Lecture 10: Videos

December 27, 2021

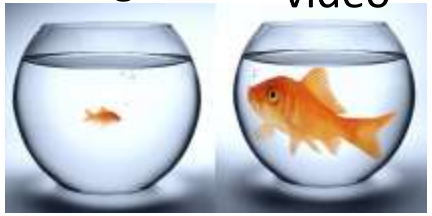
Tali Dekel

Videos

Videos are all around us

Span an enormous space of spatial and temporal signals

Challenges in Videos: size of video



Size of video >> size of image

Computational constrains → short, low-res clips

3 x H x W

4D tensor:
T x 3 x H x W

time

~30 frames per second (fps)

Uncompressed size (3 bytes per pixel):
SD (640 x 480): **~1.5 GB per minute**
HD (1920 x 1080): **~10 GB per minute**

Reduce spatial and temporal resolution

5fps, half the spatial resolution

Slide inspiration: Justin Johnson, EECS 498-007

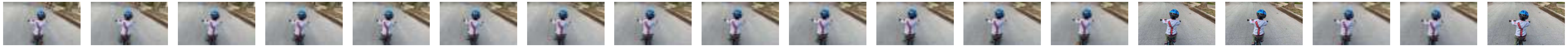
Challenges in Videos: size of video

Computational constrains → short, low-res clips

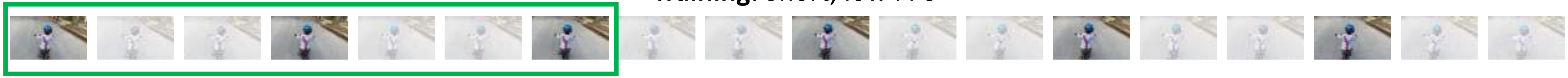
Input video

Walking
Running
Cycling
Jumping
.
.

Original video(long, high FPS)



Training: Short, low FPS



Test time: inference on different short clips, average predictions

Slide inspiration: Justin Johnson, EECS 498-007

Challenges in Videos: Videos Datasets

space of video >> space of image → lots of training data

"ImageNet"-equivalent dataset for videos?

Massive human labelling efforts

UCF101
YouTube videos
13320 videos, 101 action categories

Kinetics
YouTube videos
650,000 video clips, 600 human action classes

Sports-1M
YouTube videos
1,133,157 videos, 487 sports labels

YouTube-8M
8M video clips, Machine-generated annotations from 3,862 classes

Today

Deep Learning-based Models for Videos

- How to reduce computation cost without sacrificing accuracy?
- What architecture to best capture temporal patterns?

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

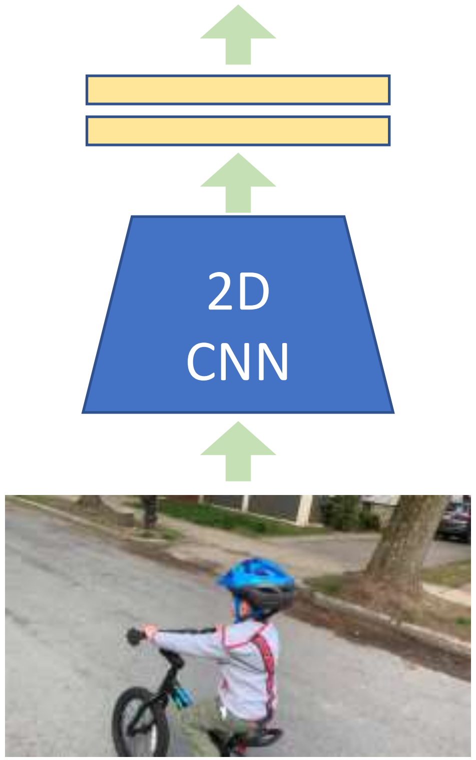
Self-Supervision in Videos

- Which types of pretext tasks can we define to capture temporal information?
- Applications

Models for Videos: Single-Frame Baseline

- Train 2D CNN to classify video frames independently

“Biking”



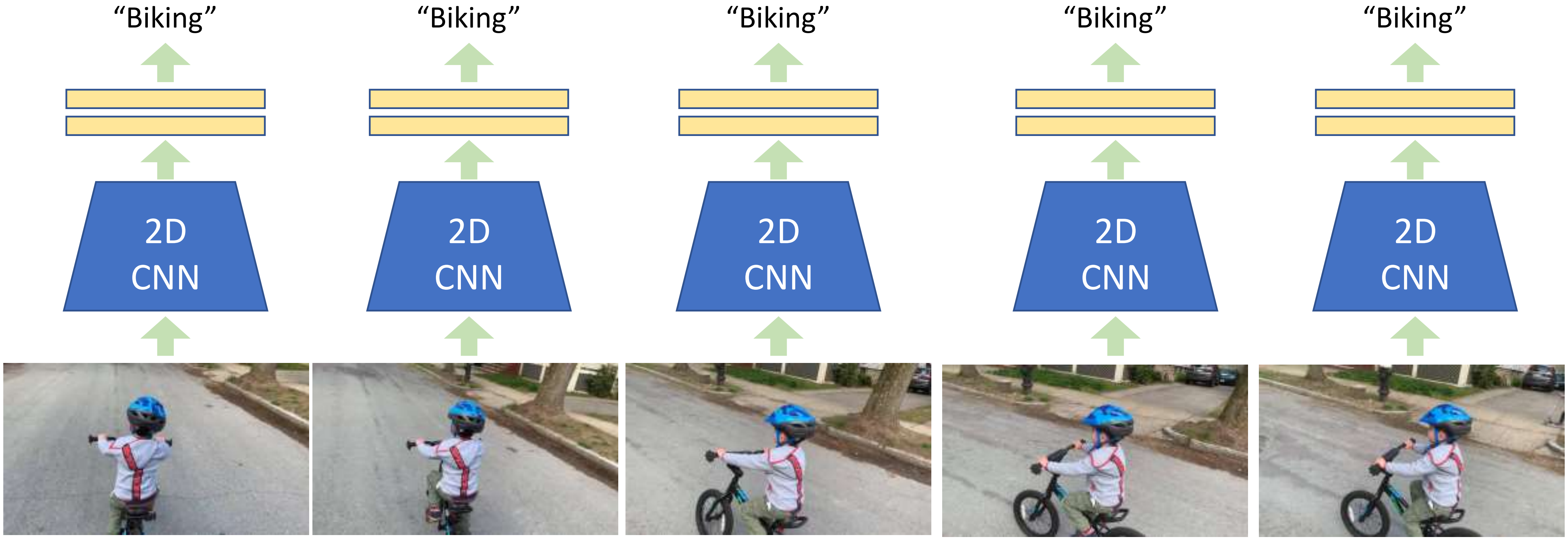
Input video frame

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

Models for Videos: Single-Frame Baseline

- Train 2D CNN to classify video frames independently
- Average predicted probs at test-time

Often a surprisingly strong baseline!

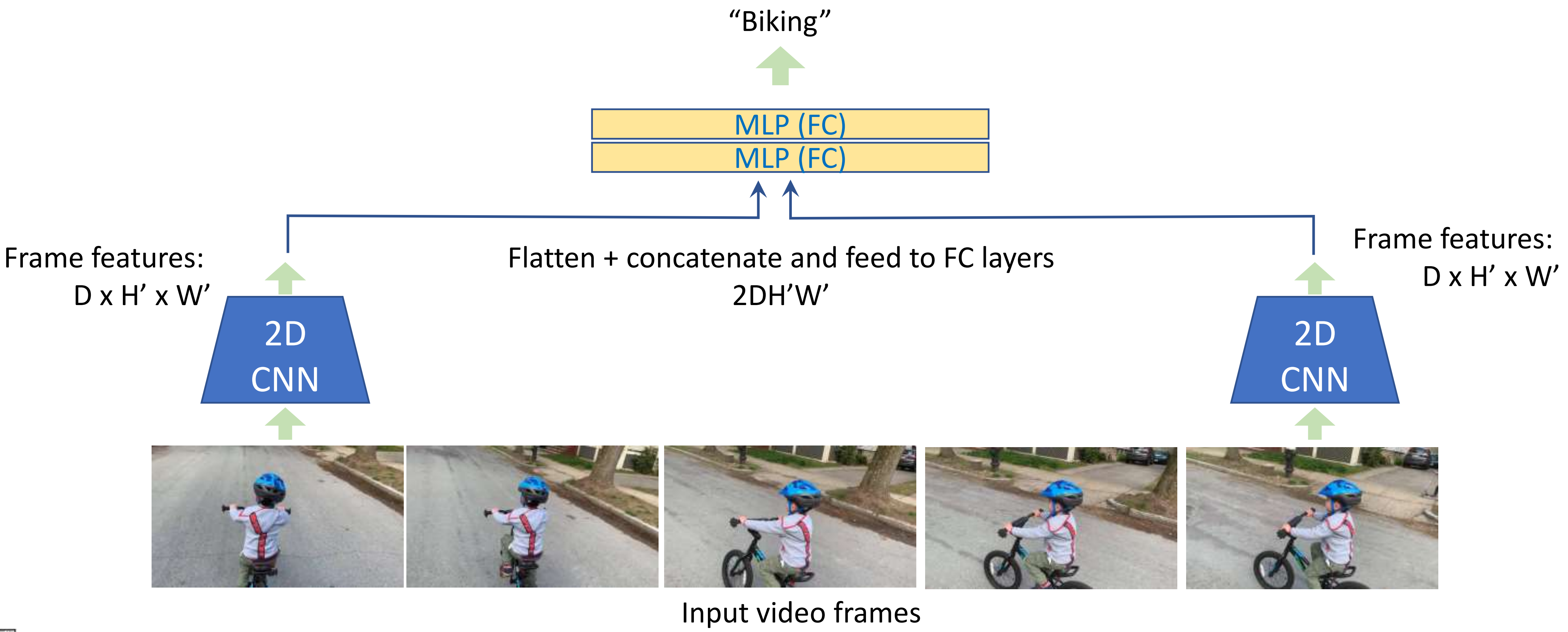


Input video frames

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

Models for Videos: Late Fusion

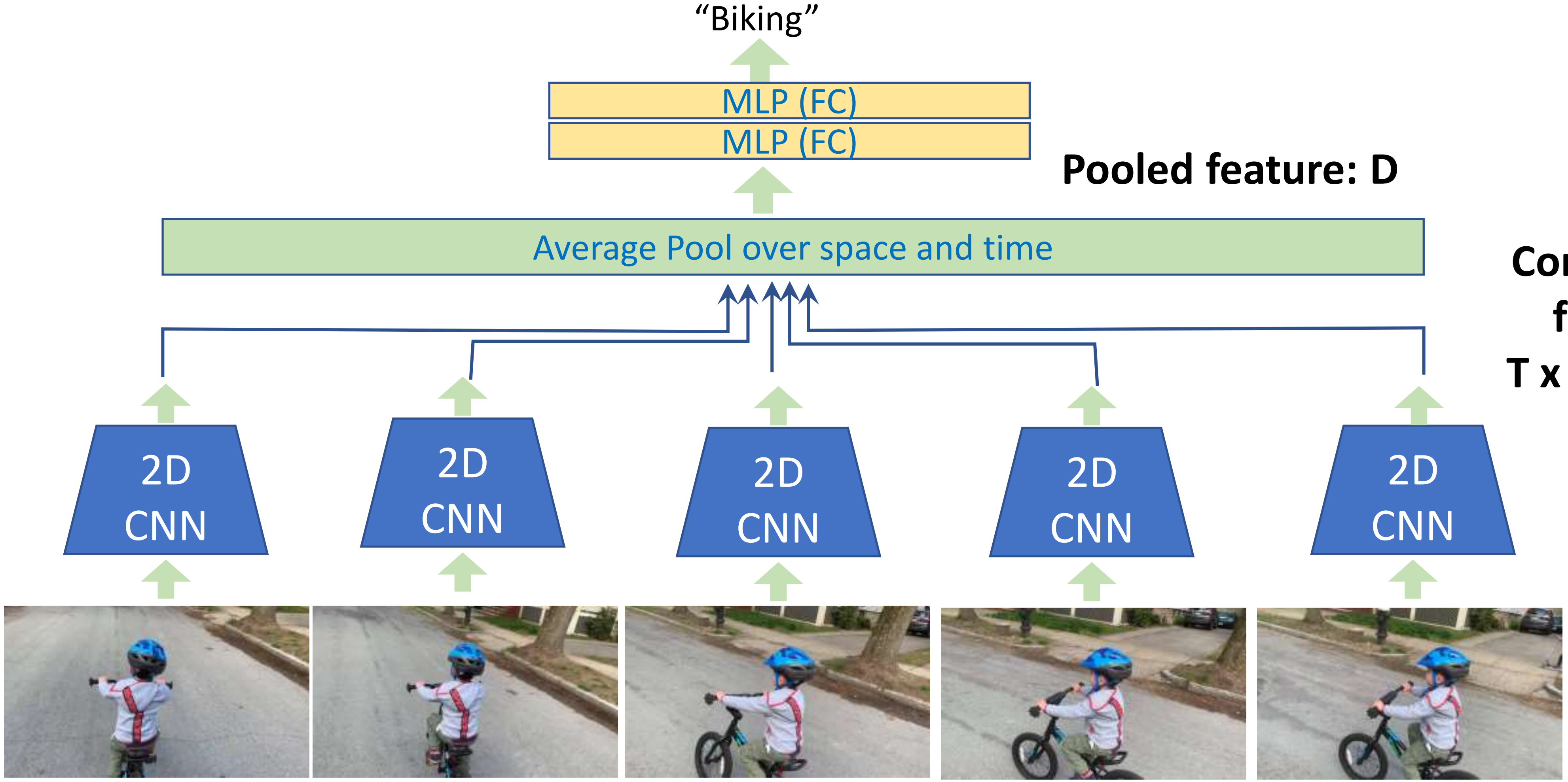
- Learn features for each frame using a 2D CNN, concatenate feature, and fuse



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

Models for Videos: Late Fusion w/ pooling

Learn features for each frame, apply spatial-temporal average pool, and then fuse



Pooled feature: D

Concatenated features: T x D x H' x W'

Input video frames

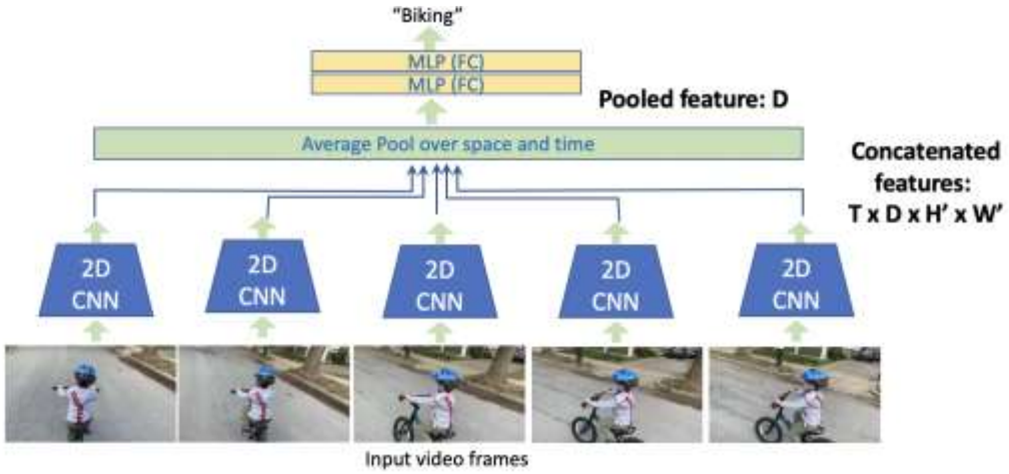
Karpathy et. al., Large-scale Video Classification with Convolutional Neural Networks, CVPR, 2014

Models for Videos: Late Fusion w/ pooling

Learn features for each frame, apply spatial-temporal average pool, and then fuse

Pros: allow the network to learn global motion characteristics by comparing outputs of both towers

Cons: late fusion is late…
hard to represent low level motion between frames

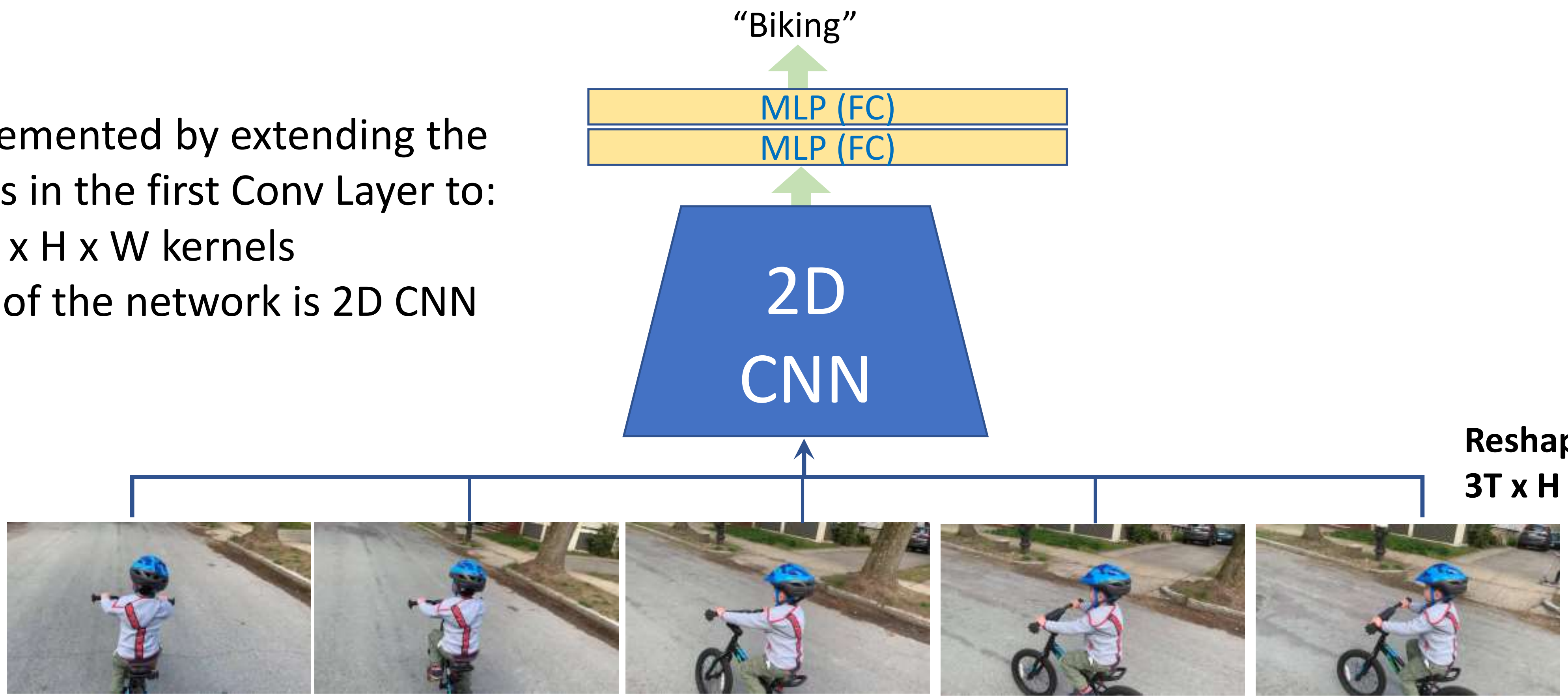


Karpathy et. al., Large-scale Video Classification with Convolutional Neural Networks, CVPR, 2014

Models for Videos: Early Fusion

- Combines temporal information immediately on the pixel level
- Treat time as another "channel" dimension

Implemented by extending the filters in the first Conv Layer to:
T x 3 x H x W kernels
Rest of the network is 2D CNN



Reshaped input:
3T x H x W

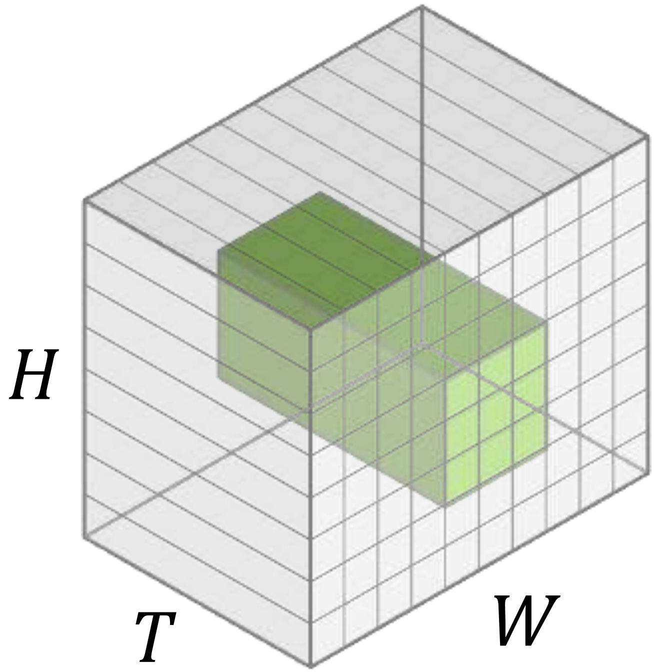
Input:
T x 3 x H x W

Input video frames

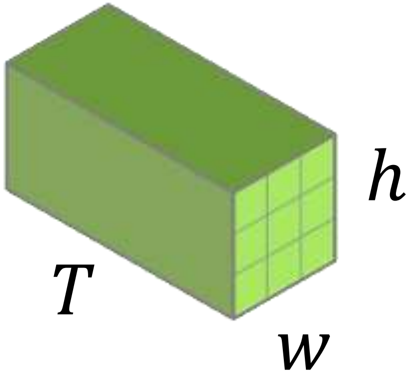
Karpathy et. al., Large-scale Video Classification with Convolutional Neural Networks, CVPR, 2014

Models for Videos: Early Fusion

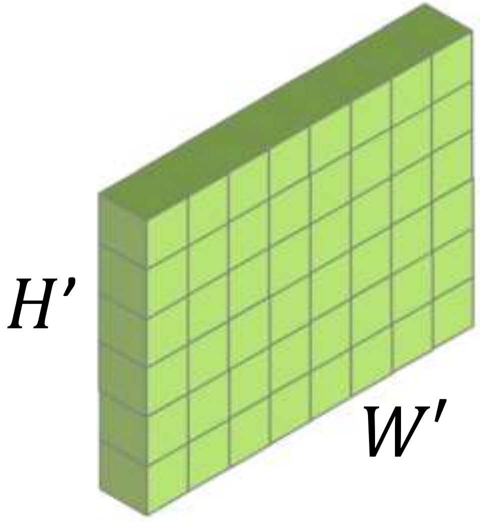
Extending the filters in the first Conv Layer to: T x 3 x H x W kernel



Input: T x 3 x H x W



Weights: C x T x 3 x h x w

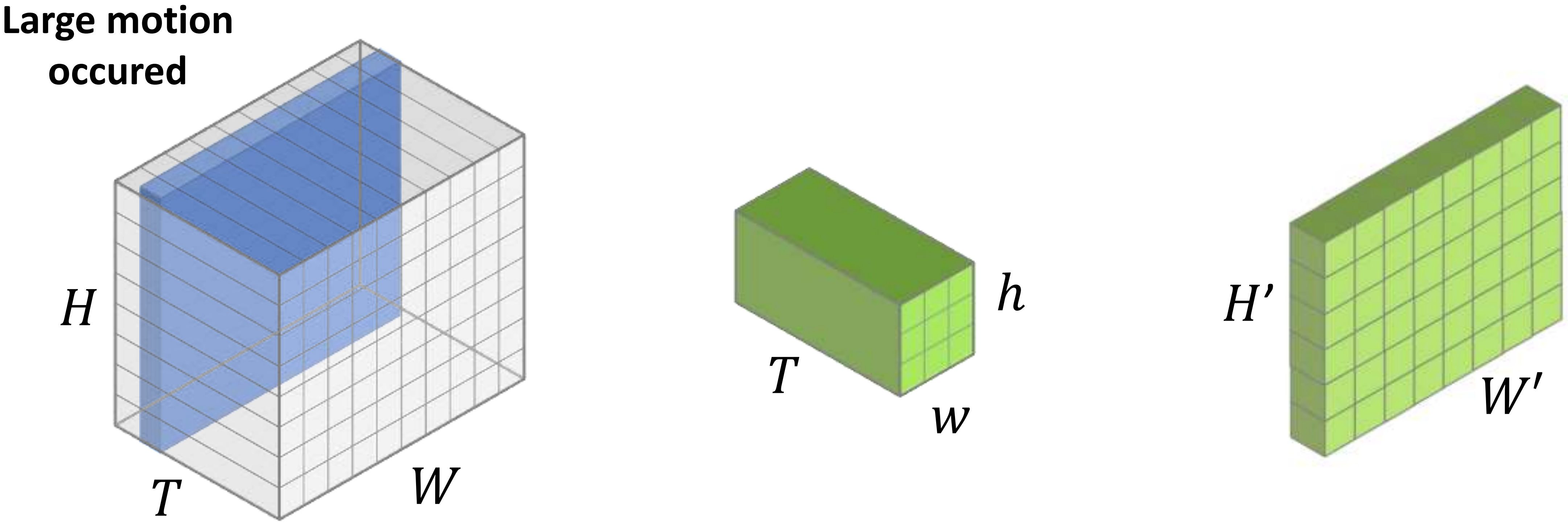


Output: C x H’ x W’

Models for Videos: Early Fusion

Extending the filters in the first Conv Layer to: T x 3 x H x W kernel

- Not temporal shift invariance; specific filter is learned to each time step



Input: T x 3 x H x W

Weights: C x T x 3 x h x w

Output: C x H' x W'

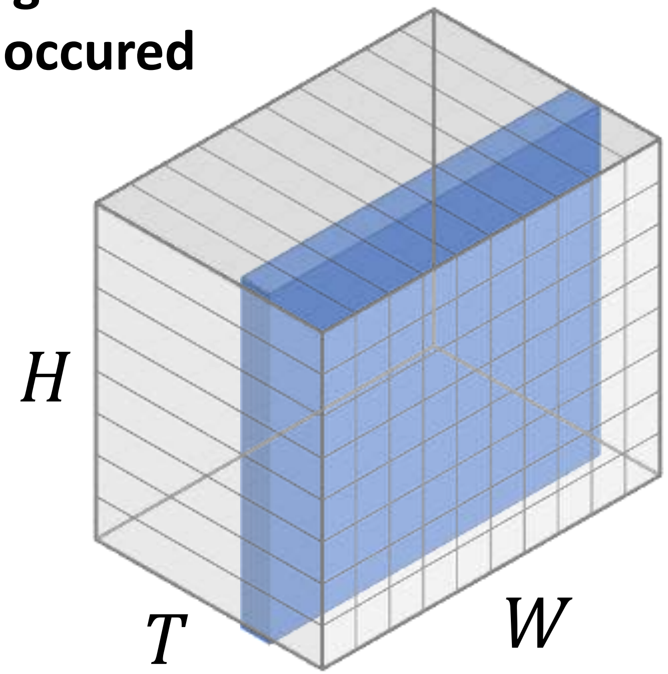
Karpathy et. al., Large-scale Video Classification with Convolutional Neural Networks, CVPR, 2014

Models for Videos: Early Fusion

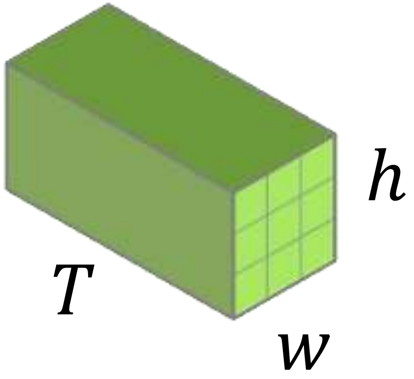
Extending the filters in the first Conv Layer to: T x 3 x H x W kernel

- Not temporal shift invariance; specific filter is learned to each time step

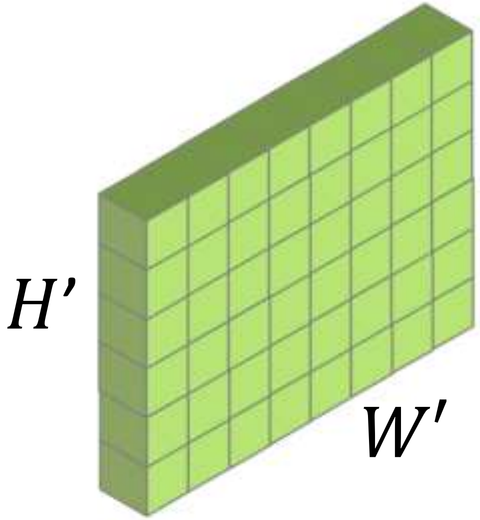
Large motion occured



Input: T x 3 x H x W



Weights: C x T x 3 x h x w



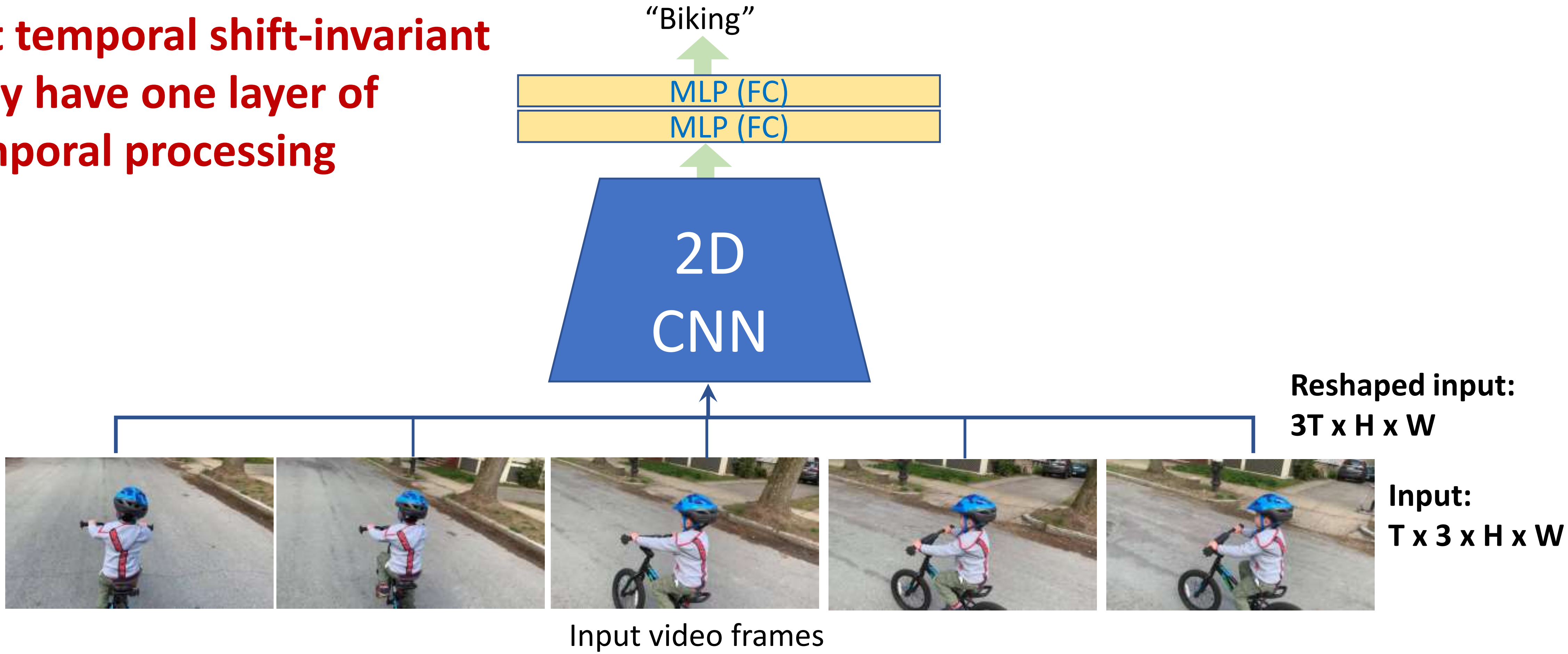
Output: C x H' x W'

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

Models for Videos: Early Fusion

Pros: Allow the network to learn local motion characteristics

Cons:
- Not temporal shift-invariant
- Only have one layer of temporal processing

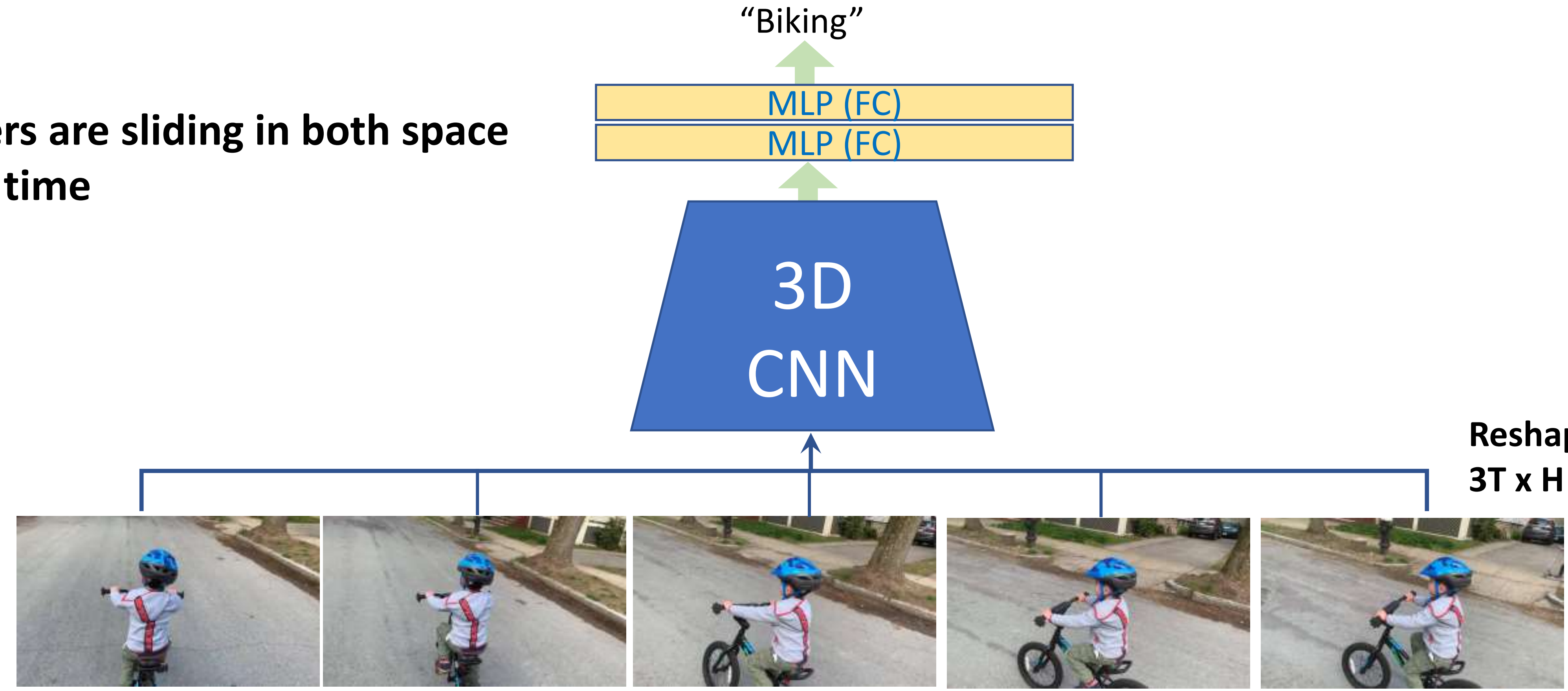


Karpathy et. al., Large-scale Video Classification with Convolutional Neural Networks, CVPR, 2014

Models for Videos: Slow Fusion a.k.a 3D Convs

- Extend 2D Convs and pooling to 3D to slowly fuse temporal information throughout the model

Filters are sliding in both space and time



Reshaped input:
3T x H x W

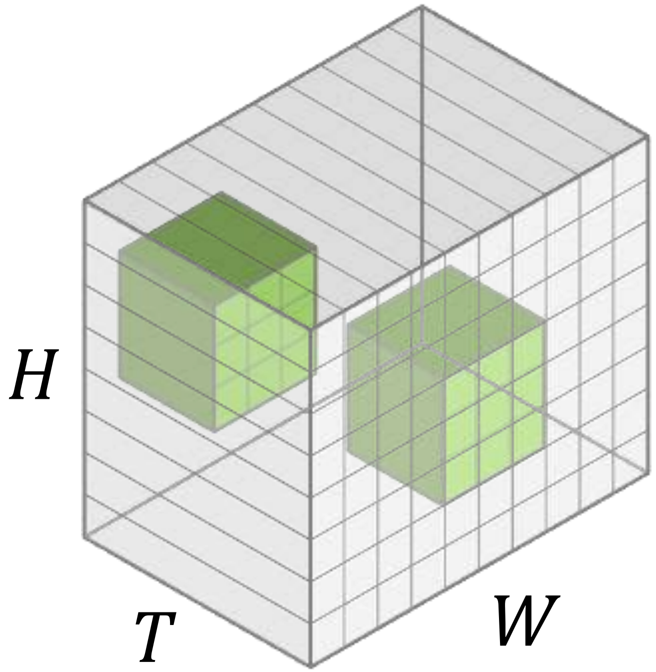
Input:
T x 3 x H x W

Input video frames

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

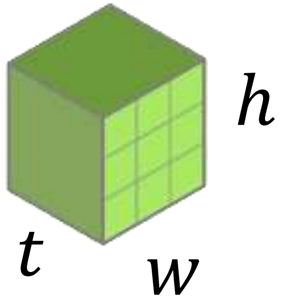
Models for Videos: Slow Fusion a.k.a 3D Convs

- Extend 2D Convs and pooling to 3D to slowly fuse temporal information throughout the model
- **Slide the kernels in both space and time**

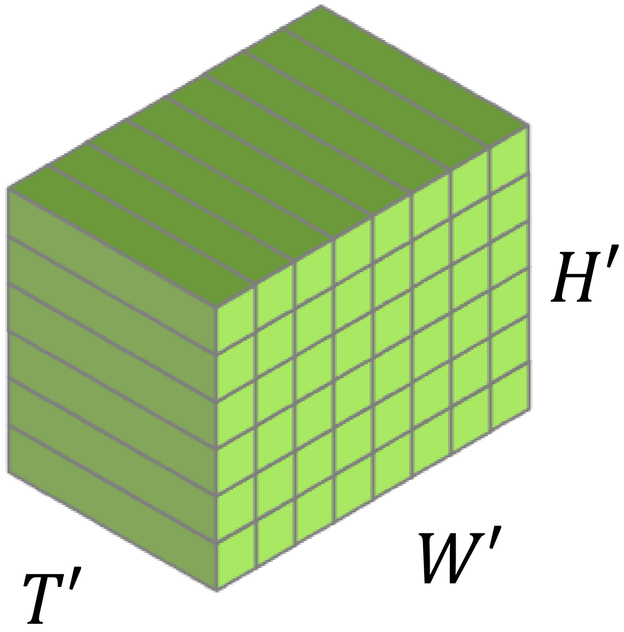


Input: T x 3 x H x W

- Temporal shift-invariant!



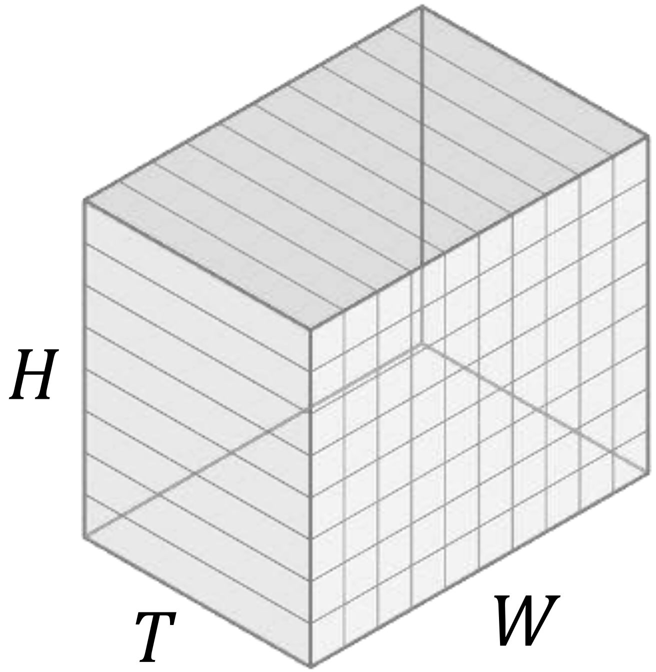
Weights: C x t x 3 x h x w



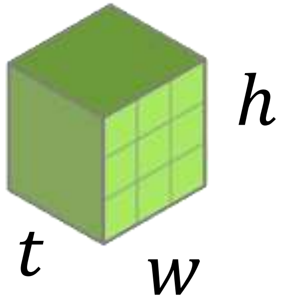
Output: C x T’ x H’ x W’

Models for Videos: Slow Fusion a.k.a 3D Convs

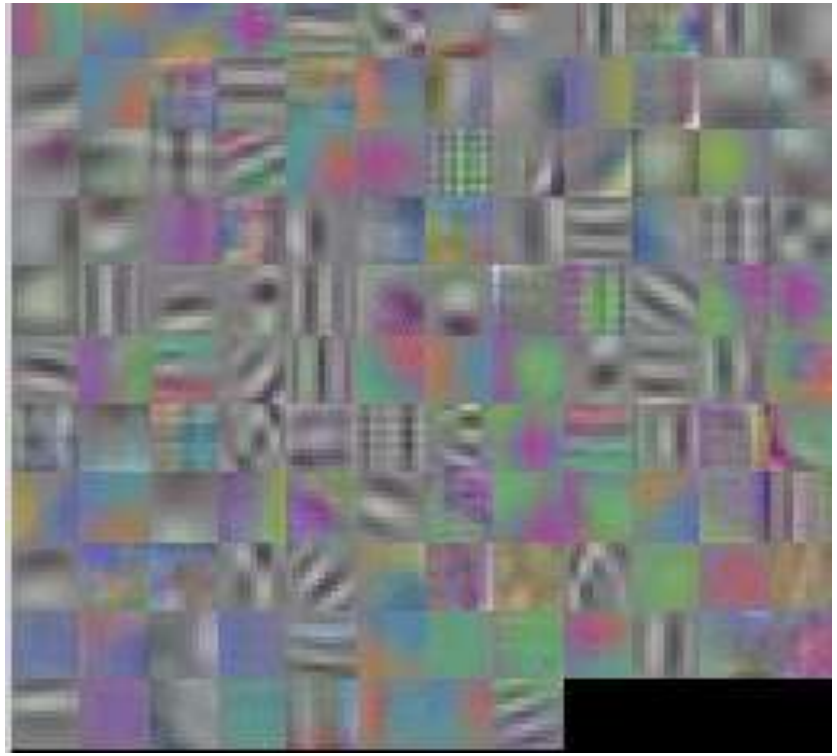
- Extend 2D Convs and pooling to 3D to slowly fuse temporal information throughout the model
- **Slide the kernels in both space and time**



Input: T x 3 x H x W



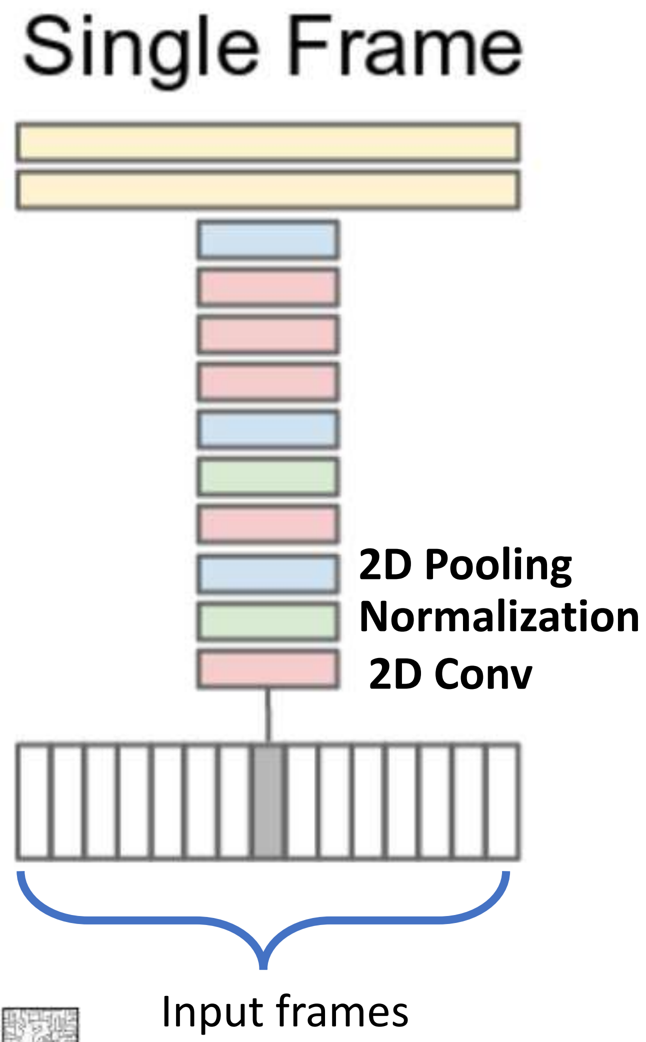
Weights: C x t x 3 x h x w



First layer filters
3(rgb) x 4 (t) x 5 (h) x 5 (w)

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

Single Frame vs. Late vs. Early vs. Slow Fusion

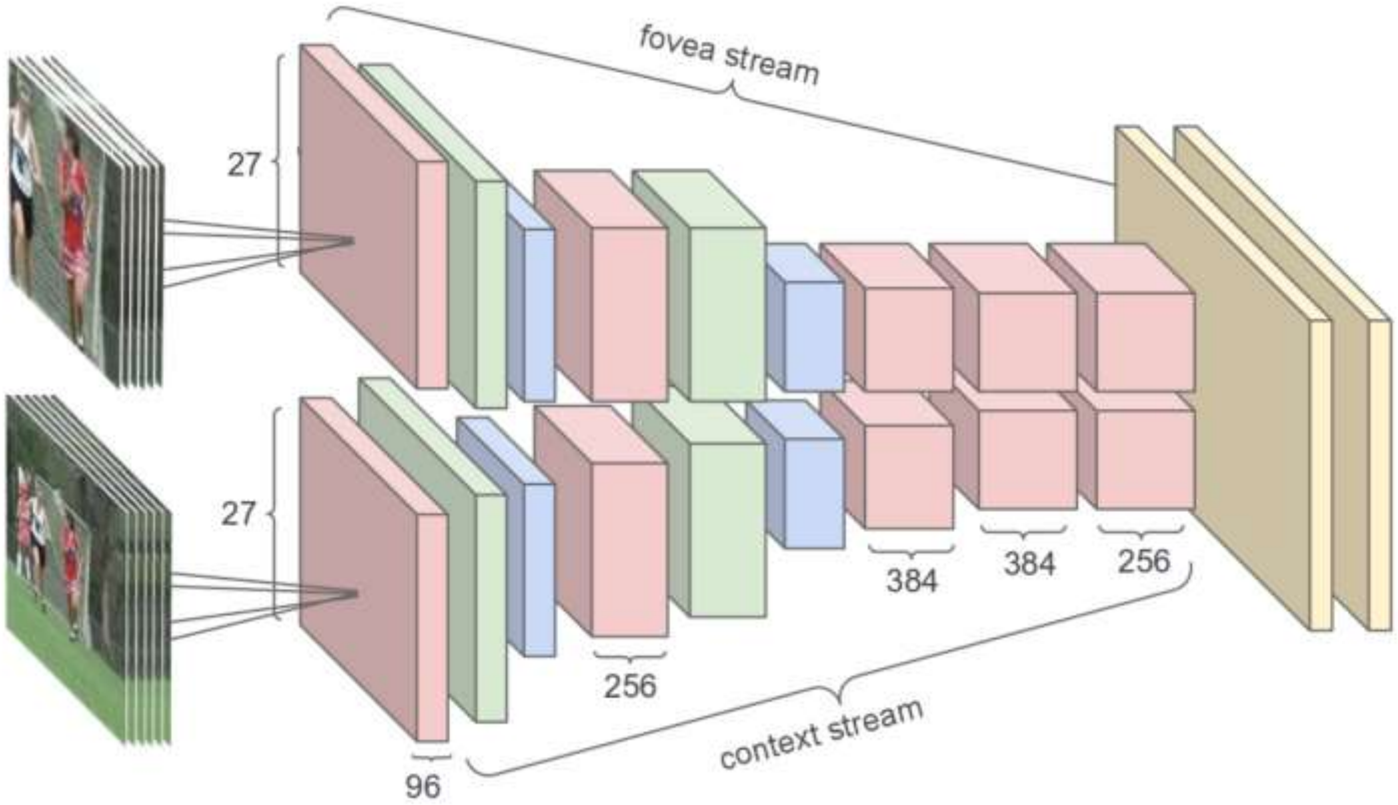


Models for Videos: Multi-scale

How can we reduce computational cost while maintaining accuracy?

Reduce video resolution → lower performance

Reduce network's capacity → lower performance



- Context stream ***(low res)***:
  process low res video frames (H/2, W/2)

- Fovea sterm ***(high res)***:
  process a (H/2, W/2) crop from the original resolution

Reduce the input dimentionalty by half

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

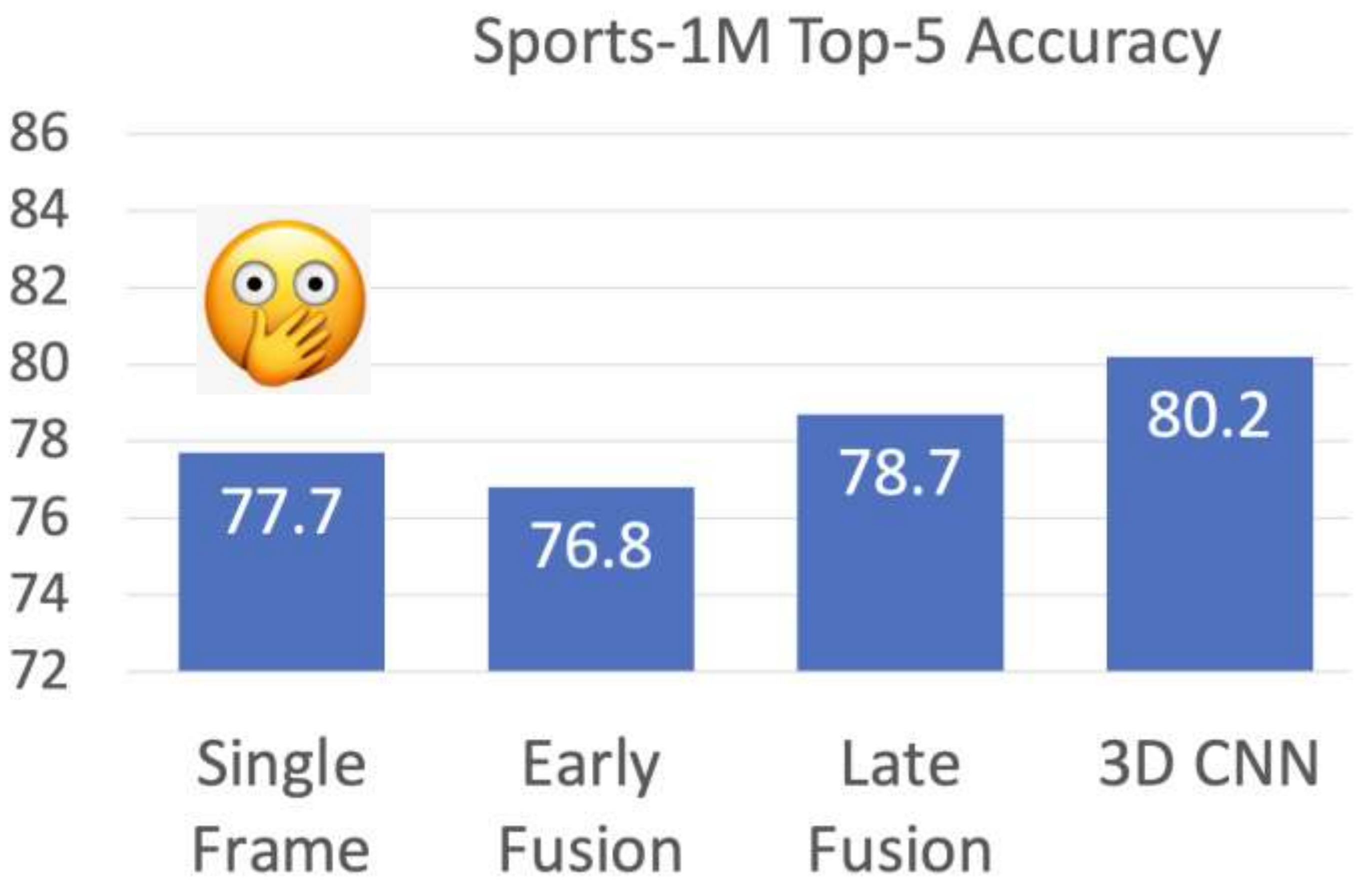
Action classification -- Sports-1M

- 1 million YouTube videos
- Fine grained labels for 487 different types of sports

- Ground truth
- Correct prediction
- Incorrect prediction

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

Action classification -- Sports-1M



Single frame: a shockly powerful baseline

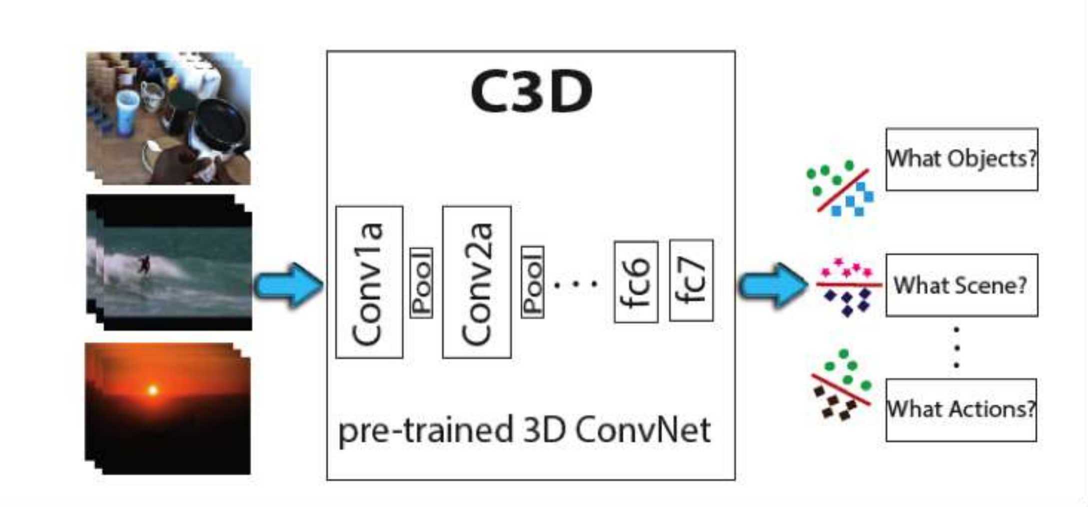
This is from 2014…

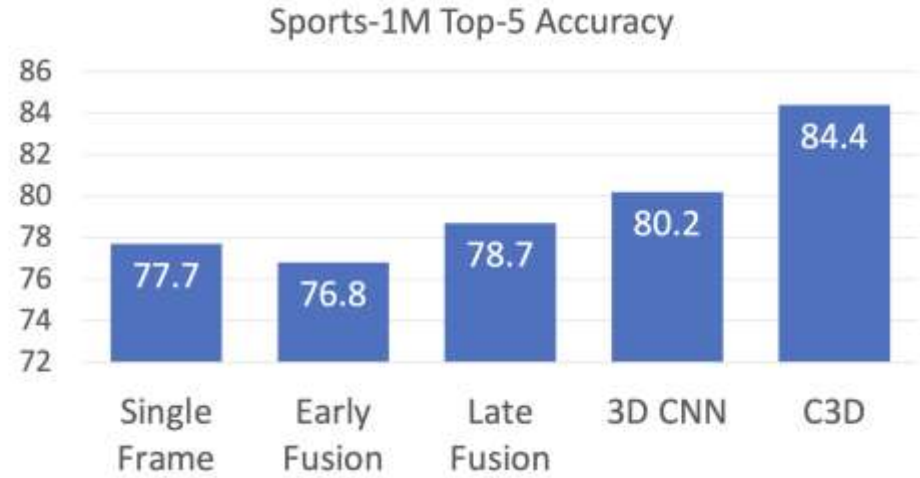
Karpathy et. al., Large-scale Video Classification with Convolutional Neural Networks, CVPR, 2014 Slide credit: Justin Johnson, EECS 498-007

Models for Videos: C3D (Convolutional 3D)

- 3D CNN that uses all 3x3x3 Convs and 2x2x2 poolings
- The "VGG" of 3D CNNs

- Transfer learning: extract learned video features, train a simple linear classifier for various tasks



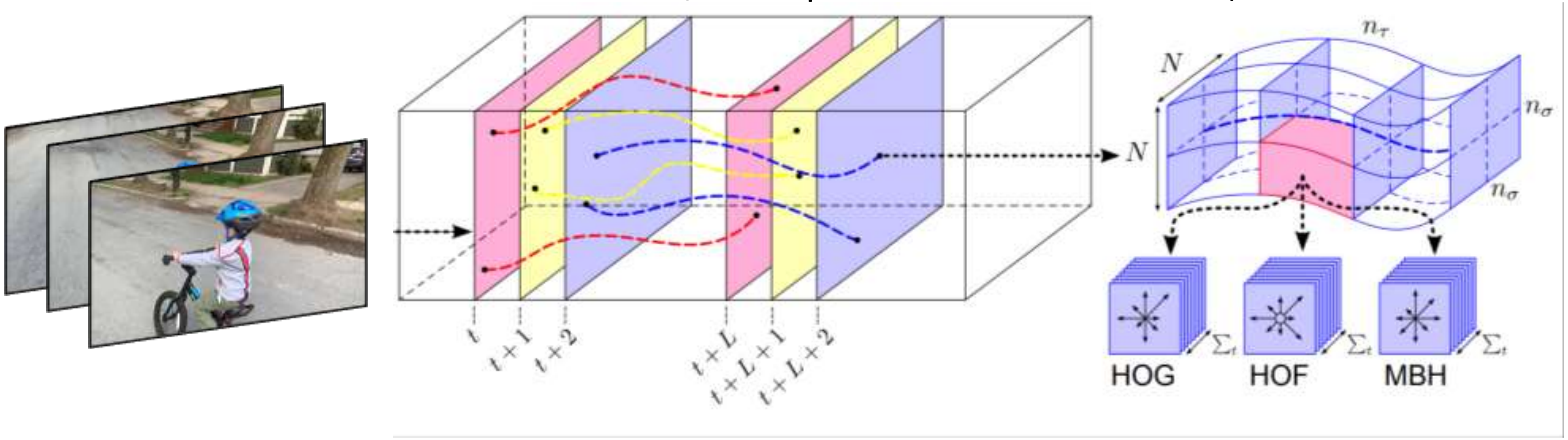


- Problem: 3D convs are VERY expensive!
  C3D on small inputs takes 3x VGG and 56x AlexNet FLOPs

Tran et al, "Learning Spatiotemporal Features with 3D Convolutional Networks", ICCV 2015

Non-deep learning video classification

Motion is the most informative cue for action recognition → design hand crafted motion features:



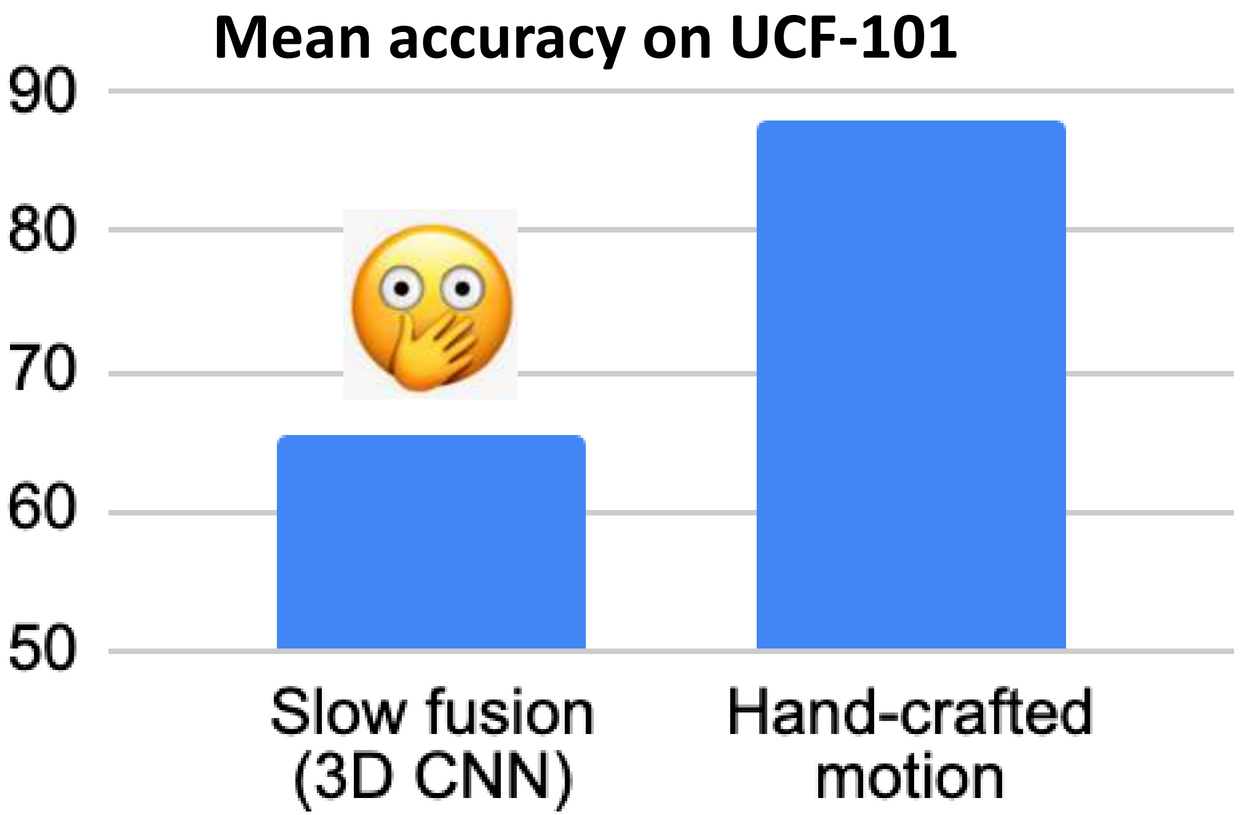
Aggregate local motion features to compute a global representation of the video → linear SVM for action recognition

MODEL MOTION EXPLICITLY

Wang et. al., Dense trajectories and motion boundary descriptors for action recognition, 2013
Peng et. al., Bag of Visual Words and Fusion Methods for Action Recognition: Comprehensive Study and Good Practice, 2014

Non-deep learning video classification

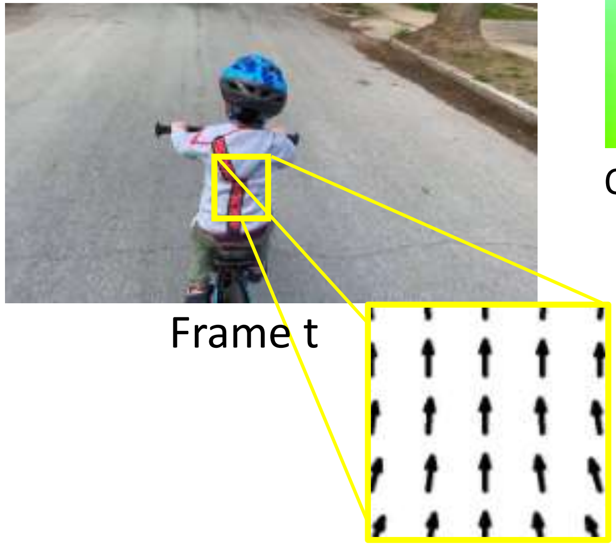
Motion is the most informative cue for action recognition → hand crafted motion features:



Explicitly modeling motion in deep-based models

Optical flow: For each pixel in frame t, determines its corresponding pixel in frame t+1

Frame t+1



Frame t

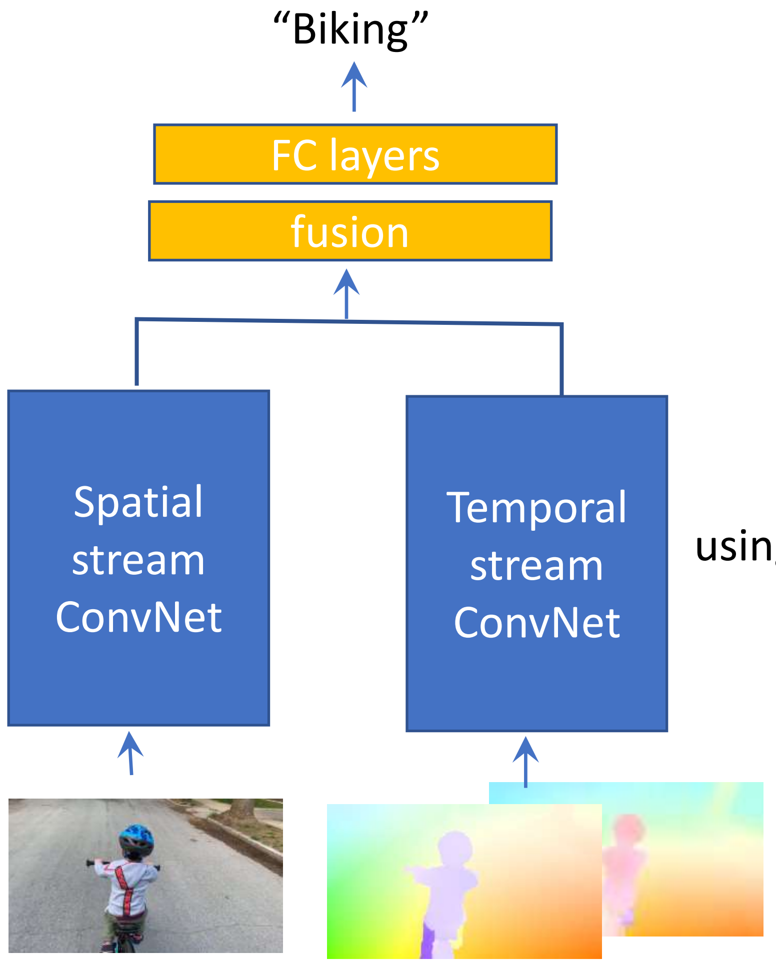
Optical flow provides **local motion cues**

Optical flow between two frames

Color wheel
Saturation = mag.
Color = angle

Two Stream Networks: modeling motion explicitly

Idea: separate motion (multi-frame) from static appearance (single frame)



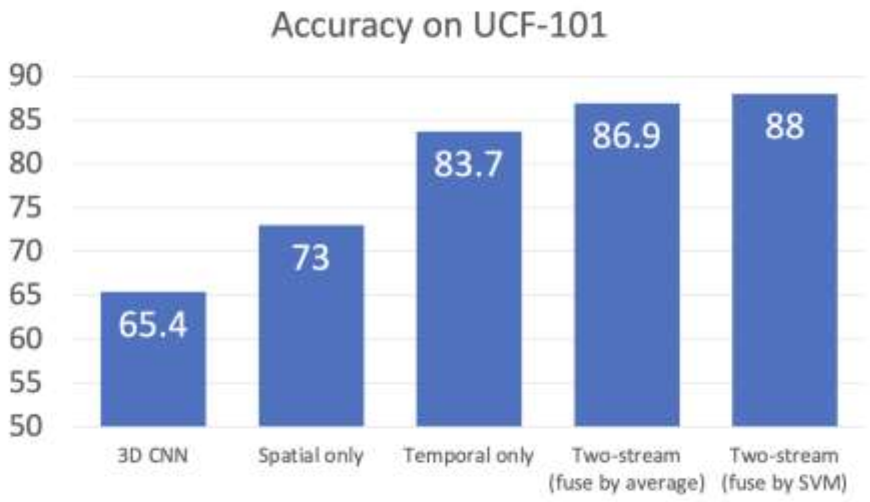
”Single Frame” baseline

using “Early Fusion” baseline

Frame t

Multi-frame optical flow

Precomputed flow fields between concuective frames



Simonyan and Zisserman, Two-Stream Convolutional Networks for Action Recognition in Videos, NIPS 2014

Two Stream Networks: modeling motion explicitly

Idea: separate motion (multi-frame) from static appearance (single frame)

“Biking”

FC layers

fusion

”Single Frame” baseline

Spatial stream ConvNet

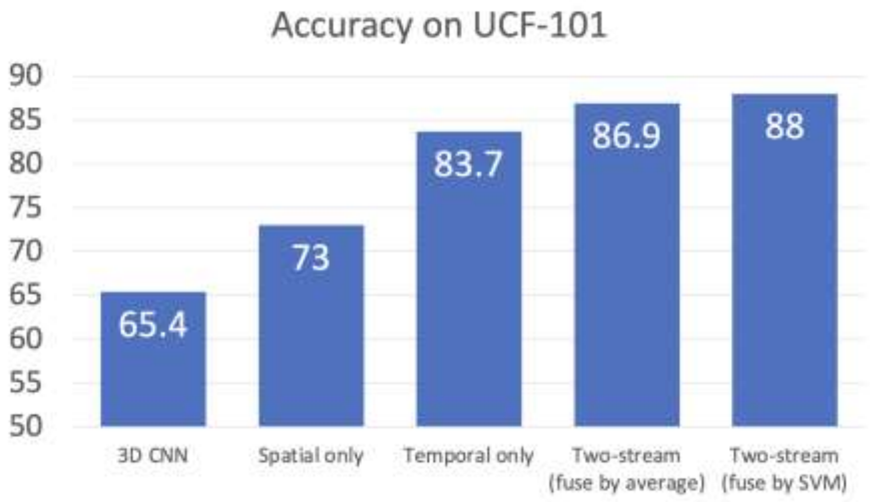
Temporal stream ConvNet

using “Early Fusion” baseline

Frame t

Multi-frame optical flow

Precomputed flow fields between concuective frames



Simonyan and Zisserman, Two-Stream Convolutional Networks for Action Recognition in Videos, NIPS 2014

Additional models

Inflating 2D networks to 3D (I3D)

Take an existing 2D CNN model → convert it to a 3D CNN model

Transfer the weights from 2D and 3D

Carreira and Zisserman, “Quo Vadis, Action Recognition? A New Model and the Kinetics Dataset”, CVPR 2017

Long range temporal processing

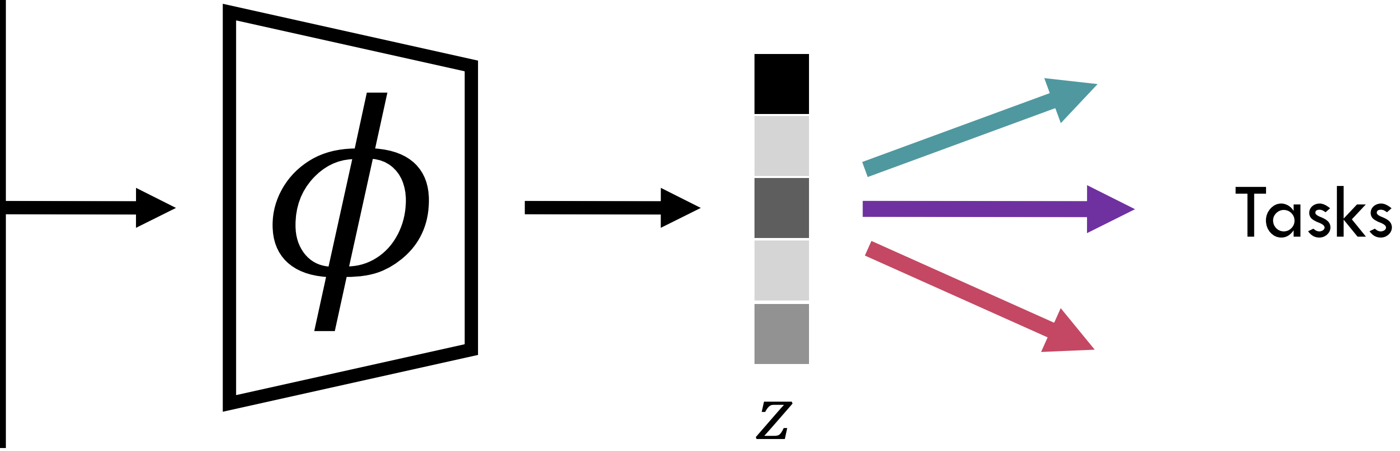
Use LSTMs and RNNs to model long range temporal information

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

Long range temporal processing

Self attention, non-local networks, Transformers

Self-Supervision in Videos

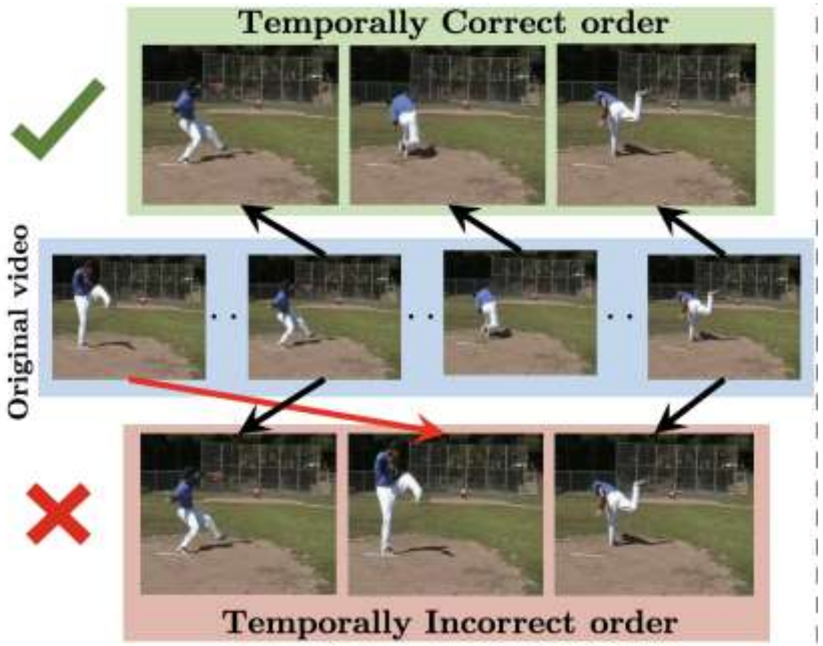


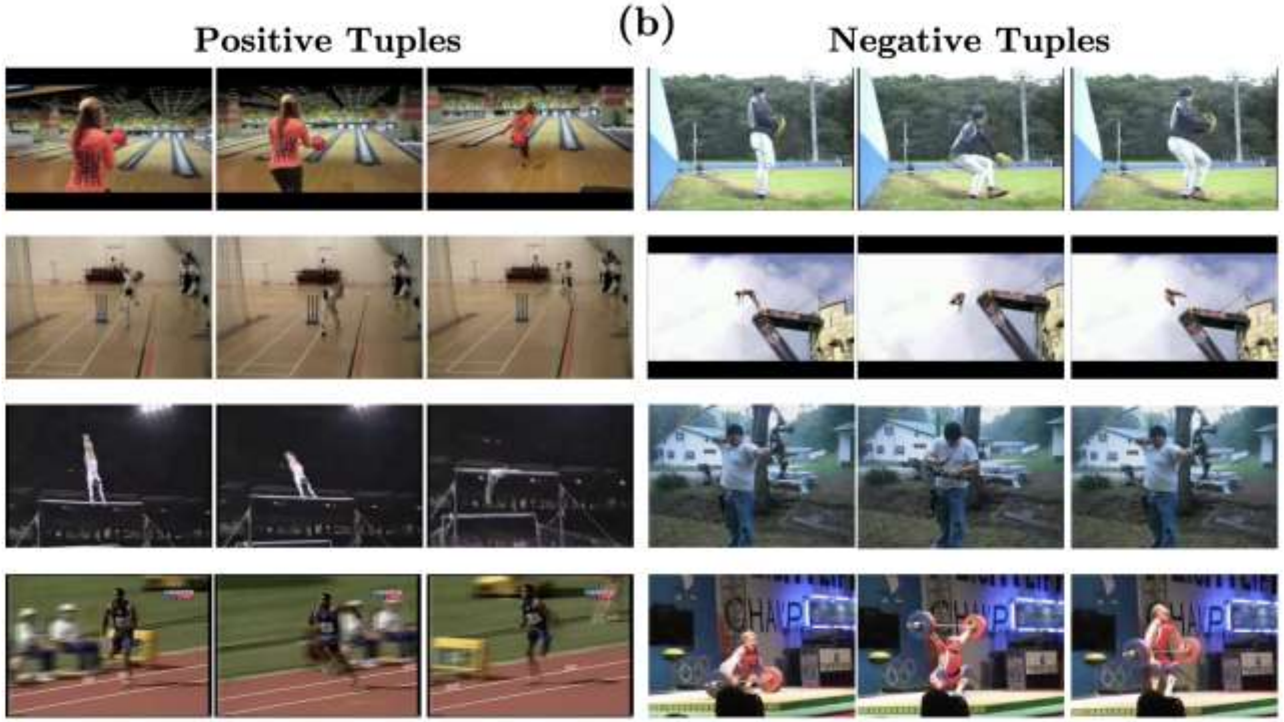
- Temporal order
- Cycle consistency
- Video Speedup
- Video colorization

Video: https://ajabri.github.io/timecycle/

Self-Supervision in Videos: frame ordering

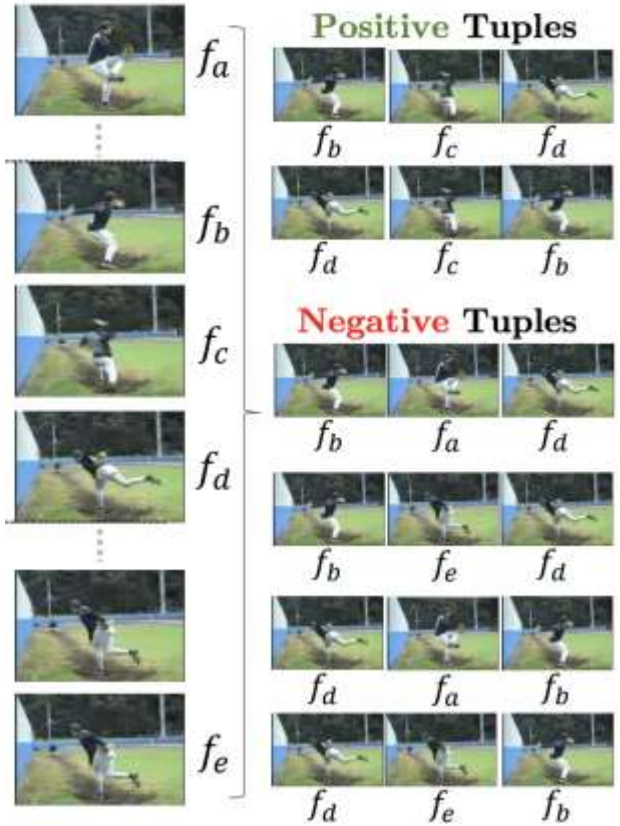
Training data: shuffled video frames, original video frames
Pretext task: predict if the frames are in the correct temporal order (binary classification task)



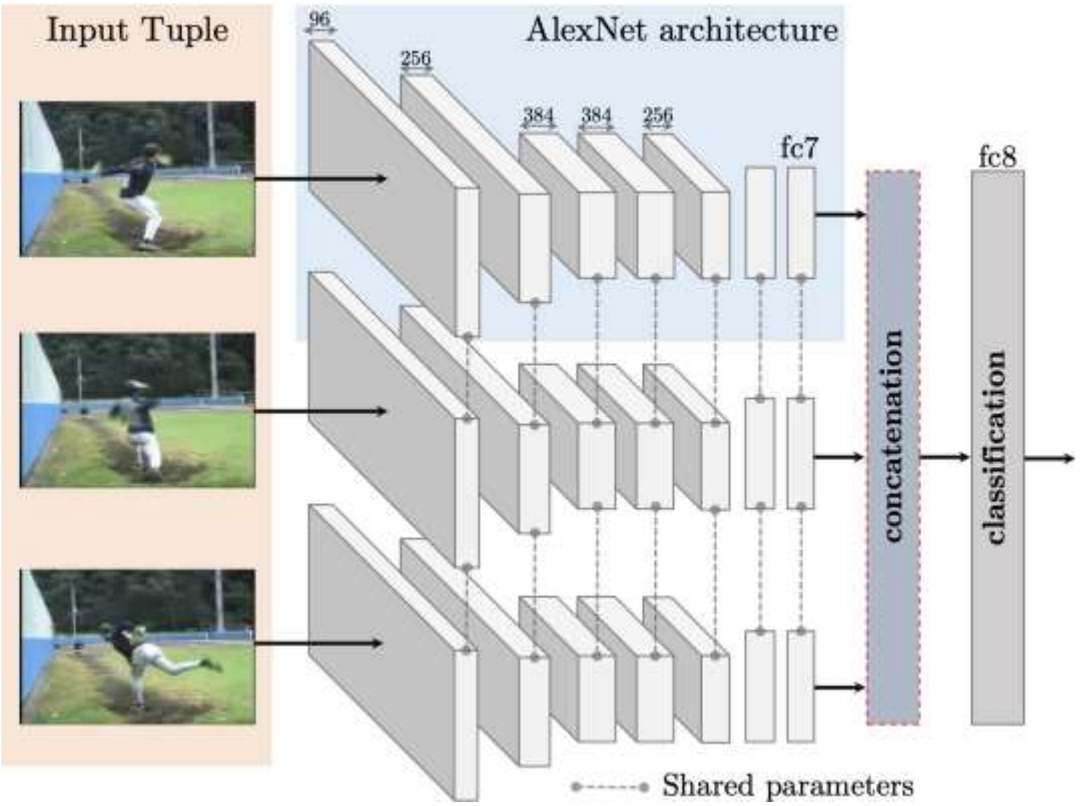


Misra et. al., Shuffle and Learn: Unsupervised Learning using Temporal Order Verification, ECCV 2016

Self-Supervision in Videos: frame ordering



Generating positive and negative examples

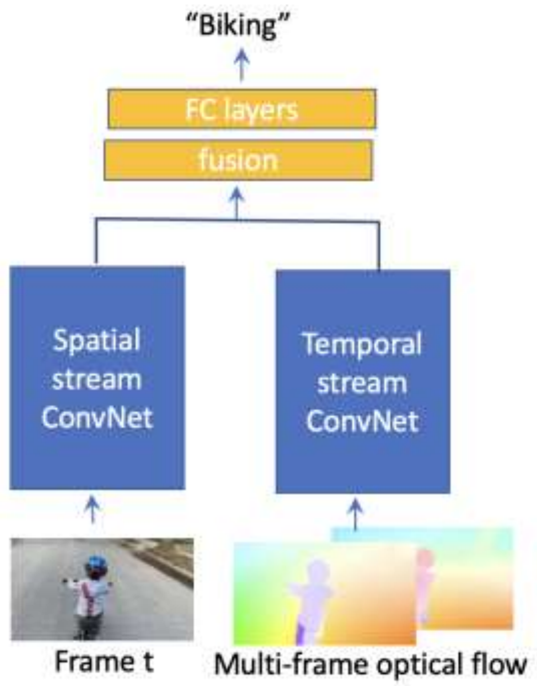


Triplet Siamese network for sequence verification

Misra et. al., Shuffle and Learn: Unsupervised Learning using Temporal Order Verification, ECCV 2016

Self-Supervision in Videos: frame ordering

Transfer learning: fine-tune spatial stream for video classification



Dataset	Initialization	Mean Accuracy
UCF101	Random	38.6
	(Ours) Tuple verification	**50.2**
HMDB51	Random	13.3
	UCF Supervised	15.2
	(Ours) Tuple verification	**18.1**

Misra et. al., Shuffle and Learn: Unsupervised Learning using Temporal Order Verification, ECCV 2016

Self-Supervision in Videos: Colorization of Moving Objects

Ultimate goal: Tracking
Pretext task: video colorization by learning to copy color from a reference frame
Training data: grayscale videos + original color videos

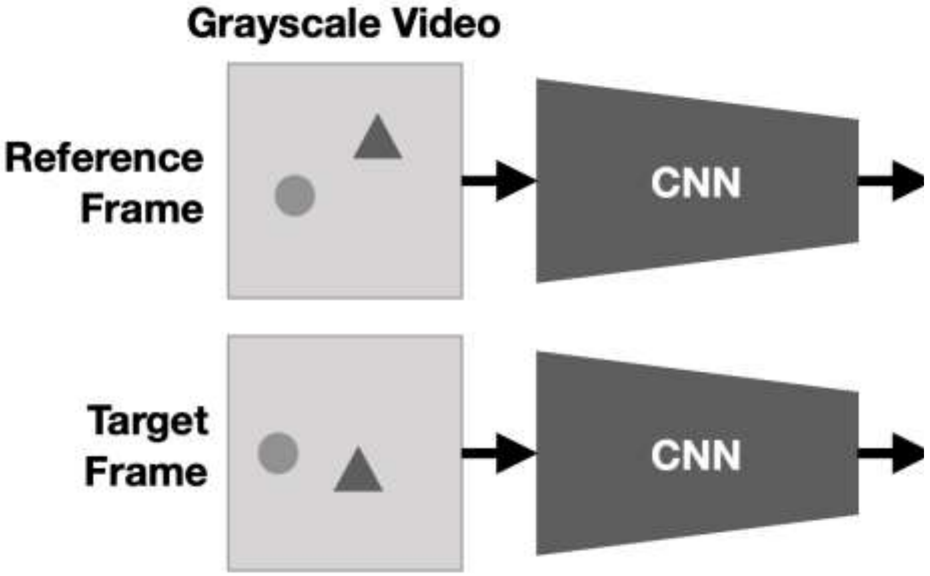
Reference frame

Grayscale video

Vondrick et. al, Tracking Emerges by Colorizing Videos, ECCV 2018

Self-Supervision in Videos: Colorization of Moving Objects

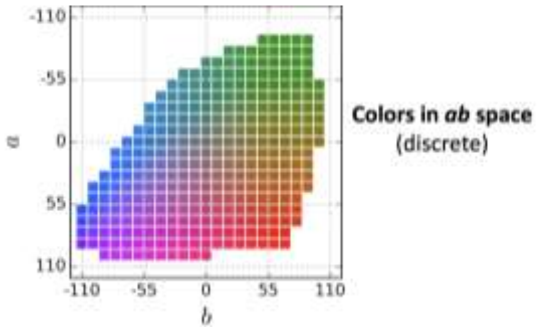
Video colorization by learning to copy color from a reference frame



Vondrick et. al, Tracking Emerges by Colorizing Videos, ECCV 2018

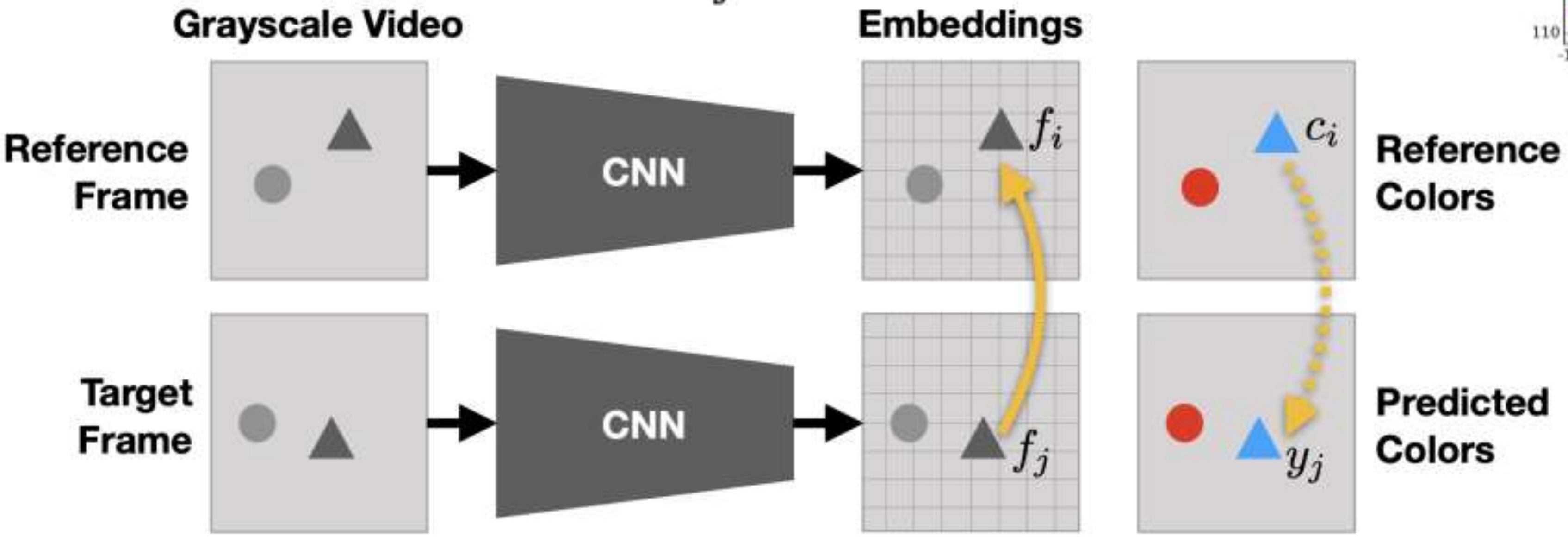
Self-Supervision in Videos: Colorization of Moving Objects

Video colorization by learning to copy color from a reference frame



$$\min_{\theta} \sum_{j} \mathcal{L}\left(y_j, c_j\right)$$

cross-entropy over color distribution



affinity matrix between reference and target (rows sum to one)

$$y_j = \sum_i A_{ij} c_i$$

linear combination of the reference colors

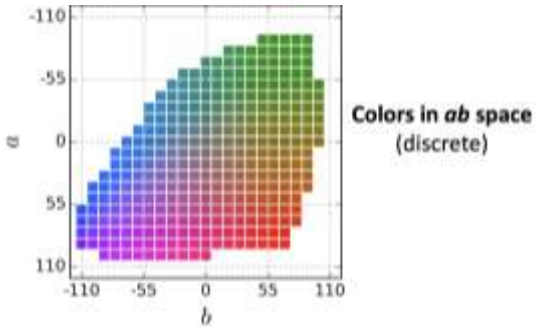
Similarity in the embedding space

$$A_{ij} = \frac{\exp\left(f_i^T f_j\right)}{\sum_k \exp\left(f_k^T f_j\right)}$$

Vondrick et. al, Tracking Emerges by Colorizing Videos, ECCV 2018

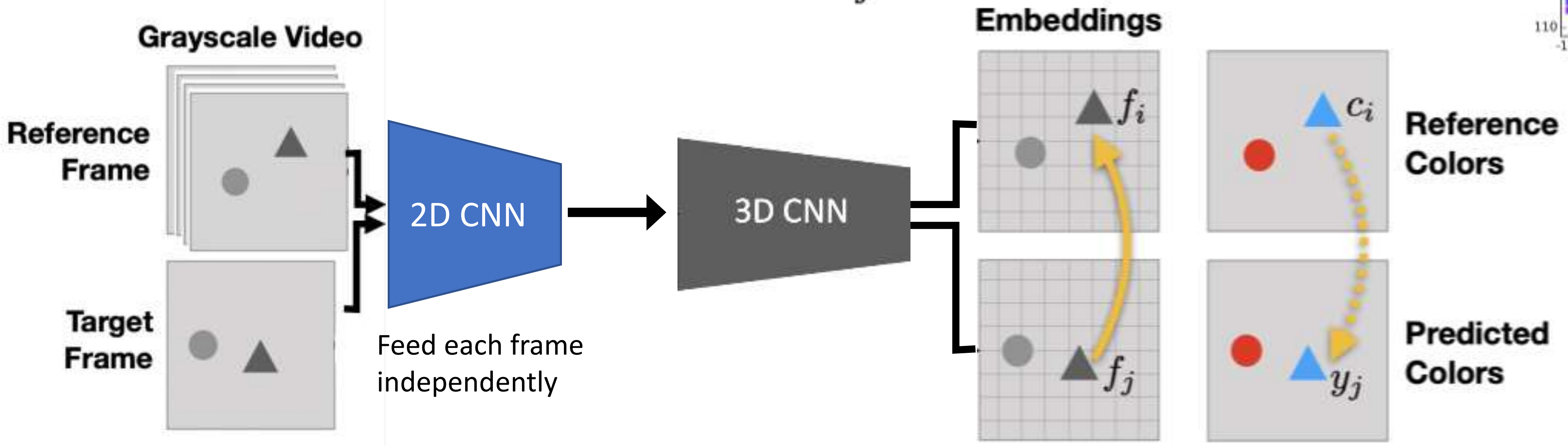
Self-Supervision in Videos: Colorization of Moving Objects

Video colorization by learning to copy color from a reference frame



$$\min_{\theta} \sum_{j} \mathcal{L}\left(y_j, c_j\right)$$

cross-entropy over color distribution



A -- a similarity matrix between reference and target (rows sum to one)

$$y_j = \sum_i A_{ij} c_i$$

linear combination of the reference colors

Similarity in the embedding space

$$A_{ij} = \frac{\exp\left(f_i^T f_j\right)}{\sum_k \exp\left(f_k^T f_j\right)}$$

Vondrick et. al, Tracking Emerges by Colorizing Videos, ECCV 2018

Self-Supervision in Videos: Colorization of Moving Objects

Video colorization by learning to copy color from a reference frame

linear combination of the reference colors

$$y_j = \sum_i A_{ij} c_i$$

a similarity matrix between reference and target (rows sum to one)

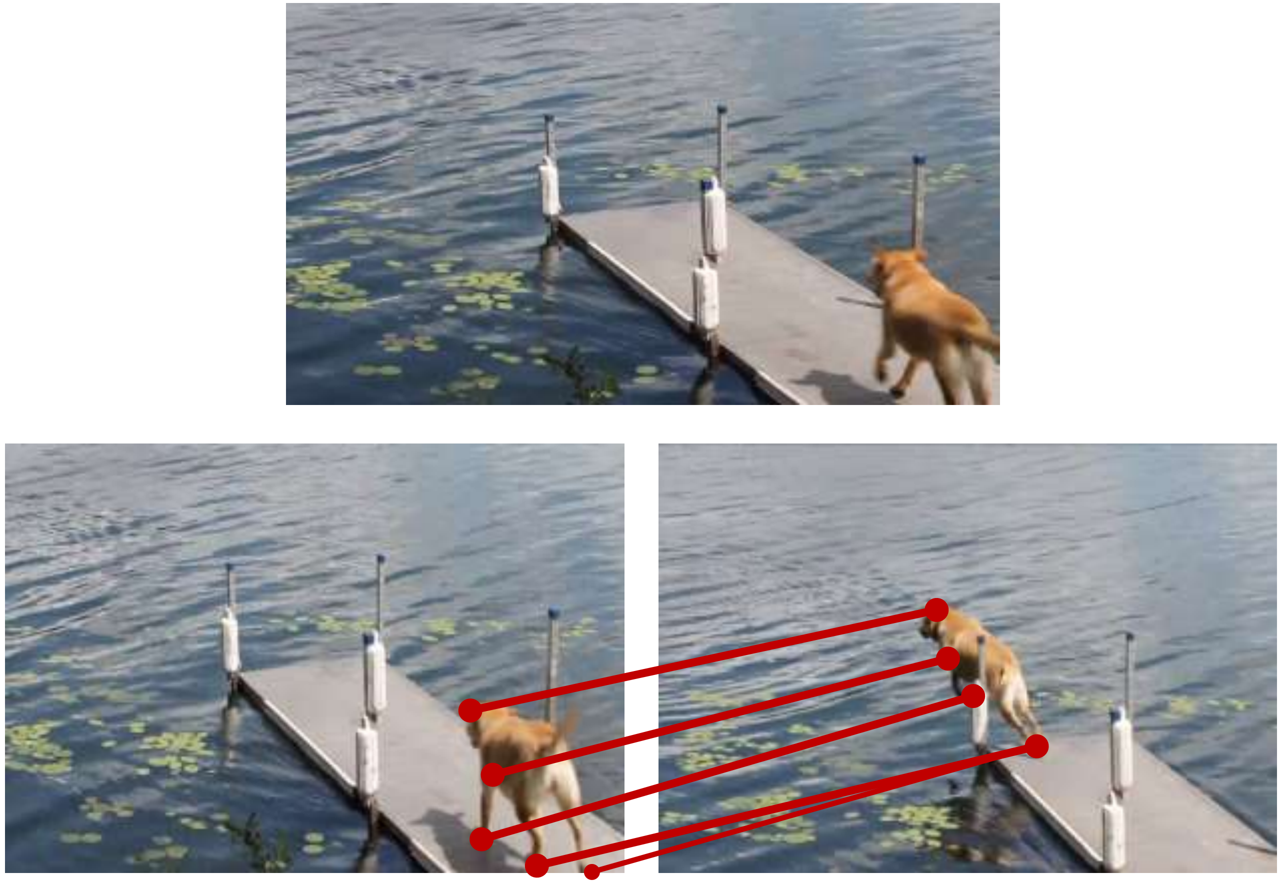
Reference

Held-out video

Vondrick et. al, Tracking Emerges by Colorizing Videos, ECCV 2018

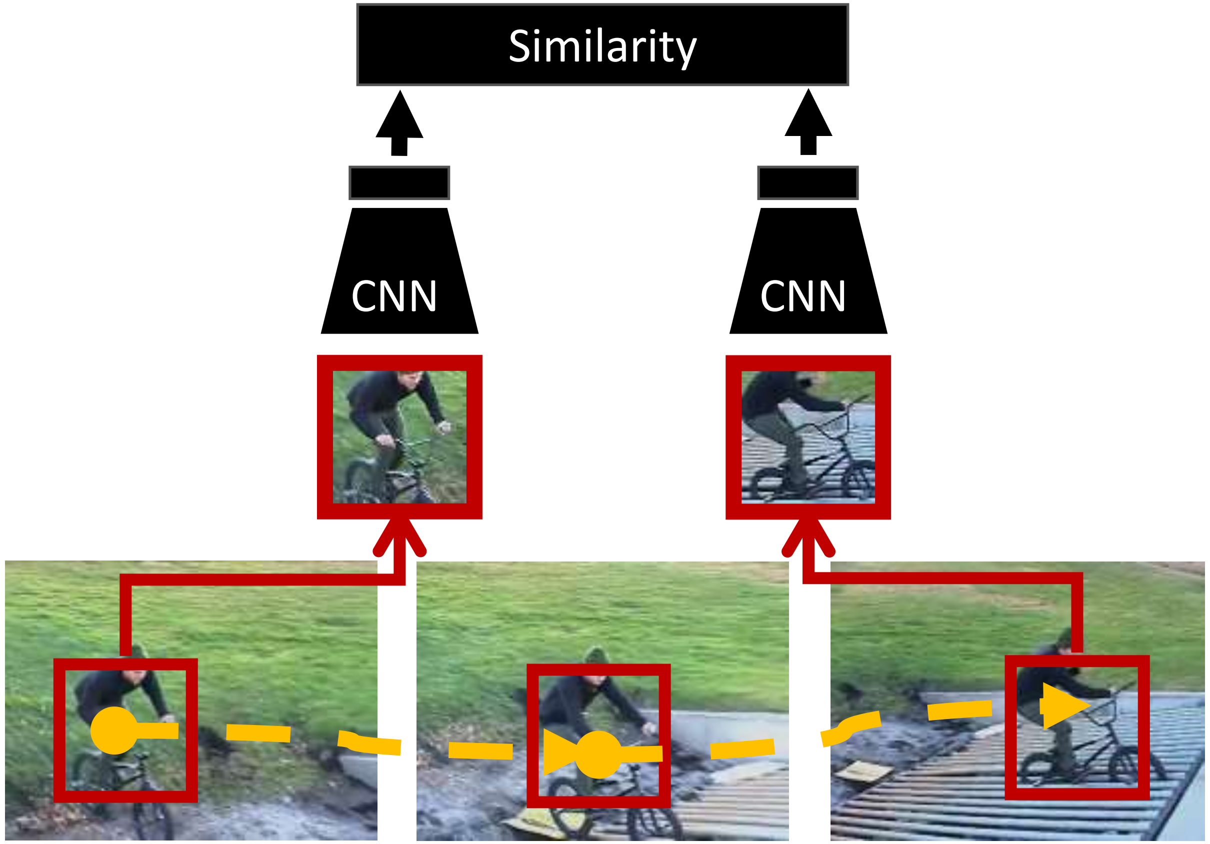
Self-Supervision in Videos: Learning correspondence

Ultimate goal: Correspondence



Wang and Efros, Learning Correspondence from the Cycle-consistency of Time, CVPR 2019

Learning Similarity from Tracking



Tracking → Similarity
[Wang et al, 2015; Pathak et al, 2017]

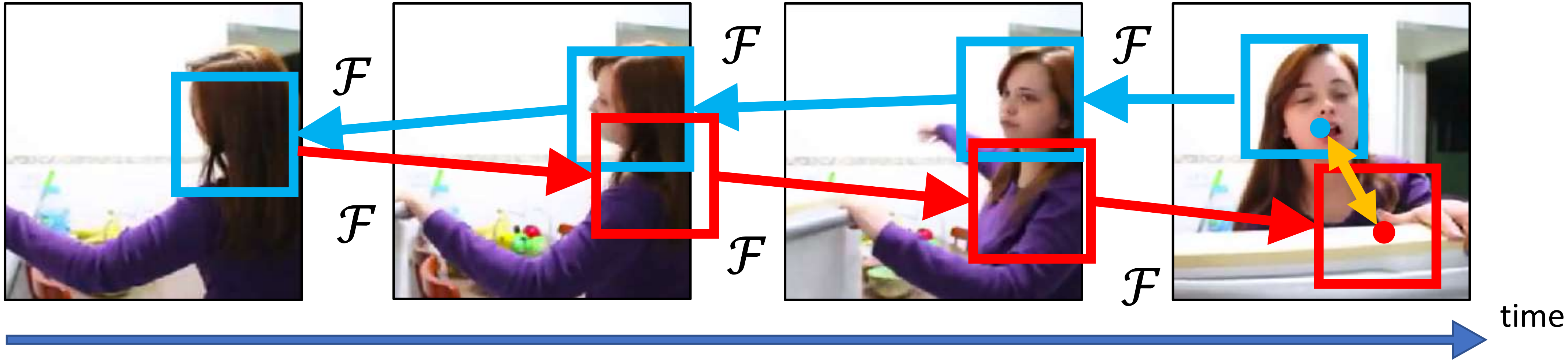
Slide credit: https://ajabri.github.io/timecycle/

Self-Supervision in Videos: Learning correspondence

Ultimate goal: Correspondence, without using off-the-shelf tracking methods

How to obtain supervision?

Supervision: Cycle-Consistency in Time



Track backwards in time

Track forwards, back to the future

Wang and Efros, Learning Correspondence from the Cycle-consistency of Time, CVPR 2019

Self-Supervision in Videos: Learning correspondence

Supervision: Cycle-Consistency in Time

Challenge: Occlusions

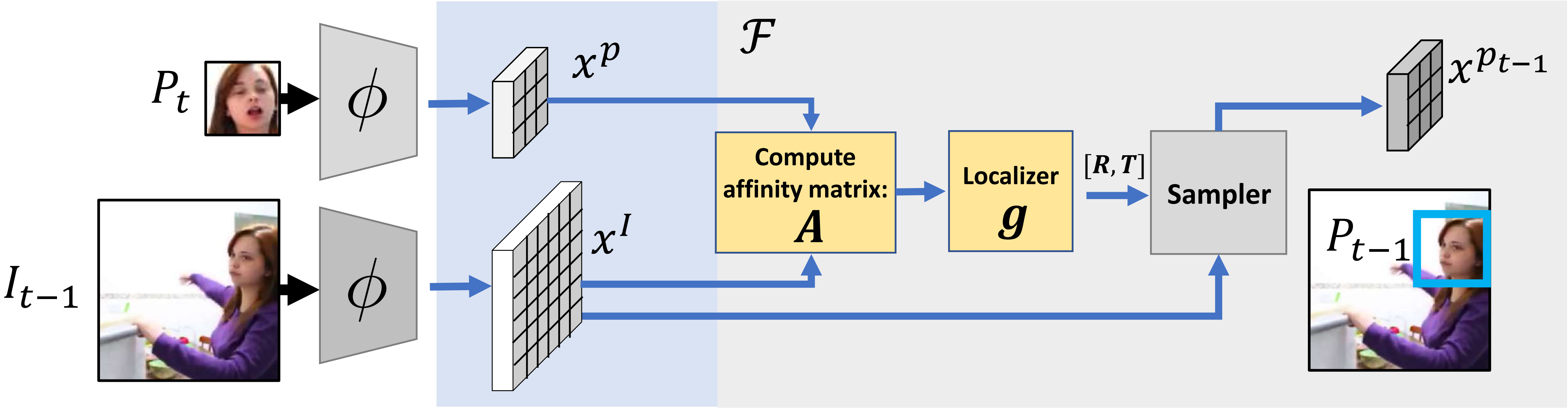
Skip-cycles: skipping occlusions

Wang and Efros, Learning Correspondence from the Cycle-consistency of Time, CVPR 2019

Self-Supervision in Videos: Learning correspondence

Differentiable tracker: densely match features in learned feature space

$$A(j,i) = \frac{\exp\left(x^I(j)^\intercal x^p(i)\right)}{\sum_j \exp\left(x^I(j)^\intercal x^p(i)\right)}$$



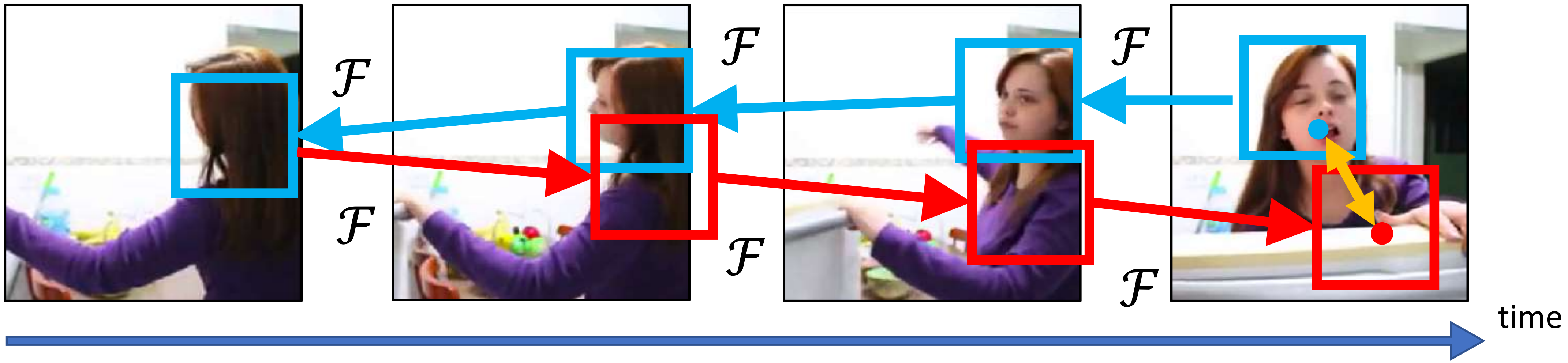
Wang and Efros, Learning Correspondence from the Cycle-consistency of Time, CVPR 2019

Self-Supervision in Videos: Learning correspondence

Ultimate goal: Correspondence, without using off-the-shelf tracking methods

How to obtain supervision?

Supervision: Cycle-Consistency in Time



Track backwards in time

Track forwards, back to the future

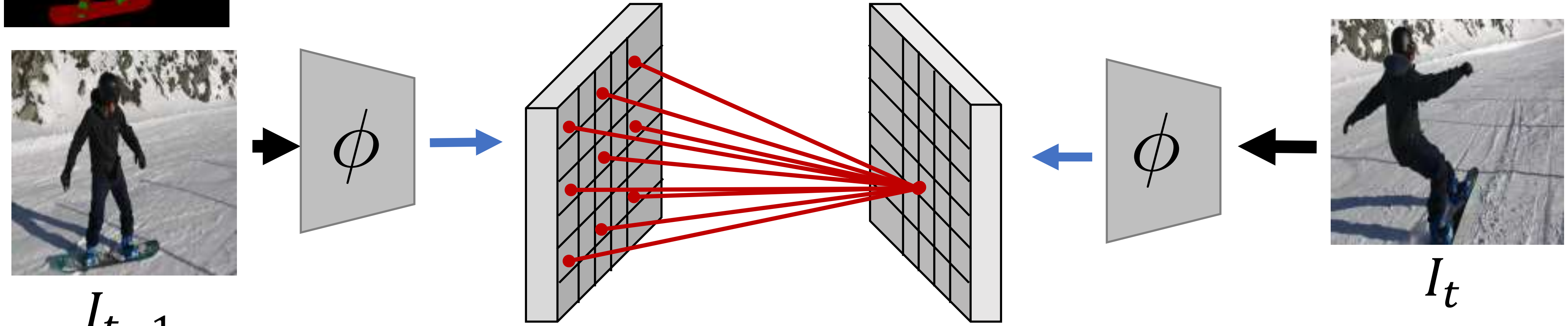
Wang and Efros, Learning Correspondence from the Cycle-consistency of Time, CVPR 2019

Self-Supervision in Videos: Learning correspondence

Test time: compute features to each frame, compute features affinity, propagate information using the affinities

$$y_i = \sum_j A_{t-1,t}(j,i) y_j ,$$

Label for pixel i in I_t



I_{t-1}

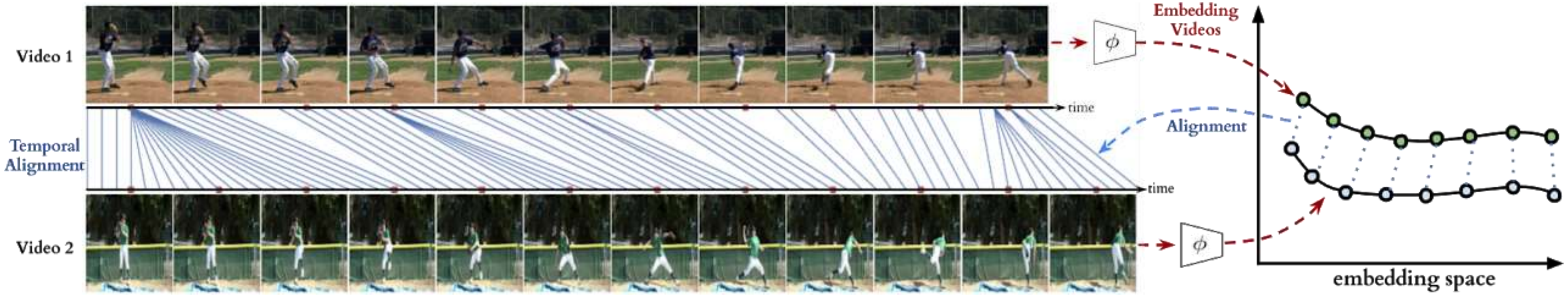
I_t

Wang and Efros, Learning Correspondence from the Cycle-consistency of Time, CVPR 2019

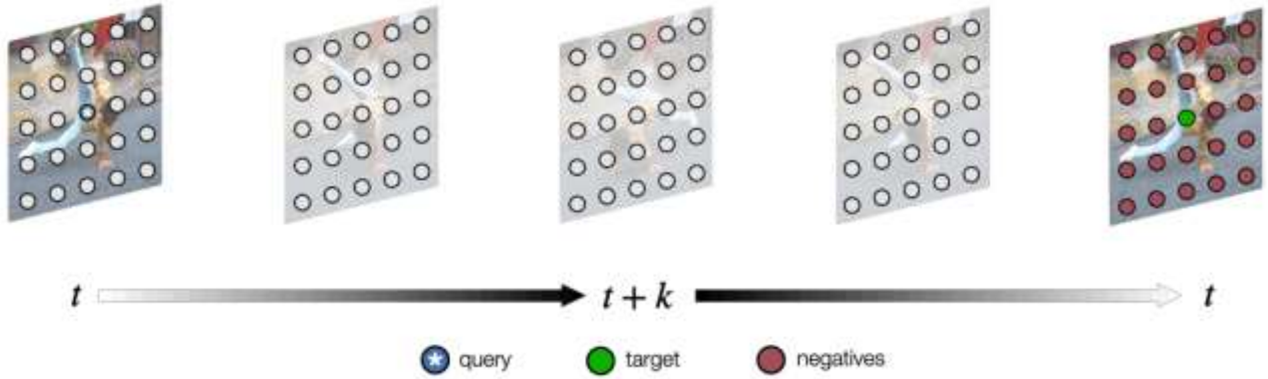
Self-Supervision in Videos: Learning correspondence

Wang and Efros, Learning Correspondence from the Cycle-consistency of Time, CVPR 2019

Self-Supervision in Videos: Temporal cycle consistency



Dwibed et. al. Temporal Cycle-Consistency Learning, CVPR'19



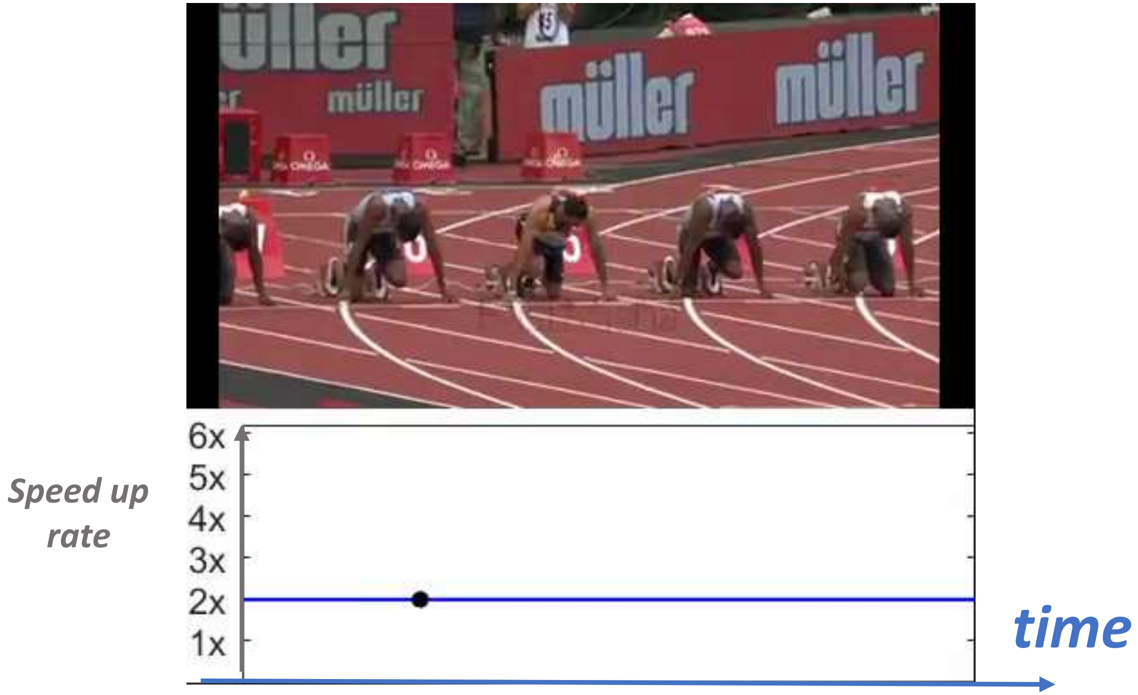
Jabri et. al, Space time correspondence as Contrastive Random Walk, NeurIPS 2020

WAIC

Self-Supervision in Videos: Learning the Speediness in Videos

Ultimate goal: Watch video content faster by adaptively speeding up the video

Uniform Speed Up (2x)



Jittery, unnatural motions

Adaptive Speed Up (2x)

Same duration, more natural

Joint work with: Sagie Benaim, Ariel Ephrat, Oran Lang, Inbar Mosseri, Bill Freeman, Miki Rubinstein and Michal Irani, CVPR 2020

“Speediness” in Videos

Slower

Normal speed

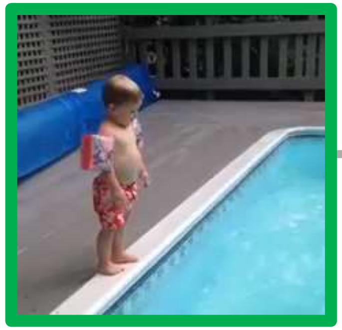
Faster

Joint work with: Sagie Benaim, Ariel Ephrat, Oran Lang, Inbar Mosseri, Bill Freeman, Miki Rubinstein and Michal Irani, CVPR 2020

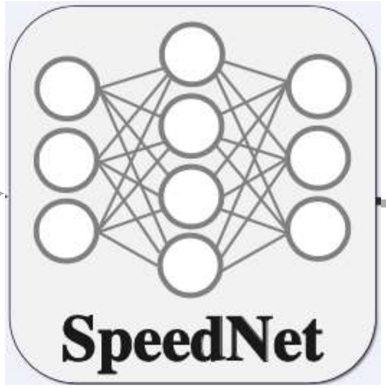
Self-Supervision in Videos: Learning the Speediness in Videos

Pretext task: Predict if a given video segment is sped up or not
Training data: sped up video segments + original video segments

Self supervised
training on Kinetics



Input segment
(30 frames)

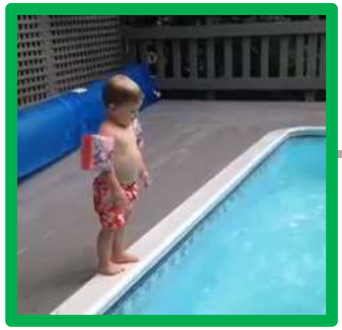


Normal speed
or
Sped Up

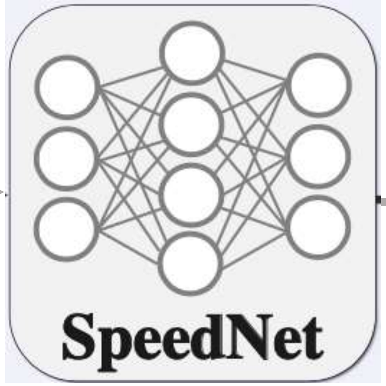
Self-Supervision in Videos: Learning the Speediness in Videos

Pretext task: Predict if a given video segment is sped up or not
Training data: sped up video segments + original video segments

Self supervised training on Kinetics



Input segment (30 frames)



Normal speed

or

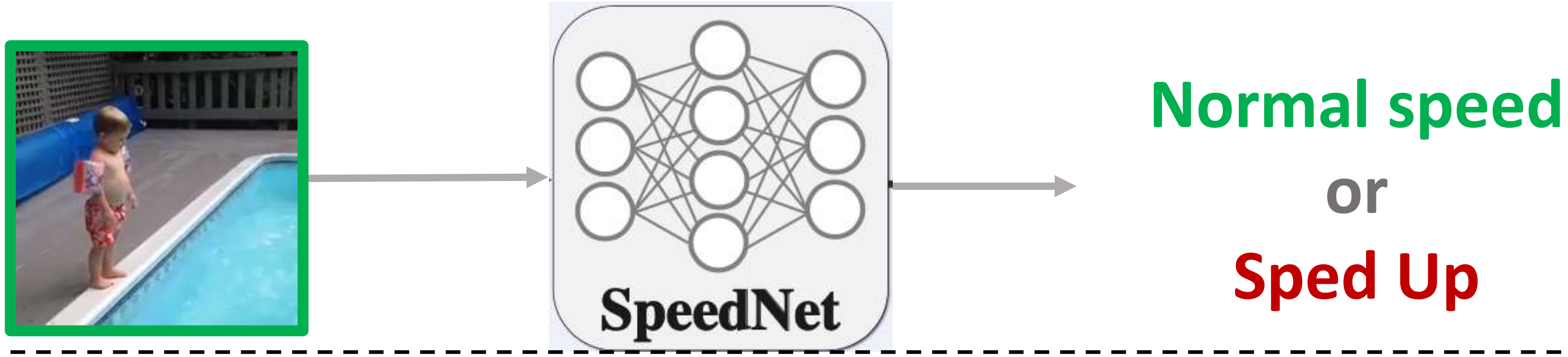
Sped Up

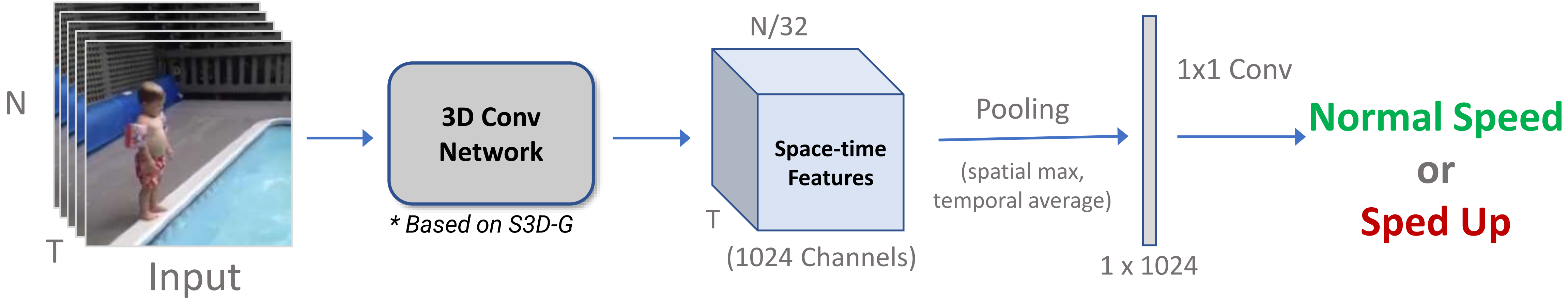
Learning properties of natural motion, avoid "easy cheats" → **very challenging!**

Self-Supervision in Videos: Learning the Speediness in Videos

Pretext task: Predict if a given video segment is sped up or not
Training data: sped up video segments + original video segments

Self supervised
training on Kinetics

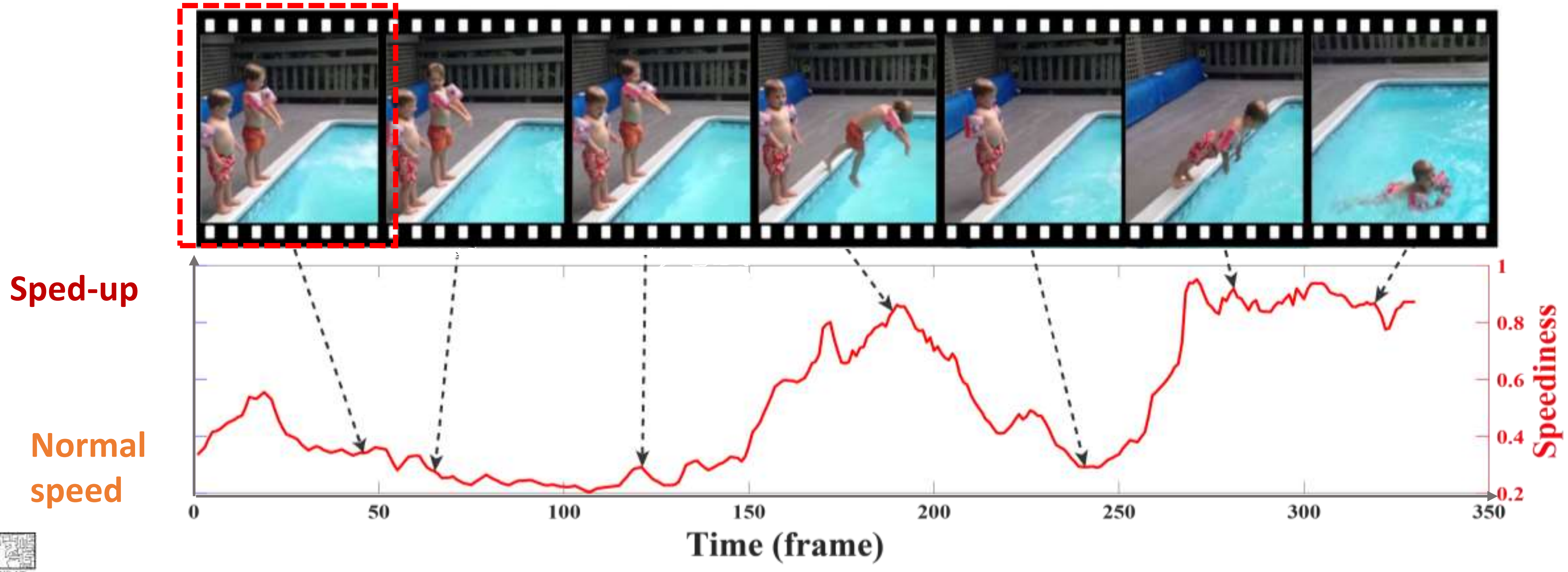




* *"Rethinking spatiotemporal feature learning: Speed-accuracy trade-offs in video classification"*, Saining Xie, Chen Sun, Jonathan Huang, Zhuowen Tu, and Kevin Murphy, ECCV'18.

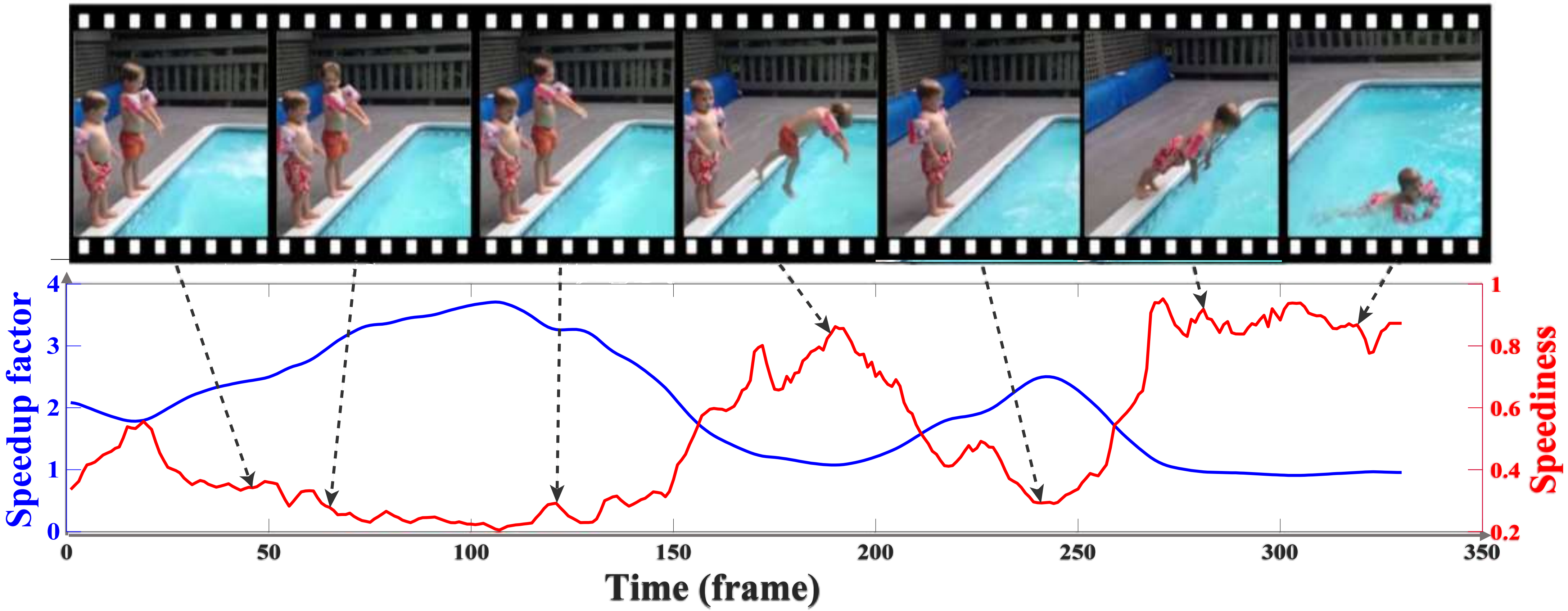
Self-Supervision in Videos: Learning the Speediness in Videos

Inference: sliding window → prediction for every frame

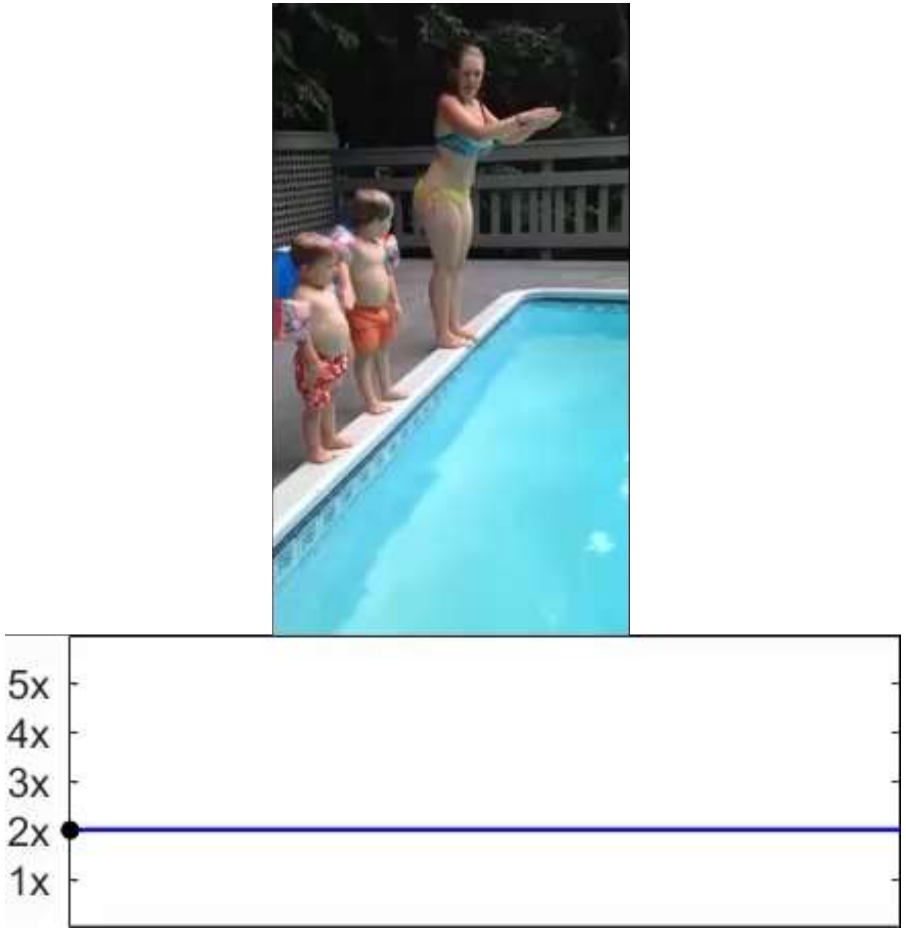


Self-Supervision in Videos: Learning the Speediness in Videos

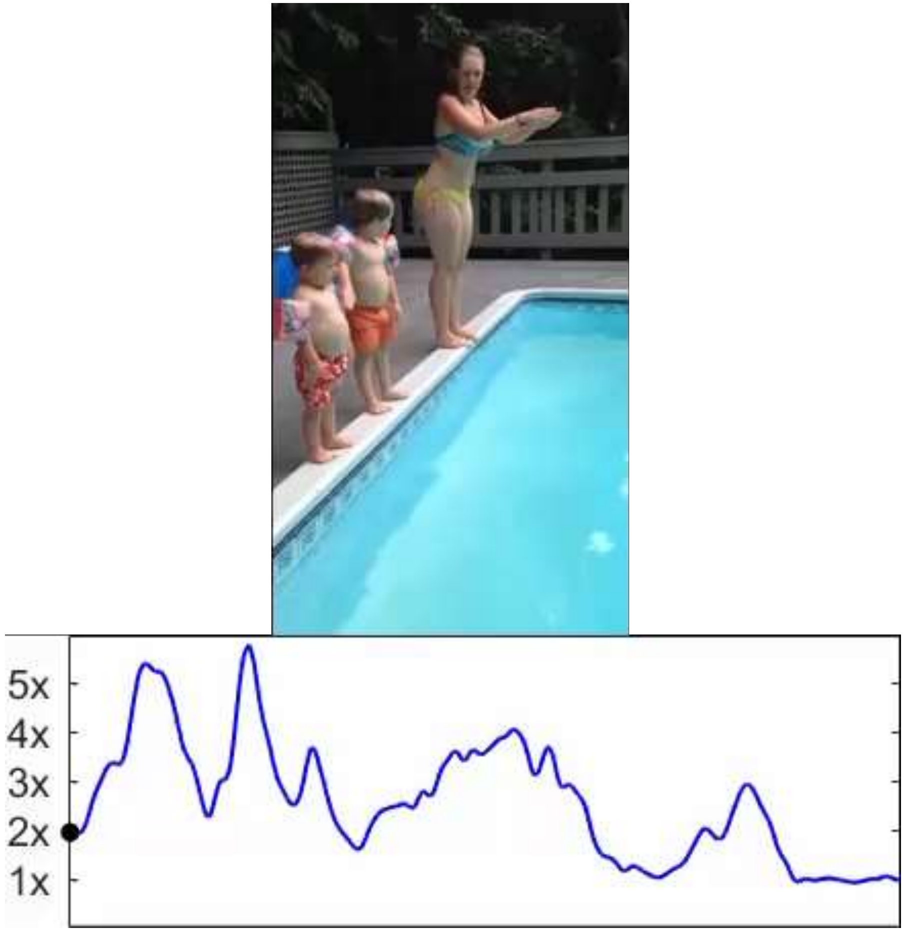
From "Speediness" to Speedup factor:
Low speediness → speedup more
High speediness→ speedup less



Learning the Speediness in Videos: Adaptive Video Speedup

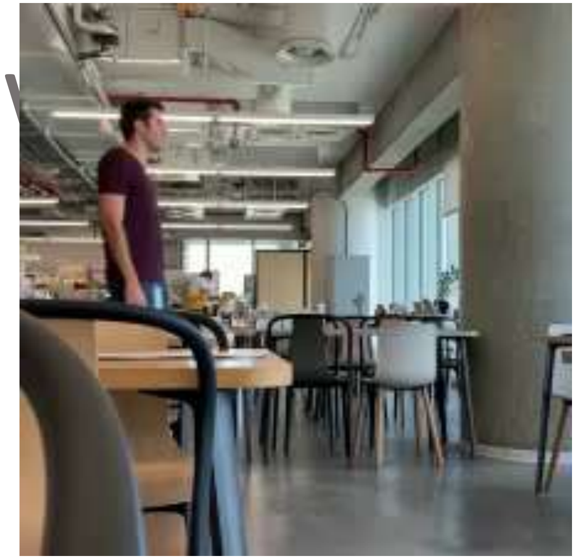


Uniform Speedup 2x



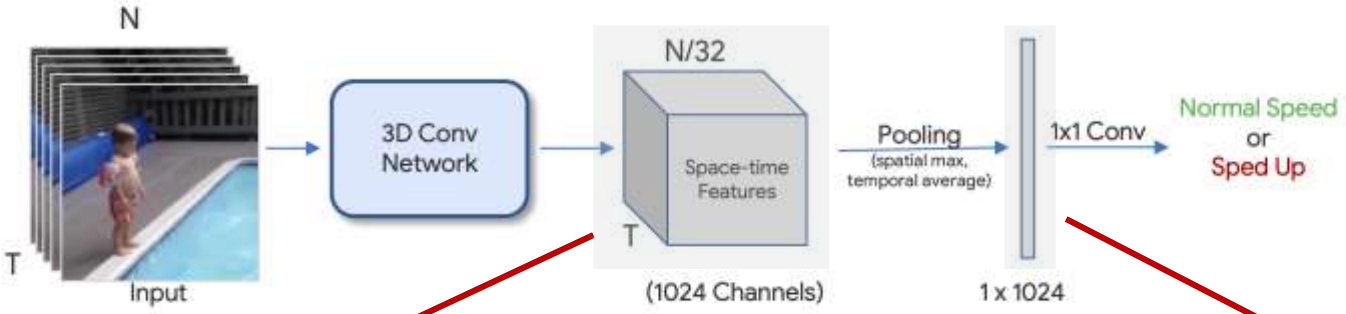
Adaptive Speedup 2x (ours)

Speediness ≠ Magnitude of Optical Flo



Learning the Speediness in Videos: Transfer Learning

Pre-trained SpeedNet

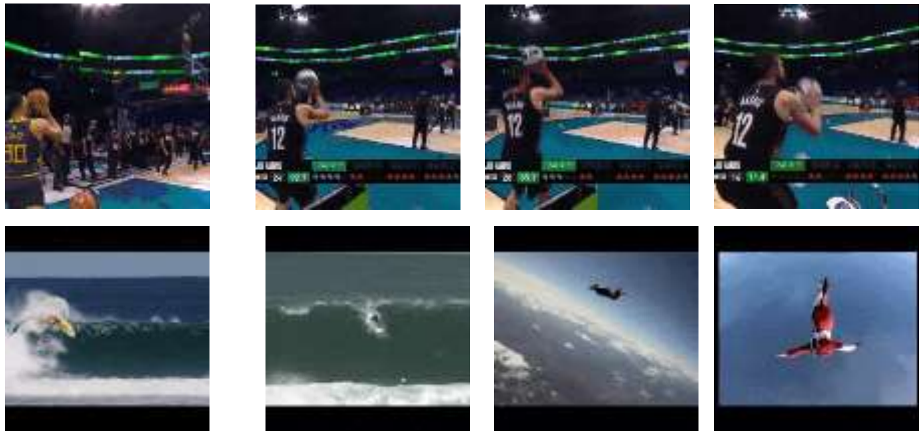


Self Supervised Action Recognition

	Initialization	Supervised accuracy	
Method	**Architecture**	**UCF101**	**HMDB51**
Random init	S3D-G	73.8	46.4
ImageNet inflated	S3D-G	86.6	57.7
Kinetics supervised	S3D-G	96.8	74.5
CubicPuzzle [19]	3D-ResNet18	65.8	33.7
Order [40]	R(2+1)D	72.4	30.9
DPC [13]	3D-ResNet34	75.7	35.7
AoT [38]	T-CAM	79.4	-
SpeedNet (Ours)	S3D-G	**81.1**	**48.8**

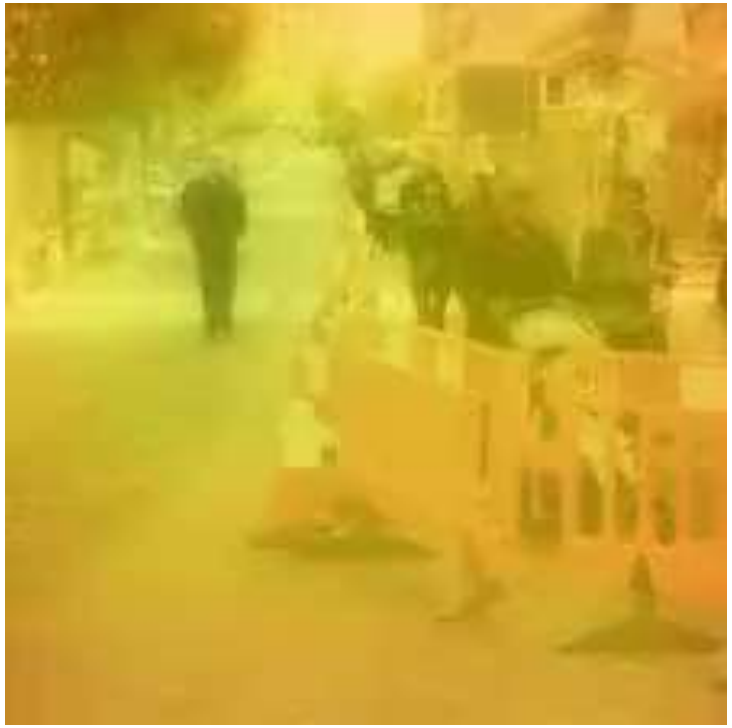
Video Retrieval

Query | Retrieved top-3 results



Learning the Speediness in Videos: CAM visualizations

"Memory Eleven"
artistic video by Bill Newsinge



Our space-time
speediness visualization

blue/green =
normal speed

yellow/orange =
slowed down

https://www.youtube.com/watch?v=djylS0Wi_Io

Next tutorial:

“Deep Learning Practitioner's Toolbox”

Next class:

” Computer Graphics and Rendering”