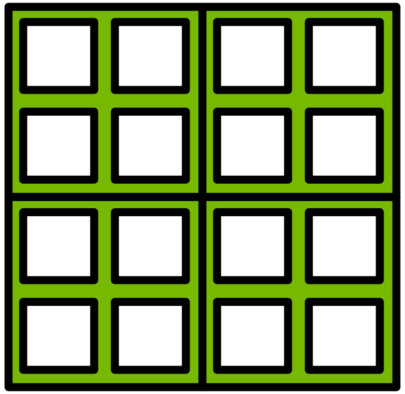
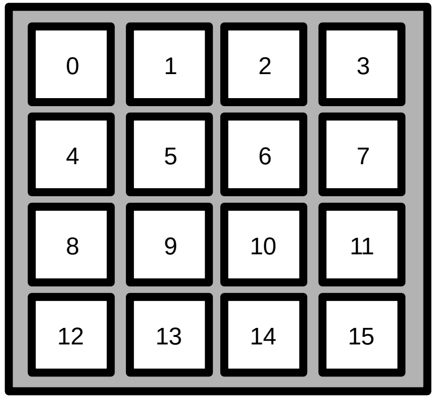
Using Shared Memory to Support Coalesced Memory Access

We will examine a matrix transpose to demonstrate how shared memory can be used to promote coalesced data transfers to and from global memory

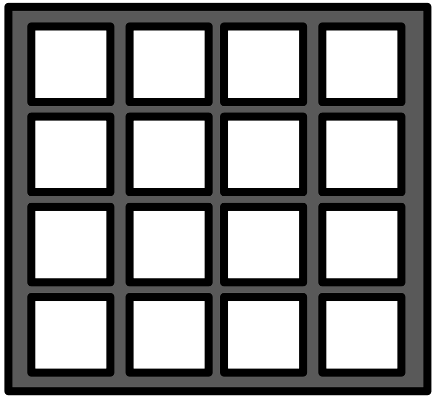
Grid



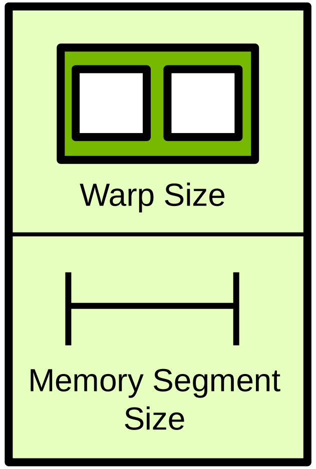
Here we have a (2,2) grid, with each block containing (2,2) threads as well as (4,4) input and output matrices



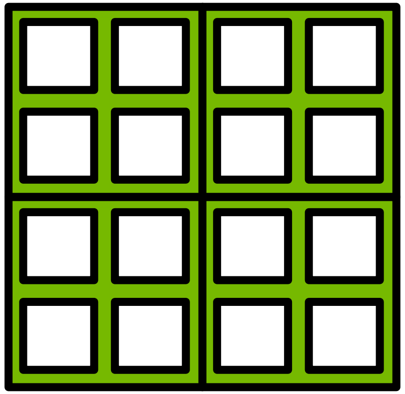
Input



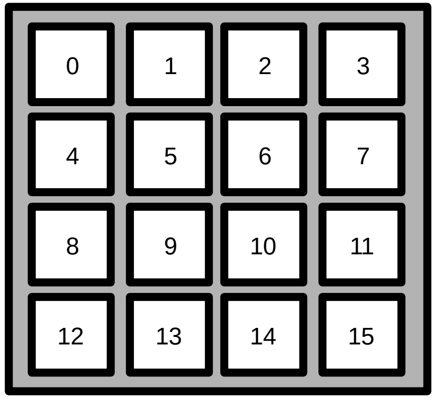
Output



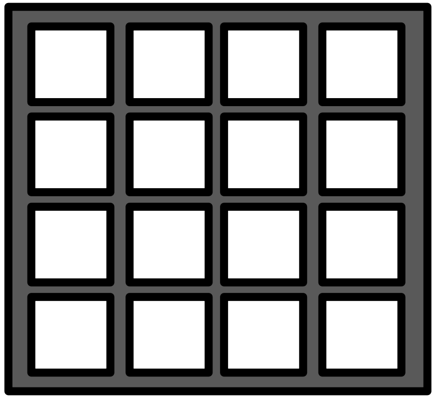
Grid



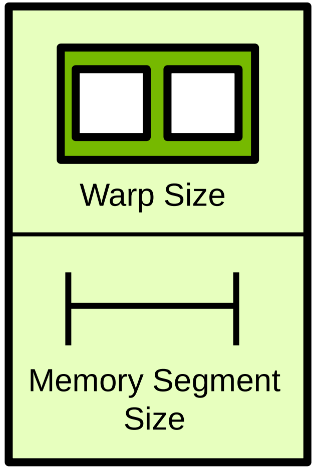
For these slides we will define a warp as 2 threads, and a memory segment as 2 data elements wide



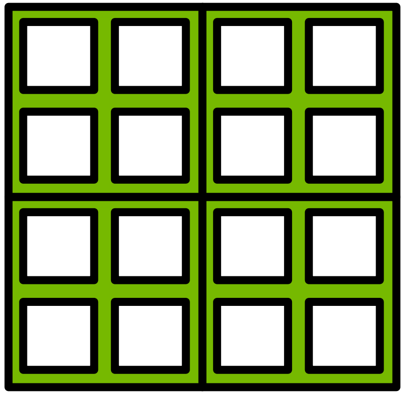
Input



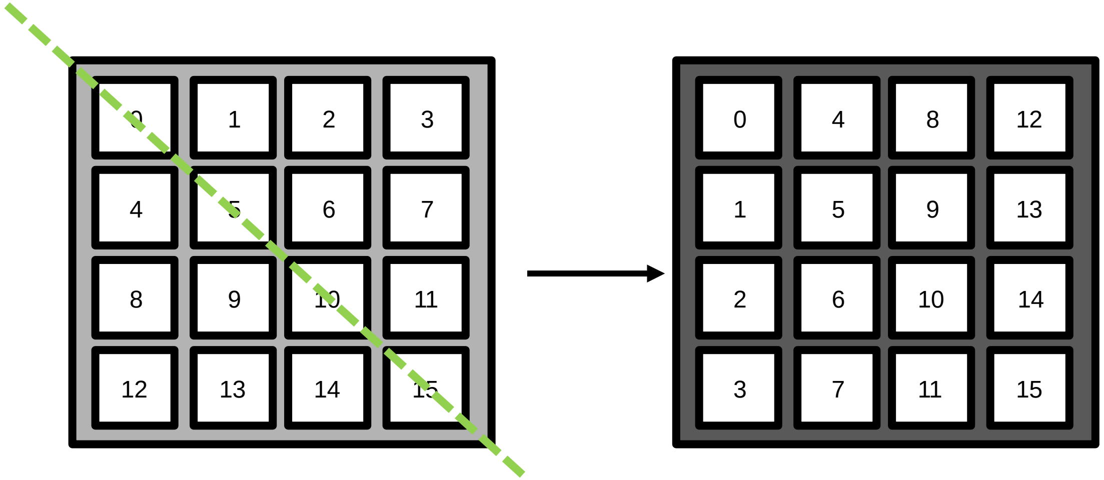
Output



Grid

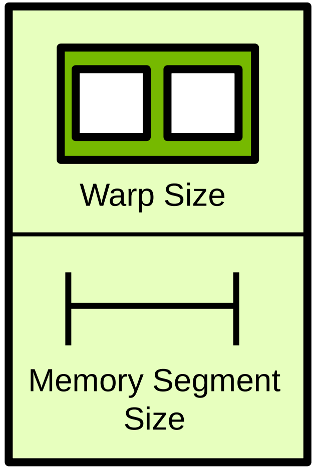


Our goal is to transpose the input by rotating all elements around the diagonal, writing the transposed elements to output

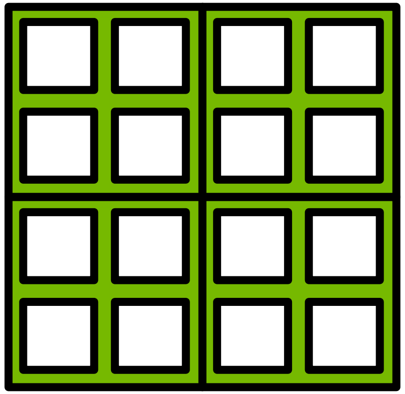


Input

Output



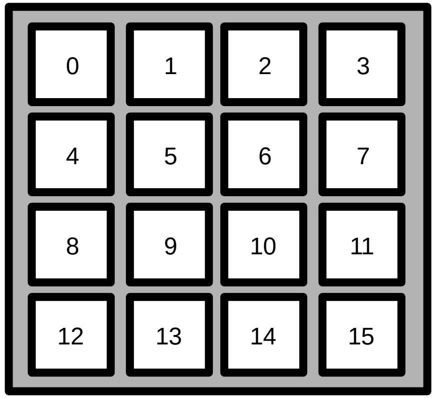
Grid

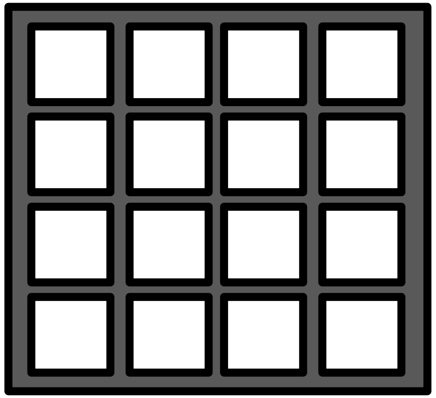


A naïve approach is to launch a grid with threads equal to input elements, and to have each thread read 1 element, then write it to output in the transposed location

```
x, y = cuda.grid(2)

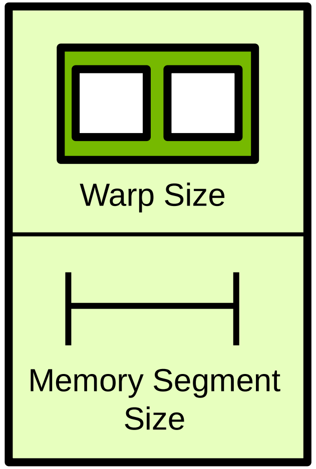
out[x][y] = in[y][x]
```



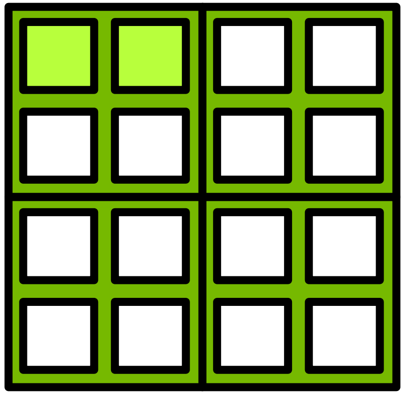


Input

Output



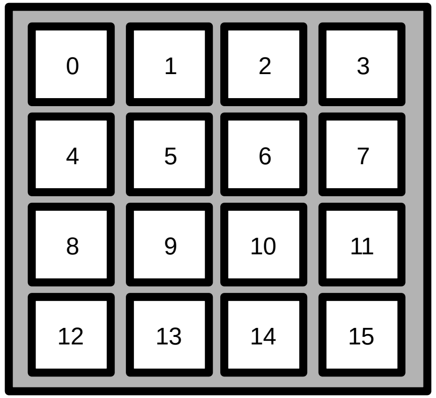
Grid



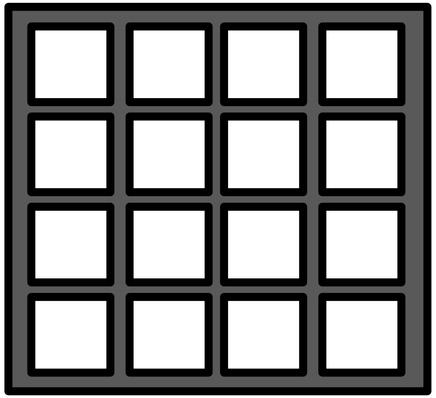
Observing the behavior of a single warp, is it the case that memory reads are coalesced? Let's dig into answering that question

```
x, y = cuda.grid(2)

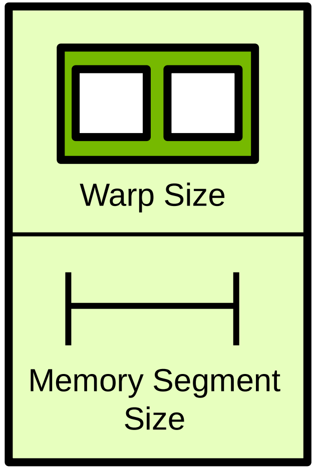
out[x][y] = in[y][x]
```



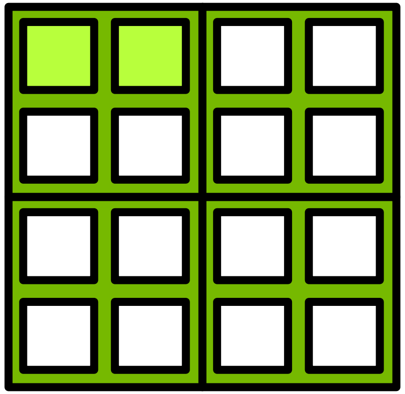
Input



Output



Grid

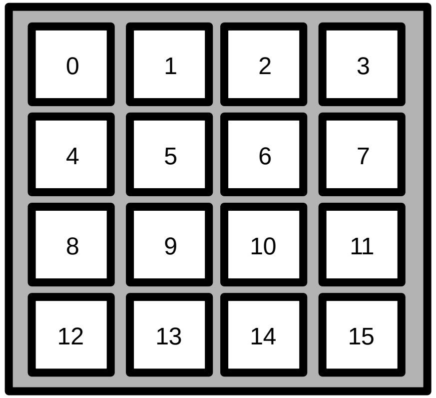


Rewriting the creation of the indexing variables, it is clearer that contiguous threads in the same warp are adjacent along the x axis

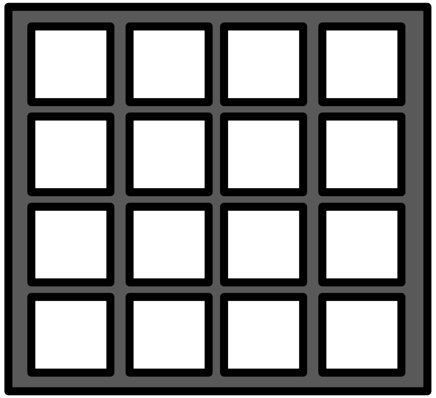
```
x = blockIdx.x * blockDim.x
        + threadIdx.x

y = blockIdx.y * blockDim.y
        + threadIdx.y

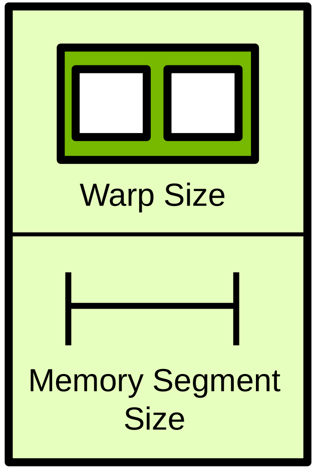
out[x][y] = in[y][x]
```



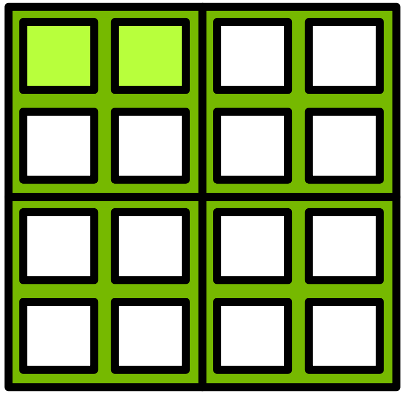
Input



Output



Grid

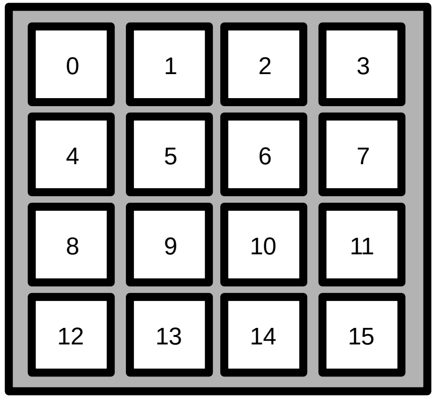


Furthermore, these contiguous threads will read elements from the rows of input where data elements are contiguous

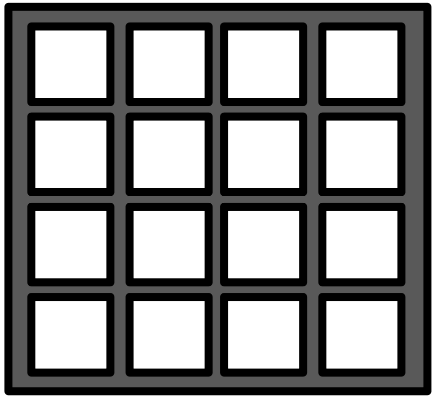
```
x = blockIdx.x * blockDim.x
        + threadIdx.x

y = blockIdx.y * blockDim.y
        + threadIdx.y

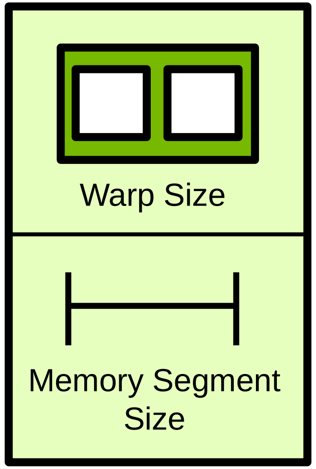
out[x][y] = in[y][x]
```

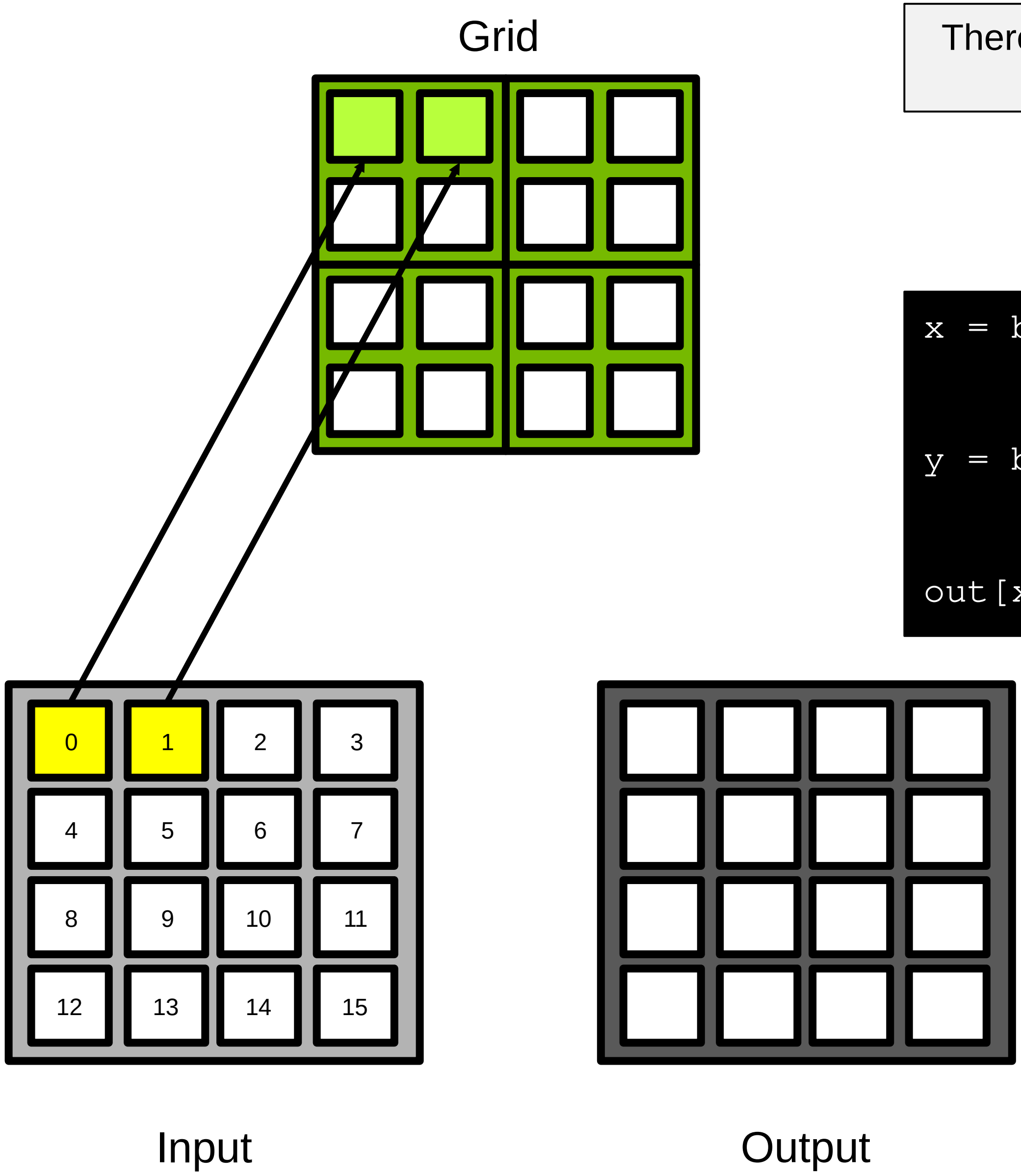


Input



Output



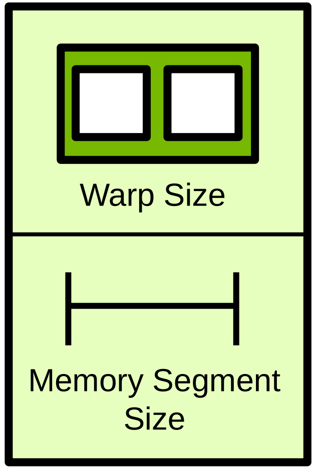


Therefore, it makes sense that reads from input are coalesced

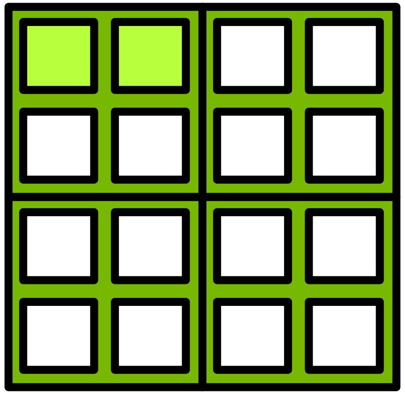
```
x = blockIdx.x * blockDim.x
        + threadIdx.x

y = blockIdx.y * blockDim.y
        + threadIdx.y

out[x][y] = in[y][x]
```



Grid

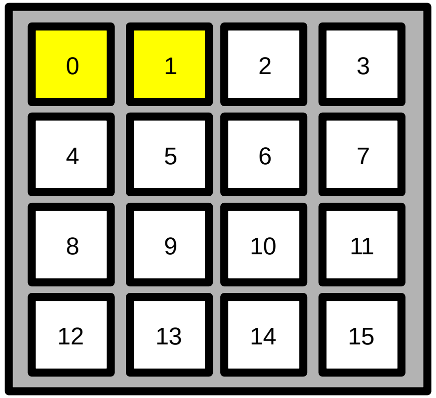


What about this warp's writes to output, will they be coalesced?

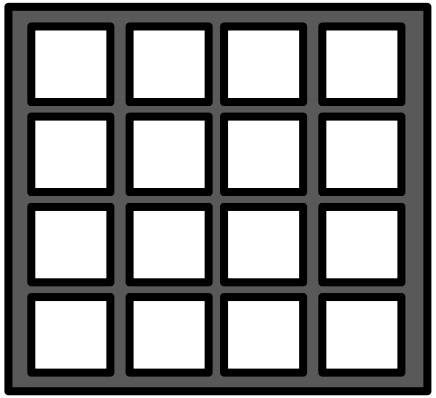
```
x = blockIdx.x * blockDim.x
        + threadIdx.x

y = blockIdx.y * blockDim.y
        + threadIdx.y

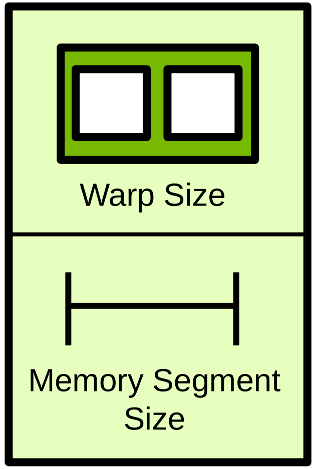
out[x][y] = in[y][x]
```



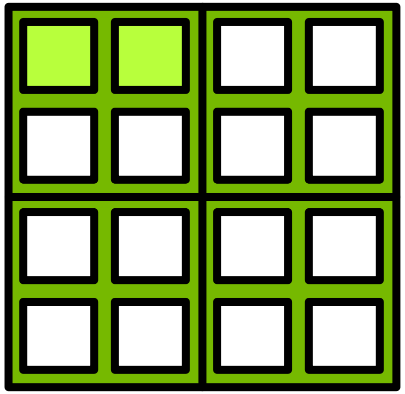
Input



Output



Grid

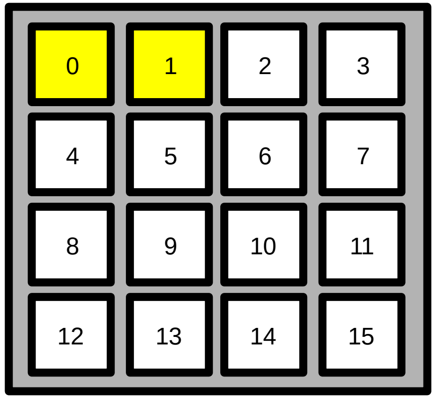


Here we see that contiguous threads in the same warp will be writing along a column in output

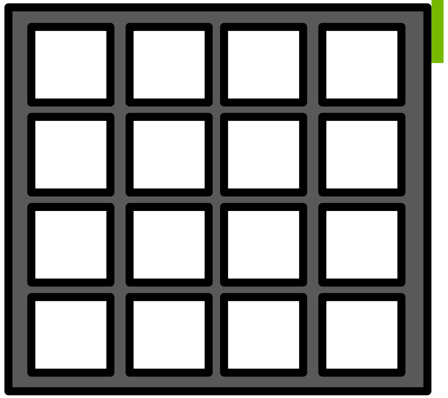
```
x = blockIdx.x * blockDim.x
        + threadIdx.x

y = blockIdx.y * blockDim.y
        + threadIdx.y

out[x][y] = in[y][x]
```

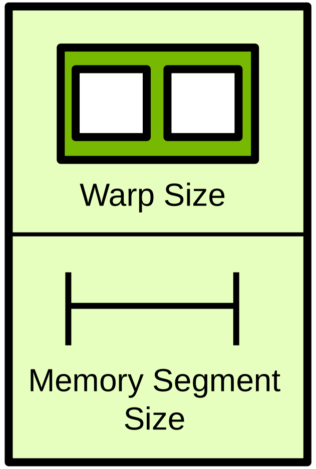


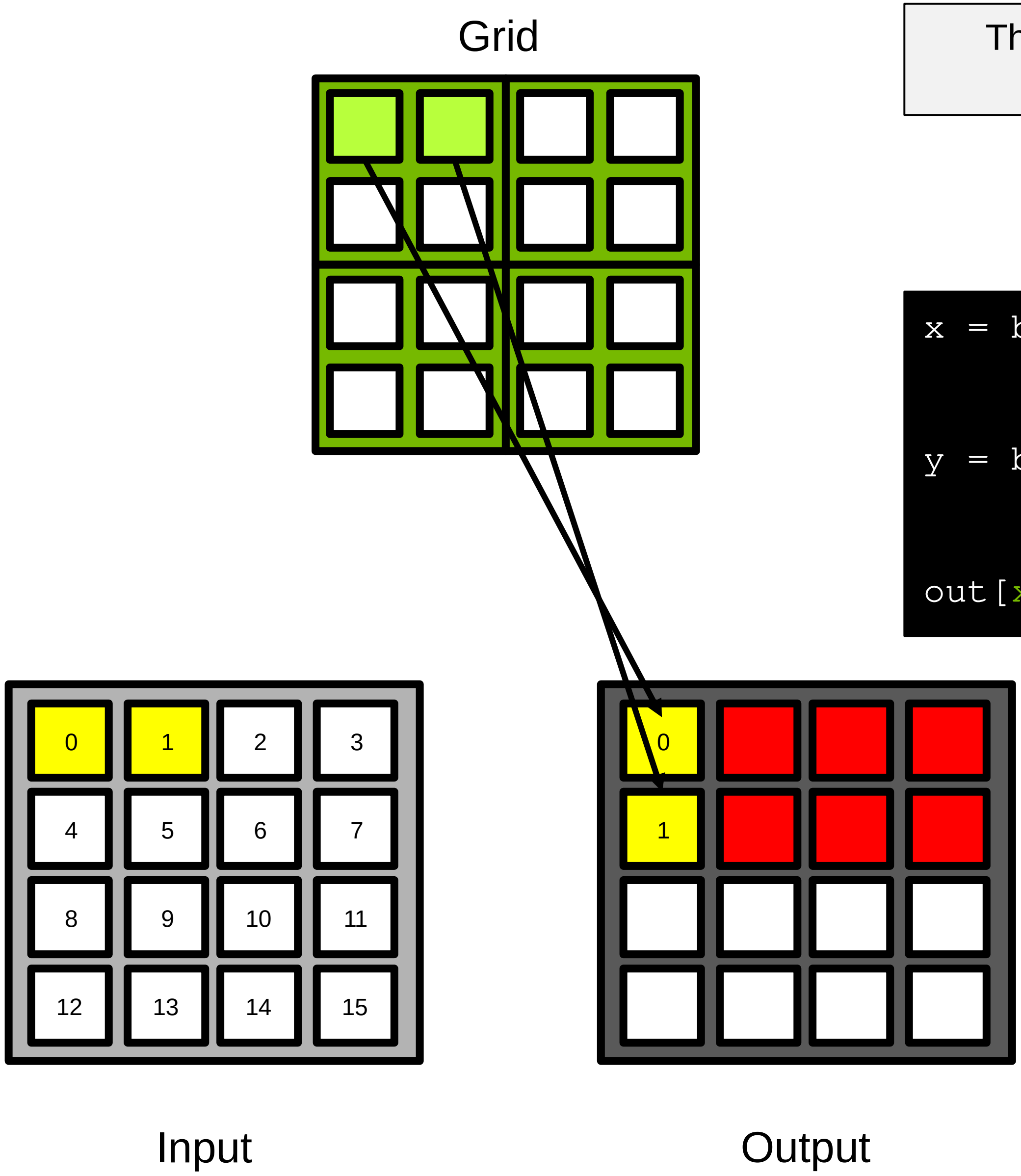
Input



Output

Therefore, the writes will not be coalesced

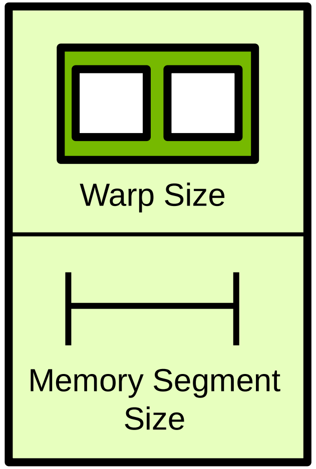


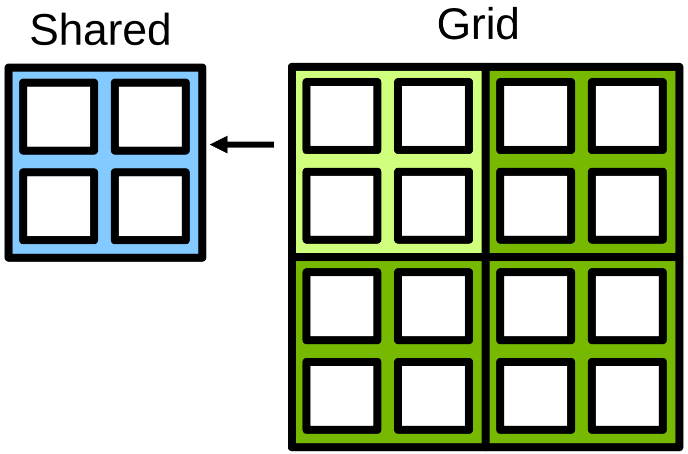



```
x = blockIdx.x * blockDim.x
        + threadIdx.x

y = blockIdx.y * blockDim.y
        + threadIdx.y

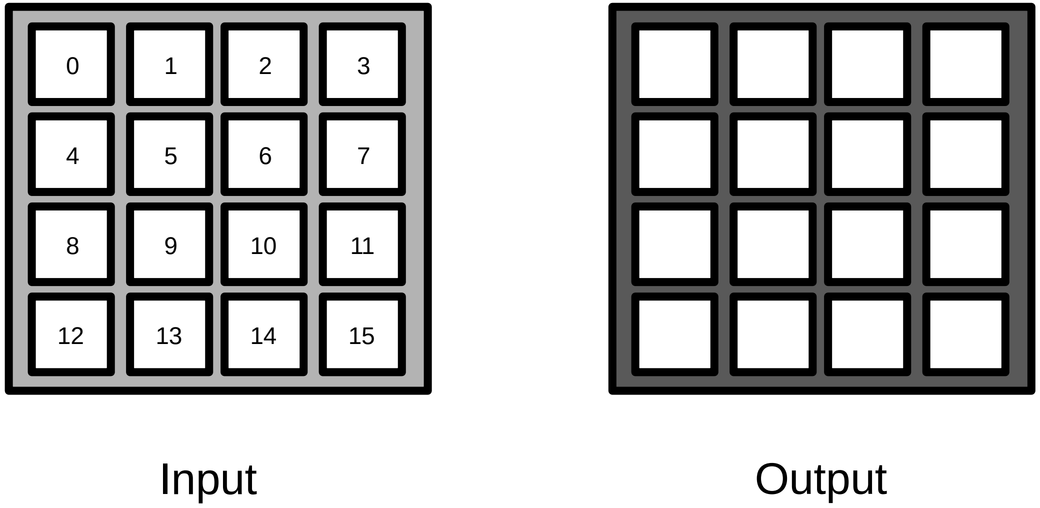
out[x][y] = in[y][x]
```

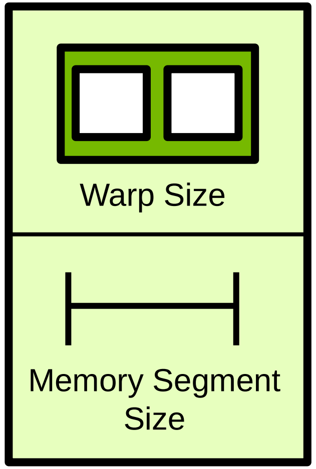


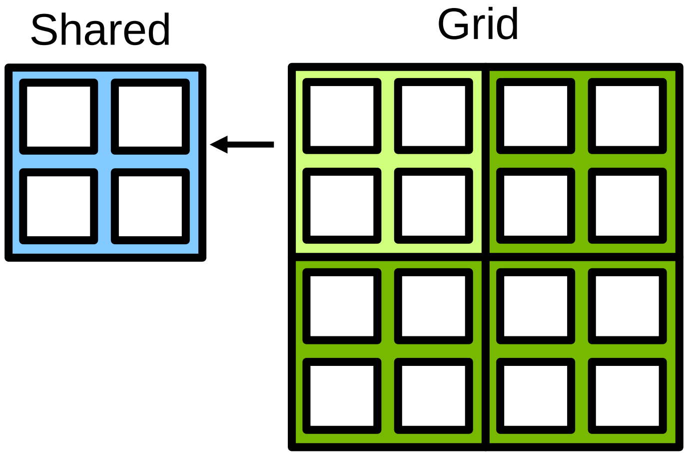


We can use shared memory to make coalesced reads and writes. Here, each block will allocate a (2,2) shared memory tile

```
tile = cuda.shared.array(2,2)
```

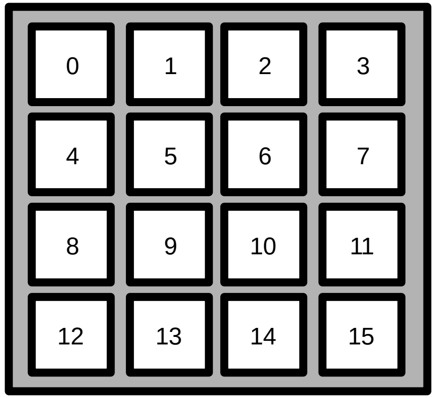




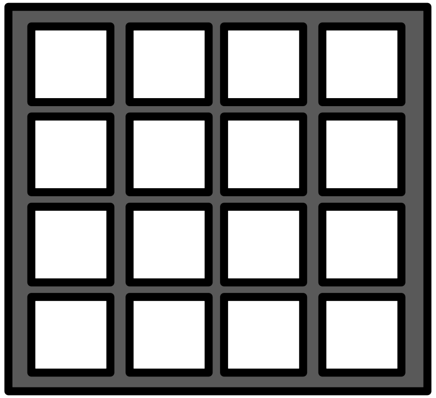


(It is worth reminding that in our slides, to preserve space, 2 threads is a warp length. A real warp is 32 threads)

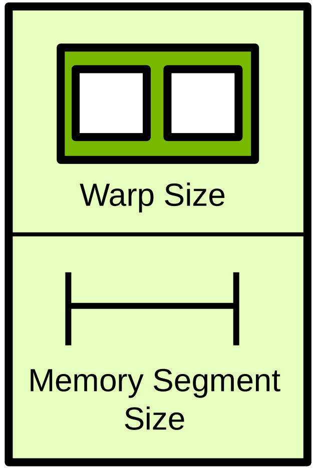
```
tile = cuda.shared.array(2,2)
```

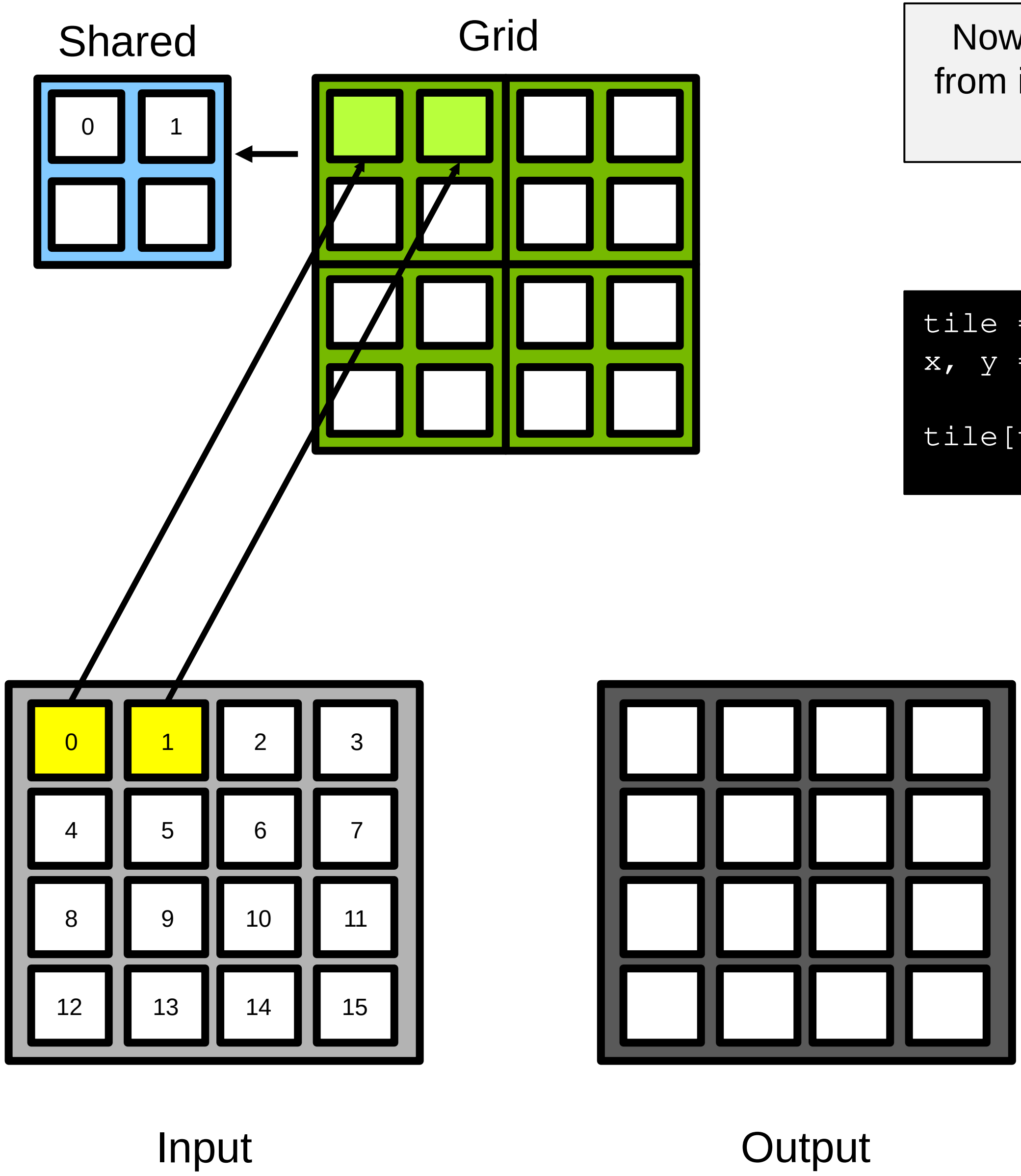


Input



Output

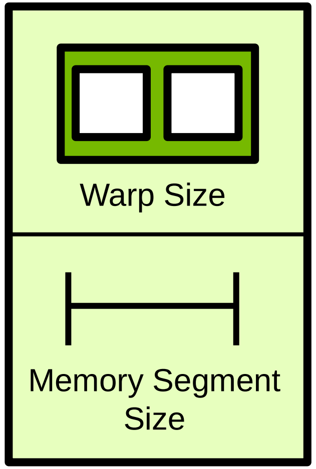


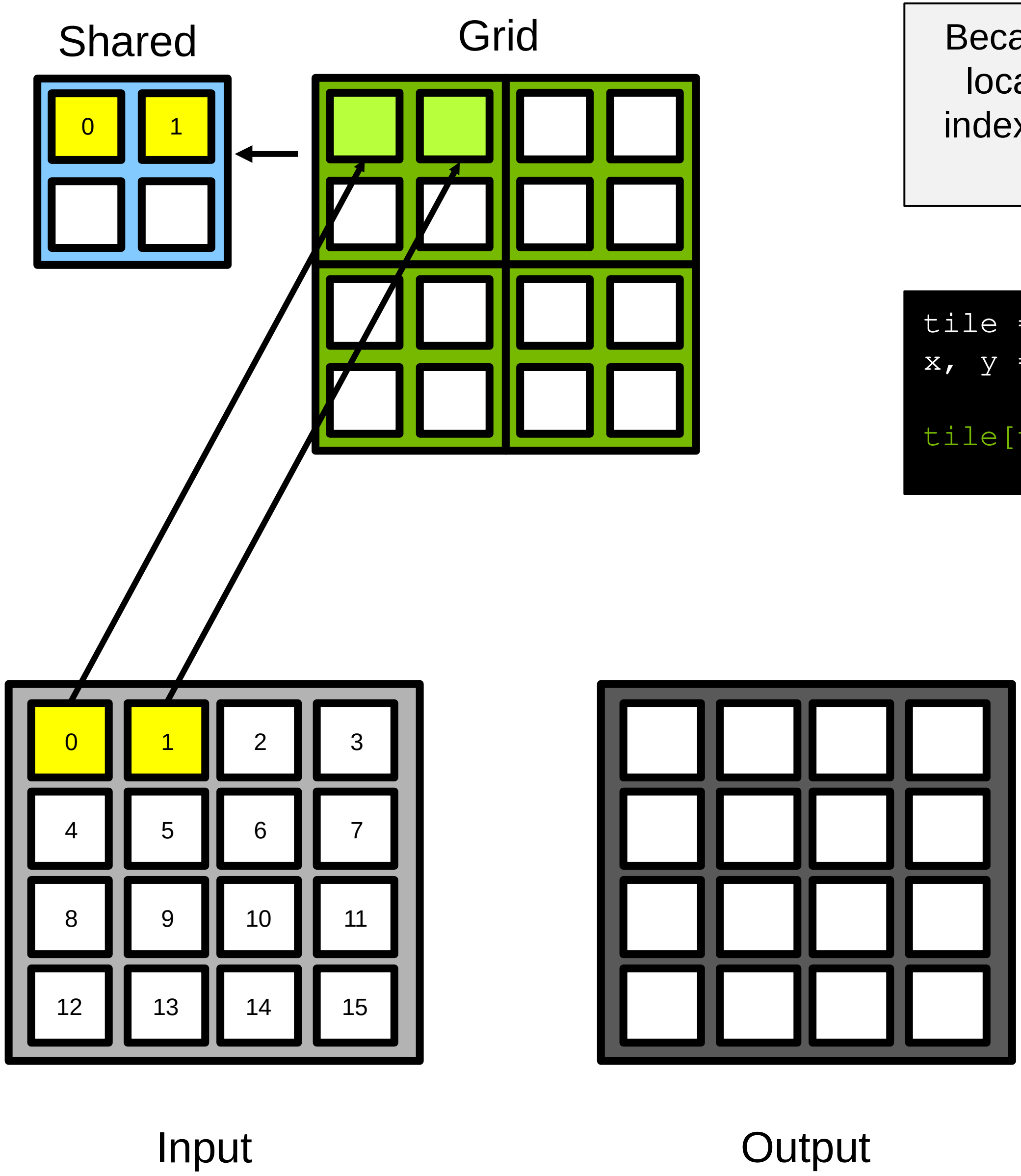


Now we can make coalesced reads from input, and write the values to the block's shared memory tile

```
tile = cuda.shared.array(2,2)
x, y = cuda.grid(2)

tile[tIdx.y][tIdx.x] = in[y][x]
```

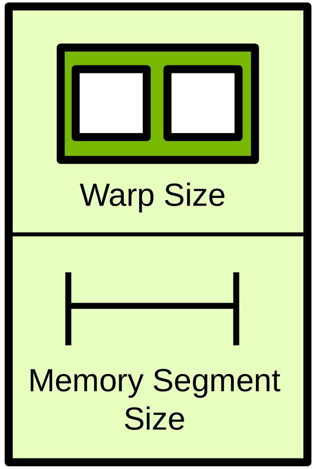


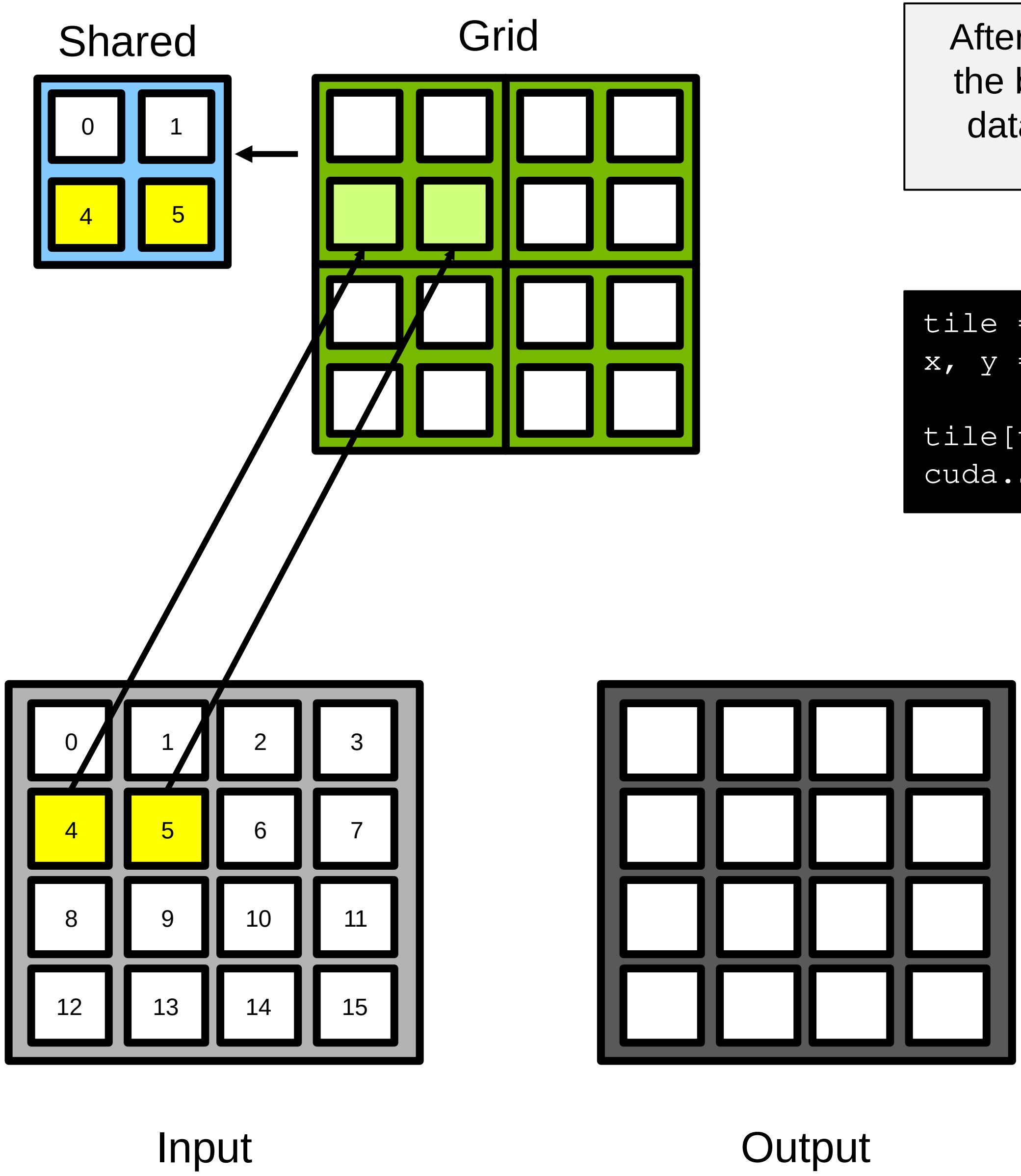


Because each shared memory tile is local to the block (not the grid) we index into it using thread indices, not grid indices

```
tile = cuda.shared.array(2,2)
x, y = cuda.grid(2)

tile[tIdx.y][tIdx.x] = in[y][x]
```

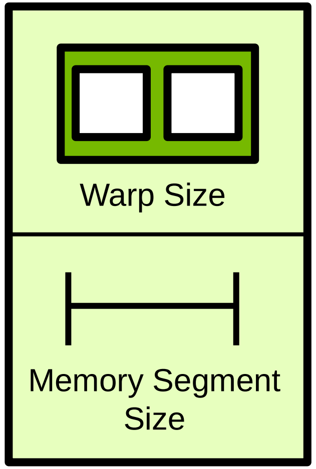


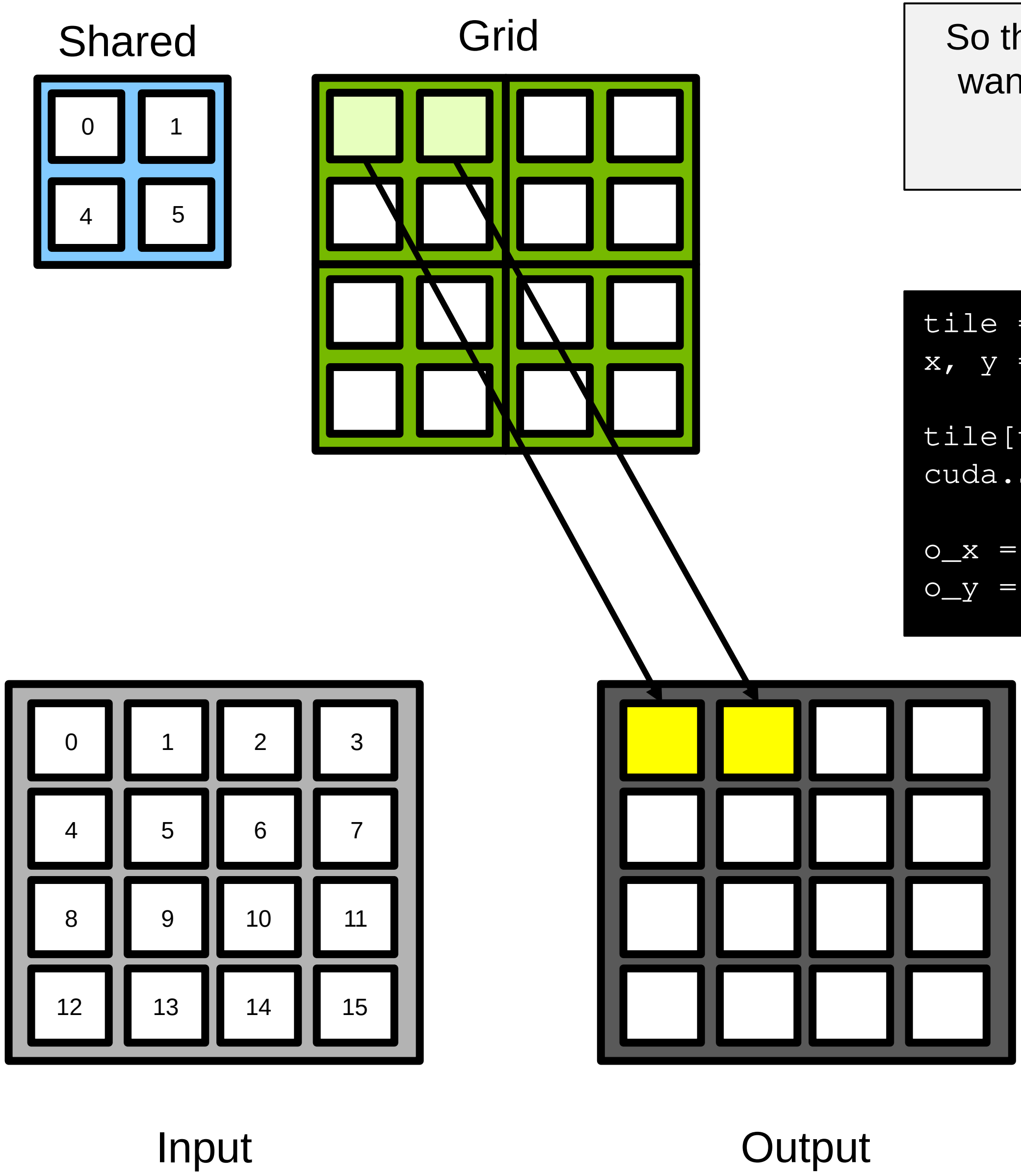


After synchronizing on all threads in the block, the tile will contain all the data this block needs to begin the writes

```
tile = cuda.shared.array(2,2)
x, y = cuda.grid(2)

tile[tIdx.y][tIdx.x] = in[y][x]
cuda.syncthreads()
```



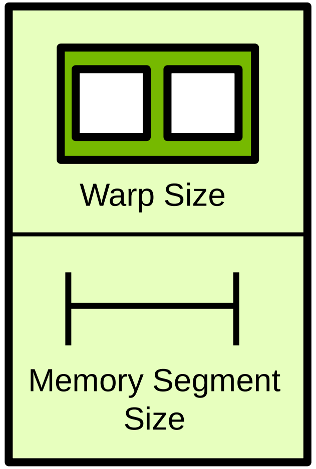


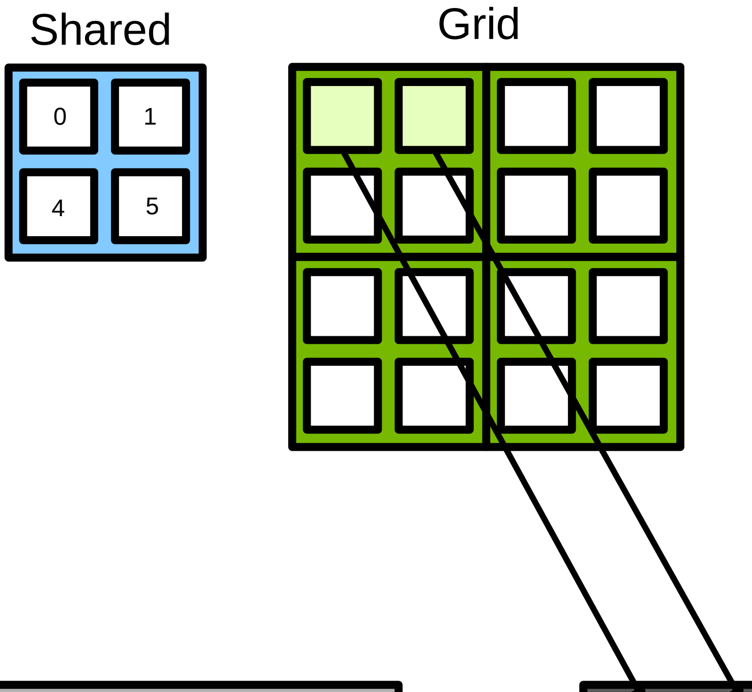
So that the writes are coalesced, we want each warp to write to a row in output

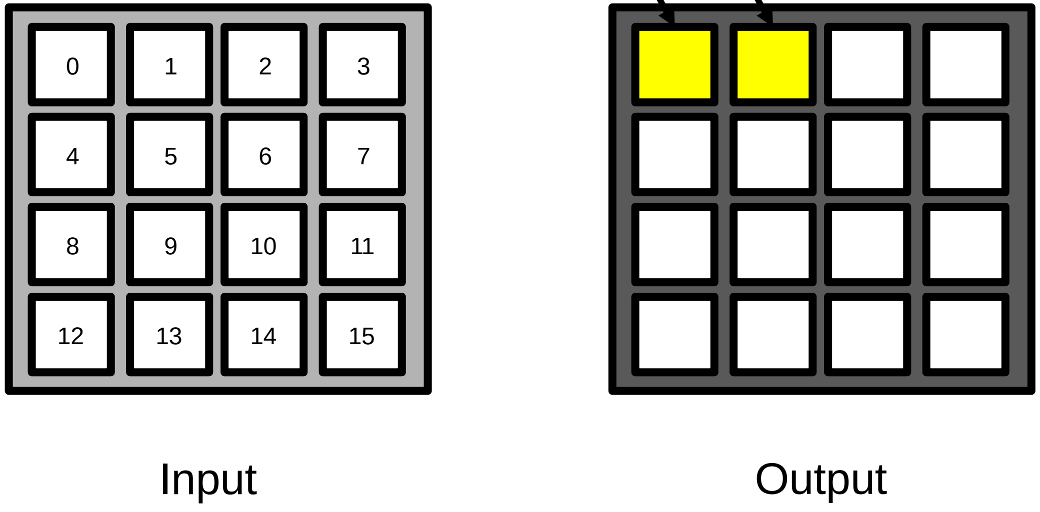
```
tile = cuda.shared.array(2,2)
x, y = cuda.grid(2)

tile[tIdx.y][tIdx.x] = in[y][x]
cuda.syncthreads()

o_x = bId.y*bDim.y + tId.x
o_y = bId.x*bDim.x + tId.y
```





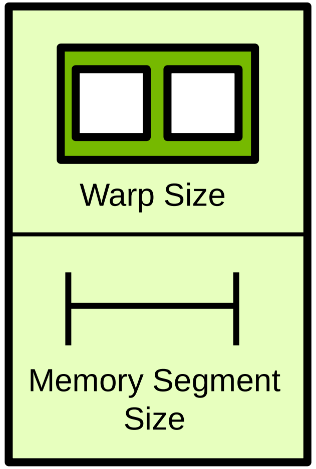


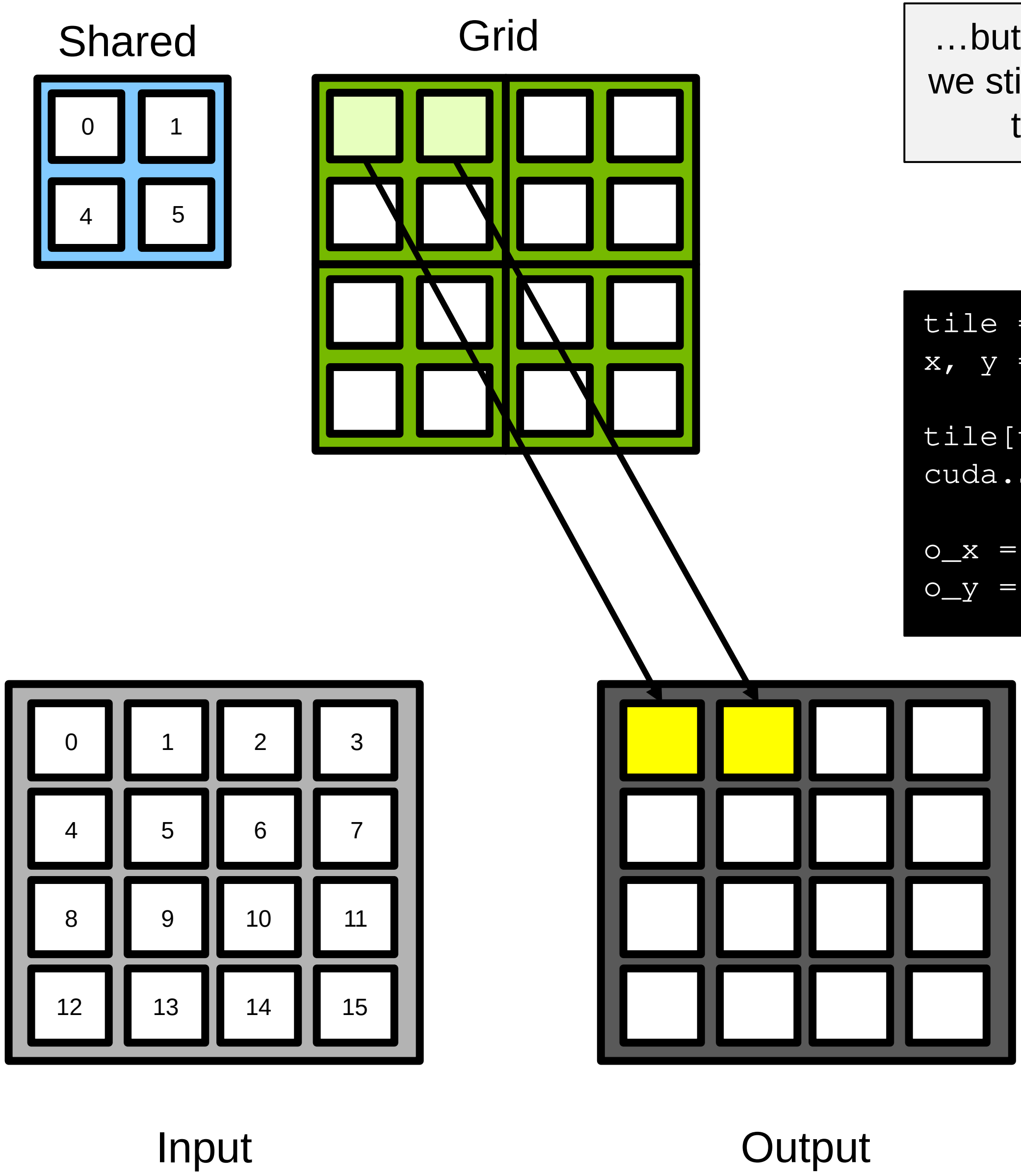
Notice that to write to output at the transposed locations we use blockIdx.y and blockDim.y to calculate the x axis index in output…

```
tile = cuda.shared.array(2,2)
x, y = cuda.grid(2)

tile[tIdx.y][tIdx.x] = in[y][x]
cuda.syncthreads()

o_x = bId.y*bDim.y + tId.x
o_y = bId.x*bDim.x + tId.y
```



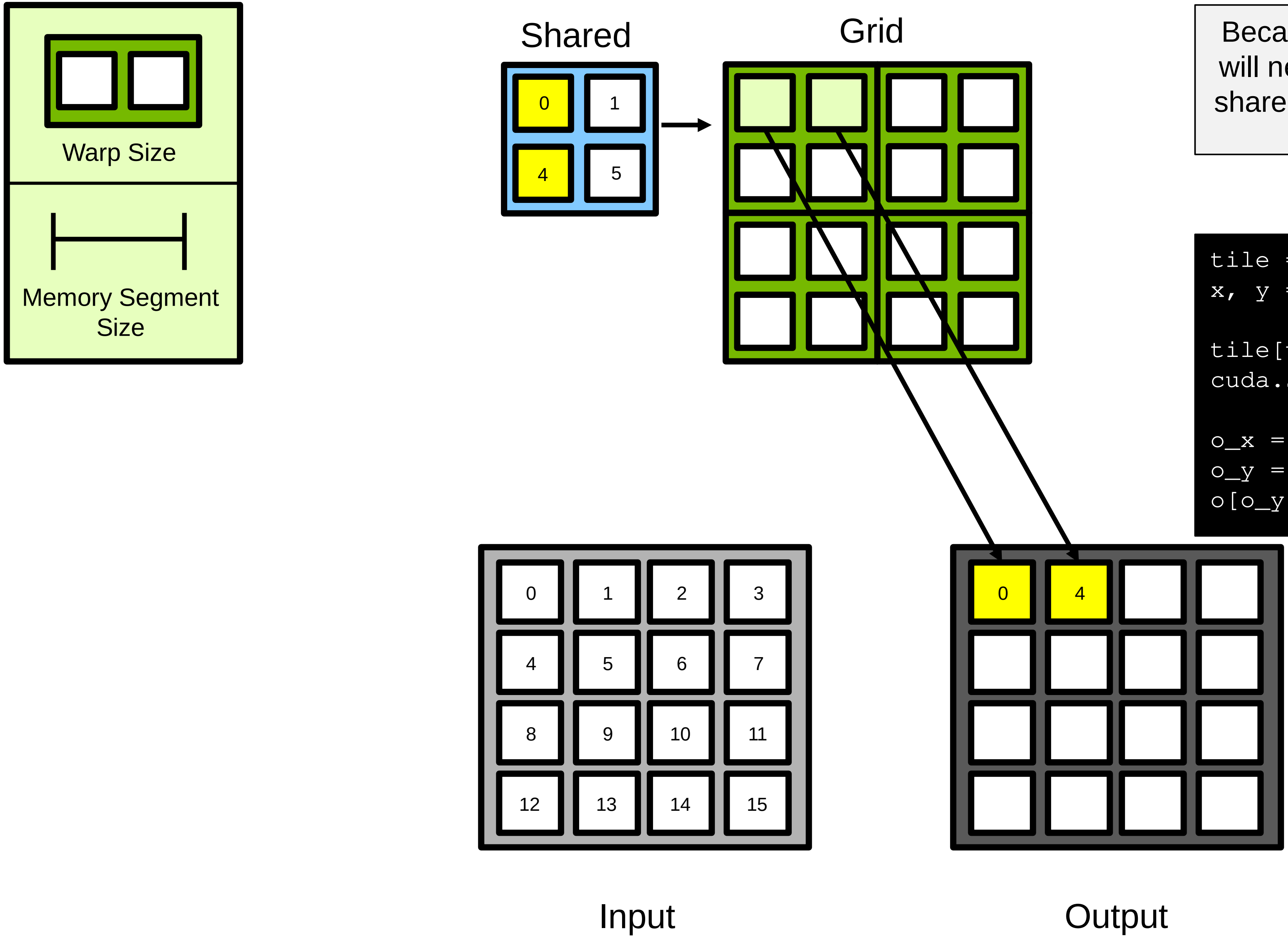


…but to accomplish coalesced writes, we still map increments to threadIdx.x to be along the x output axis

```
tile = cuda.shared.array(2,2)
x, y = cuda.grid(2)

tile[tIdx.y][tIdx.x] = in[y][x]
cuda.syncthreads()

o_x = bId.y*bDim.y + tId.x
o_y = bId.x*bDim.x + tId.y
```

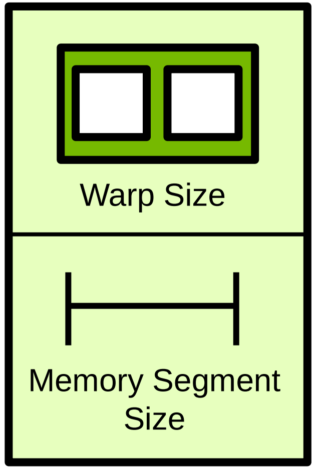


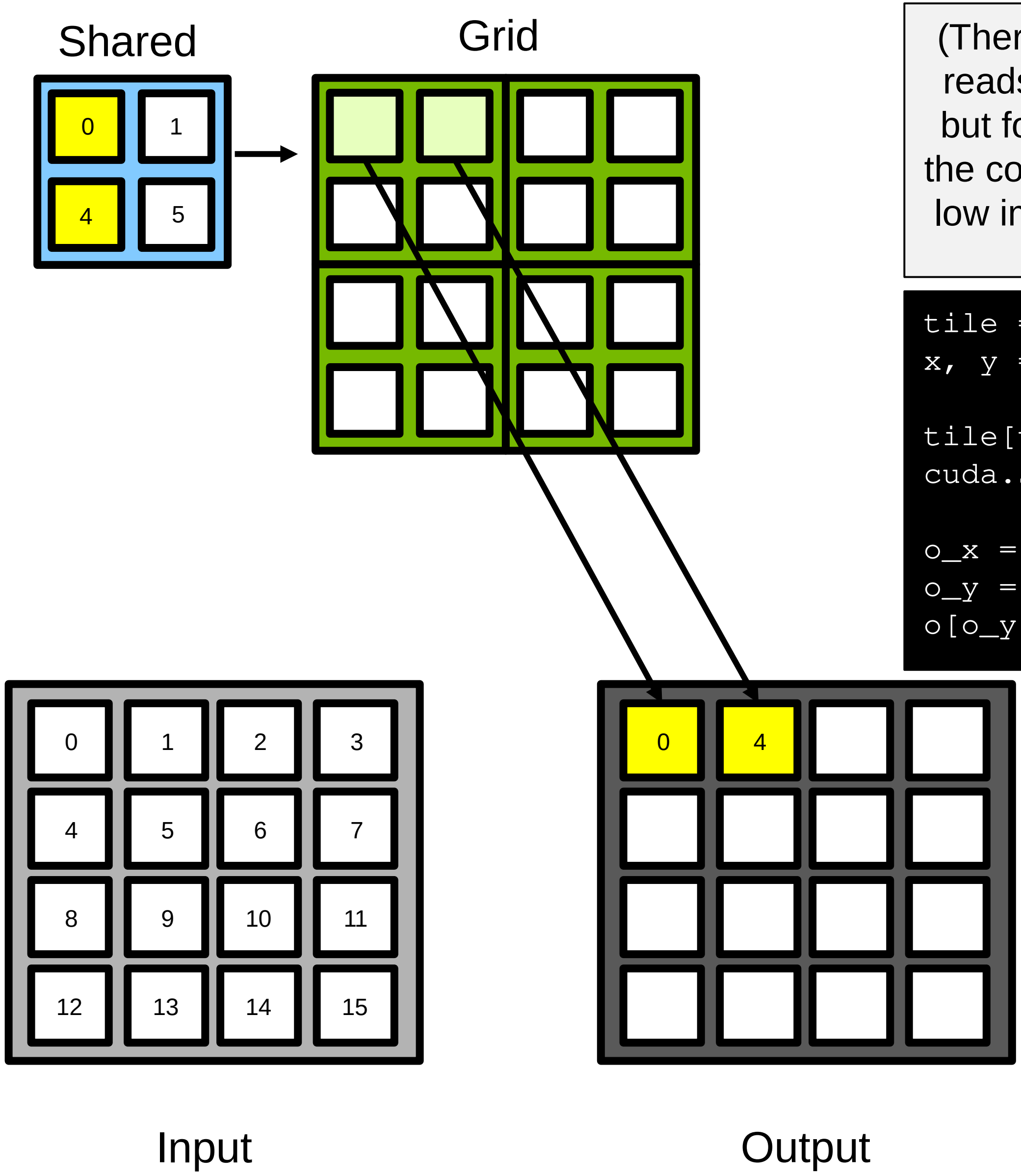
Because of this last detail, each warp will need to read from a column of the shared memory tile in order to perform the transpose

```
tile = cuda.shared.array(2,2)
x, y = cuda.grid(2)

tile[tIdx.y][tIdx.x] = in[y][x]
cuda.syncthreads()

o_x = bId.y*bDim.y + tId.x
o_y = bId.x*bDim.x + tId.y
o[o_y][o_x] = tile[tIdx.x][tIdx.y]
```





(There's more to come about efficient reads/writes to/from shared memory, but for now know that reading across the column in shared memory has very low impact compared to doing so with global memory)

```
tile = cuda.shared.array(2,2)
x, y = cuda.grid(2)

tile[tIdx.y][tIdx.x] = in[y][x]
cuda.syncthreads()

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o[o_y][o_x] = tile[tIdx.x][tIdx.y]
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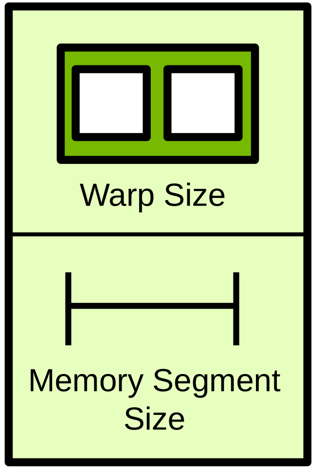

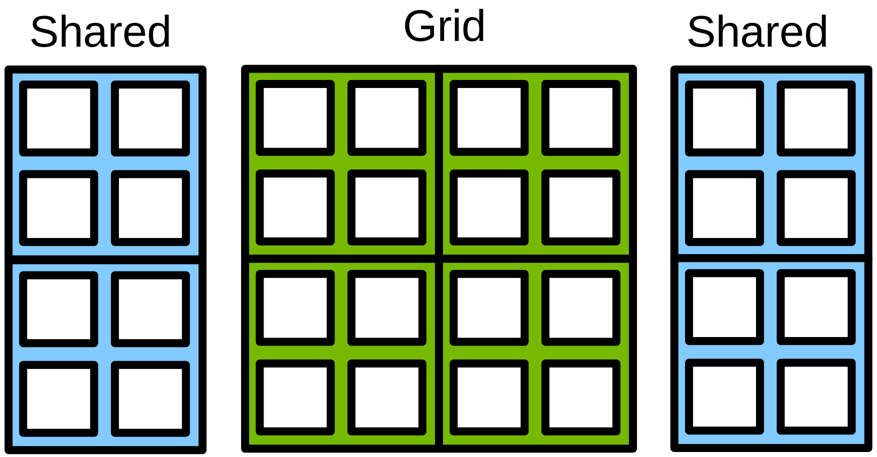

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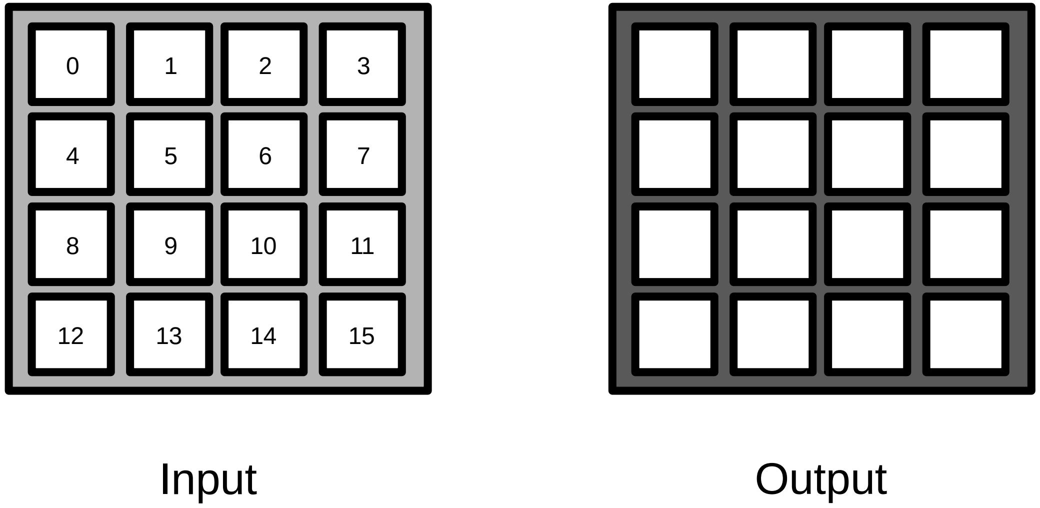

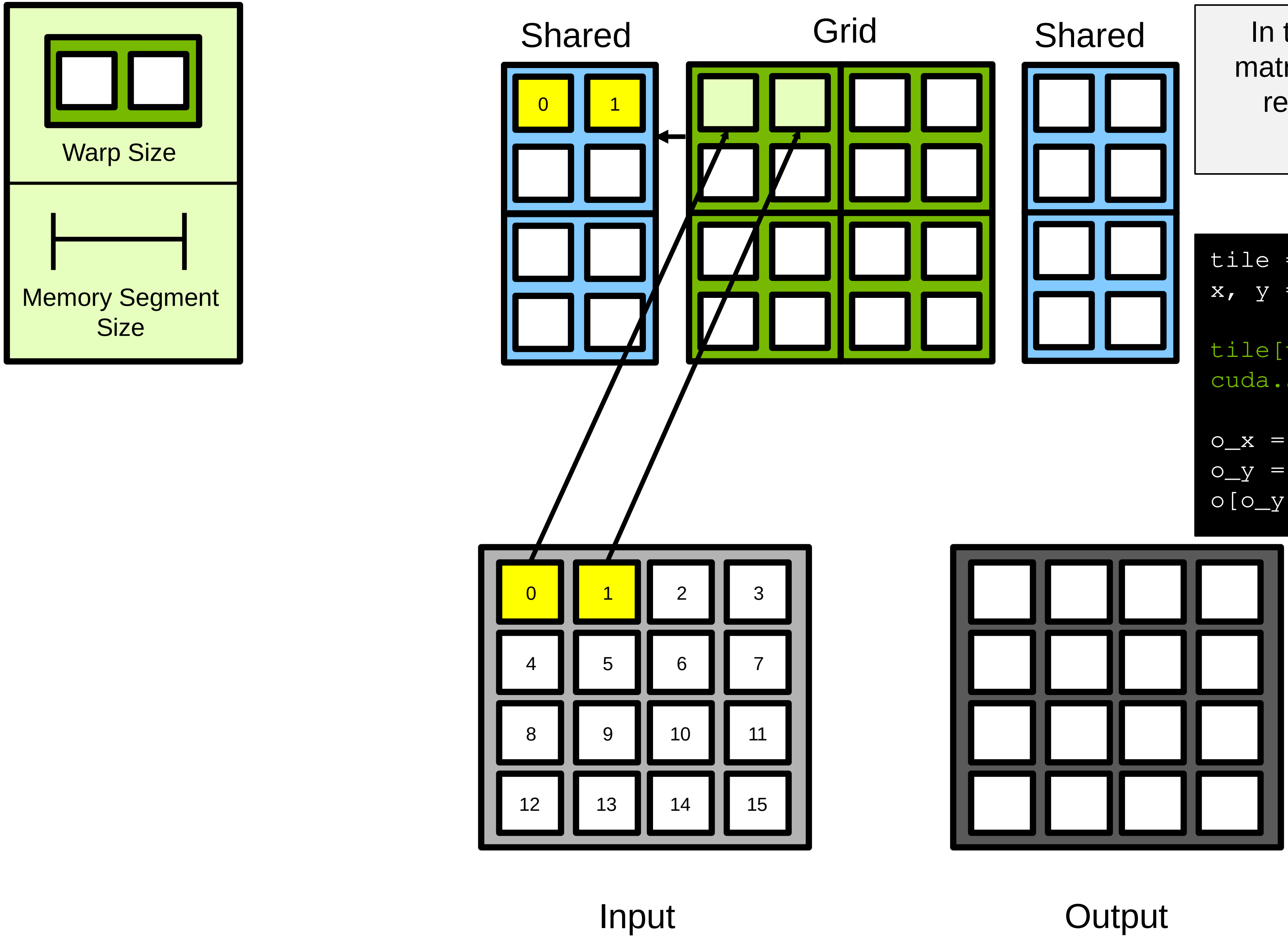

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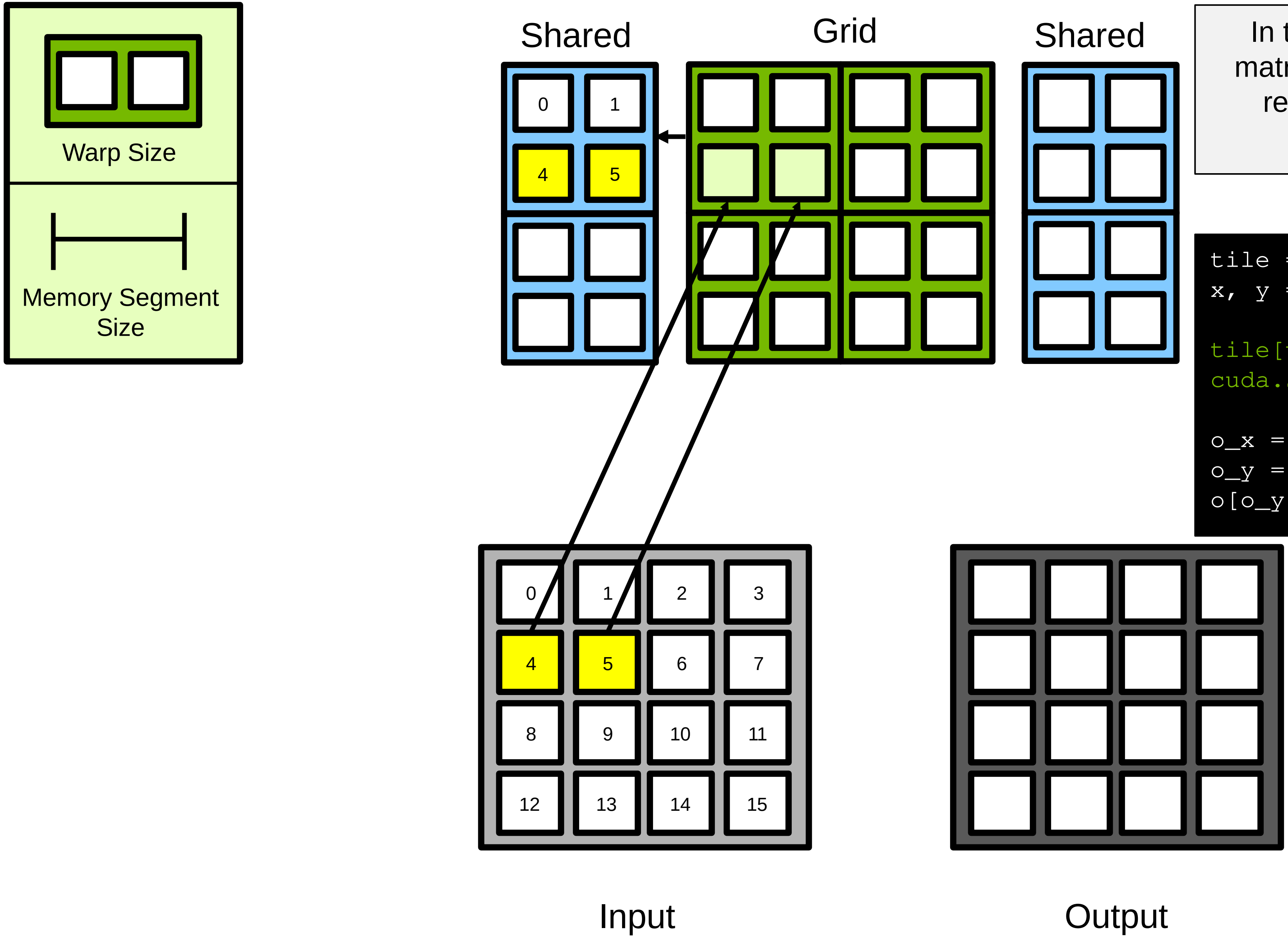

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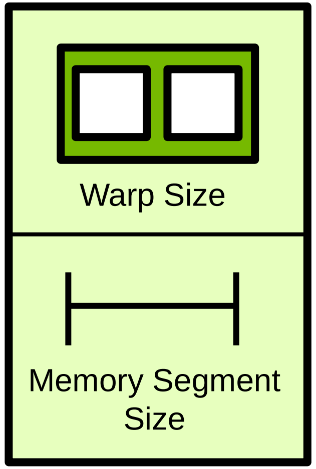

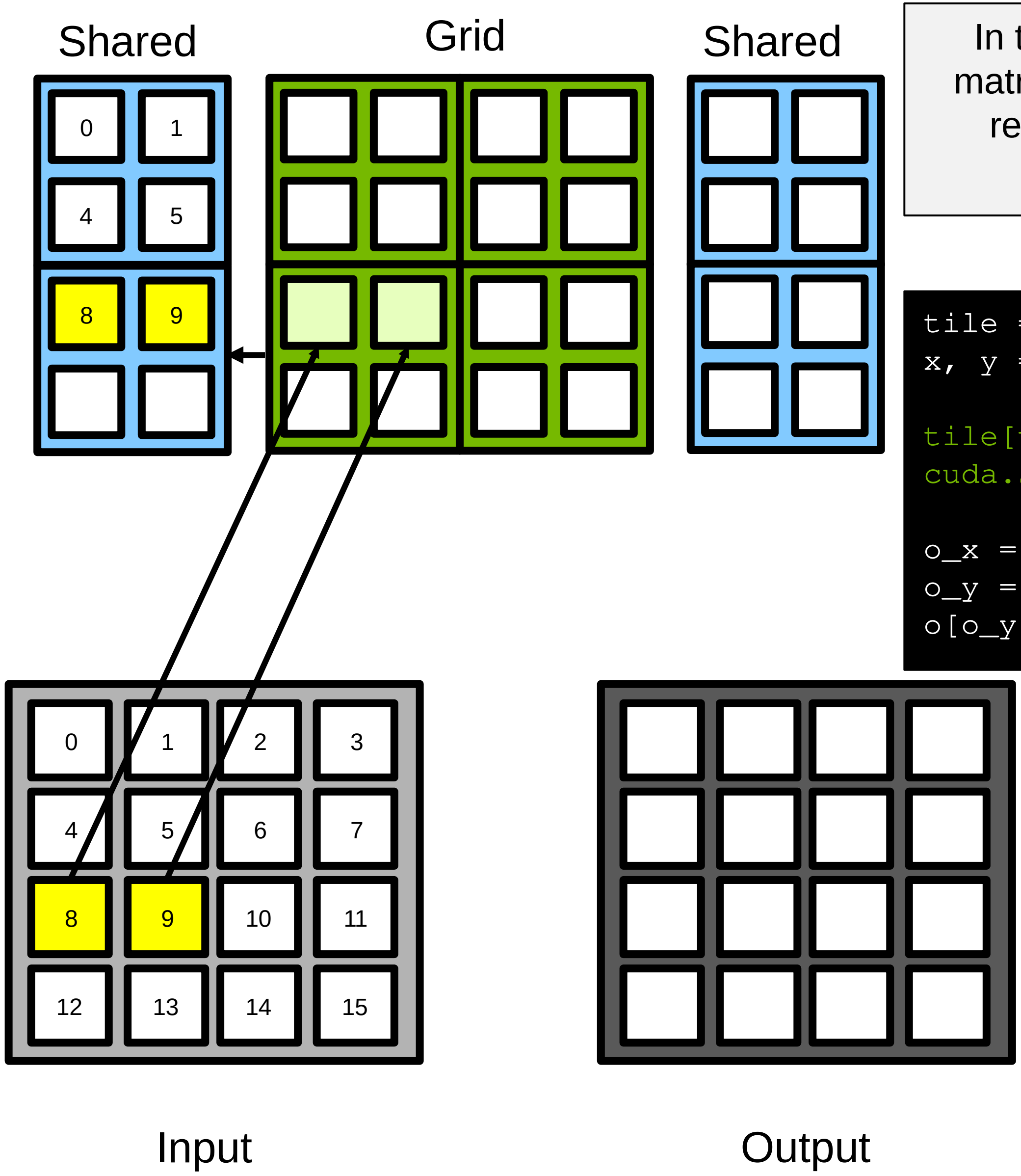

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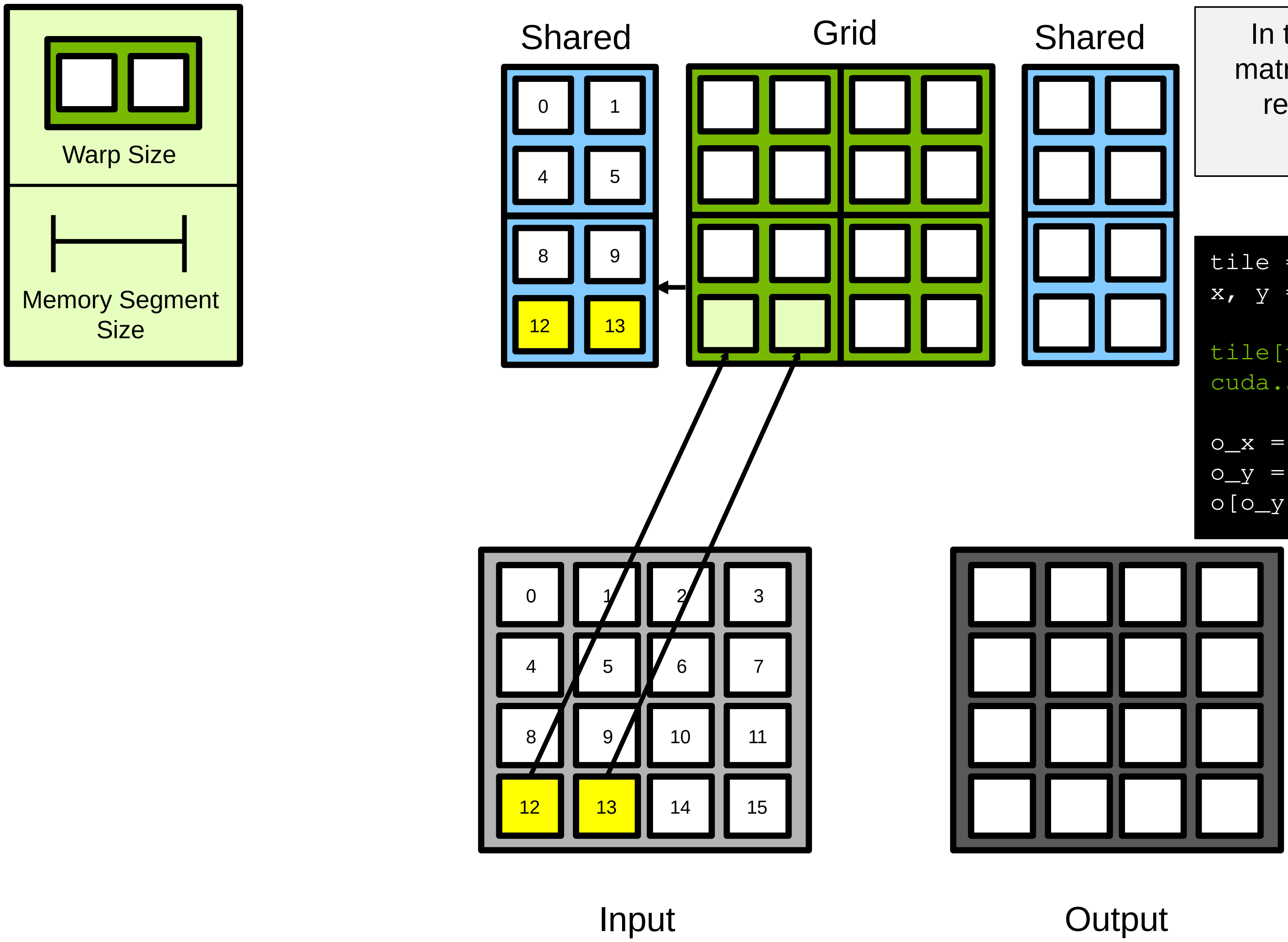

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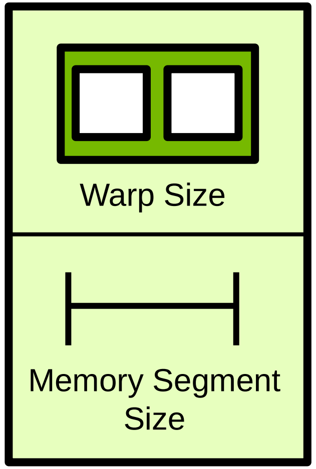

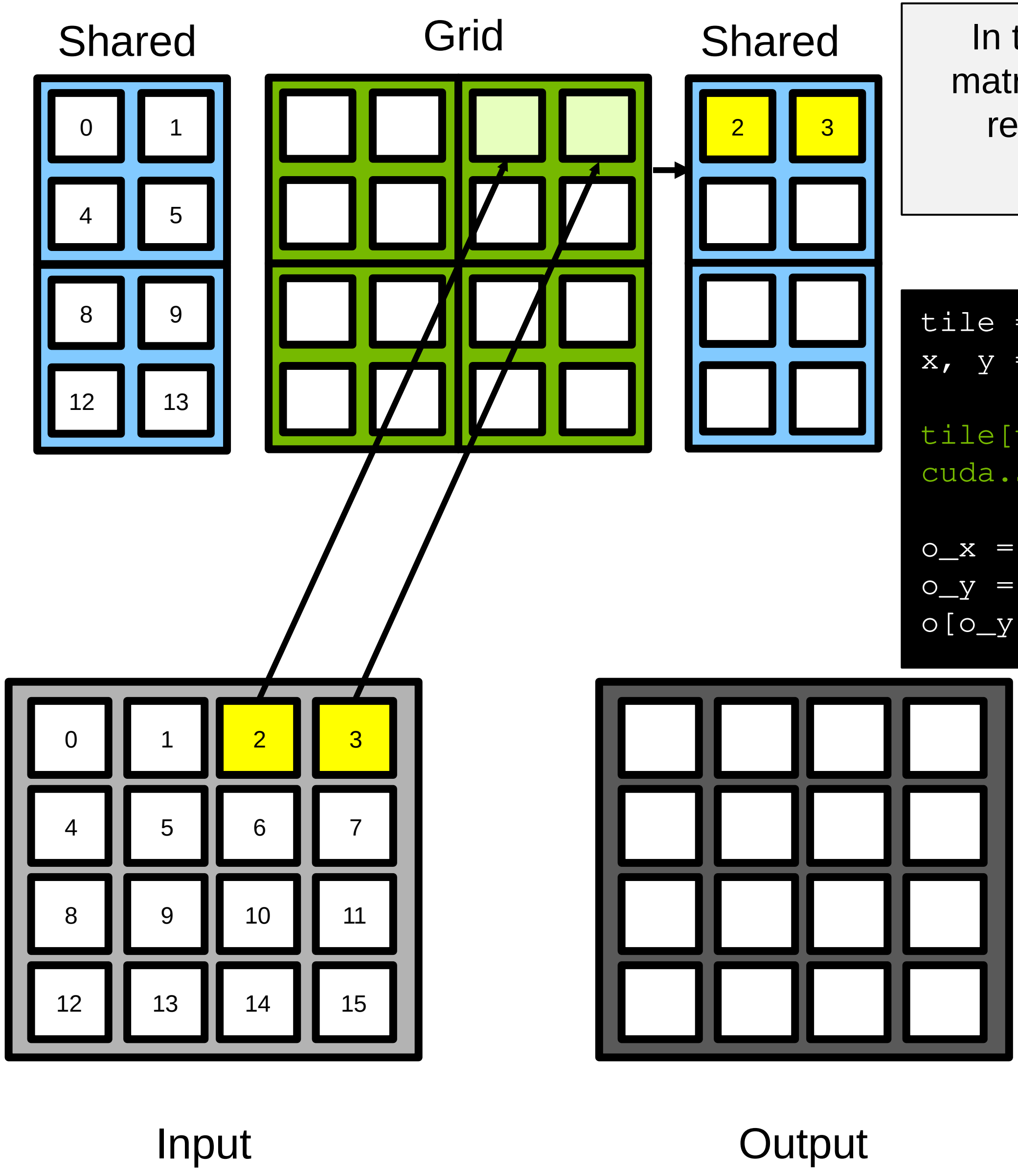

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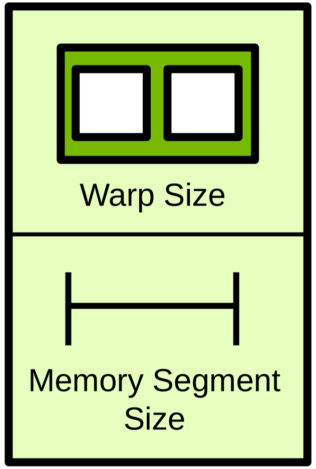

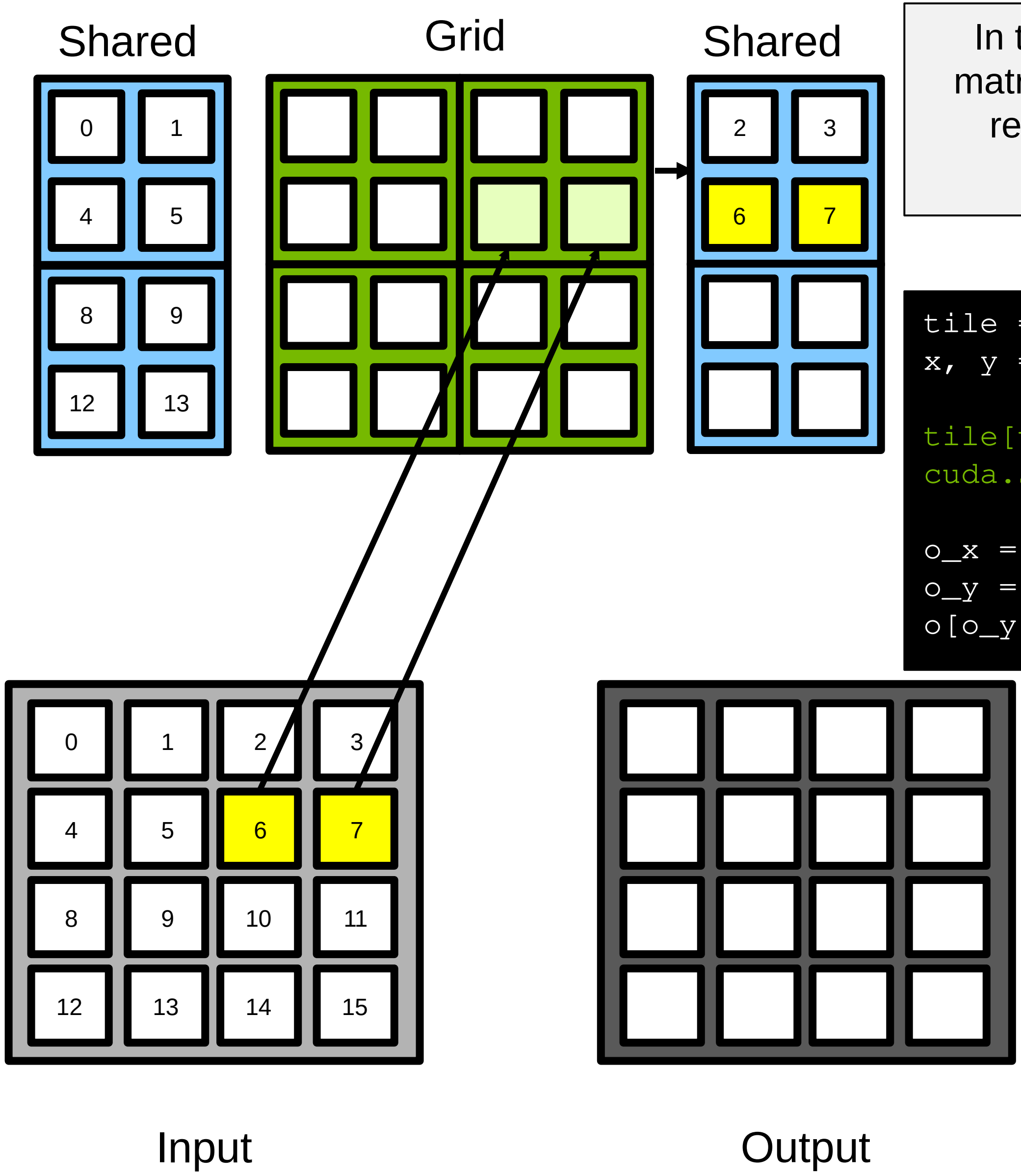

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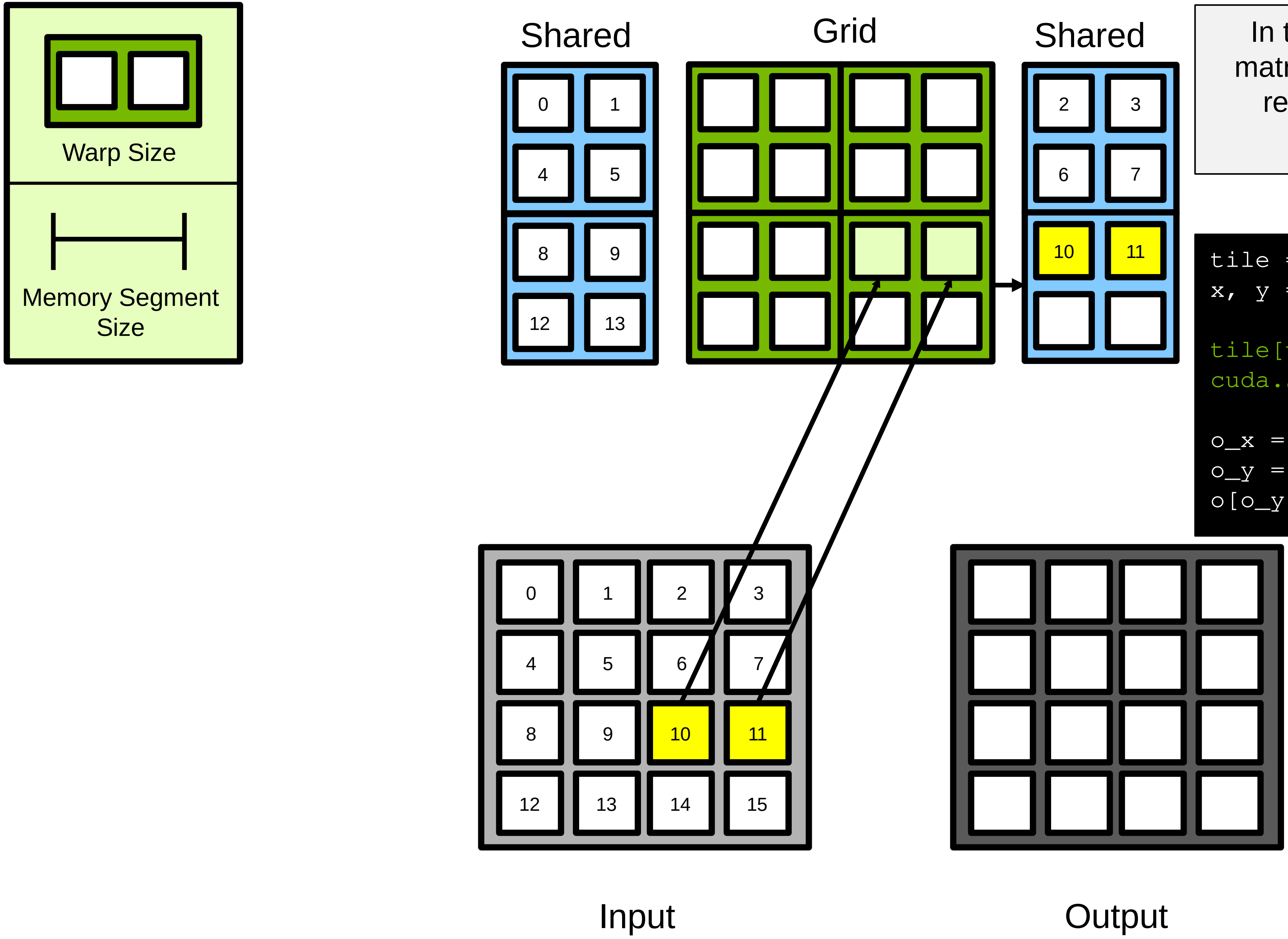

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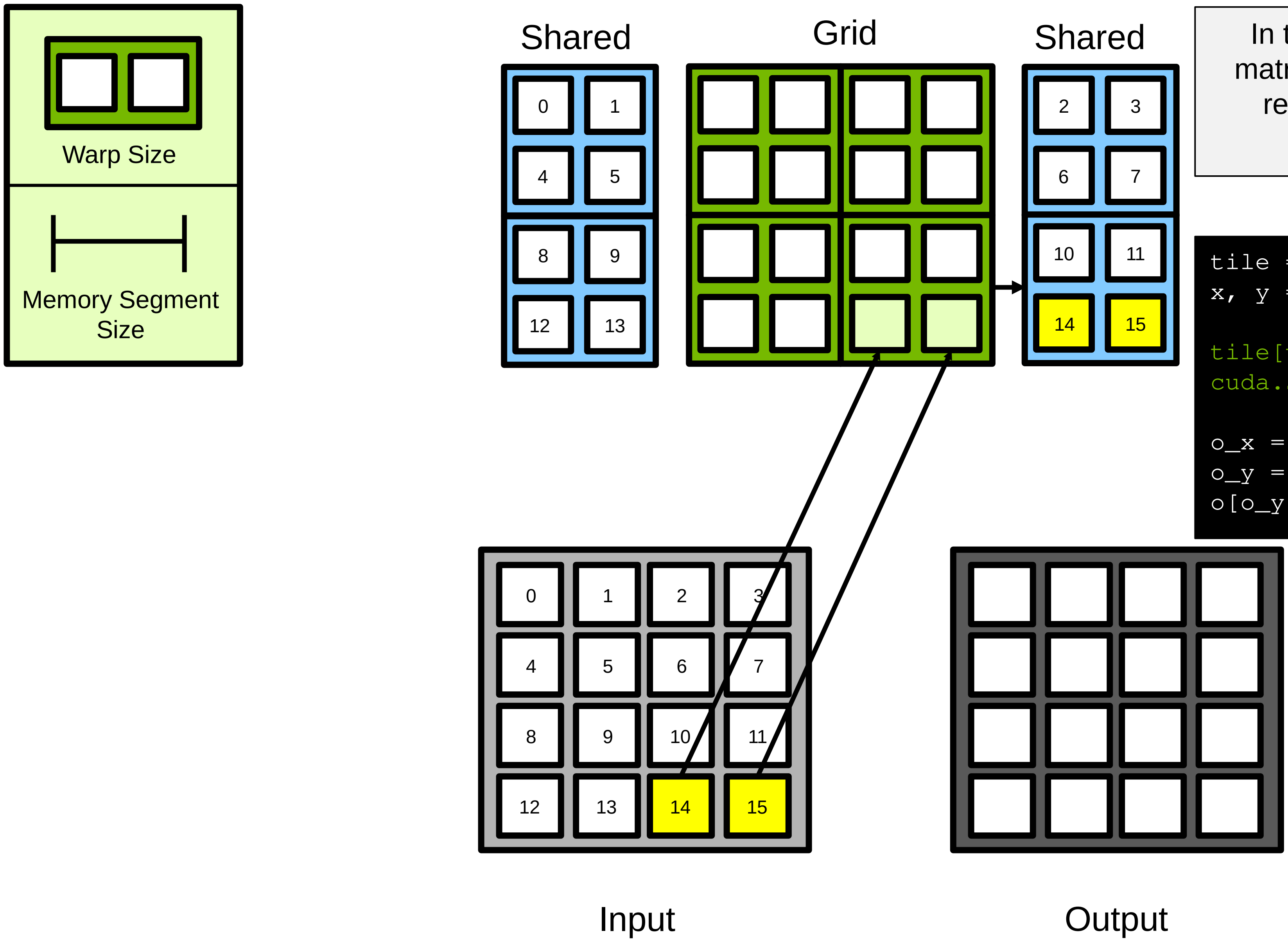

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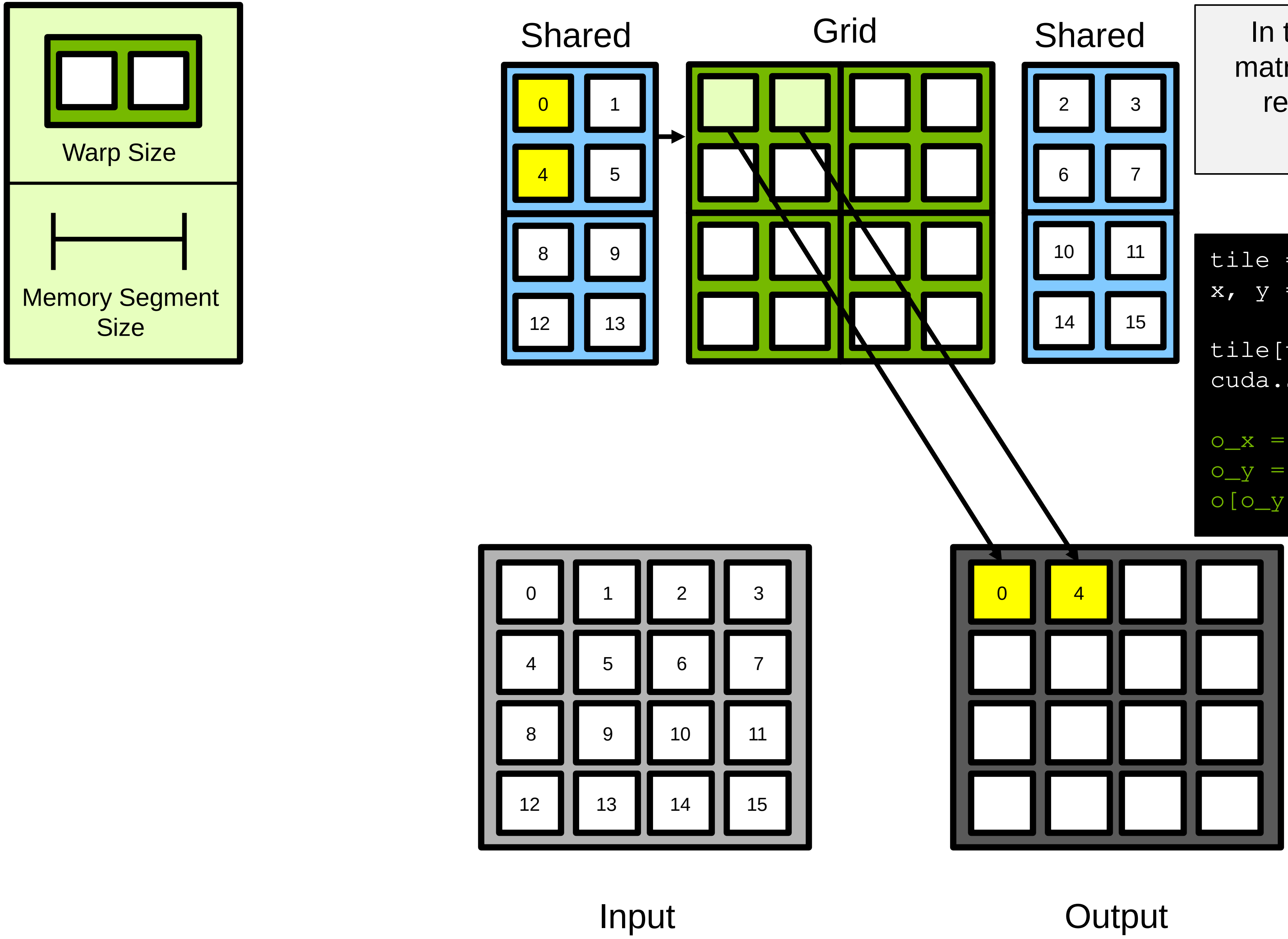

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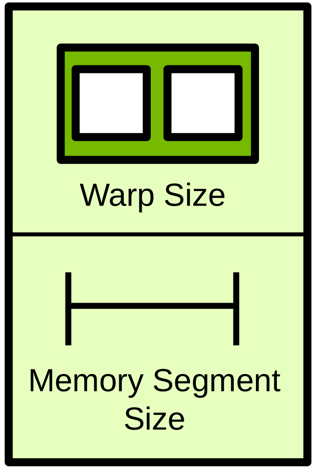

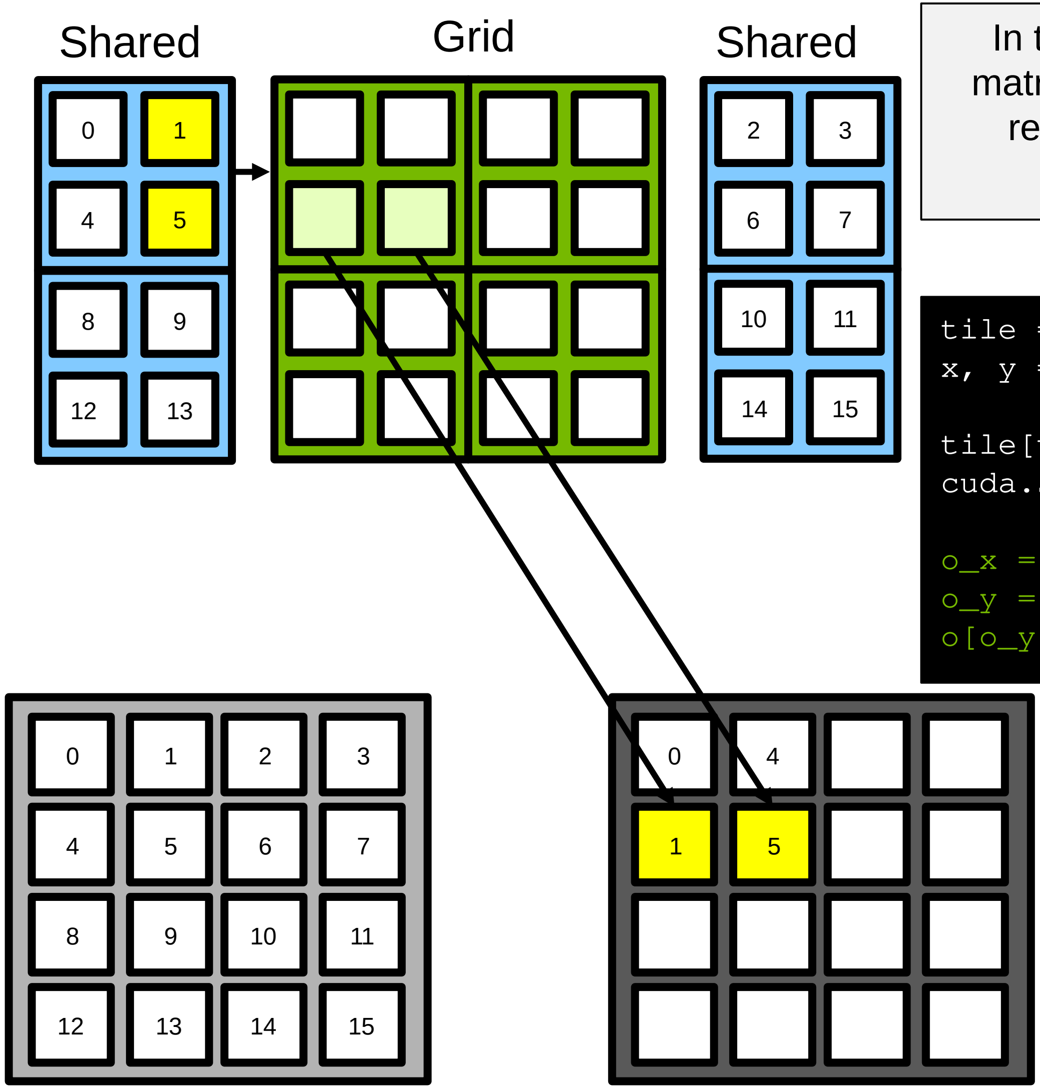

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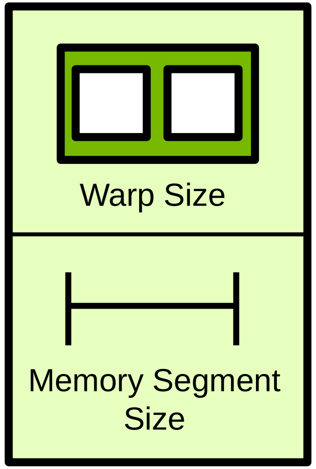
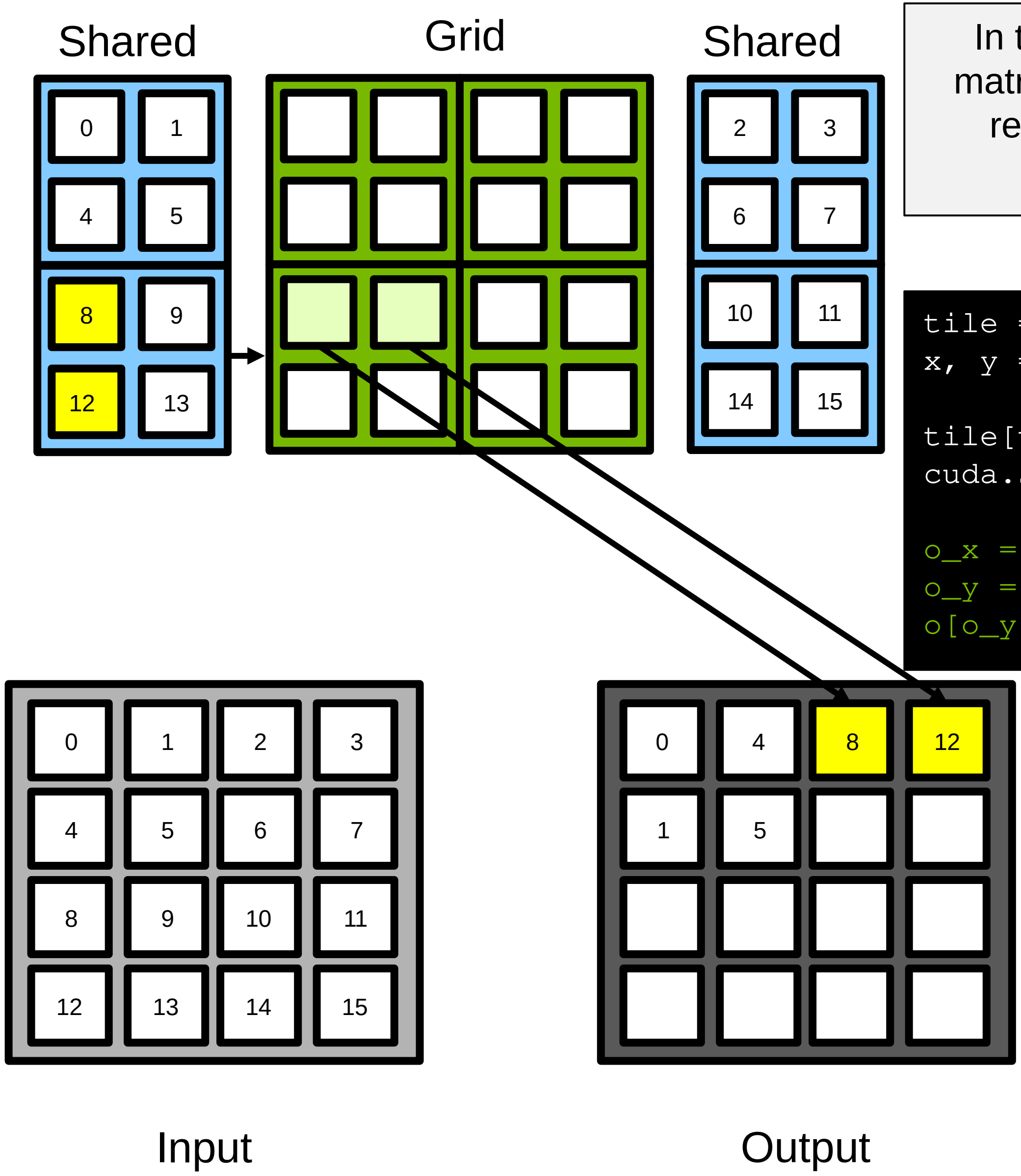
Input

Output





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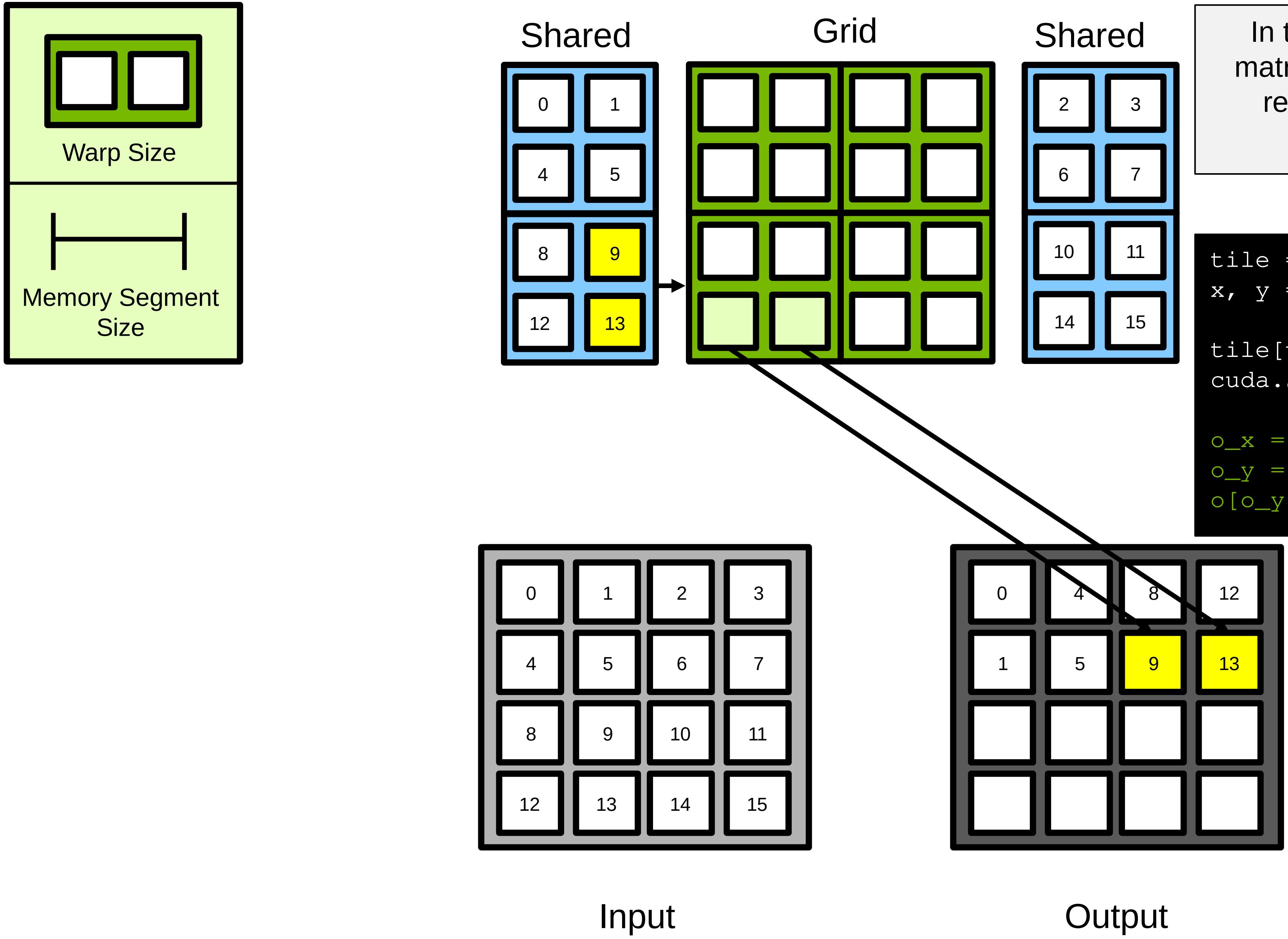

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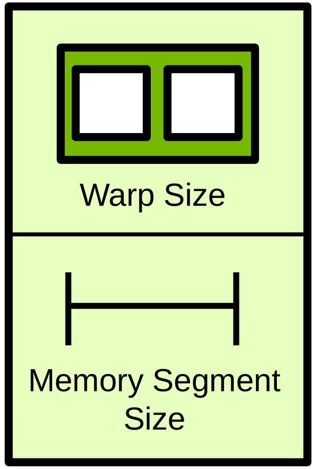

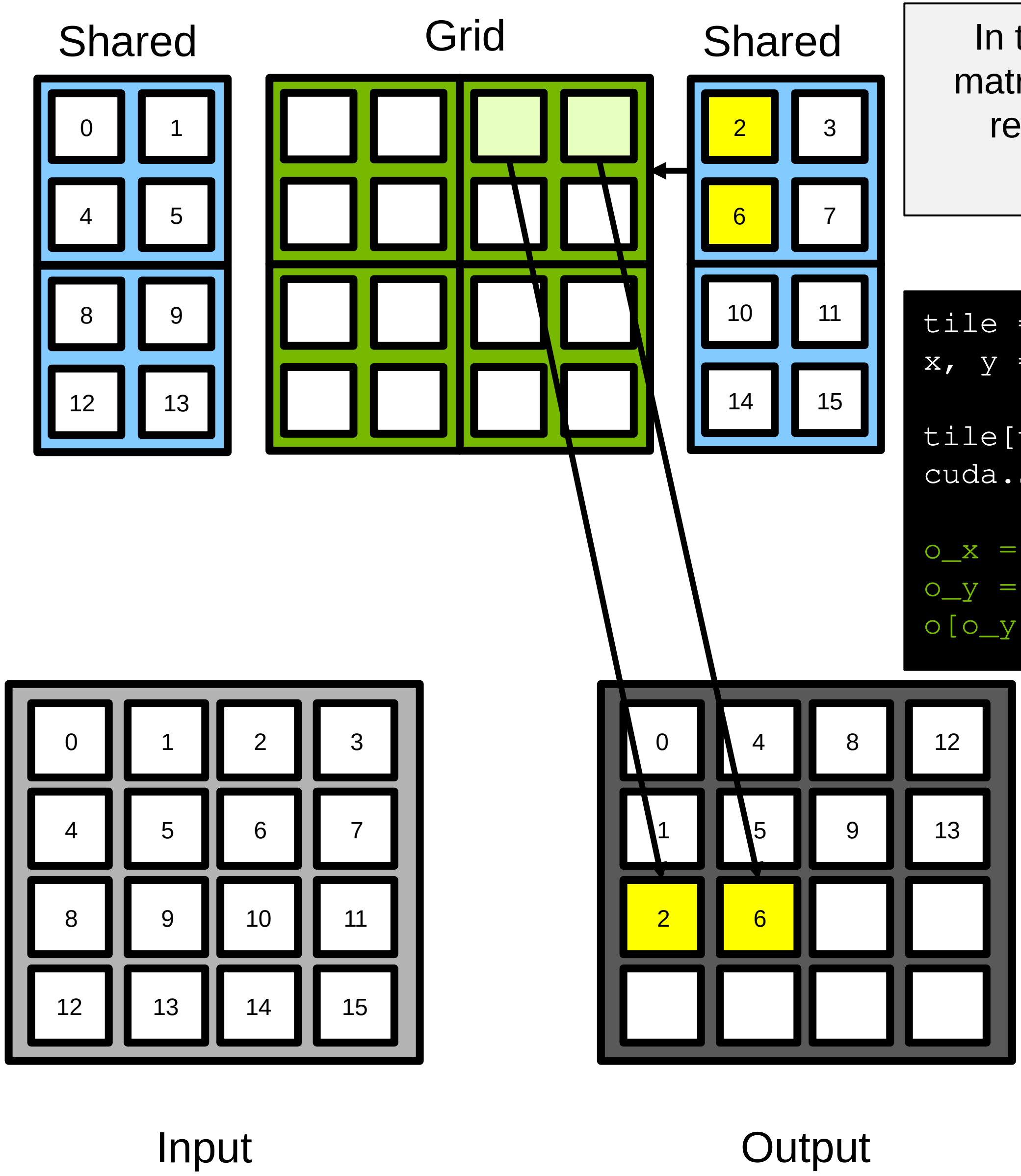

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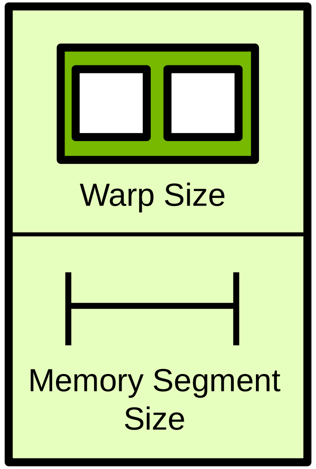

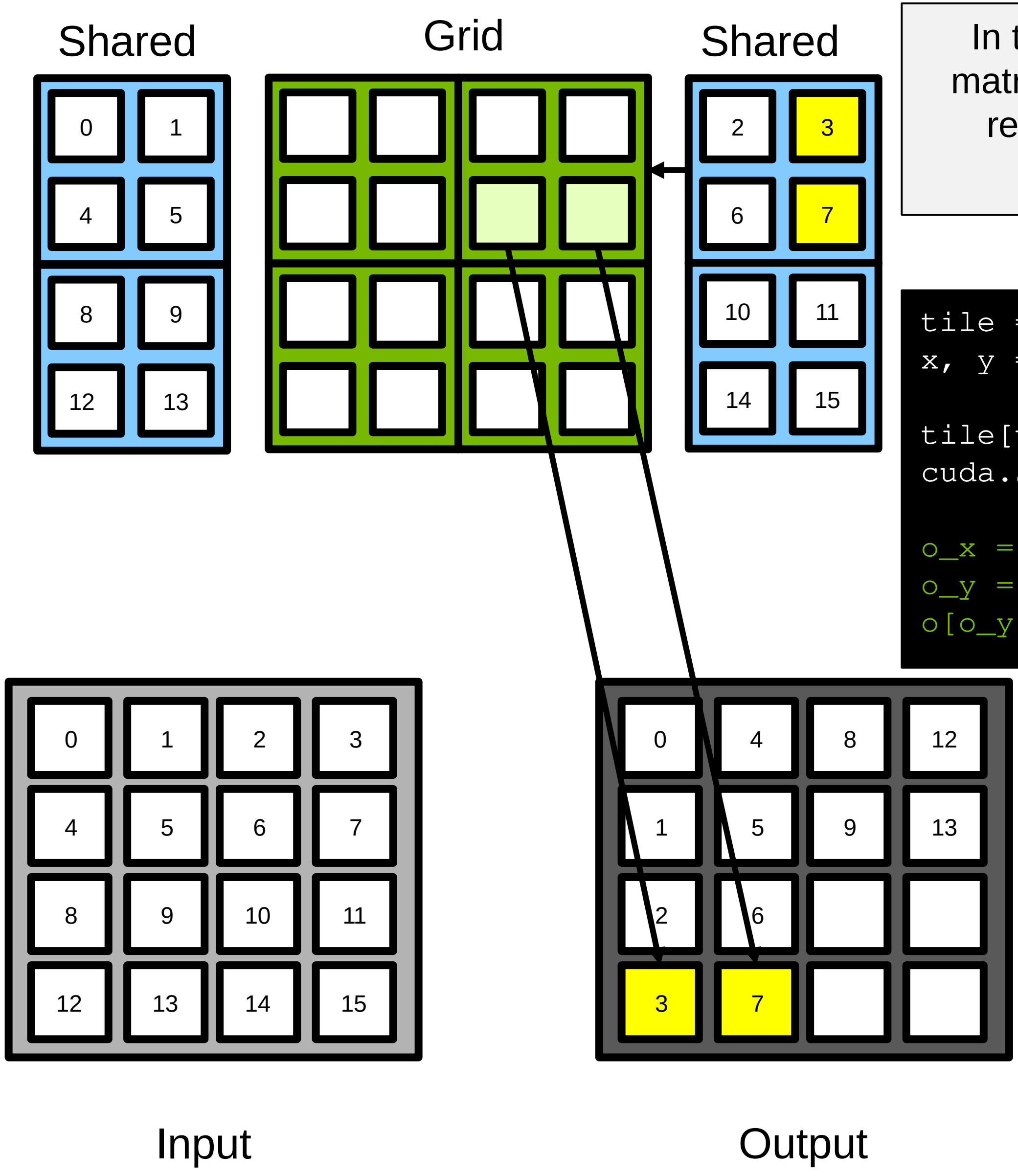

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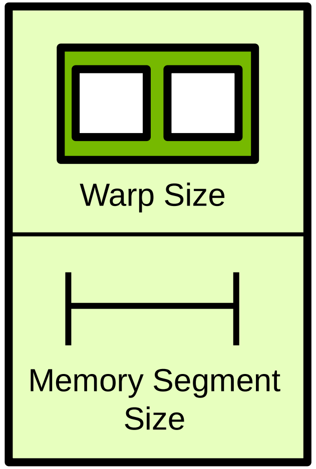

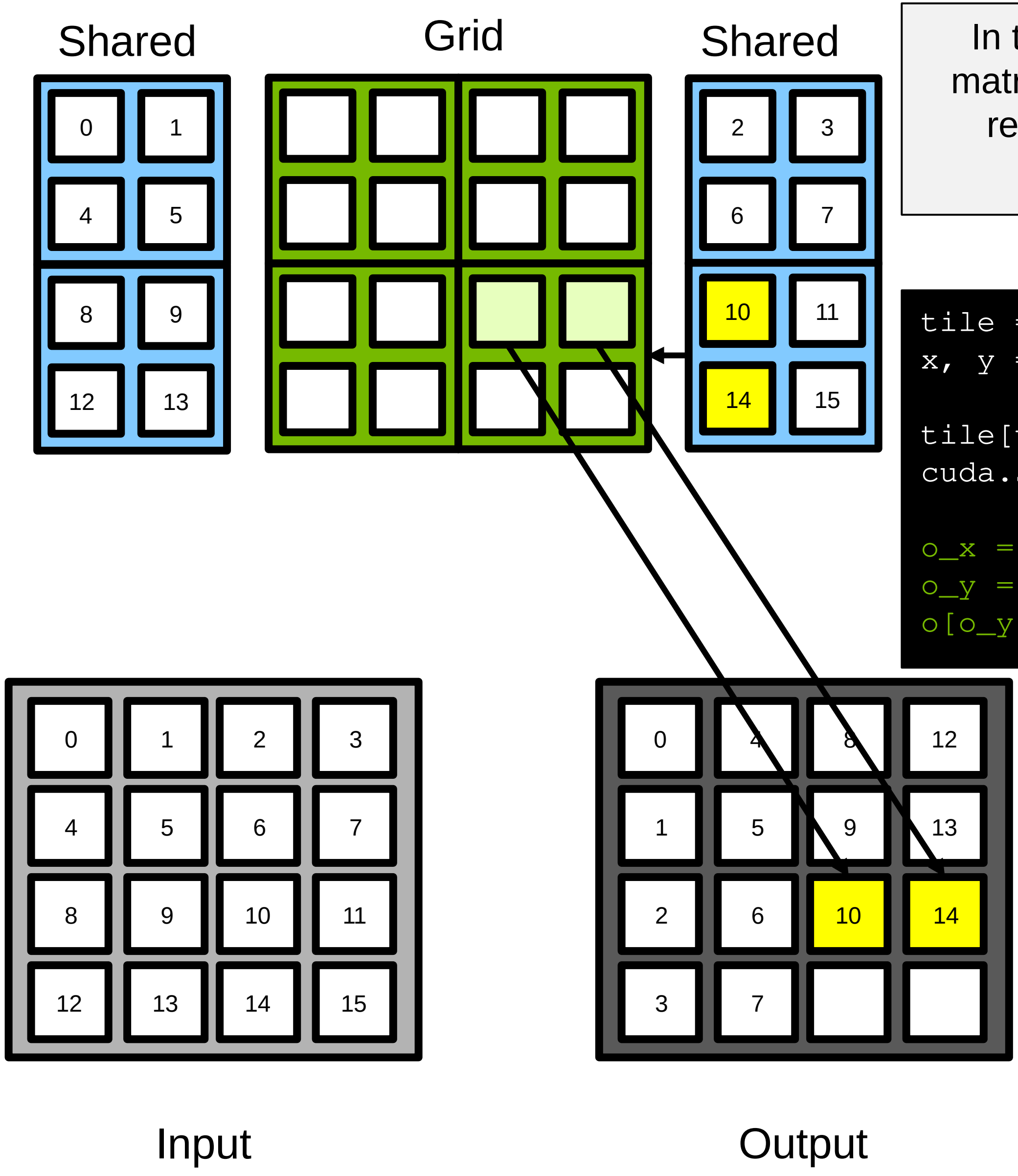

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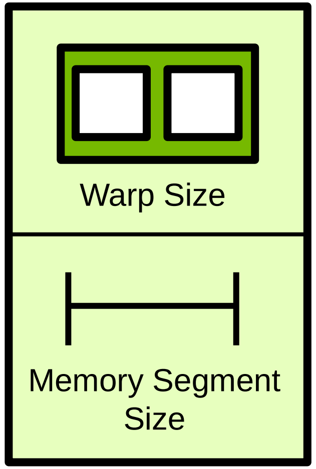

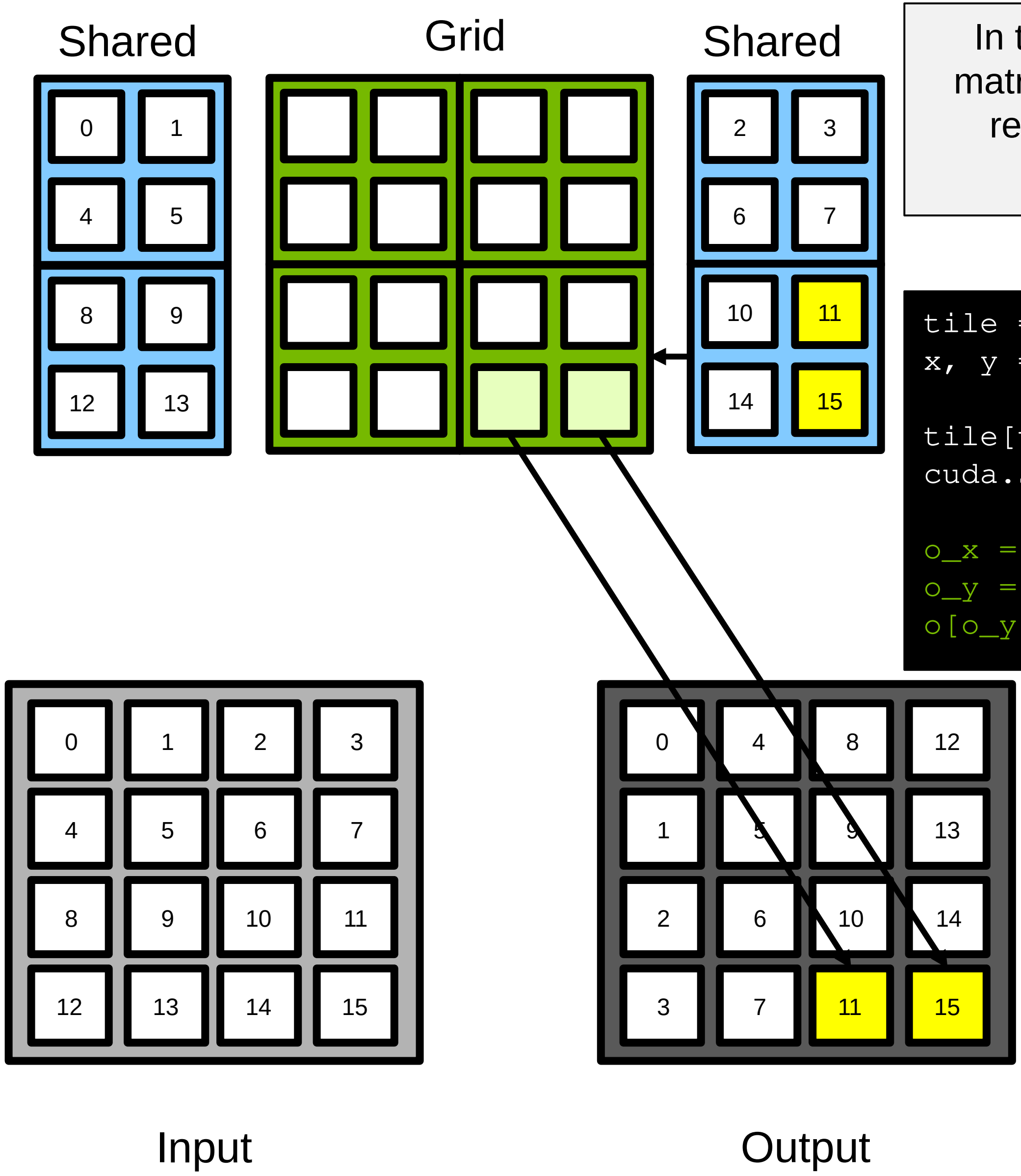

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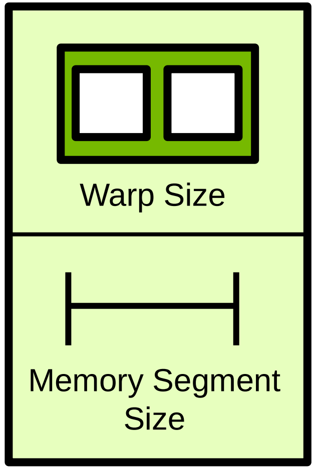

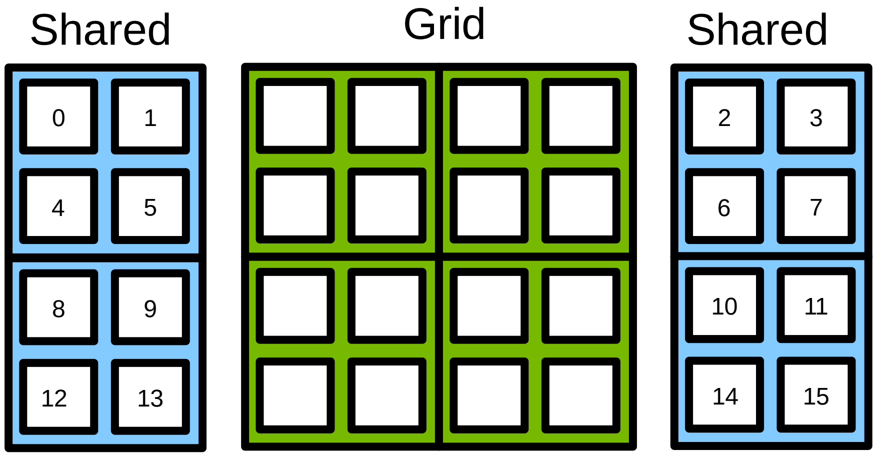

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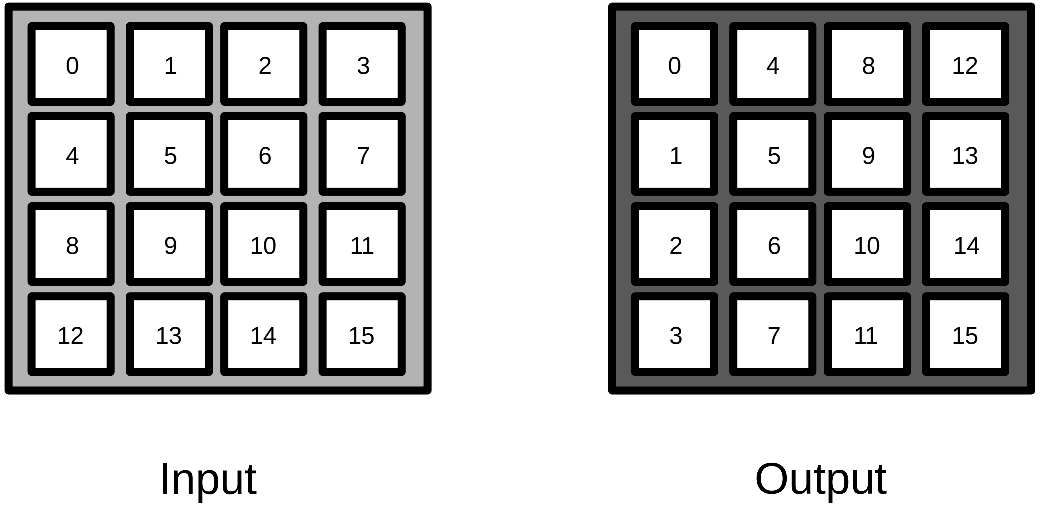

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