

Lecture 18: Videos

Computer Vision Tasks: 2D Recognition

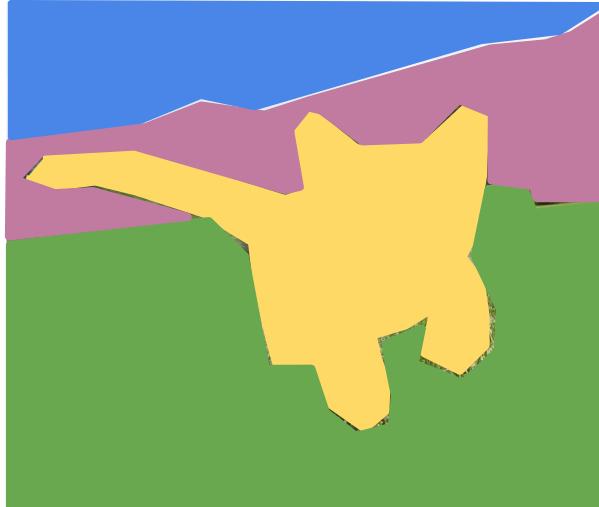
Classification



CAT

No spatial extent

Semantic Segmentation



GRASS, CAT, TREE,
SKY

No objects, just pixels

Object Detection



DOG, DOG, CAT

Multiple Objects

Instance Segmentation



DOG, DOG, CAT

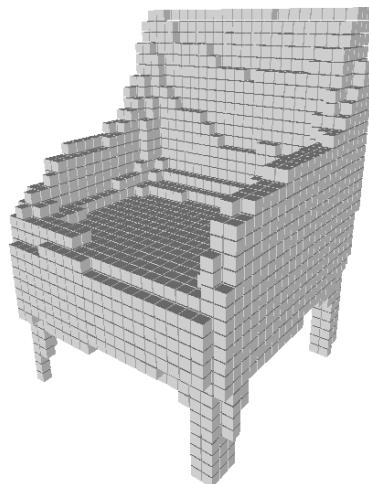
[This image](#) is CCO public domain

Last Time: 3D Shapes

Predicting 3D Shapes
from single image

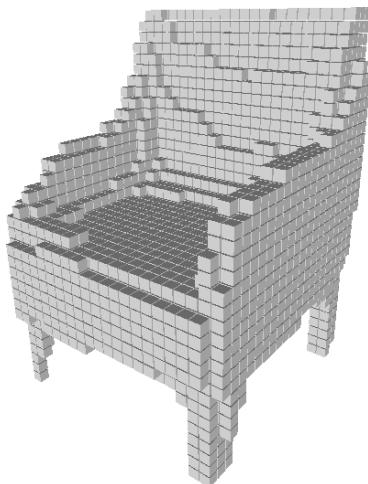


Input Image



3D Shape

Processing 3D
input data

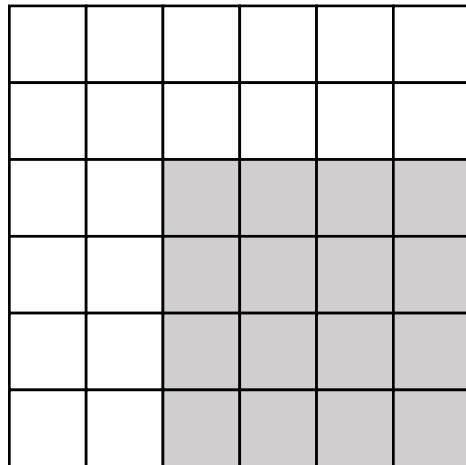


3D Shape

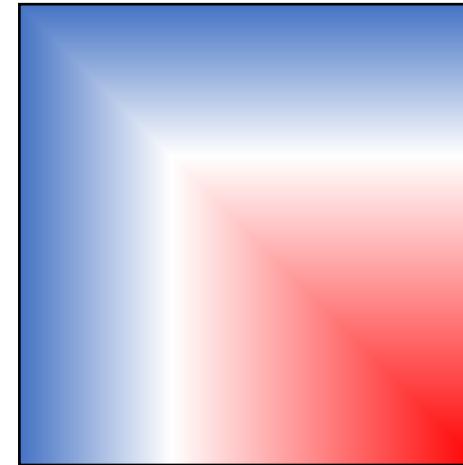
→ Chair

Last Time: 3D Shape Representations

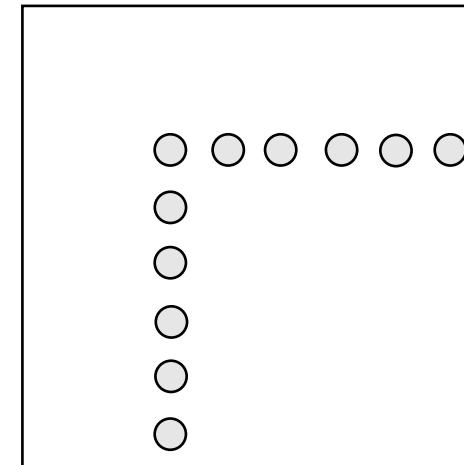
∞
∞
2
2
2
2



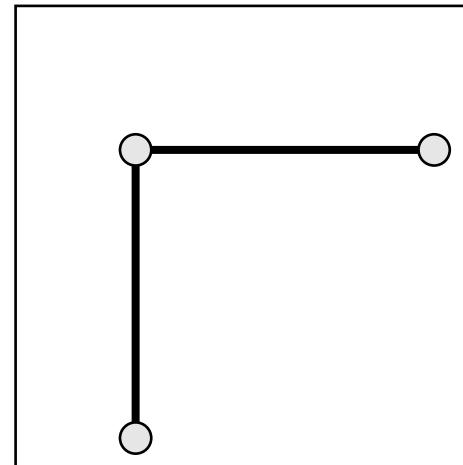
Depth Map



Implicit Surface



Pointcloud

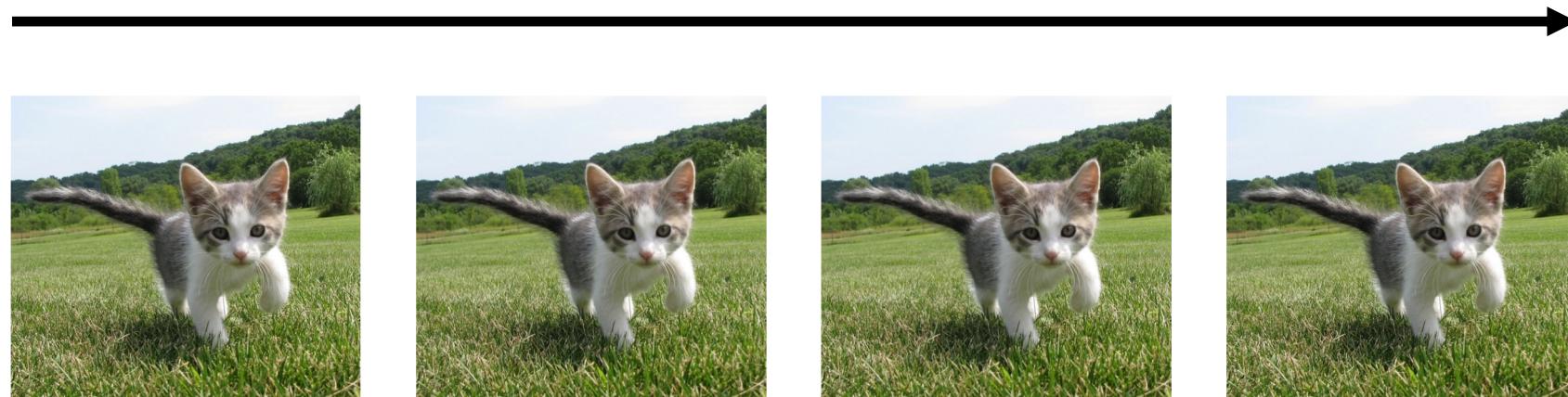


Mesh

Today: Video = 2D + Time

A video is a **sequence** of images

4D tensor: $T \times 3 \times H \times W$
(or $3 \times T \times H \times W$)



This image is [CC0 public domain](#)

Example task: Video Classification



Input video:

$T \times 3 \times H \times W$

Swimming
Running
Jumping
Eating
Standing

[Running video](#) is in the [public domain](#)

Example task: Video Classification



Images: Recognize **objects**



Dog
Cat
Fish
Truck



Videos: Recognize **actions**



Swimming
Running
Jumping
Eating
Standing

[Running video](#) is in the [public domain](#)

Problem: Videos are big!

Videos are ~30 frames per second (fps)



Size of uncompressed video
(3 bytes per pixel):

SD (640 x 480): **~1.5 GB per minute**

HD (1920 x 1080): **~10 GB per minute**

Input video:

$T \times 3 \times H \times W$

Problem: Videos are big!



Input video:

$T \times 3 \times H \times W$

Videos are ~30 frames per second (fps)

Size of uncompressed video
(3 bytes per pixel):

SD (640 x 480): **~1.5 GB per minute**

HD (1920 x 1080): **~10 GB per minute**

Solution: Train on short **clips**: low
fps and low spatial resolution
e.g. $T = 16$, $H=W=112$
(3.2 seconds at 5 fps, 588 KB)

Training on Clips

Raw video: Long, high FPS



Training on Clips

Raw video: Long, high FPS



Training: Train model to classify short **clips** with low FPS



Training on Clips

Raw video: Long, high FPS



Training: Train model to classify short **clips** with low FPS



Testing: Run model on different clips, average predictions

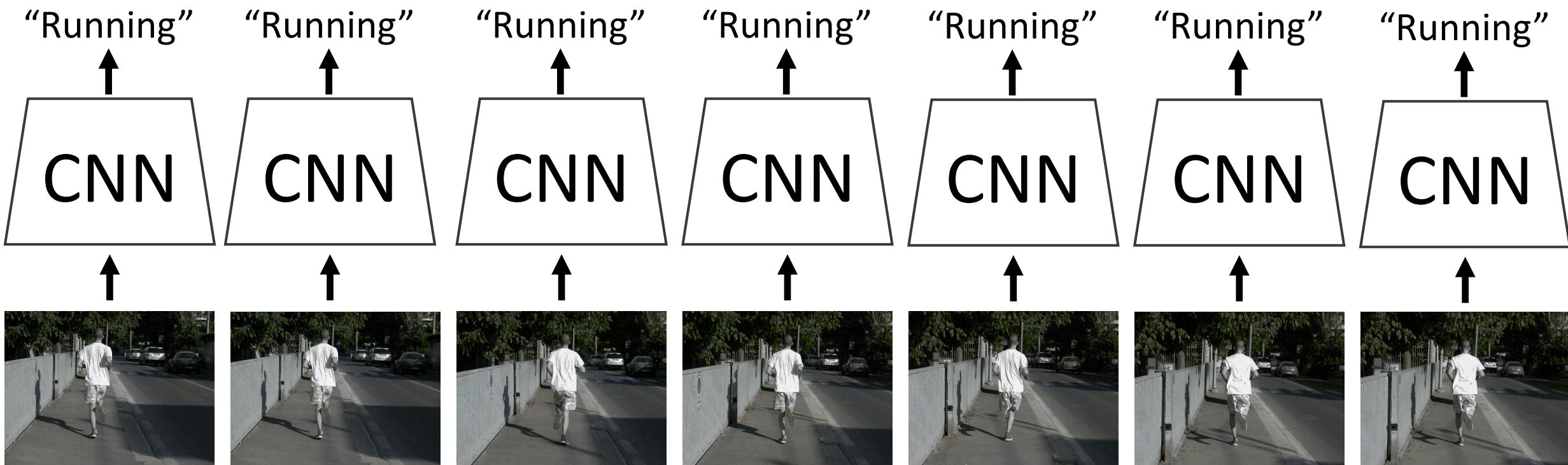


Video Classification: Single-Frame CNN

Simple idea: train normal 2D CNN to classify video frames independently!

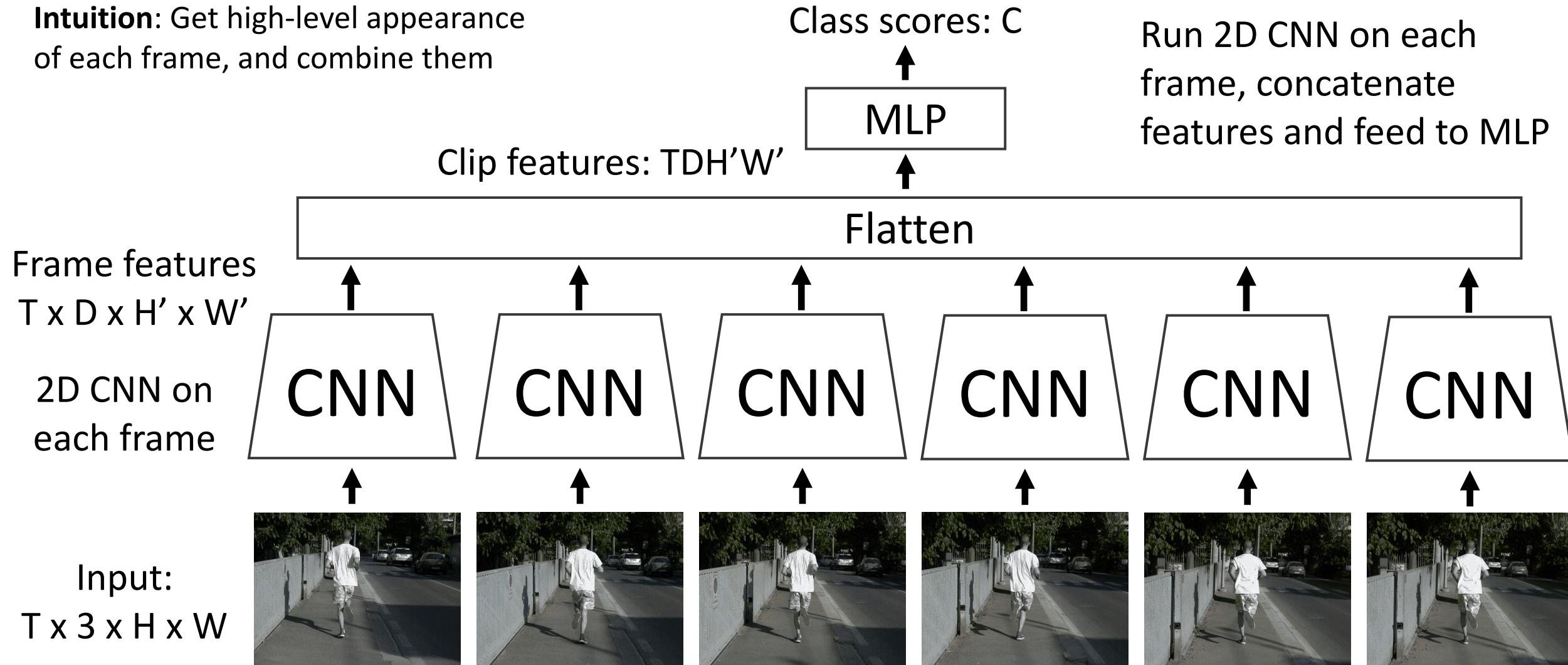
(Average predicted probs at test-time)

Often a **very** strong baseline for video classification



Video Classification: Late Fusion (with FC layers)

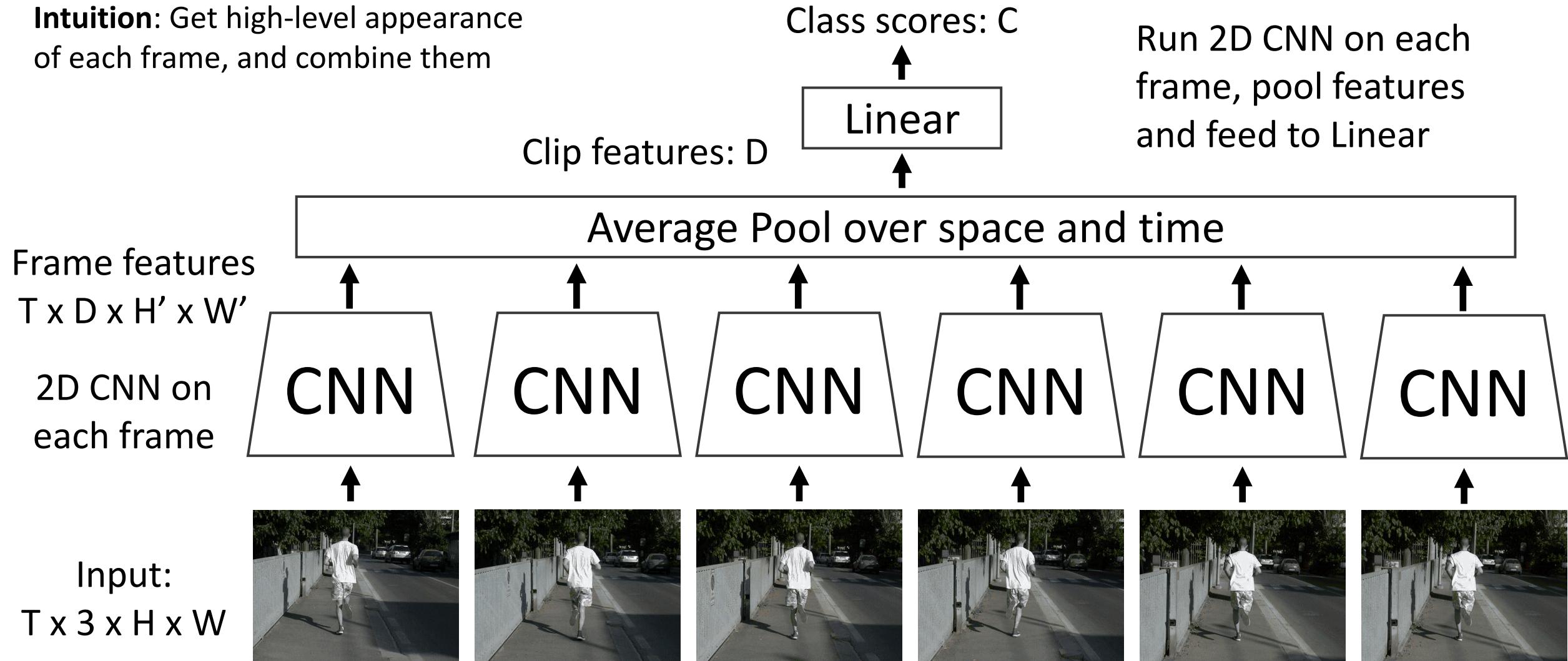
Intuition: Get high-level appearance of each frame, and combine them



Karpathy et al, "Large-scale Video Classification with Convolutional Neural Networks", CVPR 2014

Video Classification: Late Fusion (with pooling)

Intuition: Get high-level appearance of each frame, and combine them



Video Classification: Late Fusion (with pooling)

Intuition: Get high-level appearance of each frame, and combine them

Problem: Hard to compare low-level motion between frames

Class scores: C

Linear

Run 2D CNN on each frame, pool features and feed to Linear

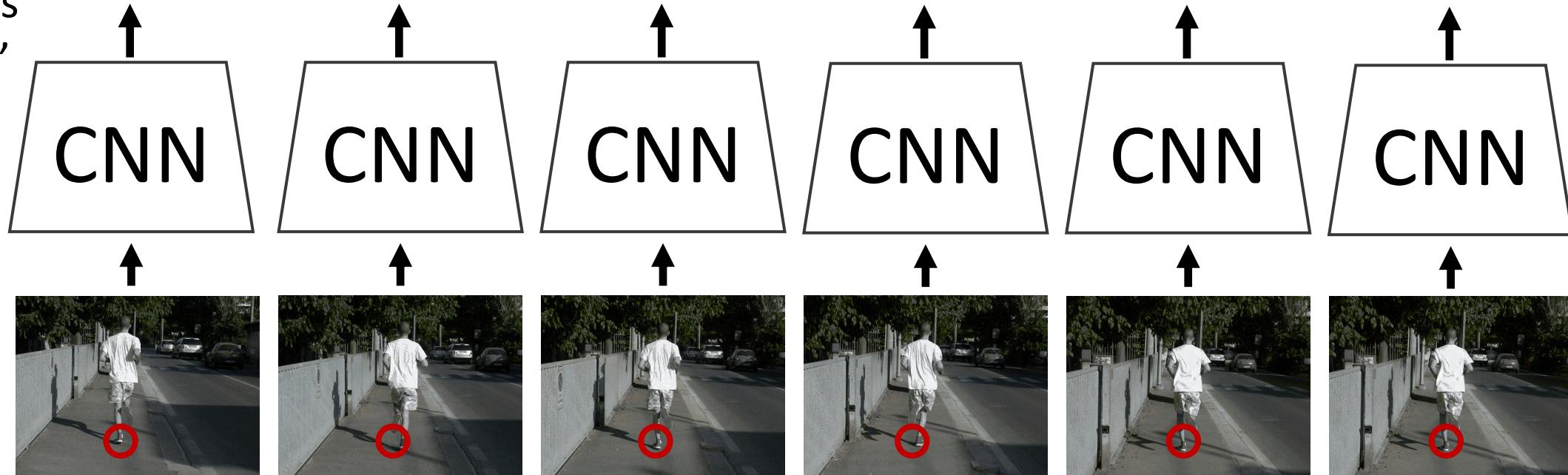
Clip features: D

Frame features

$T \times D \times H' \times W'$

2D CNN on each frame

Average Pool over space and time



Input:

$T \times 3 \times H \times W$

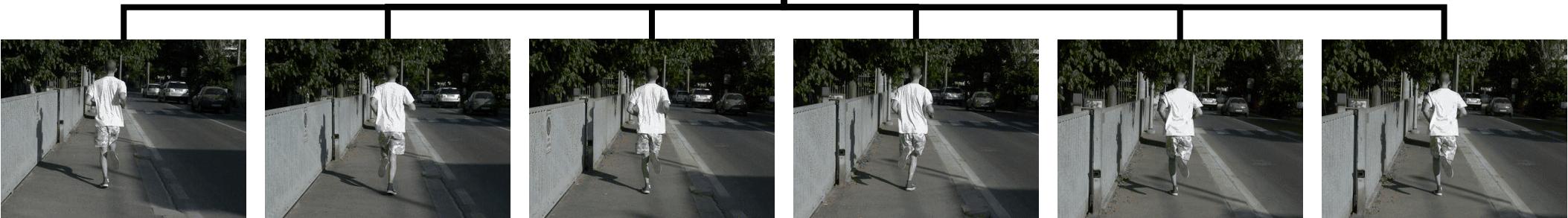
Video Classification: Early Fusion

Intuition: Compare frames with very first conv layer, after that normal 2D CNN

First 2D convolution collapses all temporal information:
Input: $3T \times H \times W$
Output: $D \times H \times W$

Reshape:
 $3T \times H \times W$

Input:
 $T \times 3 \times H \times W$



Karpathy et al, "Large-scale Video Classification with Convolutional Neural Networks", CVPR 2014

Video Classification: Early Fusion

Intuition: Compare frames with very first conv layer, after that normal 2D CNN

Problem: One layer of temporal processing may not be enough!

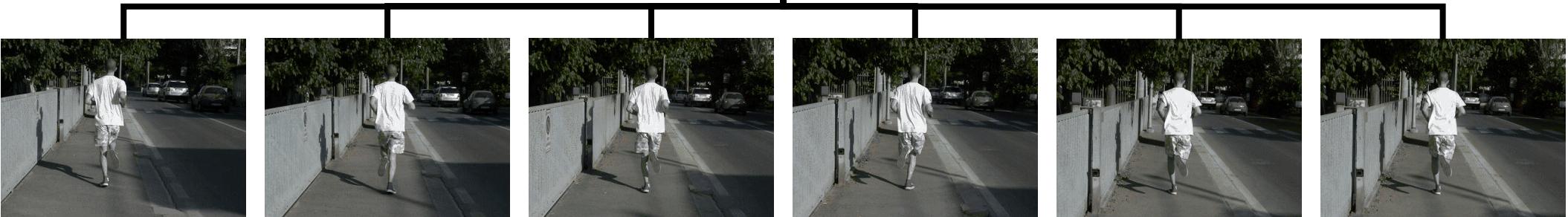
First 2D convolution collapses all temporal information:

Input: $3T \times H \times W$

Output: $D \times H \times W$

Reshape:
 $3T \times H \times W$

Input:
 $T \times 3 \times H \times W$

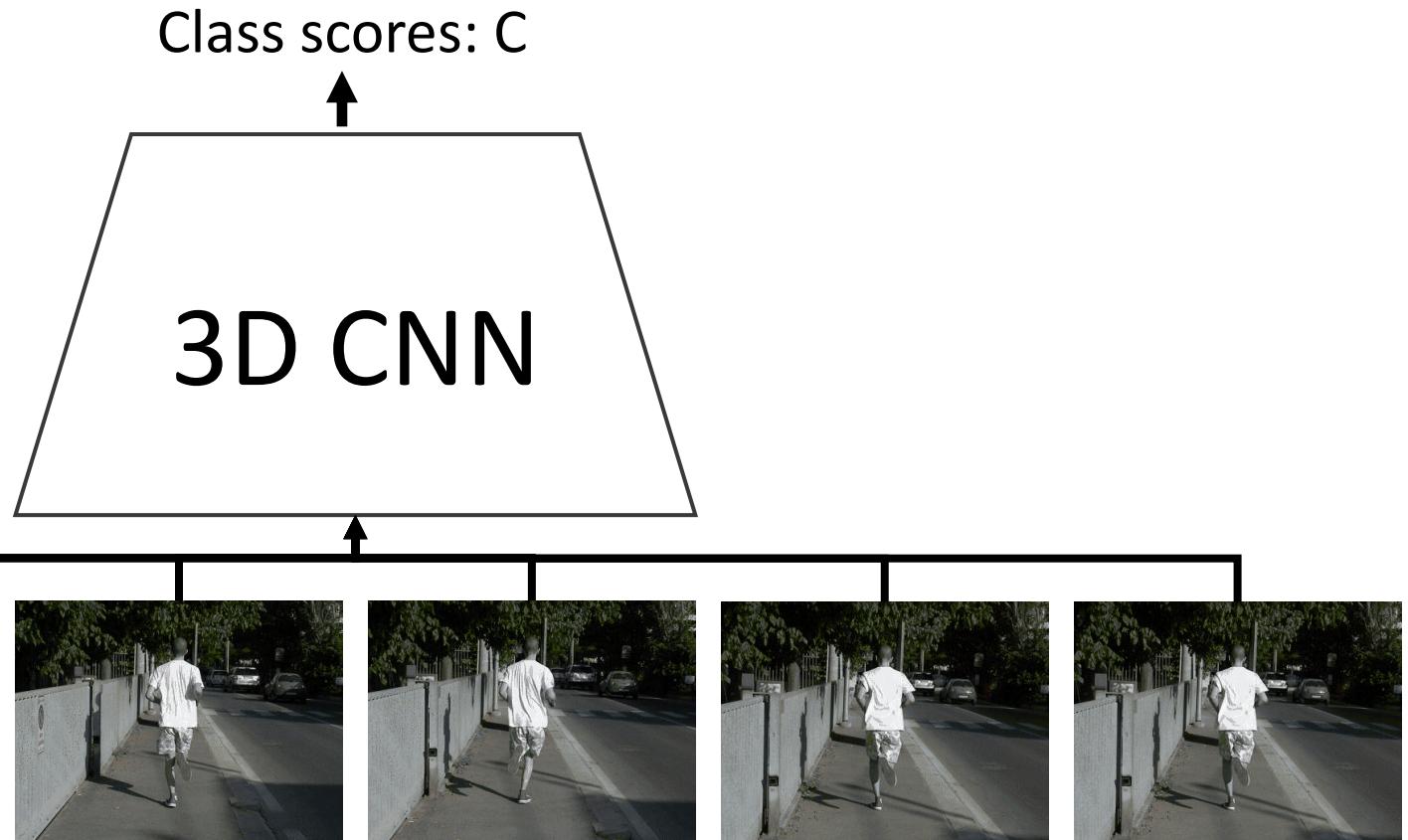


Karpathy et al, "Large-scale Video Classification with Convolutional Neural Networks", CVPR 2014

Video Classification: 3D CNN

Intuition: Use 3D versions of convolution and pooling to slowly fuse temporal information over the course of the network

Each layer in the network is a 4D tensor: $D \times T \times H \times W$
Use 3D conv and 3D pooling operations



Ji et al, "3D Convolutional Neural Networks for Human Action Recognition", TPAMI 2010 ; Karpathy et al, "Large-scale Video Classification with Convolutional Neural Networks", CVPR 2014

Early Fusion vs Late Fusion vs 3D CNN

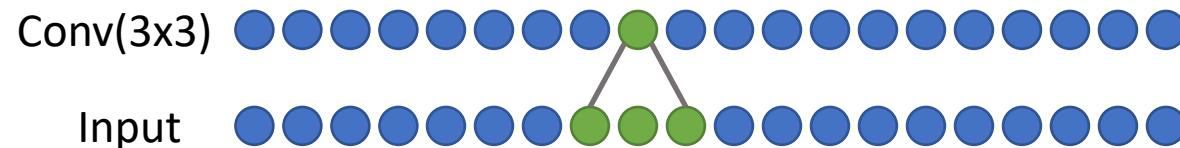
Late
Fusion

Layer	Size (C x T x H x W)	Receptive Field (T x H x W)
Input	3 x 20 x 64 x 64	
Conv2D(3x3, 3->12)	12 x 20 x 64 x 64	1 x 3 x 3

Early Fusion vs Late Fusion vs 3D CNN

Late
Fusion

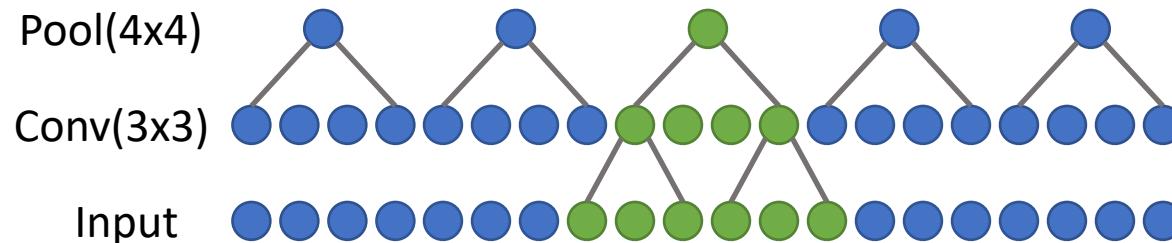
Layer	Size (C x T x H x W)	Receptive Field (T x H x W)
Input	$3 \times 20 \times 64 \times 64$	
Conv2D(3x3, 3->12)	$12 \times 20 \times 64 \times 64$	$1 \times 3 \times 3$



Early Fusion vs Late Fusion vs 3D CNN

Late
Fusion

Layer	Size (C x T x H x W)	Receptive Field (T x H x W)
Input	$3 \times 20 \times 64 \times 64$	
Conv2D(3x3, 3->12)	$12 \times 20 \times 64 \times 64$	$1 \times 3 \times 3$
Pool2D(4x4)	$12 \times 20 \times 16 \times 16$	$1 \times 6 \times 6$

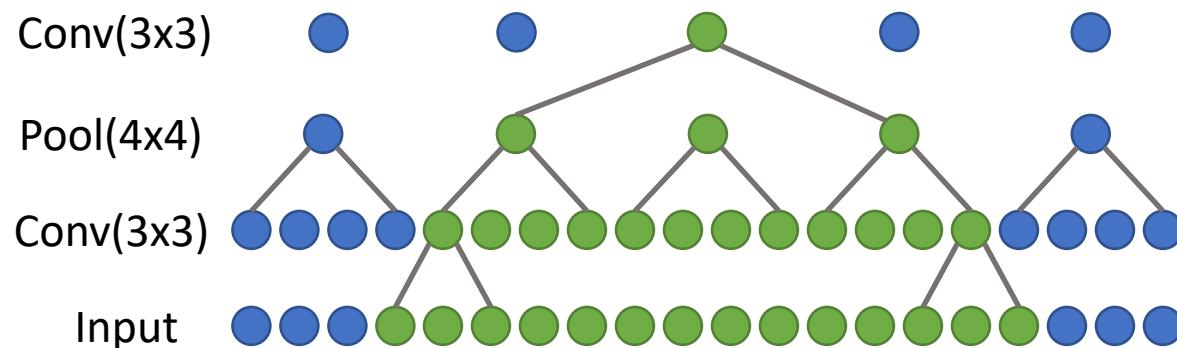


Early Fusion vs Late Fusion vs 3D CNN

Late
Fusion

Layer	Size (C x T x H x W)	Receptive Field (T x H x W)
Input	$3 \times 20 \times 64 \times 64$	
Conv2D(3x3, 3->12)	$12 \times 20 \times 64 \times 64$	$1 \times 3 \times 3$
Pool2D(4x4)	$12 \times 20 \times 16 \times 16$	$1 \times 6 \times 6$
Conv2D(3x3, 12->24)	$24 \times 20 \times 16 \times 16$	$1 \times 14 \times 14$

Build slowly in space

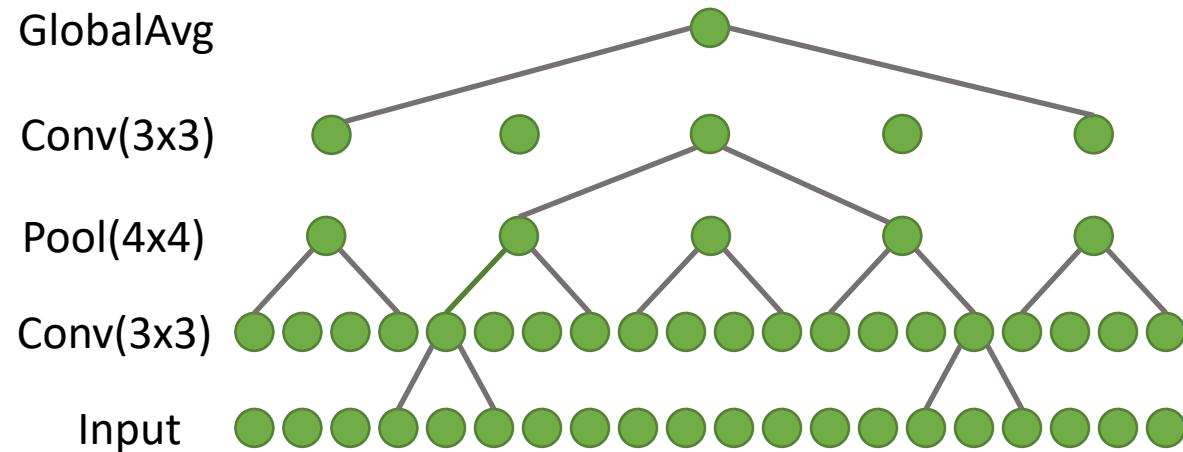


Early Fusion vs Late Fusion vs 3D CNN

Late
Fusion

Layer	Size (C x T x H x W)	Receptive Field (T x H x W)
Input	$3 \times 20 \times 64 \times 64$	
Conv2D(3x3, 3->12)	$12 \times 20 \times 64 \times 64$	$1 \times 3 \times 3$
Pool2D(4x4)	$12 \times 20 \times 16 \times 16$	$1 \times 6 \times 6$
Conv2D(3x3, 12->24)	$24 \times 20 \times 16 \times 16$	$1 \times 14 \times 14$
GlobalAvgPool	$24 \times 1 \times 1 \times 1$	$20 \times 64 \times 64$

Build slowly in space,
All-at-once in time at end



Early Fusion vs Late Fusion vs 3D CNN

Late
Fusion

Layer	Size (C x T x H x W)	Receptive Field (T x H x W)
Input	3 x 20 x 64 x 64	
Conv2D(3x3, 3->12)	12 x 20 x 64 x 64	1 x 3 x 3
Pool2D(4x4)	12 x 20 x 16 x 16	1 x 6 x 6
Conv2D(3x3, 12->24)	24 x 20 x 16 x 16	1 x 14 x 14
GlobalAvgPool	24 x 1 x 1 x 1	20 x 64 x 64
Input	3 x 20 x 64 x 64	
Conv2D(3x3, 3*10->12)	12 x 64 x 64	20 x 3 x 3
Pool2D(4x4)	12 x 16 x 16	20 x 6 x 6
Conv2D(3x3, 12->24)	24 x 16 x 16	20 x 14 x 14
GlobalAvgPool	24 x 1 x 1	20 x 64 x 64

Build slowly in space,
All-at-once in time at end

Early
Fusion

Build slowly in space,
All-at-once in time at start

(Small example architectures,
in practice much bigger)

Early Fusion vs Late Fusion vs 3D CNN

Late
Fusion

Layer	Size (C x T x H x W)	Receptive Field (T x H x W)
Input	3 x 20 x 64 x 64	
Conv2D(3x3, 3->12)	12 x 20 x 64 x 64	1 x 3 x 3
Pool2D(4x4)	12 x 20 x 16 x 16	1 x 6 x 6
Conv2D(3x3, 12->24)	24 x 20 x 16 x 16	1 x 14 x 14
GlobalAvgPool	24 x 1 x 1 x 1	20 x 64 x 64

Build slowly in space,
All-at-once in time at end

Early
Fusion

Input	3 x 20 x 64 x 64	
Conv2D(3x3, 3*10->12)	12 x 64 x 64	20 x 3 x 3
Pool2D(4x4)	12 x 16 x 16	20 x 6 x 6
Conv2D(3x3, 12->24)	24 x 16 x 16	20 x 14 x 14
GlobalAvgPool	24 x 1 x 1	20 x 64 x 64

Build slowly in space,
All-at-once in time at start

3D CNN

Input	3 x 20 x 64 x 64	
Conv3D(3x3x3, 3->12)	12 x 20 x 64 x 64	3 x 3 x 3
Pool3D(4x4x4)	12 x 5 x 16 x 16	6 x 6 x 6
Conv3D(3x3x3, 12->24)	24 x 5 x 16 x 16	14 x 14 x 14
GlobalAvgPool	24 x 1 x 1	20 x 64 x 64

Build slowly in space,
Build slowly in time
"Slow Fusion"

Early Fusion vs Late Fusion vs 3D CNN

What is the difference?

Late Fusion

Layer	Size (C x T x H x W)	Receptive Field (T x H x W)
Input	3 x 20 x 64 x 64	
Conv2D(3x3, 3->12)	12 x 20 x 64 x 64	1 x 3 x 3
Pool2D(4x4)	12 x 20 x 16 x 16	1 x 6 x 6
Conv2D(3x3, 12->24)	24 x 20 x 16 x 16	1 x 14 x 14
GlobalAvgPool	24 x 1 x 1 x 1	20 x 64 x 64

Build slowly in space,
All-at-once in time at end

Early Fusion

Input	3 x 20 x 64 x 64	
Conv2D(3x3, 3*10->12)	12 x 64 x 64	20 x 3 x 3
Pool2D(4x4)	12 x 16 x 16	20 x 6 x 6
Conv2D(3x3, 12->24)	24 x 16 x 16	20 x 14 x 14
GlobalAvgPool	24 x 1 x 1	20 x 64 x 64

Build slowly in space,
All-at-once in time at start

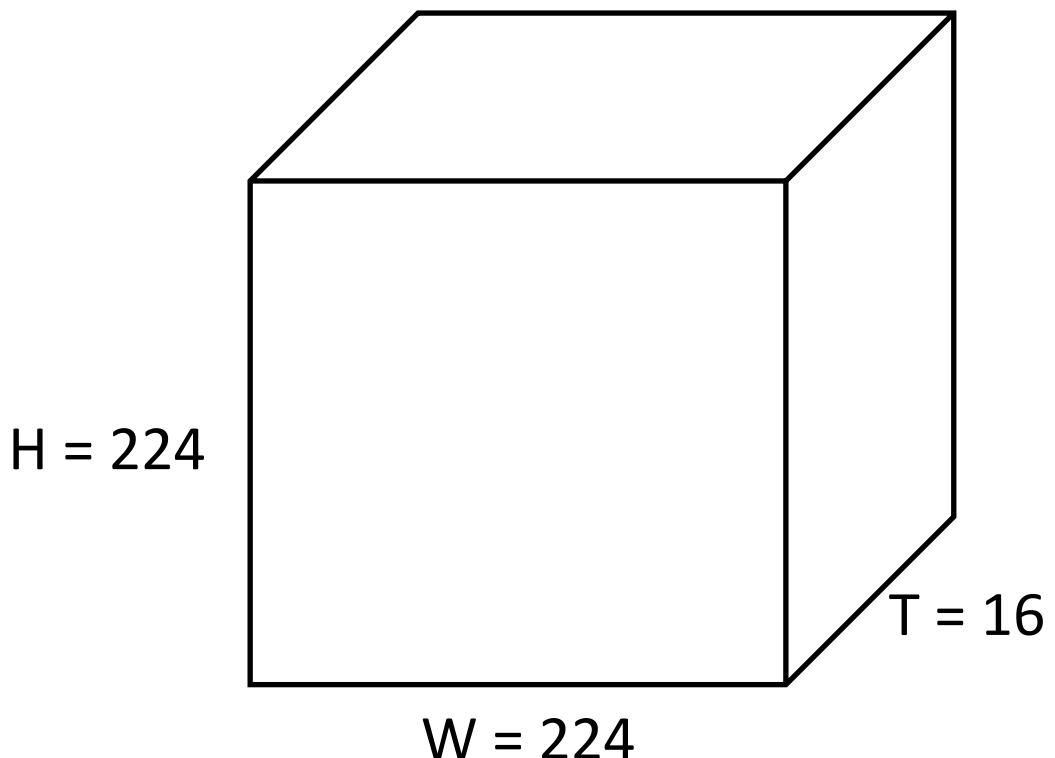
3D CNN

Input	3 x 20 x 64 x 64	
Conv3D(3x3x3, 3->12)	12 x 20 x 64 x 64	3 x 3 x 3
Pool3D(4x4x4)	12 x 5 x 16 x 16	6 x 6 x 6
Conv3D(3x3x3, 12->24)	24 x 5 x 16 x 16	14 x 14 x 14
GlobalAvgPool	24 x 1 x 1	20 x 64 x 64

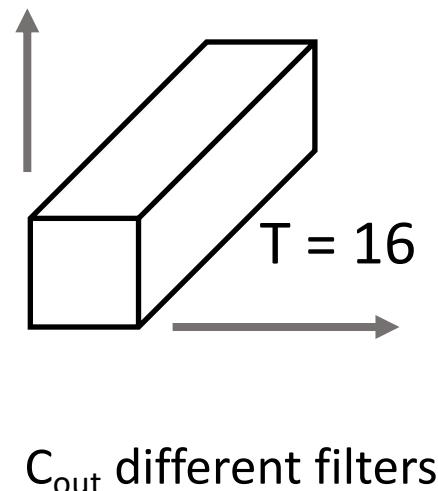
Build slowly in space,
Build slowly in time
"Slow Fusion"

2D Conv (Early Fusion) vs 3D Conv (3D CNN)

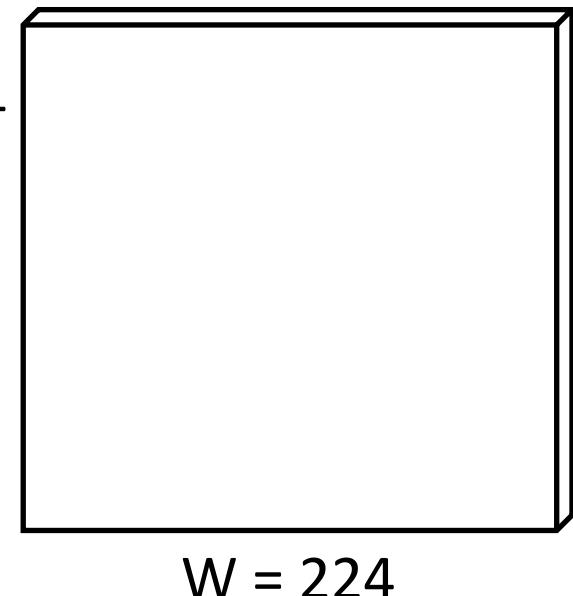
Input: $C_{in} \times T \times H \times W$
(3D grid with C_{in} -dim
feat at each point)



Weight:
 $C_{out} \times C_{in} \times T \times 3 \times 3$
Slide over x and y

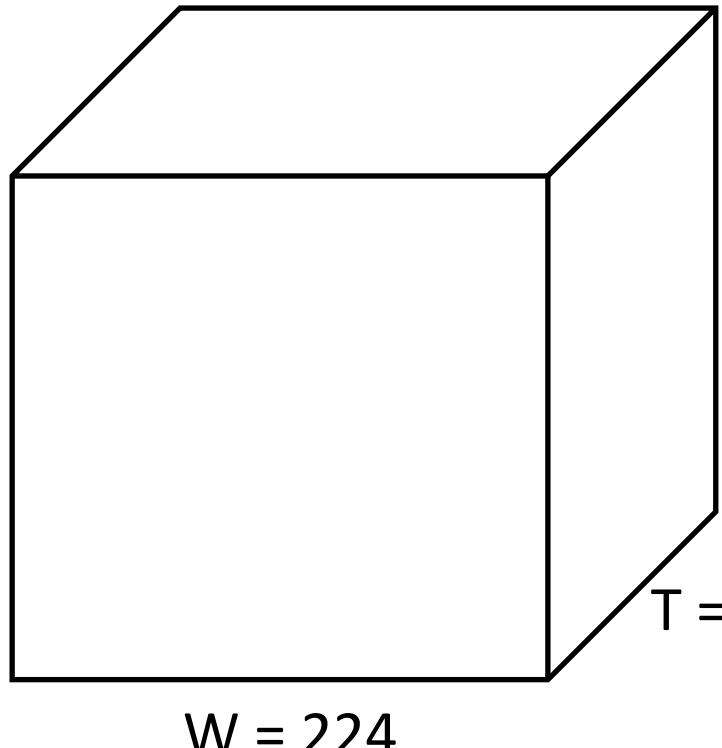


Output:
 $C_{out} \times H \times W$
2D grid with C_{out} -dim
feat at each point



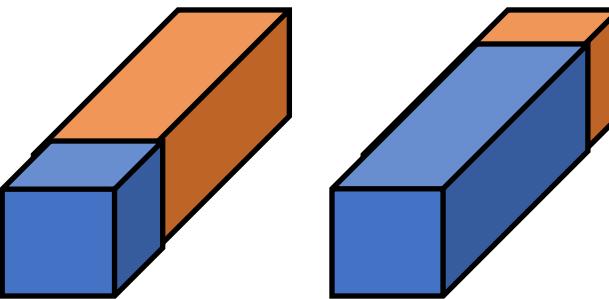
2D Conv (Early Fusion) vs 3D Conv (3D CNN)

Input: $C_{in} \times T \times H \times W$
(3D grid with C_{in} -dim
feat at each point)



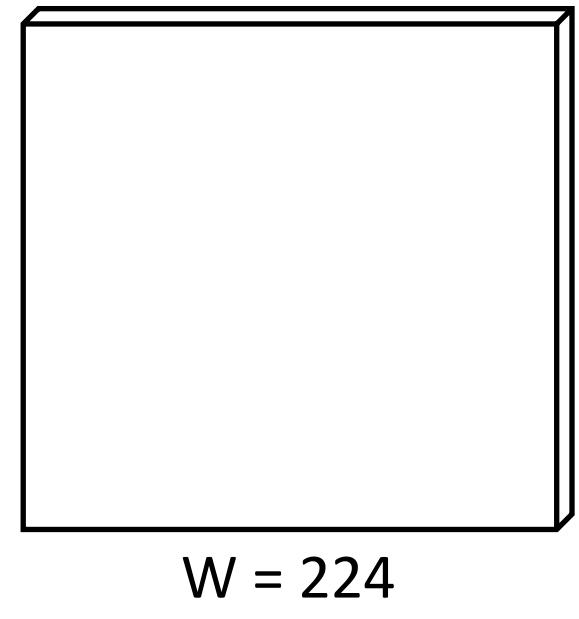
Weight:
 $C_{out} \times C_{in} \times T \times 3 \times 3$
Slide over x and y

No temporal shift-invariance! Needs
to learn separate filters for the same
motion at different times in the clip



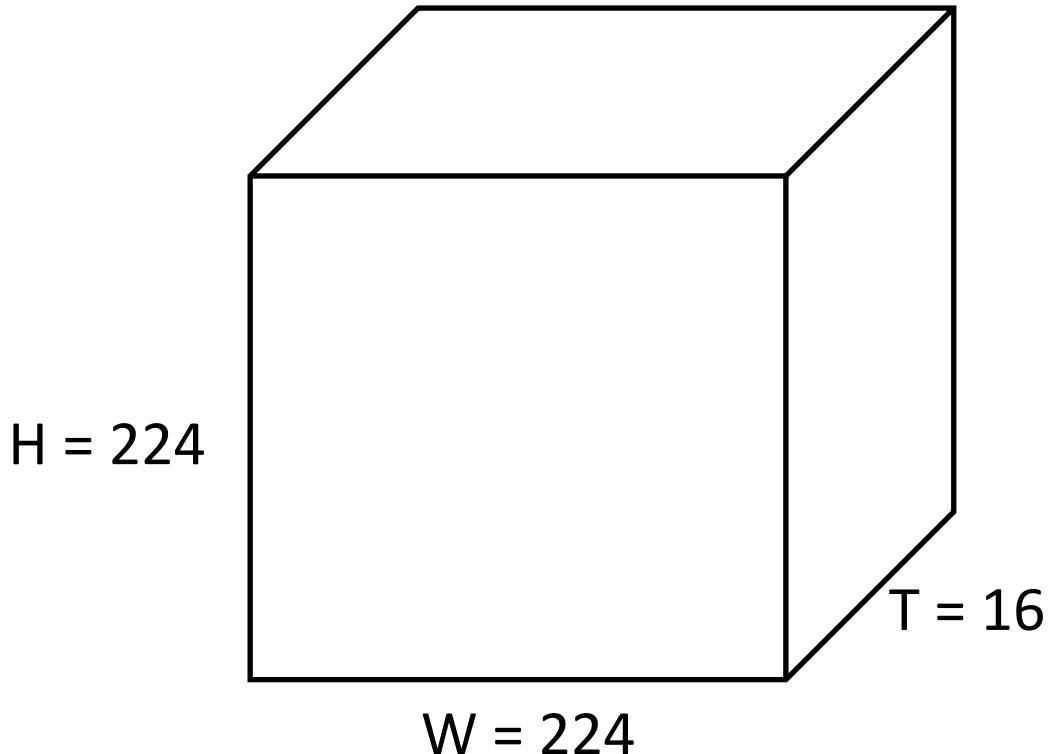
C_{out} different filters

Output:
 $C_{out} \times H \times W$
2D grid with C_{out} -dim
feat at each point

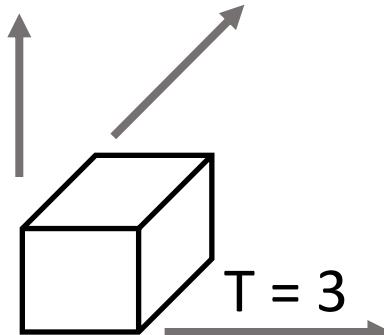


2D Conv (Early Fusion) vs 3D Conv (3D CNN)

Input: $C_{in} \times T \times H \times W$
(3D grid with C_{in} -dim
feat at each point)

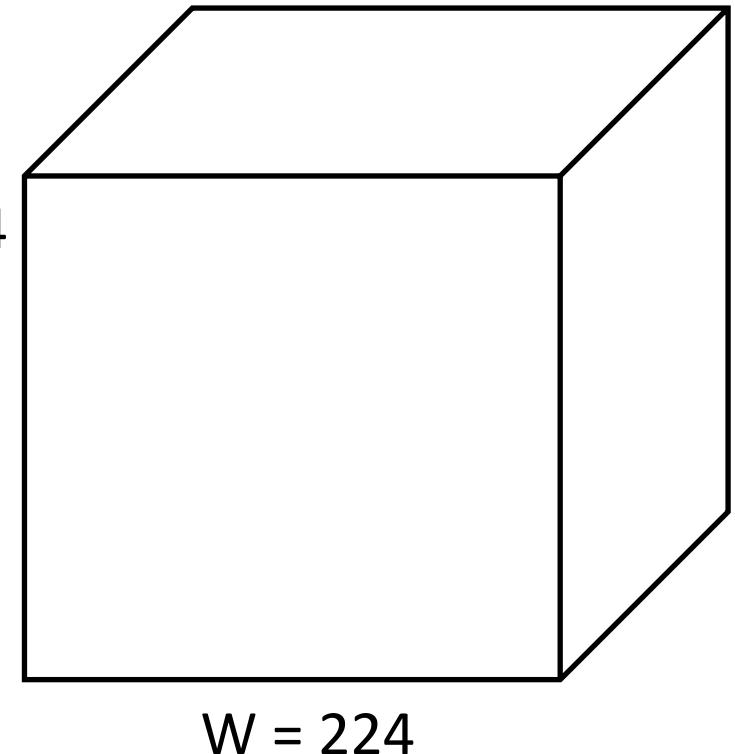


Weight:
 $C_{out} \times C_{in} \times 3 \times 3 \times 3$
Slide over x and y



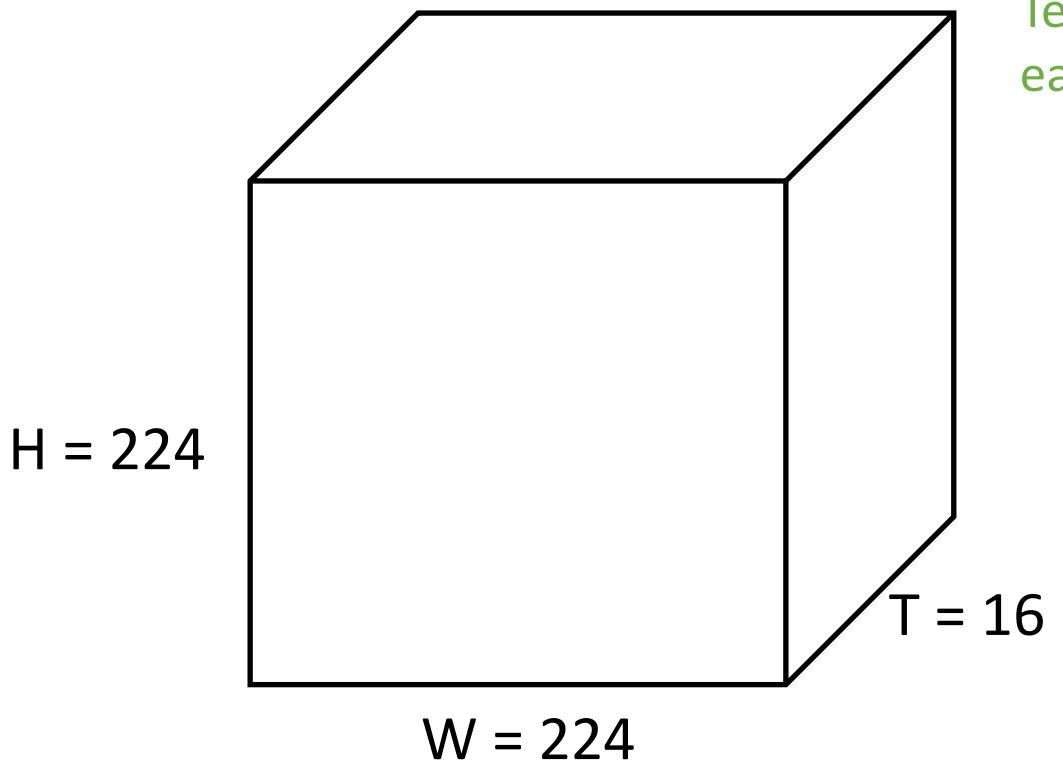
C_{out} different filters

Output:
 $C_{out} \times T \times H \times W$
3D grid with C_{out} -dim
feat at each point



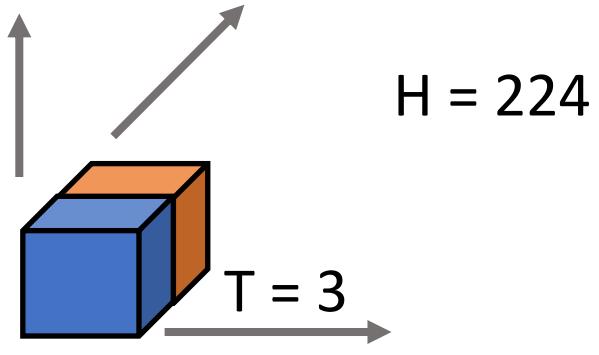
2D Conv (Early Fusion) vs 3D Conv (3D CNN)

Input: $C_{in} \times T \times H \times W$
(3D grid with C_{in} -dim
feat at each point)



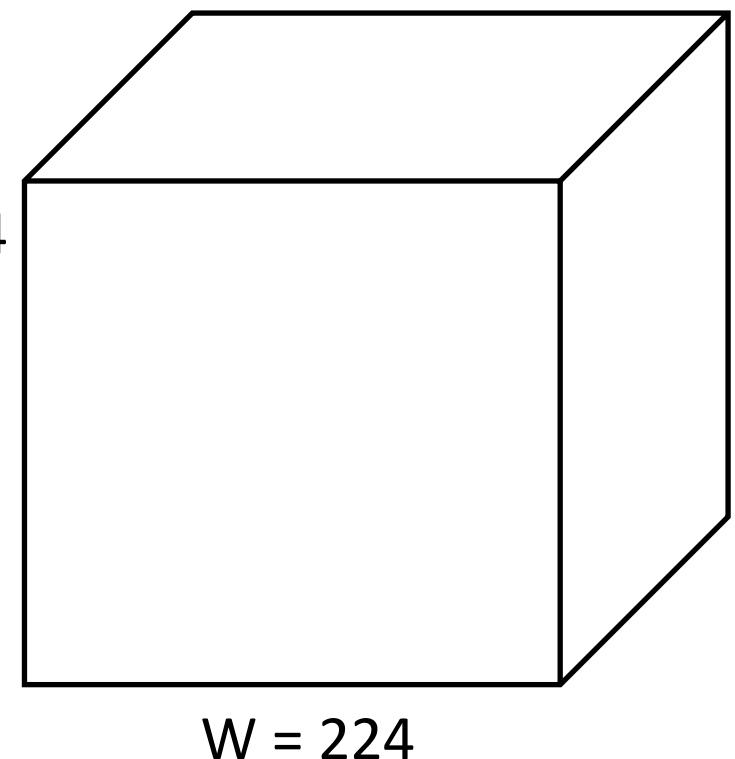
Weight:
 $C_{out} \times C_{in} \times 3 \times 3 \times 3$
Slide over x and y

Temporal shift-invariant since
each filter slides over time!



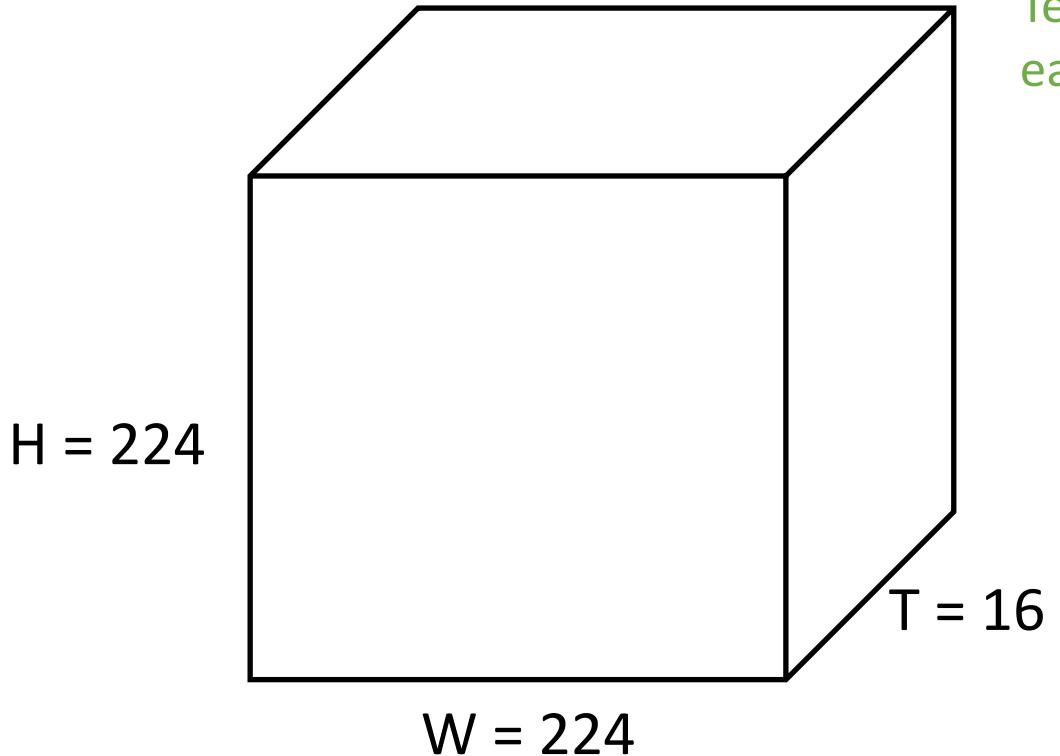
C_{out} different filters

Output:
 $C_{out} \times T \times H \times W$
3D grid with C_{out} -dim
feat at each point



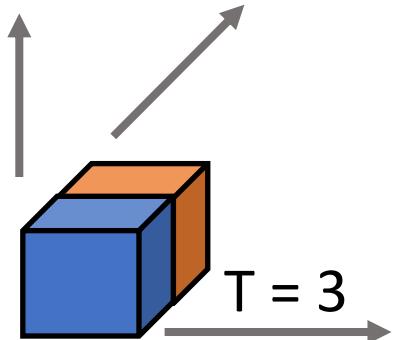
2D Conv (Early Fusion) vs 3D Conv (3D CNN)

Input: $C_{in} \times T \times H \times W$
(3D grid with C_{in} -dim
feat at each point)



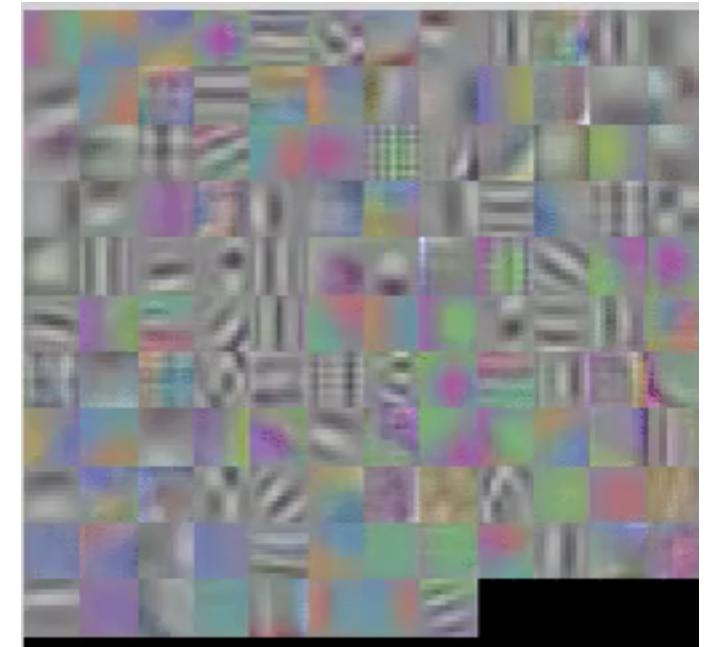
Weight:
 $C_{out} \times C_{in} \times 3 \times 3 \times 3$
Slide over x and y

Temporal shift-invariant since
each filter slides over time!



C_{out} different filters

First-layer filters have shape
3 (RGB) \times 4 (frames) \times 5 \times 5 (space)
Can visualize as video clips!



Karpathy et al, "Large-scale Video Classification with Convolutional Neural Networks", CVPR 2014

Example Video Dataset: Sports-1M

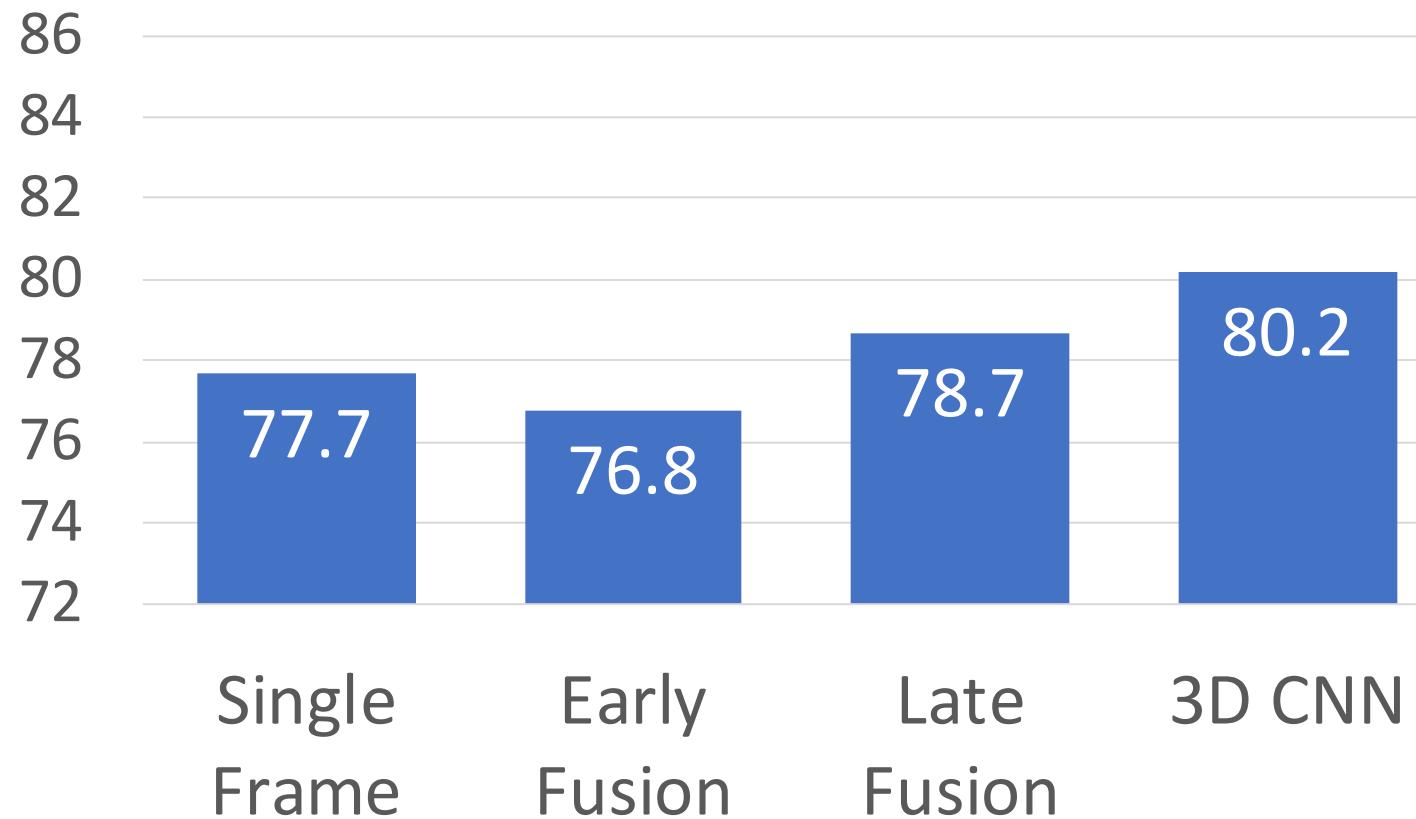


1 million YouTube videos
annotated with labels for
487 different types of sports

Ground Truth
Correct prediction
Incorrect prediction

Early Fusion vs Late Fusion vs 3D CNN

Sports-1M Top-5 Accuracy



Single Frame model works well – always try this first!

3D CNNs have improved a lot since 2014!

C3D: The VGG of 3D CNNs

3D CNN that uses all $3 \times 3 \times 3$ conv and
 $2 \times 2 \times 2$ pooling
(except Pool1 which is $1 \times 2 \times 2$)

Released model pretrained on Sports-
1M: Many people used this as a video
feature extractor

Layer	Size
Input	$3 \times 16 \times 112 \times 112$
Conv1 ($3 \times 3 \times 3$)	$64 \times 16 \times 112 \times 112$
Pool1 ($1 \times 2 \times 2$)	$64 \times 16 \times 56 \times 56$
Conv2 ($3 \times 3 \times 3$)	$128 \times 16 \times 56 \times 56$
Pool2 ($2 \times 2 \times 2$)	$128 \times 8 \times 28 \times 28$
Conv3a ($3 \times 3 \times 3$)	$256 \times 8 \times 28 \times 28$
Conv3b ($3 \times 3 \times 3$)	$256 \times 8 \times 28 \times 28$
Pool3 ($2 \times 2 \times 2$)	$256 \times 4 \times 14 \times 14$
Conv4a ($3 \times 3 \times 3$)	$512 \times 4 \times 14 \times 14$
Conv4b ($3 \times 3 \times 3$)	$512 \times 4 \times 14 \times 14$
Pool4 ($2 \times 2 \times 2$)	$512 \times 2 \times 7 \times 7$
Conv5a ($3 \times 3 \times 3$)	$512 \times 2 \times 7 \times 7$
Conv5b ($3 \times 3 \times 3$)	$512 \times 2 \times 7 \times 7$
Pool5	$512 \times 1 \times 3 \times 3$
FC6	4096
FC7	4096
FC8	C

C3D: The VGG of 3D CNNs

3D CNN that uses all $3 \times 3 \times 3$ conv and
 $2 \times 2 \times 2$ pooling
(except Pool1 which is $1 \times 2 \times 2$)

Released model pretrained on Sports-1M: Many people used this as a video feature extractor

Problem: $3 \times 3 \times 3$ conv is very expensive!

AlexNet: 0.7 GFLOP

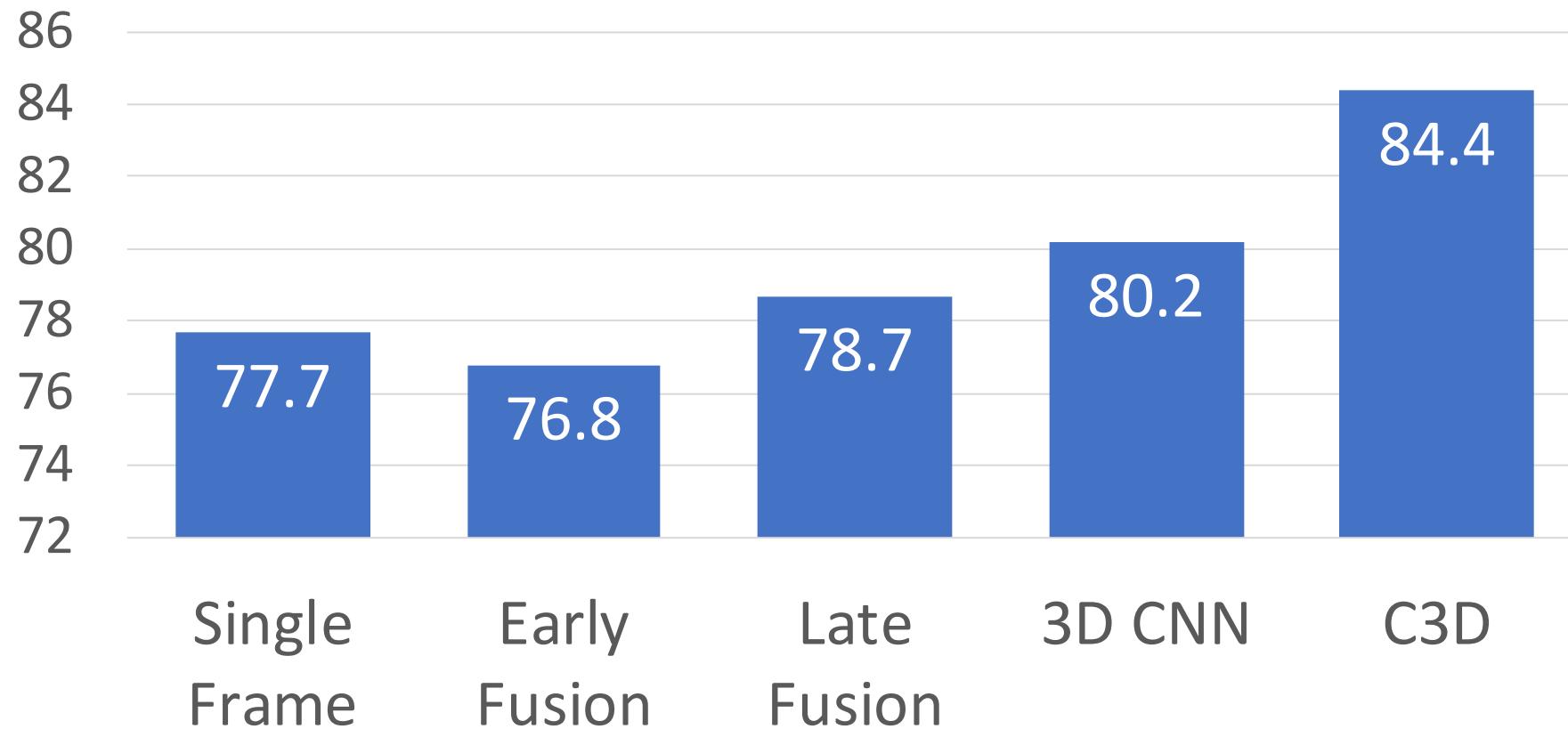
VGG-16: 13.6 GFLOP

C3D: 39.5 GFLOP (2.9x VGG!)

Layer	Size	MFLOPs
Input	$3 \times 16 \times 112 \times 112$	
Conv1 ($3 \times 3 \times 3$)	$64 \times 16 \times 112 \times 112$	1.04
Pool1 ($1 \times 2 \times 2$)	$64 \times 16 \times 56 \times 56$	
Conv2 ($3 \times 3 \times 3$)	$128 \times 16 \times 56 \times 56$	11.10
Pool2 ($2 \times 2 \times 2$)	$128 \times 8 \times 28 \times 28$	
Conv3a ($3 \times 3 \times 3$)	$256 \times 8 \times 28 \times 28$	5.55
Conv3b ($3 \times 3 \times 3$)	$256 \times 8 \times 28 \times 28$	11.10
Pool3 ($2 \times 2 \times 2$)	$256 \times 4 \times 14 \times 14$	
Conv4a ($3 \times 3 \times 3$)	$512 \times 4 \times 14 \times 14$	2.77
Conv4b ($3 \times 3 \times 3$)	$512 \times 4 \times 14 \times 14$	5.55
Pool4 ($2 \times 2 \times 2$)	$512 \times 2 \times 7 \times 7$	
Conv5a ($3 \times 3 \times 3$)	$512 \times 2 \times 7 \times 7$	0.69
Conv5b ($3 \times 3 \times 3$)	$512 \times 2 \times 7 \times 7$	0.69
Pool5	$512 \times 1 \times 3 \times 3$	
FC6	4096	0.51
FC7	4096	0.45
FC8	C	0.05

Early Fusion vs Late Fusion vs 3D CNN

Sports-1M Top-5 Accuracy



Karpathy et al, "Large-scale Video Classification with Convolutional Neural Networks", CVPR 2014
Tran et al, "Learning Spatiotemporal Features with 3D Convolutional Networks", ICCV 2015

Recognizing Actions from Motion

We can easily recognize actions using only **motion information**



Johansson, "Visual perception of biological motion and a model for its analysis." Perception & Psychophysics. 14(2):201-211. 1973.

Measuring Motion: Optical Flow

Image at frame t

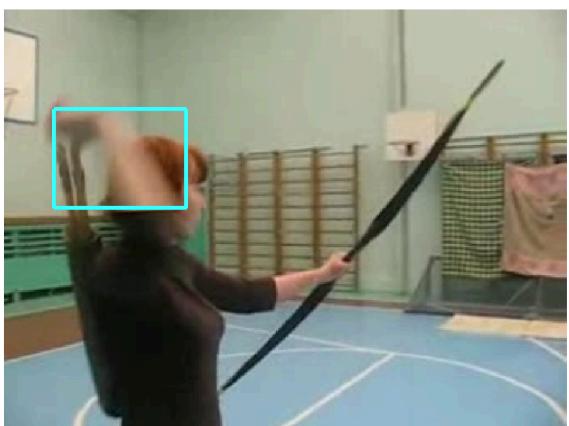


Image at frame t+1

Simonyan and Zisserman, "Two-stream convolutional networks for action recognition in videos", NeurIPS 2014

Measuring Motion: Optical Flow

Image at frame t

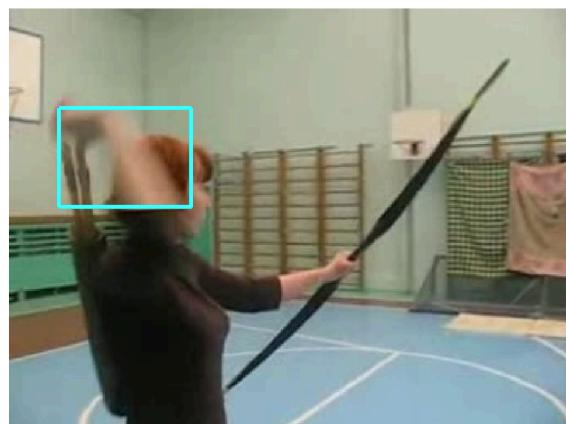
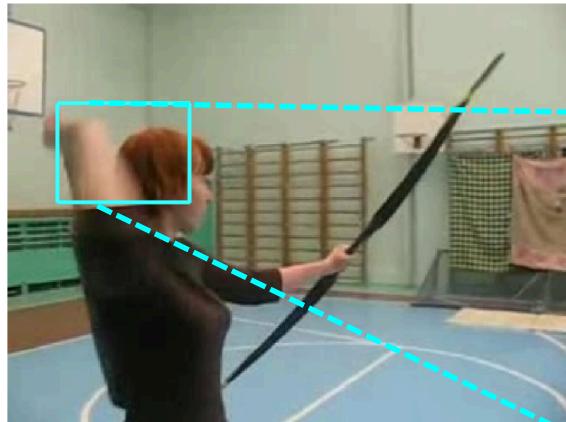
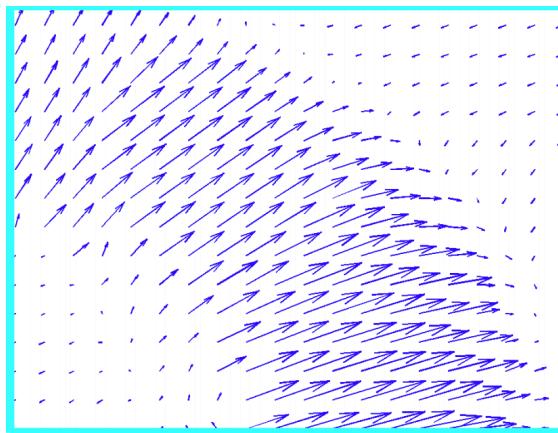


Image at frame $t+1$

Optical flow gives a displacement field F between images I_t and I_{t+1}



Tells where each pixel will move in the next frame:
 $F(x, y) = (dx, dy)$
 $I_{t+1}(x+dx, y+dy) = I_t(x, y)$

Measuring Motion: Optical Flow

Image at frame t

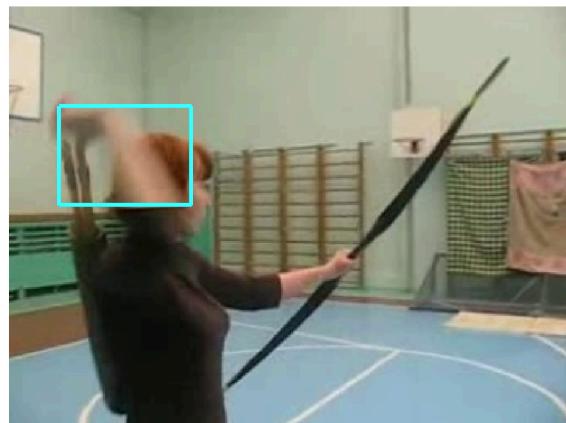
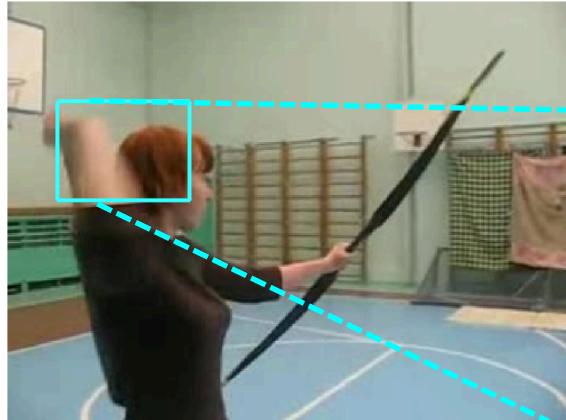
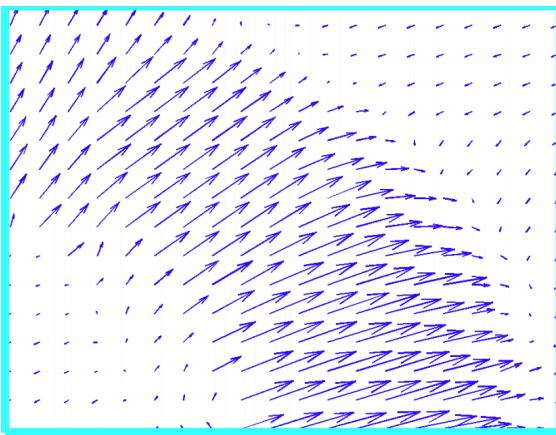


Image at frame $t+1$

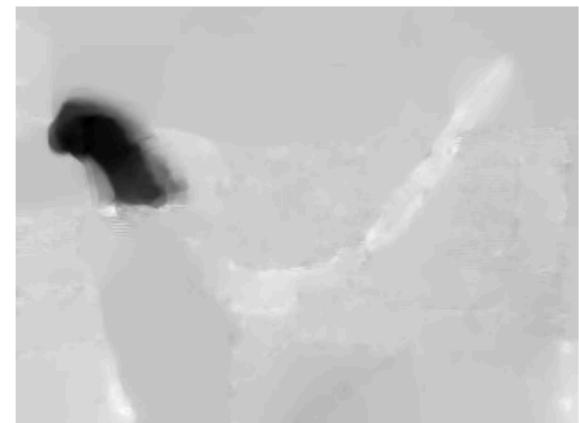
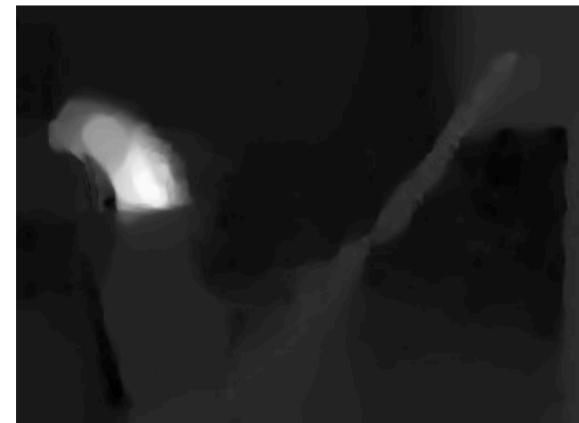
Optical flow gives a displacement field F between images I_t and I_{t+1}



Tells where each pixel will move in the next frame:
 $F(x, y) = (dx, dy)$
 $I_{t+1}(x+dx, y+dy) = I_t(x, y)$

Optical Flow highlights local motion

Horizontal flow dx

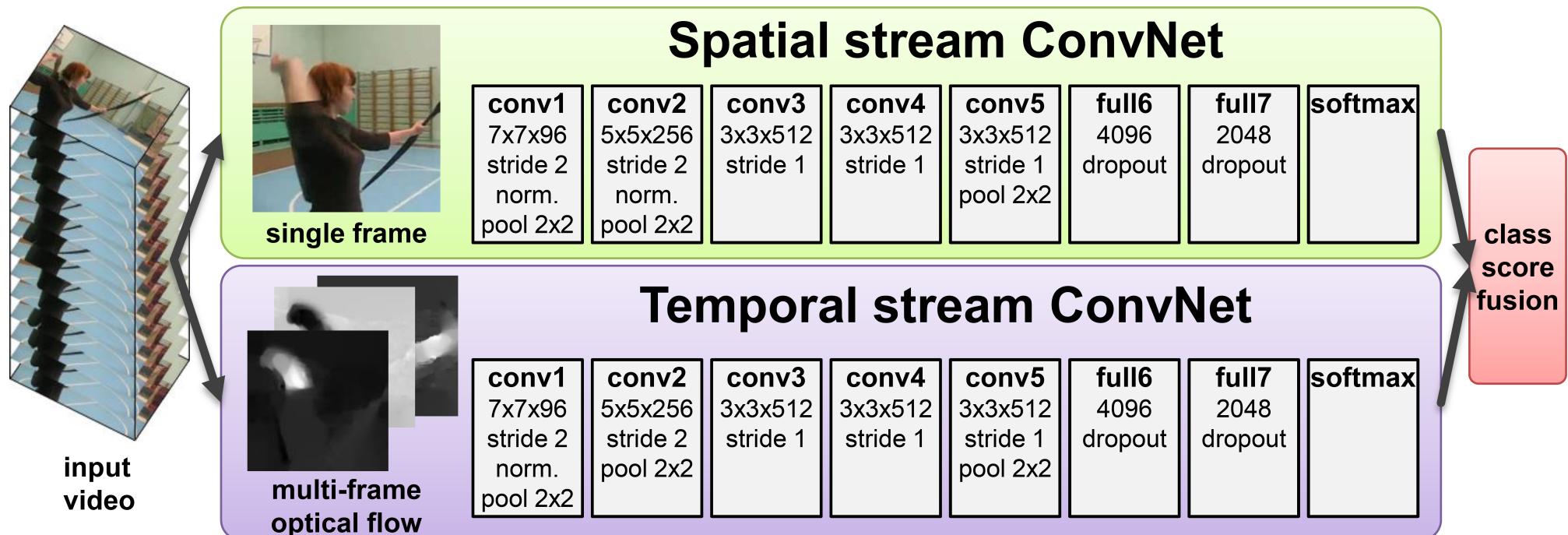


Vertical Flow dy

Separating Motion and Appearance: Two-Stream Networks

Input: Single Image

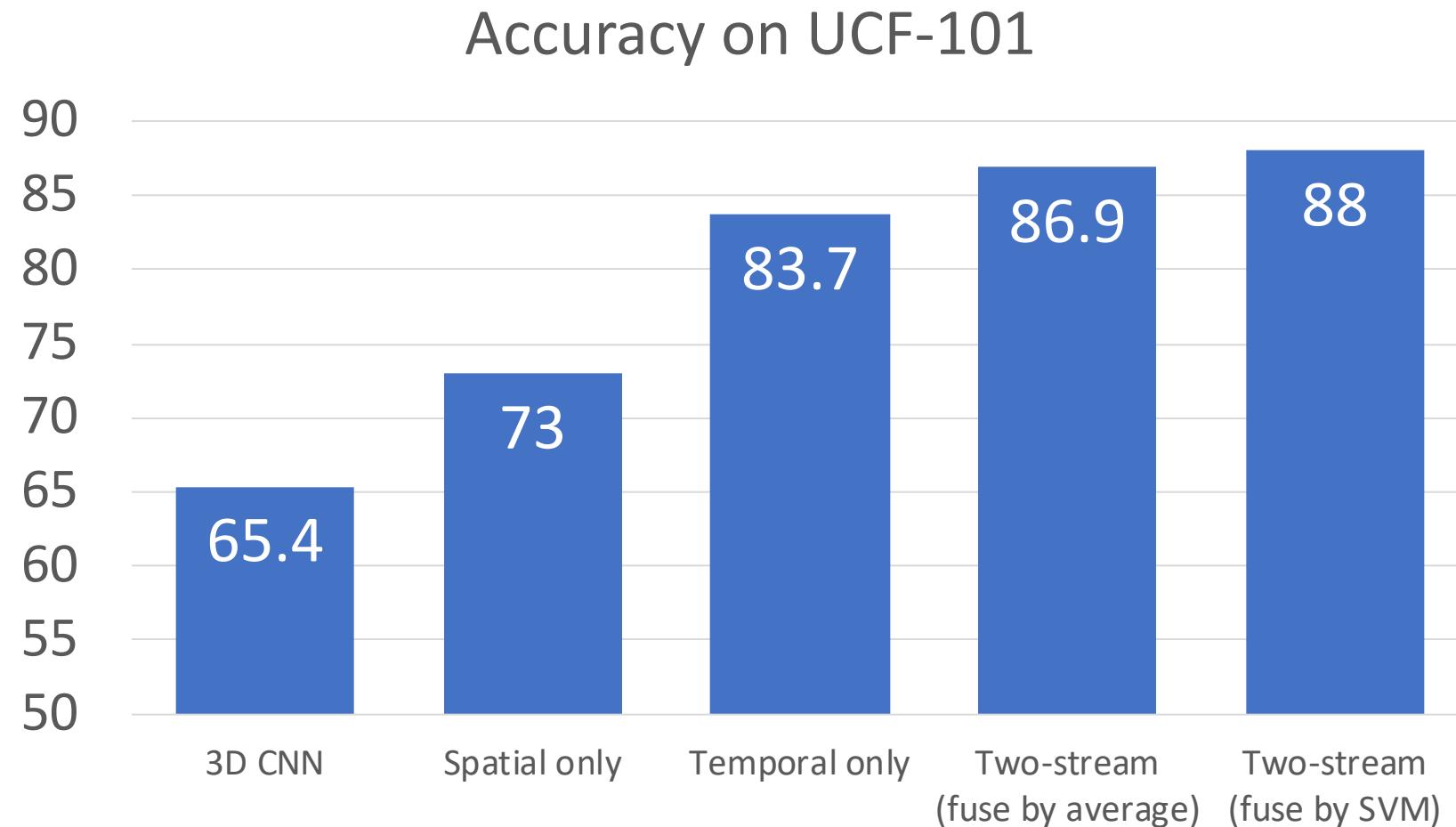
$3 \times H \times W$



Input: Stack of optical flow:
 $[2*(T-1)] \times H \times W$

Early fusion: First 2D conv
processes all flow images

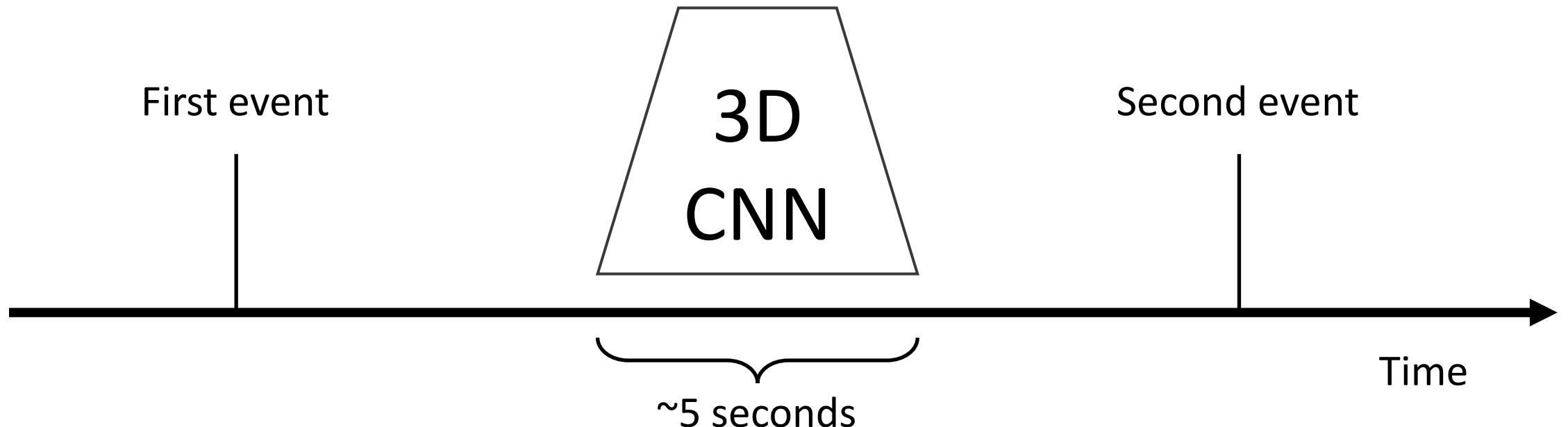
Separating Motion and Appearance: Two-Stream Networks



Simonyan and Zisserman, "Two-stream convolutional networks for action recognition in videos", NeurIPS 2014

Modeling long-term temporal structure

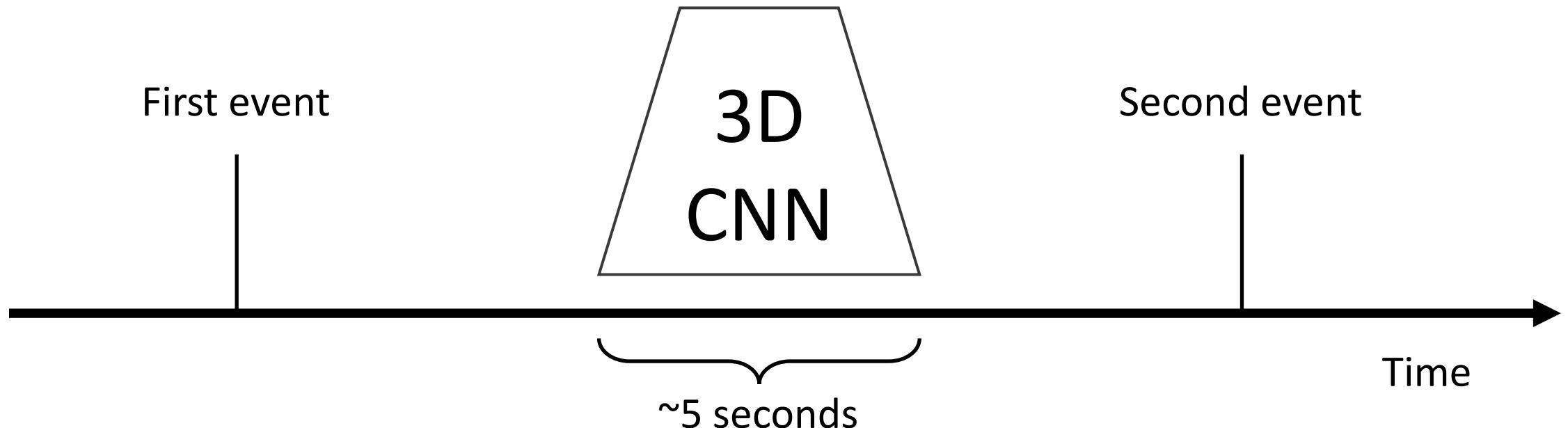
So far all our temporal CNNs only model local motion between frames in very short clips of ~2-5 seconds. What about long-term structure?



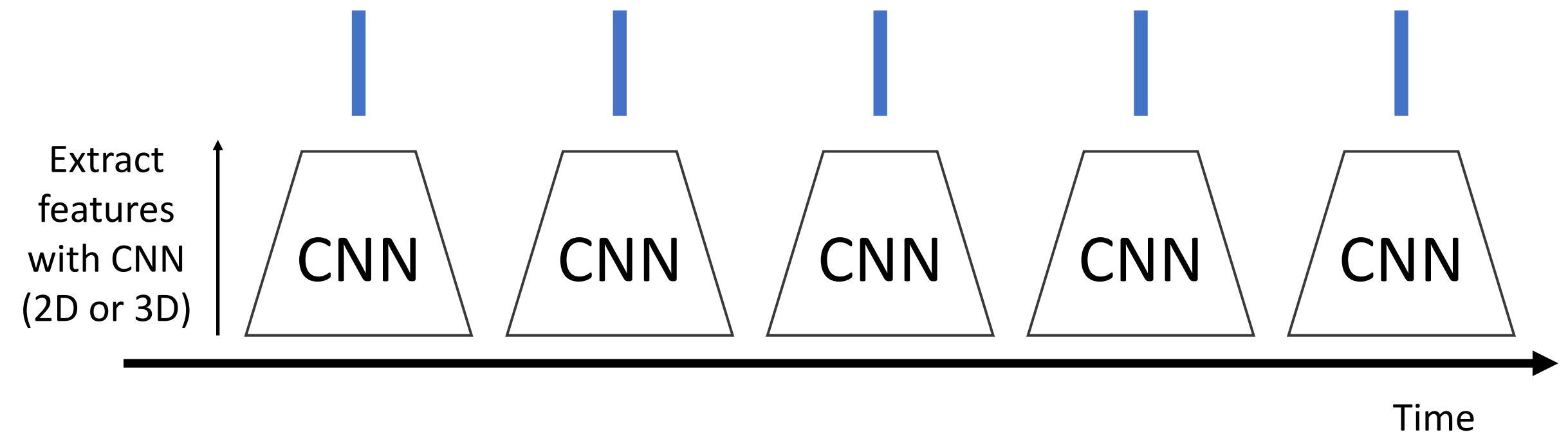
Modeling long-term temporal structure

So far all our temporal CNNs only model local motion between frames in very short clips of ~2-5 seconds. What about long-term structure?

We know how to handle sequences!
How about recurrent networks?

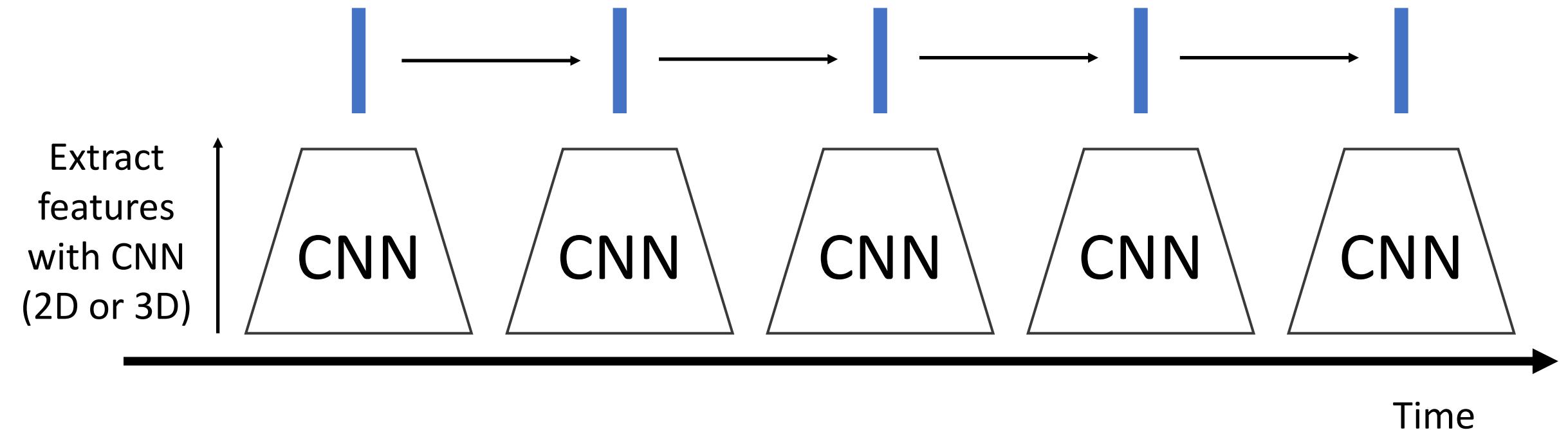


Modeling long-term temporal structure



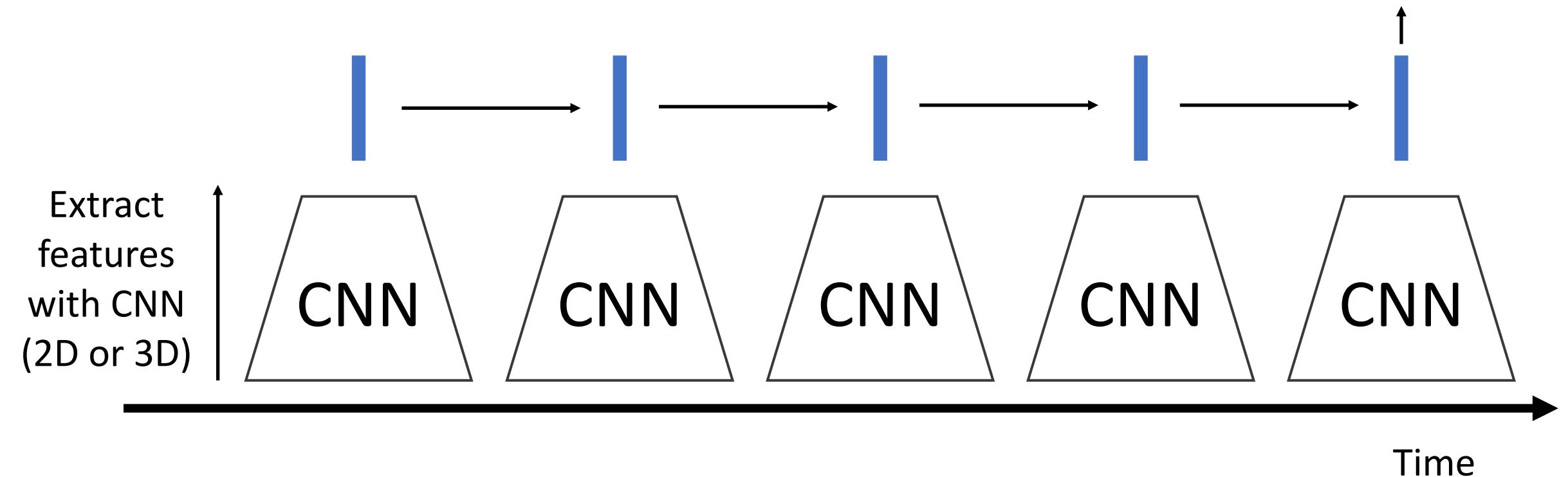
Modeling long-term temporal structure

Process local features using recurrent network (e.g. LSTM)



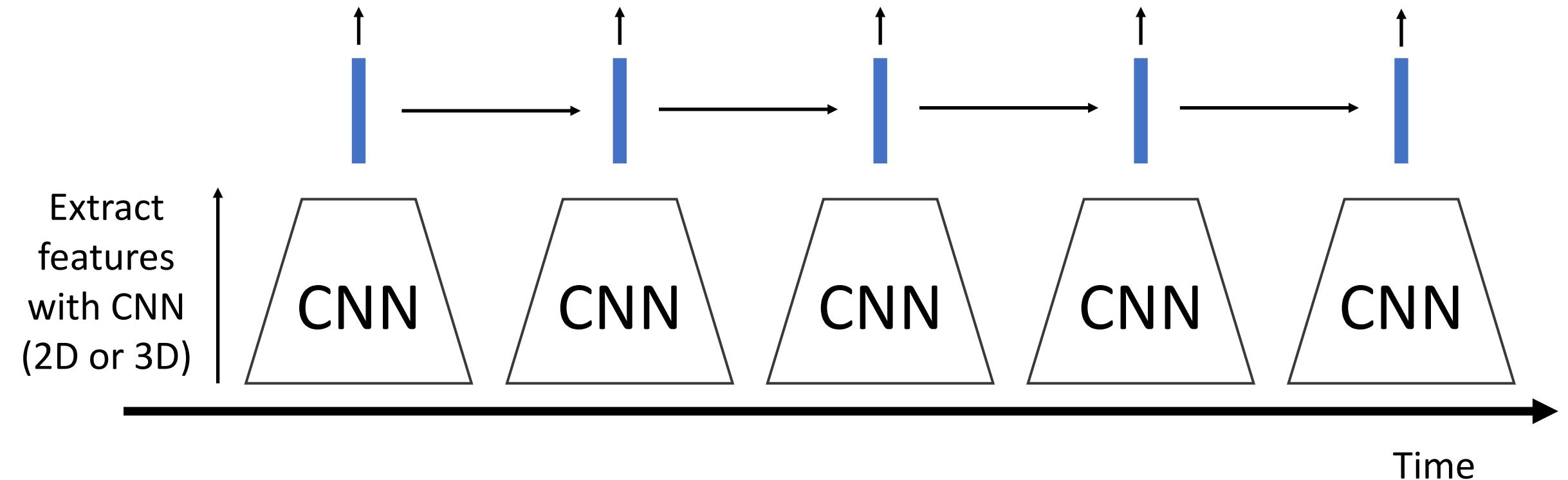
Modeling long-term temporal structure

Process local features using recurrent network (e.g. LSTM)
Many to one: One output at end of video



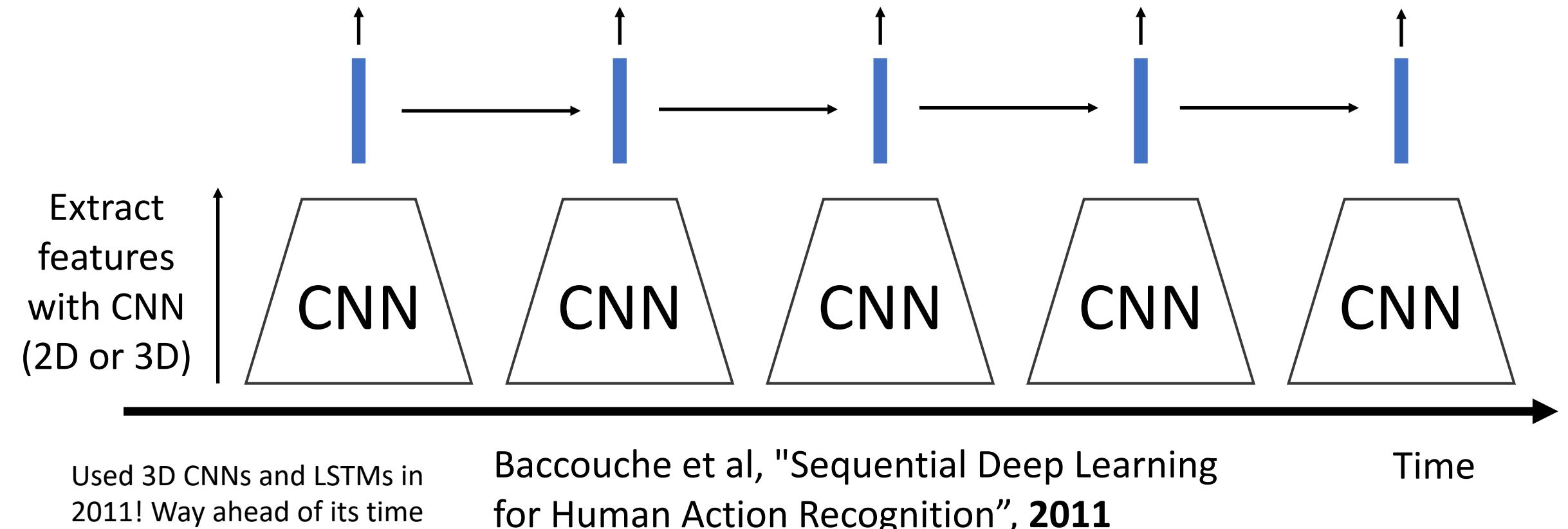
Modeling long-term temporal structure

Process local features using recurrent network (e.g. LSTM)
Many to many: one output per video frame



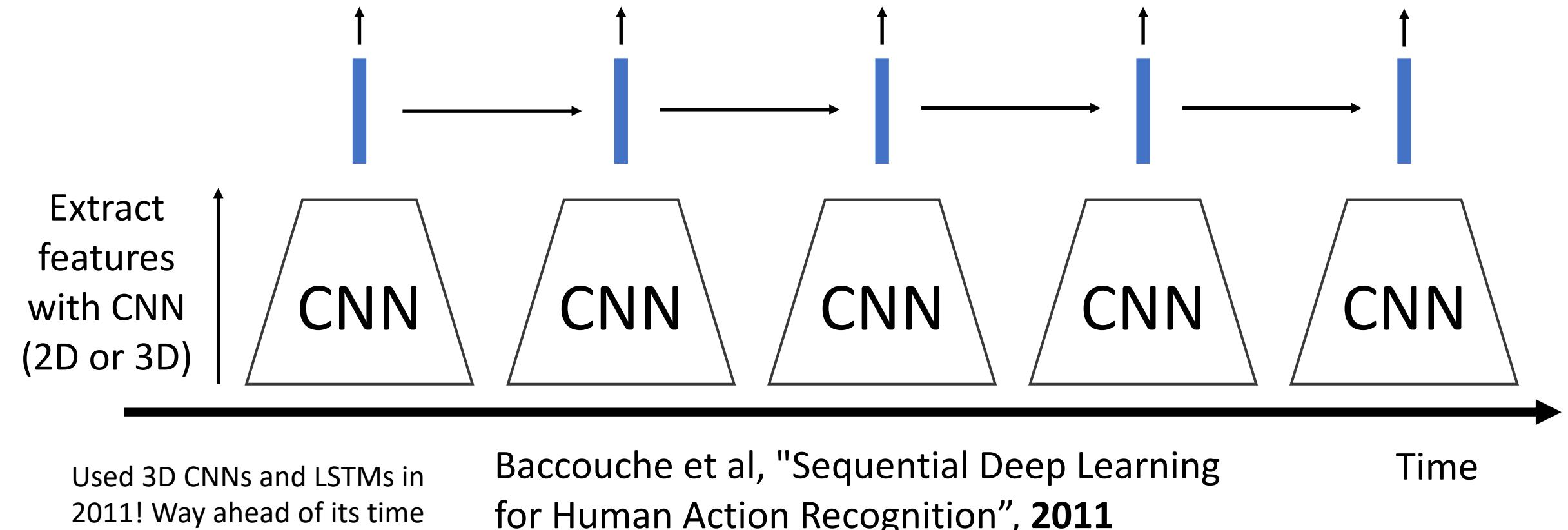
Modeling long-term temporal structure

Process local features using recurrent network (e.g. LSTM)
Many to many: one output per video frame



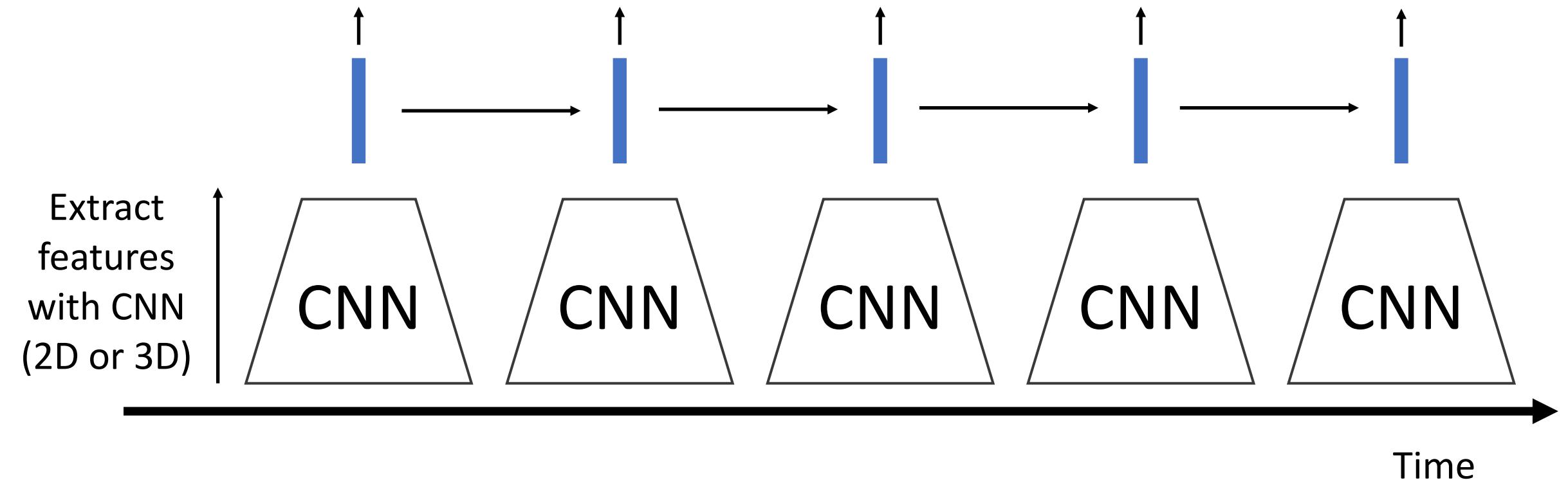
Modeling long-term temporal structure

Process local features using recurrent network (e.g. LSTM)
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Modeling long-term temporal structure

Process local features using recurrent network (e.g. LSTM)
Many to many: one output per video frame

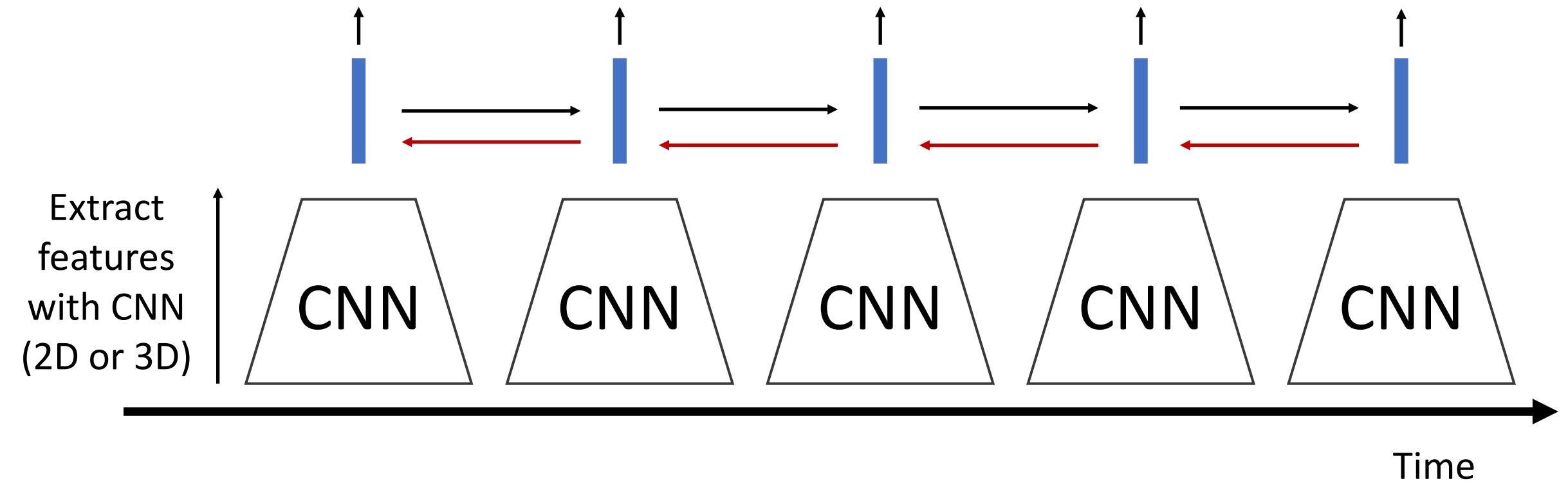


Baccouche et al, "Sequential Deep Learning for Human Action Recognition", 2011

Donahue et al, "Long-term recurrent convolutional networks for visual recognition and description", CVPR 2015

Modeling long-term temporal structure

Sometimes don't backprop to CNN to save memory;
pretrain and use it as a feature extractor



Baccouche et al, "Sequential Deep Learning for Human Action Recognition", 2011

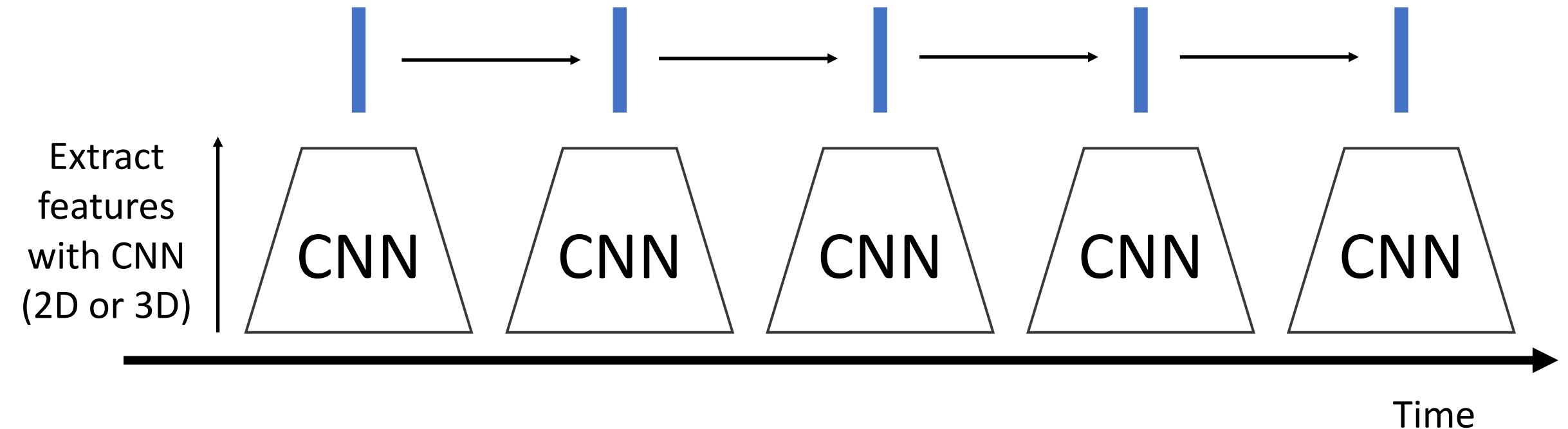
Donahue et al, "Long-term recurrent convolutional networks for visual recognition and description", CVPR 2015

Modeling long-term temporal structure

Inside CNN: Each value a function of a fixed temporal window (local temporal structure)

Inside RNN: Each vector is a function of all previous vectors (global temporal structure)

Can we merge both approaches?

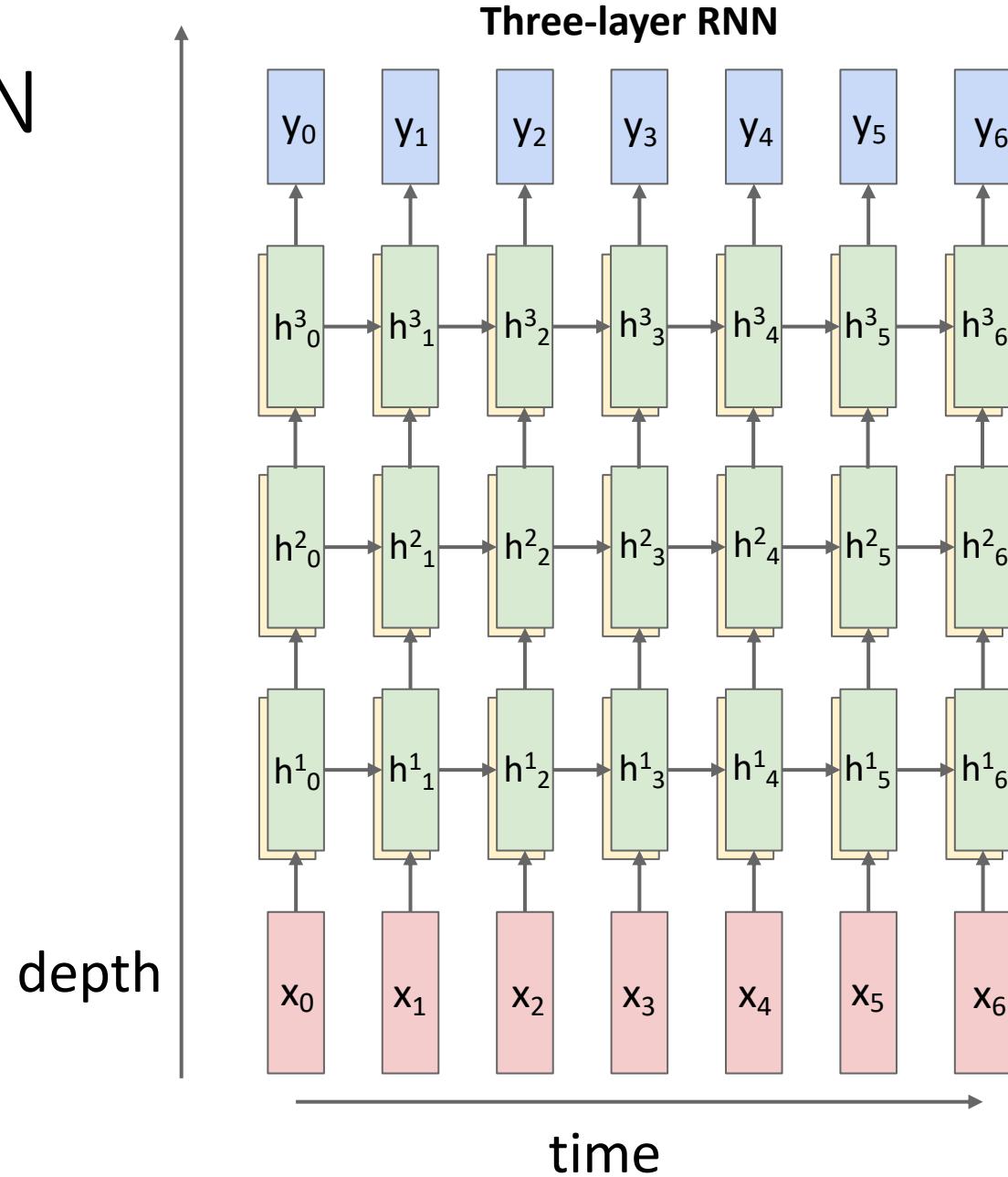


Baccouche et al, "Sequential Deep Learning for Human Action Recognition", 2011

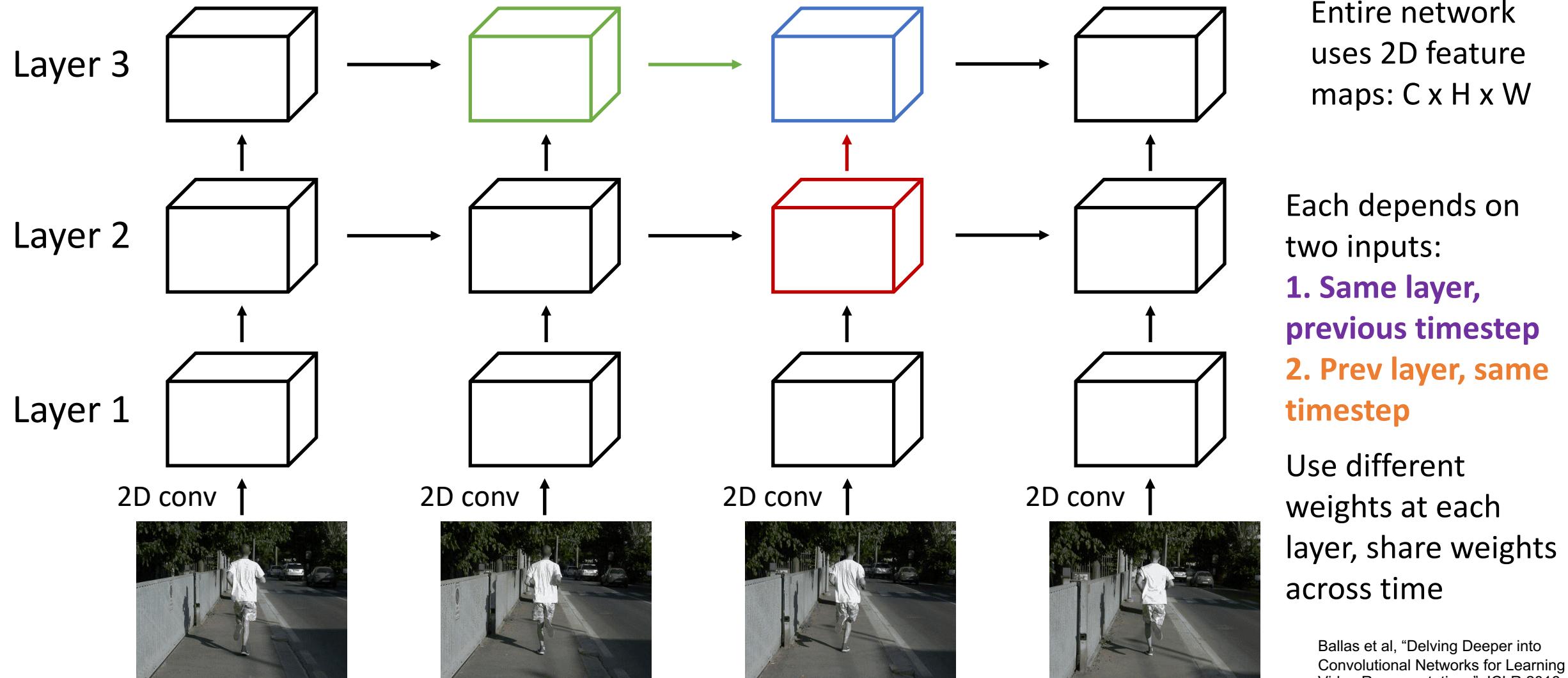
Donahue et al, "Long-term recurrent convolutional networks for visual recognition and description", CVPR 2015

Recall: Multi-layer RNN

We can use a similar structure to process videos!



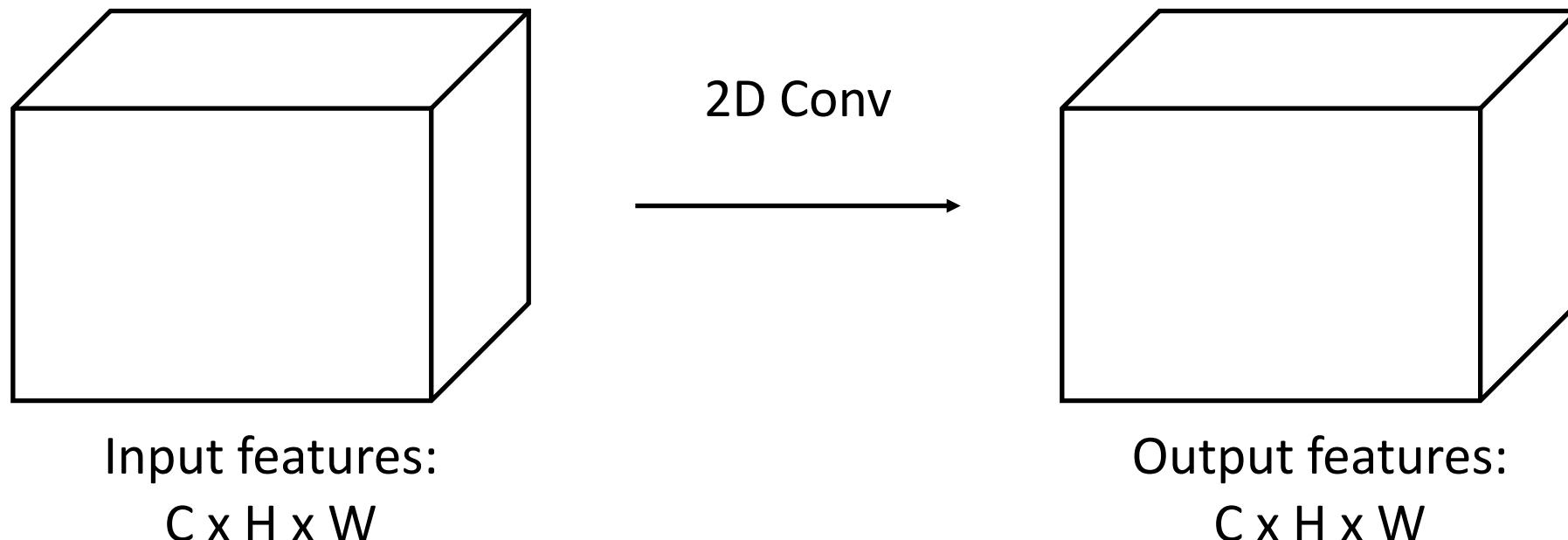
Recurrent Convolutional Network



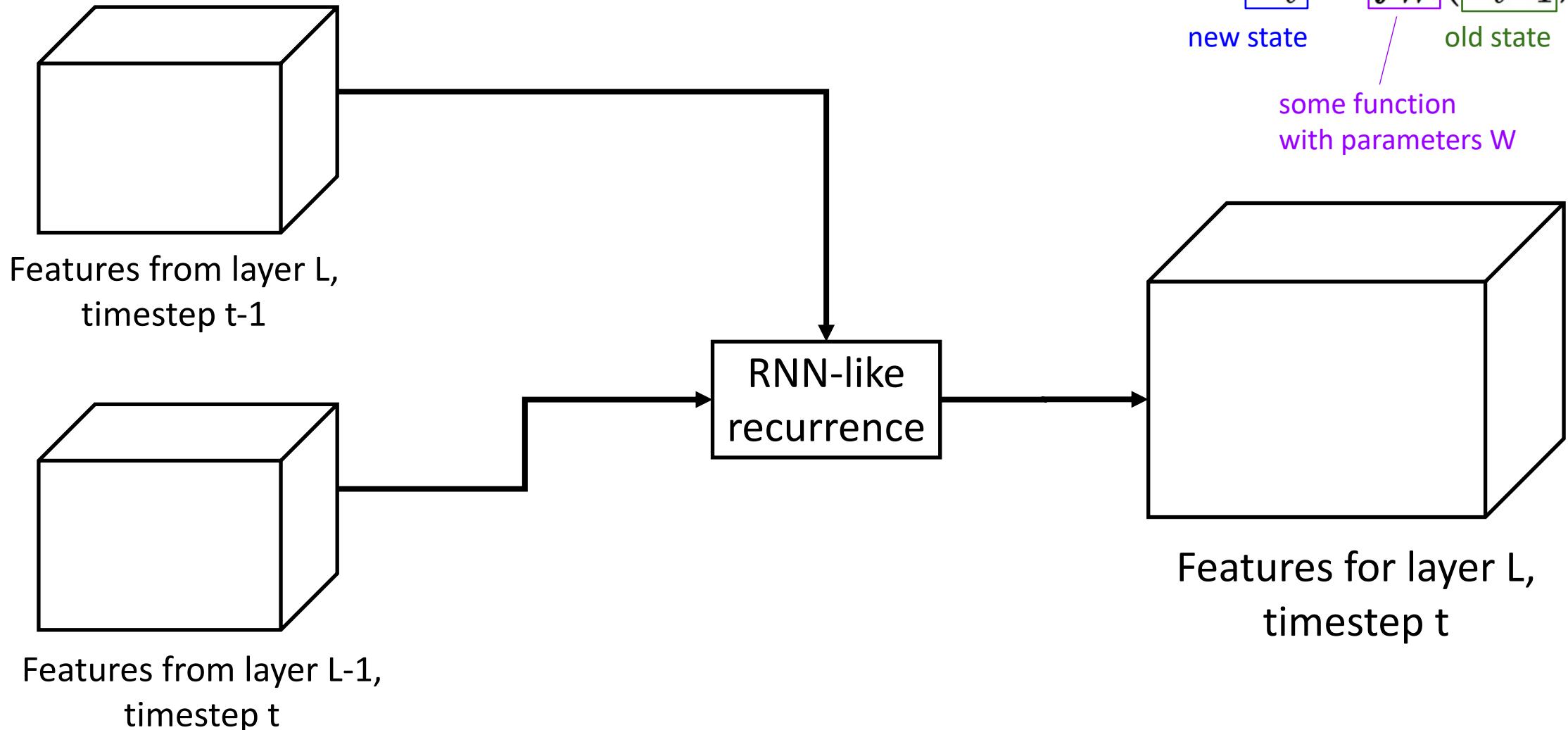
Ballas et al, "Delving Deeper into Convolutional Networks for Learning Video Representations", ICLR 2016

Recurrent Convolutional Network

Normal 2D CNN:

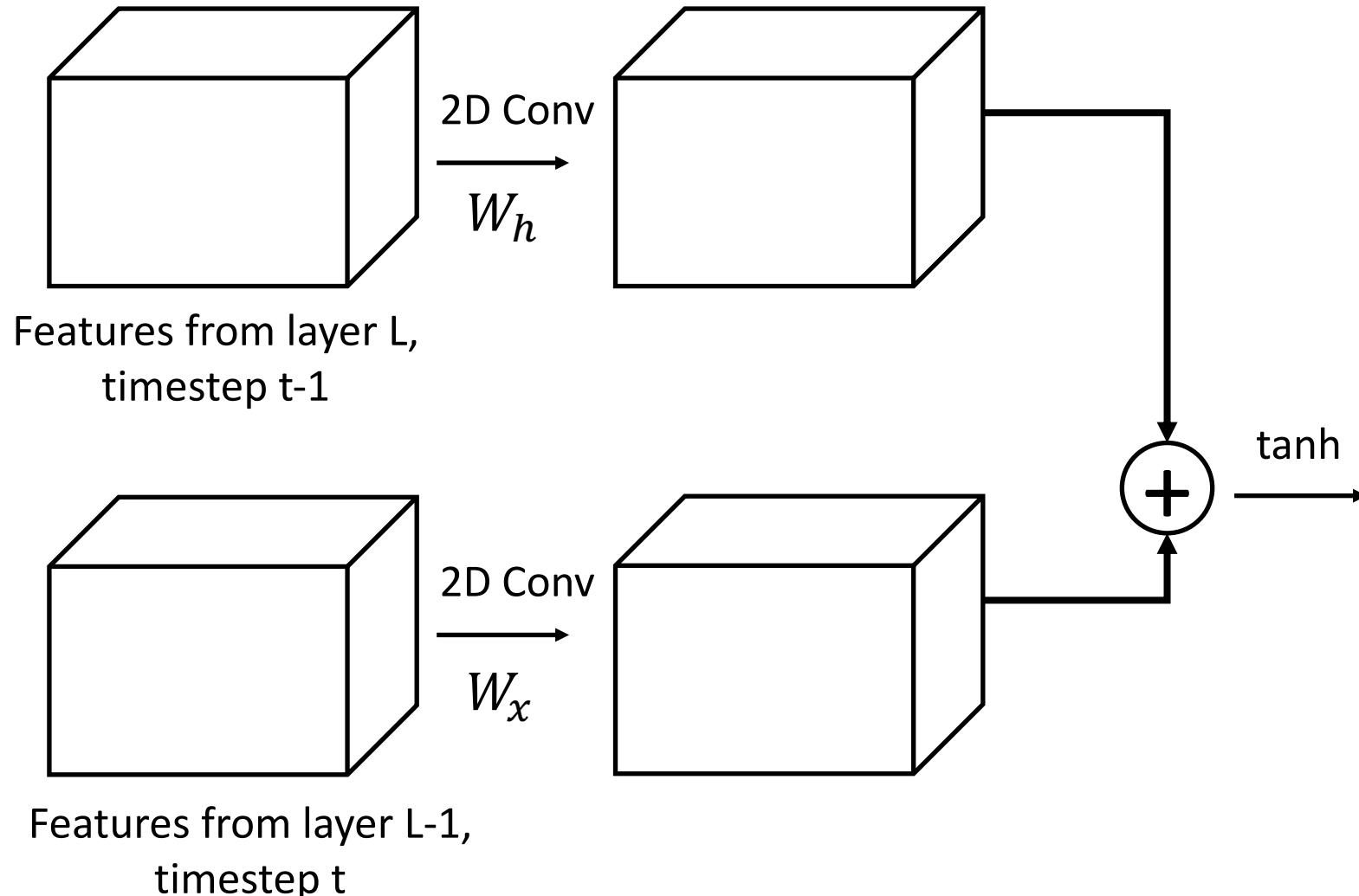


Recurrent Convolutional Network



Ballas et al, "Delving Deeper into Convolutional Networks for Learning Video Representations", ICLR 2016

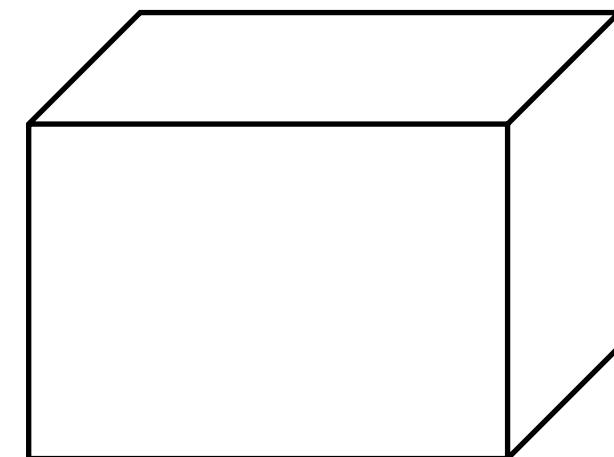
Recurrent Convolutional Network



Recall: Vanilla RNN

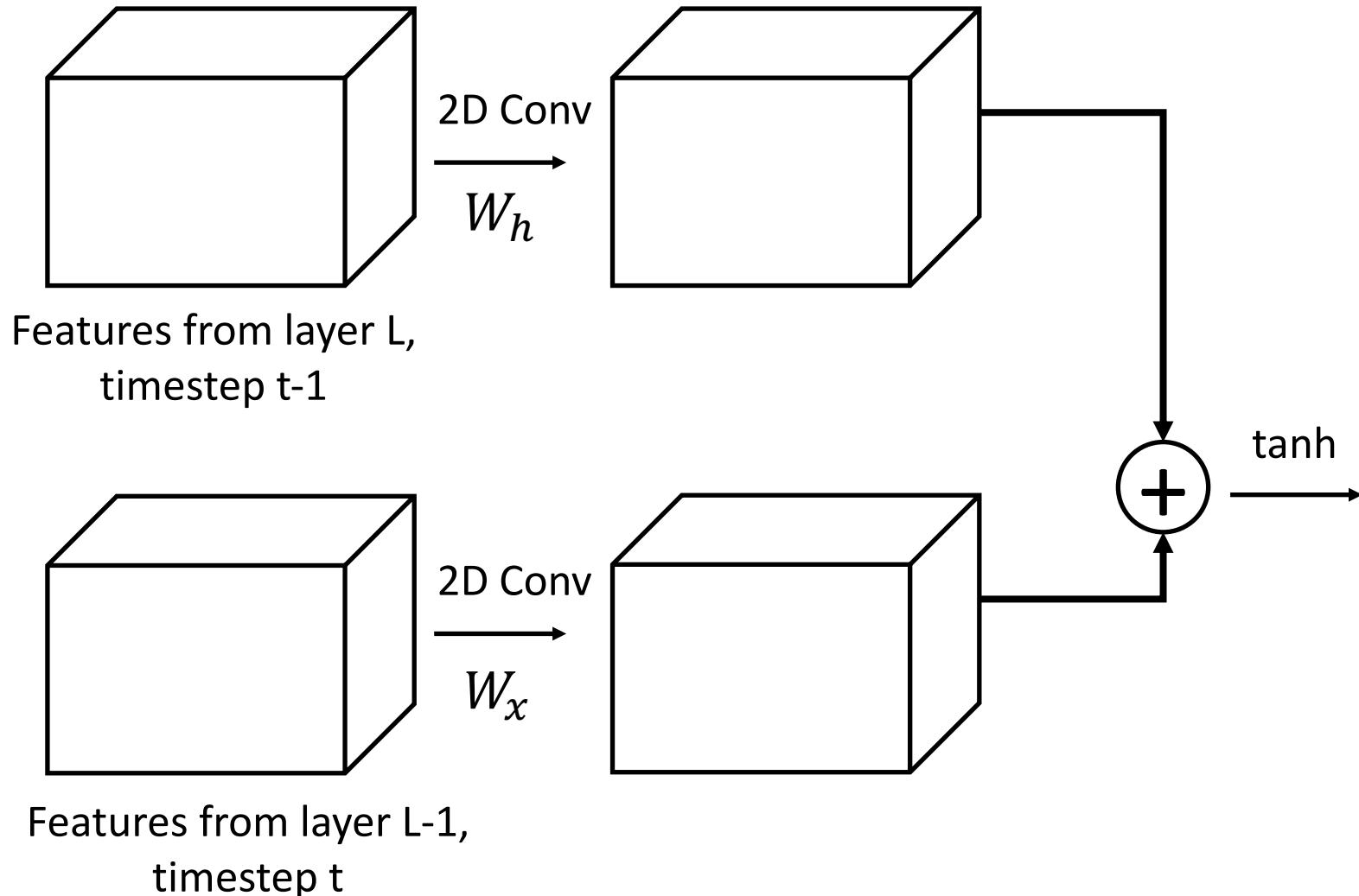
$$h_{t+1} = \tanh(W_h h_t + W_x x)$$

Replace all matrix multiply
with 2D convolution!



Features for layer L,
timestep t

Recurrent Convolutional Network



Recall: GRU

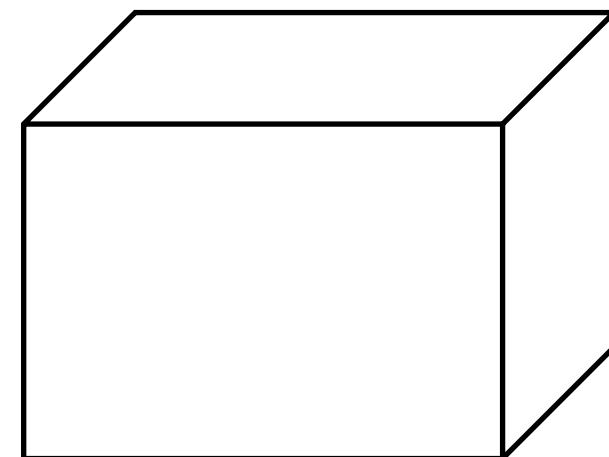
$$r_t = \sigma(W_{xr}x_t + W_{hr}h_{t-1} + b_r)$$

$$z_t = \sigma(W_{xz}x_t + W_{hz}h_{t-1} + b_z)$$

$$\tilde{h}_t = \tanh(W_{xh}x_t + W_{hh}(r_t \odot h_{t-1}) + b_h)$$

$$h_t = z_t \odot h_{t-1} + (1 - z_t) \odot \tilde{h}_t$$

Can do similar transform for other RNN variants (GRU, LSTM)

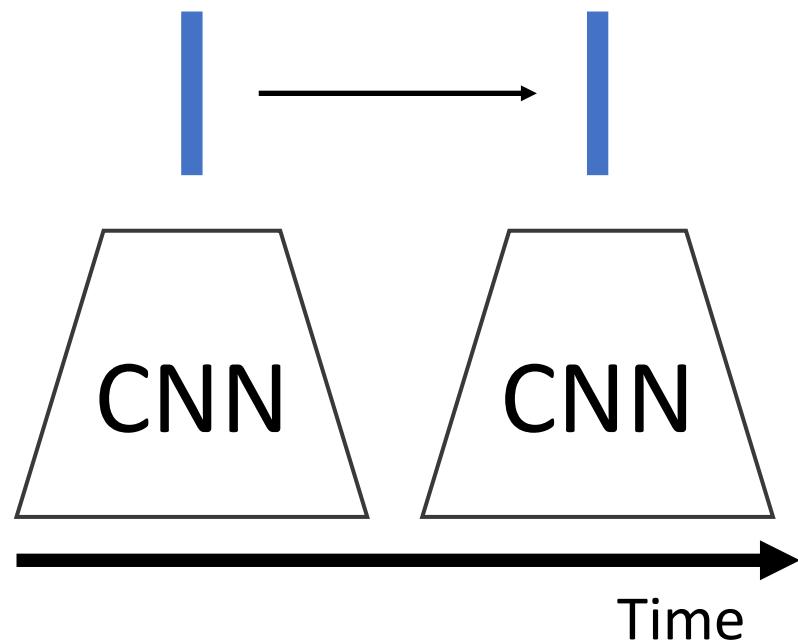


Features for layer L,
timestep t

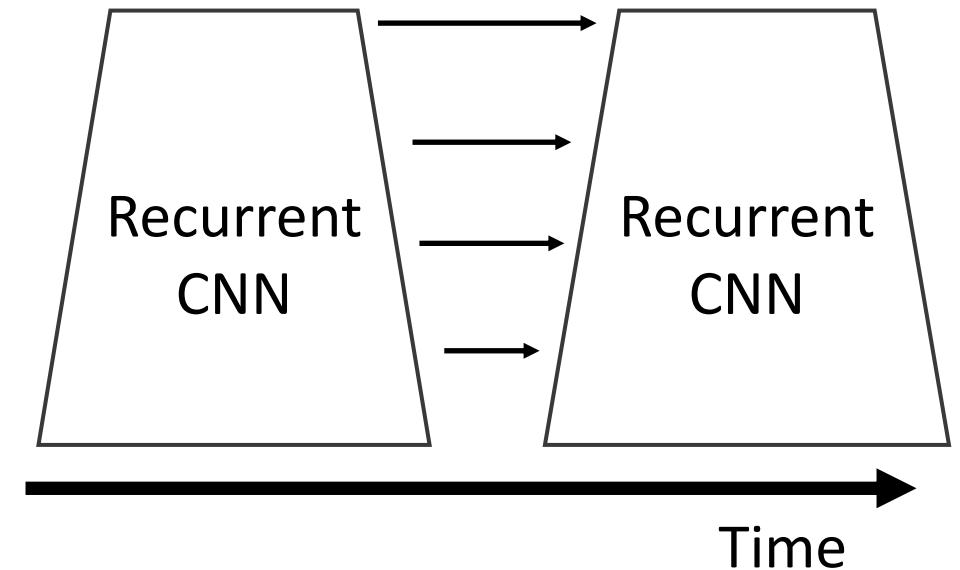
Modeling long-term temporal structure

RNN: Infinite
temporal extent
(fully-connected)

CNN: finite
temporal extent
(convolutional)



Recurrent CNN: Infinite
temporal extent
(convolutional)



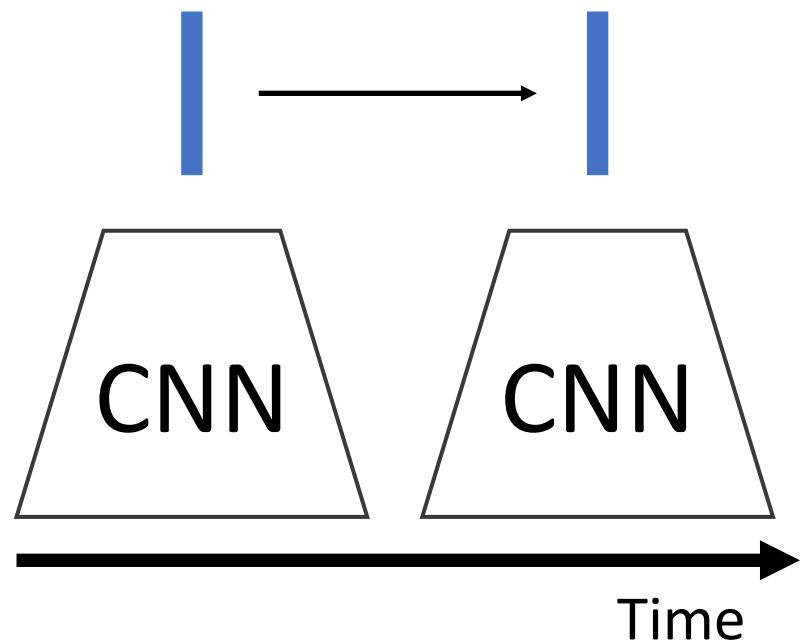
Baccouche et al, "Sequential Deep Learning for Human Action Recognition", 2011
Donahue et al, "Long-term recurrent convolutional networks for visual recognition and description", CVPR 2015

Ballas et al, "Delving Deeper into Convolutional Networks for Learning Video Representations", ICLR 2016

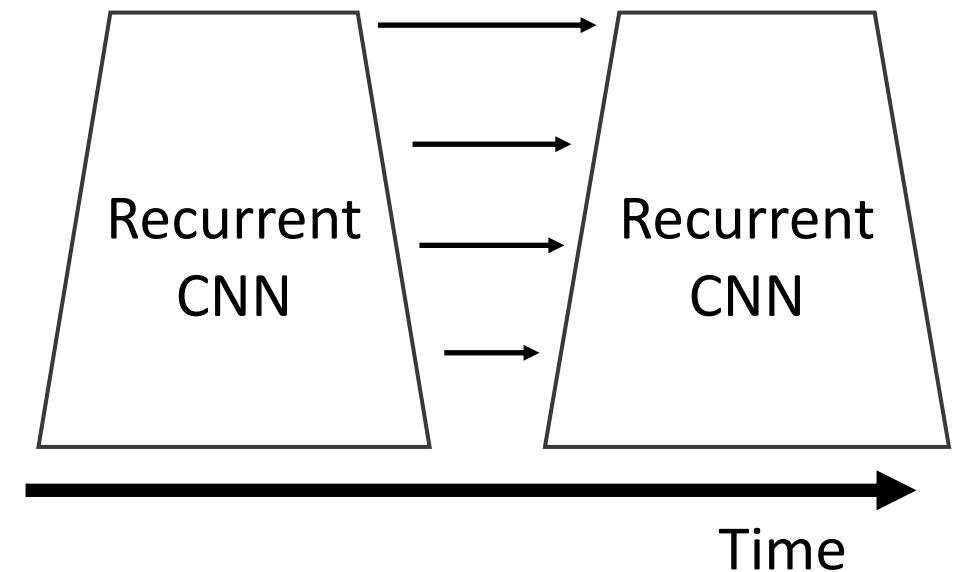
Modeling long-term temporal structure

Problem: RNNs are slow for long sequences (can't be parallelized)

RNN: Infinite temporal extent (fully-connected)

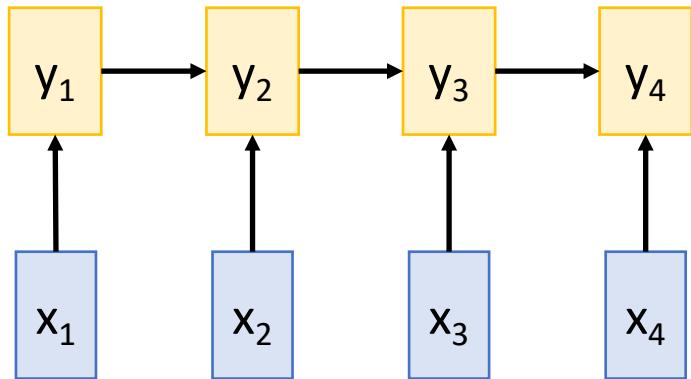


Recurrent CNN: Infinite temporal extent (convolutional)

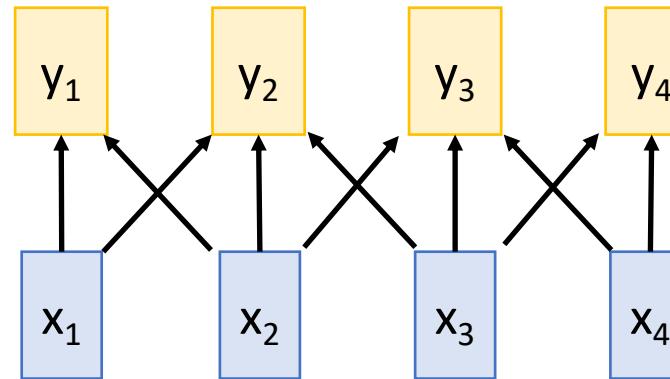


Recall: Different ways of processing sequences

Recurrent Neural Network



1D Convolution



Works on **Ordered Sequences**

(+) Good at long sequences: After one RNN layer, h_T "sees" the whole sequence

(-) Not parallelizable: need to compute hidden states sequentially

In video: CNN+RNN, or recurrent CNN

Works on **Multidimensional Grids**

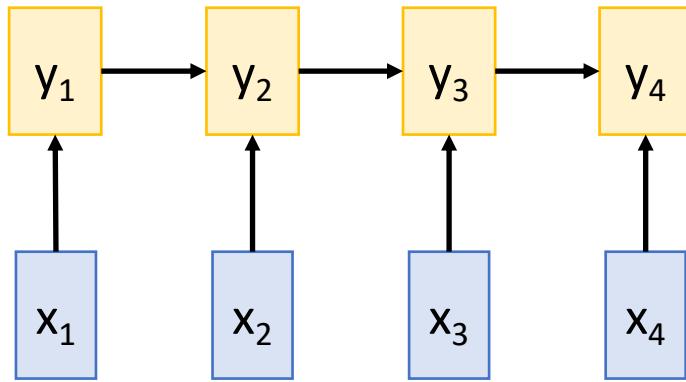
(-) Bad at long sequences: Need to stack many conv layers for outputs to "see" the whole sequence

(+) Highly parallel: Each output can be computed in parallel

In video: 3D convolution

Recall: Different ways of processing sequences

Recurrent Neural Network



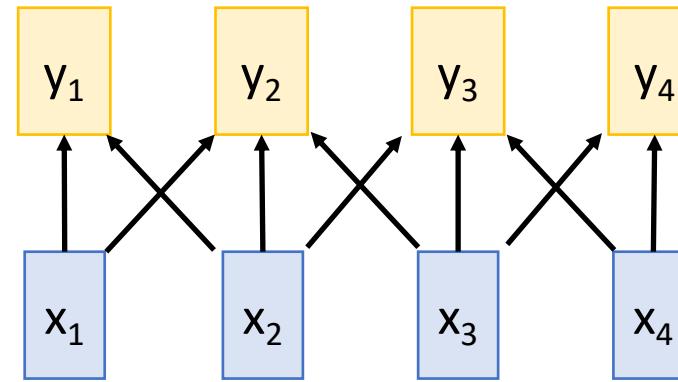
Works on **Ordered Sequences**

(+) Good at long sequences: After one RNN layer, h_T "sees" the whole sequence

(-) Not parallelizable: need to compute hidden states sequentially

In video: CNN+RNN, or recurrent CNN

1D Convolution



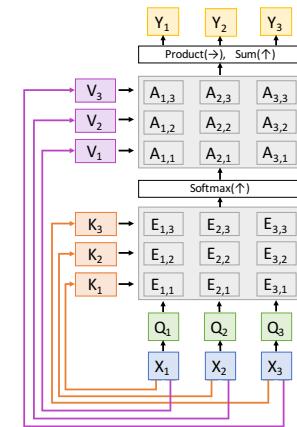
Works on **Multidimensional Grids**

(-) Bad at long sequences: Need to stack many conv layers for outputs to "see" the whole sequence

(+) Highly parallel: Each output can be computed in parallel

In video: 3D convolution

Self-Attention



Works on **Sets of Vectors**

(-) Good at long sequences: after one self-attention layer, each output "sees" all inputs!

(+) Highly parallel: Each output can be computed in parallel

(-) Very memory intensive

In video: ????

Recall: Self-Attention

Input: Set of vectors x_1, \dots, x_N

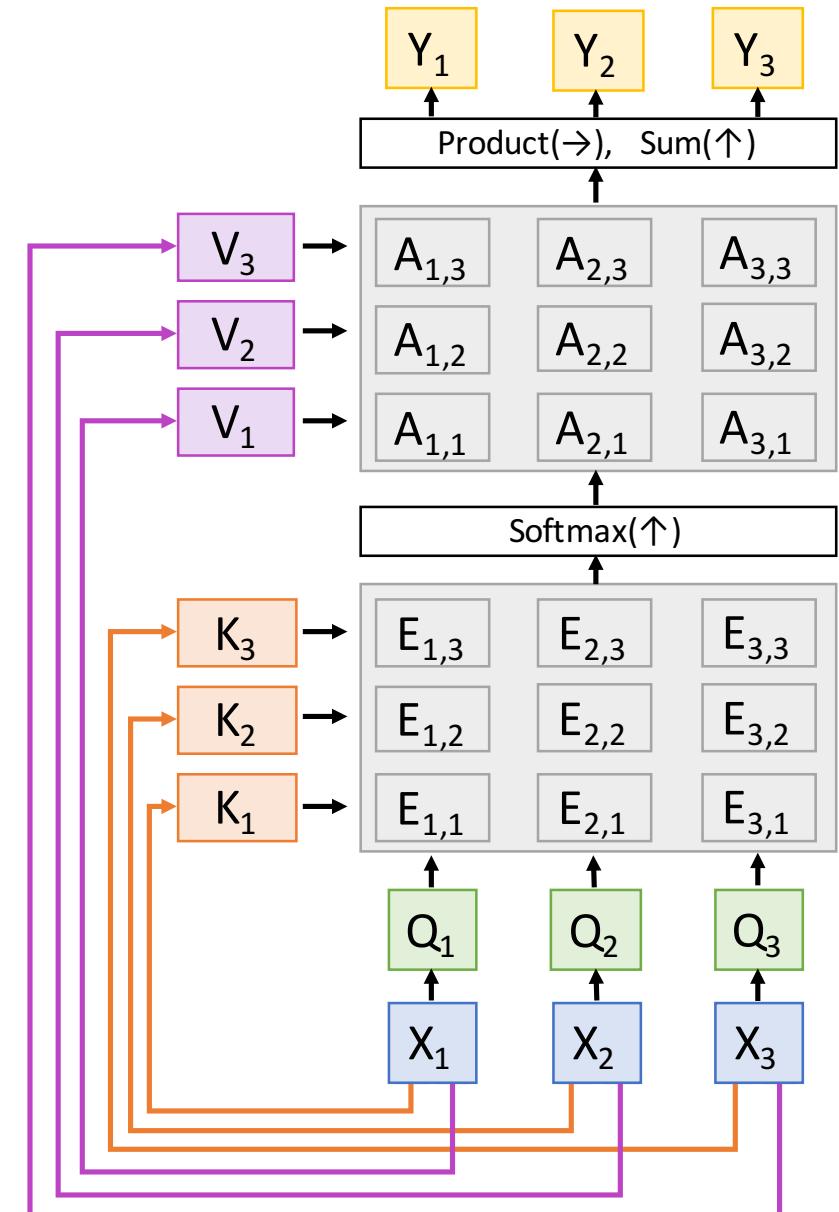
Keys, Queries, Values: Project each x to a key, query, and value using linear layer

Affinity matrix: Compare each pair of x , (using scaled dot-product between keys and values) and normalize using softmax

Output: Weighted sum of values, with weights given by affinity matrix

Features in 3D CNN: $C \times T \times H \times W$

Interpret as a set of THW vectors of dim C

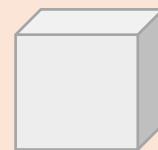


Spatio-Temporal Self-Attention (Nonlocal Block)

Input clip



3D
CNN



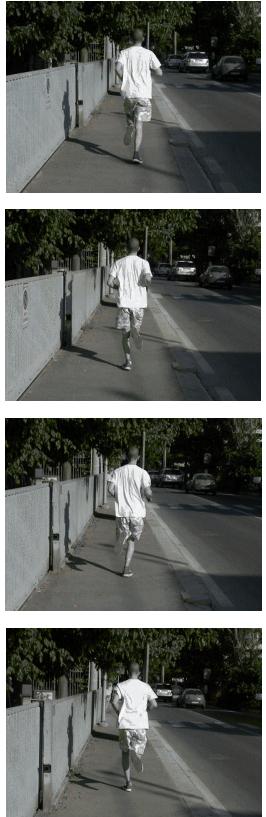
Features:
 $C \times T \times H \times W$

Nonlocal Block

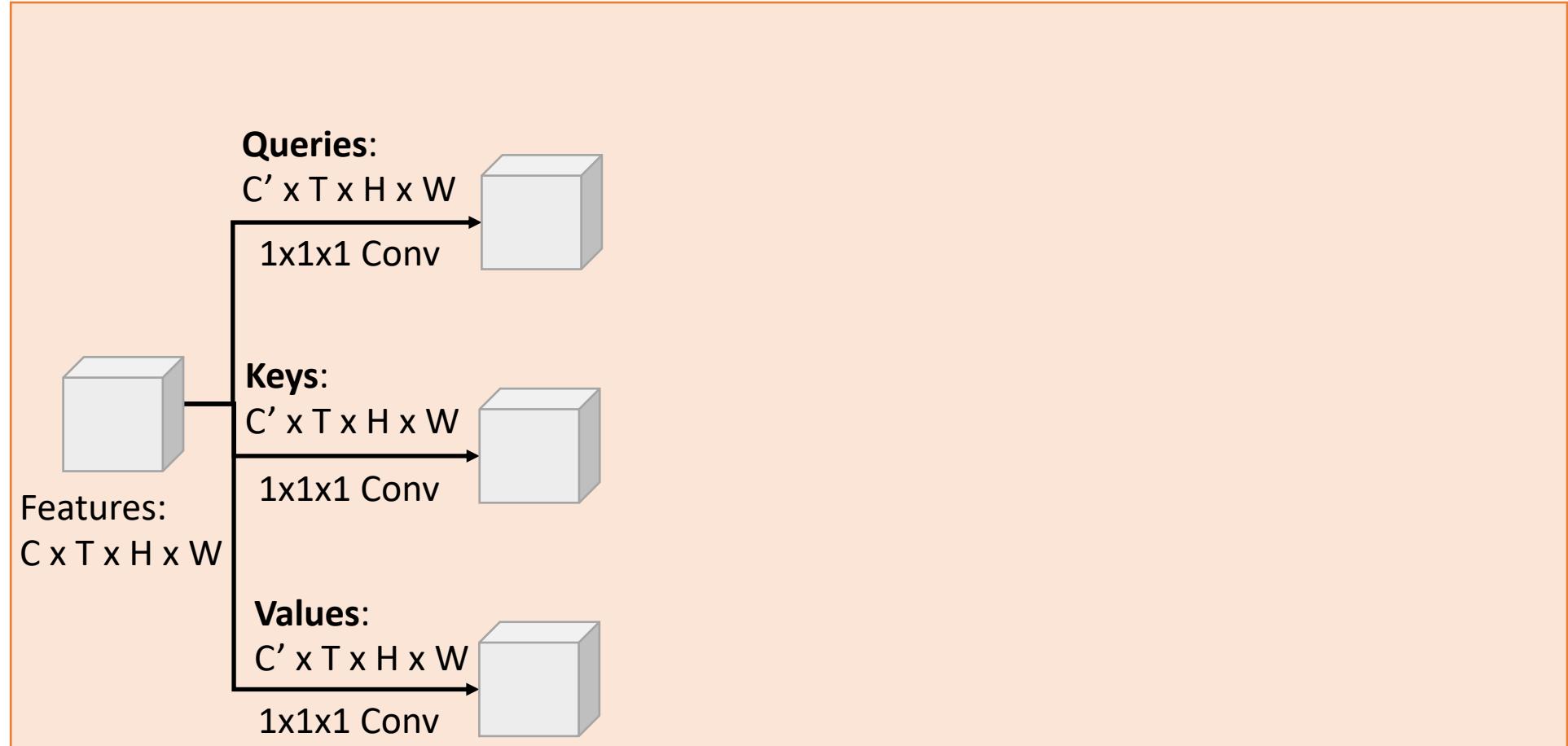
Wang et al, "Non-local neural networks", CVPR 2018

Spatio-Temporal Self-Attention (Nonlocal Block)

Input clip



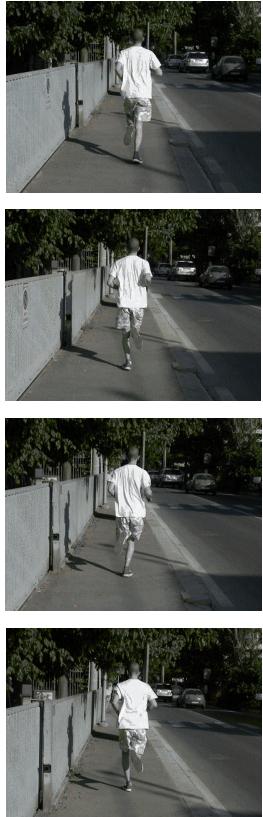
3D
CNN



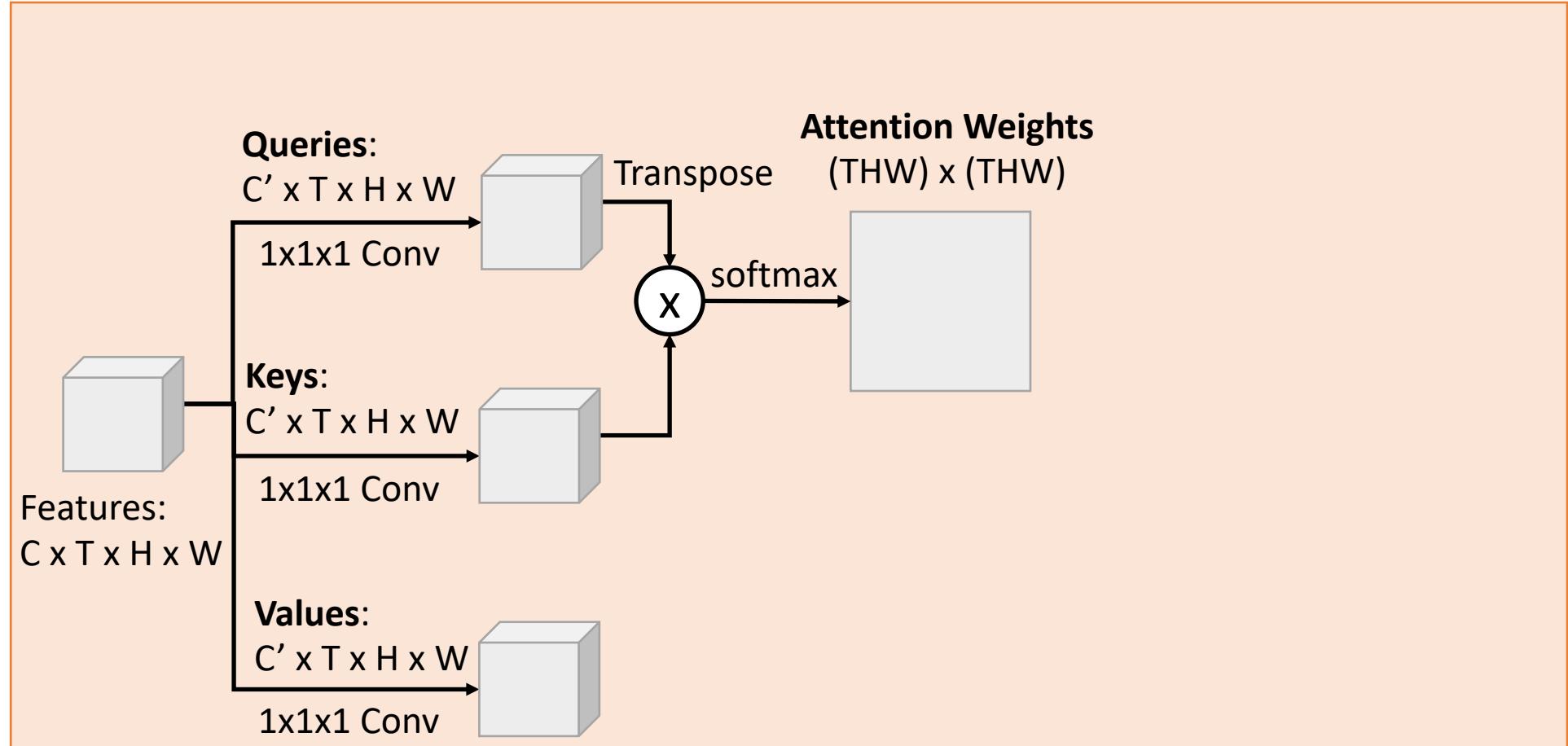
Nonlocal Block

Spatio-Temporal Self-Attention (Nonlocal Block)

Input clip

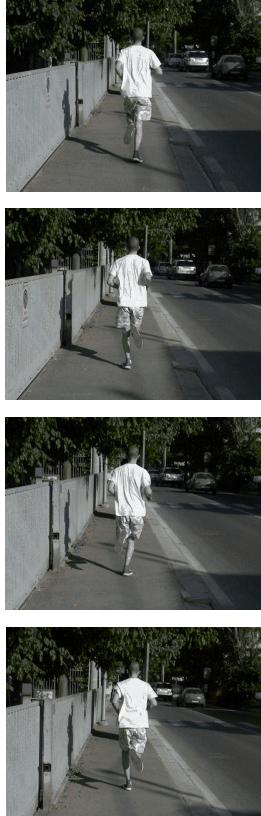


3D
CNN

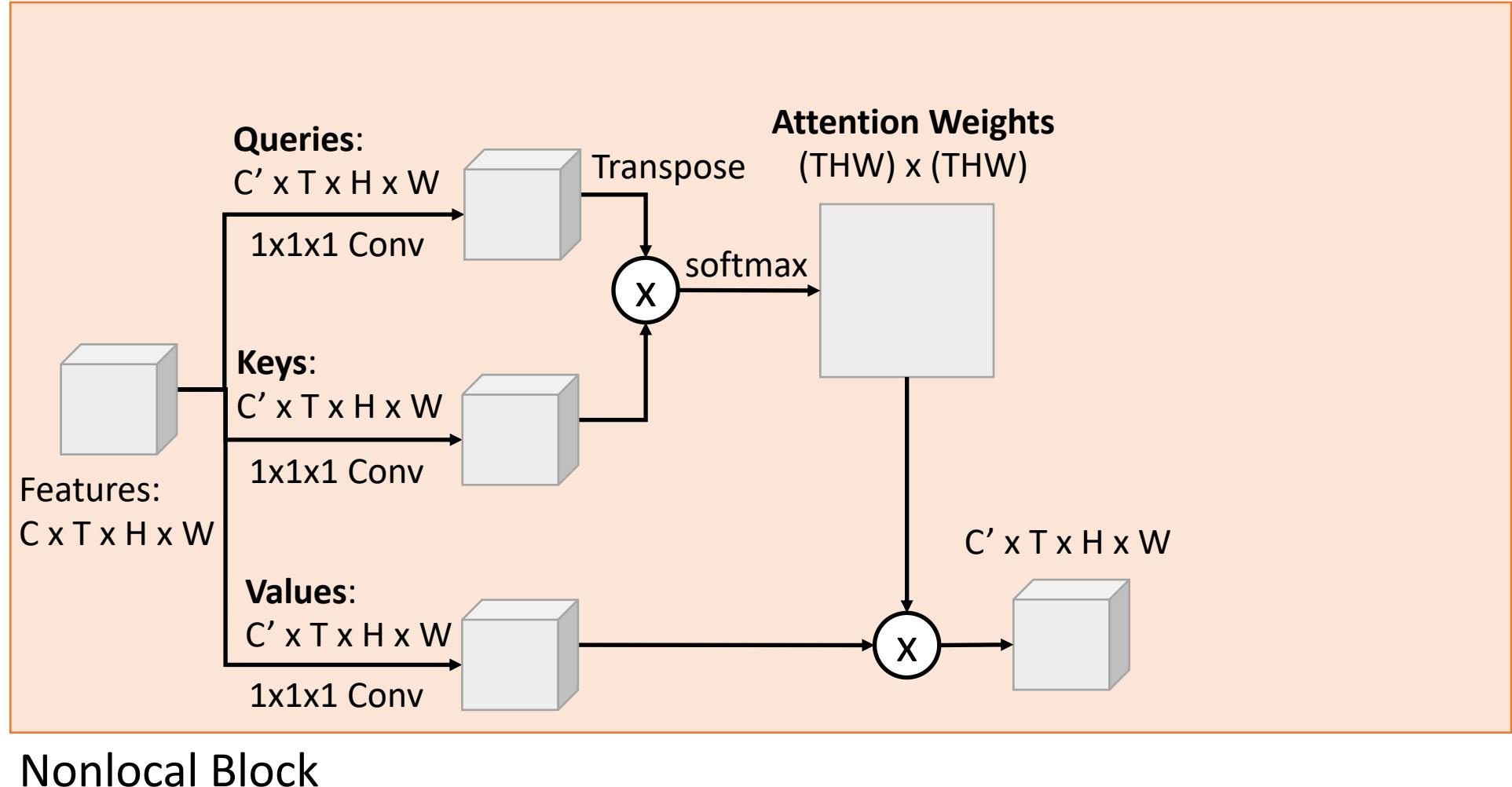


Spatio-Temporal Self-Attention (Nonlocal Block)

Input clip



3D
CNN

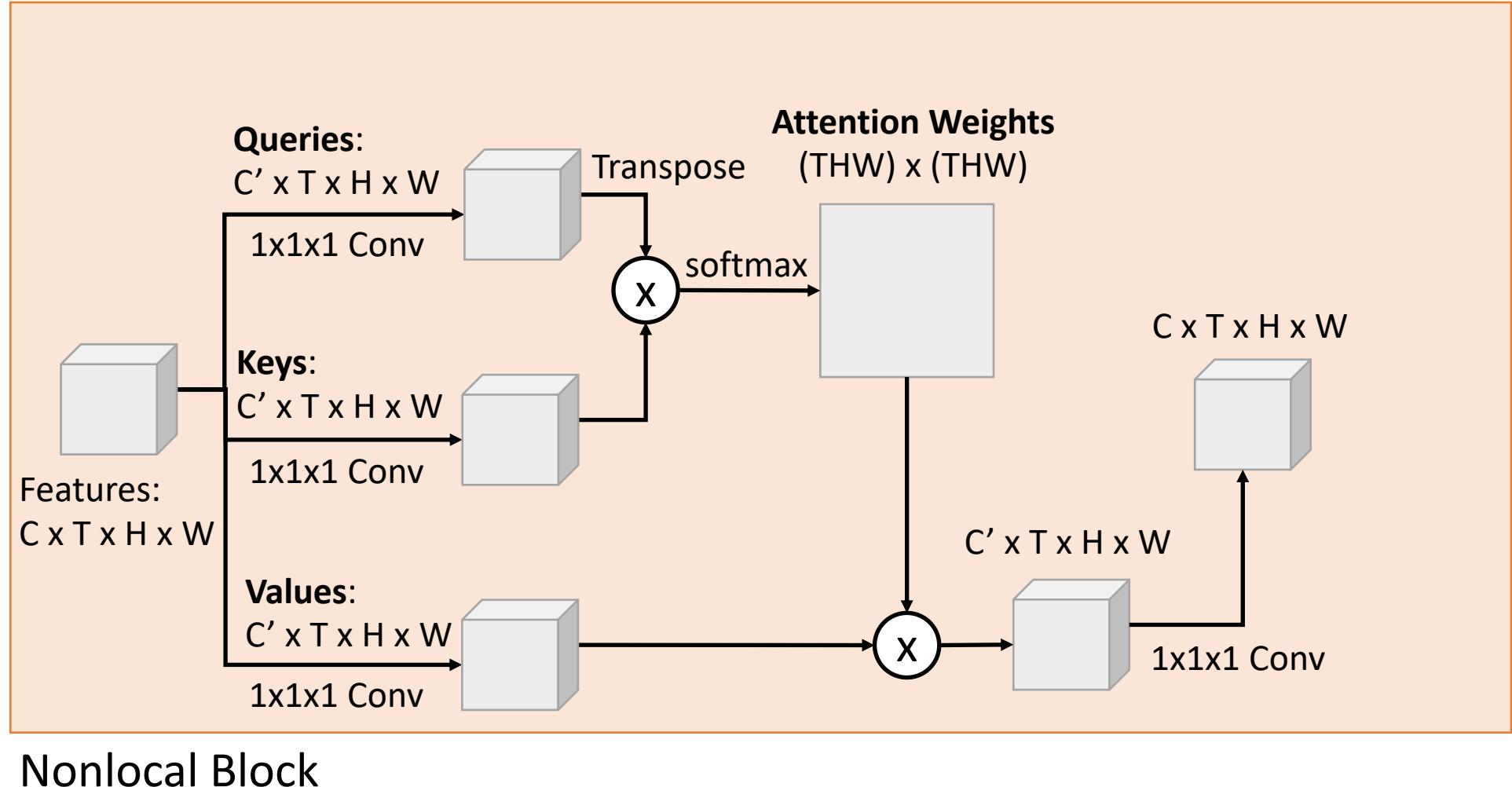


Spatio-Temporal Self-Attention (Nonlocal Block)

Input clip



3D
CNN

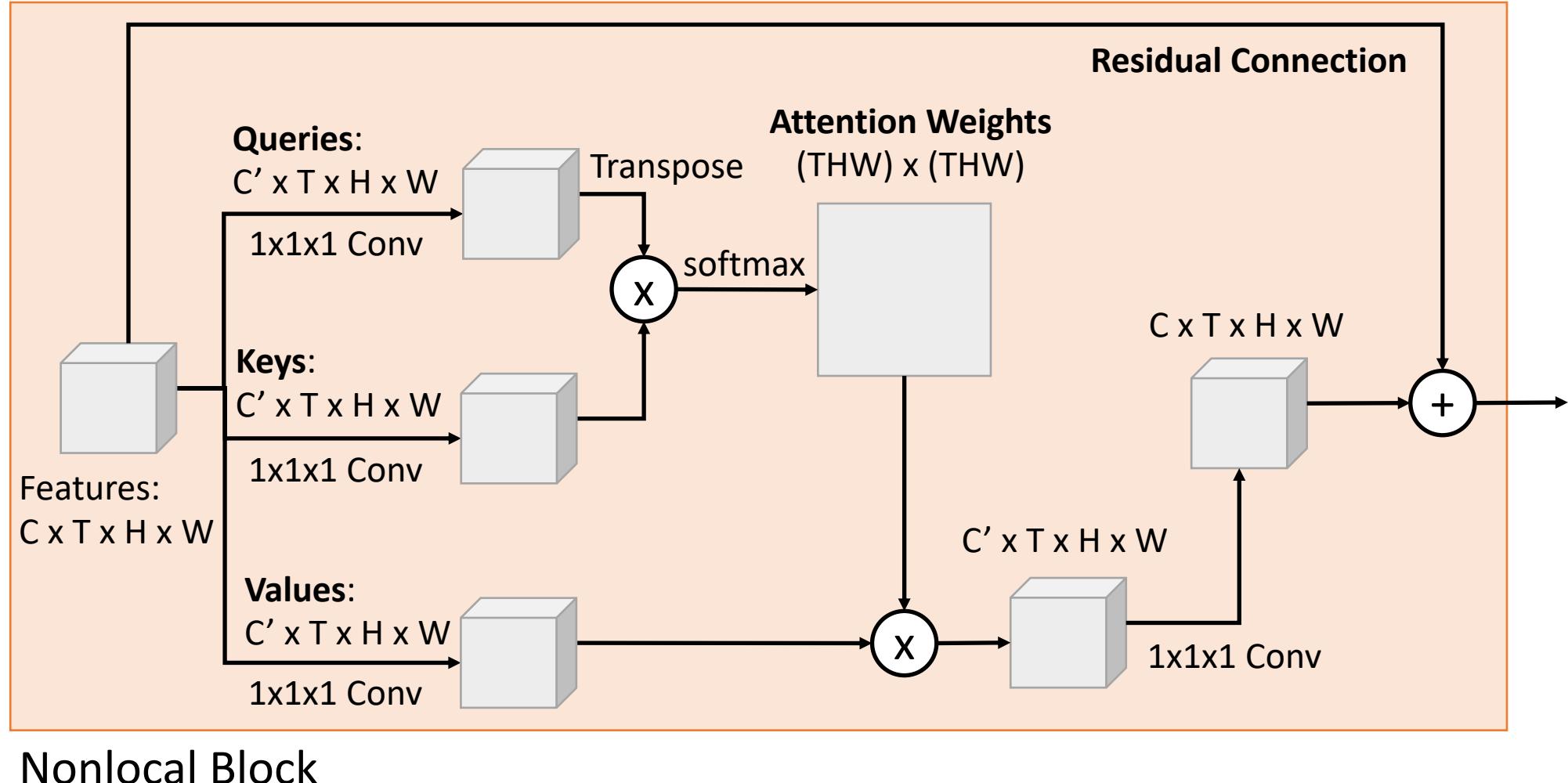


Spatio-Temporal Self-Attention (Nonlocal Block)

Input clip



3D
CNN



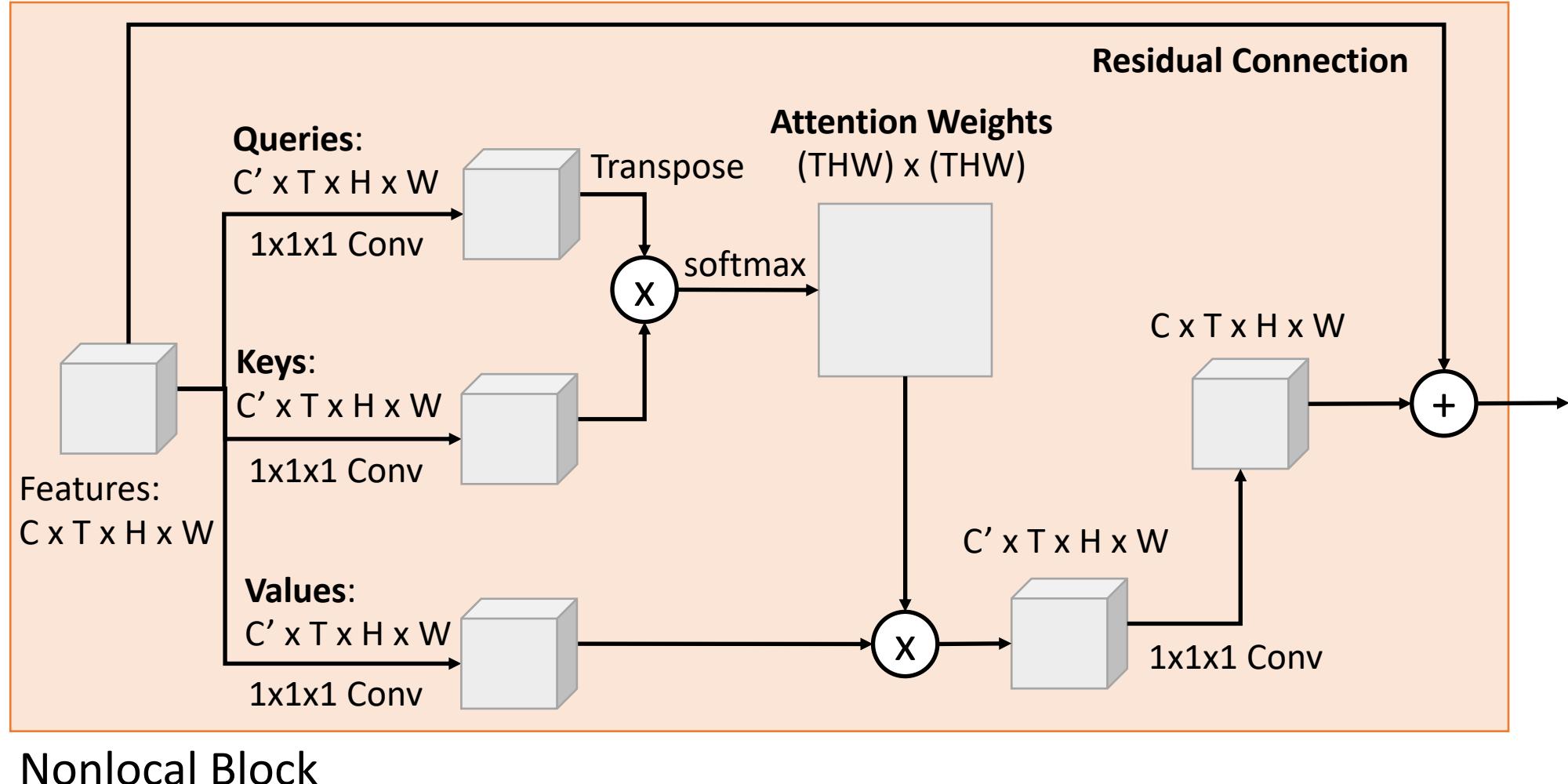
Wang et al, "Non-local neural networks", CVPR 2018

Spatio-Temporal Self-Attention (Nonlocal Block)

Input clip



3D
CNN

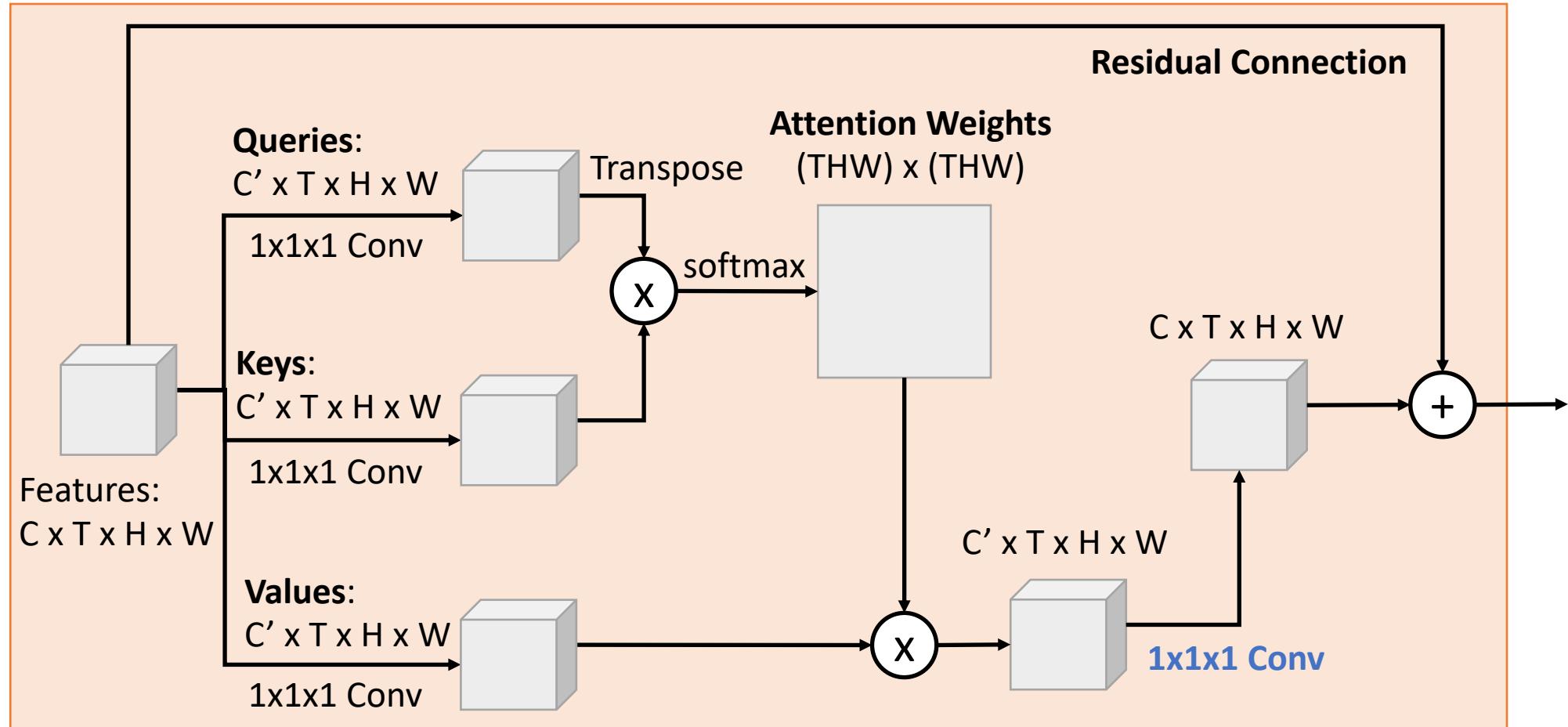


Spatio-Temporal Self-Attention (Nonlocal Block)

Input clip



3D
CNN



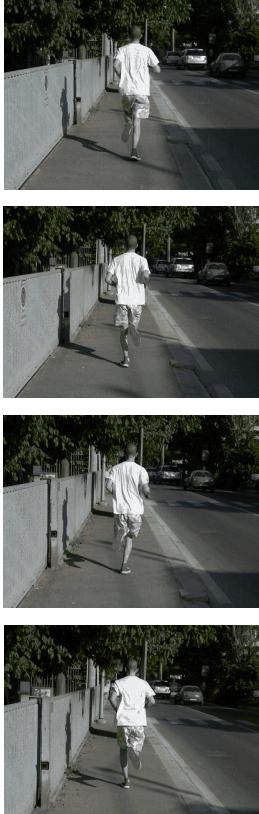
Nonlocal Block

Trick: Initialize **last conv** to 0, then entire block computes identity. Can insert into existing 3D CNNs

In practice, actually insert BatchNorm layer after final conv, and initialize scale parameter of BN layer to 0 rather than setting conv weight to 0

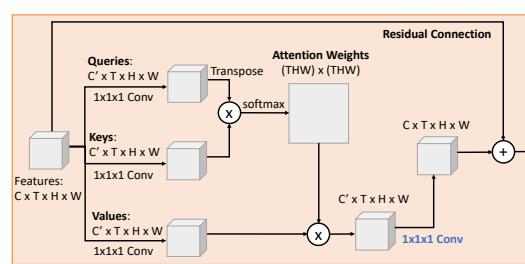
Spatio-Temporal Self-Attention (Nonlocal Block)

Input clip

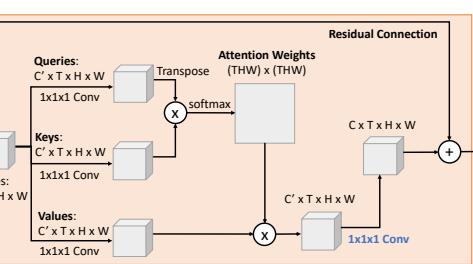
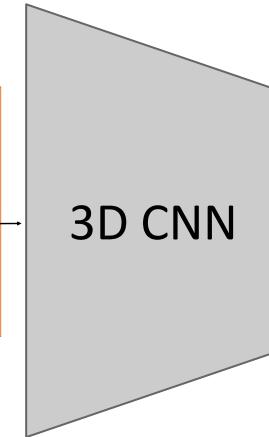


3D CNN

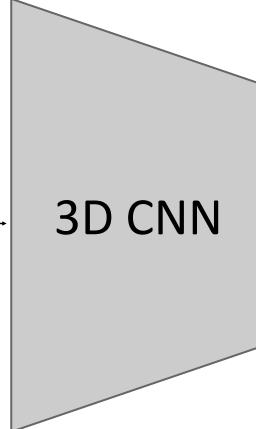
We can add nonlocal blocks into existing 3D CNN architectures.
But what is the best 3D CNN architecture?



Nonlocal Block



Nonlocal Block



Running

Inflating 2D Networks to 3D (I3D)

There has been a lot of work on architectures for images.
Can we reuse image architectures for video?

Idea: take a 2D CNN architecture.

Replace each 2D $K_h \times K_w$ conv/pool
layer with a 3D $K_t \times K_h \times K_w$ version

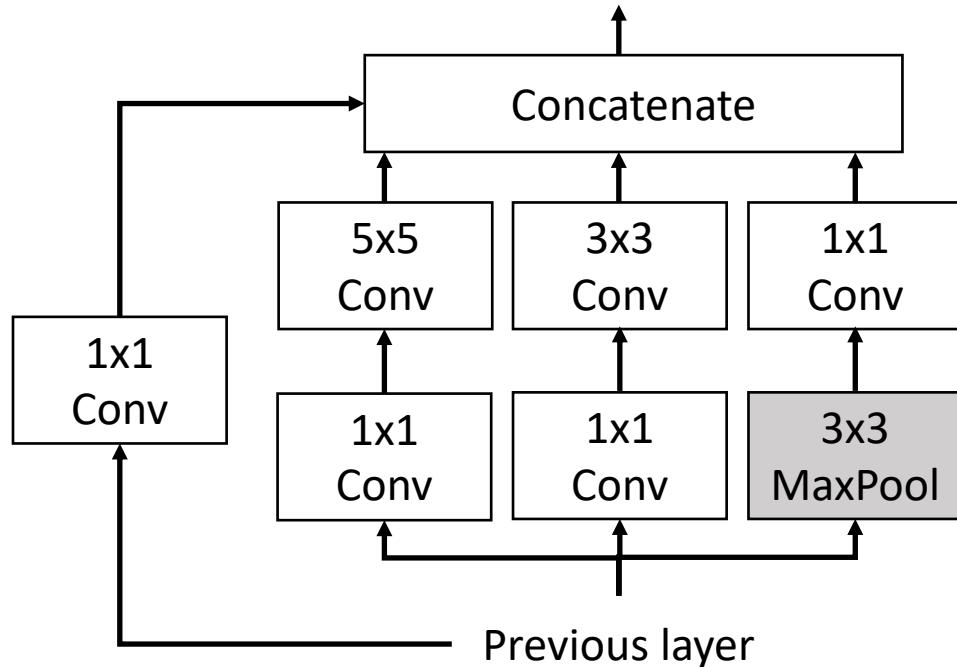
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Replace each $2D\ K_h \times K_w$ conv/pool layer with a $3D\ K_t \times K_h \times K_w$ version

Inception Block: Original



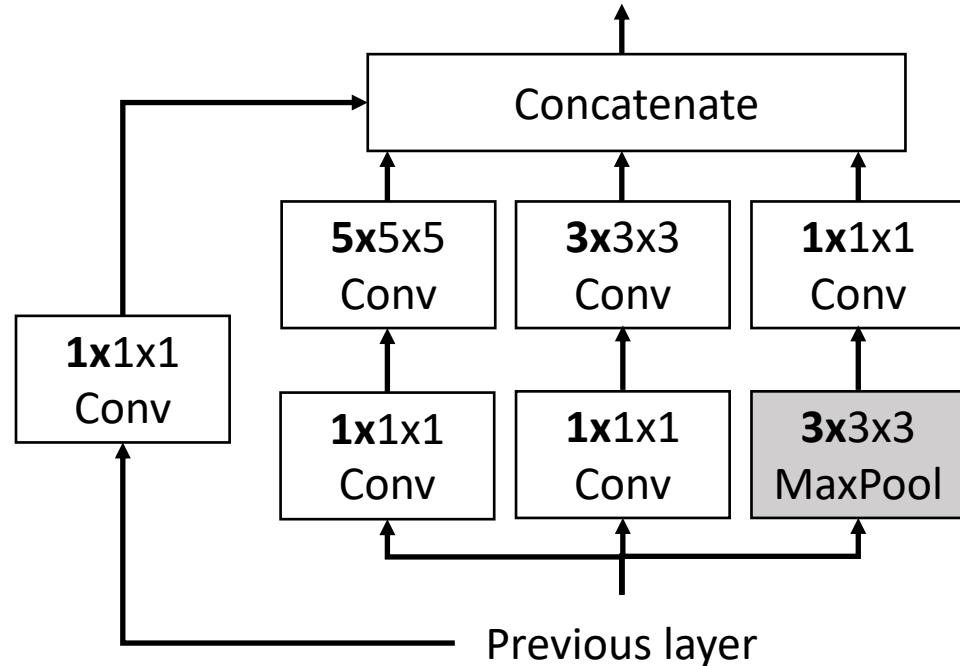
Inflating 2D Networks to 3D (I3D)

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Can we reuse image architectures for video?

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Replace each $2D K_h \times K_w$ conv/pool layer with a $3D K_t \times K_h \times K_w$ version

Inception Block: Inflated



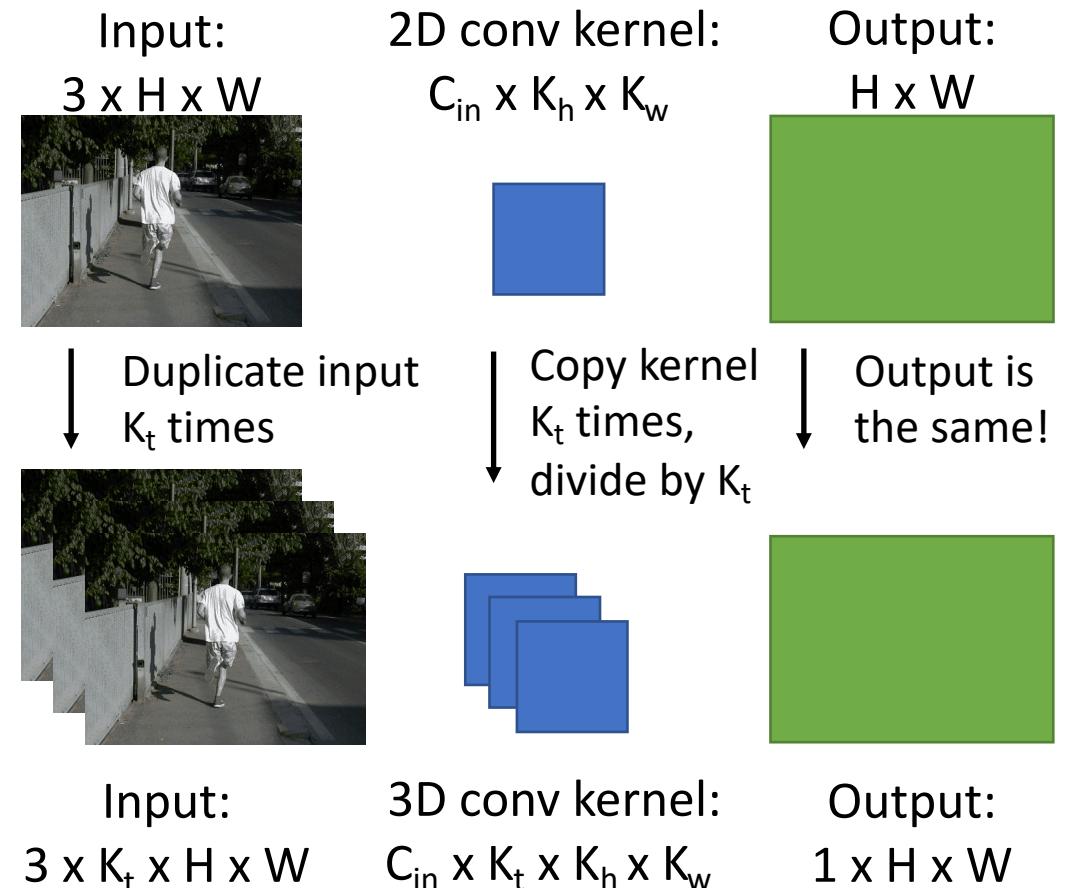
Inflating 2D Networks to 3D (I3D)

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Replace each 2D $K_h \times K_w$ conv/pool layer with a 3D $K_t \times K_h \times K_w$ version

Can use weights of 2D conv to initialize 3D conv: copy K_t times in space and divide by K_t
This gives the same result as 2D conv given “constant” video input



Inflating 2D Networks to 3D (I3D)

There has been a lot of work on architectures for images.
Can we reuse image architectures for video?

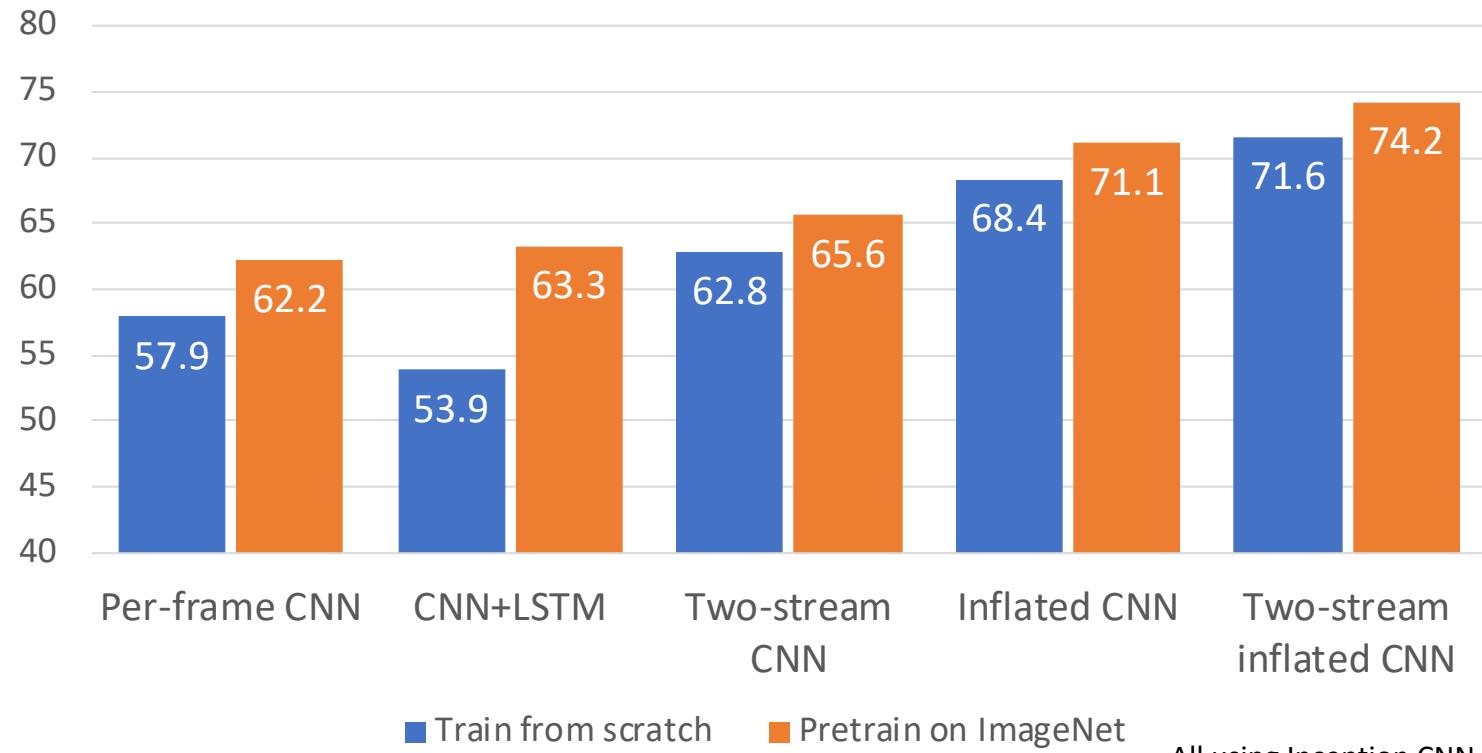
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Can use weights of 2D conv to initialize 3D conv: copy K_t times in space and divide by K_t

This gives the same result as 2D conv given “constant” video input

Top-1 Accuracy on Kinetics-400

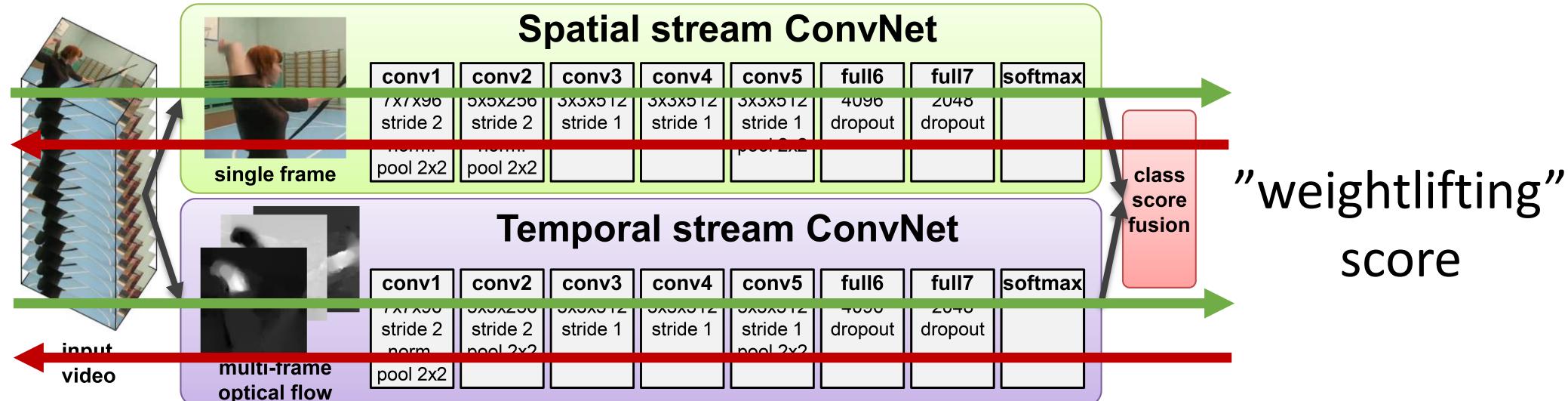


Visualizing Video Models

Image



Forward: Compute class score



Flow

Backward: Compute gradient

Add a term to encourage spatially smooth flow; tune penalty to pick out “slow” vs “fast” motion

Figure credit: Simonyan and Zisserman, “Two-stream convolutional networks for action recognition in videos”, NeurIPS 2014
Feichtenhofer et al, “What have we learned from deep representations for action recognition?”, CVPR 2018
Feichtenhofer et al, “Deep insights into convolutional networks for video recognition?”, IJCV 2019.

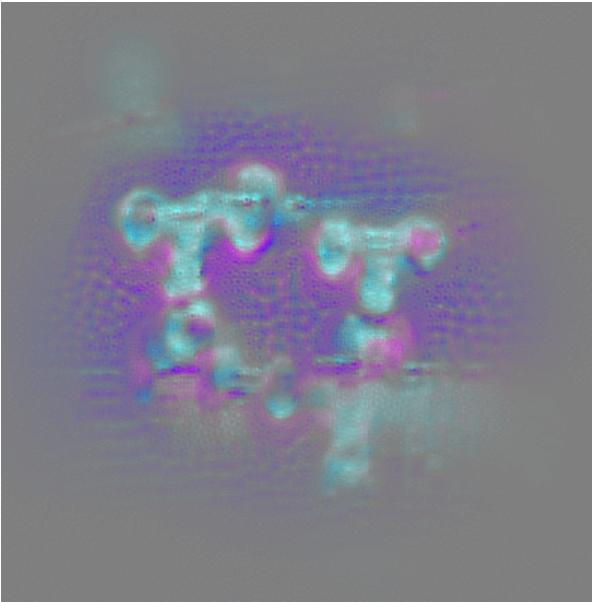
Can you guess the action?

Appearance

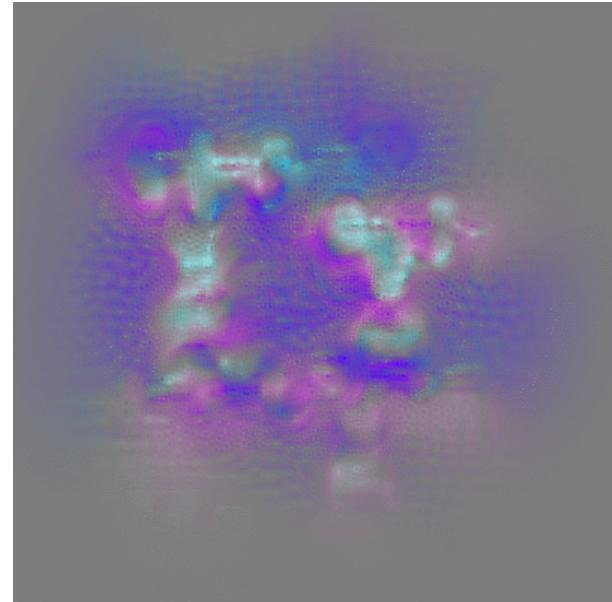


Fast motion appearance

“Slow” motion



“Fast” motion



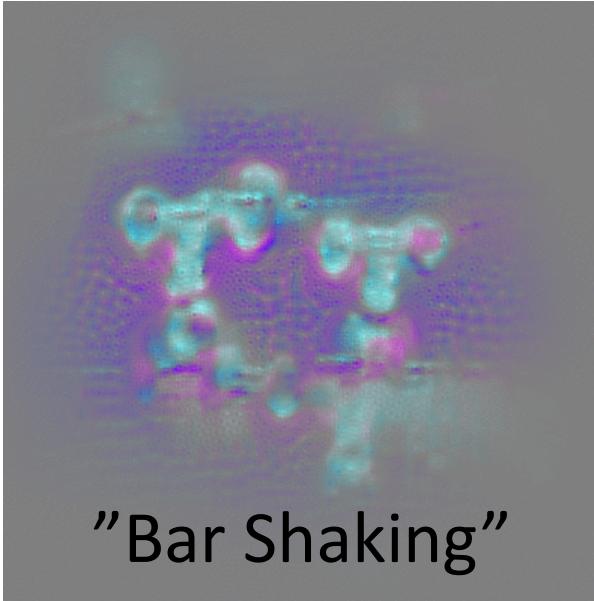
Can you guess the action? Weightlifting

Appearance



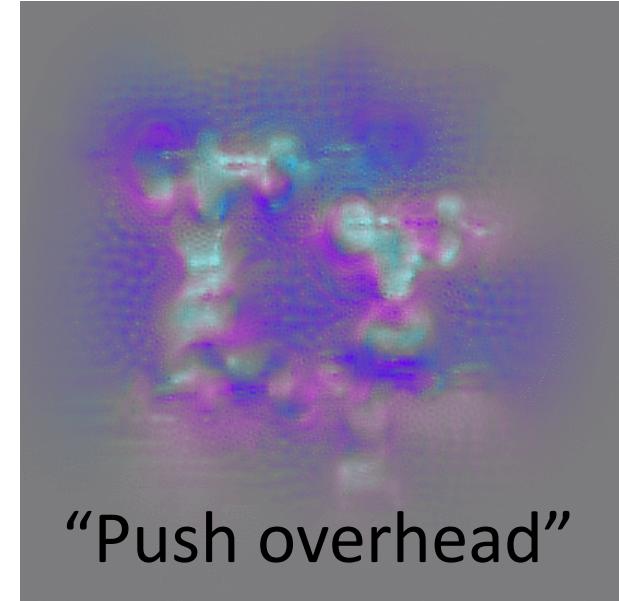
Fast motion appearance

"Slow" motion



"Bar Shaking"

"Fast" motion

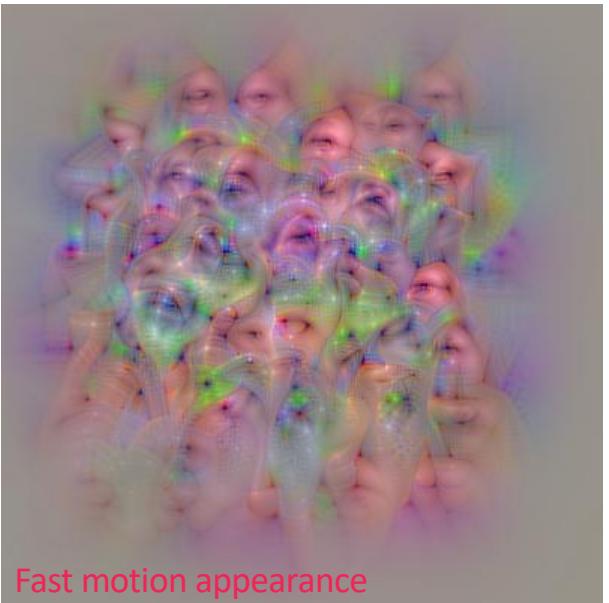


"Push overhead"

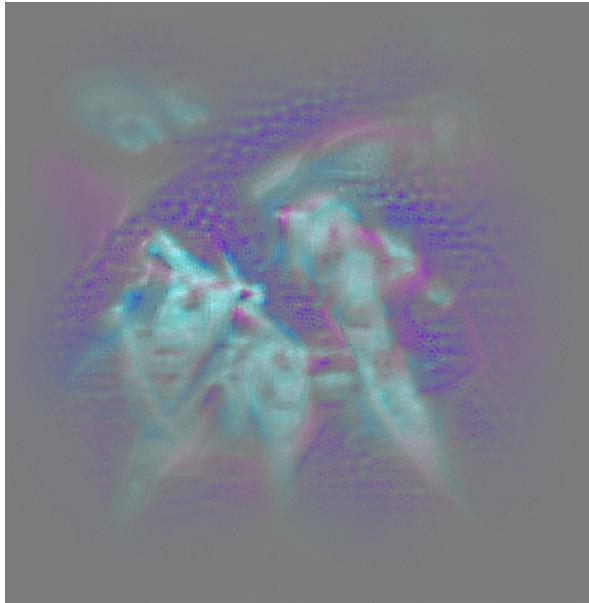


Can you guess the action?

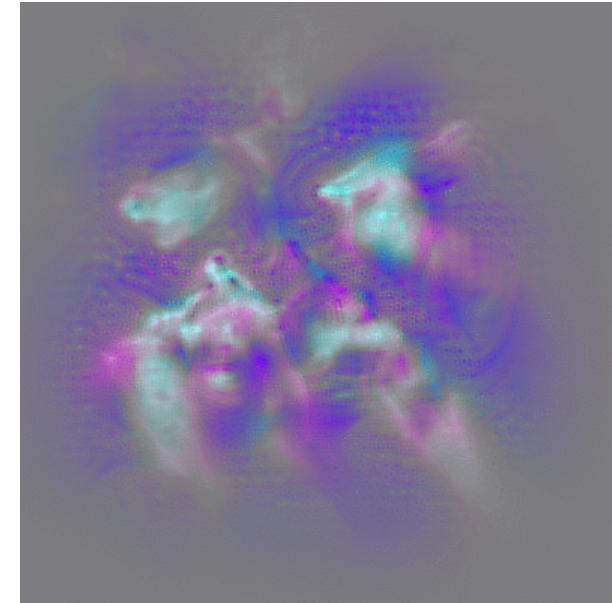
Appearance



“Slow” motion

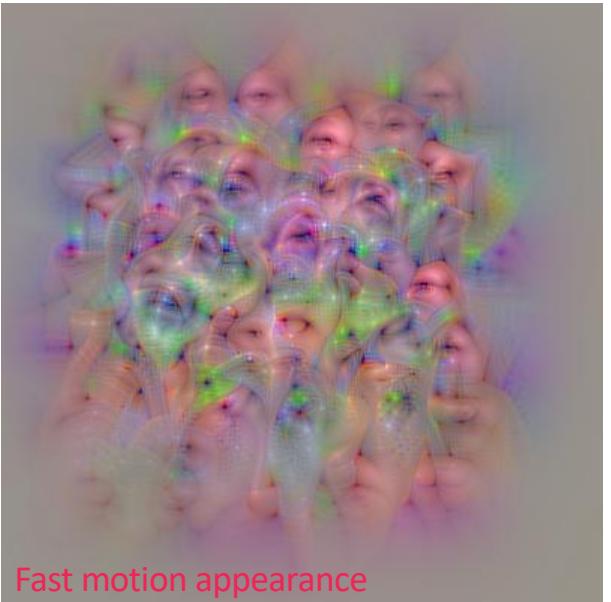


“Fast” motion

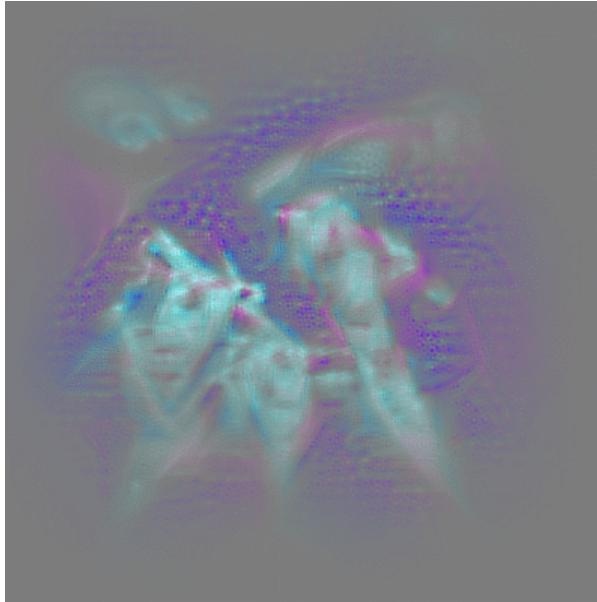


Can you guess the action? Apply Eye Makeup

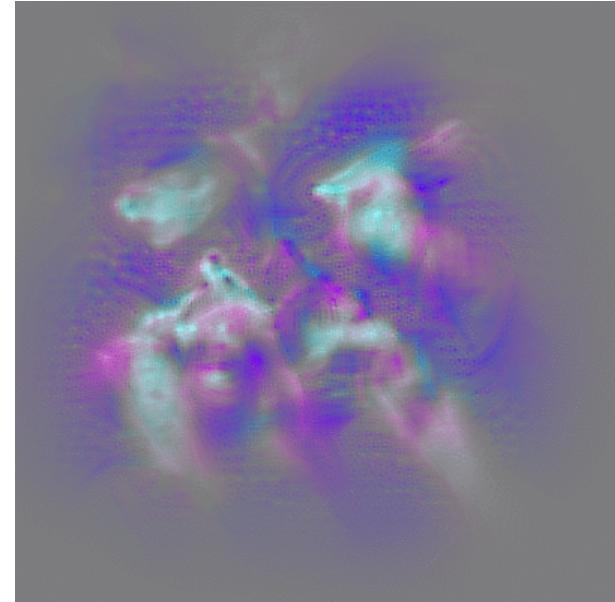
Appearance



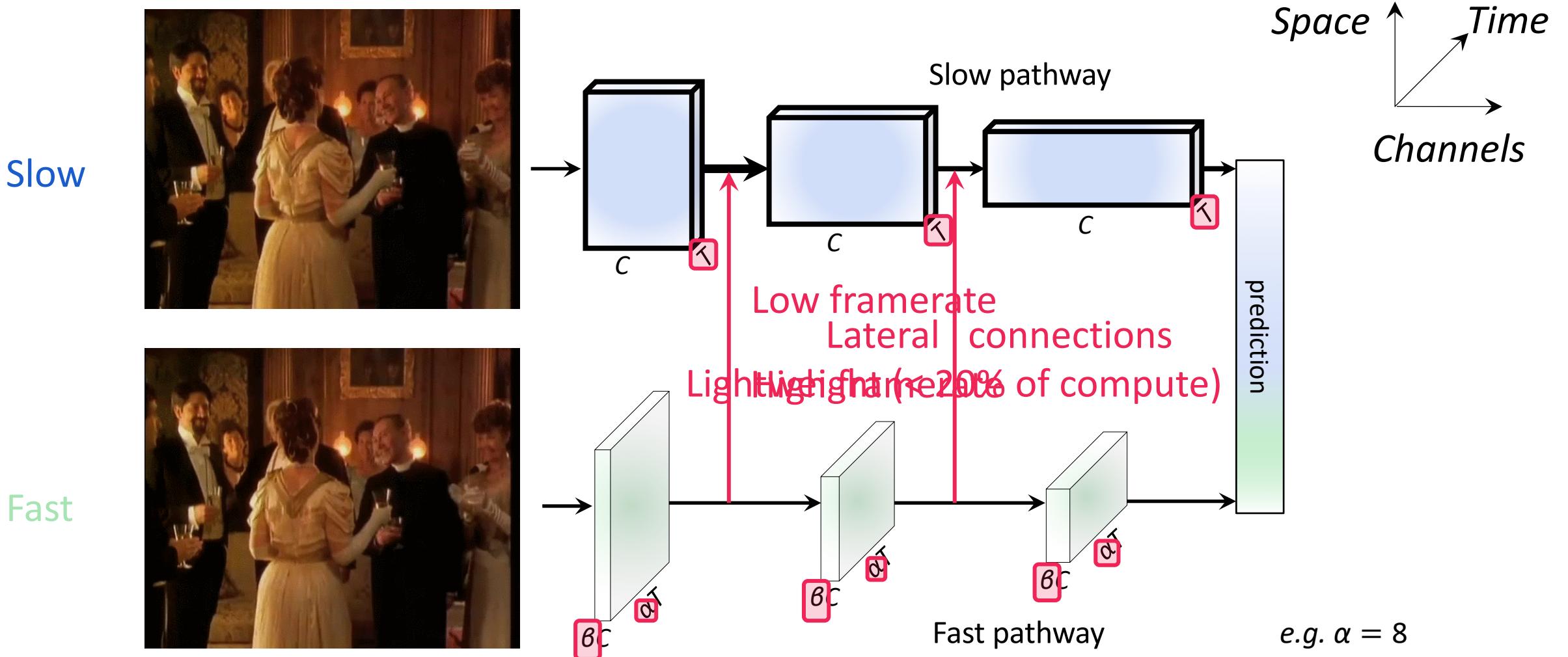
“Slow” motion



“Fast” motion



Treating time and space differently: SlowFast Networks



Feichtenhofer et al, "SlowFast Networks for Video Recognition", ICCV 2019
Slide credit: Christoph Feichtenhofer

Treating time and space differently: SlowFast Networks

- Dimensions are $\{T \times S^2, C\}$
- Strides are {temporal, spatial²}
- The backbone is ResNet-50
- Residual blocks are shown by brackets
- Non-degenerate temporal filters are underlined
- Here the speed ratio is $\alpha = 8$ and the channel ratio is $\beta = 1/8$
- Orange** numbers mark fewer channels, for the Fast pathway
- Green** numbers mark higher temporal resolution of the Fast pathway
- No temporal *pooling* is performed throughout the hierarchy

stage	Slow pathway	Fast pathway	output sizes $T \times S^2$
raw clip	-	-	64×224^2
data layer	stride 16, 1^2	stride 2 , 1^2	<i>Slow</i> : 4×224^2 <i>Fast</i> : 32 $\times 224^2$
conv ₁	$1 \times 7^2, 64$ stride 1, 2^2	<u>$5 \times 7^2, 8$</u> stride 1, 2^2	<i>Slow</i> : 4×112^2 <i>Fast</i> : 32 $\times 112^2$
pool ₁	1×3^2 max stride 1, 2^2	1×3^2 max stride 1, 2^2	<i>Slow</i> : 4×56^2 <i>Fast</i> : 32 $\times 56^2$
res ₂	$\left[\begin{array}{l} 1 \times 1^2, 64 \\ 1 \times 3^2, 64 \\ 1 \times 1^2, 256 \end{array} \right] \times 3$	$\left[\begin{array}{l} \frac{3 \times 1^2, 8}{1 \times 3^2, 8} \\ 1 \times 1^2, 32 \end{array} \right] \times 3$	<i>Slow</i> : 4×56^2 <i>Fast</i> : 32 $\times 56^2$
res ₃	$\left[\begin{array}{l} 1 \times 1^2, 128 \\ 1 \times 3^2, 128 \\ 1 \times 1^2, 512 \end{array} \right] \times 4$	$\left[\begin{array}{l} \frac{3 \times 1^2, 16}{1 \times 3^2, 16} \\ 1 \times 1^2, 64 \end{array} \right] \times 4$	<i>Slow</i> : 4×28^2 <i>Fast</i> : 32 $\times 28^2$
res ₄	$\left[\begin{array}{l} \frac{3 \times 1^2, 256}{1 \times 3^2, 256} \\ 1 \times 1^2, 1024 \end{array} \right] \times 6$	$\left[\begin{array}{l} \frac{3 \times 1^2, 32}{1 \times 3^2, 32} \\ 1 \times 1^2, 128 \end{array} \right] \times 6$	<i>Slow</i> : 4×14^2 <i>Fast</i> : 32 $\times 14^2$
res ₅	$\left[\begin{array}{l} \frac{3 \times 1^2, 512}{1 \times 3^2, 512} \\ 1 \times 1^2, 2048 \end{array} \right] \times 3$	$\left[\begin{array}{l} \frac{3 \times 1^2, 64}{1 \times 3^2, 64} \\ 1 \times 1^2, 256 \end{array} \right] \times 3$	<i>Slow</i> : 4×7^2 <i>Fast</i> : 32 $\times 7^2$
	global average pool, concat, fc		# classes

So far: Classify short clips



Videos: Recognize **actions**



Swimming
Running
Jumping
Eating
Standing

Temporal Action Localization

Given a long untrimmed video sequence, identify frames corresponding to different actions

Running



Jumping

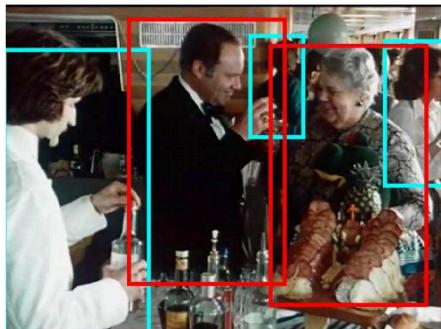


Can use architecture similar to Faster R-CNN:
first generate **temporal proposals** then **classify**

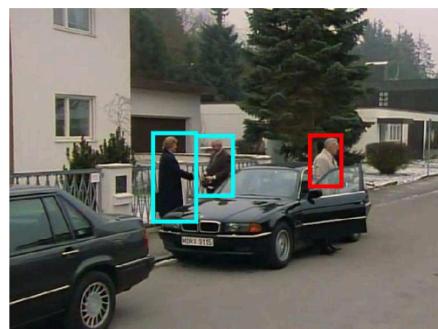
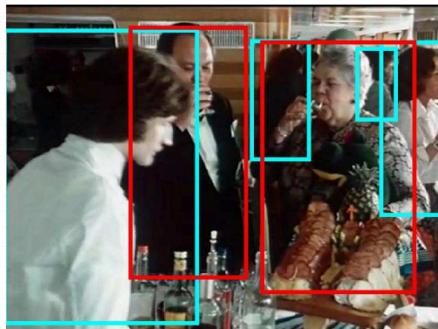
Chao et al, "Rethinking the Faster R-CNN Architecture for Temporal Action Localization", CVPR 2018

Spatio-Temporal Detection

Given a long untrimmed video, detect all the people in space and time and classify the activities they are performing
Some examples from AVA Dataset:



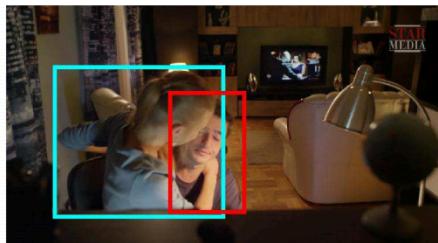
click glass → drink



open → close



grab (a person) → hug



look at phone → answer phone



Gu et al, "AVA: A Video Dataset of Spatio-temporally Localized Atomic Visual Actions", CVPR 2018

Recap: Video Models

Many video models:

Single-frame CNN (Try this first!)

Late fusion

Early fusion

3D CNN / C3D

Two-stream networks

CNN + RNN

Convolutional RNN

Spatio-temporal self-attention

SlowFast networks (current SoTA)

Next time:
Generative Models, part 1
Generative Adversarial Networks