

Long-Short Temporal Contrastive Learning of Video Transformers

Jue Wang¹

¹Facebook AI Research

Gedas Bertasius²

²UNC Chapel Hill

Du Tran¹

Lorenzo Torresani^{1,3}

³Dartmouth

Abstract

Video transformers have recently emerged as a competitive alternative to 3D CNNs for video understanding. However, due to their large number of parameters and reduced inductive biases, these models require supervised pretraining on large-scale image datasets to achieve top performance. In this paper, we empirically demonstrate that self-supervised pretraining of video transformers on video-only datasets can lead to action recognition results that are on par or better than those obtained with supervised pretraining on large-scale image datasets, even massive ones such as ImageNet-21K. Since transformer-based models are effective at capturing dependencies over extended temporal spans, we propose a simple learning procedure that forces the model to match a long-term view to a short-term view of the same video. Our approach, named Long-Short Temporal Contrastive Learning (LSTCL), enables video transformers to learn an effective clip-level representation by predicting temporal context captured from a longer temporal extent. To demonstrate the generality of our findings, we implement and validate our approach under three different self-supervised contrastive learning frameworks (MoCo v3, BYOL, SimSiam) using two distinct video-transformer architectures, including an improved variant of the Swin Transformer augmented with space-time attention. We conduct a thorough ablation study and show that LSTCL achieves competitive performance on multiple video benchmarks and represents a convincing alternative to supervised image-based pretraining.

1. Introduction

Since the introduction of AlexNet [36], deep convolutional neural networks (CNNs) have emerged as the prominent model in numerous computer vision tasks [21, 22, 30, 55, 65, 66]. More recently, the Transformer model [62] has received much attention due to its impressive performance in the field of natural language processing (NLP) [15]. While CNNs rely on the local operation of convolution, the building block of transformers is self-attention [62] which is particularly effective at modelling long-range de-

pendencies. In the image domain, the Vision Transformer (ViT) [16] was proposed as a convolution-free architecture which uses self-attention between non-overlapping patches in all layers of the model. ViT was shown to be competitive with state-of-the-art CNNs on the task of image categorization. In the last few months, several adaptations of ViT to video have been proposed [3, 6, 45]. In order to capture salient temporal information from the video, these works typically extend the self-attention mechanism to operate along the time axis in addition to within each frame. Since video transformers have a larger numbers of parameters and fewer inductive biases compared to CNNs, they typically require large-scale pretraining on supervised image datasets, such as ImageNet-21K [53] or JFT [3], in order to achieve top performance.

Self-supervised learning has been shown to be an effective solution to eliminate the need for large-scale supervised pretraining of transformers both in NLP [15] as well as in image-analysis [9, 60]. In this work, we show that, even in the video domain, self-supervised learning provides an effective way for pretraining video transformers. Specifically, we introduce Long-Short Temporal Contrastive Learning (LSTCL), a contrastive formulation that maximizes representation similarity between a long video clip (say, 8 seconds long) and a much shorter clip (say, 2 seconds long) where both clips are sampled from the same video. We argue that by training the short-clip representation to match the long-clip representation, the model is forced to extrapolate from a short extent the contextual information exhibited in the longer temporal span. As the long clip includes temporal segments not included in the short clip, this self-supervised strategy trains the model to anticipate the future and to predict the past from a small temporal window in order to match the representation extracted from the long clip. We believe that this is a good pretext for video representation learning, as it can be accomplished only by a successful understanding and recognition of the structure and correlation of atomic actions in a long video. Furthermore, such framework is particularly suitable for video transformers as they have been recently shown to effectively capture long-term temporal cues [6]. In this work we demonstrate that these long-term temporal cues can be effectively encoded

into a short-range clip-level representation leading to a substantial improvement in video classification performance.

To demonstrate the generality of our findings, we experiment with two different video transformer architectures whose code is publicly available. The first is TimeSformer [6], which reduces the computational cost of self-attention over the 3D video volume by means of a space-time factorization. The second architecture is the Swin transformer [39], which we further extend into a 3D version, dubbed Space-Time Swin transformer, that computes hierarchical spatiotemporal self-attention by using 3D shifting windows. We show that our unsupervised LSTCL pre-training scheme allows both of these video transformers to outperform their respective counterparts pretrained with full supervision on the large-scale ImageNet-21K dataset.

In summary, the contributions of this paper can be summarized as follows:

- We introduce Long-Short Temporal Contrastive Learning (LSTCL), which enables encoding temporal context from the longer video into a short-range clip representation.
- We demonstrate that for recent video transformer models, our proposed LSTCL pretraining provides an effective alternative to large-scale supervised pretraining on images.
- We propose a Space-Time Swin transformer for spatiotemporal feature learning, and show that it achieves strong results on multiple action recognition benchmarks.

2. Related work

Self-supervised Learning in Images. Early attempts at self-supervised visual representation learning used a variety of pretext tasks, such as image rotation prediction [35], auto-encoder learning [49, 56, 63], or solving jigsaw puzzles [46]. In comparison, recent approaches in self-supervised learning leverage contrastive learning [9, 11, 12, 14, 28, 29, 52]. The idea is to generate two views of the same image through data augmentation and then minimize the distance of their representations while, optionally, maximizing the distance to other images [11, 29]. One disadvantage of contrastive learning is that it requires a large number of negative examples, which implies a large batch size [11] or the use of a memory bank [29]. To tackle the high computational cost of such contrastive approaches, several recent methods proposed to eliminate the reliance on negative samples [8, 13, 14, 26].

Self-supervised Learning in Videos. Several methods for self-supervised video representation learning focused on predictive spatiotemporal ordering tasks [1, 23, 31, 33, 38, 44, 58, 59, 69, 71, 72]. Other approaches have leveraged temporal cues such as tempo and speed to define self-supervised pretext tasks [5, 67]. Just like in the image domain, more recent approaches [20, 27, 51] adopt contrastive learning objectives. Our method also falls into the category of contrastive approaches. In comparison to prior con-

trastive video methods, we propose a contrastive formulation where a positive pair is generated from a short clip and a long clip, both of which are sampled from the same video. This pushes our model to learn a short clip-level representation that captures global video-level context.

The approach that is most closely related to our own is the BraVe system [52]. BraVe shares the same underlying idea of training a model to match a long (broad) view to a short (narrow) view of the same video. However, our work differs in several aspects. First of all, our main focus is to leverage self-supervised learning as a means to train video transformers without labeled image data, while BraVe is applied to 3D CNNs. Video transformers are emerging as a competitive alternative to 3D CNNs. However, as discussed earlier, they suffer from the limitation of requiring image-based supervised pretraining. Thus, we believe that this is an important and timely problem to address. Additionally, we note that our LSTCL is a lot simpler than BraVe: while our model uses shared parameters, a single projection network, and a single prediction network, BraVe requires separate backbones, separate projection networks, and separate prediction networks for the two views in order to achieve the best performance; furthermore, while LSTCL can be applied with any traditional contrastive loss (as demonstrated by our experiments with MoCo v3, BYOL, and SimSiam), BraVe uses a combination of two specific regression objectives (broad-to-narrow and narrow-to-broad) and employs distinct augmentation strategies for the two views. Despite the bare-bone simplicity of our learning formulation, we demonstrate that it delivers impressive results, elevating the accuracy of video transformers to the state-of-the-art on challenging action classification benchmarks *without* the need of any supervised image-level pretraining.

Transformers in Vision. Transformer-based models [15, 62] currently define the state-of-the-art for the majority of natural language processing (NLP) tasks. Similarly, there have also been several attempts to adopt transformer-based architectures for vision problems. Initially, these attempts focused on architectures mixing convolution with self-attention [7, 32, 68, 70, 73]. The recent introduction of Vision Transformer (ViT) [16] has demonstrated that it is possible to achieve competitive image classification results with a convolution-free architecture. To increase the data-efficiency aspect of the original ViT, Touvron et al. [60] proposed a training recipe based on distillation. Lastly, the recently introduced Swin transformer [39] significantly reduces the number of parameters and the cost of ViT by employing local rather than global self-attention.

ViT models were also adapted to the video domain by introducing different forms of spatiotemporal self-attention [2, 3, 6, 50]. However, due to their large number of parameters, these models typically require large amounts of training data, which typically comes in the form of a large

scale labeled dataset (such as ImageNet or JFT). To address this issue, Fan et al. [17] introduced a multi-scale vision transformer (MViT), which uses a much smaller number of parameters and can be successfully trained from scratch. Instead of reducing the model capacity, as done in MViT, we show that it is possible to train large-capacity video transformer models without any external data by means of our proposed LSTCL self-supervised learning framework.

3. Video Transformers

Several recent attempts have been made to extend ViT to the video domain [2, 3, 6, 17, 50]. Most video transformers share common principles, which we review below. We then discuss specific designs differentiating the video transformers considered in our experiments.

3.1. Overview

Linear and positional embeddings. Each patch $\mathbf{p}_{(i,t)}$ is linearly embedded into a feature vector $\mathbf{z}_{(i,t)}^0 \in \mathbb{R}^D$ obtained by means of a learnable matrix $W \in \mathbb{R}^{D \times (P^2 \cdot C)}$ and a learnable vector $e_{(i,t)} \in \mathbb{R}^D$ representing the spatial-temporal positional embedding: $\mathbf{z}_{(i,t)}^0 = W\mathbf{p}_{(i,t)} + e_{(i,t)}$.

Multi-headed attention. The multi-headed self-attention (MHA) is the key component of the transformer. It implements the query-key-value computation for each patch, and it is interleaved with layer normalization [4] (LN) and a multilayer perceptron (MLP) within each block ℓ . Thus, the intermediate representation \mathbf{z}^ℓ for a patch in block ℓ is obtained from its features in the previous block, as:

$$\tilde{\mathbf{z}}^\ell = \text{MHA}(\text{LN}(\mathbf{z}^{\ell-1})) + \mathbf{z}^{\ell-1} \quad (1)$$

$$\mathbf{z}^\ell = \text{MLP}(\text{LN}(\tilde{\mathbf{z}}^\ell)) + \tilde{\mathbf{z}}^\ell. \quad (2)$$

Classification. As in BERT [15], a classification token $\mathbf{p}_{(0,0)}$ is added at the beginning of the input sequence. In the last layer of the network, a linear layer with softmax activation function is attached to the classification token in order to output the final classification probabilities.

3.2. TimeSformer

TimeSformer [6] extends ViT [16] to the video domain. It uses two independent multi-head attention blocks for spatial and temporal self-attention. As shown in Figure 1, the spatial self-attention compares the query patch only to image patches appearing in the same frame. Conversely, the temporal self-attention compares the query patch to the image patches in the same spatial location but from the other frames. The decomposition over space and time dramatically reduces the cost of self-attention compared to a dense comparison over all pairs of patches of the video. Thus, the feature representation is computed as:

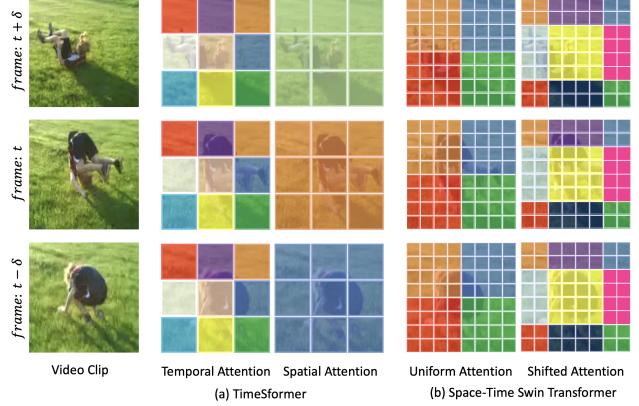


Figure 1. An illustration of the self-attention mechanisms in TimeSformer [6] and Space-Time (ST) Swin Transformer. Each column in the figure depicts a different self-attention block. Patches that have the same color are compared during the self-attention computation.

$$\begin{aligned} \mathbf{z}_t^\ell &= \text{MHA}_{\text{Time}}(\text{LN}(\mathbf{z}^{\ell-1})) + \mathbf{z}^{\ell-1} \\ \mathbf{z}_s^\ell &= \text{MHA}_{\text{Space}}(\text{LN}(\mathbf{z}_t^\ell)) + \mathbf{z}_t^\ell \\ \mathbf{z}^\ell &= \text{MLP}(\text{LN}(\mathbf{z}_s^\ell)) + \mathbf{z}_s^\ell \end{aligned} \quad (3)$$

3.3. Space-Time Swin Transformer

Compared to ViT, the Swin Transformer [39] applies self-attention locally. The features are learned hierarchically by aggregating information from local neighborhoods of patches in each layer. Here we adapt the original Swin transformer, which was introduced for still-images, to video. We name this new variant Space-Time Swin Transformer (ST Swin). Instead of considering 2D neighborhoods of image patches for self-attention computation, ST Swin uses local 3D space-time volumes. Specifically, as proposed in the original paper [39], ST Swin uses two distinct self-attention mechanisms: uniform partition and shifted partition. In our case, both of these self-attention schemes are adapted to video by considering the temporal dimension in the local patch neighborhoods. As shown in Figure 1, the uniform partition splits the entire clip into 4 non-overlapping 3D sections, with each section sharing the same partition index. Spatiotemporal self-attention is then computed between image patches that have the same partition index. Similarly, shifted partition generates multiple non-overlapping 3D sections at different scales, and spatiotemporal patches within each section are compared for self-attention computation. The uniform partition and the shifted partition are stacked to form two successive attention blocks, which implement cross-window connections

further increasing the model capacity. Thus, the complete transformation carried out in each layer ℓ of the ST Swin transformer can be summarized as follows::

$$\begin{aligned}\mathbf{z}_u^\ell &= \text{MHA}_{\text{Uniform}}(\text{LN}(\mathbf{z}^{\ell-1})) + \mathbf{z}^{\ell-1} \\ \mathbf{z}^\ell &= \text{MLP}(\text{LN}(\mathbf{z}_u^\ell)) + \mathbf{z}_u^\ell \\ \mathbf{z}_s^{\ell+1} &= \text{MHA}_{\text{Shift}}(\text{LN}(\mathbf{z}^\ell)) + \mathbf{z}^\ell \\ \mathbf{z}_s^{\ell+1} &= \text{MLP}(\text{LN}(\mathbf{z}_s^{\ell+1})) + \mathbf{z}_s^{\ell+1}\end{aligned}\quad (4)$$

We adopt the 3D relative positional embedding and the patch merging strategy used in Swin [39]. However, we only merge image patches along the spatial axis while maintaining fixed temporal resolution through the layers.

4. Long-Short Temporal Contrastive Learning

Overview. Video transformers have been shown to be particularly effective at long-range temporal modeling [6]. Our aim is to design a contrastive learning framework that exploits this characteristic. Our proposed Long-Short Temporal Contrastive Learning (LSTCL) framework takes as input a pair of clips sampled from the same video—a long clip and a short clip. The procedure trains the video transformer to match the representation of the short clip to the representation of the long clip. This forces the model to predict the future and the past from a small temporal window, which is beneficial for capturing the general structure of the video. Below we describe specific details related to our LSTCL.

Given a batch B of *unlabeled* training videos, we randomly sample a short clip and a long clip from each of them. While both the long and the short clip include a total of T frames, we use largely different sampling temporal strides τ_S and τ_L with $\tau_S < \tau_L$ in order for the long clip to cover a much longer temporal extent than the short clip. The sets of short and long clips in the batch B are denoted as $X_S = \{x_S^1, x_S^2, \dots, x_S^B\}$ and $X_L = \{x_L^1, x_L^2, \dots, x_L^B\}$, respectively, where x_S^i and x_L^i represent the short clip and the long clip sampled from the i -th example in the batch. The set of short clips is processed by an encoder f_q to yield a set of “query” examples $Q = \{q^1, q^2, \dots, q^B\}$ where $q^i = f_q(x_S^i) \in \mathbb{R}^D$. The set of long clips is processed by a separate encoder f_k to produce “key” examples $K = \{k^1, k^2, \dots, k^B\}$. We optimize the encoders to yield similar query-key representations for pairs consisting of a long clip and a short clip taken from the same video, and dissimilar representations for cases where the long clip and the short clip are sampled from different videos. This is achieved by adopting an InfoNCE [47] loss on the sets Q and K :

$$\mathcal{L}_{\text{NCE}} = \sum_i -\log \frac{\exp(q^i \top k^i / \rho)}{\exp(q^i \top k^i / \rho) + \sum_{j \neq i} \exp(q^i \top k^j / \rho)} \quad (5)$$

where ρ is a temperature hyperparameter that controls the sharpness of the output distribution. As commonly

done [8, 13, 14, 26], we symmetrize the loss function. In our case this is achieved by adding to the loss term above a dual term obtained by reversing the role of the long and the short clips, i.e., by computing queries from long clips $q^i = f_q(x_L^i)$ and keys from short clips $k^i = f_k(x_S^i)$. The encoder f_q consists of a video transformer backbone, a MLP projection head and an additional prediction MLP head. The purpose of the prediction layer is to transform the representation of the query clip to match the key. The encoder f_k consists of a video transformer backbone and a MLP projection head. Our experiments present results obtained with different contrastive learning optimizations to update the parameters of f_q and f_k . In the case of our default optimization based on MoCo v3 [14], the parameters of f_q are updated by minimizing \mathcal{L}_{NCE} via backpropagation, while the parameters of f_k are updated as a moving average of the parameters of f_q . We refer the reader to our supplementary materials for details of the optimizations based on the other contrastive learning frameworks considered in our experiments—BYOL and SimSiam.

Clip Sampling Strategy. Since we want our model to be able to extrapolate the context observed in the entire video from the brief extent of the short clip, we propose to sample the long and the short clip *at random* and *independently* from each video. By doing so, the learning cannot leverage any synchrony between the two clips and because the temporal offset will be random for every pair of long-short samples, the optimization will force the short clip representation to encode as much as possible of the context exhibited over the entire video. To demonstrate the value of random independent sampling, in our ablation study we contrast this strategy (named “Random Independent”) to two alternative schemes. The first, named “Random Included,” consists in sampling the short clip at random but so as to fall completely within the temporal extent spanned by the long clip (which is sampled first at random). The second, named “Random Disjoint,” samples the two clips at random but it enforces the constraint that they cannot overlap at all, i.e., they are completely disjoint. We refer the reader to our experiments which validate our hypothesis that random independent sampling is indeed the superior strategy for long-short temporal contrastive learning of video transformers.

Implementation Details. We implement LSTCL under three different and popular contrastive learning frameworks: BYOL [26], MoCo v3 [14], and SimSiam [13]. For training we adopt the video data augmentations described in [20] using clips of size $224 \times 224 \times 8$ sampled from the video. We experiment with two video transformer architectures: TimeSformer with Divided Space-Time attention [6] and our adaptation of the Swin-B model [39] to video (Space-Time Swin). We use the AdamW [43] optimizer, which is commonly used for training vision transformer models [2, 3, 6, 9, 14, 16, 60]. In our default set-up, we train

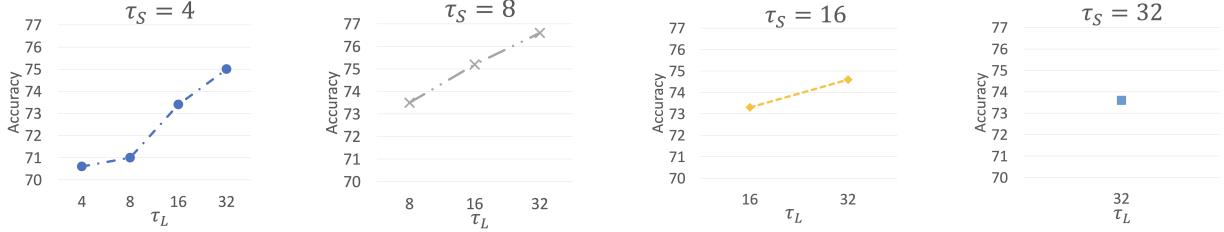


Figure 2. We study how the temporal extents of the short and the long view (controlled by τ_S and τ_L) in LSTCL affect the video-level accuracy on Kinetics-400. We can see that, for each choice of τ_S , accuracy monotonically increases as the long stride τ_L is made larger. The best result is obtained for $\tau_S = 8$ and $\tau_L = 32$, corresponding to a long view that is 4 times longer than the short view.

LSTCL for 200 epochs on the 240K videos of Kinetics-400 [34] using linear warm-up [24] during the first 40 epochs. We apply a cosine decay schedule [42] after the warm-up and the learning rate is set to $lr \times BatchSize / 256$. We adopt the base learning rate and weight decay from [14]. Our experiments are run on 64 V100 GPUs with a distributed training set-up in Pytorch [48]. The training of 200 epochs takes about three days.

5. Experiments

We evaluate our proposed LSTCL on several action recognition benchmarks: Kinetics-400 [34], Kinetics-600 [10], Something-Something-V2 [25] (SSv2), HMDB [37], and UCF101 [57]. Our experimental setup is as follows. First, we perform self-supervised LSTCL pretraining on Kinetics-400 with clips of $T = 8$ frames but using *distinct* temporal sampling strides for the short view and the long view, so that the two views effectively span temporal extents of different lengths in seconds. Afterwards, we finetune the LSTCL-pretrained model for 200 epochs in a fully supervised fashion on each of these three datasets. During inference, we sample uniformly 5 clip with center cropping from each video and average the sample-level predictions to perform video-level classification. In the following ablation studies, unless otherwise noted, we adopt TimeSformer as the backbone in our LSTCL with an input clip of size $8 \times 224 \times 224$.

5.1. Ablation Studies

Importance of the Temporal Extent. We first ablate the choice of τ_S and τ_L for self-supervised training, while keeping the finetuning temporal stride fixed to the value $\tau = 8$ (i.e., sampling a frame every 8 from the video starting from a random frame). Figure 2 shows how different combinations of τ_S and τ_L affect the final video-level accuracy on Kinetics-400. For ease of interpretation we split the visualization of results over 4 distinct plots, representing 4 different values of τ_S : $\tau_S \in \{4, 8, 16, 32\}$. Each plot shows how the final video-level accuracy varies for different temporal stride values τ_L of the long clip where $\tau_L \geq \tau_S$ and τ_S is

τ_S	τ_L	Accuracy
4	{8,16,32}	73.9
{4,8,16}	32	74.8
8	{8, 16, 32}	75.5
{8,16,32}	32	75.9
{4,8,16,32}	{4,8,16,32}	75.6
{8,16,32}	{8,16,32}	76.0
8	32	76.6

Table 1. We analyze the potential benefits of randomly sampling either τ_S and/or τ_L (for the short and the long clips, respectively). Accuracy is measured for video-level classification on Kinetics-400 after pretraining with our LSTCL system using MoCo v3. The best result is still achieved for fixed values of $\tau_S = 8$ and $\tau_L = 32$.

kept fixed. There are two important observations we can make from these results. The first is that, for each choice of τ_S , the larger the gap between the two strides (i.e., the larger the value of $\tau_L - \tau_S$), the higher is the accuracy. This can be seen in the first three plots where the accuracy curve monotonically increases as τ_L is made larger starting from the initial value of $\tau_L = \tau_S$. This validates the importance of contrasting views of different temporal lengths during self-supervised pretraining. The second observation is that our model performs best when $\tau_S = 8$ and $\tau_L = 32$. This result makes intuitive sense as a short clip sampled with $\tau_S = 8$ is temporally long enough to allow to predict the context of the long clip; at the same time it is short enough to allow the method to use a long view that is significantly longer (up to 4 times longer than the short view). Conversely, choosing a larger value of τ_S (i.e., 16 or 32) reduces the maximum possible gap $\tau_L - \tau_S$ between the two views, while choosing a smaller value of τ_S (i.e., 4) would cause the contrastive learning between the two views to be overly difficult due to the excessive brevity of the short clip.

In Table 1, we include additional performance points corresponding to settings where τ_S and/or τ_L are sampled randomly for each training video clip. Specifically, the first row in the table shows the performance of our system when $\tau_S = 4$ and τ_L is sampled randomly from $\{8, 16, 32\}$; the second row represents the opposite setting where τ_L is kept fixed ($\tau_L = 32$) and τ_S is randomly sampled from

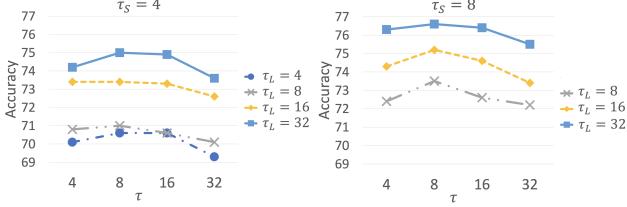


Figure 3. The plots show video-level accuracy on Kinetics-400 for different values of the temporal sampling stride τ used for supervised finetuning and test-time inference.

$\{4, 8, 16\}$; the setting in the third row is similar to that of the first row but with $\tau_S = 8$; the fourth row shows the same setting as the second row but excludes $\tau_S = 4$; the fifth and the sixth rows show configurations where both temporal strides are randomly chosen for each training video clip, subject to $\tau_S \leq \tau_L$. As before, we keep the finetuning temporal stride fixed to the value $\tau = 8$. The results in Table 1 clearly show that adding randomness in the choice of the temporal extents for the long and short clips does not produce improved performance. The best performance is still achieved when $\tau_S = 8$ and $\tau_L = 32$ (shown in the last row). Thus, we adopt this setup for all subsequent experiments.

Now we turn to study the impact of the *finetuning* stride τ on video-level accuracy. The two plots in Figure 3 show how the accuracy on Kinetics-400 varies as we change the value of τ (on the horizontal axis) for two different choices of τ_S ($\tau_S = 4$ in the left plot, and $\tau_S = 8$ in the right plot). The different curves in each plot correspond to different choices of τ_L . We see that setting the finetuning stride to $\tau = 8$ tends to produce the best results across all possible choices of τ_S and τ_L . This makes sense, since with $\tau = 8$ the 5 inference clips are short enough not to overlap so that they provide complementary information for the video-level classification. At the same time, $\tau = 8$ implies an inference clip long enough to yield good classification on its own.

Different Contrastive Learning Frameworks. Next, we investigate the effects of different contrastive learning frameworks in our LSTCL system. Specifically, we experiment with three recent approaches: BYOL, MoCo v3, and SimSiam. Figure 4 shows that a larger temporal stride τ_L for the long view leads to better accuracy for all three of these frameworks. Specifically, setting $\tau_L = 32$ leads to the following performance gains compared to the setting where $\tau_L = \tau_S = 8$: +2.6% for BYOL, +3.1% for MoCo v3, and +1.6% for SimSiam. The lower absolute performance of SimSiam can be explained by the lack of the momentum-encoder, which we observed to be important when training video transformer models with LSTCL. Thus, based on these result, for all subsequent experiments, we adopt MoCo v3 as our base learning framework.

Weight Sharing and Contrastive Loss. Here we ablate

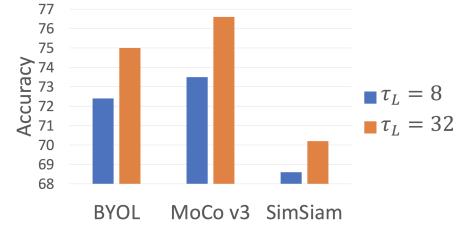


Figure 4. Kinetics-400 accuracy achieved by pretraining with LSTCL using three self-supervised strategies, with two possible stride values for the long clip ($\tau_L \in \{8, 32\}$) (stride for the short clip is fixed to $\tau_S = 8$). All three methods benefit from using views of different lengths ($\tau_L = 32$, instead of $\tau_L = \tau_S = 8$).

Loss	Shared Backbone	Accuracy	Params
InfoNCE	Yes	76.6	121.4M
InfoNCE	No	73.2	242.8M
Regression	No	70.8	242.8M

Table 2. We compare our proposed approach (first row) against the weight sharing and loss proposed in BraVe [52] by evaluating the effects on Kinetics-400.

Sampling Method	Accuracy
Random Disjoint	72.6
Random Included	76.2
Random Independent	76.6

Table 3. Comparison of different clip sampling strategies for LSTCL on Kinetics-400. In these experiments we use $\tau_S = 8$ and $\tau_L = 32$ for LSTCL and $\tau = 8$ for finetuning.

the two main differences between LSTCL and BraVe [52]. 1) BraVe has two independent backbones, projectors and predictors, which define a broad stream and a narrow stream. Instead, our LSTCL adopts online and momentum encoders with shared parameters. 2) Each stream in BraVe is specialized to process a particular type of view (either broad or narrow). Training is done by means of a combination of two regression objectives (one mapping from broad to narrow, the other mapping in the opposite direction). In LSTCL, a single encoder takes both views. Our model is optimized using a single contrastive loss, which minimizes differences between the two views.

In Table 2, we present ablation results of LSTCL with respect to differences 1) and 2) outlined above. For 1), we modify LSTCL to use distinct networks (independent backbones and projectors) for the two views, as in BraVe. 2) In addition to using separate networks, we adopt the data feeding and learning objectives from BraVe in our LSTCL. From the results, it can be seen that LSTCL (first row) achieves superior performance with only half the number of parameters compared to these two alternative setups.

Clip Sampling Strategy in LSTCL. In Table 3, we study the effect of different clip sampling strategies. These results

Model	Scratch	IN-1K	LSTCL	Params
TimeSformer [6]	60.4	75.8	76.6	121.4M
Swin	66.2	73.3	75.5	88.0M
ST Swin	71.1	76.0	79.8	88.0M

Table 4. Comparing self-supervised pretraining using LSTCL to training from scratch and supervised pretraining on ImageNet-1K (IN-1K). The results show video classification accuracy on Kinetics-400 for three video transformer architectures.

indicate that random independent sampling works best in our setting. Intuitively, this makes sense as it forces our model to extrapolate to arbitrary video views.

Video Transformers. In Table 4 we compare the performance of three distinct video transformer architectures: TimeSformer, Swin, and Space-Time (ST) Swin. We train each of these models under three different scenarios on Kinetics-400: 1) from scratch (without pretraining), 2) using supervised pretraining on the large-scale ImageNet-1K dataset, and 3) using our self-supervised LSTCL pretraining. We can see that among these three training strategies, our LSTCL pretraining provides the highest accuracy, outperforming the models that use large-scale supervised ImageNet-1K pretraining for all three architectures.

5.2. Comparison to the State-of-the-Art

For our final experiments, we adopt the Space-Time Swin transformer as it achieves the strongest results in our ablation studies. For this comparison to the state-of-the-art, we also train models using clips of $T = 16$ frames during both pretraining with LSTCL and supervised finetuning. Even in this case we set the temporal stride to $\tau_S = 4$ for short clips and $\tau_L = 16$ for long clips.

Kinetics-400 & Kinetics-600. In Table 6, we report results on Kinetics-400, listing for each method the clip size, the accuracy, the inference cost (in TFLOPs), and the number of parameters. We group methods on the basis of the input clip size, since models trained on longer clips or higher resolution frames tend to yield higher accuracy. The first two groups include models operating on clips of the same size as those used by our system (8×224^2 and 16×224^2). It can be seen that the ST Swin model pretrained with LSTCL achieves the highest accuracy among all previous methods that use the same input clip size and that do not make use of additional data. Furthermore, compared to prior video transformer models that are pretrained with full supervision on large-scaled labeled datasets (the bottom part of the table), our method still achieves competitive results and actually often yields better accuracy. Lastly, note that compared to training our ST Swin model from scratch, LSTCL pre-training leads to a significant 8.7% boost on Kinetics-400.

Table 7 shows a comparison with the state-of-the-art on the Kinetics-600 dataset. Even here we see that ST Swin pretrained with LSTCL achieves the best accuracy within the two groups of models using the same clip sizes as our

Model	Pretraining dataset	UCF101	HMDB51
BraVe [52]	K400 (Unsup.)	95.1	74.6
ρ BYOL [20]	K400 (Unsup.)	96.3	75.0
ST Swin	IN-1K (Superv.)	78.1	40.2
ST Swin	K400 (Superv.)	88.9	61.2
ST Swin w/ LSTCL	K400 (Unsup.)	96.8	75.9

Table 5. Transfer learning results on UCF101 and HMDB51. We report the performance using the full fine-tuning setting. Our method outperforms previous state-of-the-art approaches on both UCF101 and HMDB51. Furthermore, our unsupervised LSTCL pretraining scheme achieves better results than the approaches based on supervised pretraining (on IN-1K and K400).

networks. Furthermore, LSTCL produces a gain of 7.3% compared to learning from scratch.

Something-Something-V2. In Table 8 we report the performance on the Something-Something-V2 dataset. Most prior methods leverage *supervised* large-scale pre-training on external datasets in order to achieve strong performance on this benchmark, since the dataset is relatively small. The results in the table highlight that our ST Swin models pretrained *without* labels on Kinetics-400 using LSTCL achieves higher accuracy than methods that leverage pre-training on larger datasets and using manually labeled data. Moreover, our LSTCL pretraining yields a gain of 26.4% over the same model trained from scratch. This remarkable improvement is due to the fact that the Something-Something-V2 dataset requires thorough temporal reasoning for good accuracy. Our LSTCL method trains the clip representation to predict the temporal context from the entire video and thus yields strong benefits on this benchmark.

HMDB51 & UCF101. Finally, we assess the ability to transfer the unsupervised representation learned by LSTCL from Kinetics-400 to the small-scale datasets of HMDB [37] and UCF101 [57] via supervised finetuning. The results are shown in Table 5 where we include also accuracies obtained via fully-supervised pretraining (using class labels) on IN-1K and K400 and also the two recent self-supervised methods ρ BYOL [20] and BraVe [52]. It can be seen that LSTCL outperforms both (i) the previous state-of-the-art unsupervised pretraining methods, and (ii) the supervised pretraining baselines on both datasets.

6. Conclusion

This paper introduces Long-Short Temporal Contrastive Learning (LSTCL), an unsupervised pretraining scheme for video transformers. By contrasting representations obtained from a long view and a short view of each video, it forces the model to encode context from the whole video into the features of short clips. We demonstrate our LSTCL under three different contrastive frameworks and two video transformer architectures including a new variant, Space-Time Swin transformer. In our experiments we show that unsupervised pretraining with LSTCL leads to similar or better

Table 6. Comparison to the state-of-the-art on Kinetics-400. Among methods using the same clip sizes as our models and no additional data (first two groups in the table), ST Swin networks pretrained with LSTCL achieve the highest accuracy and they are on-par with models that use longer or higher-resolution clips (third group) or that leverage additional data for supervised pretraining (bottom group).

Method	Clip Size	Additional Data (# Samples)	Top-1	Top-5	TFLOPs	Params
SlowFast [19]	8 x 224 ²	-	77.9	93.2	3.0	59.9M
TimeSformer-scratch	8 x 224 ²	-	60.4	76.7	0.59	121.4M
ST Swin from scratch	8 x 224 ²	-	71.1	85.2	0.60	88.0M
ST Swin w/ LSTCL	8 x 224 ²	-	79.8	94.0	0.60	88.0M
CorrNet-101 [64]	16 x 224 ²	-	79.2	-	7.0	-
SlowFast-NL [19]	16 x 224 ²	-	79.8	93.9	7.0	59.9M
MViT-B [17]	16 x 224 ²	-	78.4	93.5	0.36	36.6M
ST Swin w/ LSTCL	16 x 224 ²	-	81.5	95.2	1.80	88.0M
X3D-XL [18]	16 x 312 ²	-	79.1	93.9	1.45	11.0M
ip-CSN-152 [61]	32 x 224 ²	-	77.8	92.8	3.3	32.8M
MViT-B [17]	64 x 224 ²	-	81.2	95.1	4.09	36.6M
TimeSformer [6]	8 x 224 ²	ImageNet-21K (14M)	78.0	93.7	0.59	121.4M
STAM [54]	16 x 224 ²	ImageNet-21K (14M)	79.3	-	0.27	96.0M
TEINet [40]	16 x 224 ²	ImageNet-1K (1.2M)	76.2	92.5	1.8	-
Mformer [50]	16 x 224 ²	ImageNet-21K (14M)	79.7	94.2	11.1	109.1M
ViViT-L [3]	16 x 224 ²	ImageNet-21K (14M)	80.6	94.7	47.9	310.0M
VATT-B [2]	32 x 320 ²	AudioSet + HowTo100M (3.2M)	79.6	94.9	9.08	88.0M
TimeSformer-L [6]	96 x 224 ²	ImageNet-21K (14M)	80.7	94.7	7.14	121.4M

Table 7. Video-level accuracy on Kinetics-600. The ST Swin model trained with LSTCL achieves results comparable with the state-of-the-art *without* using additional data or labels.

Method	Clip Size	Additional Data (# Samples)	Top-1	Top-5
SlowFast [19]	8 x 224 ²	-	80.4	94.8
ST Swin from scratch	8 x 224 ²	-	74.7	92.2
ST Swin w/ LSTCL	8 x 224 ²	-	82.0	95.5
SlowFast [19]	16 x 224 ²	-	81.8	95.1
MViT-B [17]	16 x 224 ²	-	82.1	95.7
ST Swin w/ LSTCL	16 x 224 ²	-	83.6	96.6
X3D-XL [18]	16 x 312 ²	-	81.9	95.9
MViT-B [17]	32 x 224 ²	-	83.4	96.3
TimeSformer [6]	8 x 224 ²	ImageNet-21K (14M)	79.1	94.4
Mformer [50]	16 x 224 ²	ImageNet-21K (14M)	81.6	95.6
ViViT-L [3]	16 x 224 ²	ImageNet-21K (14M)	82.5	95.6
VATT-B [2]	32 x 320 ²	AudioSet + HowTo100M (3.2M)	80.5	95.5
VATT-L [2]	32 x 320 ²	AudioSet + HowTo100M (3.2M)	83.6	96.6
TimeSformer-L [6]	96 x 224 ²	ImageNet-21K (14M)	82.2	95.6

Table 8. Video-level classification accuracy on Something-Something-V2. Our ST Swin models pretrained *without* labels using LSTCL yield results on par with the state-of-the-art.

Method	Clip Size	Additional Data (# Samples)	Pretraining	Top-1	Top-5
TimeSformer [6]	8 x 224 ²	ImageNet-21K (14M)	supervised	59.5	-
ResNet50 [20]	8 x 224 ²	K400 (240K)	unsupervised	55.8	-
ST Swin from scratch	8 x 224 ²	-	-	38.4	65.5
ST Swin w/ LSTCL	8 x 224 ²	K400 (240K)	unsupervised	64.8	89.4
TEINet [40]	16 x 224 ²	ImageNet-1K (1.2M)	supervised	64.7	-
Mformer [50]	16 x 224 ²	ImageNet-21K + K400 (14.2M)	supervised	66.5	90.1
ViViT-L [3]	16 x 224 ²	ImageNet-21K (14M)	supervised	65.4	89.8
MViT-B [17]	16 x 224 ²	K400 (240K)	supervised	64.7	89.2
ST Swin w/ LSTCL	16 x 224 ²	K400 (240K)	unsupervised	67.0	90.5
TimeSformer-L [6]	96 x 224 ²	ImageNet-21K (14M)	supervised	62.4	-
MViT-B [17]	64 x 224 ²	K400 (240K)	supervised	67.7	90.9

video classification accuracy compared to pretraining with full supervision on ImageNet-21K and it achieves competitive results on three different video classification bench-

marks. LSTCL effectively eliminates the need for large-scaled supervised image pretraining in video transformers.

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A. Self-Supervised Learning Frameworks

In the main paper we presented experimental results obtained by implementing our proposed LSTCL procedure under three popular self-supervised contrastive learning frameworks: MoCo v3 [14], BYOL [26], and SimSiam [13]. Since we used the framework of MoCo v3 to present our method (section 4), here we provide a short description of the other two frameworks—BYOL and SimSiam—and of how we use them in our method.

BYOL. BYOL is a self-supervised learning framework consisting of a momentum-encoder (f_{θ_m}), an online encoder (f_θ) and a predictor MLP (g_{θ_p}) which is connected to the online encoder. The momentum-encoder is the moving average of the online encoder, which is controlled by a momentum parameter m . There is no back-propagation into the momentum-encoder parameters θ_m . The momentum update can be written as:

$$\theta_m = m\theta_m + (1 - m)\theta \quad (6)$$

Differently from MoCo, BYOL uses only positive pairs of examples. It minimizes the negative cosine similarity over all positive pairs. In our setting, the set of short clips is processed by the online encoder f_θ to yield a set of “query” examples $Q = \{q^1, q^2, \dots, q^B\}$ where $q^i = f_\theta(x_S^i) \in \mathbb{R}^D$. The set of long clips is processed by the momentum encoder f_{θ_m} to produce “key” examples $K = \{k^1, k^2, \dots, k^B\}$. Then, the LSTCL method with BYOL loss minimizes the following objective:

$$\mathcal{L}_{BYOL} = \sum_i [2 - 2 \cdot \frac{g_{\theta_p}(q^i)^\top k^i}{\|g_{\theta_p}(q^i)\|_2 \cdot \|k^i\|_2}]. \quad (7)$$

We symmetrize the objective by adding to this loss a dual term obtained by reversing the role of the long and the short clips, i.e., by computing queries from long clips with the online encoder ($q^i = f_\theta(x_L^i)$) and keys from the short clips with the momentum encoder ($k^i = f_{\theta_m}(x_S^i)$).

SimSiam. SimSiam can be viewed as the BYOL method without momentum-encoder and momentum update. Thus, in our setting the queries and the keys are computed from the short view and the long view, respectively, but using the same encoder: $q^i = f_\theta(x_S^i)$, $k^i = f_\theta(x_L^i)$. During training SimSiam applies the stop-gradient operation on the key view. Thus, LSTCL with SimSiam loss minimizes:

$$\mathcal{L}_{SimSiam} = \sum_i [2 - 2 \cdot \frac{g_{\theta_p}(q^i)^\top SG(k^i)}{\|g_{\theta_p}(q^i)\|_2 \cdot \|SG(k^i)\|_2}] \quad (8)$$

where $SG()$ denotes the stop-gradient operation. Even here we symmetrize the objective by adding a dual term with reversed roles for the long and the short clip.

B. Analysis of Space-Time Swin Transformer

We note that our Space-Time Swin Transformer (ST Swin) bears relations with the Video Swin model [41] which is concurrently presented in unpublished work. Video Swin differs from our ST Swin in the way it treats the temporal dimension. Video Swin subdivides the video volume into 3D neighborhoods for a self-attention computation that is *local in both space and time*. Conversely, our ST Swin inflates 2D spatial Swin blocks [39] into space-time attention tubes that cover the entire temporal extent of the clip. This gives our model the ability to compare patches from *all* frames within the same spatial neighborhood. Here we present an empirical comparison between Video Swin (using the code provided by the authors) and our ST Swin, with both models pretrained using our LSTCL and then finetuned on K400. Table 9 shows that ST Swin achieves better accuracy. We also list the result reported in the original Video Swin paper for the case when this model is pretrained on ImageNet and then finetuned on K400. This result shows that Video Swin trained with our LSTCL achieves higher accuracy than the same model pretrained on ImageNet using longer clips (32 frames instead of 16).

Model	Clip Size	Additional data	Pretraining	Acc.
ST Swin	16 x 224 ²	-	LSTCL	81.5%
Video Swin	16 x 224 ²	-	LSTCL	81.0%
Video Swin	32 x 224 ²	IN-1K	Superv.	80.6%

Table 9. Comparison between ST Swin and Video Swin on K400.