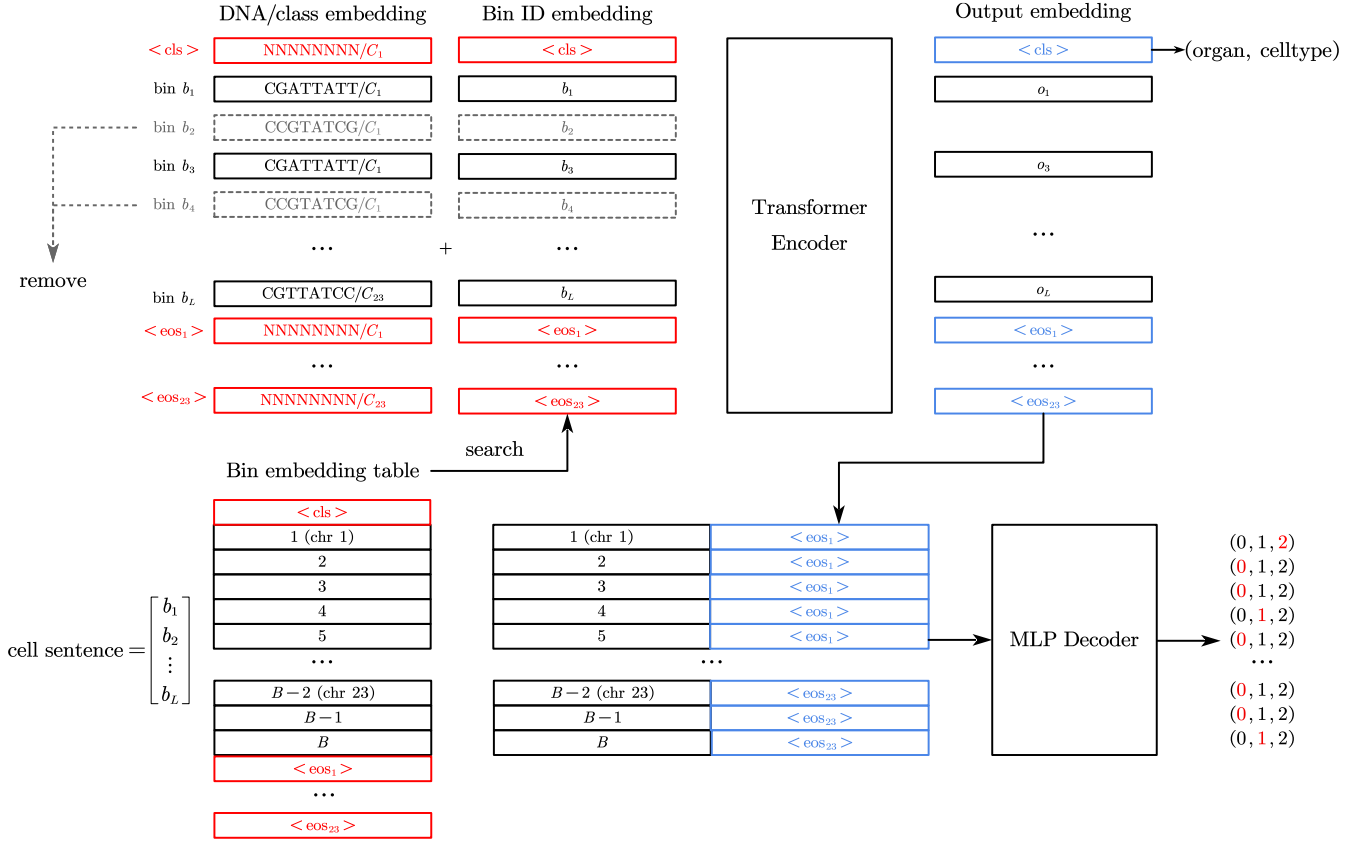


Summary of atacFormer

GE MUYANG

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1 Current Framework



Suppose that we have B different ATAC bins in total. Each bin corresponds to a DNA sequence with length 5000, as in SnapATAC. In each cell, suppose that ATAC bins b_1, b_2, \dots, b_L are open. The cell sentence is formulated as (b_1, b_2, \dots, b_L) . As the input to the model, some open bins will be removed from the sentence (as masked tokens in BERT).

Bin ID Embedding

Since the vocabulary size is very large, to reduce the number of parameters, we use **embedding factorization**: The embedding matrix E (of size $V \times d$, where V is the vocabulary size and d is the embedding dimension) is factorized into:

- E_1 : A smaller embedding matrix of size $V \times k$ (where $k \ll d$);
- E_2 : A projection matrix of size $k \times d$, which maps the reduced k -dimensional embeddings to the final d -dimensional space.

In our case, we take $V = B + 25$, where 25 is for the embeddings of $\langle cls \rangle$, $\langle pad \rangle$ and $\langle eos_1 \rangle, \dots, \langle eos_{23} \rangle$ for 23 chromosomes. We take $k = 64$ and $d = 512$.

Transformer Encoder

12 transformer encoder layers built by Flash Attention. The maximum sequence length (of cell sentence) is fixed to 6800 (8000×0.15) by default.

Decoder and MLM Loss

The output embeddings of $\langle eos_1 \rangle, \dots, \langle eos_{23} \rangle$ (512 dimensional) are first compressed to 64 dimensional, and then concatenated with bin ID embeddings on the corresponding chromosome (e.g. $\langle eos_1 \rangle$ is concatenated with all bins on chromosome 1) into 128-dimensional feature vectors. These feature vectors are feed into an MLP decoder to output the probability of 3 states: 0 (not in the cell sentence), 1 (in the cell sentence) and 2 (in the cell sentence but be removed).

DNA Embedding (Optional)

We plan to use **Nucleotide Transformer** to build DNA embedding table for all 5000-bp DNA sequence of each bin. For special tokens, the DNA embedding can be fixed to zero vector.

Supervised Loss (Optional)

The output embedding corresponding to $\langle cls \rangle$ is used to predict the organ and the celltype of the cell using MLP. For multi-omics data, we achieve the celltype label for scATAC-seq data by running **sCimilarity** for corresponding scRNA-seq data.

2 Future Perspective

Decoder by Genomic Regions

The $\langle eos \rangle$ can be designed for different genomic regions instead of chromosomes. The following are possible annotated regions for ATAC bins.

1. Gene-related Regions

- **Promoter**: Located in the gene promoter region (typically 2 kb upstream to 0.5 kb downstream of the transcription start site).
- **Exon**: Located in the exon region of a gene.
- **Intron**: Located in the intron region of a gene.
- **5' UTR**: Located in the 5' untranslated region of a gene.
- **3' UTR**: Located in the 3' untranslated region of a gene.
- **TTS (Transcription Termination Site)**: Located near the transcription termination site of a gene.

2. Non-gene-related Regions

- **Intergenic**: Located in intergenic regions, far from any known genes.
- **Non-coding RNA (ncRNA)**: Located in non-coding RNA gene regions.

3. Regulatory Elements

- **Enhancer**: Located in known or predicted enhancer regions.
- **Insulator**: Located in insulator regions.
- **CTCF Binding Site**: Located in CTCF binding site regions.

4. Other Features

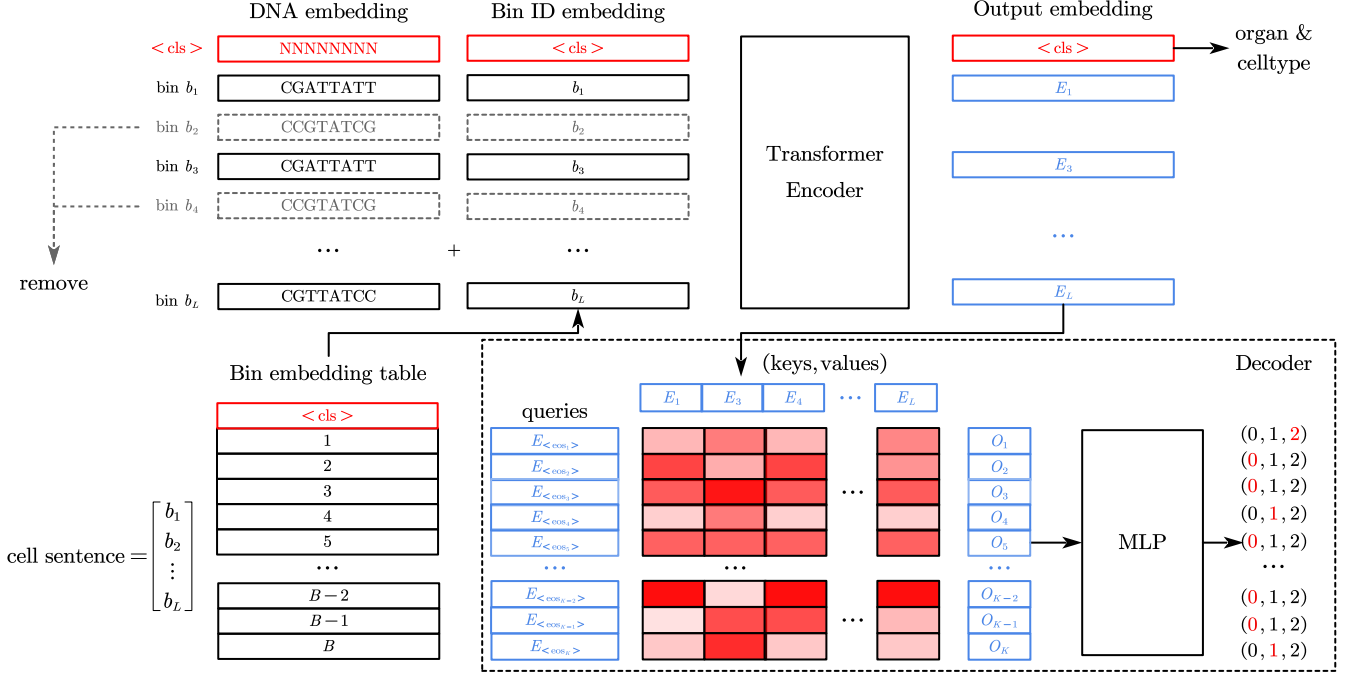
- **Repeat**: Located in repeat regions (e.g., LINE, SINE, LTR).
- **Conserved**: Located in evolutionarily conserved regions.

We can use **HOMER** to annotate ATAC bins. For each class c of bins, we use one $\langle eos_c \rangle$ to predict the open/closed state of ATAC bins in this class.

Decoder by Cross Attention

Use independent $\langle eos \rangle$ embedding vectors (not in the cell sentence).

- Use a Transformer encoder to encode the cell sentence, obtaining embeddings $E_{\text{encoder}} \in \mathbb{R}^{L \times d}$.
- Define $\langle eos_k \rangle$ tokens corresponding to different regions. Each $\langle eos_k \rangle$ token has an embedding $E_{\langle eos_k \rangle} \in \mathbb{R}^d$.
- For each $\langle eos_k \rangle$ token, compute cross-attention: $\text{Output}^k = \text{Attention}(E_{\langle eos_k \rangle}, E_{\text{encoder}}, E_{\text{encoder}})$. Each output Output^k represents the interaction between the $\langle eos_k \rangle$ token and the cell sentence.
- For each Output^i , predict the added/dropped bins in the corresponding functional region: $\text{Prediction}^i = \text{MLP}(\text{Output}^i)$



The advantages of this strategy are:

- Compared with self-attention, each $\langle \text{eos} \rangle$ token can focus on a specific functional area and dynamically select bins related to it through cross-attention.
- Each $\langle \text{eos} \rangle$ token can interact with the encoder output independently, which can avoid $\langle \text{eos} \rangle$ tokens interacting with each other in the self-attention.