

# CSDS 451: Designing High Performant Systems for AI

Lecture 10

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# Outline

- Convolution as Matrix Multiplication – Motivation
- Im2Col and Kn2Row Algorithms
- Scalar Matrix Multiplication Algorithm

# Reading Materials

- Papers on Im2Col, Implicit Im2Col
  - **Original Im2Col:** Chetlur, S., Woolley, C., Vandermersch, P., Cohen, J., Tran, J., Catanzaro, B., & Shelhamer, E. (2014). cudnn: Efficient primitives for deep learning. *arXiv preprint arXiv:1410.0759*.
  - **Implicit Im2Col Nvidia Doc:** <https://docs.nvidia.com/deeplearning/performance/dl-performance-convolutional/index.html>
  - **Implicit Im2Col:** S. Lym, D. Lee, M. O'Connor, N. Chatterjee, and M. Erez, “Delta: Gpu performance model for deep learning applications with in-depth memory system traffic analysis,” in 2019 IEEE International Symposium on Performance Analysis of Systems and Software (ISPASS). IEEE, 2019, pp. 293–303
  - **Implicit Im2Col:** Zhou, Yangjie, et al. "Characterizing and demystifying the implicit convolution algorithm on commercial matrix-multiplication accelerators." *2021 IEEE International Symposium on Workload Characterization (IISWC)*. IEEE, 2021.

# Reading Materials

- **Kn2Row:** Vasudevan, A., Anderson, A., & Gregg, D. (2017, July). Parallel multi channel convolution using general matrix multiplication. In *2017 IEEE 28th international conference on application-specific systems, architectures and processors (ASAP)* (pp. 19-24). IEEE.
- **Scalar Matrix Multiplication:** Ofir, A., & Ben-Artzi, G. (2022). Smm-conv: Scalar matrix multiplication with zero packing for accelerated convolution. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition* (pp. 3067-3075).

# Outline

- Convolution as Matrix Multiplication – Motivation
- Im2Col and Kn2Row Algorithms
- Scalar Matrix Multiplication Algorithm

# Key Operation in CNN

- Forward Propagation:

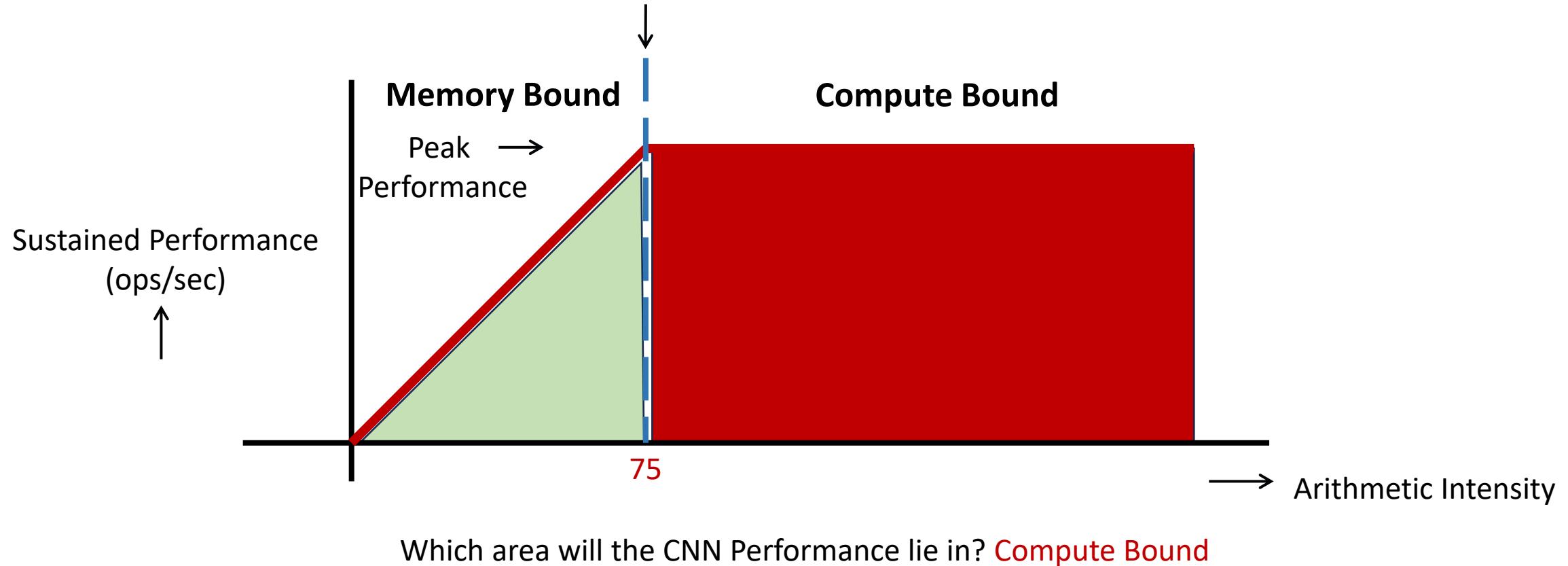
$$O_l = \text{Conv}(W_l, I_l)$$

- Backward Propagation

$$\frac{\delta E(W)}{\delta W_l} = \text{Conv}(I_l, \frac{\delta E(W)}{\delta O_l})$$

$$\frac{\delta E(W)}{\delta O_l} = \text{Conv}(W_{180}, \frac{\delta E(W)}{\delta O_{l+1}})$$

# CNN on A100 Roofline Plot (assuming infinite cache)



# Implications

- Essentially a Compute Bound Problem, assuming large cache
- Objective: How to ensure efficiency is  $O(1)$ , i.e., all compute units are fully utilized
- If cache is limited
  - Objective 1: How to improve data reuse so that compute units have enough to work on?
  - Objective 2: How to ensure efficiency is  $O(1)$ , i.e., all compute units are fully utilized
- Another approach: increase Number of Devices
  - + Larger On-chip memory
  - + Higher bandwidth
  - - Communication/Synchronization overheads

# Convolution as Matrix Multiplications

- Transform the input features and kernels into matrices and perform matrix multiplication.
- Theoretically, matrix multiplication algorithms achieve cost optimality and good data reuse
- Practically, every hardware vendor provides optimized implementations of matrix operations

# Block Matrix Multiplication

- Data Reuse Factor:
- Total Computations -  $O(\sqrt{S}^3 \times \frac{N}{\sqrt{S}} \times \frac{N}{\sqrt{S}} \times \frac{N}{\sqrt{S}})$
- Total data transfers –  $O(\sqrt{S} \times \sqrt{S} \times \frac{N}{\sqrt{S}} \times \frac{N}{\sqrt{S}} \times \frac{N}{\sqrt{S}})$  transfers
- Data Reuse Factor:  $O(\sqrt{S})$

# Blocked Matrix Multiplication

- Serial Algorithm -  $O(n^3)$
- Parallel Algorithm:
- Number of steps  $n/b$
- Work done by each processor in each step:  $O(b)$
- Cost of the algorithm:  $O\left(n^2 \times \left[\frac{n}{b} \times b\right]\right) = O(n^2 \times n) = O(n^3)$
- Cost of the algorithm  $\sim$  serial complexity. So work optimal.

# BLAS – Basic Linear Algebra Subprograms

- A specification describing a set of low level routines for performing common linear algebra operations
- Hardware vendors develop optimized versions for their platform,
- While still conforming to the specification enabling portability

# BLAS – Basic Linear Algebra Subprograms

- Three levels of operations:
- Level 1: Vector Operations such as dot products, vector addition, scaling, etc.
- Level 2: Matrix Vector Operations such as matrix-vector multiplication or
- Level 3: Matrix-Matrix Operations such as matrix multiplications, scaling, etc.

# GEMM – Generalized Matrix Matrix Multiplication

- Matrix Operation of the form

$$C \leftarrow \alpha op(A) \cdot op(B) + \beta C$$

- $\alpha, \beta$ : scalar values
- $A, B, C$ : matrices
- $op$ : transpose operation that is applied if an appropriate parameter is set



# GEMM – Generalized Matrix Matrix Multiplication

# GEMM – Generalized Matrix Matrix Multiplication

```
cublasStatus_t cublasSgemm(cublasHandle_t handle,  
                           cublasOperation_t transa, cublasOperation_t transb,  
                           int m, int n, int k,  
                           const float      *alpha,  
                           const float      *A, int lda,  
                           const float      *B, int ldb,  
                           const float      *beta,  
                           float           *C, int ldc)
```

Parameters that determine whether to transpose the matrix or not:

transa = CUBLAS\_OP\_N -> No transposition  
transa = CUBLAS\_OP\_T -> Transpose  
transa = CUBLAS\_OP\_H -> Hermitian Transpose

# GEMM – Generalized Matrix Matrix Multiplication

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```
cublasStatus_t cublasSgemm(cublasHandle_t handle,  
                           cublasOperation_t transa, cublasOperation_t transb,  
                           int m, int n, int k,  
                           const float      *alpha,  
                           const float      *A, int lda,  
                           const float      *B, int ldb,  
                           const float      *beta,  
                           float           *C, int ldc)
```

Pointers to the matrices (stored as a 1D array), leading dimension of the matrix

float A[12] = {1,2,3, 4,5,6, 7,8,9, 10,11,12};

Lda = 3; -> // 3x4 matrix

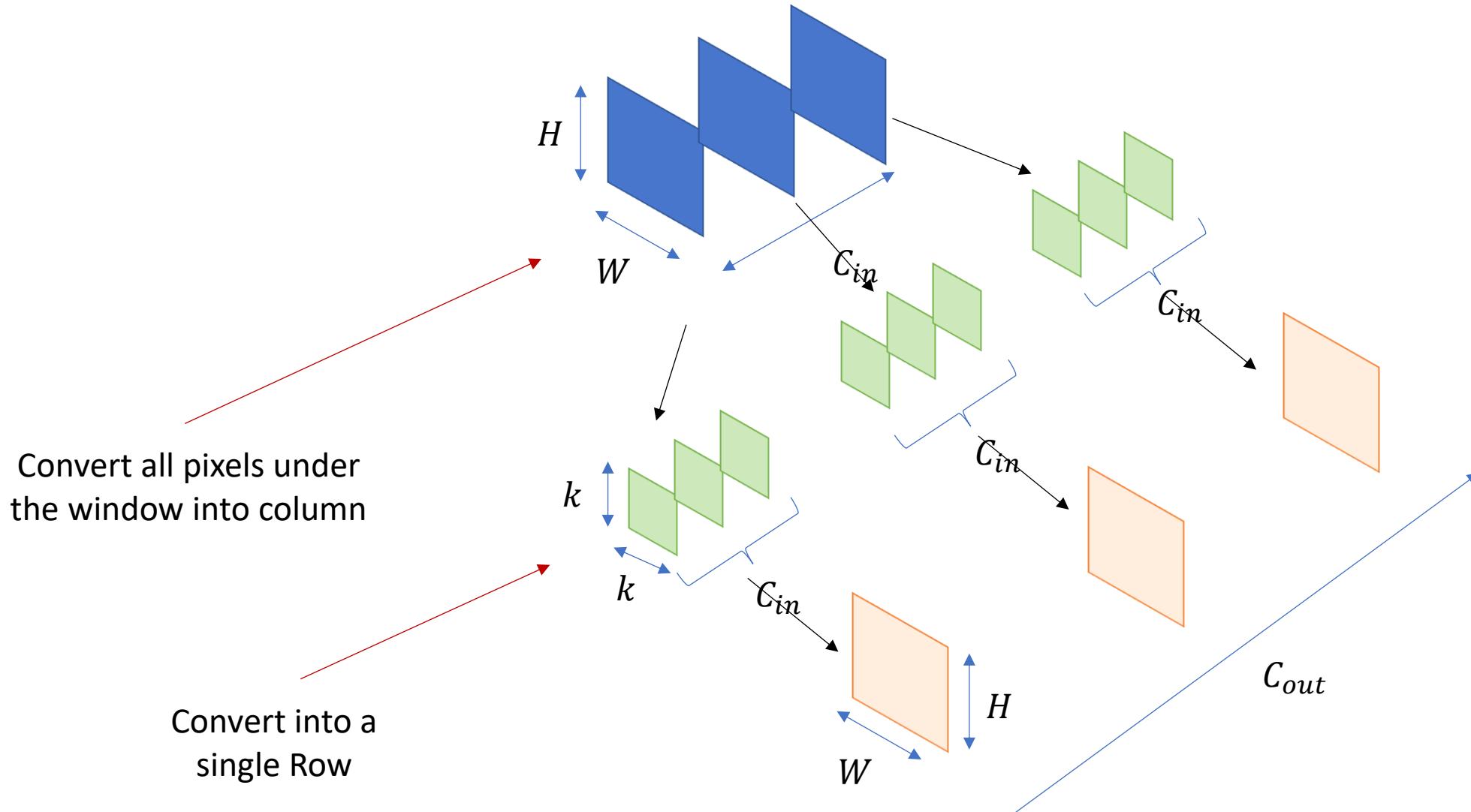
# GEMM – Generalized Matrix Matrix Multiplication

- Several variants exist – different data types, batched matrix multiplications, etc.
- Ungraded HW Assignment: Try out an example on HPC on CPU or GPU
  - Find out what library to use for the CPU and the GPU
  - Find out how to properly setup the matrices and make the call
- We will discuss the AMD library for BLAS when we study AMD HIP

# Outline

- Convolution as Matrix Multiplication – Motivation
- **Im2Col and Kn2Row Algorithms**
- Scalar Matrix Multiplication Algorithm

# Im2col Algorithm



# Im2col Algorithm

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$

$W_1$	$W_2$
$W_3$	$W_4$



$I_1$
$I_2$
$I_5$
$I_6$

Single Input Single Output Channel

# Im2col Algorithm

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$

$W_1$	$W_2$
$W_3$	$W_4$



$I_1$	$I_2$
$I_2$	$I_3$
$I_5$	$I_6$
$I_6$	$I_7$

Single Input Single Output Channel

# Im2col Algorithm

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$

$W_1$	$W_2$
$W_3$	$W_4$



$I_1$	$I_2$	$I_3$
$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$
$I_6$	$I_7$	$I_8$

Single Input Single Output Channel

# Im2col Algorithm

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$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$

$W_1$	$W_2$
$W_3$	$W_4$



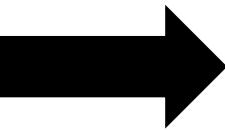
$I_1$	$I_2$	$I_3$
$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$
$I_6$	$I_7$	$I_8$
...		

Single Input Single Output Channel

# Im2col Algorithm

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
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$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$

$W_1$	$W_2$
$W_3$	$W_4$



$I_1$	$I_2$	$I_3$
$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$
$I_6$	$I_7$	$I_8$
...		



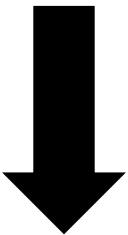
$W_1$	$W_2$	$W_3$	$W_4$
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Single Input Single Output Channel

# Im2col Algorithm

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$

$W_1$	$W_2$
$W_3$	$W_4$



$I_1$	$I_2$	$I_3$
$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$
$I_6$	$I_7$	$I_8$

...

How many columns?

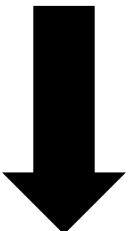
$W_1$	$W_2$	$W_3$	$W_4$
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Single Input Single Output Channel

# Im2col Algorithm

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$

$W_1$	$W_2$
$W_3$	$W_4$



$I_1$	$I_2$	$I_3$
$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$
$I_6$	$I_7$	$I_8$
...		

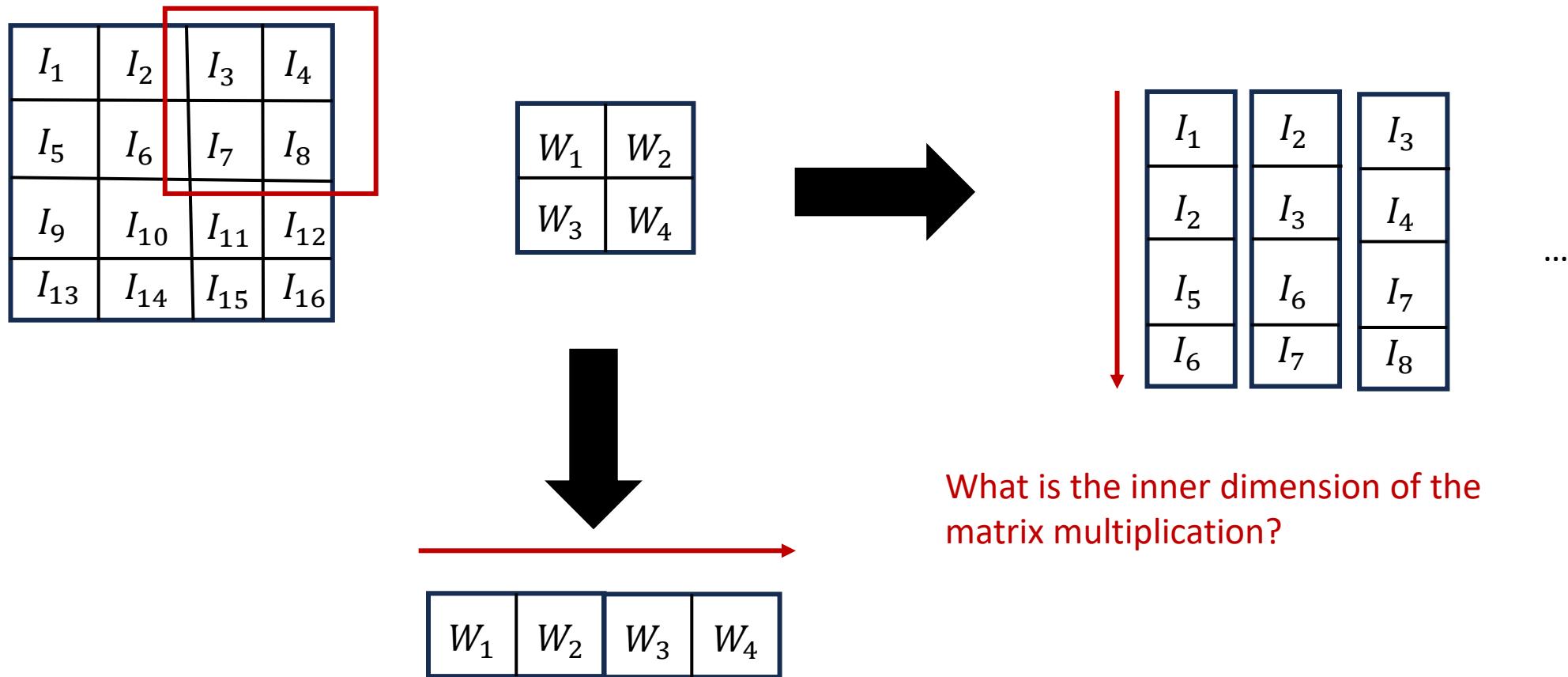
How many columns?

$$H \times W$$

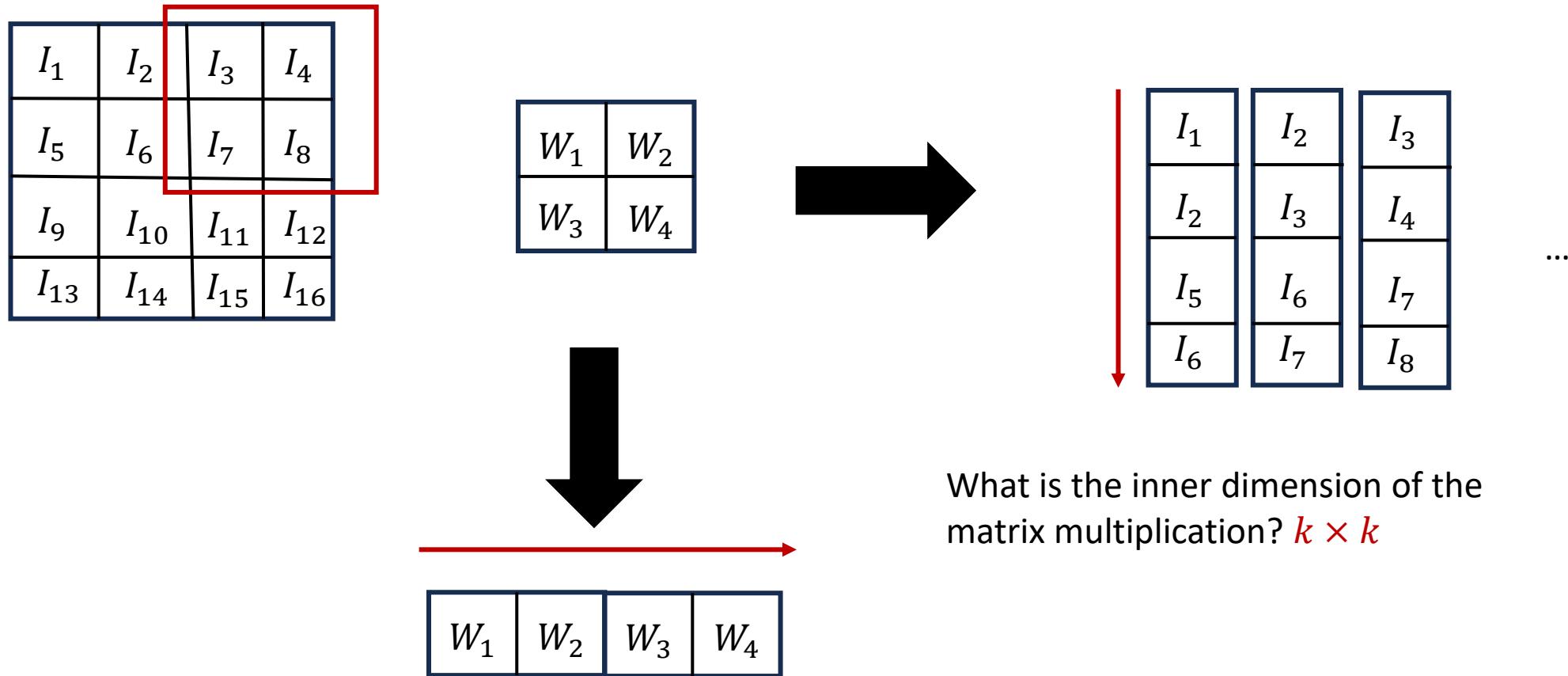
$W_1$	$W_2$	$W_3$	$W_4$
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Single Input Single Output Channel

# Im2col Algorithm



# Im2col Algorithm



What is the inner dimension of the matrix multiplication?  $k \times k$

Single Input Single Output Channel

# Im2col Algorithm

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$



$I_1$	$I_2$	$I_3$
$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$
$I_6$	$I_7$	$I_8$

$I_1$	$I_2$	$I_3$
$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$
$I_6$	$I_7$	$I_8$

$W_1$	$W_2$
$W_3$	$W_4$

$W_1$	$W_2$
$W_3$	$W_4$



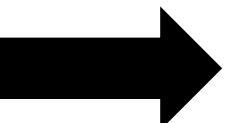
$W_1$	$W_2$	$W_3$	$W_4$	$W_1$	$W_2$	$W_3$	$W_4$
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Multiple Input Single Output Channel

# Im2col Algorithm

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$



$I_1$	$I_2$	$I_3$
$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$
$I_6$	$I_7$	$I_8$

$I_1$	$I_2$	$I_3$
$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$
$I_6$	$I_7$	$I_8$

Notice: Input channels increase the row dimension of weight matrix and column dimension of the input feature matrix

$W_1$	$W_2$
$W_3$	$W_4$

$W_1$	$W_2$
$W_3$	$W_4$



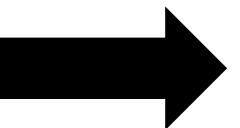
$W_1$	$W_2$	$W_3$	$W_4$	$W_1$	$W_2$	$W_3$	$W_4$
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Multiple Input Single Output Channel

# Im2col Algorithm

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$


 $k \times k \times C_{in}$ 

$I_1$	$I_2$	$I_3$
$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$
$I_6$	$I_7$	$I_8$

$I_1$	$I_2$	$I_3$
$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$
$I_6$	$I_7$	$I_8$

$W_1$	$W_2$
$W_3$	$W_4$

$W_1$	$W_2$
$W_3$	$W_4$


 $k \times k \times C_{in}$ 

$W_1$	$W_2$
$W_3$	$W_4$

$W_1$	$W_2$
$W_3$	$W_4$



$W_1$	$W_2$	$W_3$	$W_4$	$W_1$	$W_2$	$W_3$	$W_4$
-------	-------	-------	-------	-------	-------	-------	-------

$W_1$	$W_2$	$W_3$	$W_4$	$W_1$	$W_2$	$W_3$	$W_4$
-------	-------	-------	-------	-------	-------	-------	-------

 $C_{out}$ 

Multiple Input Single Multiple Channel

 $H \times W$

# Im2Col Algorithm

- Input Matrix -  $(k \times k \times C_{in}) \times (H \times W)$ 
  - $k \times k$  increase in size
- Filter Matrix -  $(C_{out}) \times (k \times k \times C_{in})$ 
  - No increase in size
- Output Matrix -  $C_{out} \times (H \times W)$ 
  - No increase in size

# Implicit GEMM based Im2Col

- In practice, the input matrix is not duplicated
- Rather tiles/blocks are fetched into the shared cache of SMP by indexing appropriate addresses

# Im2col Algorithm

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$

$W_1$	$W_2$
$W_3$	$W_4$

$W_1$	$W_2$
$W_3$	$W_4$

DRAM

$W_1$	$W_2$
$W_3$	$W_4$

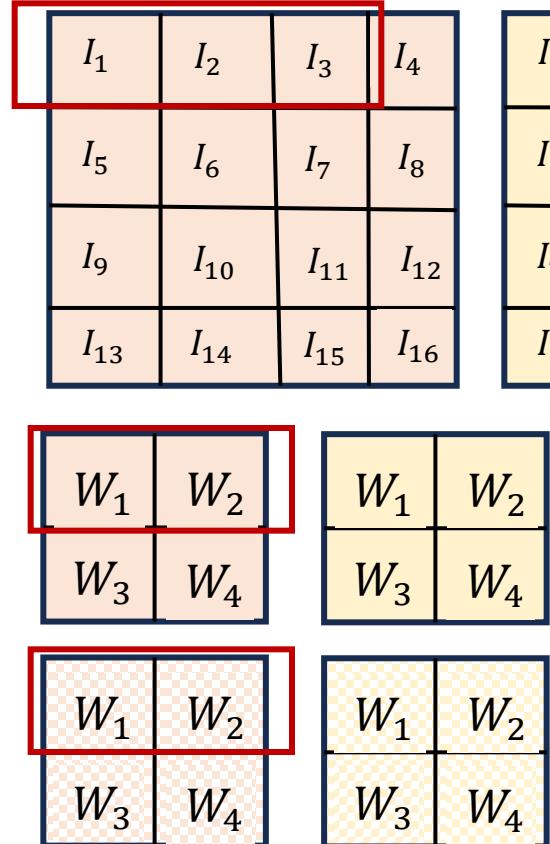
$W_1$	$W_2$
$W_3$	$W_4$

Assume blocked matrix multiplication with block sizes of  $2 \times 2$

$I_1$	$I_2$	$I_3$
$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$
$I_6$	$I_7$	$I_8$
$I_1$	$I_2$	$I_3$
$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$
$I_6$	$I_7$	$I_8$

$W_1$	$W_2$	$W_3$	$W_4$	$W_1$	$W_2$	$W_3$	$W_4$
$W_1$	$W_2$	$W_3$	$W_4$	$W_1$	$W_2$	$W_3$	$W_4$

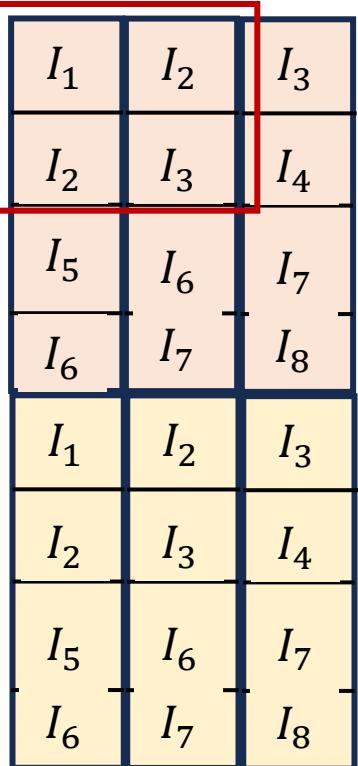
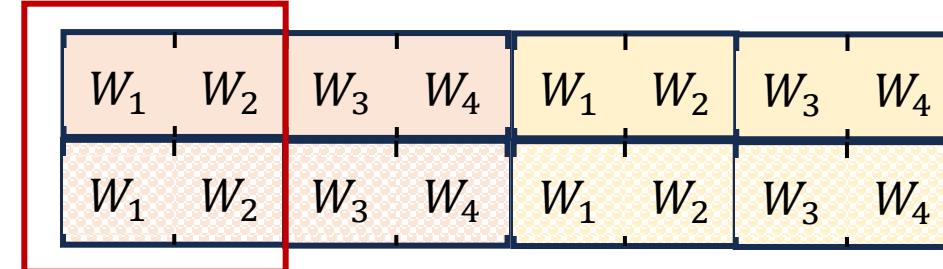
# Im2col Algorithm



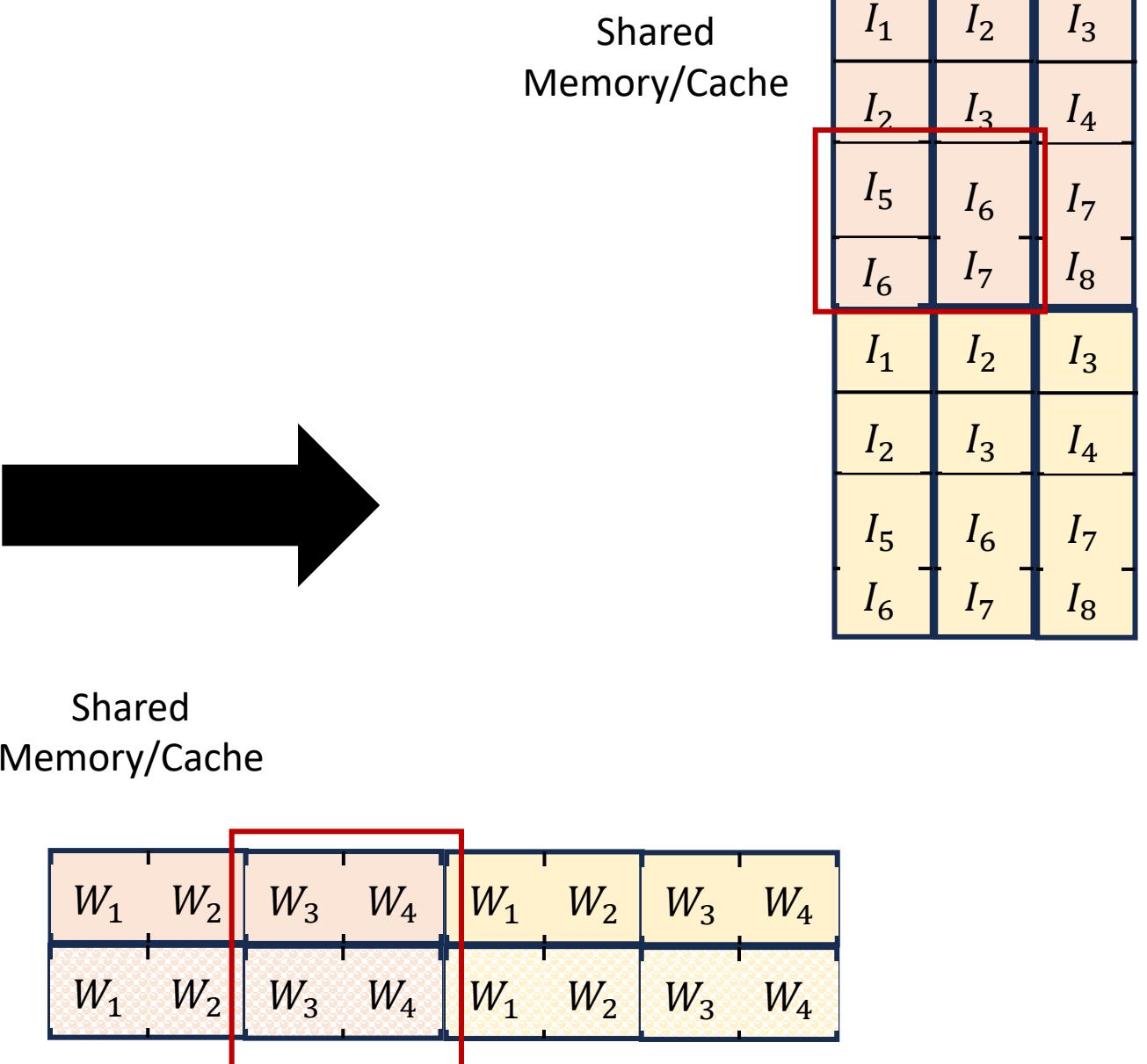
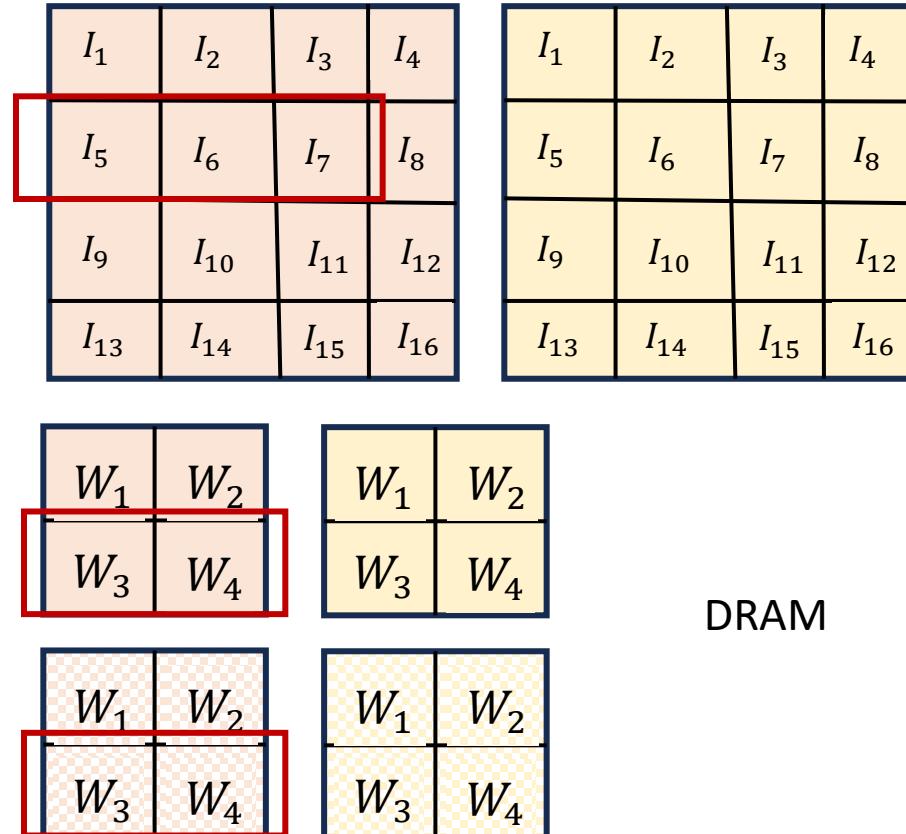
Shared  
Memory/Cache



Shared  
Memory/Cache



# Im2col Algorithm



# Im2col Algorithm

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
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$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$

$W_1$	$W_2$
$W_3$	$W_4$

$W_1$	$W_2$
$W_3$	$W_4$

$W_1$	$W_2$
$W_3$	$W_4$

DRAM



Shared  
Memory/Cache

$W_1$	$W_2$	$W_3$	$W_4$	$W_1$	$W_2$	$W_3$	$W_4$
$W_1$	$W_2$	$W_3$	$W_4$	$W_1$	$W_2$	$W_3$	$W_4$

Shared  
Memory/Cache

$I_1$	$I_2$	$I_3$
$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$
$I_6$	$I_7$	$I_8$

$I_1$	$I_2$	$I_3$
$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$
$I_6$	$I_7$	$I_8$

# Im2col Algorithm

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
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$W_1$	$W_2$
$W_3$	$W_4$

$W_1$	$W_2$
$W_3$	$W_4$

$W_1$	$W_2$
$W_3$	$W_4$

$W_1$	$W_2$
$W_3$	$W_4$

DRAM

Shared  
Memory/Cache

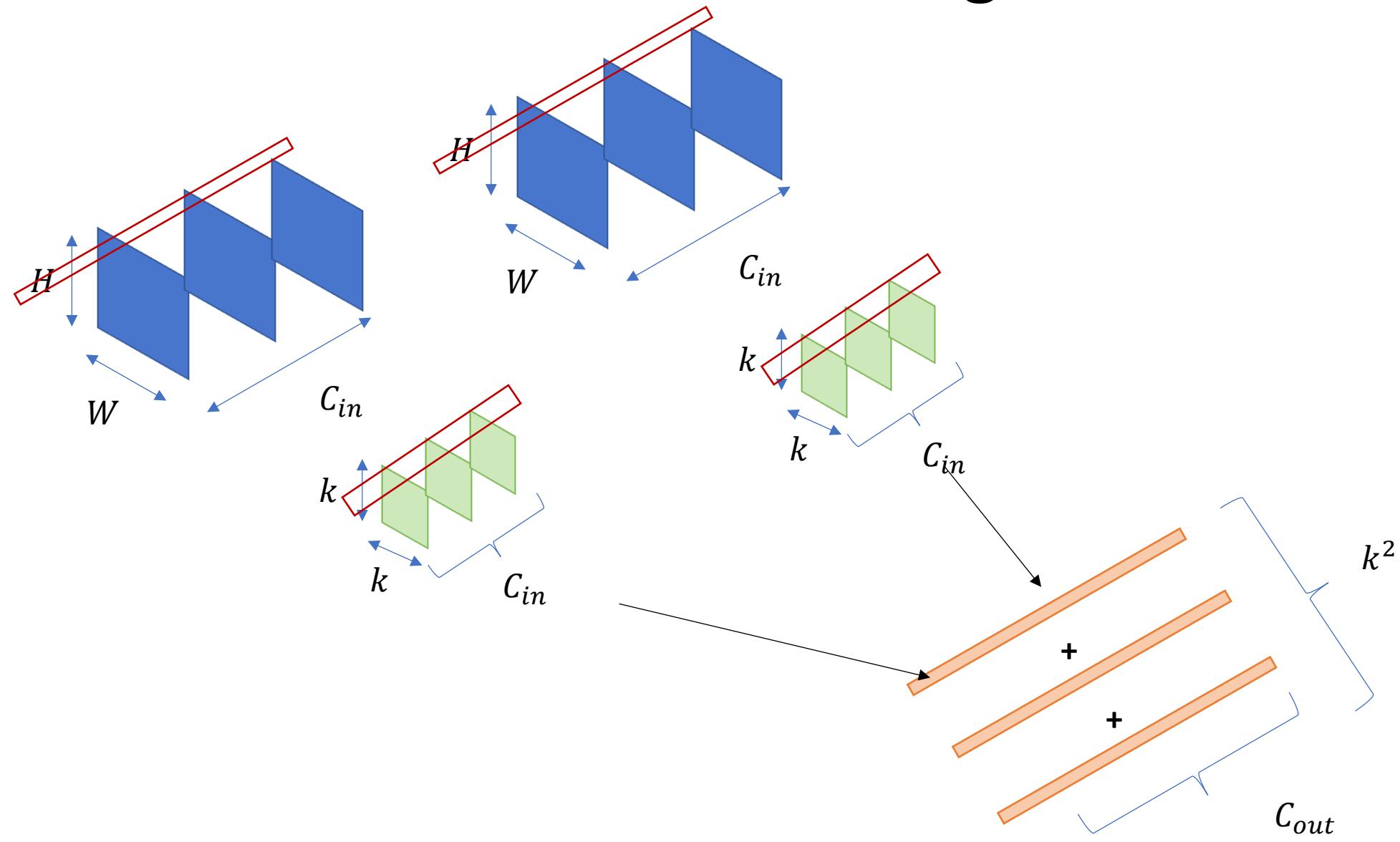
$W_1$	$W_2$	$W_3$	$W_4$	$W_1$	$W_2$	$W_3$	$W_4$
$W_1$	$W_2$	$W_3$	$W_4$	$W_1$	$W_2$	$W_3$	$W_4$

Shared  
Memory/Cache

$I_1$	$I_2$	$I_3$
$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$
$I_6$	$I_7$	$I_8$
$I_1$	$I_2$	$I_3$
$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$
$I_6$	$I_7$	$I_8$

$I_1$	$I_2$	$I_3$
$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$
$I_6$	$I_7$	$I_8$

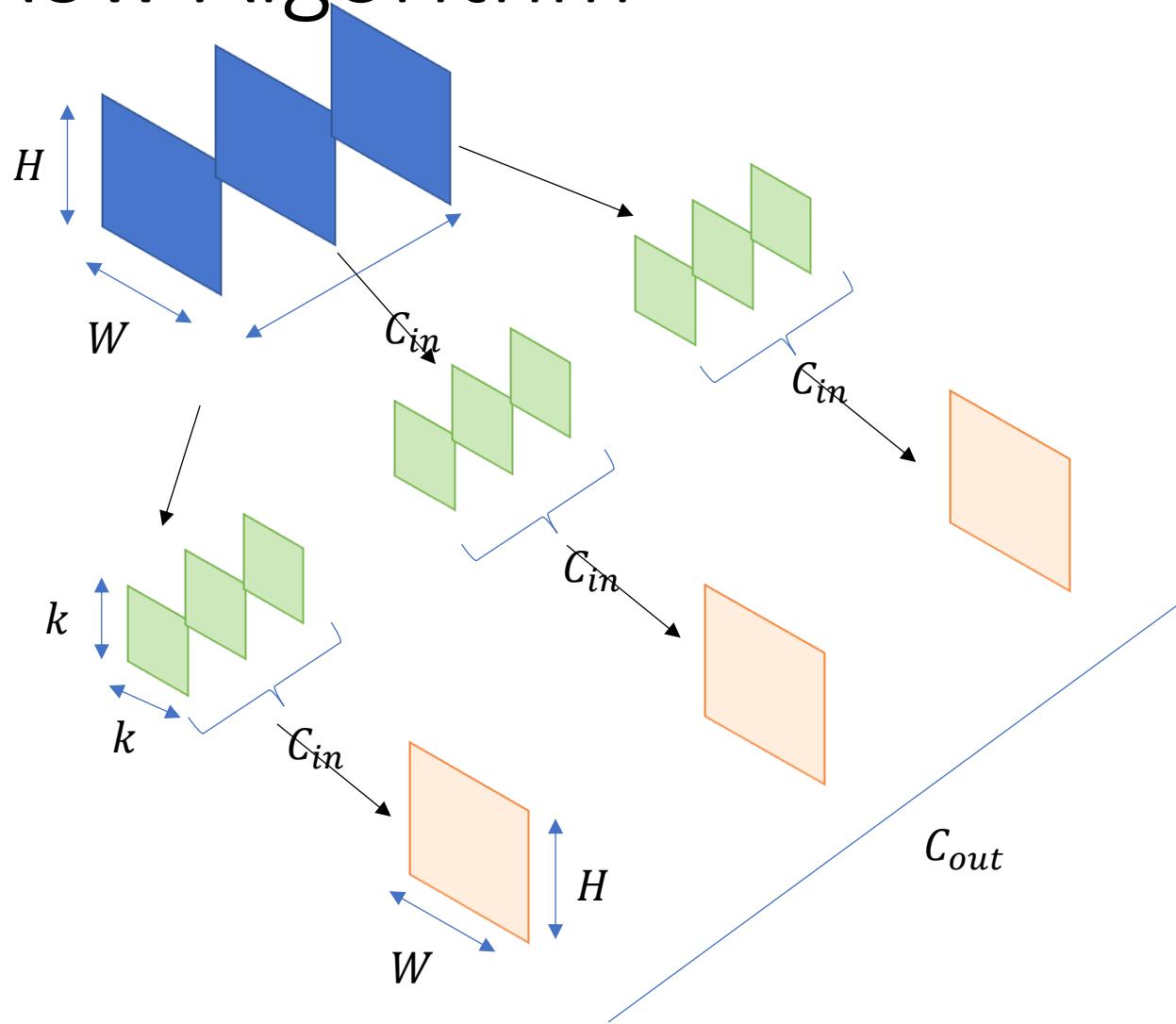
# Kn2Row Algorithm



# Kn2Row Algorithm

## Kernel Matrix

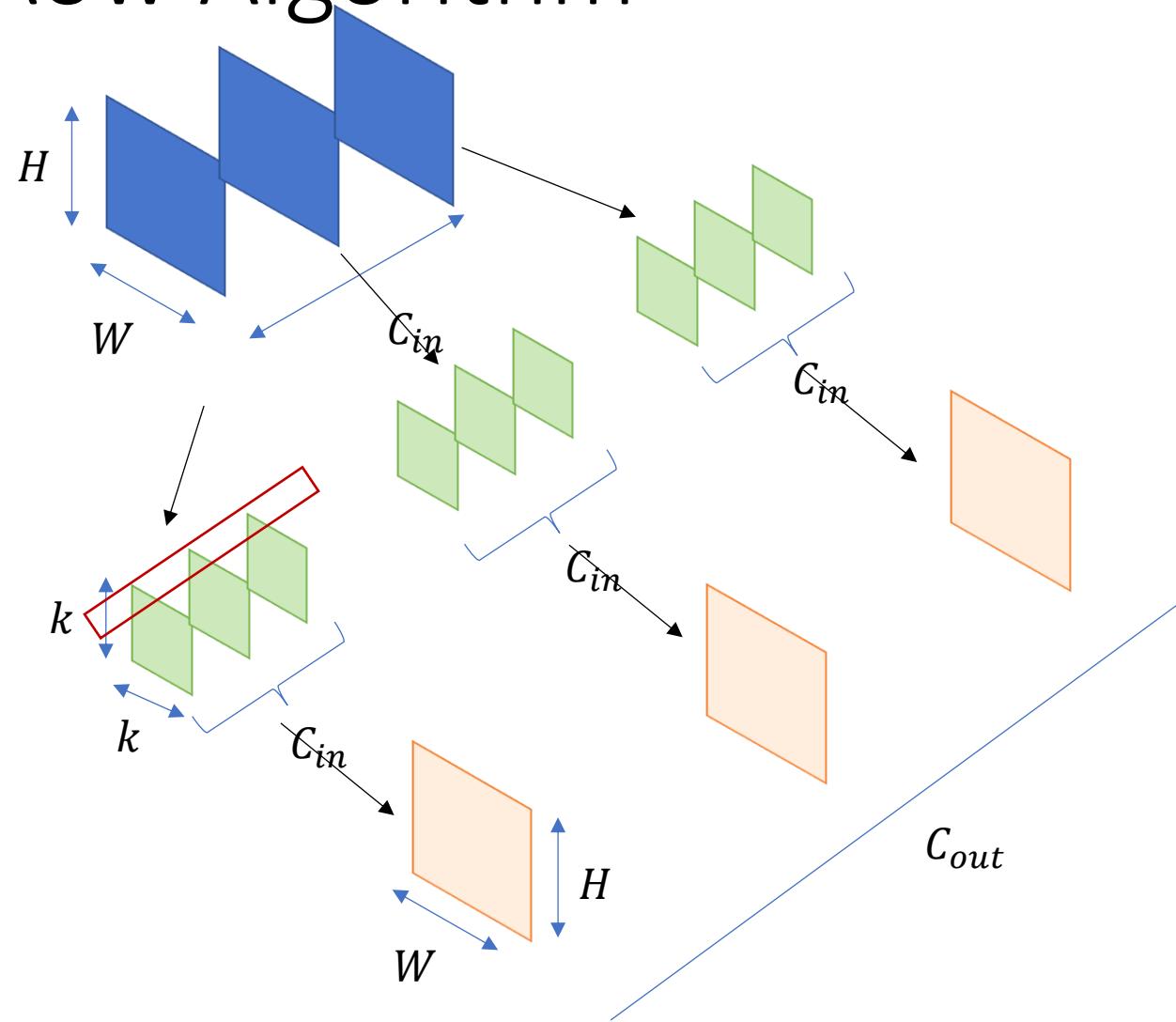
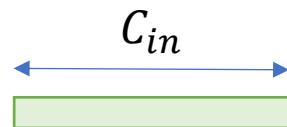
- Take a strip of  $C_{in}$  pixels of kernels of same output channel to form a row
- Create  $k^2$  rows for each output channel
- Repeat the above for all output channels



# Kn2Row Algorithm

## Kernel Matrix

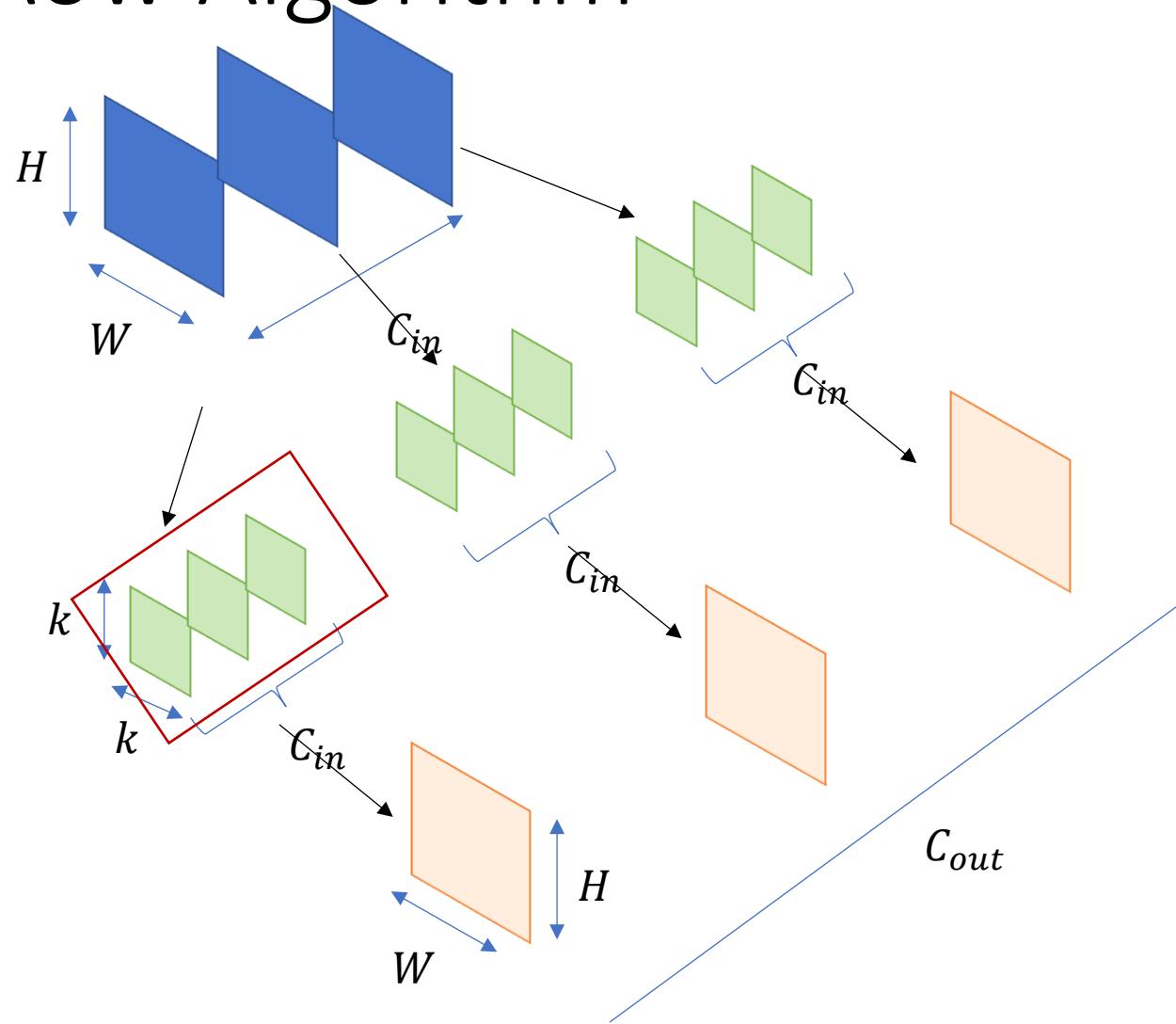
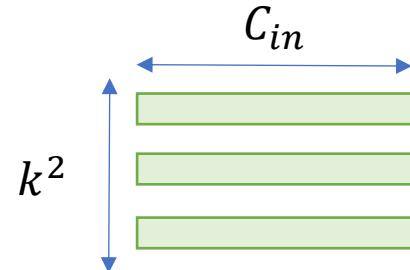
- Take a strip of  $C_{in}$  pixels of kernels of same output channel to form a row
- Create  $k^2$  rows for each output channel
- Repeat the above for all output channels



# Kn2Row Algorithm

## Kernel Matrix

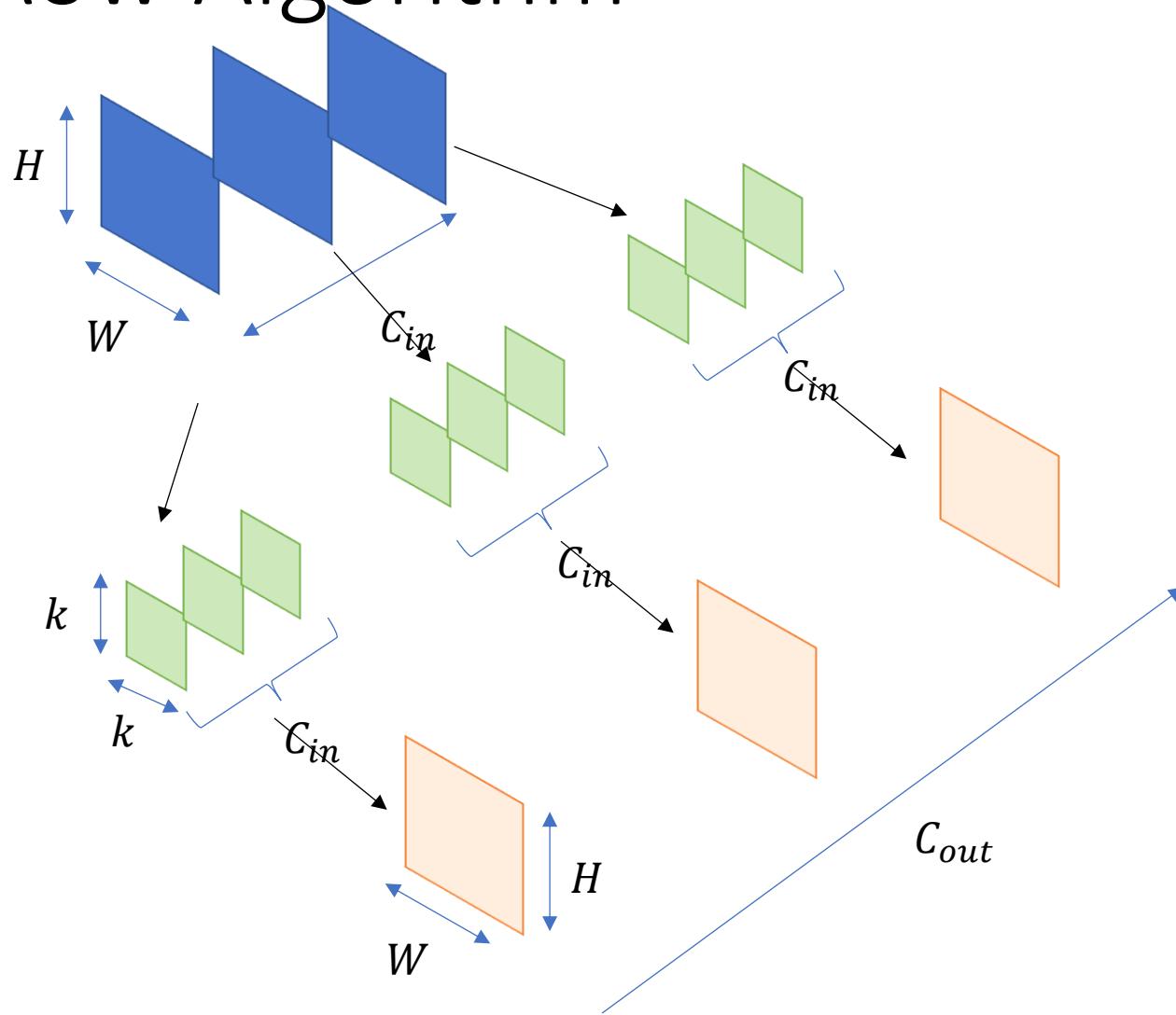
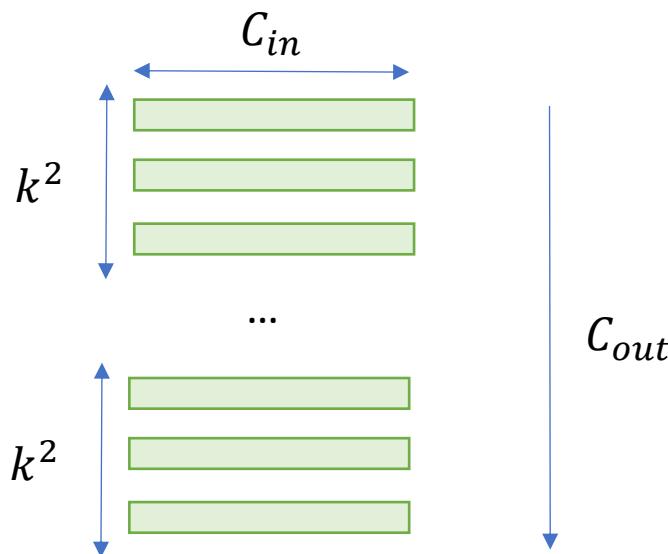
- Take a strip of  $C_{in}$  pixels of kernels of same output channel to form a row
- Create  $k^2$  rows for each output channel
- Repeat the above for all output channels



# Kn2Row Algorithm

## Kernel Matrix

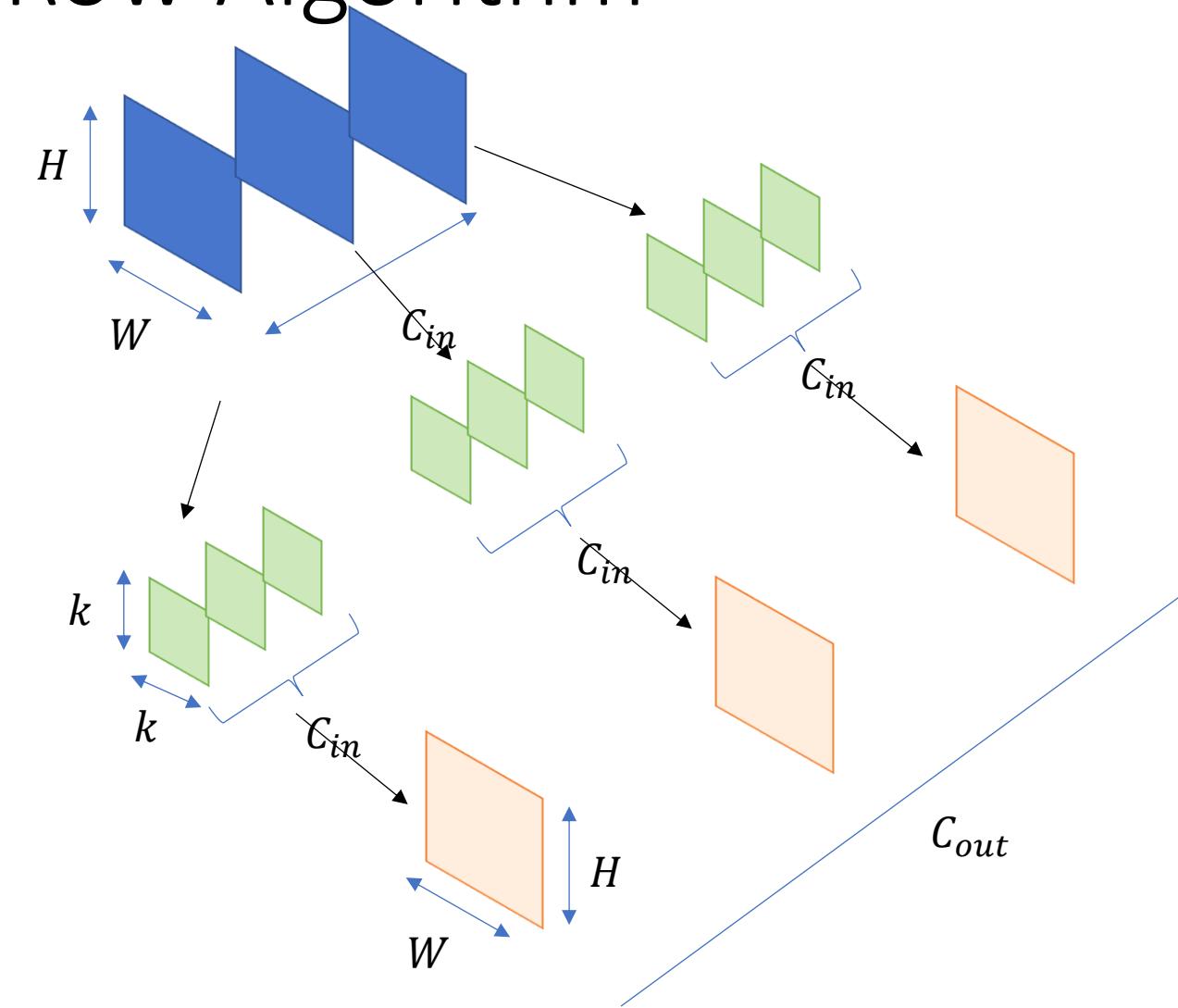
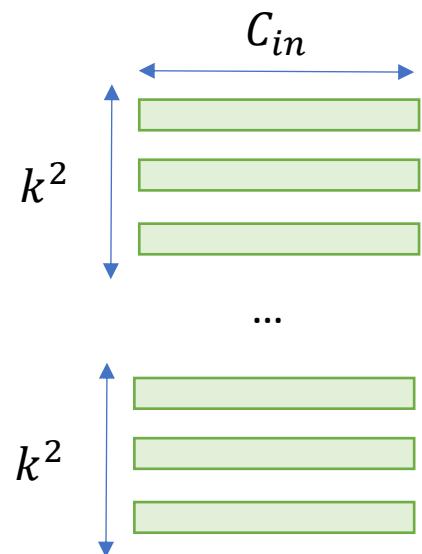
- Take a strip of  $C_{in}$  pixels of kernels of same output channel to form a row
- Create  $k^2$  rows for each output channel
- Repeat the above for all output channels



# Kn2Row Algorithm

Kernel Matrix Size

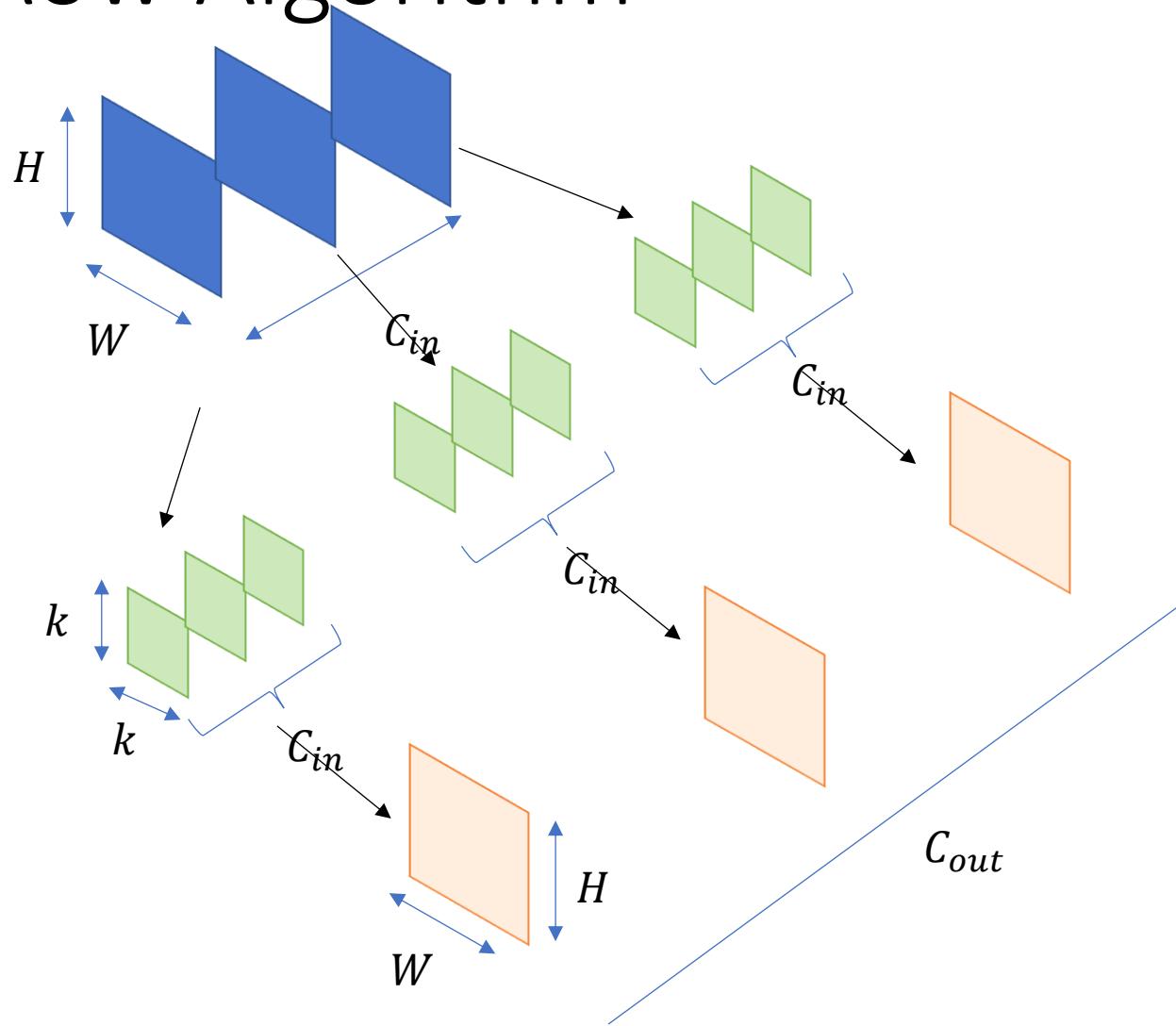
$$(C_{out} \times k^2) \times C_{in}$$



# Kn2Row Algorithm

## Input Matrix

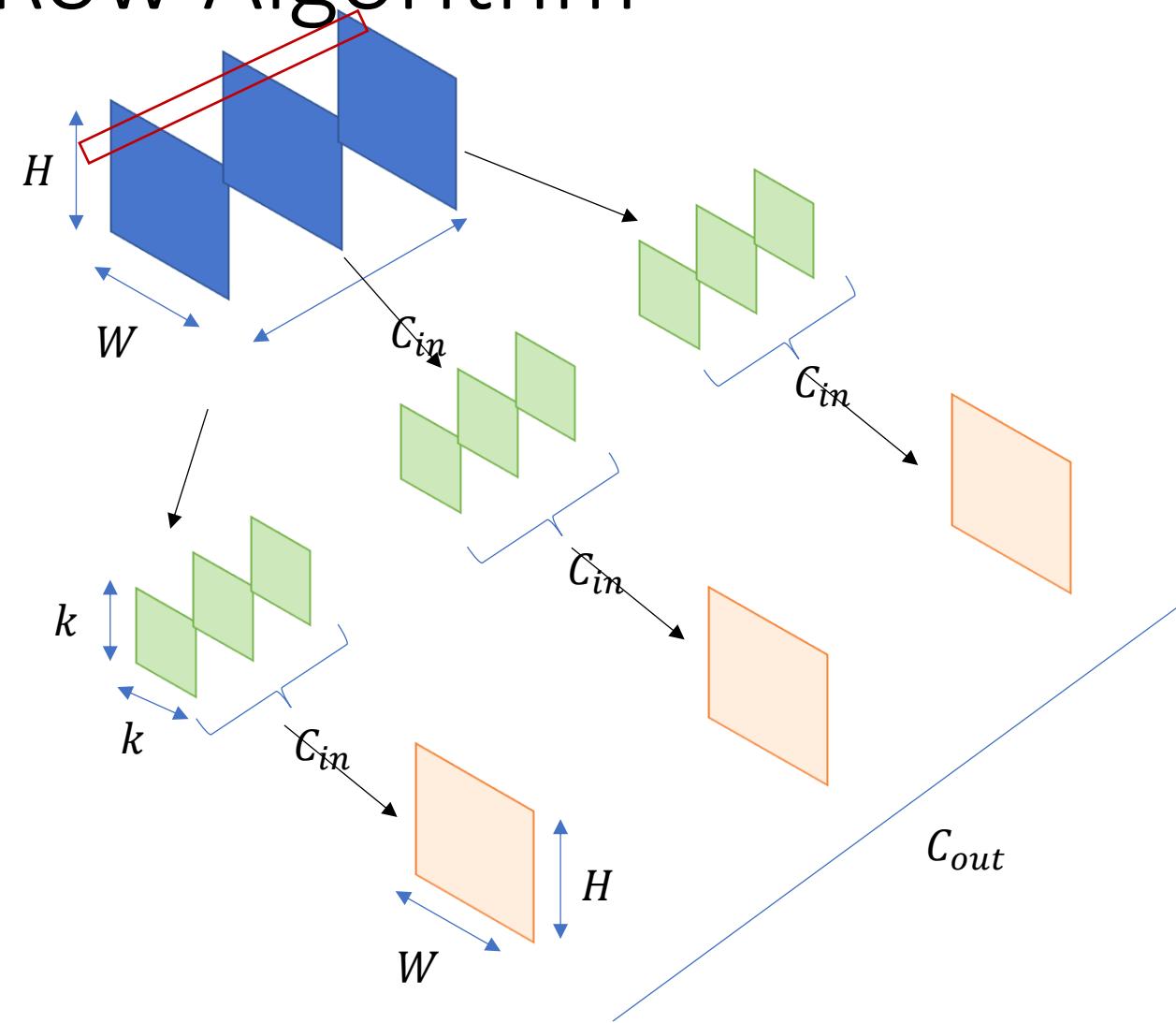
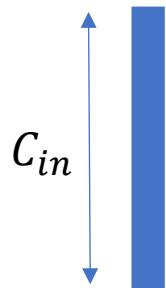
- Take a strip of  $C_{in}$  pixels of images to form a column
- Create  $H \times W$  such column



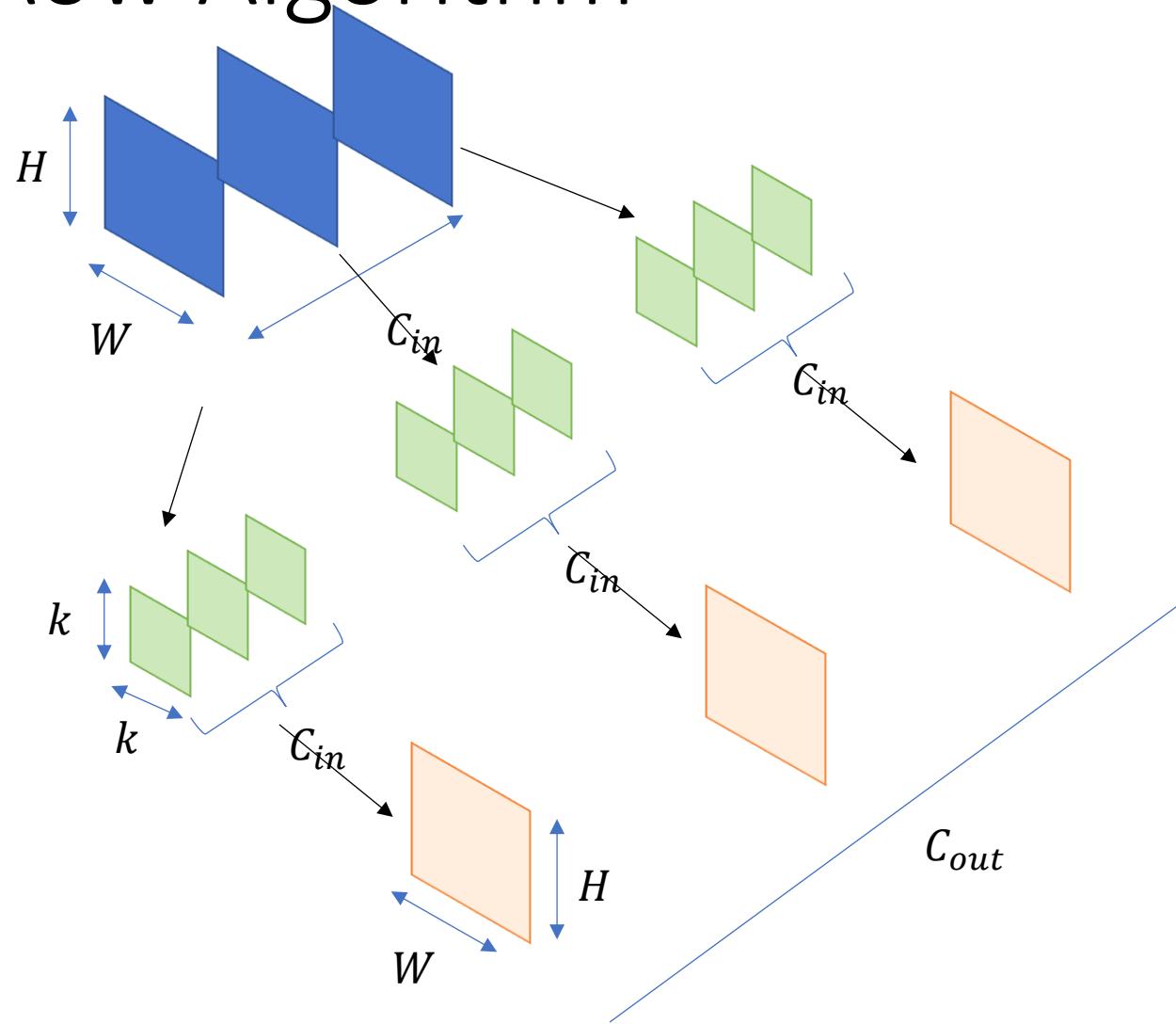
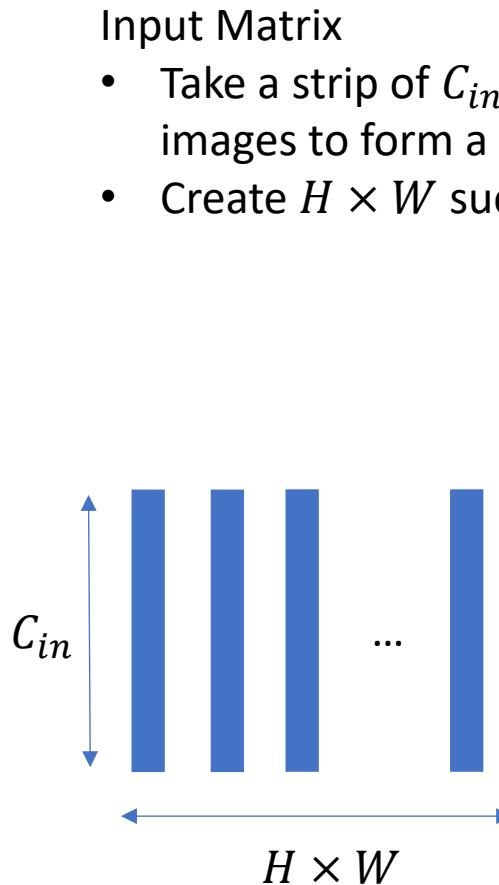
# Kn2Row Algorithm

## Input Matrix

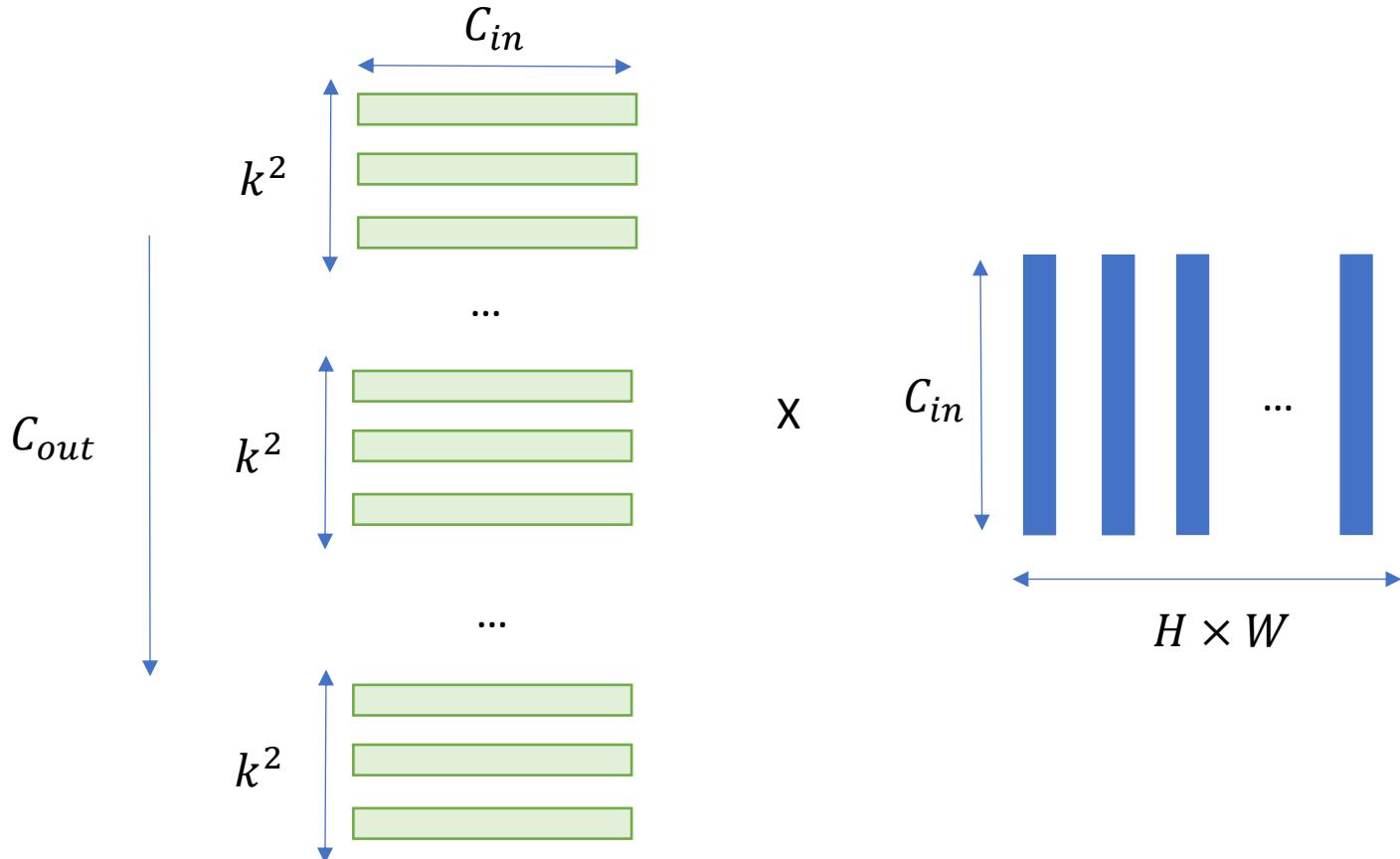
- Take a strip of  $C_{in}$  pixels of images to form a column
- Create  $H \times W$  such column



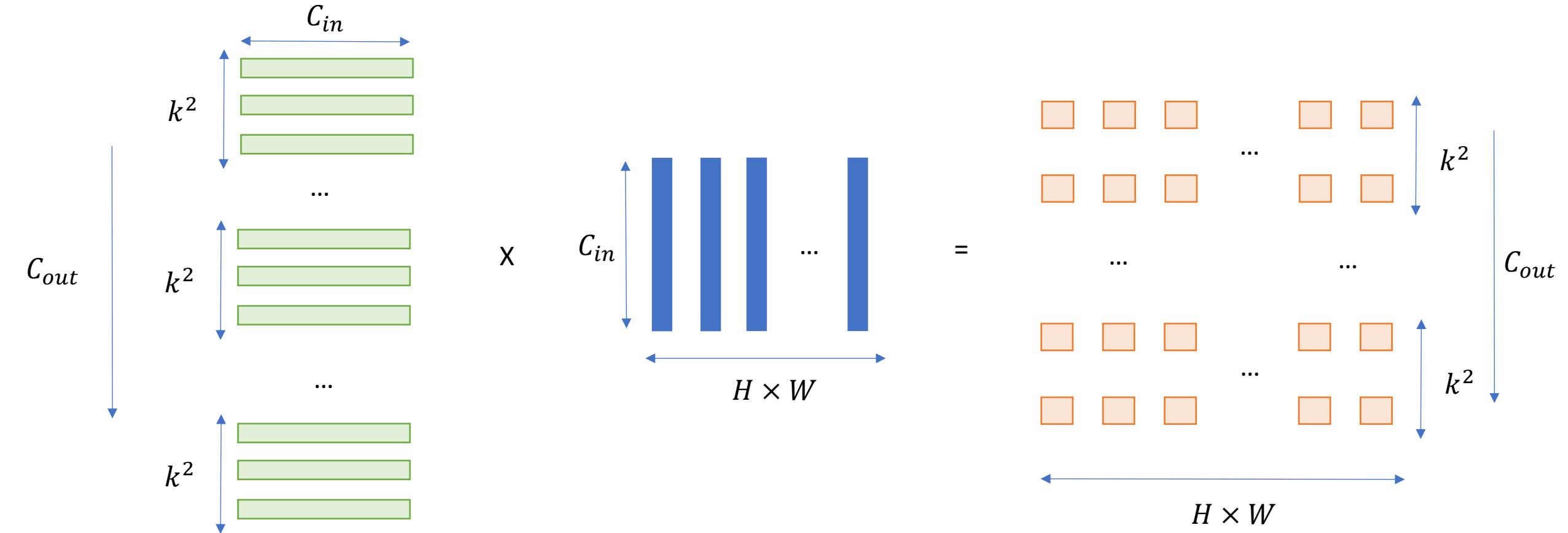
# Kn2Row Algorithm



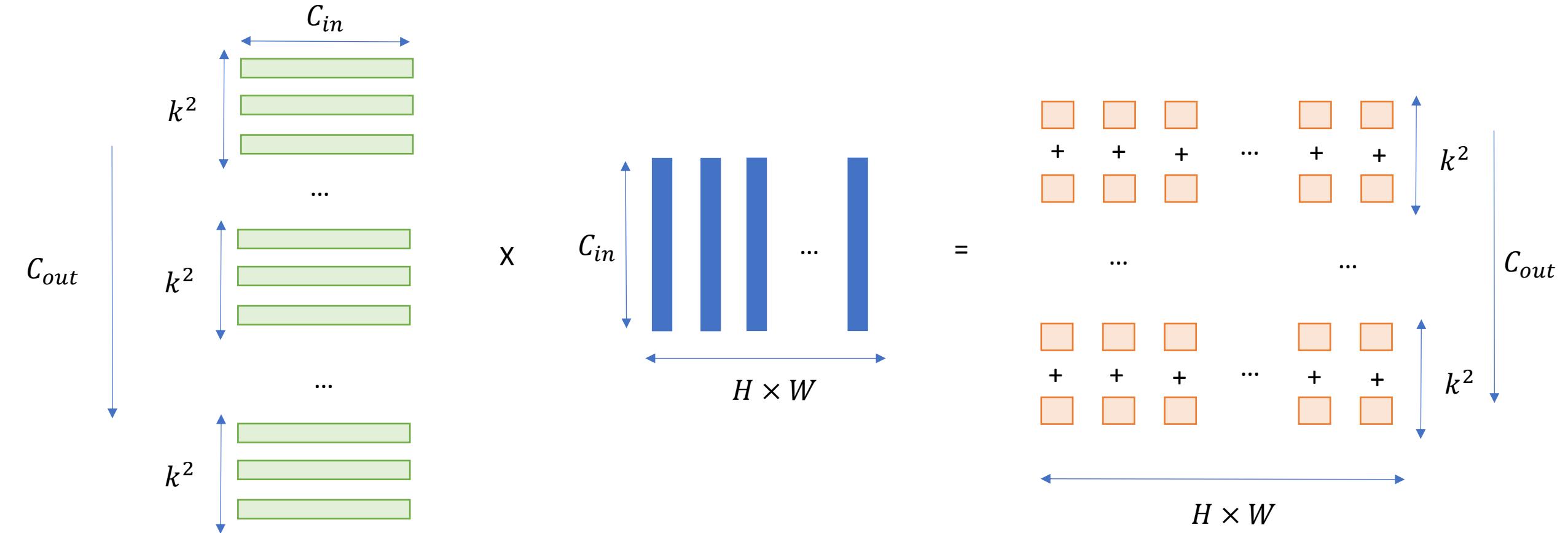
# Kn2Row Algorithm



# Kn2Row Algorithm

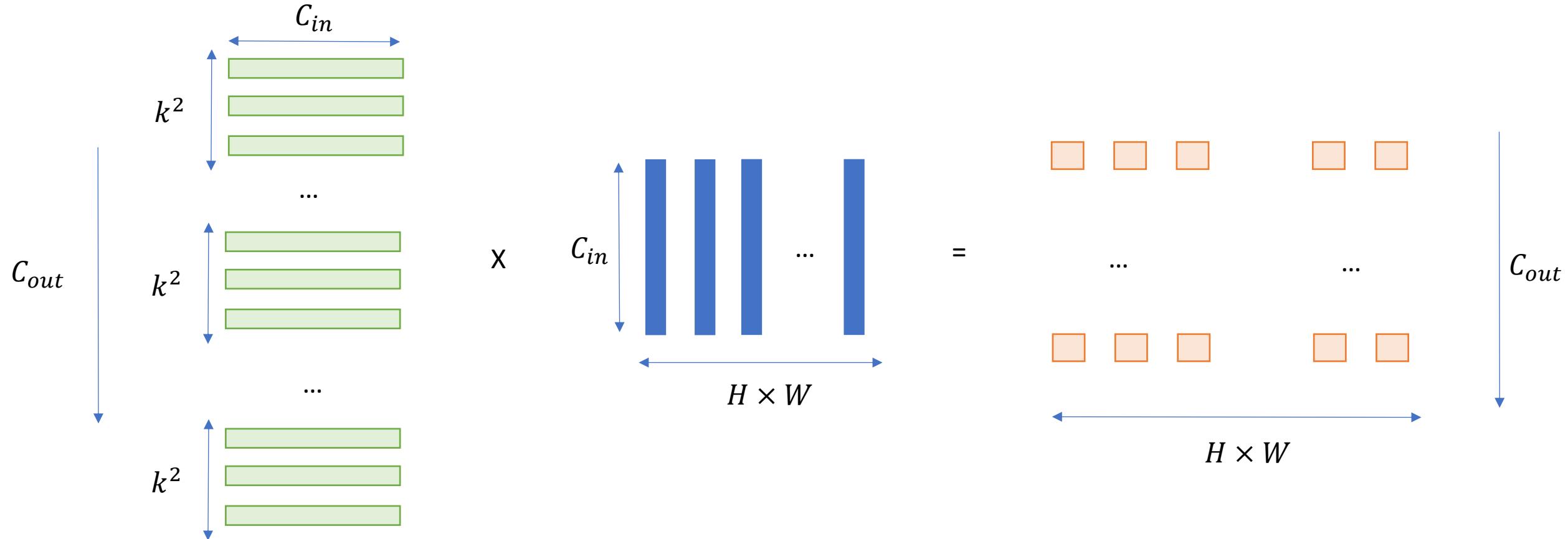


# Kn2Row Algorithm



\*The sums above are shift-add,

# Kn2Row Algorithm



# Kn2Row Algorithm

- Input Matrix -  $(C_{in}) \times (H \times W)$
- Filter Matrix -  $(C_{out} \times k^2) \times (C_{in})$ 
  - No increase in size
- Output Matrix -  $(H \times W) \times (C_{out} \times k^2)$ 
  - $k \times k$  increase in size

# Outline

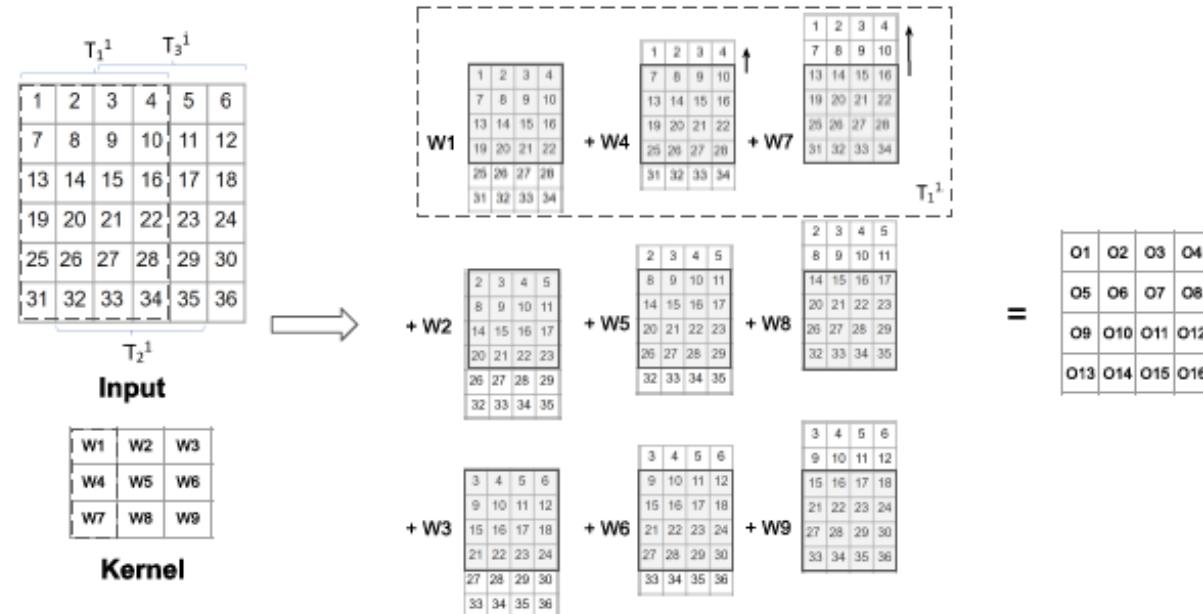
- Convolution as Matrix Multiplication – Motivation
- Im2Col and Kn2Row Algorithms
- **Scalar Matrix Multiplication Algorithm**

# Scalar Matrix Multiplication

- Approach till now
  - Transform input image and kernels into matrix
  - Directly use BLAS kernels for Matrix multiplication
- No explicit parallelization needed
  - BLAS takes care of that
- Challenge -  $k^2$  increase in memory requirements (input or output)

# Scalar Matrix Multiplication

- Key Idea: Output image is a linear combination of “portions” of input image with weights as kernels
- Avoid matrix multiplication, perform scaling and matrix addition operations
  - Scaling: Multiply entire vector/matrix with a single scalar value



# Scalar Matrix Multiplication

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$

$W_1$	$W_2$
$W_3$	$W_4$



$O_1$	$O_2$	$O_3$	$O_4$
$O_5$	$O_6$	$O_7$	$O_8$
$O_9$	$O_{10}$	$O_{11}$	$O_{12}$
$O_{13}$	$O_{14}$	$O_{15}$	$O_{16}$

Single Input, Single Output Channel

# Scalar Matrix Multiplication

$I_1$	$I_2$	$I_3$	$I_4$	$0$
$I_5$	$I_6$	$I_7$	$I_8$	$0$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$	$0$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$	$0$
0	0	0	0	0

$W_1$	$W_2$
$W_3$	$W_4$



$O_1$	$O_2$	$O_3$	$O_4$
$O_5$	$O_6$	$O_7$	$O_8$
$O_9$	$O_{10}$	$O_{11}$	$O_{12}$
$O_{13}$	$O_{14}$	$O_{15}$	$O_{16}$

Single Input, Single Output Channel

# Scalar Matrix Multiplication

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$

$W_1$	$W_2$
$W_3$	$W_4$



$O_1$	$O_2$	$O_3$	$O_4$
$O_5$	$O_6$	$O_7$	$O_8$
$O_9$	$O_{10}$	$O_{11}$	$O_{12}$
$O_{13}$	$O_{14}$	$O_{15}$	$O_{16}$

# Scalar Matrix Multiplication

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$

$W_1$	$W_2$
$W_3$	$W_4$



$O_1$	$O_2$	$O_3$	$O_4$
$O_5$	$O_6$	$O_7$	$O_8$
$O_9$	$O_{10}$	$O_{11}$	$O_{12}$
$O_{13}$	$O_{14}$	$O_{15}$	$O_{16}$

# Scalar Matrix Multiplication

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$

$W_1$	$W_2$
$W_3$	$W_4$



$O_1$	$O_2$	$O_3$	$O_4$
$O_5$	$O_6$	$O_7$	$O_8$
$O_9$	$O_{10}$	$O_{11}$	$O_{12}$
$O_{13}$	$O_{14}$	$O_{15}$	$O_{16}$

# Scalar Matrix Multiplication

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$

$W_1$	$W_2$
$W_3$	$W_4$



$O_1$	$O_2$	$O_3$	$O_4$
$O_5$	$O_6$	$O_7$	$O_8$
$O_9$	$O_{10}$	$O_{11}$	$O_{12}$
$O_{13}$	$O_{14}$	$O_{15}$	$O_{16}$

# Scalar Matrix Multiplication

- Observe: weights along the same column operate on similar inputs

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$

$W_1$	$W_2$
$W_3$	$W_4$

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$

$W_1$	$W_2$
$W_3$	$W_4$

# Scalar Matrix Multiplication

- Observe: weights along the same column operate on similar inputs

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$

$W_1$	$W_2$
$W_3$	$W_4$

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$

$W_1$	$W_2$
$W_3$	$W_4$

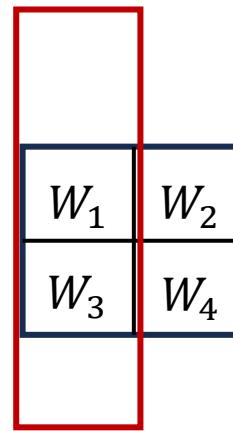
# Scalar Matrix Multiplication

- Algorithm (single input/output channel):
- For each column  $j$  of kernel
  - Load a slice of input into cache:  $T_j$
  - Load a slice of output into cache:  $O_j$
  - For each row  $i$  of the kernel with weight  $w = K[i][j]$ 
    - $O_j \leftarrow O_j + T_j[i:] * w$
  - Store  $O_j$  back

# Scalar Matrix Multiplication

- For each column  $j$

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$



# Scalar Matrix Multiplication

- Load a slice of input:  $T_j$

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$

$W_1$	$W_2$
$W_3$	$W_4$

# Scalar Matrix Multiplication

- Load a slice of output:  $O_j$

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$

$W_1$	$W_2$
$W_3$	$W_4$

$O_1$	$O_2$	$O_3$	$O_4$
$O_5$	$O_6$	$O_7$	$O_8$
$O_9$	$O_{10}$	$O_{11}$	$O_{12}$
$O_{13}$	$O_{14}$	$O_{15}$	$O_{16}$

# Scalar Matrix Multiplication

- For each row  $i$  of the kernel with weight  $w = K[i][j]$ 
  - $O_j \leftarrow O_j + T_j[i:] * w$

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$

$W_1$	$W_2$
$W_3$	$W_4$

$O_1$	$O_2$	$O_3$	$O_4$
$O_5$	$O_6$	$O_7$	$O_8$
$O_9$	$O_{10}$	$O_{11}$	$O_{12}$
$O_{13}$	$O_{14}$	$O_{15}$	$O_{16}$

# Scalar Matrix Multiplication

- For each row  $i$  of the kernel with weight  $w = K[i][j]$ 
  - $O_j \leftarrow O_j + T_j[i:] * w$

$I_1$	$I_2$	$I_3$	$I_4$
$I_5$	$I_6$	$I_7$	$I_8$
$I_9$	$I_{10}$	$I_{11}$	$I_{12}$
$I_{13}$	$I_{14}$	$I_{15}$	$I_{16}$

$W_1$	$W_2$
$W_3$	$W_4$

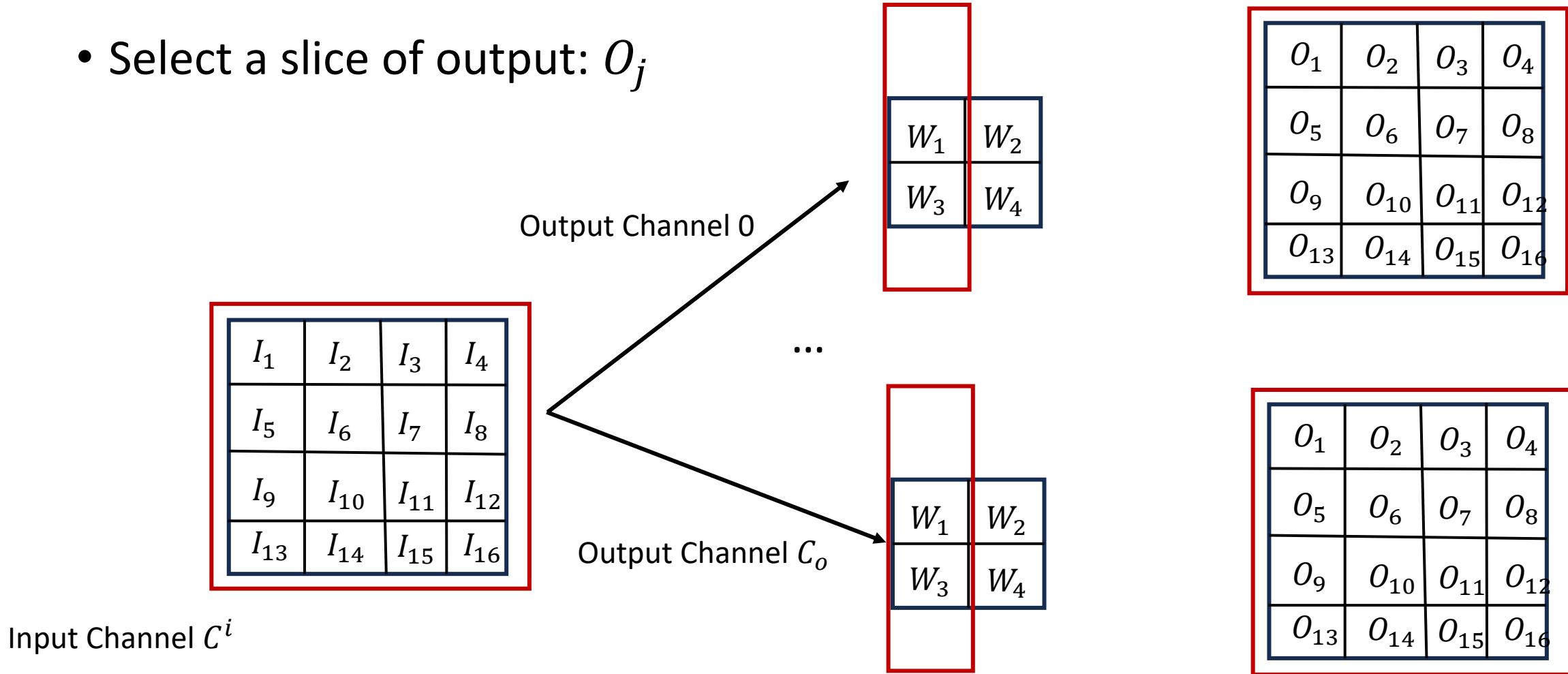
$O_1$	$O_2$	$O_3$	$O_4$
$O_5$	$O_6$	$O_7$	$O_8$
$O_9$	$O_{10}$	$O_{11}$	$O_{12}$
$O_{13}$	$O_{14}$	$O_{15}$	$O_{16}$

# Scalar Matrix Multiplication

- Algorithm ( $c_{in}$  input,  $c_{out}$  output channels):
- For each input channel  $c^i$ 
  - For each column  $j$  of kernel
    - Load a slice of input into cache:  $T_j^{c^i}$
    - For each output channel  $c^o$ 
      - Load a slice of output into cache:  $O_j^{c^o}$
      - For each row  $i$  of the kernel with weight  $w = K[i][j][c^i][c^o]$ 
        - $O_j^{c^o} \leftarrow O_j^{c^o} + T_j^{c^i}[i:] * w$
        - Store  $O_j^{c^o}$  back

# Scalar Matrix Multiplication

- Select a slice of output:  $O_j$



# Scalar Matrix Multiplication

- Claim of the paper
- Memory requirement =  $H \times W$  vs  $C_{in} \times K^2 \times H \times W$
- Technically correct, but may not be very useful
  - We care more about data transfers and computation time

# Scalar Matrix Multiplication

- Can we parallelize this algorithm?
- Ungraded HW Assignment: Apply one of the data parallelism techniques to come up with a parallel algorithm (see if you can design an algorithm that has no write conflicts)
- For each input channel  $c^i$ 
  - For each column  $j$  of kernel
    - Load a slice of input into cache:  $T_j^{c^i}$
    - For each output channel  $c^o$ 
      - Load a slice of output into cache:  $O_j^{c^o}$
      - For each row  $i$  of the kernel with weight  $w = K[i][j][c^i][c^o]$ 
        - $O_j^{c^o} \leftarrow O_j^{c^o} + T_j^{c^i}[i:] * w$

# Im2Col Algorithm

- Input Matrix -  $(k \times k \times C_{in}) \times (H \times W)$ 
  - $k \times k$  increase in size -> leads to increase in memory transfers
- Filter Matrix -  $(C_{out}) \times (k \times k \times C_{in})$ 
  - No increase in size
- Output Matrix -  $C_{out} \times (H \times W)$ 
  - No increase in size

# Kn2Row Algorithm

- Input Matrix -  $(C_{in}) \times (H \times W)$
- Filter Matrix -  $(C_{out} \times k^2) \times (C_{in})$ 
  - No increase in size
- Output Matrix -  $(H \times W) \times (C_{out} \times k^2)$ 
  - $k \times k$  increase in size -> leads to increase in memory transfers

# Scalar Matrix Multiplication

- Input Matrix -  $(C_{in}) \times (H \times W)$ 
  - No increase in size
- Filter Matrix -  $(C_{out}) \times (k \times k \times C_{in})$ 
  - No increase in size
- Output Matrix -  $C_{out} \times (H \times W)$ 
  - No increase in size
- Performs Matrix Scaling and Addition Operations

# Next Class

- 9/30 Lecture 11
  - Accelerating Convolutional Neural Networks: Exploring Sparsity in Convolutional Neural Networks

# Thank You

- Questions?
- Email: [sanmukh.kuppannagari@case.edu](mailto:sanmukh.kuppannagari@case.edu)