11-777 Spring 2021 Class Project

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Abstract

Template for 11-777 Reports using the ACL 2021 Style File

1 Introduction and Problem Definition

*Everyone Contributed Equally – Alphabetical order

2 Related Work and Background

Action segmentation The goal of action segmentation is to temporarily localize action segments and classify the category of the action in each segment in an untrimmed input video. The application of action segmentation can be found in various fields such as robotics (Pardowitz et al., 2009) and behavior analysis (Shao et al., 2012). Action segmentation is closely related but different from action recognition and action detection. Action recognition identifies one action in a trimmed video, and action detection usually outputs a sparse set of actions. By contrast, action segmentation is a more complex task that considers a longer range of temporal relations between sequential activities for more fine-grained action recognition in an untrimmed video.

Early works Traditional approaches generally fall into three categories: sliding window approaches, segmental models, and recurrent networks (Huang et al., 2020). One of the earliest attempts is to detect action segments with temporal windows of different scales and non-maximum suppression (Rohrbach et al., 2012). However, this method is limited by the tradeoff between larger window size and computational costs. Others use segmental models like spatiotemporal CNNs with the semi-Markov model for tracking object relationships, action transitions, and environment change (Lea et al., 2016; Fathi and Rehg, 2013). With each action conditioned on the previous one, these methods are good at capturing local dependencies in consecutive visual patterns rather than long-range temporal relations. Other hybrid approaches include representing frames using Fisher Vectors with HMMs and GRUs for temporal modeling (Kuehne et al., 2016; Richard et al., 2017), which have their main drawback of efficiency. Another line of research focuses on temporal convolutional networks (TCNs) that perform fine-grained action segmentation using temporal convolutions (Lea et al., 2017). The method is extended to a multi-stage architecture with a set of dilated temporal convolutions in each stage. It is proven to be able to avoid temporal pooling and better capture long-range dependencies (Farha and Gall, 2019).

Graph convolution networks Recently, existing models are further improved by the introduction of graph convolution networks (GCNs). Built on top of action segmentation models, the graph-based module models the temporal relations between initial segmentation results with temporal proximity. It refines the pre-computed action segments by performing segment boundary regression and segment classification (Huang et al., 2020). The latest extension to this approach constructs multi-level dilated temporal graphs for temporal reasoning at different timescales (Wang et al., 2020). The limitations of the graph-based module exist in its dependence on the initial backbone output. For example, it suffers from low efficiency on large graphs if the initial segmentation is heavily fragmented. However, while abundant works have been done in unimodal action segmentation, we observe that almost none of the existing work attempts at multimodal approaches. Since textual data is one of the most common and accessible annotations of video data, we are interested in incorporating texts as a complimentary domain for better segmentation results.

Text alignment Identifying the relationship between two or more modalities is one of the core challenges in Multimodal settings (Baltrušaitis et al., 2019). An example of the unsupervised approaches to text alignment is to first perform temporal clustering individually on the video input and the text input, then use the two clusters to provide complementary information to one another (Alayrac et al., 2016). For instance, differences in two video segments can provide a temporal cue to a breaking point within the narrative script. Contextual information is used to assist the alignment of textual scripts and video frames (Shi et al., 2020). It is built by firstly collecting a mean pooling of each modality within K units. The mean representation of two modalities is then combined through a transformer model and concatenated to the embedding of the individual. Our task concerns video and scripts in the cooking domain. In one of the similar experiments, the text script is parsed into action-object (i.e. verb-noun) classes, and the video frames are aligned to the text script by matching the tokens of action-objects to those present in the frames (Malmaud et al., 2015).

Text-image matching To build better representation for the graph nodes, we want to use the narrations to attend to regions in the frame that are closely associated with the action that is conducted. In this way, different relevant objects in different frames can be used to distinguish the segment boundaries.

To use attention methods, we first need to provide a set of image features. To better extract object features in the images, Faster R-CNN (Ren et al., 2016) firstly generates Region Of Interests (ROIs) with high objectness, and it then uses intermediate convolution feature maps to classify the region and regress bounding boxes. Fully Convolutional One-Stage Object Detection (FCOS) (Tian et al., 2019) belongs to a family of anchor-less methods. Instead of regressing bounding boxes using the anchors as references, it regresses four values, l, t, r, b that represent the distance from a location in the image to the four sides of the bounding boxes. Moreover, it uses CNN feature maps from different levels to perform bounding box regression at various scales to capture objects with different sizes. It has been shown that anchor-less detectors perform better than anchor-based detectors on seen and unseen test sets, and FCOS can identify objects involved in the action (Yoon et al., 2020).

Given a set of image features, encoding regions in the image, and a set of word features extracted from the sentence, Stacked Cross Attention (Lee et al., 2018) determines the similarity between image-sentence pair by inferring how important a region is to the sentence, and it can also reversely infer how important a sentence is to the image. An additional position feature is concatenated for the object with the visual feature extracted by ResNet (Wang et al., 2019). The image is divided into blocks, and embedding vectors representing the positions of the blocks are combined with weights determined by overlap between the block and the visual feature. The addition is motivated by the fact that the positions of objects in the image are related to the semantics of the image. This intuition aligns with our task since we expect that the relative positions of objects are associated with the action during cooking.

3 Task Setup and Data (1 page)

The main task is to segment egocentric (first-person) cooking videos from EPIC-KITCHENS dataset into action-object pairs. Given a video clip in the form of a sequence of frames, we want to identify the type of actions as well as their start and end time in the given video.

3.1 Dataset

We use the largest egocentric (first-person) dataset EPIC-KITCHENS-100, which features 100 hours, 700 variable-length videos with 90K actions of 37 participants (Damen et al., 2020). Compared to YouTube-based datasets such as HowTo100M (Miech et al., 2019), EPIC-KITCHENS contains activities that are non-scripted and thus capture more natural settings such as parallel tasking . The egocentric view provides a unique perspective on people-object interactions, attention, and intention. Meanwhile, it also imposes extra challenges compared to third-person datasets like YouCook2 (Zhou et al., 2018). One of the challenges is that certain actions, such as eating and drinking, cannot be directly observed due to the limited field of view. Other challenges include unseen participants, unseen cooking actions, frame noises from different sources (i.e. background and lighting), long videos with many action instances, fragmentation of segments resulted from interleaving actions in multi-tasking, and weaker temporal correlations in objects interfering the correlations in actions.

3.2 Task formulation

There are two input modalities: video frames of egocentric cooking scenes and narrations describing the action in the scenes. The narrations are transcribed from the audio in the form of imperative phrases: verb-noun with optional propositional phrase. The goal is to predict a verb class as well as a noun class for each frame to identify the action in the segments. Afterwards, we combine the two classes into a tuple as the final output class label.

Formally, the visual input consists of a sequence of M RGB frames in temporal order, denoted as $F = (\mathbf{f}_i)_{i=1}^{M}$. The RGB frames are sampled from untrimmed videos at a rate of 50 frames per second. The textual input is a sequence of N audio-transcribed narrations in temporal order, denoted as $C = (\mathbf{c}_i)_{i=1}^{N}$. Our goal is to infer the action-object class label for each frame. The ground truth is given by $Y = (\mathbf{y}_i)_{i=1}^{M}$. Each

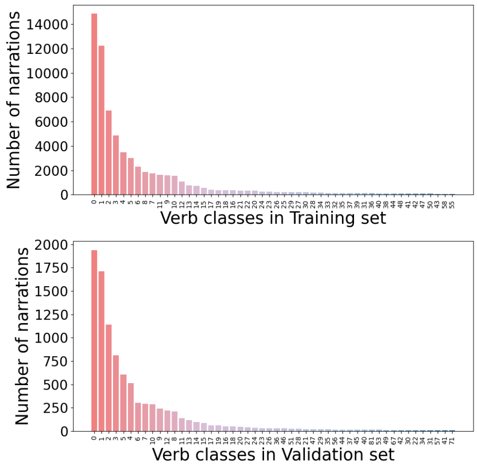

Figure 1: Frequency distribution of 50 most frequent verb class in training and validation set

$\mathbf{y}_i \in \{0,1\}^K \times \{0,1\}^L$ is a tuple of one-hot vectors encoding the true verb and noun class, where K is the number of verb classes and L is the number of noun classes.

3.3 Dataset Statistics

3.3.1 Text Analysis

Narrations in EPIC-KITCHENS-100 are mainly imperative phrases in the form of verb-noun with optional propositional phrase (e.g. *put down plate*, *put container on top of counter*). Each annotation includes start/stop timestamps and frames, action verbs and object nouns, which are extracted from the corresponding narration. Verbs and nouns are further classified into classes based on their semantic meaning. For example, *grab* and *get* belong to the same verb class. There are a total of 97 verb classes and 300 noun classes in the training and validation set.

We define the frequency of a verb/noun class as the number of narrations that contain a verb/noun from that class. Both verb and noun classes have a heavy tailed distribution with tail classes ($\leq$ 1/15 of the maximum frequency) accounting for 13.02% and 11.67% total verbs and 5.38% and 1.85% total nouns in the training and validation set respectively (Figure 1). Such a distribution indicates the intrinsic complexity and entropy of the text data. The training and validation set have similar composition: in the validation set, there are no unseen verb class and only four unseen noun classes, accounting for 0.03% of all narrations. Narration timestamps are relatively complete: only 0.17% in training and 0.72% in validation are missing. On the other

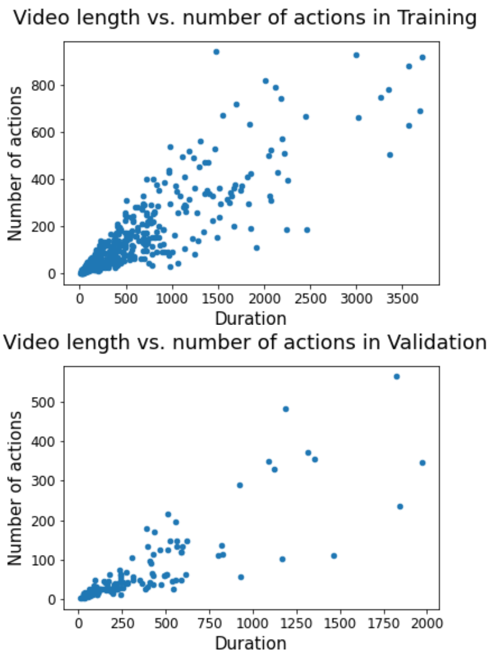

Figure 2: Number of action in each video against video length (in seconds)

hand, since there were no constraints on the recording duration, we observe a great variability across videos. Average sentence length of training and validation set is 15.1 and 14.8 with standard deviation of 6.3 and 6.0 words, respectively. Average number of actions per video is 135.8 (training) and 70.1 (validation) with standard deviation of 167.7 and 93.2. More distribution statistics can be found in Appendix A Table 1.

A natural assumption of our task is that there is none or minimal overlapping between action segments, i.e. only one action in almost all time frames. We check that there are at most 4 narrations in parallel in training and 3 in validation; only 3832 (5.70%) and 617 (0.92%) pairs of consecutive actions overlap for more than 1 second. We also inspect the feature embeddings of the verb and noun classes. Using GloVe word vectors pre-trained on Twitter (200d vectors) (Pennington et al., 2014), we do not notice significant interclass or intraclass clustering effect (Appendix A Figure 4).

3.3.2 Video Frame Analysis

We extract 1920 × 1080 RGB frames from the videos at a sampling rate of 50 FPS. Each frame is identified by participant id, video id, and a start/end frame number. More than half of the total 700 videos in the dataset have less than 25,000 frames.

Videos in EPIC-KITCHENS-100 have varied length with the longest video of 3708 seconds and shortest video of 10 seconds. 85.7 % of the videos are shorter than 1000 seconds and 66.0 % are less than 500 seconds (Appendix A Table 1, Figure 5). We also see that the number of narrations grows roughly linearly with video length (Figure 2).

We compile all training and validation samples of a given verb class and compute the average number of frames for this class (Appendix Figure 8). The top-10 verb classes with the most number of frames include actions like *grate, wait, prepare, knead, stir*, and *cut*; while those with the least number of frames contain actions like *bend, turn-off, turn-on, take, close*. It seems that actions involved during cooking take longer than those related to intermediate preparatory steps, and the average length of the action aligns with how people would respond if asked about which action would take longer. For most verb classes, the average number of frames in each class are roughly the same in both training and validation set, except a few where the validation sets have more frames. We also count the total number of frames for each verb class, summed over all training and validation samples in the class. We notice that such frequency corresponds to the trend of verb-class frequency in the annotations (Appendix A Figure 9). This indicates that within the dataset, the frequency of the verb class correlates to the amount of visual information in the dataset.

The dataset also provides bounding-box annotations for each frame, where it only distinguishes between two categories: hands and objects. Only active objects are annotated, so the number of object bounding-boxes in a frame approximates the number of objects that the person interacts with. We compute the average number of hand bounding-boxes appearing in a frame of each verb class. Class with less than 1.5 hand bounding-boxes include actions like *take, put-on, open, pull-down, walk*, and these correspond roughly to human impression on how many hands are needed for performing the action. We also compute the average number of objects bounding boxes in a frame of a given verb class. Verb classes with less than 1.8 object bounding boxes include actions like *open, close, shake, check, fold*, and *drink* (Appendix A Figure 6, 7). The average numbers of hand and object bounding boxes for the training and validation sets are mostly equal, despite the validation set misses a few verb classes. Full details can be found in Appendix A.

3.4 Metrics

We measure three metrics: frame-wise accuracy, segmental edit distance and segmental F1 score.

Frame-wise metrics is most commonly used in segmentation and include accuracy, precision, and recall. However, this group of metrics tends to be influenced more by actions with long duration than by those with short duration (Wang et al., 2020). Another problem is that it does not penalize for over-segmentation errors in the model (Wang et al., 2020; Lea et al., 2017). Therefore, we also consider segmental edit distance, which is useful because it reflects out-of-order and over-segmentation errors (Lea et al., 2017).

(Lea et al., 2017) also introduces segmental F1 score, which not only penalizes for over-segmentation but also avoids penalizing for minor temporal shifts between the prediction and the ground truth. It also has the advantage of depending on the number of actions instead of their duration. For each predicted action segment, we calculate its IoU with respect to the corresponding ground truth. If the score is above a threshold τ, then the prediction is considered as a true positive (TP) otherwise a false positive (FP). Over-segmentation is addressed since if more than one correct segments lie within a single true action, only one is labelled as TP and all others are FP. Here we consider overlapping thresholds of 10%, 25% and 50%, denoted by F1@$\{10, 25, 50\}$.

4 Models (2 pages)

4.1 Baselines

We use four methods as our baseline models: both EDTCN (Lea et al., 2017) and MS-TCN++ (Li et al., 2020) use temporal convolution networks to capture long-range dependencies. (Richard et al., 2017) proposed a hybrid usage of GRU-based RNN and HMM to refine action alignment. DTGRM (Wang et al., 2020) uses multi-level dilated temporal graphs with an auxiliary self-supervised task to help correct wrong temporal relation in videos.

EDTCN and Dilated TCN EDTCN (Lea et al., 2017) is the first work to present temporal convolution network (TCN), which aims to capture not only segmental features but also long-range patterns using a hierarchy of temporal convolution filters. It emphases the concept of receptive fields, which means a fixed-length input that the prediction output corresponds to. The encoder in the Encode-Decoder TCN (EDTCN) consists of layers of temporal convolutions, non-linear activation, and max pooling; the decoder has a similar structure, except that pooling is replaced with upsampling. Dilated TCN shares a similar structure with MS-TCN: a series of blocks, each with layers of dilated convolutions with exponentially growing dilation rates, and a residual connection between layer input and convolution signal.

MS-TCN++ MS-TCN (Farha and Gall, 2019) is a multi-stage architecture using TCN. The first layer of a single-stage TCN (SS-TCN) adjusts inputs dimension, followed by several dilated 1D temporal convolution layers with dilation factor doubled at each layer. All layers have ReLU activation with residual connection. MS-TCN stacks four SS-TCNs so that each takes an initial prediction probabilities from the previous stage and refines it. The overall architecture is trained with the cross entropy classification loss and a truncated mean squared error over the frame-wise log probabilities that penalizes over-segmentation. Extended from MS-TCN, MS-TCN++ (Li et al., 2020) decouples the prediction phase and the refinement phase and enables parameter sharing in the latter. Furthermore, it replaces the dilated layer with a dual dilated layer that combines two convolutions with different dilation factors in the first stage to address limited receptive field. The SS-TCN in MS-TCN++ has 11 layers, each of which has 64 filters, kernel size 3 with dropout rate 0.5. The learning rate is set to be 0.0005 in training.

Weakly-supervised approach Richard et al. (2017) tackles the action alignment task by iteratively refining the coarsely proposed segmentation. Given a set of video frames and an ordered action sequence, the model assigns an action segment index to each frame. The initial proposal for boundaries are constructed by equally dividing the frames upon actions in the action sequence in the sequence's original order. The model uses a hybrid component of both an GRU-based RNN network and an HMM network to train and realign the proposal. To create more fine-grained proposals, the authors propose to further split each action into a sequence of subactions. The model attempts to create more fine-grained segmentation by modeling the probability distribution of the subactions within an action using the HMM network. To alleviate the computational need for recurrent neural networks used for processing videos, the authors propose to split the video frames into overlapping chunks. For instance, a single input would be a video frame at time period t and 20 frames before that. By splitting the input into smaller chunks, the model is able to take advantage of parallelism and utilize batch training.

DTGRM Wang et al. (2020) proposed DTGRM which refines a predicted result given by backbone model (e.g. I3D) in an iterative manner. The model stacks K dilated graph convolution layers to perform temporal reasoning across long timescales, where each layer updates the hidden representation of every input frame. To reduce over-segmentation error, an additional self-supervised task is introduced to simulate over-segmentation error by randomly exchanging part of input frames. Both the original and exchanged frame sequences are fed into the model as input, with output being action class likelihood for two frame sequences as well as exchange likelihood for each frame. Since the model was trained on datasets with relatively shorter video compared to EPIC-KITCHENS, we plan to trim the videos into overlapping clips of length 15 minutes with fixed fps for consistency.

4.2 Proposed Approach

5 Results (1 page)

The columns above are just examples that should be expanded to include all metrics and baselines.

Methods	Dev			Test		
	Acc	Edit	F1@$\{10, 25, 50\}$	Acc	Edit	F1@$\{10, 25, 50\}$
EDTCN (Lea et al., 2017)						
MS-TCN++ (Farha and Gall, 2019)						
(Richard et al., 2017)						
DTGRM (Wang et al., 2020)						
Proposed Method						

6 Analysis (2 pages)

This section should include at least two to three plots

6.1 Ablations and Their Implications

6.2 Qualitative Analysis and Examples

This section should likely contain a table of examples demonstrating how the current approach succeeds/fails.

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Appendix A Data Analysis

In this section, we present the full details of our data analysis.

	Training				Validation			
	Max.	Min.	Avg.	Std.	Max.	Min.	Avg.	Std.
Verb class frequency	14848	73	1314	2829	1937	71	191	398
Noun class frequency	3617	178	724	655	430	25	108	92
Sentence length	77	3	15.1	6.3	71	3	14.8	6.0
Actions per video	940	1	136	168	564	3	70	93
Frames per verb class	2129212	20165	225170	408408	407425	2702	42016	76950
Video length	3708	10	543	645	1969	11	344	377

Table 1: Statistics of EPIC-KITCHENS-100 training and validation set

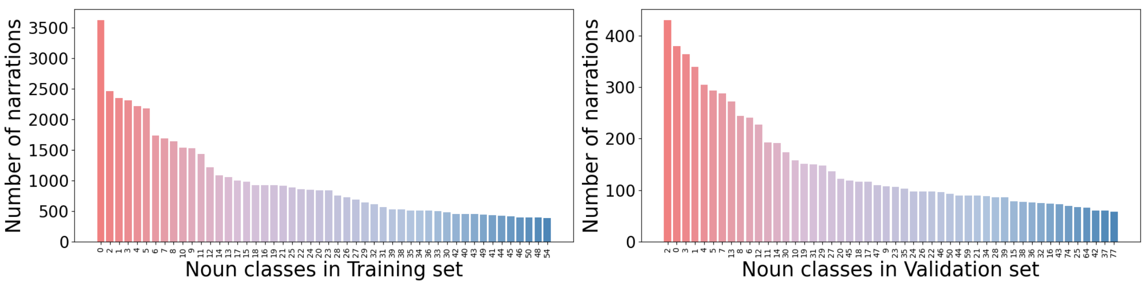

Figure 3: Frequency distribution of 50 most frequent noun classes in training and validation set

Figure 4: Example of visualizing feature embeddings of verb and noun classes in 2D and 3D space

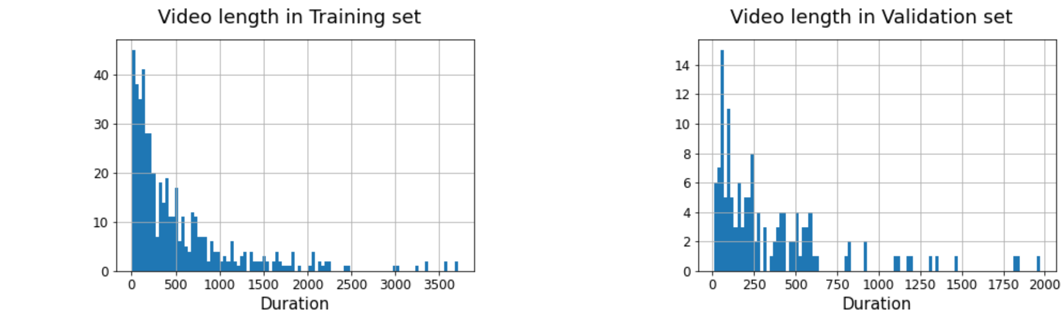

Figure 5: Distribution of video length (in seconds)

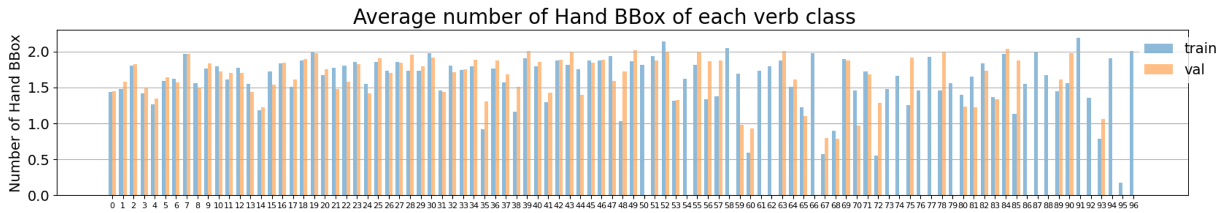

Figure 6: Average number of hand bounding-boxes in each frame of given verb class

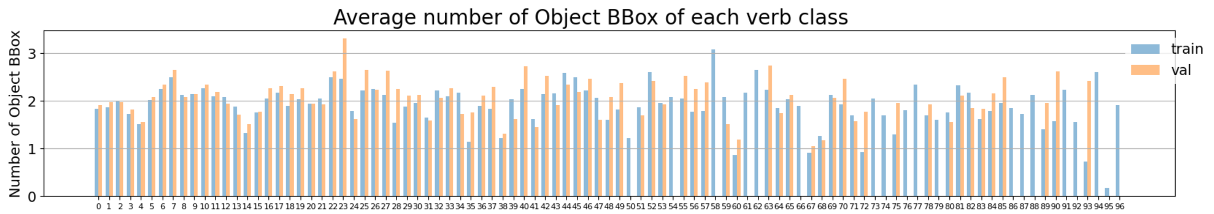

Figure 7: Average number of object bounding-boxes in each frame of given verb class

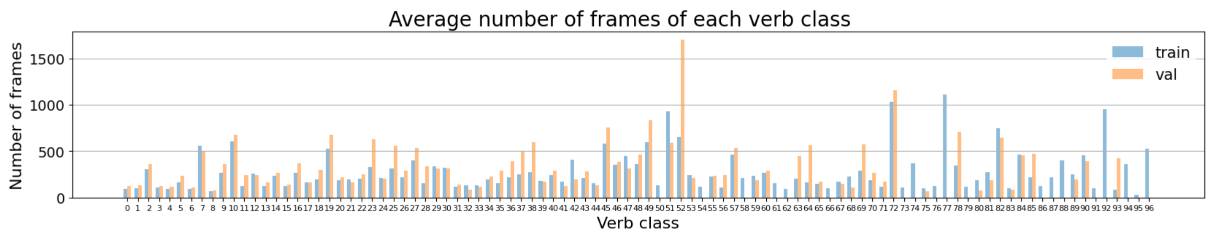

Figure 8: Average number of frames in a narration of a given verb class in training and validation set

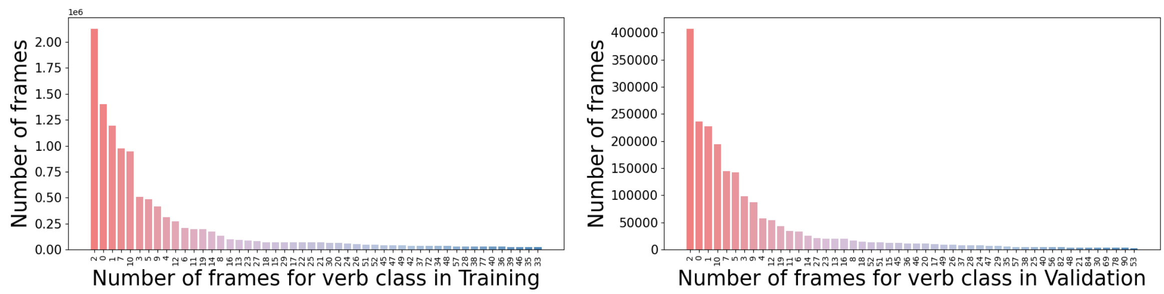

Figure 9: Distribution of number of frames in each video