

INTRODUCTION TO GPU ARCHITECTURE & PROGRAMMING

COMP4300/8300 PARALLEL SYSTEMS

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Australian
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University

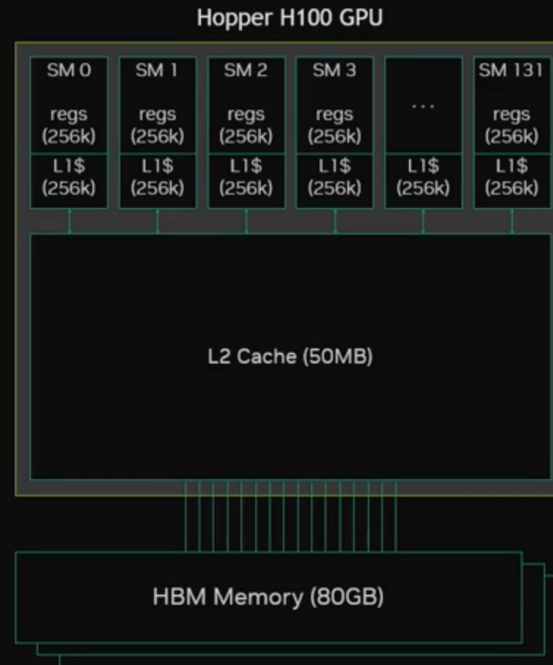
Logistics

- Attendance to the Lab sessions is highly encouraged. Most of the practical aspects of the programming models are covered in the Labs.

Introduction to the key concepts of the CUDA Programming Model

The H100 Architecture

It's very, very parallel



Hopper architecture

132 SMs

64 warps/SM = 8,448 warps total

32 threads/warp = 270,336 threads total

4-way superscalar

4-way * 132 SMs = 528 active warps

4 warps * 132 SMs = 33,792 live threads

For typical-size block of 256 threads

256 threads = 8 warps → max 8 blocks / SM

8 blocks * 132 SMs = 1,056 concurrent blocks

- Programming for the GPU is not an extension of CPU programming
- GPU hardware is changing rapidly, ever more *massive* parallelism
- You need to understand the scale of a problem that a GPU can address

GPU and the CUDA Programming Model

Software

GPU



Thread

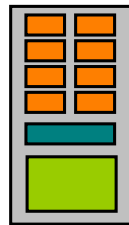


CUDA Core

Threads are executed by cuda core.
A *warp is 32 threads* that are executed simultaneously.



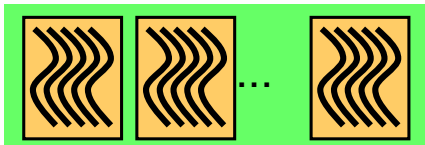
Thread Block



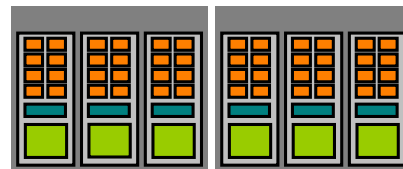
SM

Multiple warps can make up a thread block.
Thread blocks are executed on a *Streaming Multiprocessor*.

Several concurrent thread blocks can reside on one multiprocessor - limited by multiprocessor resources



Grid

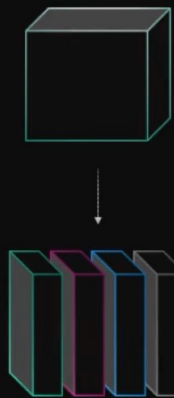


Device

A *kernel* is launched as a grid of thread blocks



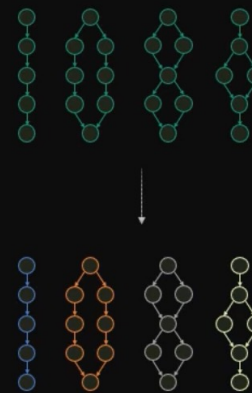
There Are Many Types of Parallelism Patterns



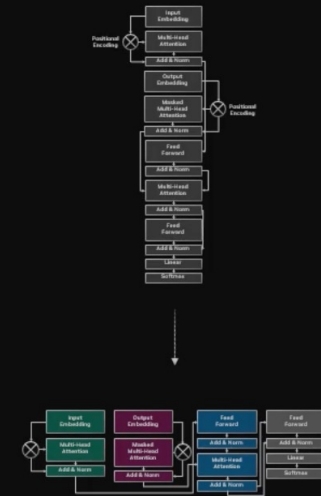
Tensor Parallelism
Divide data along **dimensions** across processors



Data Parallelism
Divide individual **elements** across processors



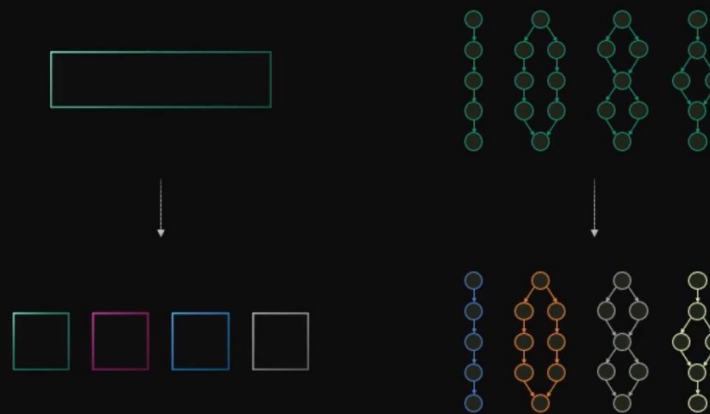
Task Parallelism
Divide independent **workflows** across processors



Model Parallelism
Divide sequences of **operations** across processors

➤ There are lots of different types of parallelism that are referred to in the literature

But Really There Are Only Two Types of Parallelism Patterns



Data Parallelism

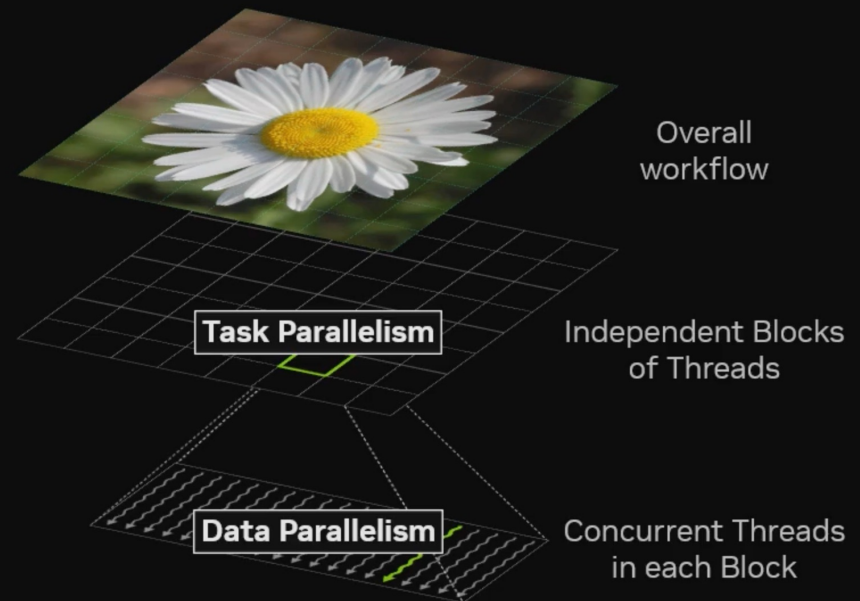
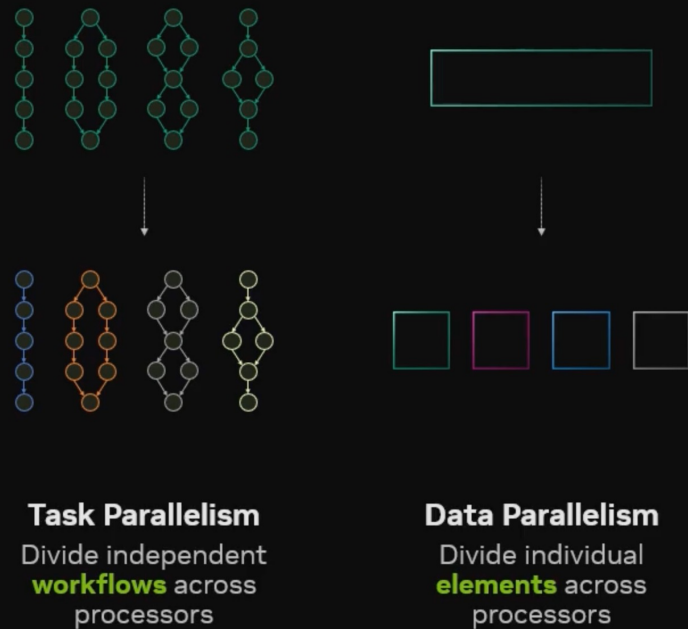
Divide individual
elements across
processors

Task Parallelism

Divide independent
workflows across
processors

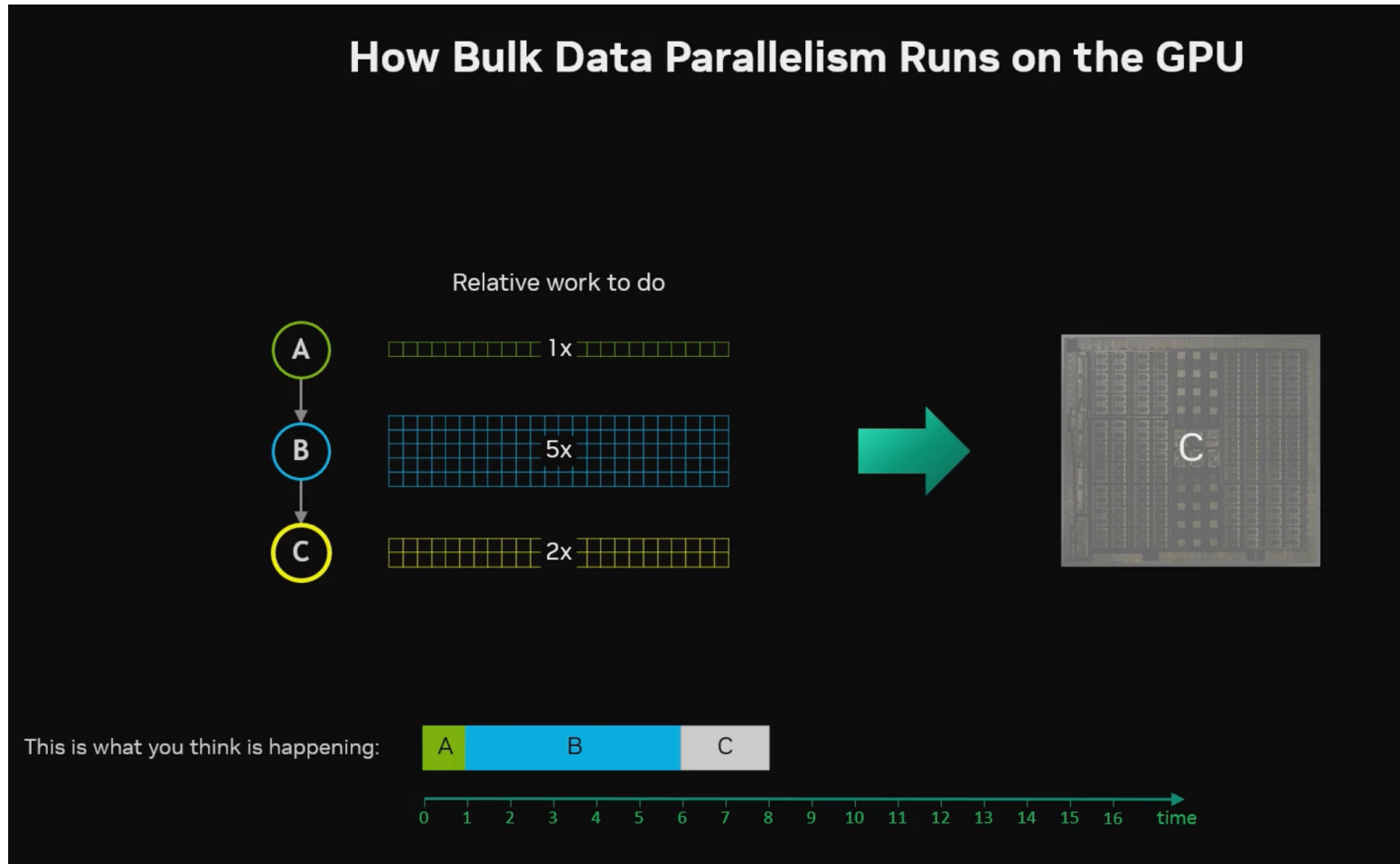
- The reality for the GPU is that there are two fundamental types of parallelism
- Also referred too as fine- and coarse-grained parallelism

CUDA is Both: Data Parallelism Inside Task Parallelism



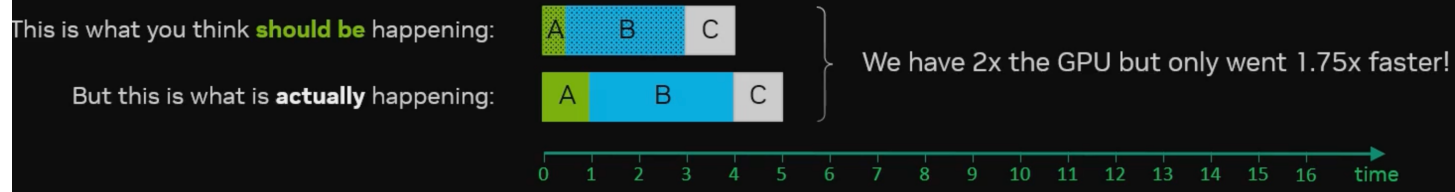
- To achieve high performance on the GPU you need to address both types of parallelism
- If you address only one you will see only a fraction of the possible performance

How Bulk Data Parallelism Runs on the GPU



- Task A → Task B → Task C (Task B can only start after Task A completes)
- We must understand how the hardware implements parallelism
- Future lectures will delve in to this in more detail

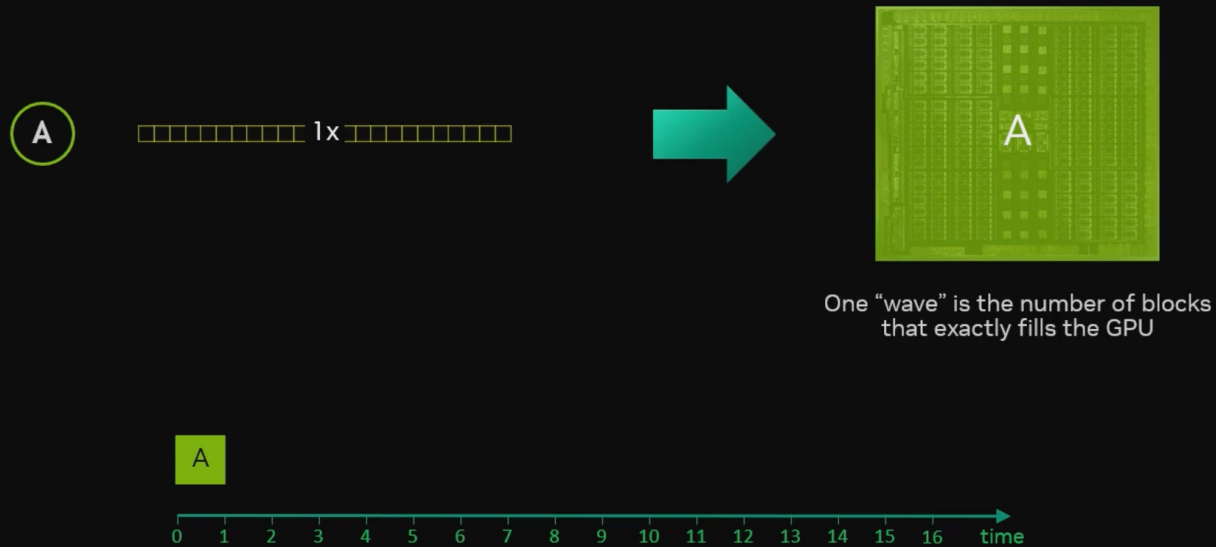
Bulk Per-Kernel Data Parallelism



- What happens when we double the size or number of GPUs?
- Task A and the last step of B fit in half the expanded GPU
- For a fixed problem size that fits in one GPU we do not get a 2x gain

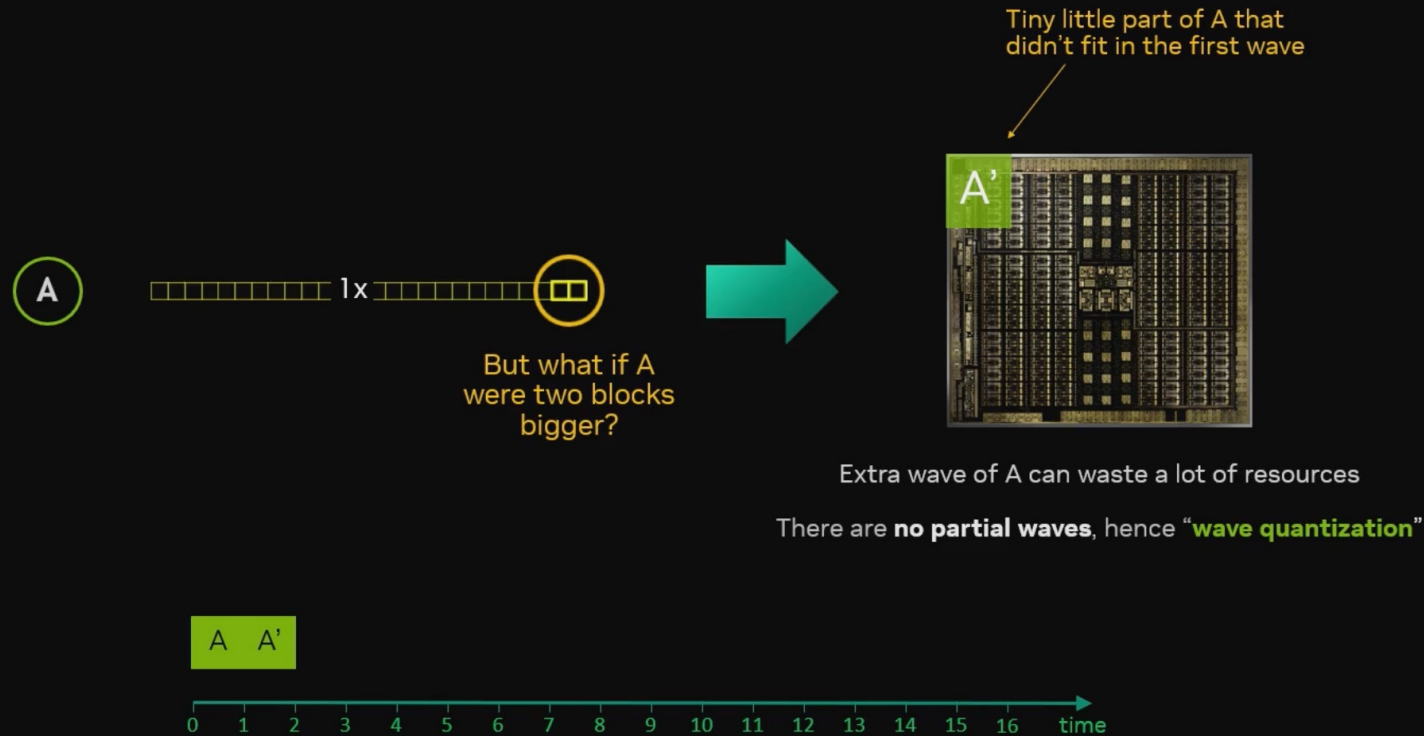


The Scourge of the Ninja: Wave Quantization



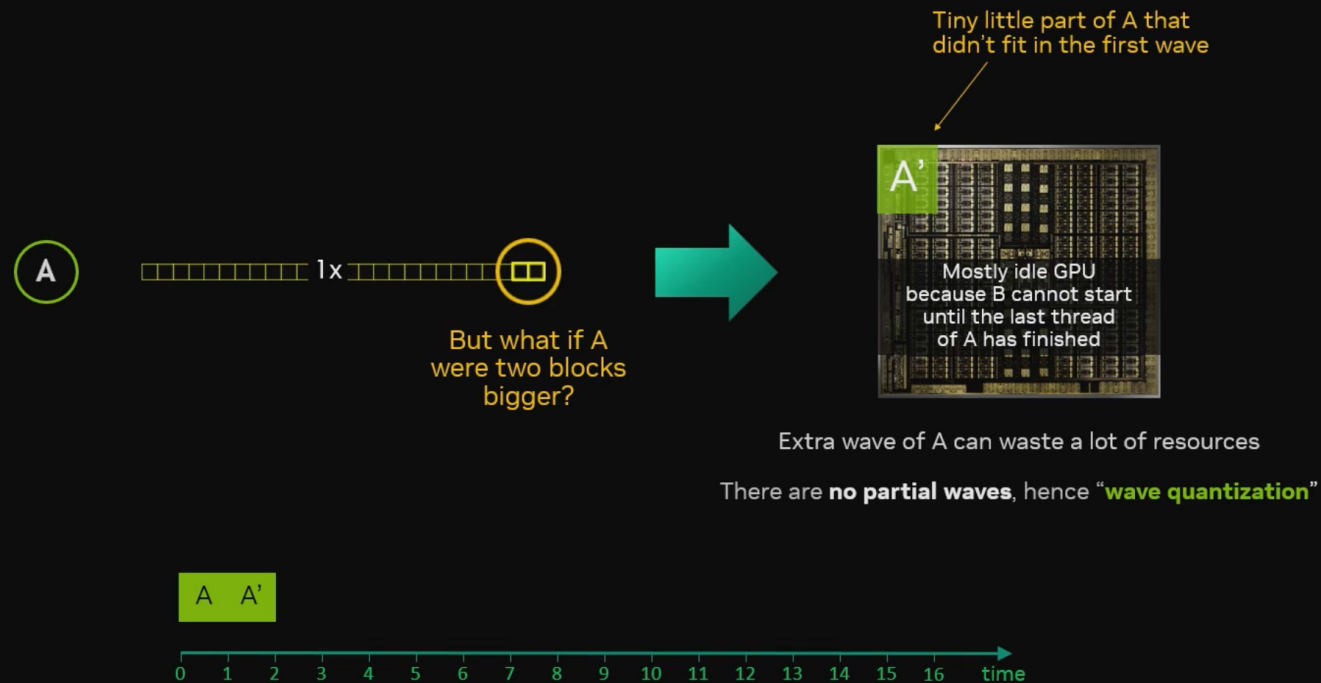
- A Wave is the ideal number of blocks that fills a GPU
- Wave quantization is a key challenge

The Scourge of the Ninja: Wave Quantization



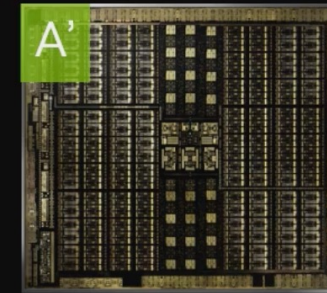
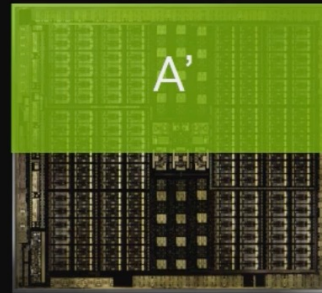
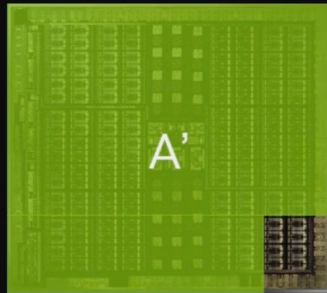
- Here is an extreme example of the problem of wave quantization
- The problem size is just a little larger than a wave
- Lots of resources will be wasted

The Scourge of the Ninja: Wave Quantization



- Here is an extreme example of the problem of wave quantization
- The problem is just a little larger than a wave (2 blocks)
- Most of the GPU will be idle when running A' , Task B cannot start

The Scourge of the Ninja: Wave Quantization



Unless you've intentionally sized your grid launch to be one wave, the quantization effect will on average be random

Lose ~50% (+/- 50%) of efficiency on the final wave

- Wave quantization Statistics: on average you will lose 50% of the performance
- Without planning, you may lose much more performance

Yes, More Waves Mitigates This, But Bigger GPUs = Fewer Waves



Kepler GK110
Full Chip
15 SMs

Hopper H100 Full Chip

132 SMs

2012: Kepler GK110 architecture = **15 SMs**

2022: Hopper H100 architecture = **132 SMs**

9x SM count increase in 10 years

So a kernel which ran in 10 waves on GK110
now runs in 1.1 waves on H100

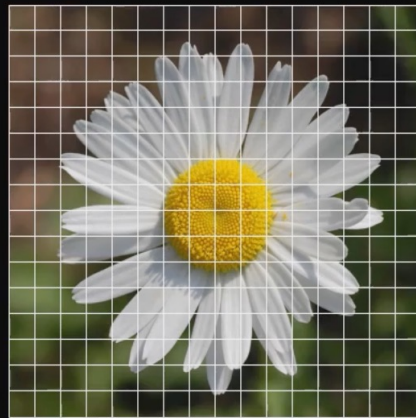
We went from **10% overhead** from wave
quantization **to 50% overhead**

That is: **you could be running twice as fast**

- More waves can reduce the impact of wave quantization –
- original design assumption was for 100 waves
- The dramatic increase in the size of GPUs (the number of SMs) has reduced the number of waves for a fixed workload and increased the overhead

Ninjas Use Single-Wave Kernels

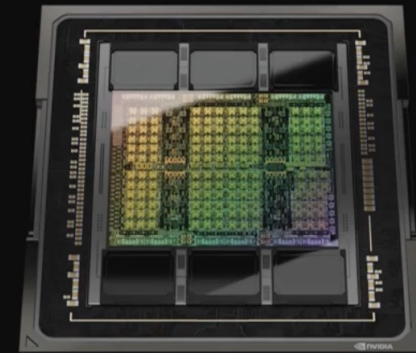
Don't map threads to data; map data to threads



1024x1024 image divided into 16x16 tiles

Image suggests 16x16 tiles = 256 blocks

Hardware suggests $\sqrt{132}$ SMs = 11.5 x 11.5 tiles

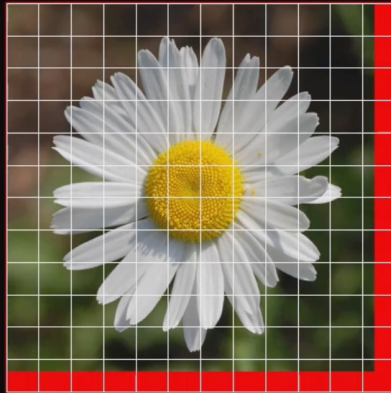


H100 with 132 SMs

- Natural assumption is to map threads to data
- Correct mapping is the reverse - data to threads
- Divide your tasks across 132 SMs

Ninjas Use Single-Wave Kernels

Don't map threads to data; map data to threads



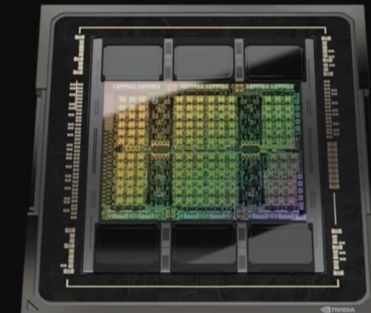
1024x1024 image divided into **12x12 tiles**

Red edge indicates where naïve rounding leaves imbalanced workload(*)

Image suggests 16x16 tiles = 256 blocks

Hardware suggests $\sqrt{132}$ SMs = 11.5 x 11.5 tiles

Where possible, always map data to threads

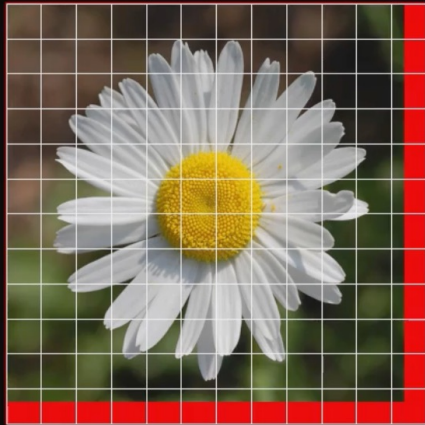


H100 with 132 SMs

(*) For better load balancing alternate tile sizes of 11 and 12, although this increases complexity and may be impossible depending on application

➤ The consequence of poor mapping is that we have an imbalanced workload

Not a Silver Bullet



Single-wave kernels are better in almost all cases than non-integer-wave

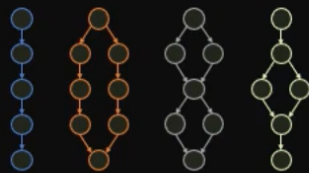
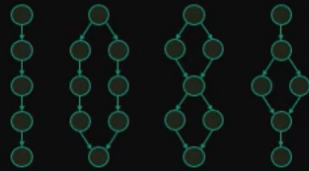
Similar to “grid-stride loop” pattern frequently taught for CUDA

But there are a number of problems which may prevent use:

1. Some algorithms require specific size of tiling
2. Must account for GPUs of different sizes (e.g. RTX-3090/80/70/60)
3. Increase in code complexity by having non-constant tile size
4. Load imbalance remains; may be no better than an extra partial wave

- The optimal programming approach is to produce single-wave kernels
- This will not always be possible, watch out for load imbalance
- Bulk data parallelism will not typically achieve 100% efficiency





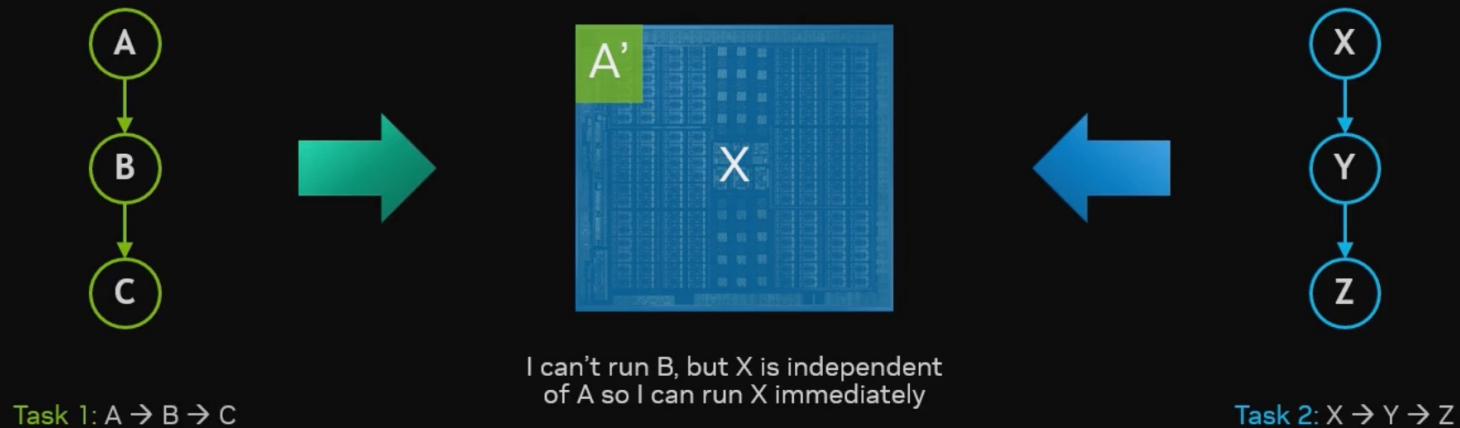
Task Parallelism
Divide independent
workflows across
processors

**How about the other
kind of parallelism?**

- Data parallelism alone will rarely be sufficient to achieve top performance
- Task parallelism will help, but it is harder to implement



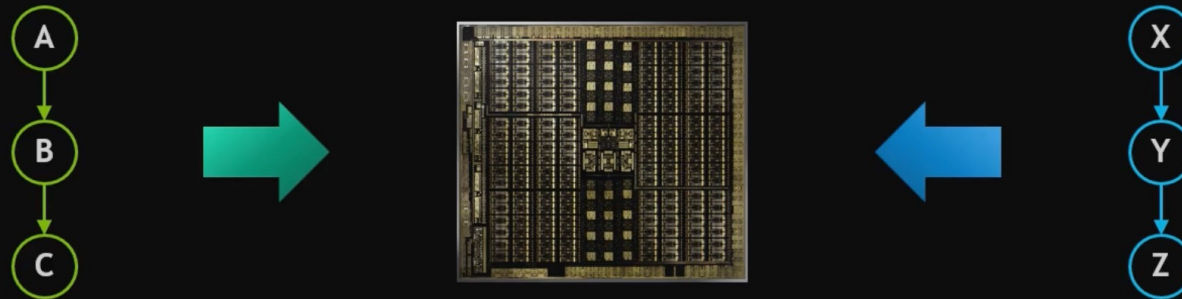
So Why Does Task Parallelism Help?



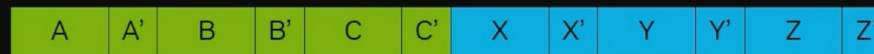
- Task A does not fill the GPU and Task B cannot run until A finishes
- Task X is independent of Task A, so Task X can now fill the GPU

So Why Does Task Parallelism Help?

But ABC runs faster **in parallel** with XYZ than ABC+XYZ would run sequentially



Two independent tasks in series:



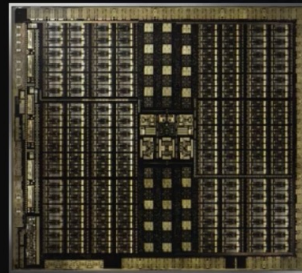
Are slower than two tasks in parallel:



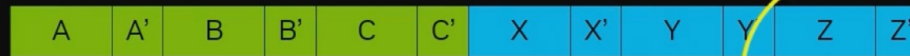
- CUDA streams – concurrent execution
- Stream = A sequence of operations that execute in issue-order on the GPU
- CUDA operations from different streams may be interleaved

So Why Does Task Parallelism Help?

But ABC runs faster **in parallel** with XYZ than ABC+XYZ would run sequentially



Two independent tasks in series:



But tasks 1 & 2 complete sooner overall with higher **throughput**

Are slower than two tasks in parallel:

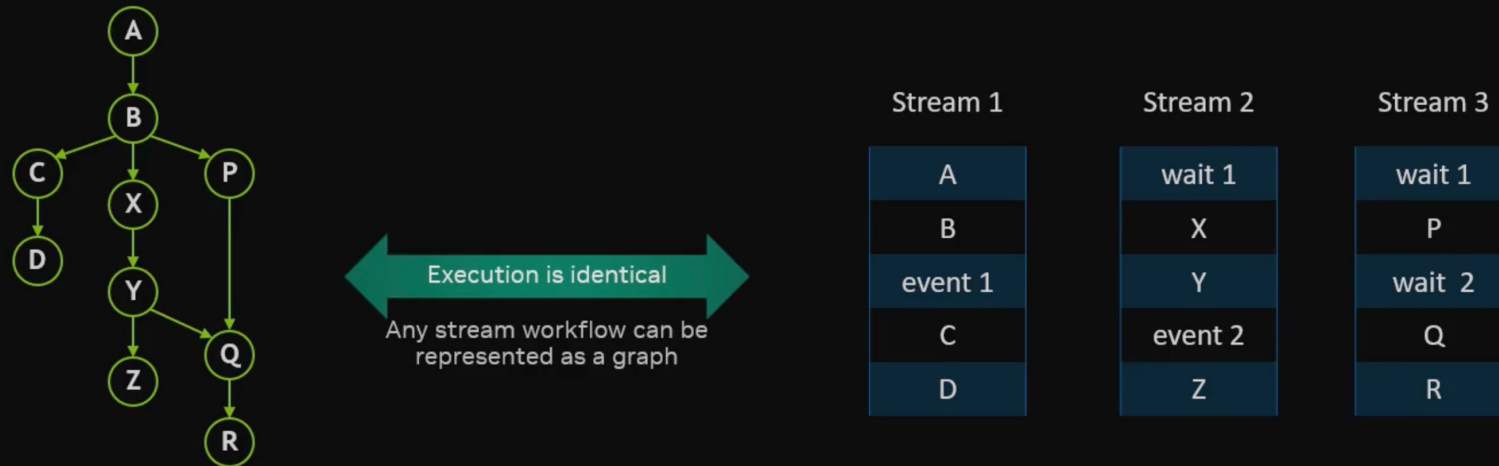


Task ABC experiences longer **latency**

➤ Throughput is faster with task parallelism

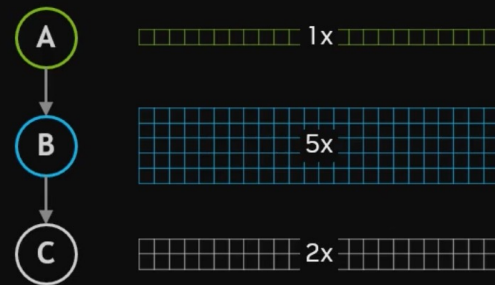


I Can Turn It All Into A CUDA Graph



- Complex task parallelism can be represented in a CUDA graph
- A CUDA graph enables multiple GPU operations to be launched through a single CPU operation
- Build and launch CUDA graphs

But What If I **DON'T** Conveniently Have Independent Work To Do?

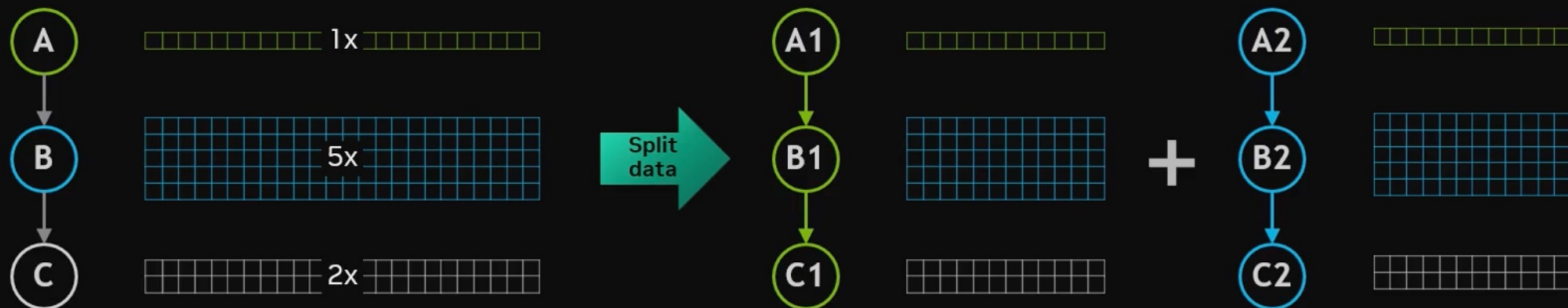


How do I create task parallelism when there's only one task?

- Not all problems you may encounter can be divided into multiple independent tasks ...

The Obvious Approach: Split The Data In Two

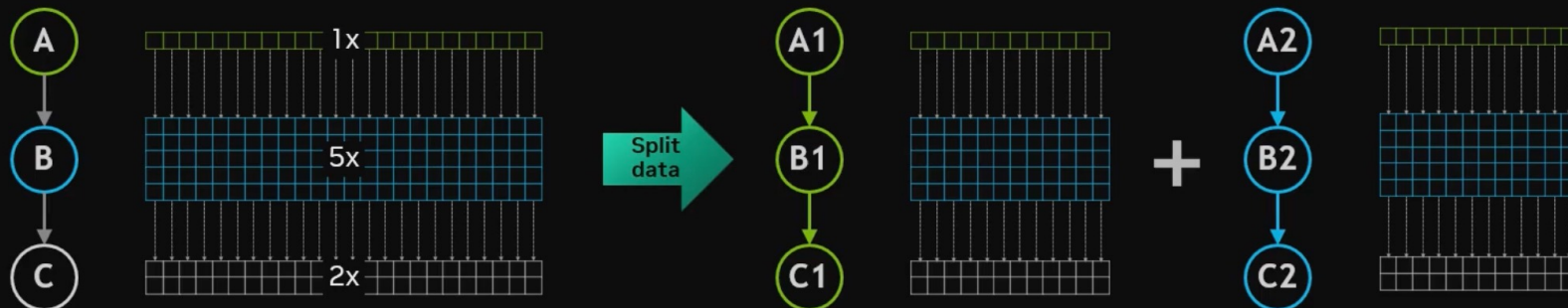
Also known as “Pipeline Parallelism” – yet another type of parallelism which is really just task parallelism



- Pipeline parallelism allows you to create and take advantage of parallel tasks

Easy For Elementwise Programs

Programs never are entirely elementwise, but splitting the kernels which are will always win a little



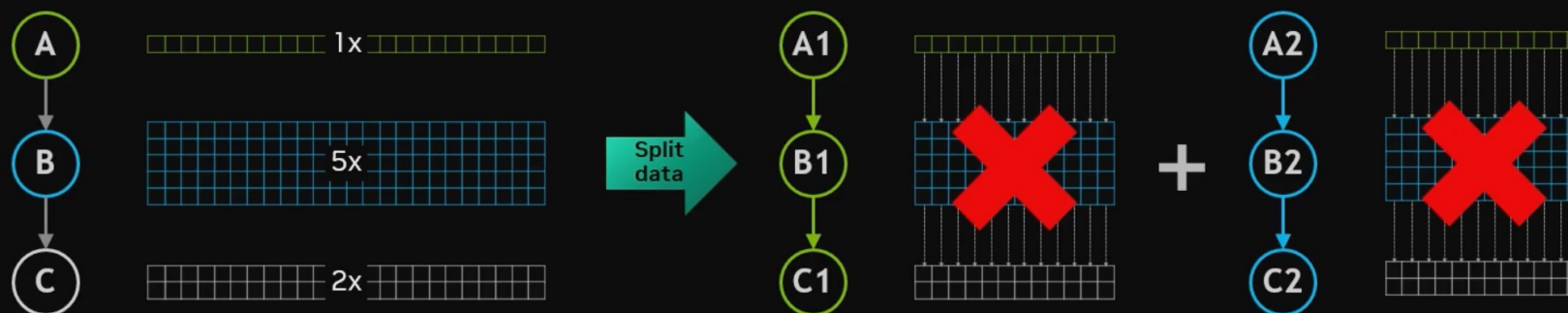
```
void daxpy(int n, double alpha, double *x, double *y)
{
    for( i = 0; i < n; i++ )
    {
        y[i] = alpha * x[i] + y[i];
    }
}
```

Elementwise "ax plus y" vector scale-and-addition

- Always take advantage of elementwise kernels if they are greater than one wave

But The Real World Is Almost Never Elementwise

However, it is very often localised, like a stencil, instead of needing random access to all data



Simple split obviously does not work for stencils



Example: 1D Stencil, radix-5

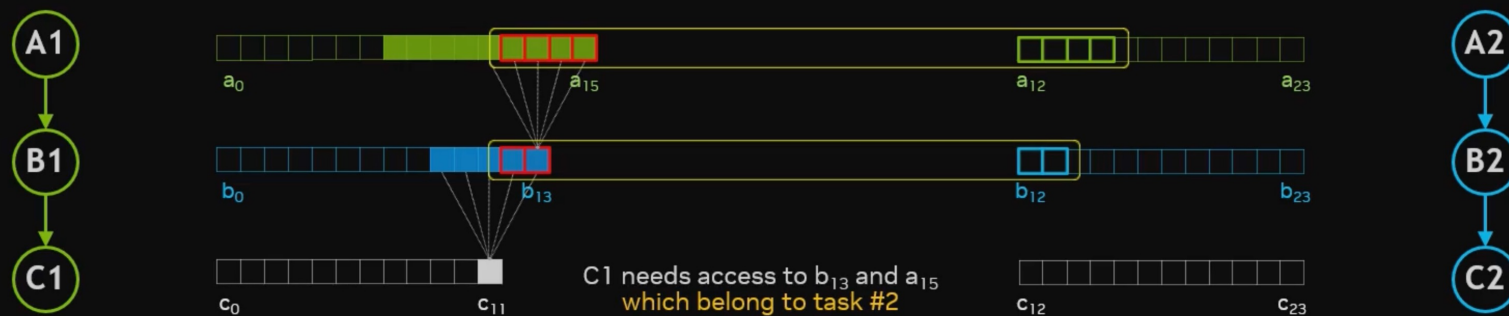
- Elementwise operations are a rare opportunity
- Convolutions are an example where surrounding data is required

... Create Dependencies Between Tasks 1 & 2

This makes it very hard to co-schedule sub-portions of A, B and C



Example: 1D Stencil, radix-5



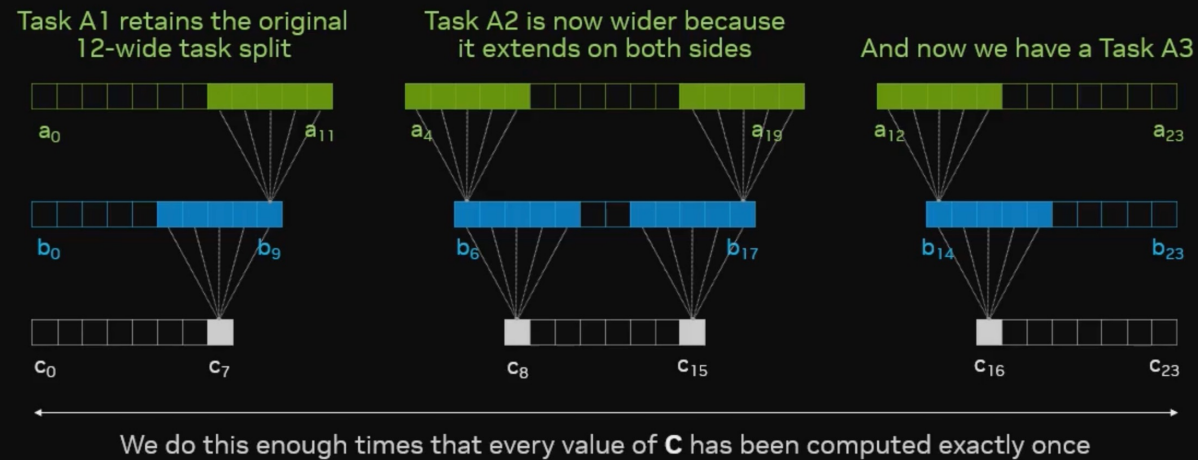
C1 needs access to b_{13} and a_{15}
which belong to task #2

B1 needs to wait until A2 has done its work
C1 has to wait until B2 has done its work
But B2 has to wait until A1 has done its work
... and this is why pipeline parallelism is hard

- Pipeline parallelism by splitting tasks can lead to chained dependencies and undermine any performance gains

So Instead, Reduce the Sizes of B & C

Of course, now you need more than two tasks



- Avoid the dependencies by reducing the size of dependent tasks (B&C)
- Reducing the size of tasks increases the number of tasks

Cost Of Redundant Computation Depends On Data Size

because it's common that each sub-task A1, A2, A3 operates over many data elements

Often, recomputing something is faster than writing it out to memory and then reading it back in

Typically arrays are large so overlap is a small fraction,
but redundancy grows with each dependent kernel



- This approach also introduces redundant computation at the edges
- The impact of redundant computation can be small as a few % over large arrays



The Real Problem: All-to-All Algorithms

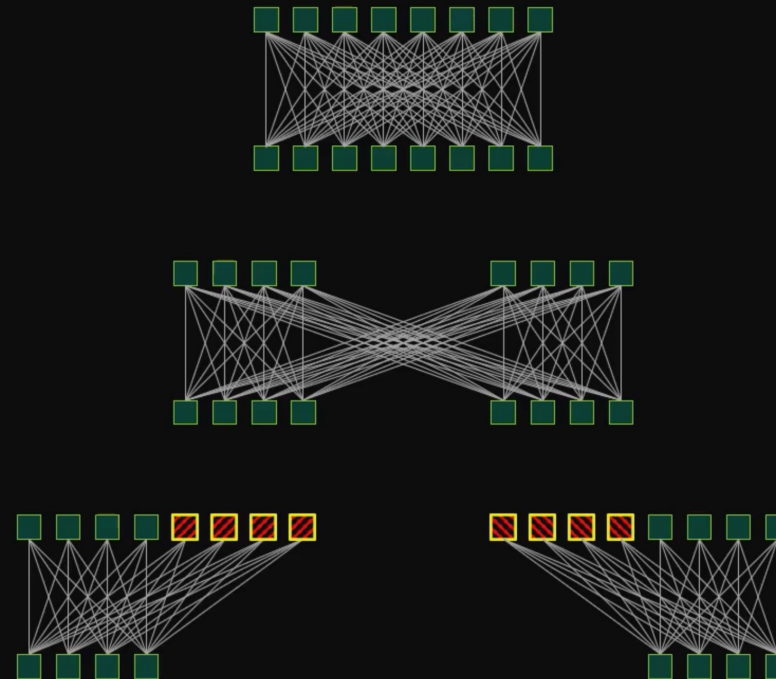
For example: sorting, fourier transforms, and unfortunately many other useful things



- All to all algorithms require extensive communication and synchronization
- Memory usage and bandwidth can limit performance

All-to-All Algorithms Break Pipelining

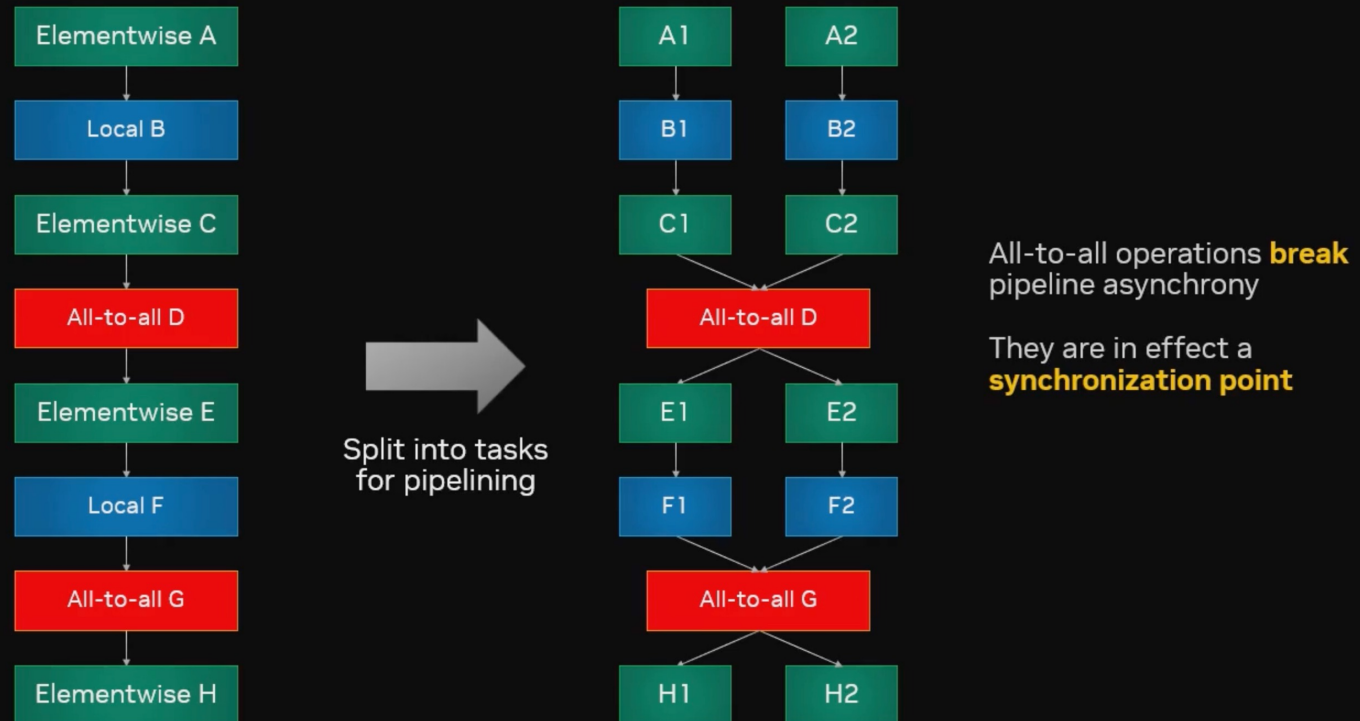
I always end up with 100% redundant computation, so there's no point splitting the operation



- The pipelining solution delivers no benefits in this case
- You will often be working with all-to-all algorithms

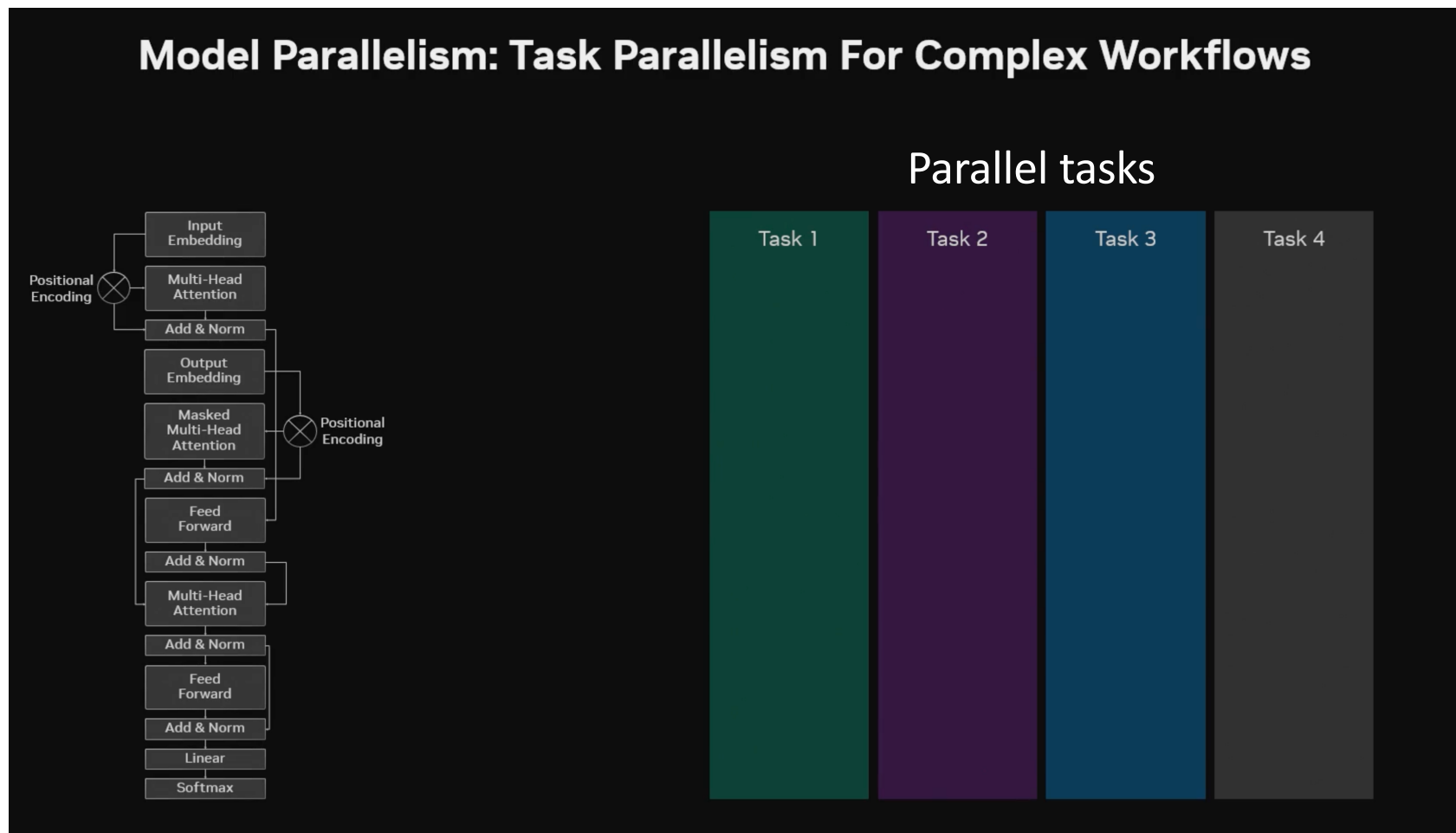
All-to-All Algorithms Break Pipelining

I can run until I hit an all-to-all operation, but then I need to sync across the whole workload



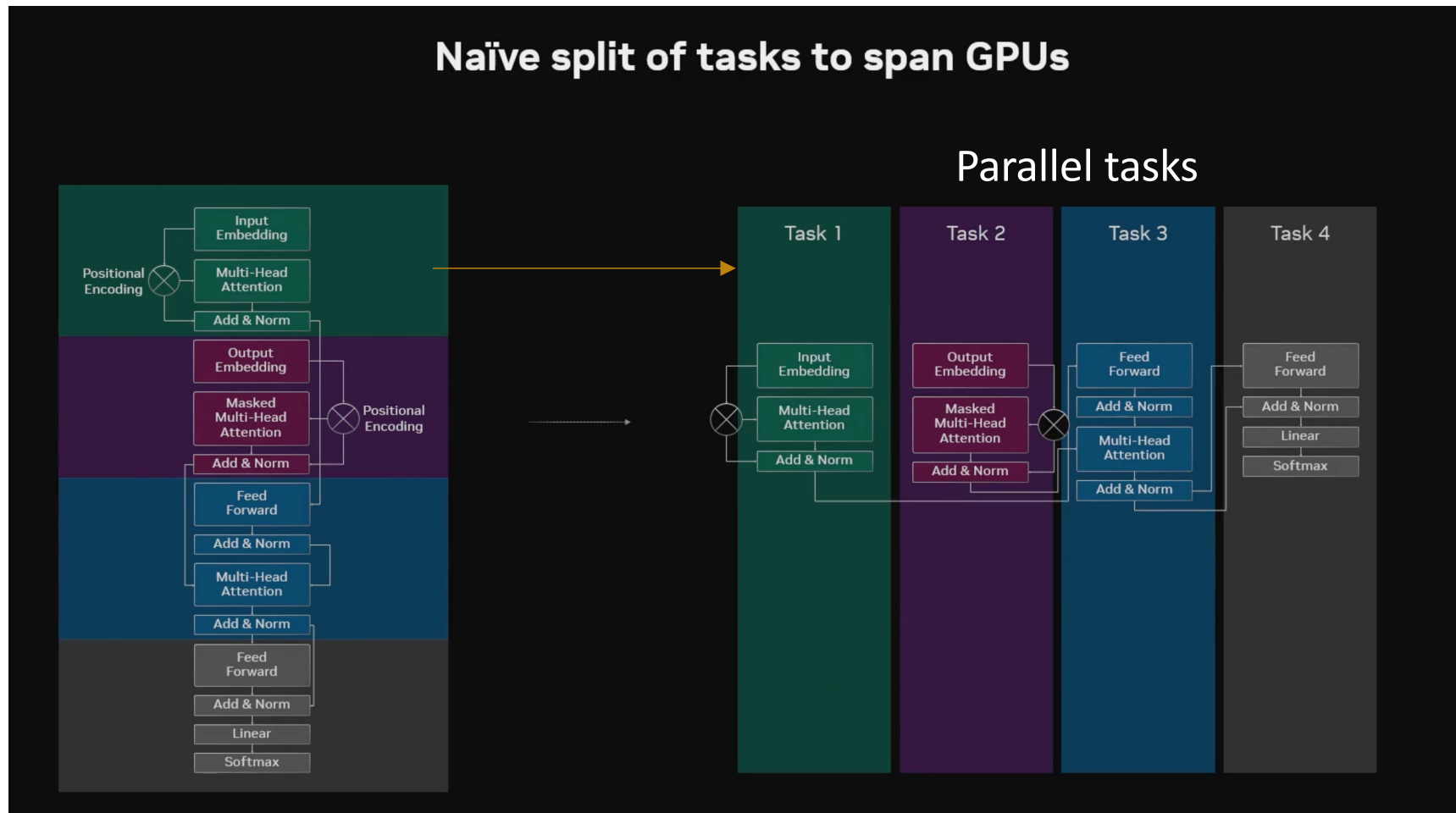
- You may be able to break chunks of your problem into pipelines
- All-to-all will act as a synchronization point

Model Parallelism: Task Parallelism For Complex Workflows



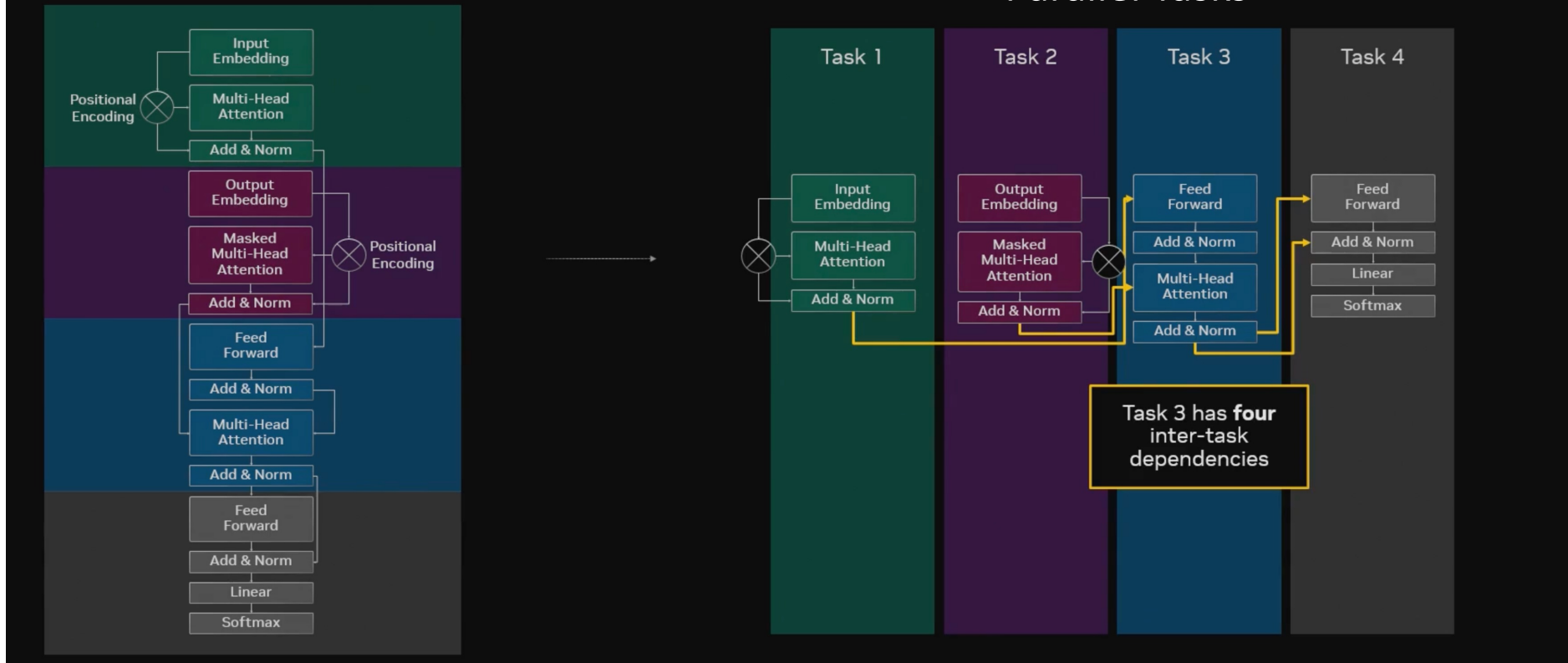
- Model parallelism divides a model into separate tasks
- The example is a multi-layer deep learning model

Naïve split of tasks to span GPUs



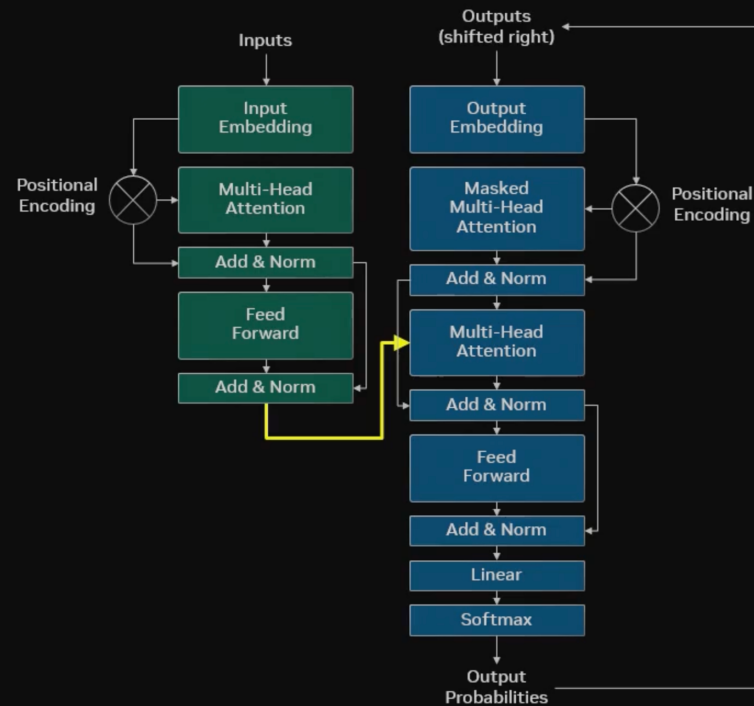
- We can divide the model into separate parts
- This is a form of task parallelism for complex workflows

Naïve split of tasks to span GPUs



- A simple split may not work well if you ignore dependencies between tasks
- In this example Task 3 will act as a bottleneck

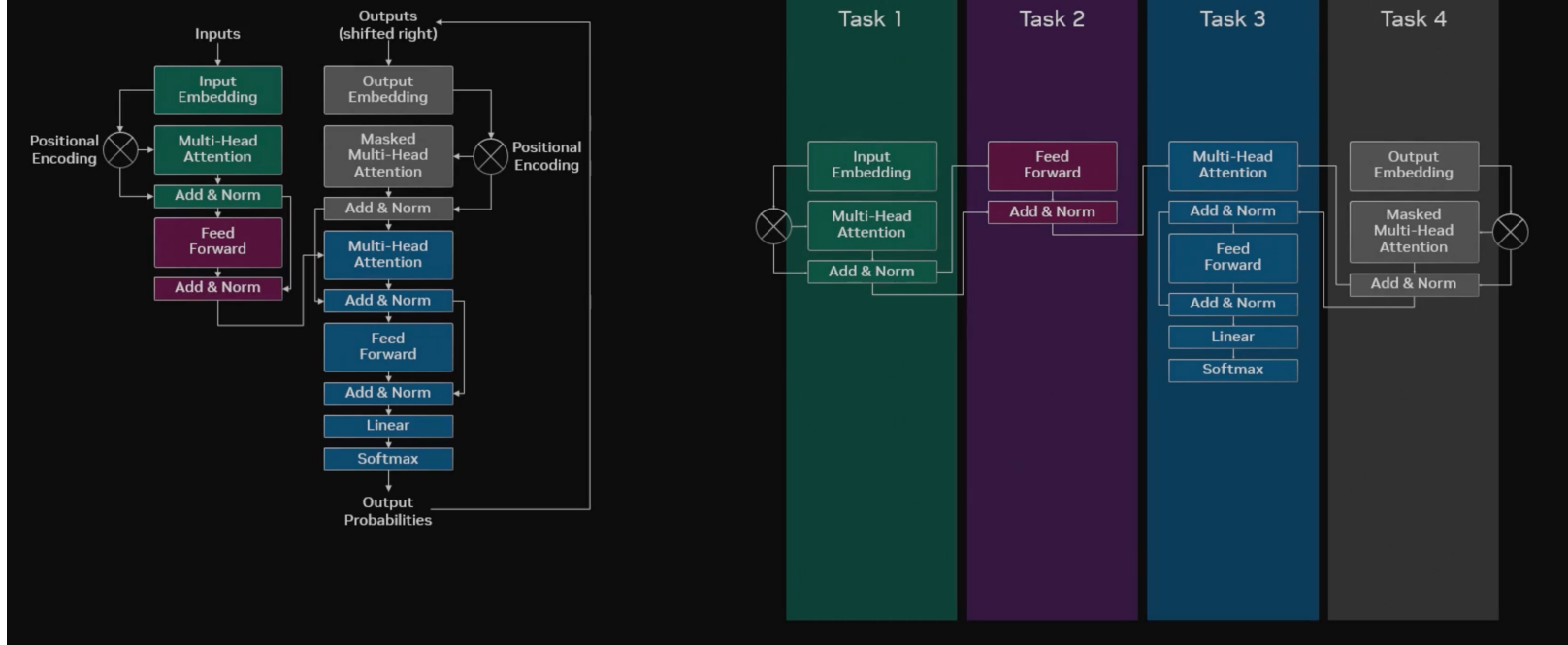
Unbalanced Tasks Are Often Much Cheaper Than Over-Synchronization



- Reducing synchronization can be more efficient than attempting to balance the task workload

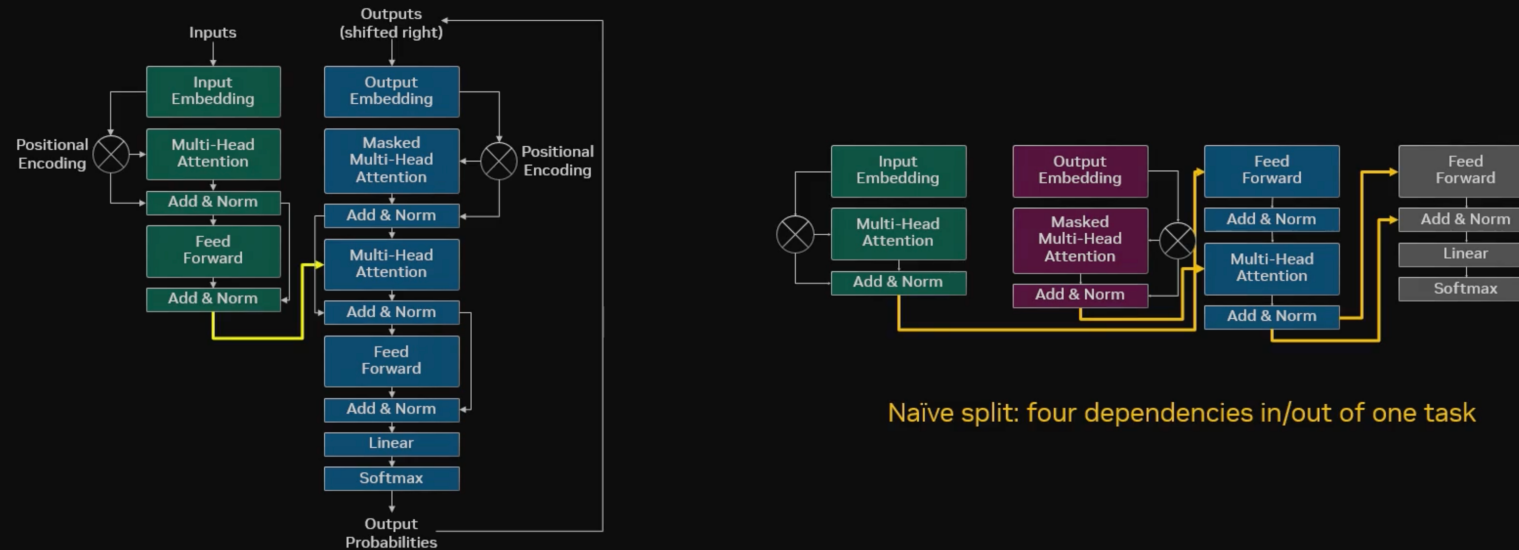
And If You Need To Split More, Do It Hierarchically

Parallel tasks



- Once you have identified a split that minimizes synchronization you can then further split based on that hierarchy

In Other Words, Split The Model To Minimise Inter-Task Sync

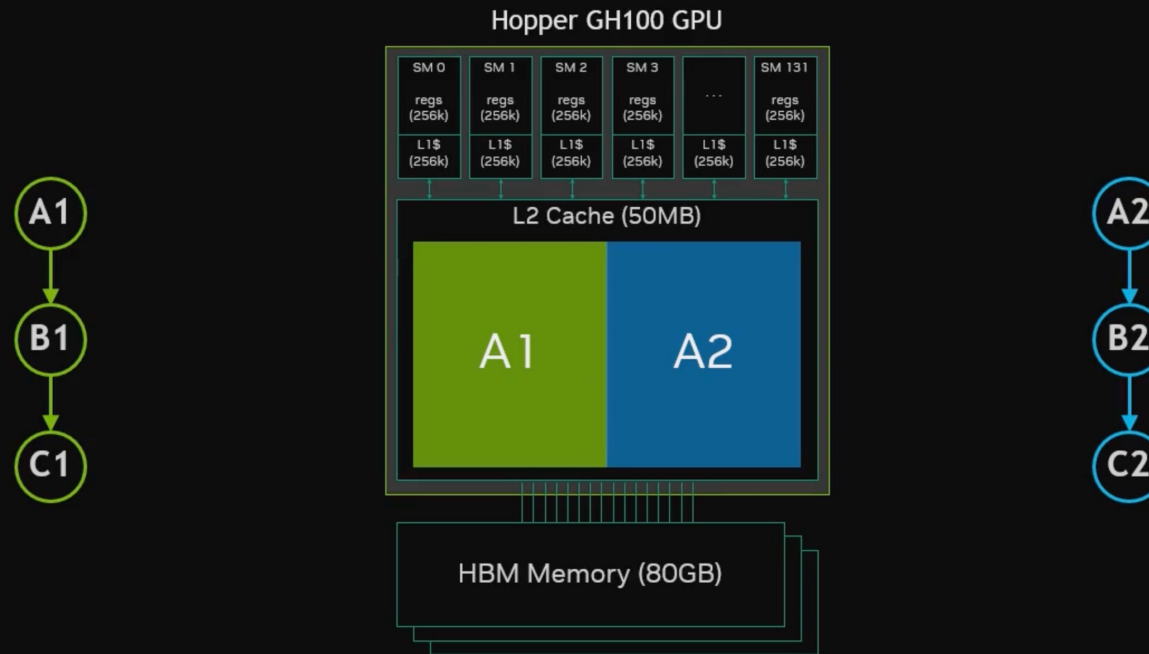


Producer/Consumer split: one dependency

- A key goal when implementing model parallelism is to minimize inter-task synchronization i.e. Reduce waiting time and keep the GPU busy
- This applies to task parallelism in general

A Big Problem With Task Parallelism: Thrashing The Cache

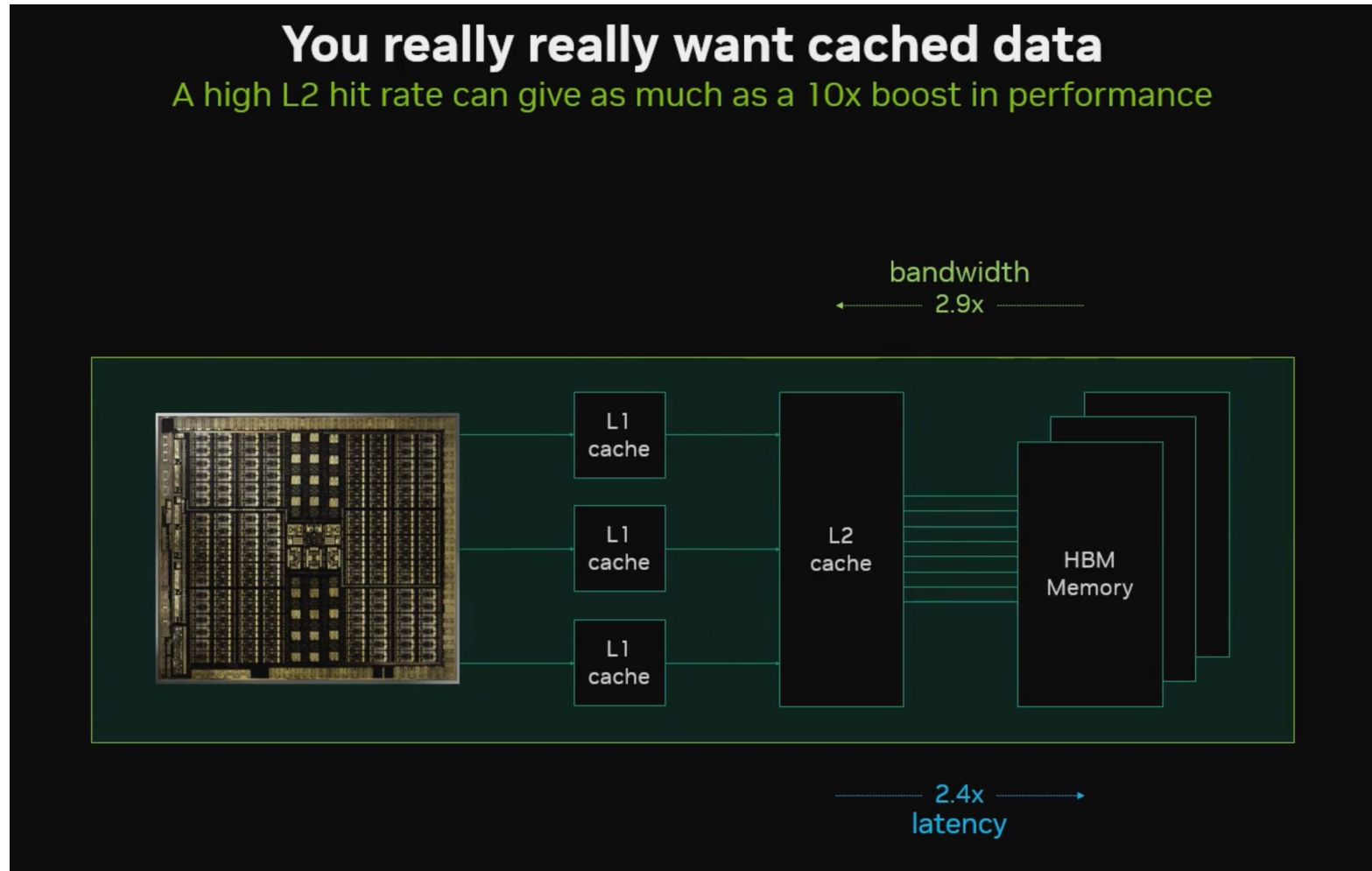
Each task sees a proportionately smaller cache because by definition they are working on different data



- As with many compute architectures, GPU memory is a critical resource
- The more tasks the less cache available, the more cache misses that undermine efficiency

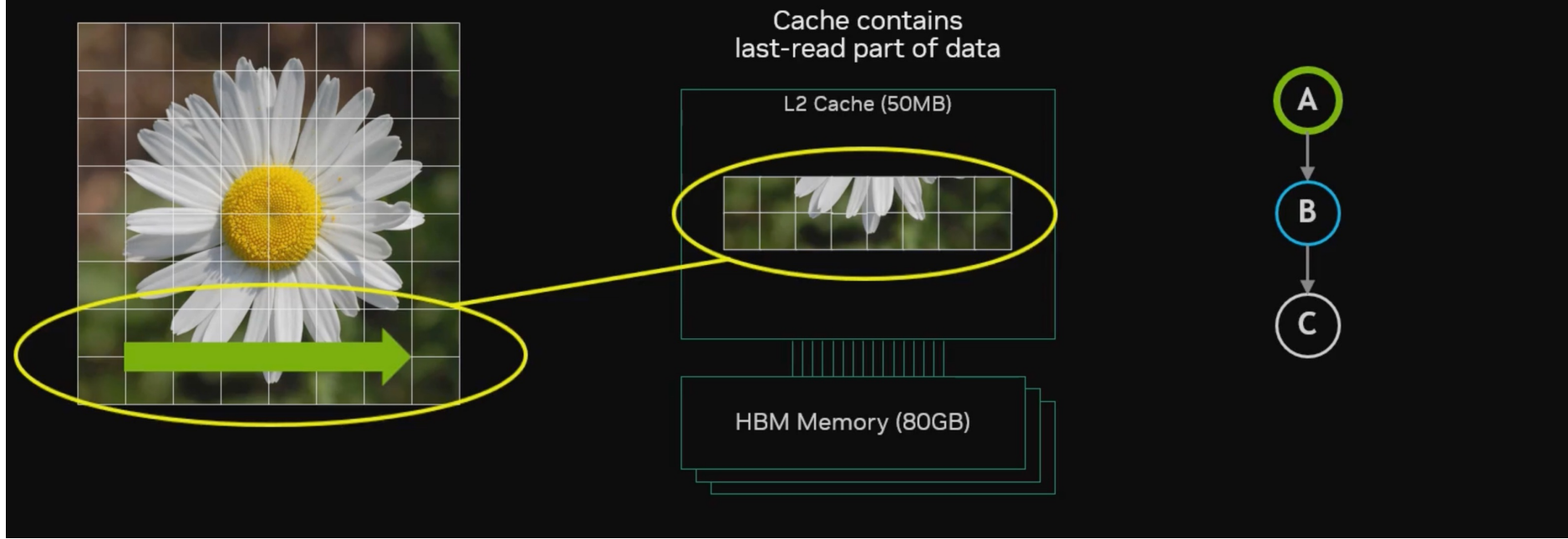
You really really want cached data

A high L2 hit rate can give as much as a 10x boost in performance



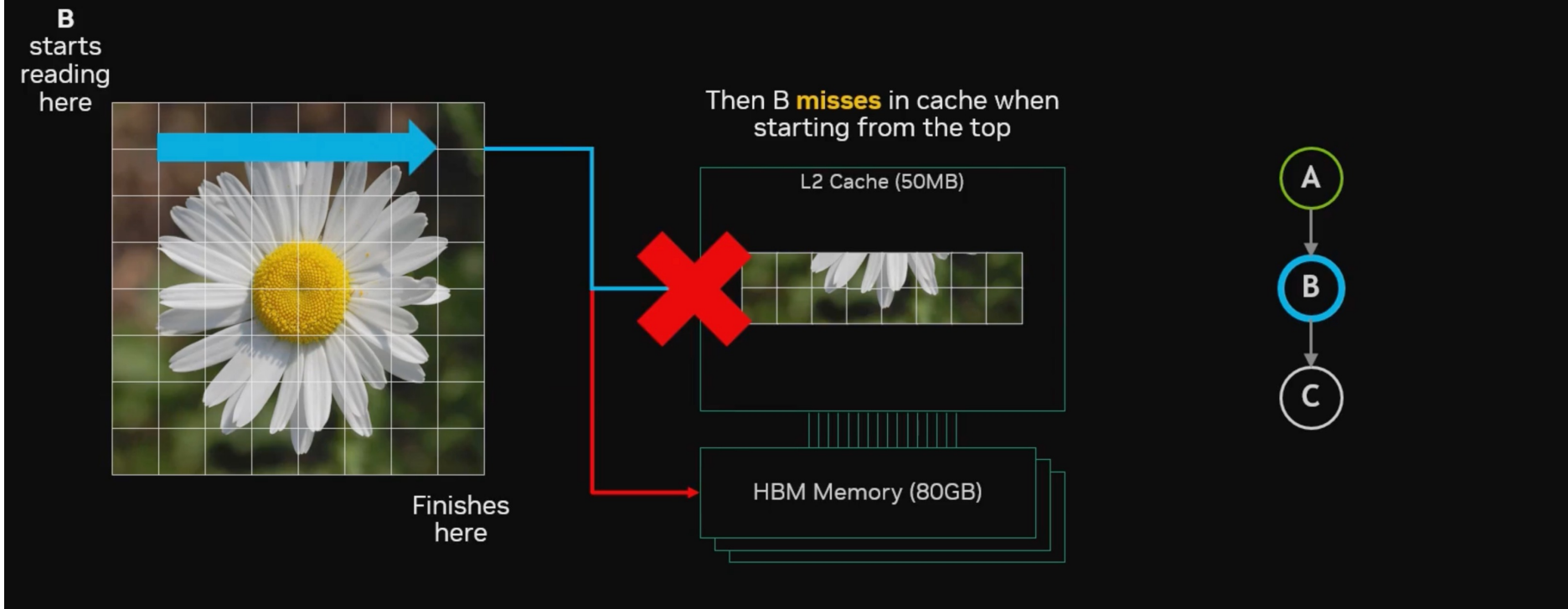
- A high cache hit rate produces the highest performing code
- L2 cache has higher bandwidth and lower latency than HBM memory

Aside: Stop running all your kernels row-major from the top left



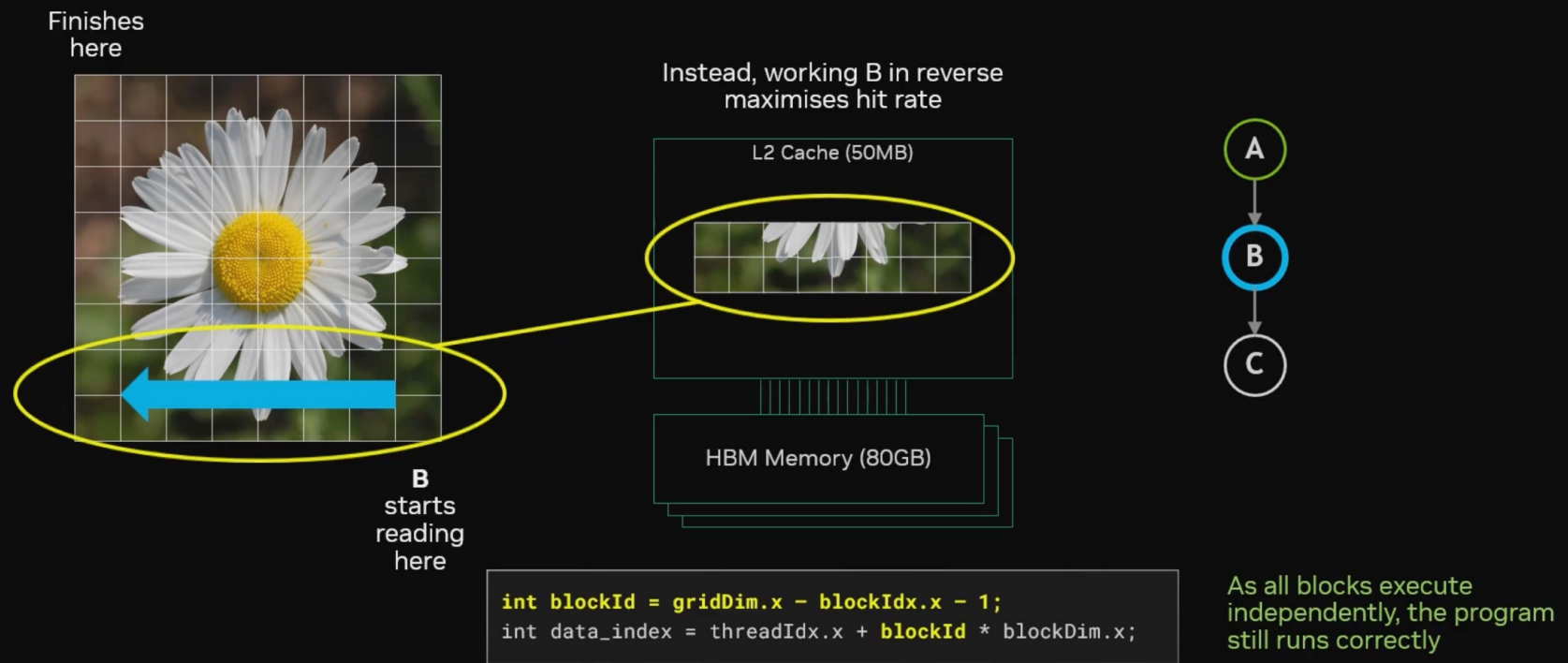
- Row-major finishes at the bottom
- Task B will start again at the top left

Aside: Stop running all your kernels row-major from the top left

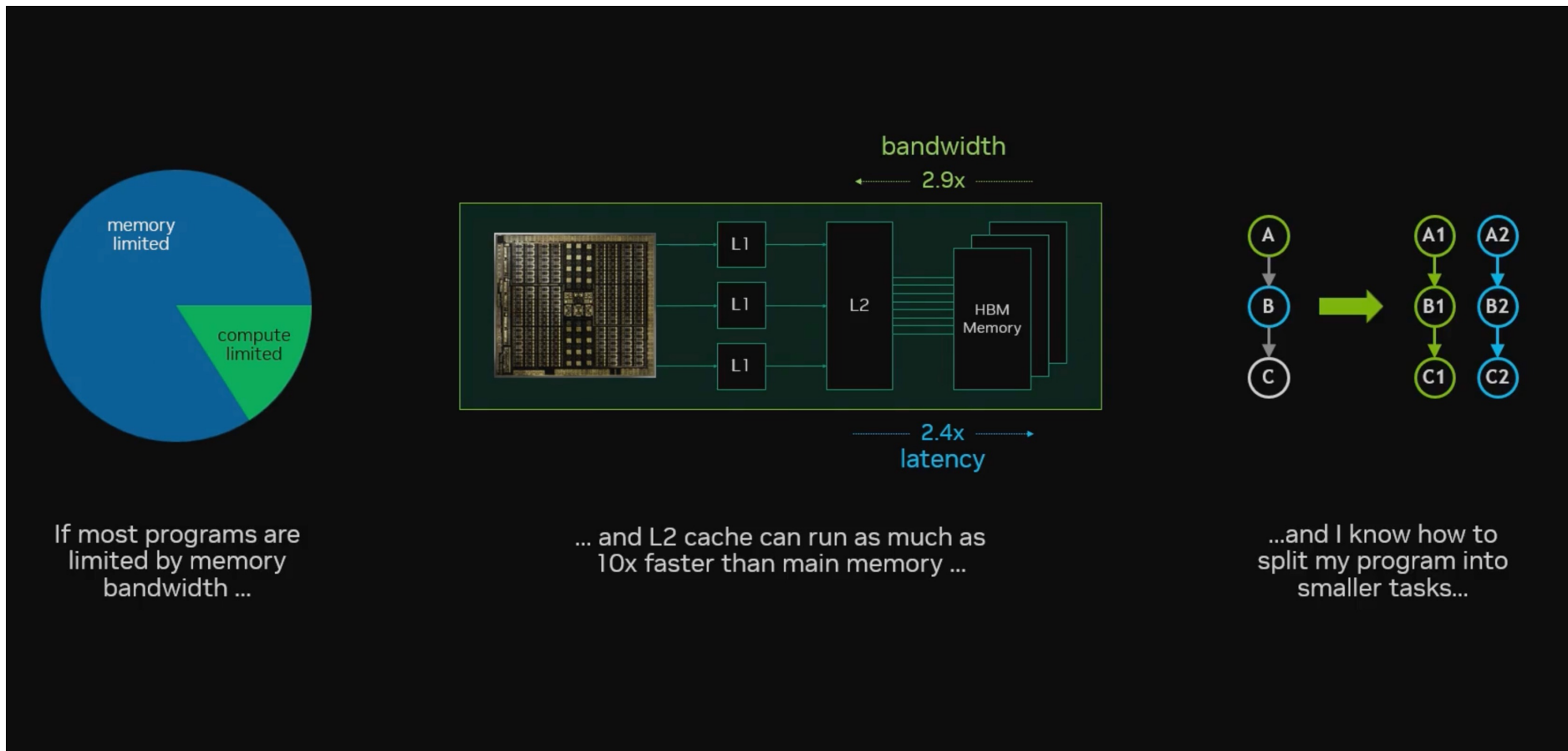


- When switching to Task B you will always generate a cache-miss with row-major kernels

Aside: Stop running all your kernels row-major from the top left



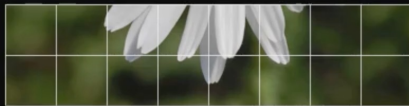
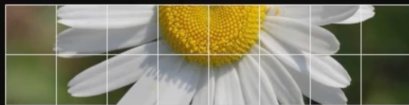
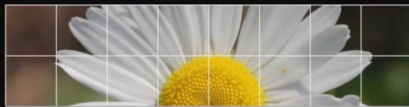
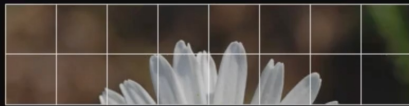
- Running with B in reverse order will produce a cache hit (~10x faster)
- Managing cache effectively can deliver significant benefits



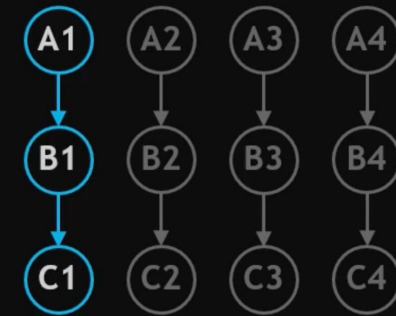
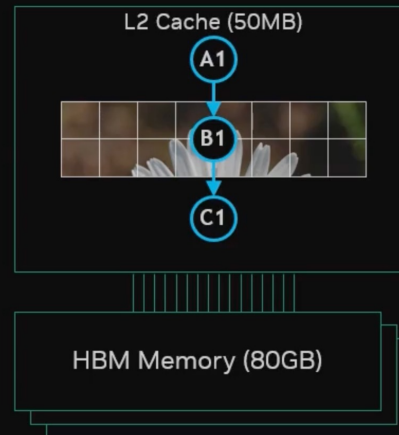
- Identifying whether your program is bandwidth limited is essential to producing high performing code
- For most problems that you encounter this will be the case
- Can we run our problem in L2 cache?



To Keep Data in Cache We Run Each Task in Series, **NOT** in Parallel



Split data into cache-sized chunks



We'll have one task per chunk

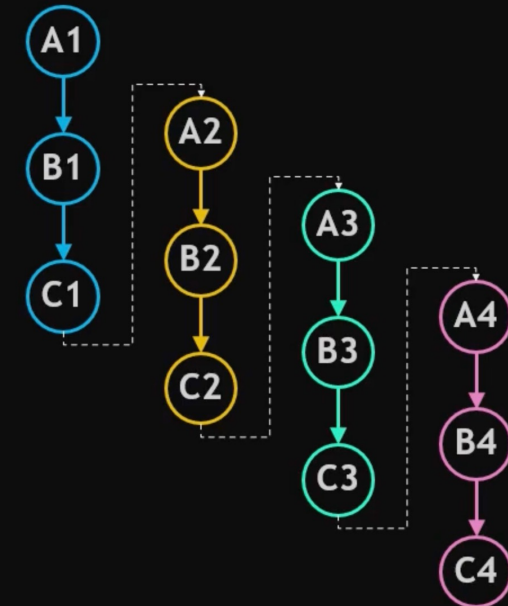
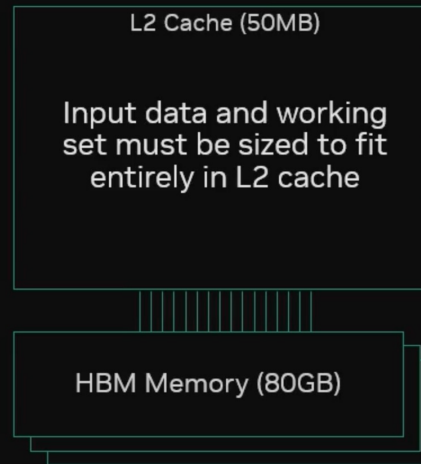
- Previous examples demonstrated how to split problems into smaller tasks
- Split the tasks into L2 cache-sized chunks
- Run each Task in series on the cache size chunk!

This is Known As “Tiling” Your Execution in Cache

You'll really want to design your program for this up-front



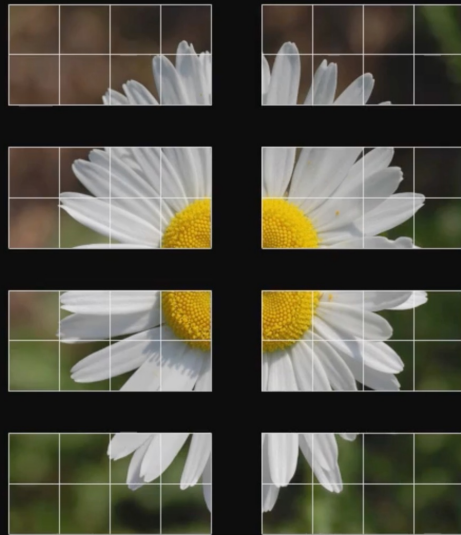
Split data into cache-sized chunks



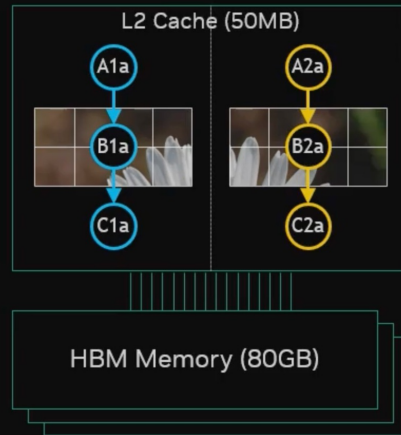
- Running tasks in series is known as tiling e.g tile-based graphics rendering
- Choosing the optimal tiling size is crucial for achieving good performance

So We Can Task-Parallelise Our Task-Based Cache Tiling

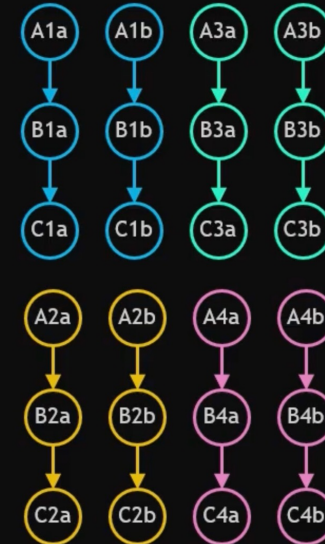
This can get silly pretty fast...



Split data into **half**-cache-sized chunks



So now my tasks fit in 25MB each



Now we need twice as many tasks

- Can take advantage of both task and data parallelism, all running in cache
- Programming complexity increases
- Design from the start, refactoring to achieve this most likely will be hard

The grid stride loop pattern in CUDA

- The **grid stride loop pattern** is a technique used in CUDA programming to ensure that a kernel can efficiently process data arrays of any size

```
__global__ void saxpy(int n, float a, float *x, float *y) {  
    for (int i = blockIdx.x * blockDim.x + threadIdx.x; i < n; i += blockDim.x * gridDim.x) {  
        y[i] = a * x[i] + y[i];  
    }  
}
```

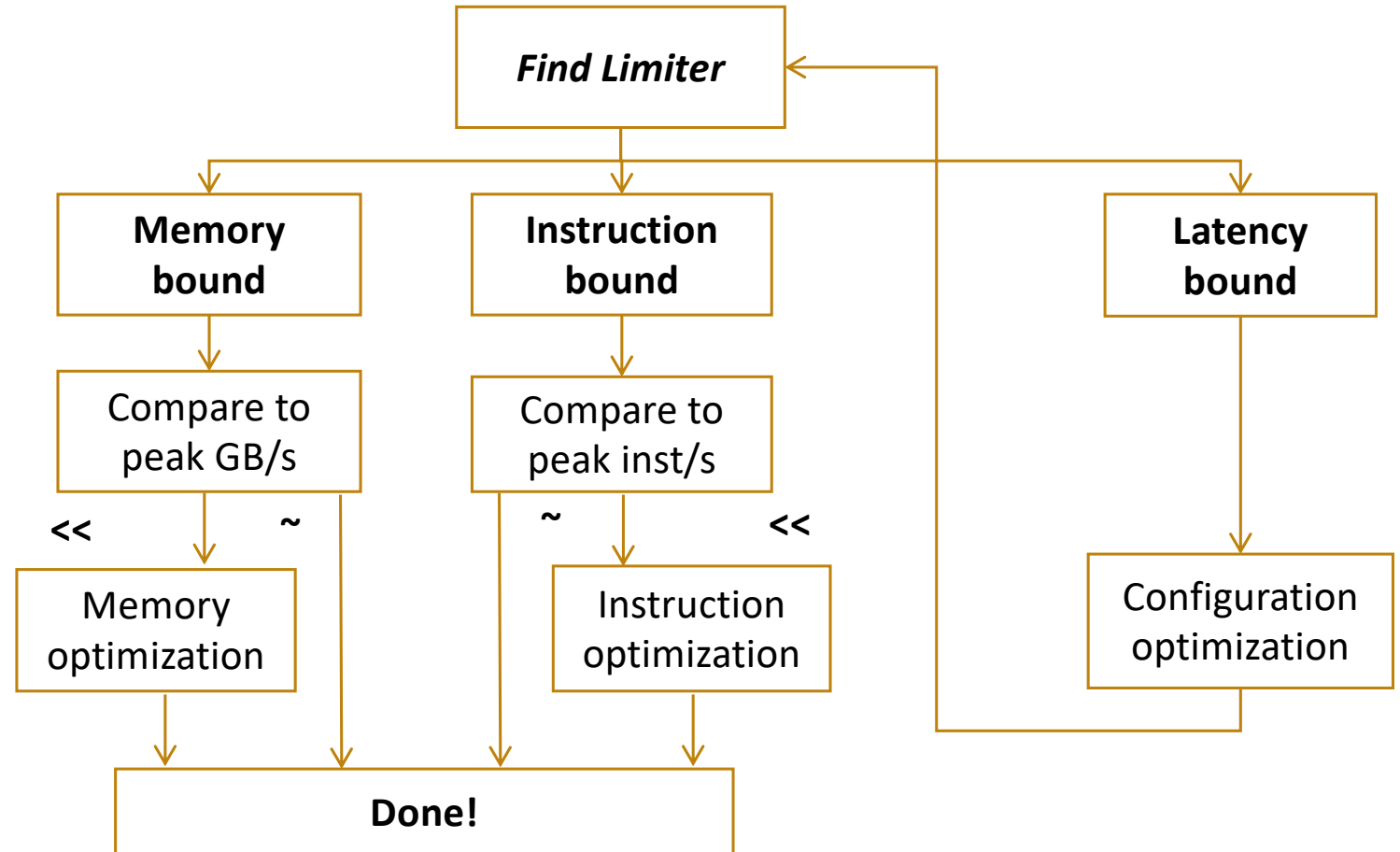
- In this example, each thread calculates its unique index in the array ($i = \text{blockIdx.x} * \text{blockDim.x} + \text{threadIdx.x}$), and then processes the element at that index.
- The thread then increments its index by the total number of threads in the grid ($\text{blockDim.x} * \text{gridDim.x}$), and processes the next element, repeating this process until all elements have been processed
- This pattern allows the kernel to handle data arrays of any size, even when the number of threads launched is less than the number of data elements.
- It also makes your CUDA kernels more flexible and scalable



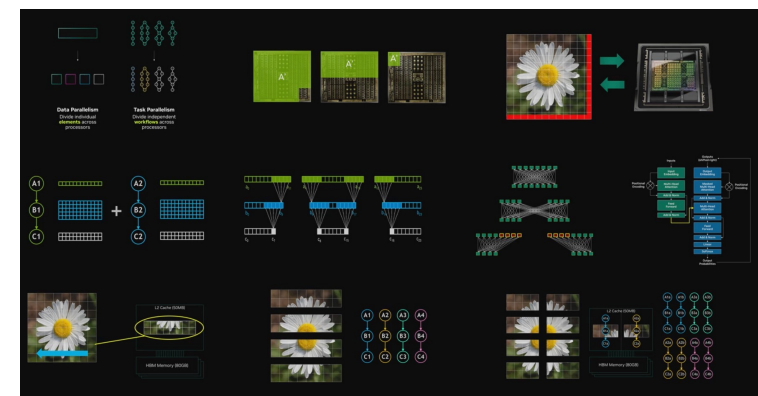
Optimization Workflow in CUDA

Wrong View of Optimization!

- Try all the optimization methods in the book
- ...optimization is endless...



Summary



- Programming a *streaming multiprocessor* is not an extension of CPU programming!
- Is a GPU required based on the scale of the task and the ability to expose parallelism?
- Data and task parallelism concepts are the GPU fundamentals that you should master
- Seek to achieve wave quantization on the target GPU
- Task parallelism
- All-to-all algorithms break task parallelism, use higher level model parallelism
- Create a CUDA graph of complex model parallelism tasks, reduce dependencies
- Avoid bandwidth limitations, tile execution in cache