why don’t we have this problem with CPUs?

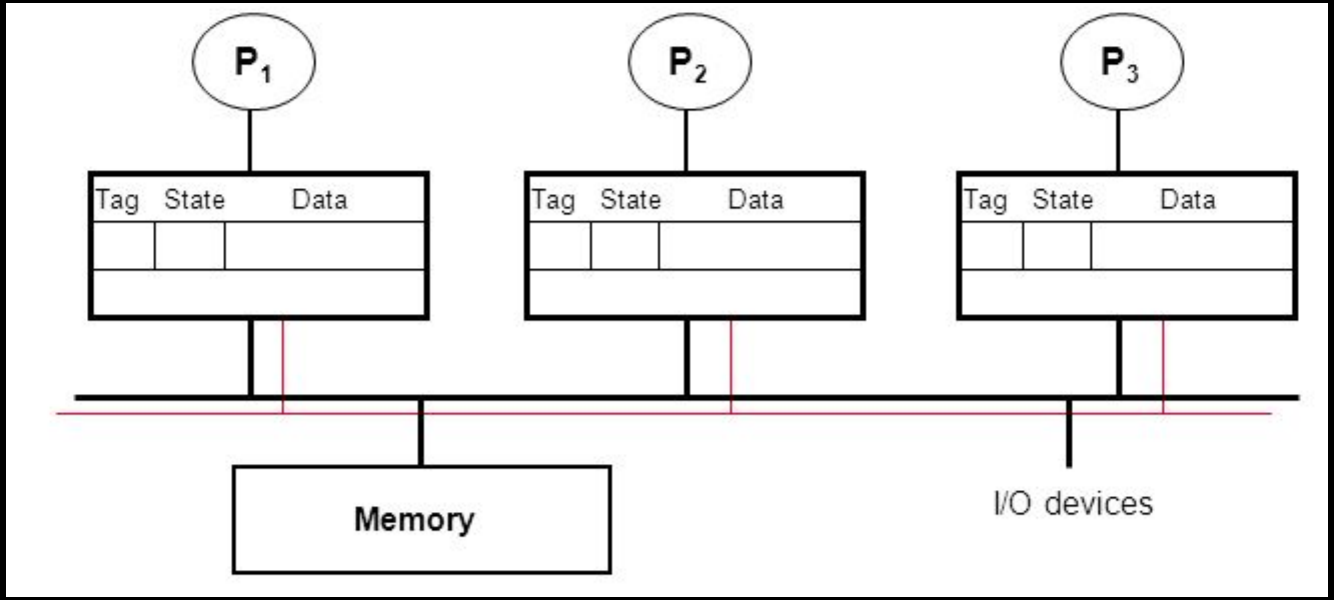
Dataflow: a better abstraction



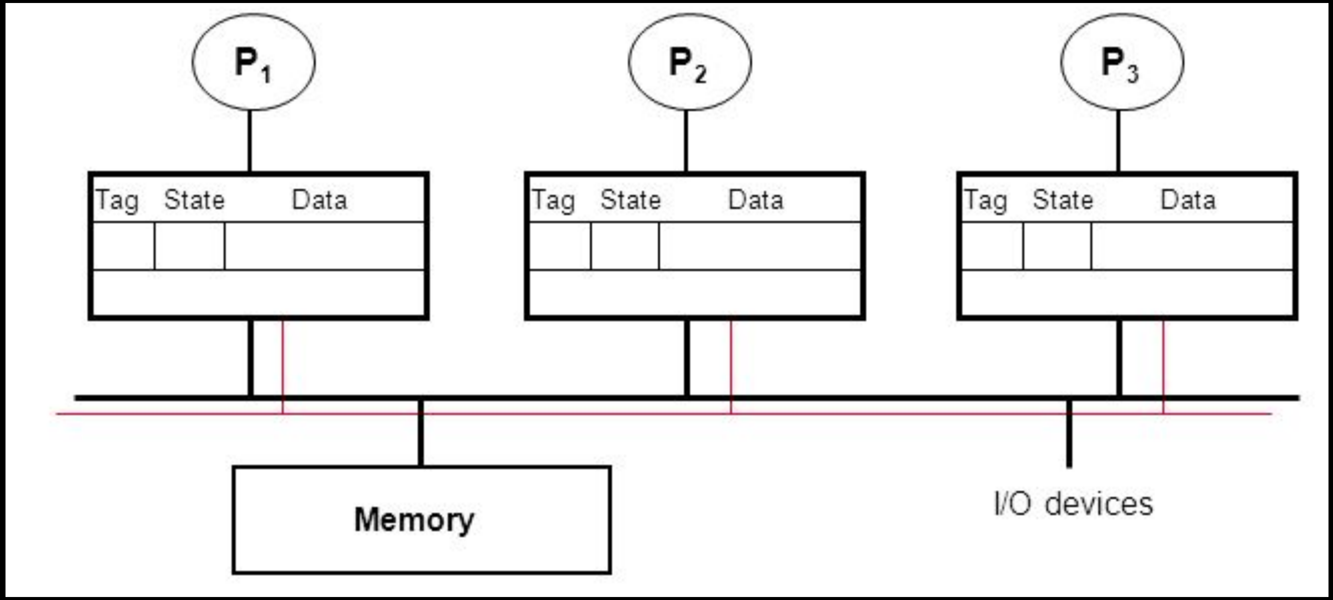
- nodes → computation
- edges → communication
- Expresses parallelism explicitly
- Minimal specification of data movement: runtime does it.
- asynchrony is a runtime concern (not programmer concern)
- No specification of compute→device mapping: like threads!

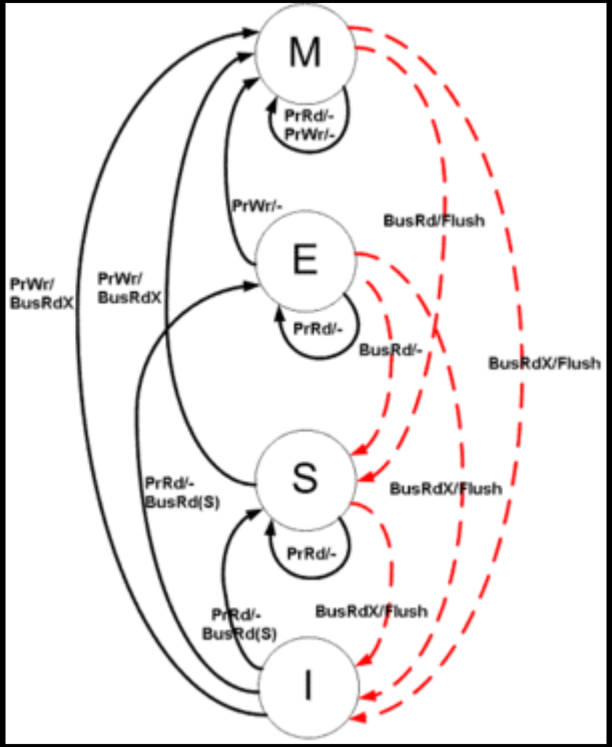
Advanced Topic: GPU Coherence

Review: Cache Coherence



Review: Cache Coherence





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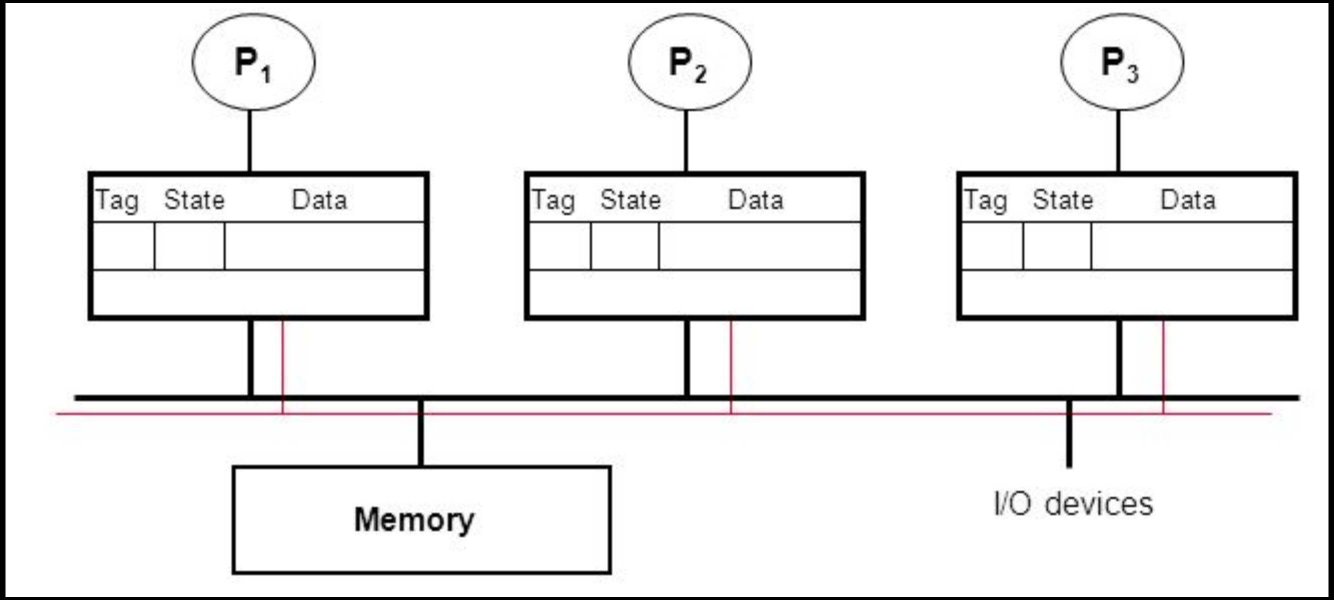
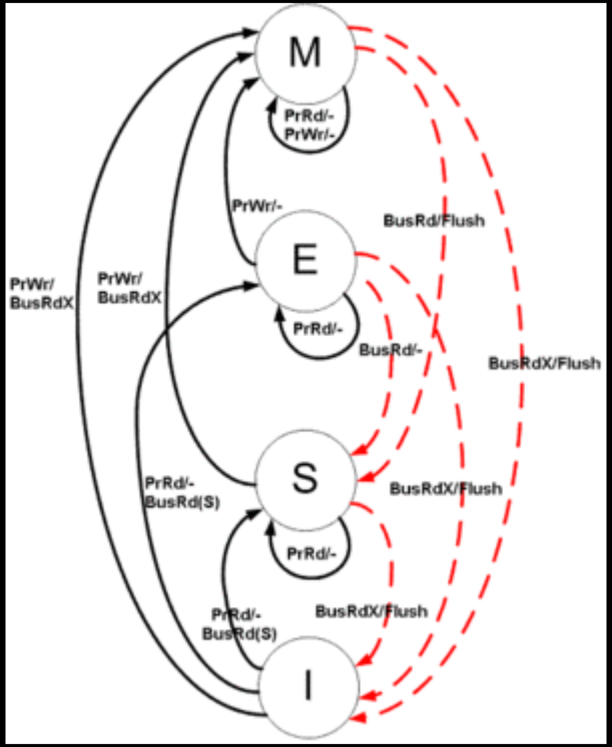


Each cache line has a state (M, E, S, I)



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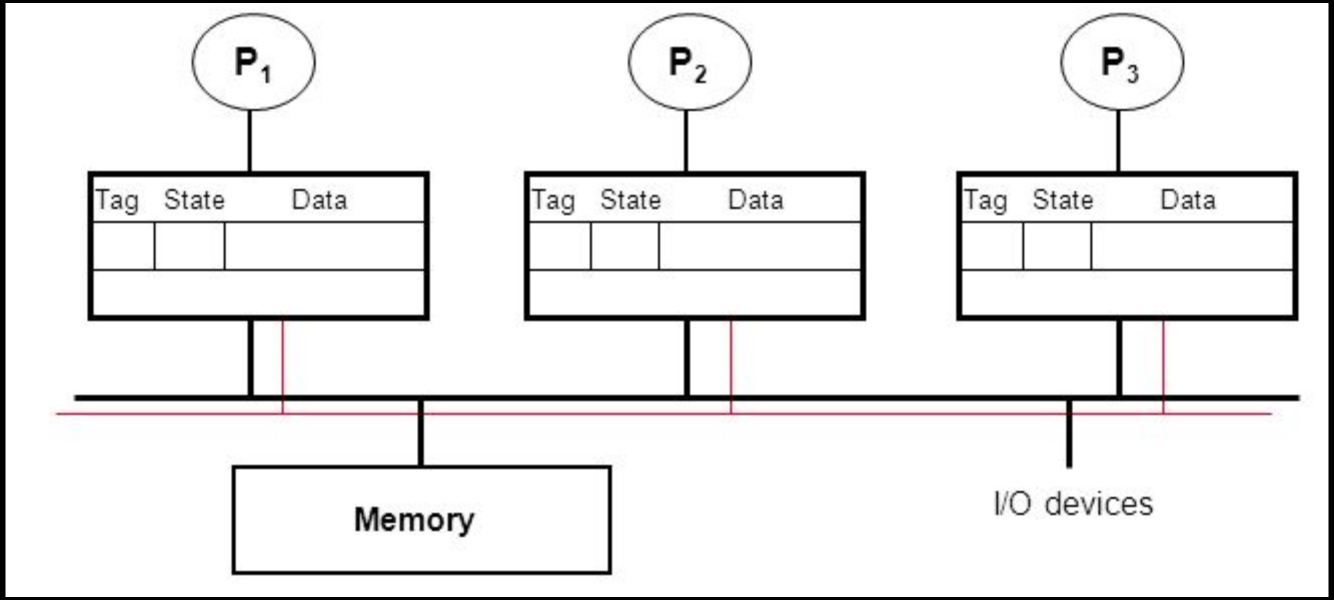
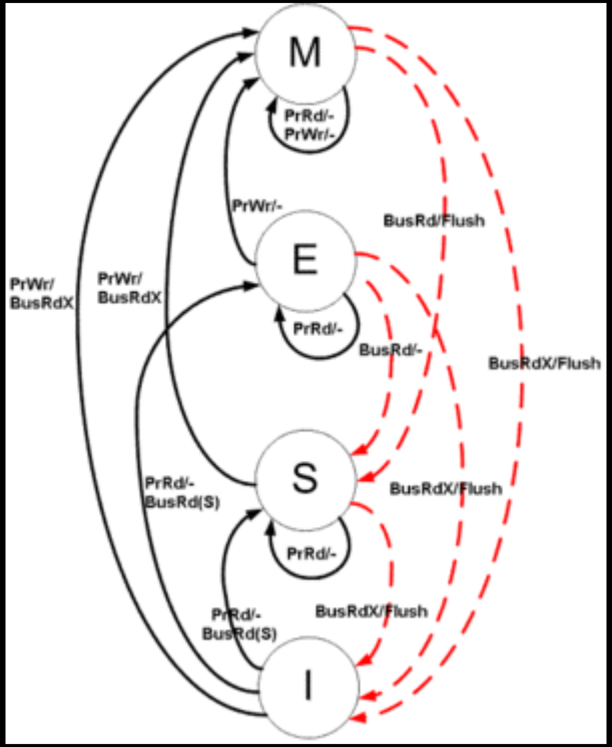
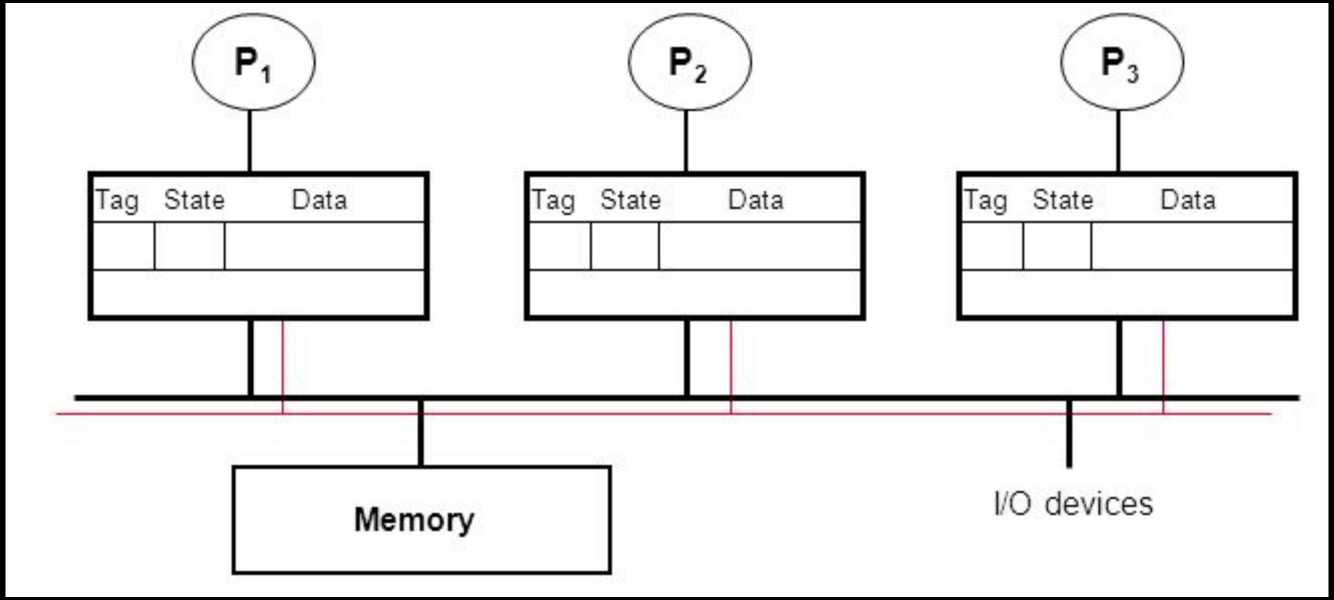


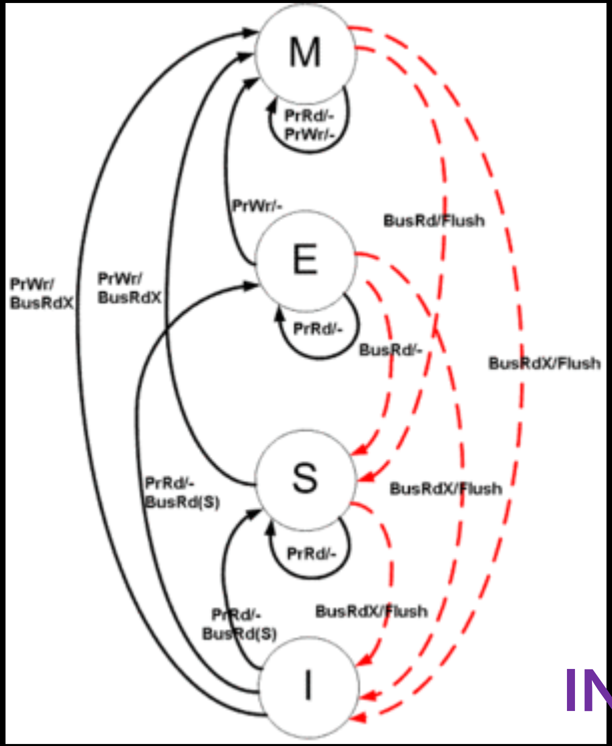


Each cache line has a state (M, E, S, I)

- Processors "snoop" bus to maintain states

Review: Cache Coherence



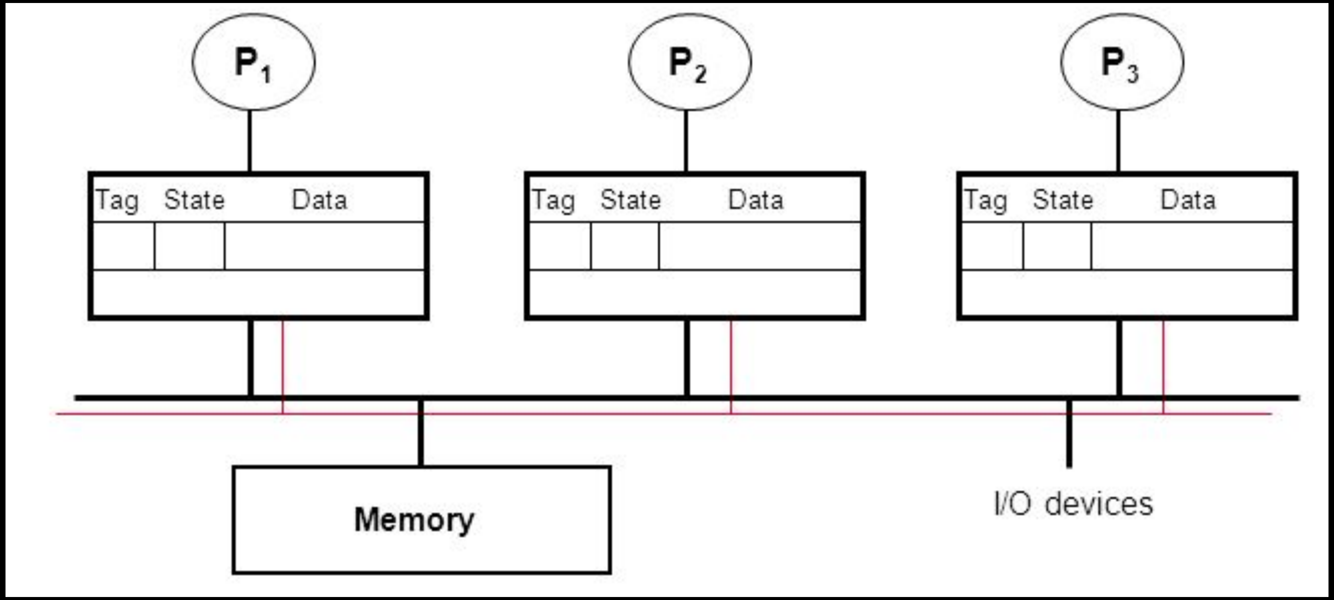


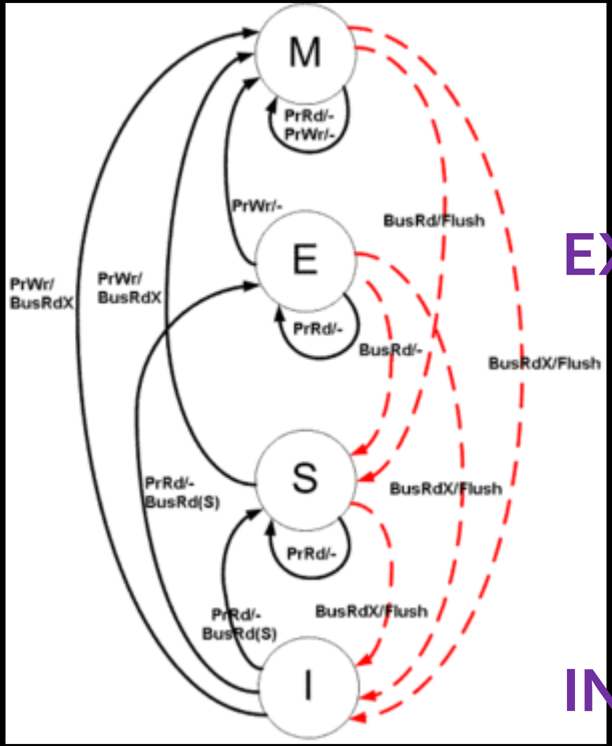
INVALID

Each cache line has a state (M, E, S, I)

- Processors "snoop" bus to maintain states
- Initially → 'I' → Invalid

Review: Cache Coherence





EXCLUSIVE

INVALID

Each cache line has a state (M, E, S, I)

- Processors “snoop” bus to maintain states
- Initially → ‘I’ → Invalid
- Read one → ‘E’ → exclusive

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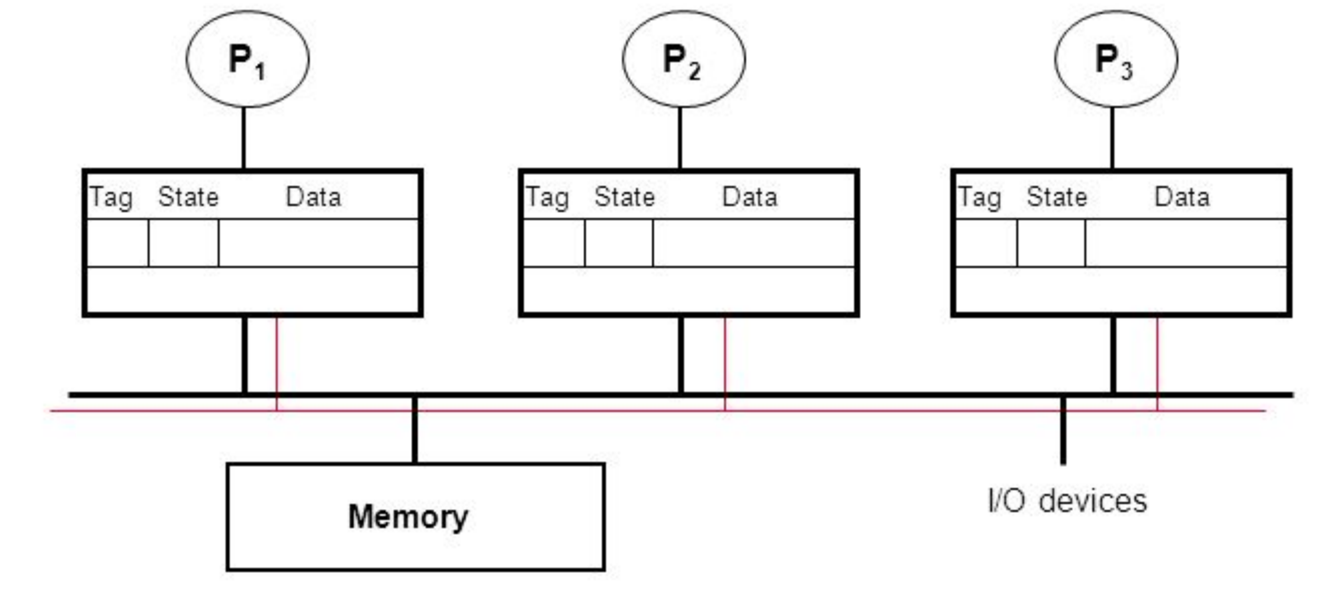

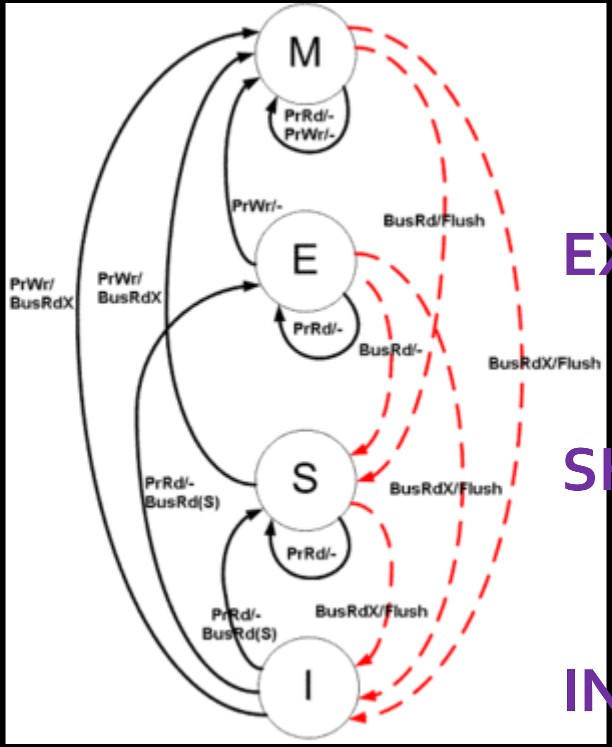

EXCLUSIVE

SHARED

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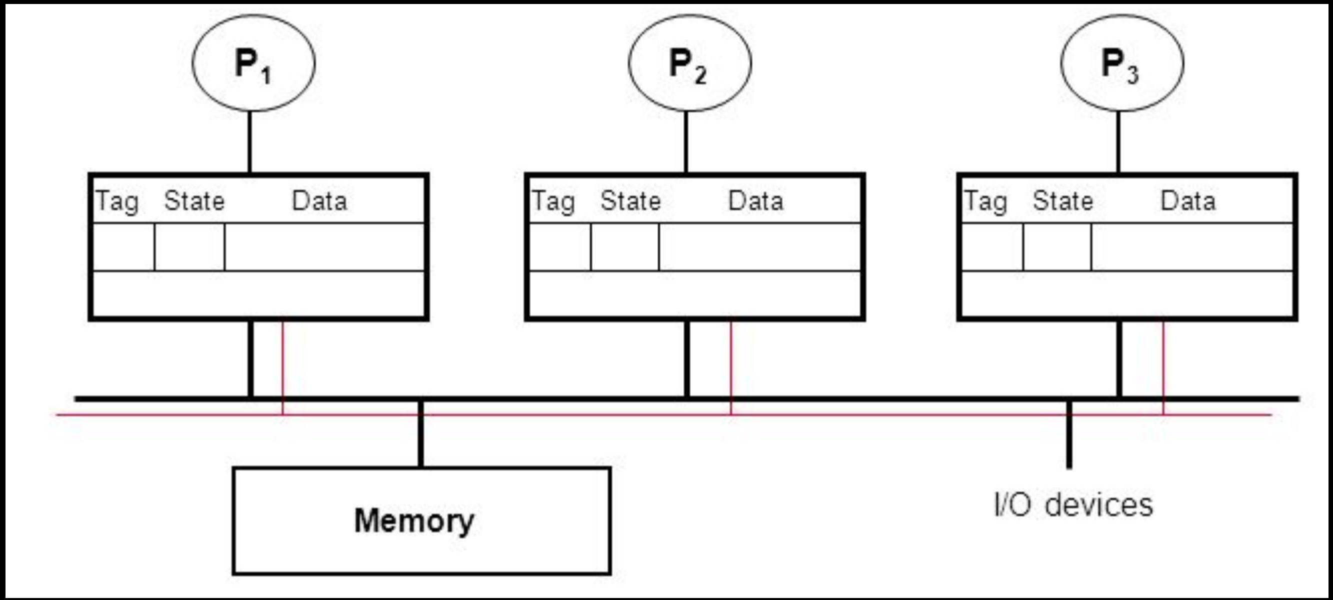

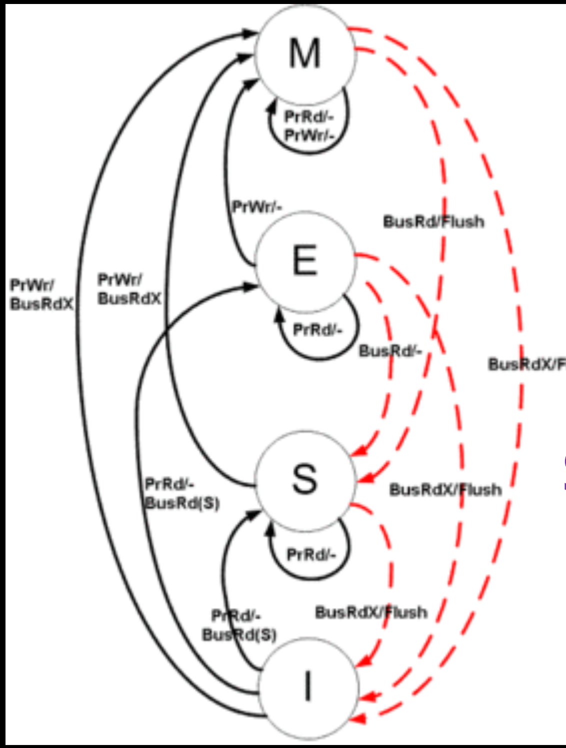

EXCLUSIVE

SHARED

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- Write → 'M' → single copy → lots of cache coherence traffic

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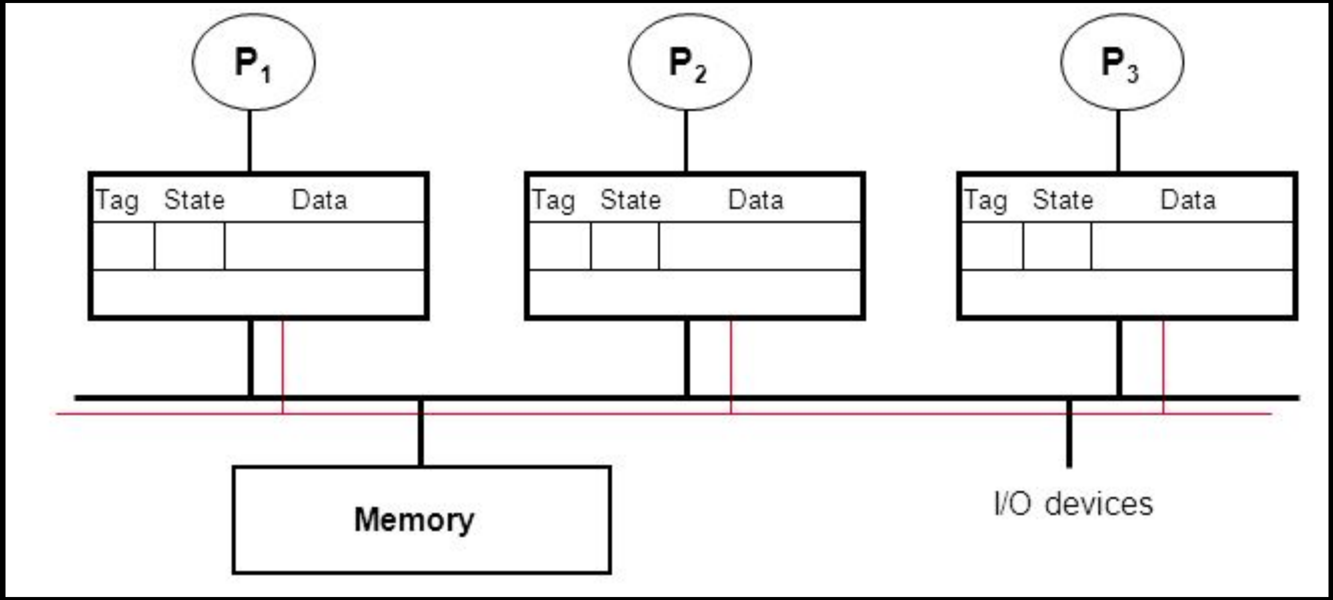

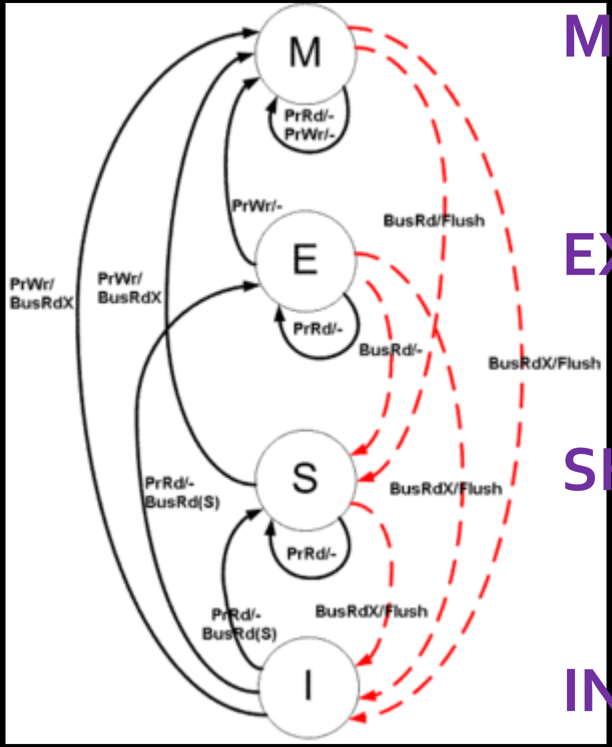

MODIFIED

EXCLUSIVE

SHARED

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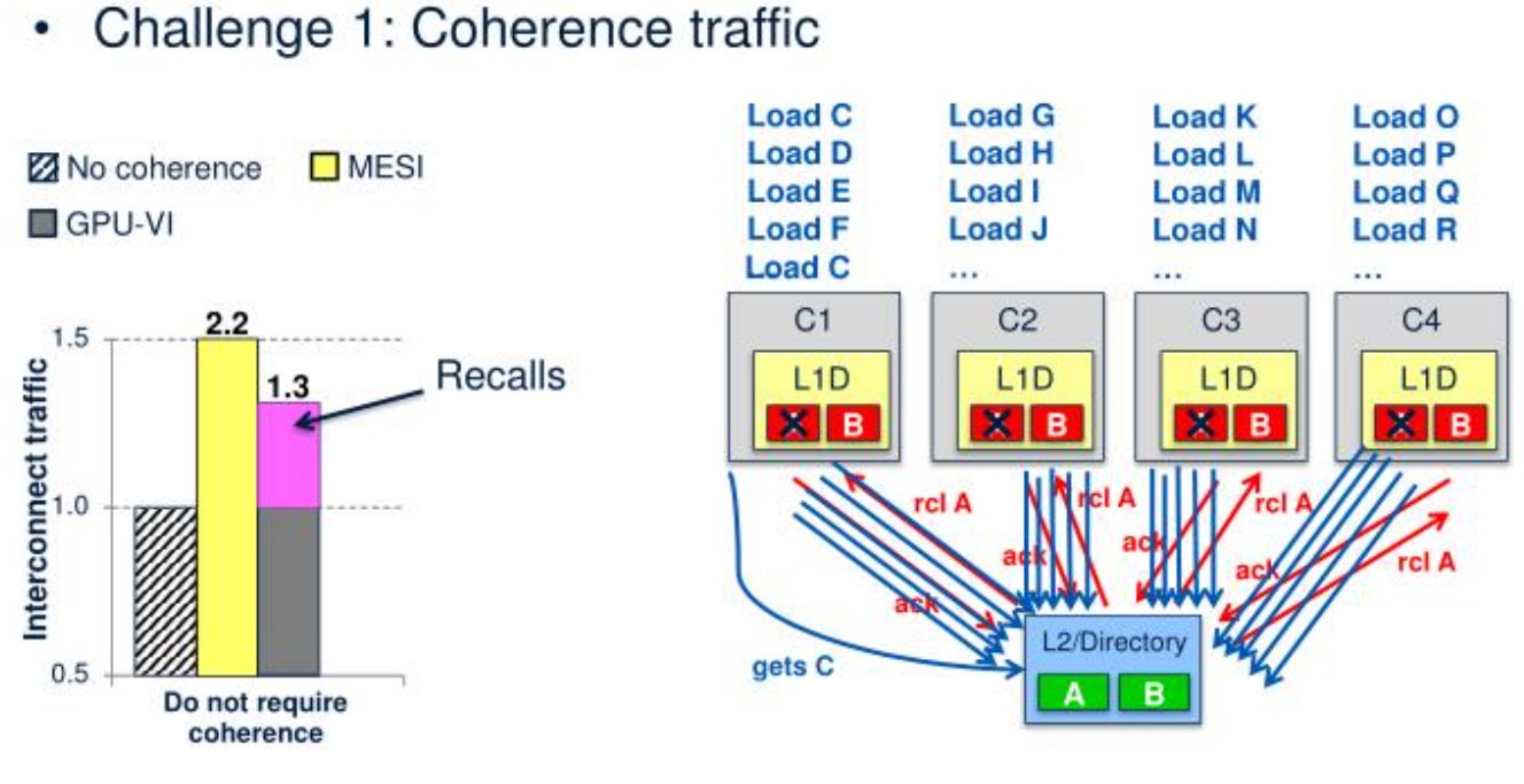
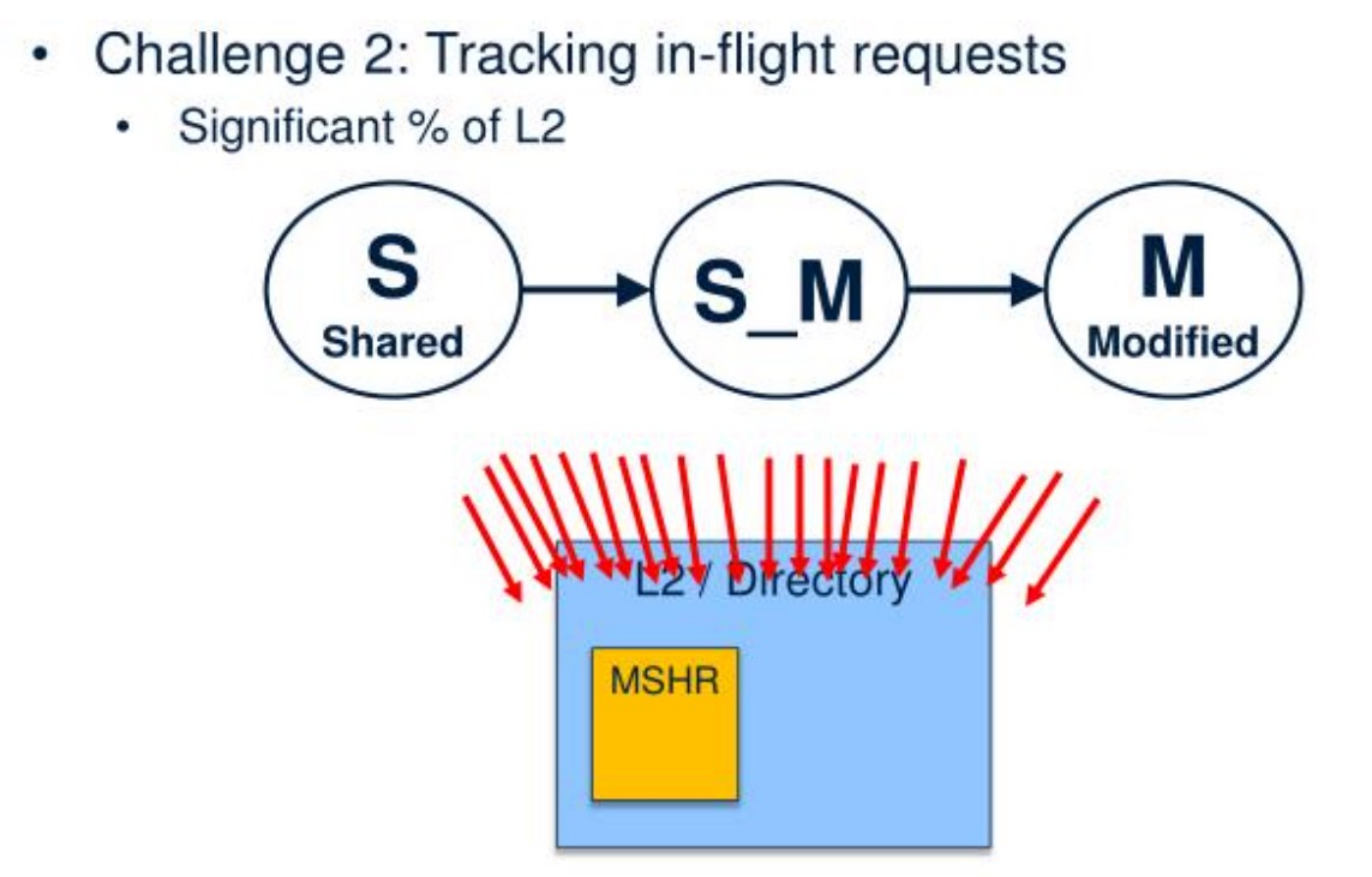
GPU Cache Coherence Challenges



- Challenge 1: Coherence traffic

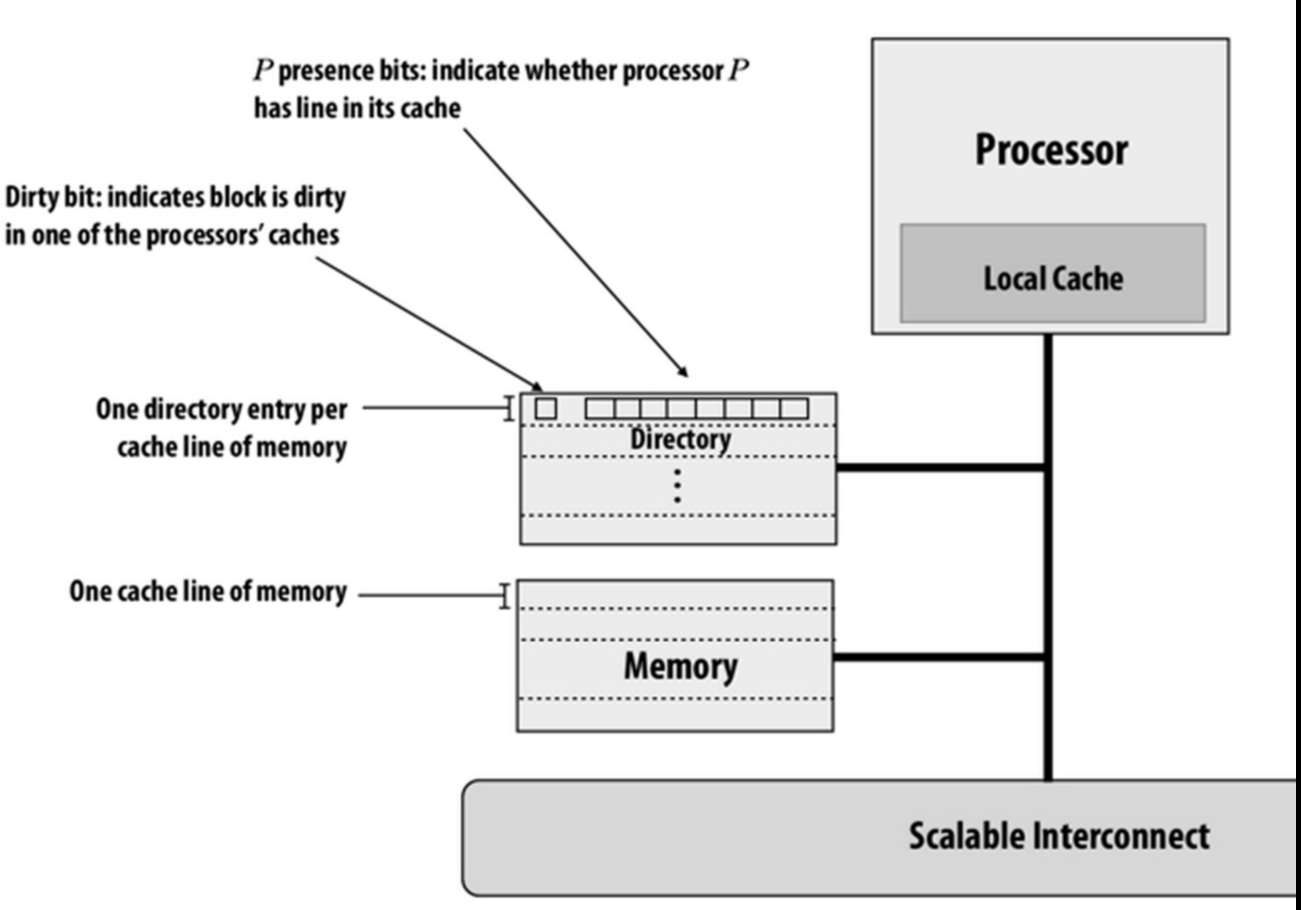
GPU Cache Coherence Challenges



- Challenge 2: Tracking in-flight requests
  - Significant % of L2

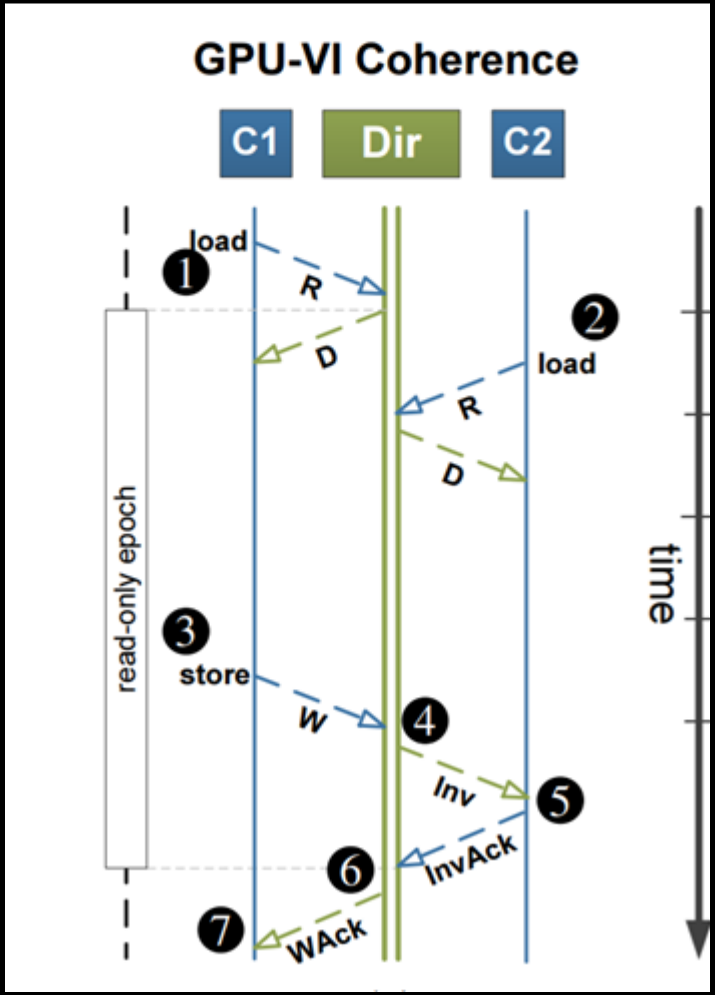
Background: Directory Protocol

- For each block: centralized "directory" for state in caches
- Directory is co-located with some global view of memory
- Requests are no longer seen by everyone
  - ***Writes are serialized through directory***

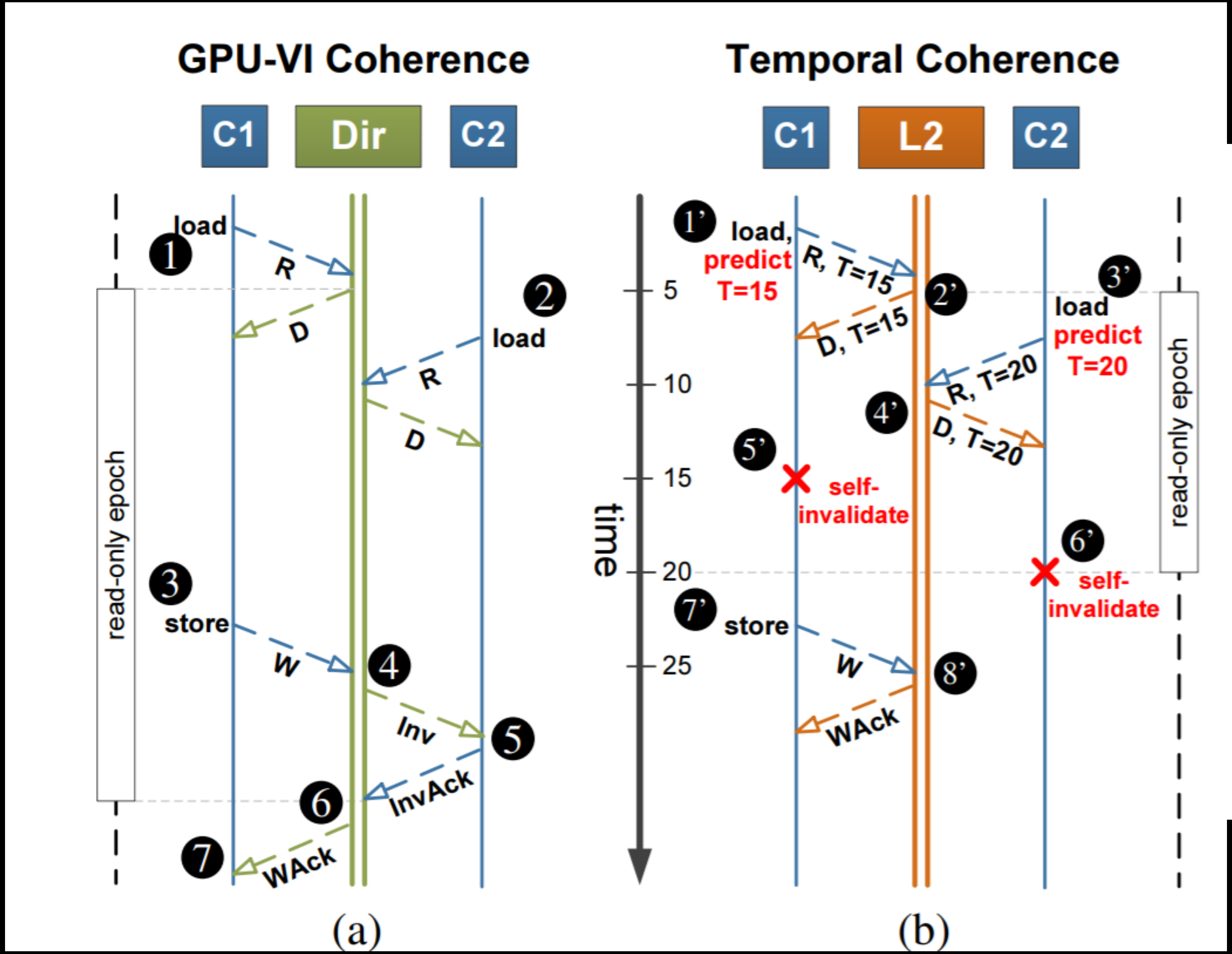

P presence bits: indicate whether processor P has line in its cache
Dirty bit: indicates block is dirty in one of the processors' caches
One directory entry per cache line of memory
Directory
One cache line of memory
Memory
Processor
Local Cache
Scalable Interconnect

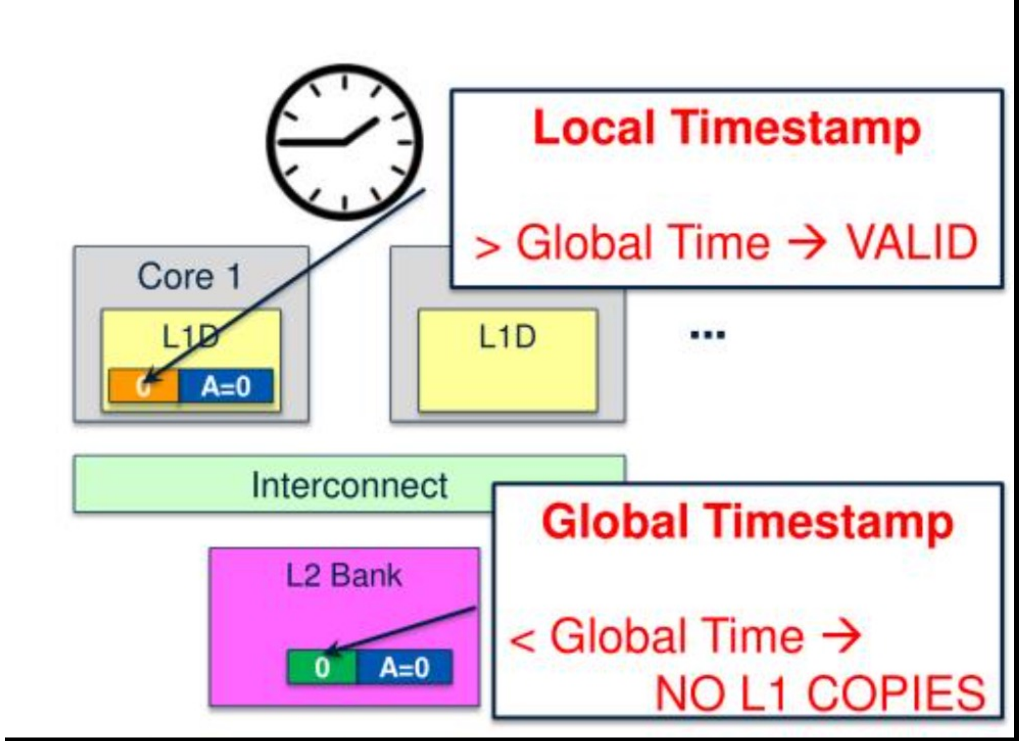
GPU-VI

- Directory-Based
  - Different from snoop-model
  - Global directory metadata at L2
- Two states
  - Valid
  - Invalid
- Writes invalidate other copies

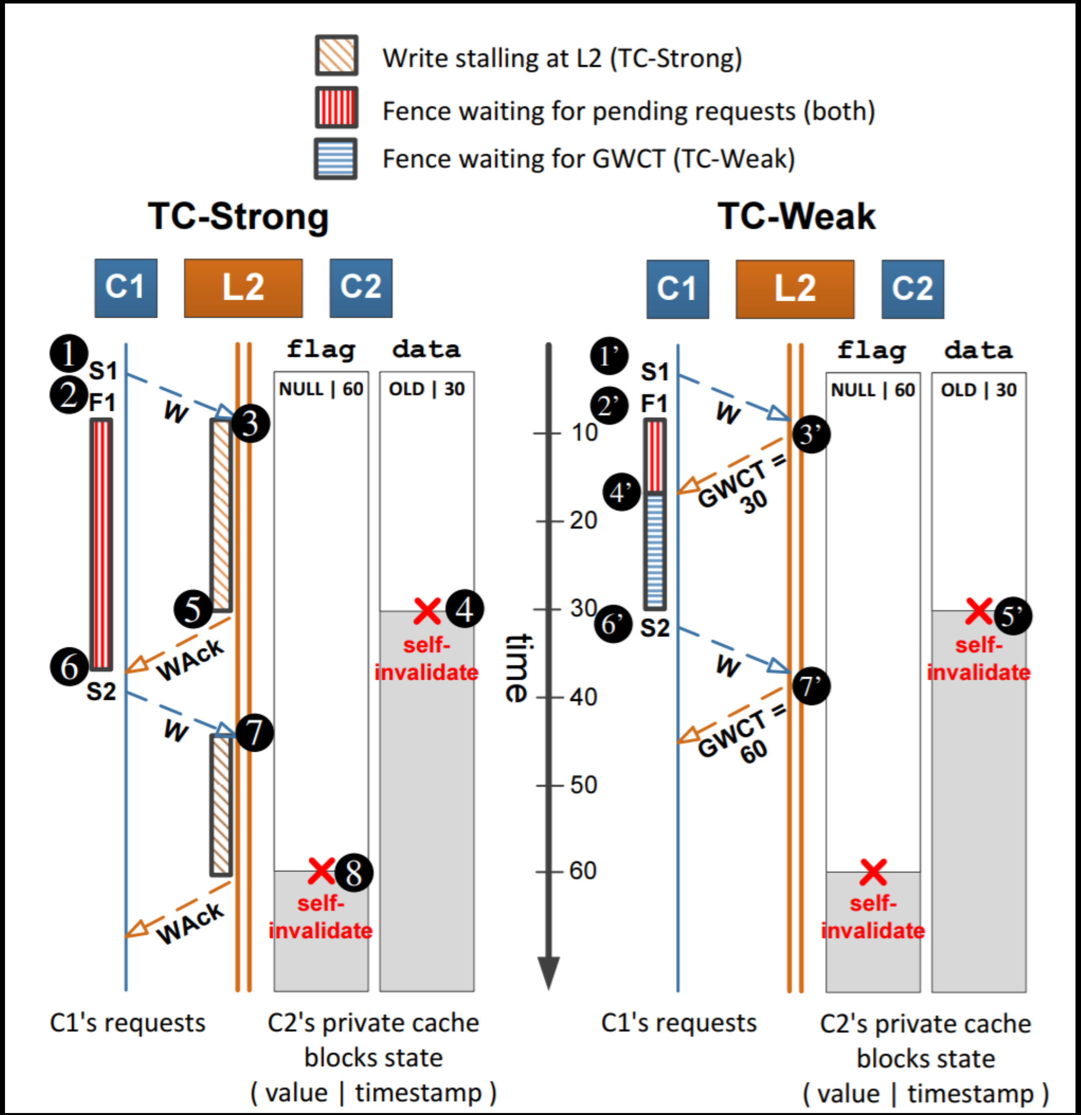


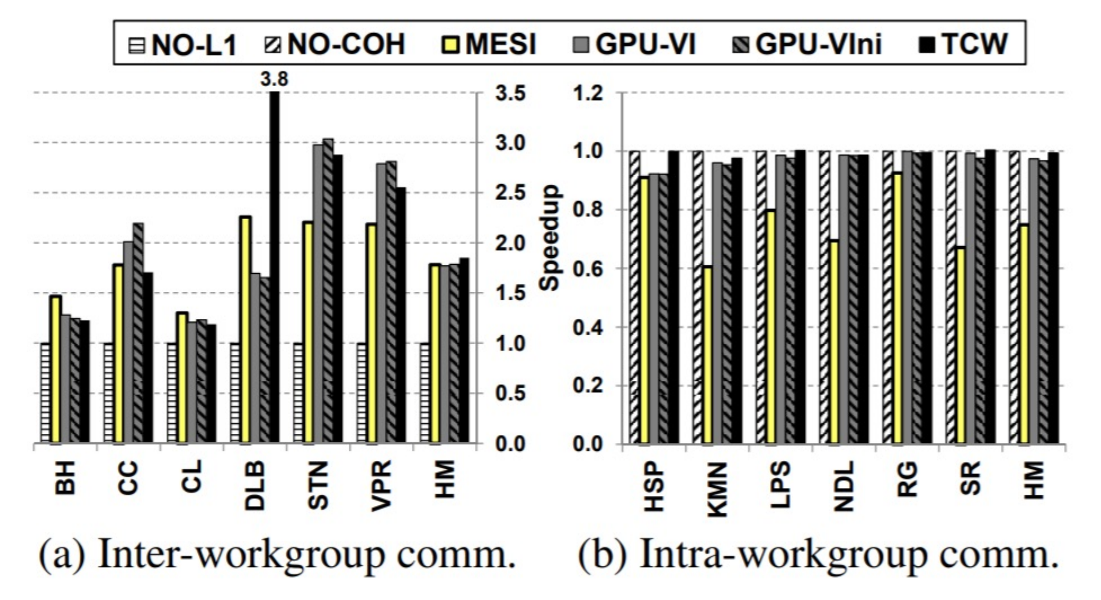
Temporal Coherence (TC)





TC-Strong vs TC-Weak


Write stalling at L2 (TC-Strong)
Fence waiting for pending requests (both)
Fence waiting for GWCT (TC-Weak)
TC-Strong
TC-Weak
C1
L2
C2
flag
data
NULL | 60
OLD | 30
S1
F1
S2
W
WAck
GWCT = 30
GWCT = 60
self-invalidate
time
10
20
30
40
50
60
C1's requests
C2's private cache blocks state (value | timestamp)



(a) Inter-workgroup comm. (b) Intra-workgroup comm.