Dynamic Concept Composition for Zero-Example Event Detection

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Abstract
In this paper, we focus on automatically detecting events in unconstrained videos without the use of any visual training exemplars. In principle, zero-shot learning makes it possible to train an event detection model based on the assumption that events (e.g. birthday party) can be described by multiple mid-level semantic concepts (e.g. “blowing candle”, “birthday cake”). Towards this goal, we first pre-train a bundle of concept classifiers using data from other sources. Then we evaluate the semantic correlation of each concept w.r.t. the event of interest and pick up the relevant concept classifiers, which are applied on all test videos to get multiple prediction score vectors. While most existing systems combine the predictions of the concept classifiers with fixed weights, we propose to learn the optimal weights of the concept classifiers for each testing video by exploring a set of online available videos with freeform text descriptions of their content. To validate the effectiveness of the proposed approach, we have conducted extensive experiments on the latest TRECVID MEDTest 2014, MEDTest 2013 and CCV dataset. The experimental results confirm the superiority of the proposed approach.

Introduction
In multimedia event detection (MED), a large number of unseen videos is presented and the the learning algorithm must rank them according to their likelihood of containing an event of interest, such as rock climbing or attempting a bike trick. Compared to traditional recognition of visual concepts (e.g. actions, scenes, objects, etc.), event detection is more challenging for the following reasons. First, an event is a higher level abstraction of video sequences than a concept and consists of multiple concepts. For example, an event, say birthday party, can be described by multiple concepts (e.g. “birthday cake”, “blowing candle”, etc.) Second, an event spreads over the entire duration of long videos while a concept can be detected in a shorter video sequence or even in a single frame. As the first important step towards automatic categorization, recognition, search, indexing and retrieval, MED has attracted more and more research attention in the computer vision and multimedia communities (Chen et al. 2014; Chang et al. 2015b; Cheng et al. 2014; Lai et al. 2014; Li et al. 2013; Chang et al. 2015c; Ma et al. 2012; Yan et al. 2015a; 2015b).

Current state-of-the-art systems for event detection first seek a compact representation of the video using feature extraction and encoding with a pre-trained codebook (Lowe 2004; Bay, Tuytelaars, and Gool 2006; Wang and Schmid 2013). With labeled training data, sophisticated statistical classifiers, such as support vector machines (SVM), are then applied on top to yield predictions. With sufficient labeled training examples, these systems have achieved remarkable performance in the past (Lai et al. 2014; Sun and Nevatia 2014; Li et al. 2013; Cheng et al. 2014). However, MED faces the severe data-scarcity challenge: only very few, perhaps even none, positive training samples are available for some events, and the performance degrades dramatically once the number of training samples falls short. Reflecting this challenge, the National Institute of Standards and Technology (NIST) hosts an annual competition on a variety of retrieval tasks, of which the Zero-Exemplar Multimedia Event Detection (0Ex MED in short) in TRECVID 2013 (TRECVID 2013) and 2014 (TRECVID 2014) has received considerable attention. Promising progress (Dalton, Allan, and Mirjakar 2013; Habibian, van de Sande, and Snoek 2013; Habibian, Mensink, and Snoek 2014; Chang et al. 2015a) has been made in this direction, but further improvement is still anticipated.

In this paper, we aim to detect complex event without any labeled training data for the event of interest. Following previous work on zero-shot learning (Lampert, Nickisch, and Harmeling 2009; Palatucci et al. 2009), we regard an event as compositions of multiple mid-level semantic concepts. These semantic concept classifiers are shared among events and can be trained using other resources. We then learn a skip-gram model (Mikolov et al. 2013) to assess the semantic correlation of the event description and the pre-trained vocabulary of concepts, based on which we automatically select the most relevant concepts to each event of interest. This step is carried out without any visual training data at all. Such concept bundle view of event also aligns with the cognitive science literature, where humans are found to conceive objects as bundles of attributes (Roach and Lloyd...
We conduct extensive experiments on three real video datasets (namely MEDTest 2014 dataset, MEDTest 2013 dataset and CCVsub), and achieve state-of-the-art performances.

Related Works

Complex event detection on unconstrained web videos has attracted wide attention in the field of multimedia and computer vision. Significant progress has been made in the past (Lai et al. 2014; Li et al. 2013; Sun and Nevatia 2014). A decent video event detection system usually consists of a good feature extraction module and a highly effective classification module (such as large margin support machines and kernel methods). Various low-level features (static, audio, etc.) already achieve good performances under the bag-of-words representation. Further improvements are obtained by aggregating complementary features in the video level, such as coding (Boureau et al. 2010; Perronnin, Sánchez, and Mensink 2010) and pooling (Cao et al. 2012). It is observed that with enough labeled training data, superb performance can be obtained. However, when the number of positive training videos falls short, the detection performance drops dramatically. In this work, we focus on the more challenging zero-exemplar setting where no labeled training videos for the event of interest are provided.

Our work is inspired by the general zero-shot learning framework (Lampert, Nickisch, and Harmeling 2009; Palatucci et al. 2009; Mensink, Gavves, and Snoek 2014), which arises from practical considerations such as the tremendous cost of acquiring labeled data and the constant need of dealing with dynamic and evolving real-world object categories. On the event detection side, recent works have begun to explore intermediate semantic concepts (Chang et al. 2015a), and achieved limited success on the zero-exemplar setting (Dalton, Allan, and Mirakjar 2013; Habibian, van de Sande, and Snoek 2013; Habibian, Mensink, and Snoek 2014) also considered selecting more informative concepts. However, none of these works consider discovering the optimal weights of different concept classifiers for each individual testing video.

The Proposed Approach

In this paper, we focus on the challenging zero-exemplar event detection problem. In a nutshell, we are given a sequence of unseen testing videos and also the event description, but without any labeled training data for the event of interest. The goal is to rank the testing videos so that positive videos (those contain the event of interest) are ranked above negatives. With this goal in mind, we first associate a query event with related semantic concepts that are pre-trained using other sources. Then we aggregate the individual concept prediction scores using the proposed dynamic composition approach.

Semantic Query Generation

Our work is built upon the observation that each event can be described by multiple semantic concepts. For example, the marriage proposal event can be attributed to several concepts, such as “ring” (object), “kissing” (action), “kneeling
down” (action) and “cheering” (acoustic). Since semantic concepts are shared among different events and each concept classifier can be trained independently using data from other sources, zero-example event detection can be achieved by combining the relevant concept prediction scores. Different from the pioneer work (Lampert, Nickisch, and Harmeling 2009), which largely relies on human knowledge to decompose classes (events) into attributes (concepts), our goal is to automatically evaluate the semantic similarity between the event of interest and the concepts, based on which we select the relevant concepts for each event.

Events come with textual side information, e.g., an event name or a short description. For example, the event *dog show* in the TRECVID MEDTest 2014 (TRECVID 2014) is defined as “a competitive exhibition of dogs”. With the availability of a pre-trained vocabulary of concept classifiers, we can evaluate the semantic correlation between the query event and each individual concepts. Specifically, we learn a skip-gram model (Mikolov et al. 2013) using the English Wikipedia dump\(^1\). The skip-gram model infers a D-dimensional vector space representation by fitting the joint probability of the co-occurrence of surrounding contexts on large unstructured text data, and places semantically similar words near each other in the embedding vector space. Thus it is able to capture a large number of precise syntactic and semantic word relationships. For short phases consisting of multiple words (e.g., event descriptions), we simply average its word-vector representations. After properly normalizing the respective word-vectors, we compute the cosine distance of the event description and all individual concepts, resulting in a correlation vector \( \mathbf{w} \in [0, 1]^m \), where \( w_k \) measures a priori relevance of the \( k \)-th concept and the event of interest. Based on the relevance vector, we select the most informative concept classifiers for each event.

**Weak Label Generation**

According to the NIST standard, we utilize the TRECVID MED research dataset to explore the optimal weights for the testing videos. All the videos in the research set come with a sentence of description, summarizing the contents contained in the videos. Note that all the videos in the research set has no event-level label information. We further collect a set of videos with free-form text descriptions of their content, which are widely available online in websites such as YouTube and NetFlix.

As the descriptions of the videos in both research set and online website are very noisy, we apply standard natural language processing (NLP) techniques to clean up the annotations, including removal of the common stop words and stemming to normalize word inflections.

Similar to the steps of SQG, we measure the semantic correlation between the cleaned sentence and each concept description, and use it as a weak label for each concept. In the next section, we will learn the optimal aggregation weights for the individual testing video by exploiting the supervision information with weak label, which accounts for the differences in the concept classifiers’ prediction abilities on the individual testing video, and hence achieve robust aggregation results.

**Dynamic Composition**

Up until now, we have \( l \) videos with weak label and \( u \) testing videos. We propose to learn an aggregation function \( f_i(s_i) = w_i^T s_i \) for each testing video \( i = 1, \cdots, l + u \), where \( \mathbf{w} = [w_1^T, \cdots, w_m^T]^T \) is a non-negative aggregation weight vector with \( w_i^T \) being the aggregation weight of \( s_i^T \). Clearly, it is straightforward for us to learn the optimal aggregation weights for the videos in the collected set based on the weak label information. However, it is challenging to derive the optimal aggregation weights for the unlabeled videos since no label information is available.

To achieve this goal, we build our model based on the local smoothness property in graph-based semi-supervised learning, which assumes visually similar videos have comparable labels within a local region of the sample space (Liu et al. 2013; Lai et al. 2015). To exploit this property, we build a nearest neighbor graph based on the low level features (In this paper, the improved dense trajectories feature (Wang and Schmid 2013) is used). Note that other graph construction methods (Li et al. 2015) can be used in our approach. We put an edge between the video \( x_i \) and the video \( x_j \) if \( x_i \) is among \( k \) nearest neighbors of \( x_i \) or \( x_j \) is among \( k \) nearest neighbors of \( x_i \). The weight of the edge \( G_{ij} \) in the graph matrix \( G \) is calculated by

\[
G_{ij} = \begin{cases} 
\exp(-\frac{d(x_i, x_j)}{\sigma}), & \text{if } i \in N_k(j) \text{ or } j \in N_k(i), \\
0, & \text{otherwise},
\end{cases}
\]

where \( N_k(i) \) denotes the index set of the \( k \) nearest neighbors of video \( x_i \) (in this paper, we empirically set \( k \) to 5), in which \( d(x_i, x_j) \) denotes the distance calculated based on the low-level feature. \( \sigma \) is the radius parameter of the Gaussian function. In our experiment, following (Liu et al. 2013; Lai et al. 2015) we set it as the mean value of all pairwise average distances among the videos.

Our dynamic composition model learns the optimal aggregation weight vectors \( \mathbf{W} = [w_1, \cdots, w_{l+u}] \) for both the collected videos and the testing videos by solving the following problem:

\[
\min_{\mathbf{W}} \Omega(\mathbf{W}) + \lambda L(\{f_i\}_{i=1}^l; \mathcal{Q}, \mathcal{R}),
\]

\[
s.t. \ w_i \geq 0, \ i = 1, \cdots, l + u,
\]

where \( \lambda \) is a trade-off parameter among the two competing terms, \( \mathcal{Q} \) denotes positive examples and \( \mathcal{R} \) denotes negative examples. The normalized weight matrix is defined as \( \mathbf{E} = \mathbf{U}^{-\frac{1}{2}} \mathbf{G} \mathbf{U}^{-\frac{1}{2}} \), where \( \mathbf{U} \) is diagonal matrix with its element defined as \( u_{ii} = \sum_{j=1}^{l+u} G_{ij} \). Noting that visually similar videos are presumed to have the same label information and thus the same composition weights, we propose a regularization term to propagate the aggregation weights (Belkin and Niyogi 2001):

\[
\Omega(\mathbf{W}) = \sum_{i,j=1}^{l+u} (w_i^T s_i - w_j^T s_j)^2 \mathbf{E}_{ij},
\]
By simple algebra formulation, the regularized term Equation (3) can be rewritten as:

$$
\Omega(W) = (\pi(W))^T L(\pi(W)),
$$

(4)

where $L = I - E$ is the graph laplacian, $\pi(W)$ is a vector calculated by $\pi(W) = ((W^T S) \circ I)l$, where $\circ$ is the Hadamard matrix product. To make visually similar videos have comparable aggregation scores and similar aggregation weights, we propose to minimize (4), which enforces a smooth aggregation score propagation over the constructed graph structure.

To step further, we incorporate an infinite push loss function (Rakotomamonjy 2012) to achieve robust aggregation result. The goal of infinite push loss function is to minimize the number of positive videos which are ranked below the highest scored negative videos. The infinite push loss function has shown promising performance for event detection problem in (Chang et al. 2015c). In fact, the number of positive videos ranked below the highest scored negative videos equals to the maximum number of positive videos ranked below any negative videos. Hence, we define it as follows:

$$
\ell(\{f_i\}_{i=1}^l; \mathcal{P}, \mathcal{R}) = \max_{j \in \mathcal{R}} \left( \frac{1}{p} \sum_{i \in \mathcal{P}} f_i(s_i^+) < f_j(s_j^-) \right),
$$

(5)

where $I$ is the indicator function whose value is 1 if $f_i(s_i^+) < f_j(s_j^-)$ and 0 otherwise. The maximum operator over $j$ equals to calculating the $l_\infty$-norm of a vector consisting of $n$ entries, each of which corresponds to one value based on $j$ in the parentheses of Equation (5). By minimizing this penalty, positive videos tend to score higher than any negative videos. This essentially ensures positive videos have higher combined scores than the negatives, leading to more accurate combined results.

For computational tractability we upper bound the discrete 0-1 loss $I(\delta < 0)$ by the convex hinge loss $(1 - \delta)_+$, where as usual $(\delta)_+ := \max(\delta, 0)$ is the positive part. Since we usually pay more attention, if not exclusively, to the top of the rank list, we focus on minimizing the maximum ranking error among all negative exemplars $j \in \mathcal{R}$:

$$
\ell(\{f_i\}_{i=1}^l; \mathcal{P}, \mathcal{R}) = \max_{j \in \mathcal{R}} \left( \frac{1}{p} \sum_{i \in \mathcal{P}} (1 - (w_i^T s_i^+ - w_j^T s_j^-) )_+ \right),
$$

(6)

Finally, the objective function can be written as:

$$
\min_{W}(\pi(W))^T L(\pi(W))
+ \lambda \max_{j \in \mathcal{R}} \left( \frac{1}{p} \sum_{i \in \mathcal{P}} (1 - (w_i^T s_i^+ - w_j^T s_j^-) )_+ \right),
$$

(7)

s.t. $w_i \geq 0, i = 1, \ldots, l + u$.

The above objective function is convex, and thus can achieve the global optimum. Thanks to the proximal map (Yu 2013), we employ the faster ADMM proposed in (Chang et al. 2015c) for efficient solution.

### Experiments

In this section, we conduct extensive experiments to validate the proposed Dynamic Concept Composition for zero-exemplar event detection task, abbreviated as DCC.

### Experiment Setup

**Dataset:** To evaluate the effectiveness of the proposed approach, we conduct extensive experiments on the following three large-scale event detection datasets:

- TRECVID MEDTest 2014 dataset (TRECVID 2014): This dataset has been introduced by the NIST for all participants in the TRECVID competition and research community to perform experiments on. There are in total 20 events, whose description can be found in (TRECVID 2014). We use the official test split released by the NIST, and strictly follow its standard procedure (TRECVID 2014). To be more specific, we detect each event separately, treating each of them as a binary classification/ranking problem.

- TRECVID MEDTest 2013 dataset (TRECVID 2013): The settings of MEDTest 2013 dataset is similar to MEDTest 2014, with 10 of their 20 events overlapping.

- Columbia Consumer Video dataset (Jiang et al. 2011): The official Columbia Consumer Video dataset contains 9,317 videos in 20 different categories, including scenes like “beach”, objects like “cat”, and events like “basketball” and “parade”. Since the goal of this work is to search complex events, we only use the 15 event categories.

According to the standard of the NIST, each event is detected separately and the performance of event detection is evaluated using the mean Average Precision (mAP).

**Concept Detectors:** 3,135 concept detectors are pre-trained using TRECVID SIN dataset (346 categories) (Over et al. 2014; Jiang et al. 2014), Google sports (478 categories) (Karpathy et al. 2014; Jiang et al. 2014), UCF101 dataset (101 categories) (Soomro, Zamir, and Shah 2012; Jiang et al. 2014), YFCC dataset (609 categories) (YFC; Jiang et al. 2014) and DIY dataset (1601 categories) (Yu, Jiang, and Hauptmann 2014; Jiang et al. 2014). The improved dense trajectory features (including trajectory, HOG, HOF and MBH) are first extracted using the code of (Wang and Schmid 2013) and encode them with the Fisher vector representation (Perronnin, Sánchez, and Mensink 2010). Following (Wang and Schmid 2013), the dimension of each descriptor is first reduced by a factor of 2 and then use 256 components to generate the Fisher vectors. Then, on top of the extracted low-level features, the cascade SVM (Graf et al. 2004) is trained for each concept detector.

**Competitors:** We compare the proposed approach with the following alternatives: 1) Prim (Habibian, Mensink, and Snoek 2014): Primitive concepts, separately trained. 2) Sel (Mazloom et al. 2013): A subset of primitive concepts that are more informative for each event. 3) Bi (Rastegari et al. 2013): Bi-concepts discovered in (Rastegari et al. 2013). 4) OR (Habibian, Mensink, and Snoek 2014): Boolean OR combinations of Prim concepts. 5) Fu (Habibian, Mensink, and Snoek 2014): Boolean AND/OR combinations of Prim
Table 1: Experiment results for 0Ex event detection on MEDTest 2014, MEDTest 2013, and CCV_sub. Mean average precision (mAP), in percentages, is used as the evaluation metric. Larger mAP indicates better performance.

<table>
<thead>
<tr>
<th>ID</th>
<th>Prim</th>
<th>Sel</th>
<th>Bi</th>
<th>OR</th>
<th>Fu</th>
<th>Bor</th>
<th>PCF</th>
<th>DCC</th>
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<td>2.98</td>
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<td>3.97</td>
<td>3.12</td>
<td>4.64</td>
<td>6.37</td>
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<td>0.97</td>
<td>0.83</td>
<td>1.36</td>
<td>1.49</td>
<td>1.15</td>
<td>1.48</td>
<td>2.85</td>
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<td>35.23</td>
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<td>1.01</td>
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<td>1.59</td>
<td>1.32</td>
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<td>E027</td>
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<td>15.12</td>
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<td>2.25</td>
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<tr>
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<td>0.98</td>
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</table>

concepts, w/o concept refinement. 6). Bor: The Borda rank aggregation with equal weights on the discovered semantic concepts. 7). PCF (Chang et al. 2015a): The pair-comparison framework is incorporated for zero-shot event detection.

Zero-exemplar event detection

We report the full experimental results on the TRECVID MEDTest 2014 dataset in Table 1 and also a summary on the MEDTest 2013 dataset and CCV_sub. From the experimental results shown in Table 1, the proposed algorithm, DCC, performs better than the other approaches with a large margin (13.37% vs 11.44% achieved by PCF). The proposed approach gets significant improvement on some vents, such as Dog Show (E023), Rock Climbing (E027), Beekeeping (E031) and Non-motorized Vehicle Repair (E033). By analyzing the discovered concepts for these events, we find that their classifiers are very discriminative and reliable. For example, for the event Rock Climbing, we discovered the concepts ‘‘Sport climbing’, ‘Person climbing’ and ‘Bouldering’, which are the most informative concepts for Rock climbing in the concept vocabulary. Figure 1 illustrates the top retrieved results on the non-motorized vehicle repair event. To save space, we only show the top 4 compared algorithms (OR, Fu, PCF and DCC). It is clear that videos retrieved by the proposed DCC are more accurate and visually coherent.

We make the following observations from the results shown in Table 1: 1). Sel significantly outperform Prim with mAP of 9.55% vs 6.40% on MEDTest 2014, which indicates that selecting the most discriminative concepts generally improves detection performance than naively using all the concepts. 2). Comparing the results of Bi, OR, Fu and Bor, we verify that the selected informative concept classifiers are not equally important for event detection. It is beneficial to derive the weights for each concept classifier. By treating the concept classifiers differentially, better performance is achieved. 3). Comparing the results of DCC with the other alternatives, we observe that learning optimal weights of concept classifiers for each testing video significantly improves performance of event detection. This confirms the importance of dynamic concept composition.

We made similar observations from the results on the TRECVID MEDTest 2013 dataset and CCV_sub dataset.

Extension to few-exemplar event detection

The proposed zero-example event detection framework can also be used for few-exemplar event detection: we aggregate the concept classifiers and the supervised classifier using the dynamic concept composition approach. In this section, experiments are conducted to demonstrate the benefit of this hybrid approach. Table 2 summarizes the mAP on both the MEDTest 2014 and 2013 datasets, while Figure 2 compares the performance event-wise.

According to the NIST standard, we consider the 10 Ex experiments are conducted to demonstrate the benefit of this dynamic concept composition approach. In this section, experiments are conducted to demonstrate the benefit of this hybrid approach. Table 2 summarizes the mAP on both the MEDTest 2014 and 2013 datasets, while Figure 2 compares the performance event-wise.

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which had no labeled training data can get comparable results with the supervised classifier (mAP 13.37% vs 13.92% on MEDTest 2014). This demonstrates that proper aggregation with optimal weights for each testing video can get promising results for event detection.

We compare DCC with IDT event-wise in Figure 2. From the results we can see that our DCC outperforms the supervised IDT on multiple events, namely E023, E024, E031 and E033. To be specific, on the event Beekeeping (E031), DCC significantly outperform the supervised IDT (77.45% vs 33.92%). This is not supervising, since DCC significantly benefited from the presence of informative and reliable concepts such as “apiary bee house” and “honeycomb” on the particular Beekeeping event.

Finally we combine DCC with IDT to get the final few-example event detection result. This improves the performance from 13.92% to 16.98% on the MEDTest 2014 dataset. As expected, the gain obtained from such simple hybrid diminishes when combining with more sophisticated methods. Overall, the results clearly demonstrate the utility of our framework even in the few-exemplar setting.

**Conclusions**

To address the challenging task of zero-exemplar or few-exemplar event detection, we proposed to learn the optimal weights for each testing video by exploring the collected videos from other sources. Data-driven word embedding models were used to seek the relevance of the concepts to the event of interest. To further derive the optimal weights of the concept classifiers for each testing video, we have proposed a novel dynamic concept composition method by exploiting the textual information of the collected videos. Extensive experiments are conducted on three real video datasets. The experimental results confirm the efficiency of the proposed approach.

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