Sub-Sentence Encoder: Contrastive Learning of Propositional Semantic Representations

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Abstract

We introduce *sub-sentence encoder*, a contrastively learned contextual embedding model for fine-grained semantic representation of text. In contrast to the standard practice with sentence embeddings, where the meaning of an entire sequence of text is encoded into a fixed-length vector, the sub-sentence encoder learns to produce distinct contextual embeddings corresponding to different *atomic propositions*, i.e. distinct units of meaning expressed within a text sequence. The sub-sentence embeddings are contrastively learned to recognize (inferred) semantic equivalence between propositions across different text sequences. Our experiments show the effectiveness of sub-sentence encoders in applications, such as retrieving supporting facts for fine-grained text attribution or recognizing the conditional semantic similarity between texts. In practice, we demonstrate that sub-sentence encoders keep the same level of inference cost and space complexity compared to sentence encoders.

https://github.com/schen149/sub-sentence-encoder

1 Introduction

Sentence embeddings are a class of techniques that represent text semantics as dense vector embedding(s), which are widely used in zero-shot or transfer learning settings on information retrieval and text classification tasks (Conneau et al., 2017; Cer et al., 2018; Reimers and Gurevych, 2019; Karpukhin et al., 2020; Gao et al., 2021). Sentence embeddings are typically learned to recognize the semantic relation between two text inputs. The common practice is to encode each text input as one fixed-length vector, where the semantic relation with the other input is modeled by a similarity function (Bromley et al., 1993).

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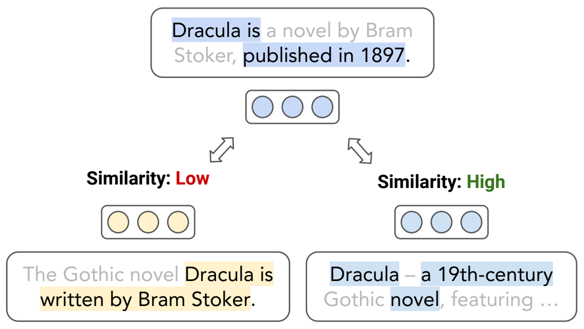
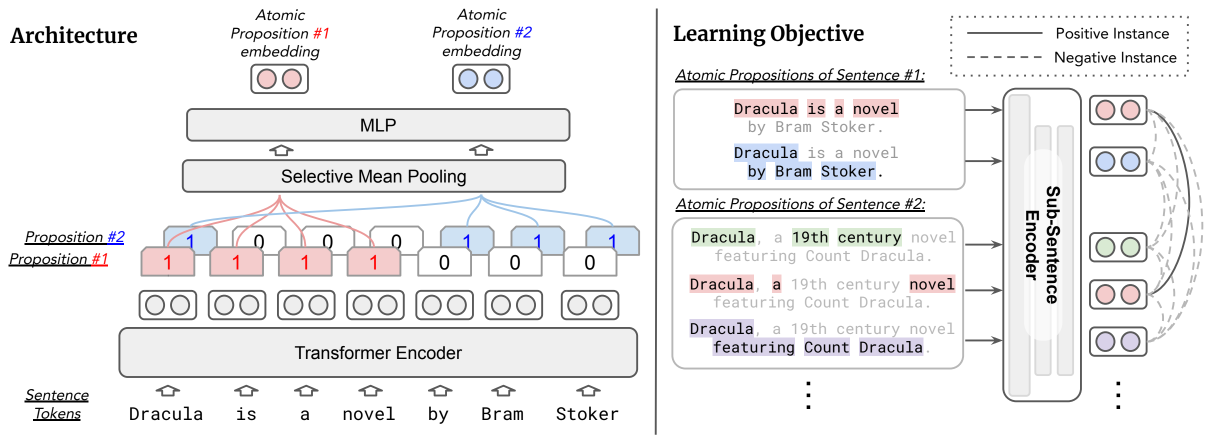

Dracula is a novel by Bram Stoker, published in 1897.
Similarity: Low
Similarity: High
The Gothic novel Dracula is written by Bram Stoker.
Dracula – a 19th-century Gothic novel, featuring ...

Figure 1: Given a *proposition* in a sentence (represented by a highlighted subset of tokens), the *sub-sentence encoder* produces a contextual embedding for the meaning of the proposition. The cosine similarity between the sub-sentence embeddings captures the (inferred) semantic similarity between the propositions.

While sentence embeddings provide a unified and compact representation for text semantics, it is difficult to query for the semantics on the *sub-sentence* level. For example, consider the two sentences with blue highlights in Figure 1 about the novel *Dracula*. Because the two sentences as a whole convey different meanings, they would have a low similarity between their sentence embeddings. However, the two sentences in-part share similar meanings on the level of *propositions*, i.e., distinct units of meaning in each sentence.

Being able to (efficiently) index textual information and model semantic similarity on a more granular level potentially have a profound impact on applications like long-form text evaluation (Amplayo et al., 2022), attribution (Rashkin et al., 2023) or factuality estimation (Min et al., 2023). With long-form generated text, multiple propositions in the same text might have different truthfulness values. The prerequisites for verifying or attributing such long-form text involve (1) representing text on a more granular level of propositions and (2) being able to retrieve evidence for different propositions within text. (Kamoi et al., 2023).

Motivated by such, we introduce *sub-sentence*



Architecture
Atomic Proposition #1 embedding
Atomic Proposition #2 embedding
MLP
Selective Mean Pooling
Proposition #2
Proposition #1
Transformer Encoder
Sentence Tokens
Dracula is a novel by Bram Stoker
Learning Objective
Positive Instance
Negative Instance
Atomic Propositions of Sentence #1:
Dracula is a novel by Bram Stoker.
Atomic Propositions of Sentence #2:
Dracula, a 19th century novel featuring Count Dracula.
Sub-Sentence Encoder

Figure 2: Overview of the *sub-sentence encoder* architecture and learning objective: The model takes a sentence and its propositions (represented as binary token masks) as input and outputs an embedding for each proposition. Given a minibatch of sentences, the model learns to identify pairs of propositions that express the same meaning. All others (including other propositions within the same sentence) are taken as negative examples (§3).

encoder, a contrastively-learned contextual embedding model for representing sub-sentence-level semantics. As shown in Figure 2, the sub-sentence encoder takes a proposition within a text sequence as input. It outputs an embedding that represents the meaning of the proposition. Each proposition takes the format of a binary token mask sequence over the text, which denotes the tokens included in each proposition (Chen et al., 2023). We train the sub-sentence encoder model to recognize the semantic equivalence between pairs of *propositions* via in-batch supervised contrastive learning (Khosla et al., 2020). We sample and create training examples from a large corpus of unlabeled sentence pair data with proposition extraction and natural language inference (NLI) models (§3.3).

We evaluate sub-sentence encoders on two types of downstream tasks that involve semantic representation on the sub-sentence level. First, we demonstrate that sub-sentence encoders can be used for fine-grained retrieval, e.g., for text attribution, where a model is expected to retrieve supporting evidence for different parts of a sentence. Second, we show that sub-sentence encoders can be used to infer the conditional semantic similarity between a pair of text (Deshpande et al., 2023).

We discuss the design choices and challenges in applying sub-sentence encoders in large-scale indexing of a knowledge source, e.g. Wikipedia, on the proposition level. As encoding an entire corpus on the proposition level might result in a prohibitively large index, we reduce the output dimension of the sub-sentence encoder model during training (Wang et al., 2023). This simple yet effective trick yields 12 to 16× compression in index size with minimal performance drop.

The main contributions of the paper are:

- We propose *sub-sentence encoder*, a contextual embedding model for fine-grained text semantics.
- We introduce an automatic model-assisted process for sampling semantically similar propositions for sub-sentence encoder training.
- We demonstrate the utility of sub-sentence encoders in the downstream applications of atomic fact/attribution retrieval and conditional semantic textual similarity.

2 Preliminaries

2.1 Motivation: Text Attribution

Our design of the sub-sentence encoder is largely motivated by the downstream application of text attribution (Rashkin et al., 2023), i.e., identify supporting information from known sources to attribute a given text. With the widespread adoption of text generation models, evaluating and attributing generated text has become an emerging research topic in need (Gao et al., 2023a,b; Liu et al., 2023; Malaviya et al., 2023). A key challenge in such tasks lies in the granularity of attributed information, i.e., one piece of generated text usually makes more than one claim, each of which might have different veracity. For instance, as Figure 1 shows, there could exist multiple claims even within one generated sentence in the form of propositions. Each claim or proposition needs to be contextualized (Choi et al., 2021) and individually verified against potentially different information sources (Kamoi et al., 2023; Min et al., 2023). This process inevitably requires an efficient model representing the semantics of different sentence parts in context, which describes the key design principle for the sub-sentence encoder.

2.2 Limitations of Sentence Embeddings

From the perspective of downstream applications such as text attribution, our *sub-sentence encoder* seeks to address the following two shortcomings of current sentence encoder models.

Granularity. Although sentence embeddings usually capture the meaning of the entire text sequence (Morris et al., 2023), it is difficult in practice to query sentence embeddings for semantic information on a more granular level (Wang and Yu, 2023). Motivated by such, previous studies have attempted to develop embedding functions that work for finer-grained semantic units. For instance, Skip-Prop (Rudinger et al., 2017) is a counter-part of Skip-Thought (Kiros et al., 2015), where an LSTM encoder-decoder model learns to produce one embedding per proposition, as opposed to per sentence. Qin and Van Durme (2023) introduce Nugget, a transformer encoder-decoder language model, where the model learns to select k contextualized token embedding as the intermediate segment embedding for an input sequence. In the context of information retrieval, our work in-part echoes the motivation with multi-vector retrieval (Seo et al., 2019; Khattab and Zaharia, 2020; Luan et al., 2021; Lee et al., 2021a; Zhang et al., 2022), where each retrieval text unit is represented by multiple embeddings. Compared to these models, our sub-sentence encoder instead opts for a simpler input/output protocol, where the each proposition in an input text is encoded independently of others.

Contextualization. A typical assumption for sentence encoder models and training/evaluation task setup is that the sentence is encoded independently without context. This becomes a limiting factor in scenarios where similarities and discrepancies between text pairs depend on the context they appear in (Chen et al., 2019; Schuster et al., 2022; Milbauer et al., 2023a,b; Deshpande et al., 2023).

3 Sub-Sentence Encoder

We introduce *sub-sentence encoders*. Contrary to sentence encoders, sub-sentence encoders are designed to produce contextual embeddings for each atomic proposition in a sentence.

3.1 Architecture

The sub-sentence encoder architecture is instantiated similarly to transformer-based sentence bi-encoders (Reimers and Gurevych, 2019), as shown in Figure 2. The key difference is the sub-sentence encoder takes one or more binary token masks as extra inputs, which indicate the target proposition(s) of a sentence that it should produce embeddings for. The input sentence is first forwarded through a transformer encoder, which can be initialized from any pre-trained encoder model. Then, for each of the proposition token masks, the token embeddings with mask values of 1 are mean pooled and forwarded through a projection MLP layer. The model outputs k fixed length embedding corresponding to the k input propositions.

Note that the k token masks are only applied during pooling, and the encoder still gets full attention to the entire sentence. This allows the proposition embeddings to have the contextual information of the entire input sentence/paragraph, potentially alleviating the need for decontextualizing the propositions (Choi et al., 2021). In addition, since there is no cross-attention between the proposition embeddings, each proposition is encoded independently of others, and its representation is inherently invariant to the input ordering of the propositions.

Compared to sentence encoders, the sub-sentence encoder adds a small amount of parameters with the MLP layer on top. As the sentence can be forwarded only once, the extra inference cost of encoding multiple propositions in a sentence is minimal in practice, as we discuss in §4.

3.2 Contrastive Learning

With two propositions from different sentences, the goal is to make them have similar embedding representations if they express similar meanings, and have dissimilar representations otherwise. Within a minibatch of N propositions from M sentences. Let $v_i = \in \mathbb{R}^d$ be the encoded representation of the i^{th} proposition in the batch. Let $I = \{1..N\}$ denote the index of all propositions. We formulate the learning objective as minimizing the in-batch supervised contrastive loss $\mathcal{L}$ (Khosla et al., 2020):

$$\mathcal{L} = \sum_{i \in I} \frac{-1}{|P(i)|} \sum_{p \in P(i)} \log \frac{\exp(v_i \cdot v_p / \tau)}{\sum_{j \in I \setminus \{i\}} \exp(v_i \cdot v_j / \tau)}$$

where $P(i)$ is the set of indices of all positive propositions to the i^{th} proposition within the mini-batch, and $|P(i)|$ denotes its cardinality. τ controls the softmax temperature. The learning objective encourages the model to produce embeddings with higher cosine similarity with positive pairs of propositions, while all other propositions in the same batch are considered negatives. Note that if all propositions from the same sentence are packaged in the same minibatch, under the assumption that they cannot be positive examples of each other, the learning objective would inherently encourage the model to assign different representations for different parts of a sentence.

The supervised contrastive loss is a generalized form of other commonly used loss functions for bi- or dual-encoder training, e.g., N-pairs loss (Sohn, 2016) or in-batch softmax (Karpukhin et al., 2020). We opt for this formulation mostly due to its ability to generalize to an arbitrary number of positive examples in the same batch. In our case, this is important, as each proposition may have zero or more positive instances in the same minibatch.

3.3 Sampling Proposition Pairs for Training

Here, we describe how we automatically sample positive proposition pairs from a collection of unlabeled sentence pairs as training data for the sub-sentence encoder. We start from a collection of 2.5M sentence pairs from topically related news articles (Zhou et al., 2022). The data is sampled from RealNews (Zellers et al., 2019), which contains sentence pairs that generally describe the same event with slightly different angles and focuses. These instances serve as great starting points for us, as they typically share proposition pairs with both similarities and differences.

Step 1: Segment Sentences ⇒ Propositions. Given an unlabeled sentence pair, we first parse each sentence into propositions in natural language forms. First, we prompt `GPT-3.5-turbo` to generate propositions for 1% of all sentence pairs as the seed set of training data. We find that `GPT-3.5-turbo` with few shot in-context demonstrations gives reasonable performance on the task, which echos with the observations from Min et al. (2023) and Kamoi et al. (2023).

Next, we finetune T5-large (Raffel et al., 2020) on the seed training set and use the model to generate propositions for the rest of the dataset. We include more details about the prompt and training process in Appendix A.

Step 2: Identify Positive Pairs with NLI models. Given the two sets of propositions (in natural language form) in each sentence pair, we infer and label the positive proposition pairs with an off-the-shelf NLI model (Nie et al., 2020) [1]. We forward each pair of propositions across two sentences through the NLI model two times, with flipped orders between hypothesis and premise. We label a proposition pair positive if the NLI model classifies their relation as entailment in both directions. We only keep sentence pairs with at least one pair of positive propositions. This leaves us with $240k$ sentence pairs, with 3.32 propositions per sentence and 1.21 positive propositions on average.

Step 3: Convert Propositions ⇒ Token Masks. We convert the propositions in natural language form to the token mask format used for sub-sentence encoder input by aligning the tokens in each proposition to the sentence. We use NLTK (Bird et al., 2009) to lemmatize each token in a proposition and its sentence and construct an affinity matrix between the two, where tokens with identical lemmas are assigned a similarity score of 1. To break ties between multiple token matches, we apply a 2D-convolution filter on the affinity matrix, which adds a small score offset for other token matches in a context window of three tokens. We find the optimal matches between the proposition and sentence with max bipartite matching on the affinity matrix with the Hungarian algorithm (Kuhn, 1955). We include a more detailed process description in Appendix A.

4 Experimental Setup

4.1 Model Configurations

We initialize the transformer encoder layers with pre-trained weights from three types of sentence encoders: SimCSE (Gao et al., 2021), Sentence-T5 (Ni et al., 2022a), and GTR (Ni et al., 2022b). With Sentence-T5 and GTR, we experiment with the base, large, and xl-sized variants of the models. For the MLP layer, we keep the output dimension the same as the transformer encoder. We discuss the impact of varying output dimensions in §5.4.

We finetune the sub-sentence encoder with different variants of backbone sentence encoders on the

[1]`https://huggingface.co/ynie/roberta-large-snli_mnli_fever_anli_R1_R2_R3-nli`

System	Param. Size	PRECISION@1	RECALL@5	RECALL@10	RECALL@20
MiniLM-L6-v2	23M	18.36	37.28	44.87	51.62
DistilRoberta	82M	16.59	33.65	40.82	46.79
SimCSE (unsupervised)	110M	8.90	45.13	69.47	84.29
SimCSE (supervised)	110M	16.53	57.83	77.28	**87.89**
GTR$_{base}$	110M	21.90	52.50	65.54	75.69
ST5$_{base}$	110M	26.16	57.65	69.00	78.58
SUBENCODER (SimCSE)	110M (+0.5M)	**41.64**	71.48	78.22	83.34
SUBENCODER (ST5$_{base}$)	110M (+0.5M)	40.97	72.15	79.30	84.33
SUBENCODER (GTR$_{base}$)	110M (+0.5M)	40.77	**72.90**	**80.45**	85.81

Table 1: Zero-shot evaluation results on the *Atomic Fact Retrieval* task in PROPSEGMENT (Chen et al., 2023).

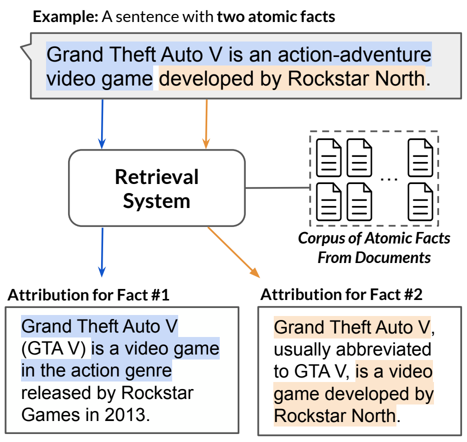

Example: A sentence with two atomic facts
Grand Theft Auto V is an action-adventure video game developed by Rockstar North.
Retrieval System
Corpus of Atomic Facts From Documents
Attribution for Fact #1
Grand Theft Auto V (GTA V) is a video game in the action genre released by Rockstar Games in 2013.
Attribution for Fact #2
Grand Theft Auto V, usually abbreviated to GTA V, is a video game developed by Rockstar North.

Figure 3: In the *Atomic Fact Retrieval* task (Chen et al., 2023), given an atomic proposition in the query, a system is expected to retrieve the set of supporting atomic propositions from the corpus. The dataset features $8.8k$ query propositions and $45k$ candidate evidence propositions from $1.5k$ documents.

$240k$ sentence pairs with at least one pair of positive propositions. We denote the resulting model as SUBENCODER. Details for our distributed training setup and hyperparameters are in Appendix B.

4.2 Evaluation

To assess the utility of the sub-sentence encoders, we evaluate our models on two types of downstream tasks in zero-shot settings.

4.2.1 Atomic Fact Retrieval for Fine-Grained Text Attribution

We first evaluate the sub-sentence encoders in retrieving fine-grained attributions (Rashkin et al., 2023) for text. We conduct the evaluations with the PROPSEGMENT dataset (Chen et al., 2023). An overview of the task setup is shown in Figure 3. Given a proposition in the sentence, a system is expected to identify and retrieve supporting evidence from a corpus of ˜$45k$ human-labeled atomic propositions from $1.5k$ News or Wikipedia documents in total. The task setup emulates the setting where each part of a sentence might have different veracity, and so each proposition in a sentence might be attributed to different supporting evidence from different source documents. On average, each query has 1.13 ground truth supporting propositions.

Metrics. Given a system's output rankings of the $45k$ candidate evidence propositions to a query proposition, we measure the precision@1 plus recall@$\{5, 10, 20\}$ of the ranking against the ground truth set of evidence propositions.

Baselines. We compare pre-trained sentence encoders as baselines. We first evaluate variants of unsupervised and supervised SimCSE, Sentence-T5, and GTR on similar model parameter sizes. In addition, we compare two popular compact models, i.e., `all-MiniLM-L6-v2` and `all-distilroberta-v1` from `sentence-transformers` (Reimers and Gurevych, 2019). We discuss the setup for sentence encoders for the tasks in Appendix C.

Results. Table 1 shows our evaluation results with sentence and sub-sentence encoders compared on the similar scale of model parameter sizes. With proposition-level contrastive learning, We observe that the SUBENCODER with different backbone encoders generally improve over their sentence encoder counterparts. We see the most visible improvements of SUBENCODER in terms of Precision@1 and Recall@5, while the performance gap becomes smaller in terms of Recall@10 and 20. As the task involves retrieving different results for different query propositions in a sentence, the evaluation results suggest that sub-sentence contrastive learning gives the model better capabilities at recognizing the nuanced semantic differences between propositions appearing in the same context.

Across different variants of SUBENCODER with different backbone sentence encoders, we observe similar performance levels overall, with the

GTR$_{base}$ variant having a slight edge. In Table 1, we mostly compare models with the same backbone encoder size and configurations. Our SubEncoder only introduces 0.5% extra parameters with the MLP layer on top. We discuss the model size, efficiency, and performance trade-off in §5.

4.2.2 Conditional Semantic Text Similarity

To assess SubEncoder's ability to produce contextual representations for fine-grained sub-sentence level semantics of text, we conduct experiments on the Condition Semantic Text Similarity (C-STS) task (Deshpande et al., 2023). Compared to STS (Agirre et al., 2012), C-STS introduces a condition notion of similarity between text pairs, where an additional natural language condition is provided along with the text pair as input. A system is expected to output a similarity score between the pair from the perspective of the given condition. Table 2 shows some examples of the task.

Method. Given the condition, we first prompt an LLM to identify a set of words in each sentence that best corresponds to the condition. Here, the LLM only sees one sentence at a time, so the condition words in each sentence are identified independently. We use the sub-sentence encoder to encode the set of words in the context of each sentence as the conditional representation. We take the cosine similarity between two encoded sets of words from the text pair as their conditional similarity.

Metrics. We compare the Spearman correlation coefficient between predicted similarity from a system against human ratings.

Baselines. We compare to a list of zero- and few-shot baselines provided by Deshpande et al. (2023). This includes two bi-encoder models, Roberta$_{base}$ and SimCSE$_{base}$ that do not make use of the condition as input, as well as zero- and few-shot prompting results with FlanT5$_{large}$, `GPT-3.5-turbo` and `GPT-4`, where each LLM provided detailed instructions of the task, and is prompted to generate a similarity score from 1 to 5 given the text pair and condition with/without in-context demonstrations.

Results. Table 3 shows the evaluation results. By having SubEncoder comparing the contextual similarity between the set of words selected by `gpt-3.5-turbo`, we see an improvement in zero-shot setting from Spearman's $r = 14.1 \rightarrow 33.0$, compared to directly prompt LLM to output the similarity. However, the performance gap when using `gpt-4` becomes much smaller ($r = 36.9 \rightarrow 37.2$). This is reasonable considering the fact that direct `gpt-4` prompting demonstrates on-par performance with supervised systems on C-STS, as reported in Deshpande et al. (2023). We show examples of typical mistakes made by our model in Table 2. We observe that our method typically fails when (1) the LLM fails to identify a good set of condition words, or when no such corresponding words explicitly exist in the sentence, or (2) SubEncoder fails to correctly infer the similarity between the two sets of condition words. For instance, with the third example in Table 2, the inference is particularly challenging for the model, considering the relation is modeled only via a cosine similarity with no learned parameters.

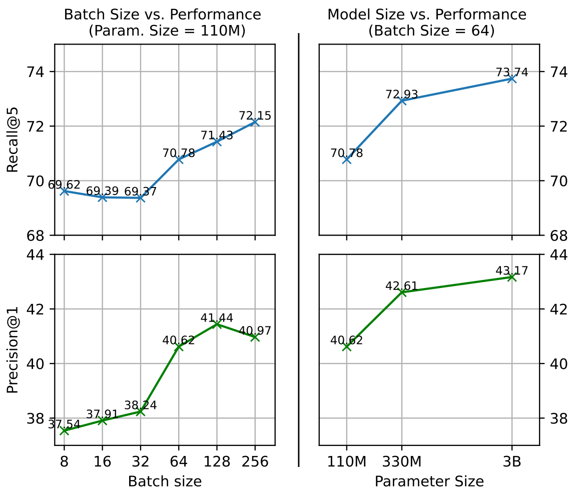


Figure 4: The effect of varying batch size and model parameter size on the atomic fact retrieval performance, tested with the Sentence-T5 variant of SubEncoder.

5 Analysis and Discussions

5.1 Scaling SubEncoder

In Figure 4, we show an analysis of the effect of scaling model sizes and batch sizes during training. For our analysis, we use the Sentence-T5 variant of SubEncoder, and evaluate the performance on the atomic fact retrieval task.

Scaling Batch Size. As our contrastive learning objective leverages in-batch negative sampling, scaling up the batch sizes during training could bring performance gains. To illustrate this, we initialize SubEncoder with Sentence-T5 base encoder parameters and finetune with a varying batch size of $\{8, 16, 32, 64, 128, 256\}$. We observe that increasing the batch size generally increases perfor-

Type	Sentence 1	Sentence 2	Condition	Label	Pred.
Correct.	A group of people go sledding on a snowy hill, and a dog chases one as he slides.	A person, dressed in black, skipping down a snow covered road and playing with a black dog.	The physical activity.	4	3.44
Mistake: fails to find a good set of words.	A man being thrown into the air while being trampled by a bull.	The cowboy holds on to the bull who is desperately trying to throw him off.	The person's elevation.	4	1
Mistake: correct set of words; failed inference.	A man wearing a white tank top and a white hard hat is holding two pieces of pipe at a construction site.	A construction worker in a lime-green safety vest and orange hard hat is looking closely at something held in his hands.	The occupation of the man.	5	2.47

Table 2: Example outputs and typical mistakes of SUBENCODER on C-STS. The set of words identified by `gpt-3.5` is highlighted yellow. For display purposes here, the model predicted cosine similarity is normalized to match the human labels' scale of 1 - 5, where 1 = Least similar, and 5 = Most similar

Model	Setting	Spearman r ↑
Roberta$_{base}$	*0-shot (No. Cond.)*	-0.43*
SimCSE$_{base}$	*0-shot (No. Cond.)*	1.66*
`FlanT5`$_{large}$	*0-shot*	-3.0*
	2-shot	11.7*
`GPT-3.5`	*0-shot*	14.1
	2-shot	15.4
`GPT-4`	*0-shot*	36.9
	2-shot	**40.7**
`GPT-3.5` + SUBENCODER (0-shot)	(SimCSE$_{base}$)	27.5
	(GTR$_{base}$)	31.9
	(ST5$_{base}$)	**33.0**
`GPT-4` + SUBENCODER (0-shot)	(SimCSE$_{base}$)	34.5
	(GTR$_{base}$)	36.9
	(ST5$_{base}$)	37.2

Table 3: Spearman correlation coefficient (×100) of model predictions evaluated in zero- or few-shot settings on the *Conditional Semantic Textual Similarity* (C-STS) task. * denotes results from Deshpande et al. (2023).

mance, which suggests that batch size scaling could yield better model generalizability. We observe a significant performance gain when increasing batch size from 32 → 64 while seeing diminishing gains with further increase. This echoes the empirical findings with in-batch contrastive learning in general (Khosla et al., 2020). The phenomena can be attributed to the model-predicted labels in our training dataset, which can be noisy.

Scaling Model Size. We initialize the encoder with different sizes of Sentence-T5 from 110M to 3B parameters and finetune with a fixed batch size of 64. We observe that starting from a larger pretrained encoder brings better performance. We see a bigger gain when increasing the model size from 110M to 330M, while the gain becomes smaller when we increase from 330M to 3B.

5.2 Using SUBENCODER for Sentence or Document Retrieval

In §4, we compare SUBENCODER's performance on the atomic fact retrieval task against the baseline sentence encoders. In reality, a more likely application scenario is when the system is expected to retrieve supporting evidence on the sentence or document level. To evaluate this, we cast the atomic fact retrieval task as a sentence or document retrieval task, where given a query proposition, a system is expected to retrieve the set of sentences or documents that contain the target proposition(s).

From the intuition that finer-grained retrieval, e.g., with propositions, entails the more coarse sentence- or document-level retrieval, we follow Lee et al. (2021b) and use a simple strategy with SUBENCODER for sentence- and document-level retrieval. Given each query, we retrieve a slightly larger number of propositions. From the set of sentences and documents where the propositions belong, we use the highest score among the set of propositions as the score for each sentence or document. The top k unique sentences or documents are then returned as results.

Table 4 shows the the evaluation result. Compared to GTR$_{base}$ and Sentence-T5$_{base}$, which are trained for document-level and sentence-level retrieval, respectively, we observe a similar level of performance with retrieving by propositions with SUBENCODER. Overall, we see lower top-1 accuracy compared to the baselines. This is possibly due to the more complex nature of the proposition retrieval task. However, we generally see an improvement in terms of recall @ 5. The findings indicate the potential of using SUBENCODER for multi-vector retrieval across different granularities.

Model	Sentence-Level P@1	Sentence-Level R@5	Document-Level P@1	Document-Level R@5
GTR$_{base}$	49.35	77.01	**51.93**	81.97
Sentence-T5$_{base}$	**50.59**	79.37	45.27	77.10
SUBENCODER (GTR)	42.94	**82.27**	45.04	**90.13**
SUBENCODER (ST5)	43.49	81.44	45.93	89.19

Table 4: Sentence and document retrieval performance of the atomic fact retrieval task. We evaluate GTR$_{base}$ and Sentence-T5$_{base}$ variants of SUBENCODER.

Model	Dim.	Precision@1	Recall@5
SUBENCODER (ST5-Large)	1024	42.61	72.93
	64	42.10 (-0.51)	70.17 (-2.76)
SUBENCODER (ST5-Base)	768	40.97	72.15
	64	40.45 (-0.52)	71.62 (-0.53)

Table 5: The performance difference on the atomic fact retrieval task with vs. without reducing the output dimensionality of SUBENCODER.

5.3 Robustness to Input Formats/Boundaries

Although SUBENCODER is fine-tuned with data formatted as propositions specifically, we observe from the C-STS evaluations that the model generalizes to not necessarily proposition-shaped inputs, as shown in Table 2. In downstream applications, we would expect the model to generalize to input token masks with imperfect boundaries, e.g., propositions generated by a model instead of labeled by humans. Alongside the C-STS evaluation results, which indirectly support our hypothesis, we conduct a simple evaluation with the atomic fact retrieval task. Instead of human-annotated queries, we use queries generated by `gpt-3.5-turbo`. The evaluation results of the proposition segmentation performance of `gpt-3.5-turbo` and the distilled T5-Large model can be found in Appendix A. When we test the atomic fact retrieval performance on the set of model-generated propositions that can be fuzzy-matched under Jaccard similarity of > 0.8 with the human-annotated ones, we only see a small drop in performance, e.g., with the GTR-base variant of SUBENCODER, precision@1 drops from 40.77 $\rightarrow$ 39.56, recall@5 drops from 73.14 $\rightarrow$ 72.23. This indicates that our model is robust to imperfect proposition boundaries.

5.4 Offline Indexing and Compression

With the promising performance gain from SUBENCODER in the atomic fact retrieval task, we discuss and assess the possibility of applying SUBENCODER for fine-grained retrieval on larger-scale corpora, which involves offline indexing and caching the encoded corpora. In our case, the indexing happens on the level of propositions, where we need to store one embedding for every proposition in the corpora. Compared to document-level indexing, indexing on the proposition level would result in a prohibitively large index size. In previous works (Lee et al., 2021b), this is commonly addressed with techniques such as product quantization (Jegou et al., 2010) to compress index size or approximate nearest neighbor search (Malkov and Yashunin, 2018) for faster inference.

Index	Num. Entries	Dim.	Index Size
Propositions	270M	64	62GB
`dpr-100w`	21M	768	61GB

Table 6: The resulting index size with proposition-level indexing with compressed dimension, compared to a DPR index of 100-word blocks (Karpukhin et al., 2020).

Orthogonal to the two techniques above, we study a simpler yet effective compression strategy by reducing the output dimension of SUBENCODER. In the context of sentence encoders, Wang et al. (2023) discover that reducing the output dimensionality during training generally incurs minimal downstream performance loss. Following this idea, we finetune the Sentence T5 base and large variants of SUBENCODER with a bottlenecked output dimension of 64 instead of the original output dimensions of 1024 and 768, respectively. Table 5 shows the performance comparison when evaluated on the atomic fact retrieval task. Overall, we observe a very small performance drop while gaining 12$\times$ to 16$\times$ reduction in output embedding size.

To demonstrate the implication of this in practice, we use the Sentence T5 large variant of SUBENCODER to encode an English Wikipedia dump from 2021/10/13, as used by Bohnet et al. (2022). We segment all sentences in Wikipedia into propositions with the T5-large model (§3.3). This results in ˜270M propositions from 5.3M Wikipedia pages. Table 6 shows the resulting index. The resulting size of 62GB is close to a prebuilt (uncompressed) dense passage retrieval (DPR) index on the level of 100-word blocks (Karpukhin et al., 2020). We see that decreasing the output dimension of the embeddings helps in reducing the cached idnex size. It is worth noting that compared to the document-level index, we still expect the query speed of the index to increase slightly due to the increase in the number of entries. However, in practice, we observe a reasonable overall time and space complexity involved in offline indexing and online similarity querying on the proposition-level.

6 Conclusion

We introduce sub-sentence encoders, a contrastive learning framework for learning contextual embeddings for semantic units on the sub-sentence level. Beyond the use cases covered in the paper, the sub-sentence encoder architecture could potentially serve as the backbone for any cross-document information linking tasks in context, and the learning objectives could potentially apply to a broader range of tasks with various granularity of information, e.g., linking sentences or spans within different documents (Ma et al., 2023). We hope that the findings in this paper will facilitate further exploration along these directions.

Limitations

The goal of this work is to validate the idea behind sub-sentence encoder architecture and learning objectives. We acknowledge the limited scale of our experiments, specifically (1) *Number of tasks or applications evaluated*: This is mostly due to the limited number of human-labeled benchmark datasets suitable for our case. (2) *Language covered*: In our experiments, we explore the idea of *sub-sentence encoder* with English text only. However, the techniques described in the paper for sampling training data and training the *sub-sentence encoder* can be applied to other languages as well. We leave the exploration on multilingual *sub-sentence encoder* for future work.

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A Proposition Segmentation

In this section, we provide details on the few-shot prompt and distilled T5-large model we use for segmenting sentences into propositions. We provide evaluations the two methods against PROPSEGMENT (Chen et al., 2023).

A.1 Prompt for Proposition Segmentation

We use the following prompt with `gpt-3.5-turbo` to generate the initial set of seed training data for segmenting sentences into propositions. We provide one example from PROPSEGMENT for in-context learning demonstration. We process ˜23, 000 sentence pairs with the prompt, which generates a total of 44,970 sentences with propositions, after filtering out malformed and empty generations.

Prompt for sentence ⇒ propositions

Given the following sentence, tell me what claims they are making. Please split the sentence as much as possible, but do not include information not in the sentence.

Sentence: The Andy Warhol Museum in his hometown, Pittsburgh, Pennsylvania, contains an extensive permanent collection of art.

Claims:

1. The Andy Warhol Museum is in Pittsburgh.
2. Andy Warhol's hometown is in Pittsburgh.
3. Pittsburgh is in Pennsylvania.
4. The Andy Warhol Museum contains an extensive permanent collection of art.

Sentence: (*input sentence*)
Claims:

A.2 Training detail of T5 for proposition segmentation

We finetune a T5-large (Raffel et al., 2020) model on a seed set of training data generated via `GPT-3.5-turbo`. We use an AdamW optimizer with a constant learning rate of $1e^{-4}$, with a batch size of 128. We train the model for 3 epochs on 8x Nvidia A6000s, which takes 2 hours to finish.

A.3 Converting propositions from natural language to token masks

Given a proposition of a sentence in the natural language form, we convert and align it to a subset of tokens from the original sentence with the

Model	Jaccard $\theta = 0.8$			Jaccard $\theta = 0.5$		
	Precision	Recall	F1	Precision	Recall	F1
Systems used in this paper						
`GPT-3.5-turbo`	35.79	31.65	33.60	71.52	63.87	67.48
T5-Large (w/ GPT3.5 training data)	35.91	31.70	33.68	70.27	63.39	66.65
Systems fine-tuned on PROPSEGMENT *(Chen et al., 2023)*						
BERT-Large	34.97	33.42	34.17	67.42	64.17	65.75
T5-Large	55.95	55.05	55.50	78.03	76.74	77.38

Table 7: Sentence segmentation performance of systems used in this paper when evaluated in zero-shot settings on PROPSEGMENT. We include the performance of models trained on PROPSEGMENT reported by Chen et al. (2023) as a reference.

following steps. We first tokenize and lemmatize each of the tokens in the proposition using NLTK (Bird et al., 2009). Next, we construct an affinity matrix between the set of lemmatized tokens from the proposition and the sentence. With the matrix, we assign tokens with identical lemmas are assigned a similarity score of 1. To break ties between multiple token matches, we apply a 2D-convolution filter on the affinity matrix, which adds a small score offset for other token matches in a context window of three tokens. With the affinity matrix, we find the optimal alignment between the proposition and sentence tokens with max bipartite matching on the affinity matrix with the Hungarian algorithm (Kuhn, 1955).

A.4 Proposition Segmentation Evaluation on PROPSEGMENT

To evaluate the quality of propositions extracted via our pipeline, we evaluate the proposition segmentation performance on PROPSEGMENT. The results are shown in Table 7. For details of the Jaccard similarity based evaluation metrics for proposition segmentation, please refer to Chen et al. (2023).

B Training and Hyperparameters

We implement the sub-sentence encoder architecture with `pytorch` (Paszke et al., 2019) and `pytorch-lightning` (Falcon and The PyTorch Lightning team, 2019). All of our sub-encoder model variants are trained on 8$\times$ Nvidia A6000 GPUs with 48GB VRAM.

Distributed Training Since we adopt in-batch contrastive loss, we scale up the number of negative examples by increasing the batch size with distributed training across GPUs. We distribute training processes across GPU nodes via Distributed Data Parallel (DDP) in PyTorch. Specifically, given a minibatch of $N_{gpu} \times M$ sentences, each GPU gets M sentences, which get forwarded through model parameters on the GPU. Next, we gather and copy all the encoded propositions along with gradients to each of the GPUs, so that each GPU has the full minibatch for loss computation. Each GPU process backpropagates the loss independently on its copy of the model parameters.

Hyperparameters For all experiments, we use the temperature parameter $\tau = 0.01$ for the supervised contrastive loss, with AdamW optimizer. For Sentence-T5 and GTR variants of the model, we use a learning rate of $1e^{-4}$. For SimCSE, we use a learning rate of $5e^{-5}$. We train the models for 10 epochs, and a linear decay is applied at the end of each epoch, which decreases the learning to 0 after 10 epochs. We select the best checkpoint based on validation loss after each epoch.

C Evaluation Setup

C.1 Representing Atomic Propostion with Sentence Encoder

With the atomic fact retrieval evaluation on PROPSEGMENT, since the ground truth query and target propositions are both represented in the format of token masks, we experiment with a few different strategies of formatting the input for sentence encoders. Specifically, with respect to the input sentence and the token masks denoting the proposition, here are the different strategies in consideration.

1. **Mask pooling only.** Encoder has full attention, apply proposition mask during pooling. Note that this is the same method we use for the sub-sentence encoder.

2. **Full mask.** Apply proposition mask as attention mask during both encoding and pooling.

3. **Token subset only.** Take the subset of tokens and discard the rest. Feed only the subset of tokens as a sequence to the encoder and pooling layer.

When tested on a small validation set for the atomic fact retrieval task, we generally observe that **mask pooling only** yields the best result across most models, except for the two compact models, i.e. MiniLM-L6-v2 and DistilRoberta. On the two compact models, we see **full mask** outperforming the **mask pooling only** strategy by a small margin. We observe that with the third strategy **token subset only**, the validation performance trails behind the other two across all models.

C.2 Robustness to Input Boundaries

Base Model	P@1	R@5
GTR$_{base}$	40.77 → 38.39	72.90 → 71.47
ST5$_{base}$	40.97 → 38.14	72.15 → 70.94
ST5$_{base}$	41.64 → 37.28	71.48 → 69.32

Table 8: The retrieval performance of SUBENCODER with model predicted propositions instead of ground truth in input. We only consider propositions with Jaccard similarity > 0.8 in the evaluation.