Multi-Modal Protein Representation Learning with CLASP

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ABSTRACT

Effectively integrating data modalities pertaining to proteins' amino acid sequences, three-dimensional structures, and curated biological descriptions can lead to informative representations capturing different views of proteins. Here, we introduce CLASP, a unified tri-modal framework that combines the strengths of geometric deep learning, natural large language models (LLMs), protein LLMs, and contrastive learning to learn informative protein representations based on their structure, amino acid sequence, and description. We show that CLASP enables accurate zero-shot classification and retrieval tasks, such as matching a protein structure to its sequence or description, outperforming state-of-the-art baselines. CLASP embeddings also exhibit superior clustering by protein family, and ablation studies confirm that all three modalities contribute synergistically to performance. Our results highlight the power of integrating structural, sequential, and textual signals in a single model, establishing CLASP as a general-purpose embedding framework for protein understanding.

Keywords: Protein representation learning, multi-modal contrastive learning, protein structure embedding, sequence–structure–text alignment, graph neural networks, zero-shot protein classification

1 Introduction

Advances in deep learning have led to powerful protein large language models (pLLMs), which learn rich representations from large unlabeled sequence databases. Similar to their natural large language model (LLM) counterparts, pLLMs are trained on millions of amino acid sequences based on masked language modeling or causal language modeling (e.g., ESM3 [1], ProtT5 [2], SqueezeProt [3]). However, proteins are more than linear amino acid strings; their three-dimensional structures and biochemical contexts are crucial for their function [4]. In fact, protein structures tend to be more conserved than sequences, with structural comparisons revealing remote homology and functional relationships that are invisible to sequence-based methods [5]. The recent proliferation of experimentally determined and computationally predicted protein structures presents a unique opportunity to enhance protein representations with structural information [6]. High-resolution experimental techniques such as X-ray crystallography, nuclear magnetic resonance (NMR) spectroscopy, and cryo-electron microscopy produce Protein Data Bank (PDB) files [7], capturing atomic-level structural information and coordinates of proteins.

In addition to important signals present in proteins' amino acid sequence and structure, their biochemical properties and functions are often described and curated in natural language, through research articles, biological databases, and annotation resources like UniProt [8]. These textual descriptions capture high-level semantic knowledge, including cellular roles, disease associations, and molecular activities, which may not be directly inferable from structure or sequence. Integrating such unstructured text into protein representations offers a promising route to bridge the gap between low-level molecular data and the rich, human-interpretable understanding of protein function [9].

To enrich protein representations, various methods have begun combining structure and sequence modalities. Graph-based deep learning has proven effective for modeling protein 3D structures. For example, Progres [6] em-

beds protein structures as graphs via a simple graph neural network (GNN) and contrastive learning, yielding fixed-length vectors that enable fast structure searches at scale [6]. Such embeddings can be compared in constant time, dramatically speeding up remote fold detection across massive structure databases [6]. Unsupervised pretraining on protein tertiary structures has also been explored; for instance, Chatzianastasis et al. proposed a self-supervised scheme where 3D graph neural networks are trained to predict geometric relationships between protein subgraphs and the global structure, leading to improved downstream classification performance [10]. In parallel, E(n)-invariant GNN (EGNN) architectures have been introduced to better capture molecular geometry [11]. These models enforce rotational and translational symmetry in 3D space, ensuring that learned representations depend only on the intrinsic shape and not on an arbitrary orientation [11]. Such E(n)-invariant networks have demonstrated state-of-the-art performance in molecular property prediction, enabling more robust protein structure embeddings [11]. Overall, these advances illustrate the value of integrating structural information into protein representations; however, purely geometric approaches often overlook other rich data modalities, such as free-text functional annotations.

In parallel, there is a growing interest in multi-modal models that align protein sequences with textual descriptions or annotations [9]. The motivation is that natural language can encode functional and contextual information that may not be readily inferable from sequence alone. Early efforts, such as OntoProtein [12], augmented sequence embeddings with knowledge graph information from biological databases, effectively injecting curated textual knowledge into learned protein representations [12]. More recently, several groups have drawn inspiration from the CLIP (Contrastive Language-Image Pre-training) [13] paradigm, which has achieved remarkable image-text alignment via contrastive learning, to pair proteins with their corresponding descriptions (e.g., ProteinCLIP [14], ProtCLIP [9]). On the other hand, Xu et al. used biomedical ontology terms and descriptions to guide protein language models (ProtST) [15], while Liu et al. introduced a multi-modal framework (ProteinDT) that aligns sequence embeddings with free-text functional descriptions for protein design applications [16]. These approaches demonstrate that language-supervised protein models can be transferred to a variety of tasks, ranging from property prediction to semantic similarity inference [9]. However, most prior protein biotext models are bimodal. They align sequences with text only, using objectives adapted from image-text CLIP [9], but do not explicitly incorporate 3D structural information during pretraining despite the known importance of structure for function. This highlights a need to build tri-modal representation learning strategies that integrate sequence, structure, and textual descriptions, allowing models to link the physical determinants of protein function with the semantic, often higher-level biological contexts described in natural language. Such integration can facilitate more interpretable representations and support tasks that span both mechanistic and functional domains, such as retrieving disease-relevant proteins from structural similarity or predicting functional effects grounded in both geometry and literature [4].

Here, we introduce CLASP (Contrastive Language–Amino acid Sequence–Structure Pretraining), a unified tri-modal framework for protein representation learning. CLASP jointly embeds a protein's structure (captured through PDB representation), amino acid sequence, and natural language description into a shared vector space by leveraging a contrastive learning objective inspired by CLIP Goes 3D (CG3D) [17]. Empirically, we demonstrate that CLASP's joint representations enable accurate zero-shot classification and retrieval across modalities – for example, identifying the correct sequence given a structure or its description – outperforming other models limited to one or two modalities. Moreover, CLASP's structure and projected sequence embeddings exhibit clear clustering by protein family and functional class, indicating that the model learns biologically meaningful structure-function relationships. Finally, ablation studies demonstrate that removing any single modality during training leads to a marked drop in performance, underscoring the complementary value of sequence, structure, and text in capturing protein semantics. Together, these findings suggest that CLASP offers a biologically grounded, modality-agnostic embedding space that unifies structural, sequential, and functional views of proteins, laying the groundwork for more interpretable, general-purpose models in protein science.

2 Results

2.1 CLASP learns protein representations using multi-modal contrastive learning, geometric deep learning and large language models

CLASP (Contrastive Language-Amino acid sequence-Structure Pretraining) is a deep learning model to learn protein representations using multi-modal data. It combines the strength of natural large language models (LLMs), protein LLMs (pLLMs), geometric deep learning, and contrastive learning to learn informative protein representations based on their structure, amino acid sequence, and description (Figure 1). CLASP serves as a unified framework for learning multi-modal protein representations, achieving representative embeddings by jointly optimizing all components through contrastive learning.

CLASP's architecture is comprised of two main components. The first component is a structure encoder module that utilizes geometric deep learning to generate low-dimensional embeddings from the proteins' PDB files [7] (Figure 1A). This module first converts the PDB file of a protein into a graph representation using Graphein [18]. In this graph, nodes represent the atoms (annotated with biochemical features) and edges describe their spatial relationships. Edge weights in this graph represent Euclidean distances. These graphs are then processed by an E(3)-invariant graph neural network (EGNN) [11], which generates low-dimensional structure embeddings that are invariant to rotations or translations and preserve the protein's geometric and structural properties. These properties arise from the architecture's use of distance-based message passing and coordinate updates that are explicitly designed to be invariant to rotations and translations [11]. Such invariance is crucial for molecular structures, where both biochemical and geometric contexts significantly influence function. The EGNN architecture combines multiple message-passing layers to capture both local and global patterns in protein graphs. This balance ensures that the resulting embeddings reflect the intricate relationships within protein graphs.

The second component is an alignment module that utilizes three-dimensional contrastive learning to align structure embeddings with precomputed amino acid sequence and natural language description embeddings in a shared embedding space (Figure 1B). We used precomputed 1024-dimensional ProtT5 [2] amino acid sequence embeddings from UniProt [8]. ProtT5 is a pLLM that models protein sequences using a transformer architecture trained on large-scale sequence databases in a masked language modeling framework, enabling it to capture contextual and evolutionary information from amino acid sequences. Protein descriptions were also compiled from UniProt [8], which consisted of possible names and functional descriptions of the proteins. These descriptions were then processed by BioGPT [19], a biology-tuned LLM, generating 1024-dimensional natural language embeddings.

The structure embeddings, along with the precomputed amino acid sequence and language description embeddings go through modality-specific linear projection layers of the same output dimensions (here 512), which map them into a shared embedding space. The outputs of each projection layer are then aligned using an objective function that includes four terms: three symmetric cross-entropy contrastive terms each tasked with aligning embeddings from pairs of modalities and a fourth regularization term. Using this loss function, CLASP learns a unified embedding space in which structure–sequence–description triplets corresponding to the same protein are brought into close proximity, while embeddings from non-matching triplets are explicitly separated, thereby capturing cross-modal correspondences. The CLASP model in its entirety was trained end-to-end, with the contrastive training loss being backpropagated all the way to the structure encoder. The details of this model are discussed in Methods.

2.2 CLASP enables accurate structure-to-sequence alignment

We first evaluated CLASP's ability to align 3D protein structures with their corresponding amino acid sequences using a zero-shot classification. Specifically, given an input PDB structure and a candidate sequence, similarity scores were computed via the dot product between their projected embeddings in the shared space. These scores were evaluated on held-out protein pairs, and an optimal decision threshold was selected on the validation set to maximize F1 score. Classification metrics were then computed on the test set using this threshold (repeated three times across distinct randomly formed training/validation/test sets).

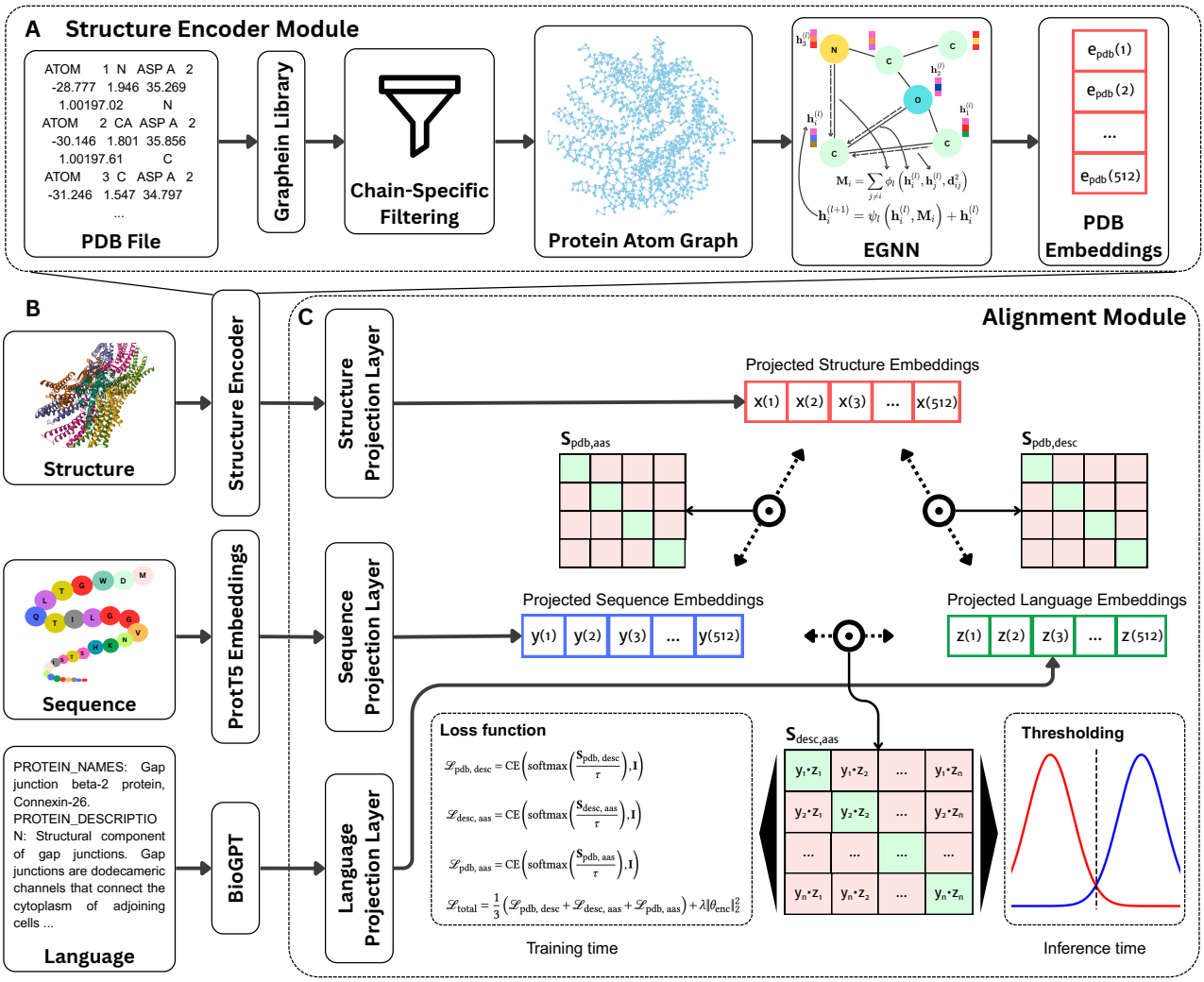

Figure 1. Architecture and pipeline of CLASP. (A) The structure encoder module converts protein structures from PDB files into atom-level graphs using the Graphein library, applying chain-specific filtering. Each node is annotated with Meiler descriptors and 3D coordinates, and edges represent spatial proximity. These graphs are processed by an E(3)-invariant Graph Neural Network (EGNN), producing 512-dimensional structure embeddings that preserve geometric and biochemical features. **(B)** Each protein is represented across three modalities: structure (PDB), amino acid sequence, and natural language description. Sequence embeddings are obtained from ProtT5 and description embeddings from BioGPT. These embeddings, along with those from the EGNN, form the inputs to the alignment module. **(C)** The alignment module projects the inputs from each modality into a shared embedding space via learnable linear layers. Pairwise dot-product similarity matrices are computed between all modality pairs and a three-dimensional contrastive learning approach is used to align them together. The entire framework is trained end-to-end using a tri-modal contrastive loss. At inference, thresholding on pairwise similarity matrices enables classification and retrieval tasks.

We compared the performance of CLASP on this task with six alternative methods. Using structure embeddings provided by two state-of-the-art models, Progres [6] and COLLAPSE [20], we trained standard CLIP models, Random Forest (RF) classifiers, and logistic regression (LR) models on each embedding set (a total of six different methods). The same training/validation/test splits were used for all methods to ensure a fair comparison.

As reported in Table 1 and Figure 2A, CLASP substantially outperformed all tested models across multiple

evaluation criteria. These results reflect the advantage of the CLASP structural encoder over other encoders, coupled with contrastive tri-modal training to ensure modality consistency. While Progres-CLIP and COLLAPSE-CLIP also adopt contrastive learning objectives, they lag behind CLASP by margins of approximately 5%–8% in Area Under the Receiver Operating Characteristic Curve (AUROC) and Area Under the Precision–Recall Curve (AUPRC), underscoring the contribution of geometry-aware encoding and the benefits of tri-modal alignment in achieving robust structure-to-sequence correspondence. Traditional classifier baselines, such as LR and RF trained on the same embeddings, also underperformed relative to their CLIP-based counterparts, highlighting the strength of contrastive approaches in this setting.

Table 1. Classification performance of all models across structure-to-sequence (PDB–AAS) and structure-to-description (PDB–DESC) alignment tasks.

Task	Model	Accuracy	F1 Score	AUROC	AUPRC	MCC
PDB–AAS	CLASP	**0.929 ± 0.003**	**0.929 ± 0.002**	**0.979 ± 0.001**	**0.981 ± 0.001**	**0.858 ± 0.005**
	Progres - CLIP	0.852 ± 0.005	0.855 ± 0.004	0.929 ± 0.002	0.928 ± 0.002	0.705 ± 0.010
	Progres - RF	0.804 ± 0.002	0.800 ± 0.004	0.890 ± 0.001	0.901 ± 0.003	0.608 ± 0.004
	COLLAPSE - CLIP	0.798 ± 0.002	0.810 ± 0.001	0.880 ± 0.002	0.877 ± 0.002	0.600 ± 0.001
	COLLAPSE - RF	0.697 ± 0.007	0.708 ± 0.010	0.780 ± 0.007	0.778 ± 0.005	0.396 ± 0.014
	Progres - LR	0.584 ± 0.002	0.595 ± 0.006	0.623 ± 0.004	0.610 ± 0.002	0.169 ± 0.004
	COLLAPSE - LR	0.580 ± 0.006	0.599 ± 0.009	0.616 ± 0.007	0.584 ± 0.007	0.162 ± 0.012
PDB–DESC	CLASP	**0.804 ± 0.005**	**0.816 ± 0.007**	**0.894 ± 0.004**	**0.886 ± 0.004**	**0.614 ± 0.012**
	Progres - RF	0.760 ± 0.003	0.747 ± 0.002	0.846 ± 0.002	0.865 ± 0.001	0.522 ± 0.007
	Progres - CLIP	0.715 ± 0.010	0.746 ± 0.006	0.811 ± 0.006	0.813 ± 0.006	0.445 ± 0.017
	COLLAPSE - CLIP	0.693 ± 0.015	0.728 ± 0.007	0.782 ± 0.002	0.774 ± 0.005	0.402 ± 0.020
	COLLAPSE - RF	0.649 ± 0.005	0.670 ± 0.001	0.715 ± 0.005	0.713 ± 0.004	0.302 ± 0.007
	COLLAPSE - LR	0.574 ± 0.007	0.587 ± 0.008	0.601 ± 0.007	0.562 ± 0.004	0.149 ± 0.014
	Progres - LR	0.555 ± 0.009	0.555 ± 0.008	0.583 ± 0.009	0.572 ± 0.010	0.110 ± 0.019

Note: Values are reported as mean ± standard deviation across three random seeds. AUROC = Area Under the Receiver Operating Characteristic Curve, AUPRC = Area Under the Precision–Recall Curve, MCC = Matthews Correlation Coefficient, RF = Random Forest, LR = Logistic Regression. Bold indicates the best value in each task.

Visualization of similarity score distributions (Figure 2A, right panel) reinforces these findings. CLASP exhibits minimal overlap between positive and negative pair distributions, leading to a better separation and more precise decision boundaries. By contrast, baseline models show significant inter-class distributional overlap, indicating poorer separation of relevant and irrelevant structure–sequence pairs (Supplementary Figure S1). ROC and PR curves Figure 2A corroborate this trend, with CLASP consistently exhibiting superior performance across the score spectrum. Collectively, these results demonstrate that CLASP excels at zero-shot structure-to-sequence alignment and classification.

2.3 CLASP outperforms other models in zero-shot structure-to description alignment

Next, we set out to assess CLASP's ability to align the 3D structure of proteins with their corresponding natural language descriptions in a zero-shot classification setup. Given a PDB structure and a candidate description, we computed similarity scores as the dot product between their projected embeddings in the shared space. As in the structure-to-sequence experiment, an optimal threshold was selected based on the validation set to maximize F1 score, and metrics were computed on a held-out test set using this threshold. Each experiment was repeated across three random splits of the dataset to ensure stability.

To serve as baseline comparisons, we substituted CLASP's structure encoder with Progres [6] and COLLAPSE [20] embeddings and trained both CLIP-style alignment modules and traditional classifiers, Random Forest and logistic regression, on each structure–description pair.

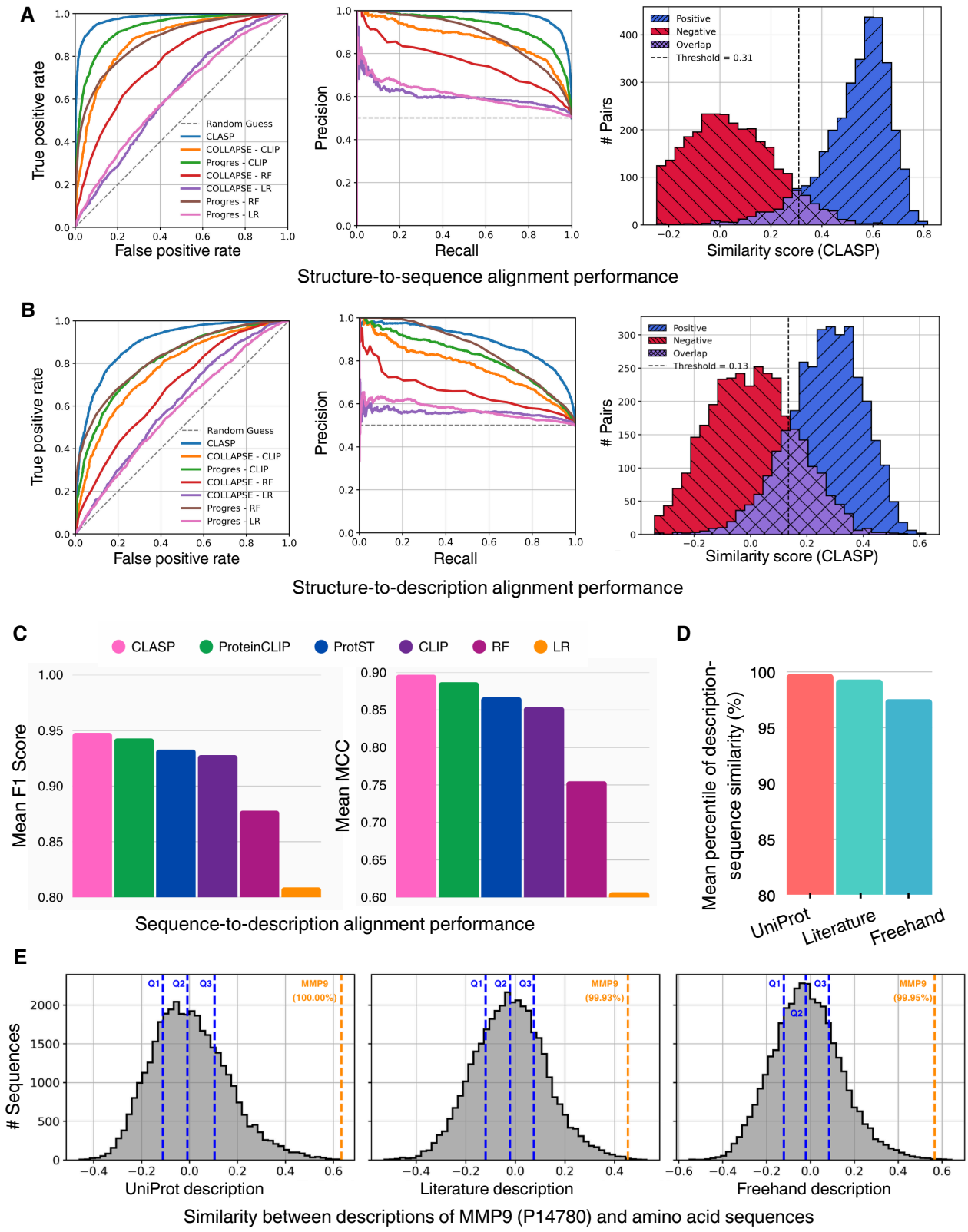

Figure 2. ***(Caption on next page.)***

Figure 2. ***(Previous Page).*** **Performance of CLASP and alternative models on cross-modal classification and retrieval tasks. (A)** ROC curves (left), PR curves (middle) and histograms of similarity-score distributions (right) for the structure-to-sequence alignment task for CLASP and alternative methods on a held-out test set. The dashed gray line in the ROC and the PR plots indicates the performance of random guessing. The vertical black dashed line in the histogram indicates the optimal decision threshold calculated using the validation set. Also see Table 1. **(B)** Same as (A) but for the structure-to-description alignment task. **(C)** Bar plot showing the mean F1 score (left) and mean Matthews correlation coefficient (MCC, right) for the sequence-to-description task across three random seeds for CLASP and alternative methods on the test set. Also see Supplementary Table S1. **(D)** Bar plots showing the mean percentile rank across four proteins in sequence retrieval. Percentiles indicate the position of the correct amino acid sequence in the ranked list of 35,911 candidates. Mean percentiles are shown for UniProt (99.81% ± 0.30%), literature (99.31% ± 0.66%), and freehand (97.56% ± 2.44%) description styles. Also see Supplementary Table S2. **(E)** Distribution of CLASP similarity scores between a given description and candidate amino acid sequences for MMP9 (P14780). Distributions are shown for UniProt (left), literature (middle), and freehand (right) description styles. Dashed blue lines indicate the quartiles of the score distribution (Q1, Q2, and Q3), and the dashed orange line indicates the position and percentile of the correct (target) protein. Note that the model used for this analysis did not include P14780 in its training or validation set. Also see Supplementary Table S2.

As shown in Table 1, CLASP achieved the highest scores across all classification metrics, with a mean AUROC of 0.894 ± 0.004 and AUPRC of 0.886 ± 0.004 (also see Figure 2B). CLASP enables this accurate structure–description classification by generating embeddings whose similarity score distributions for positive and negative test pairs are well-separated; this clear separation compared to alternative models facilitates reliable thresholding and high precision during inference (Fig. 2B, Supplementary Figure S2).

2.4 CLASP enables sequence retrieval using different description styles

We next evaluated CLASP's ability to align amino acid sequences with their corresponding natural language descriptions. We compared our model against ProteinCLIP [14], ProtST [15] fine-tuned using a CLIP-style contrastive objective, a standard CLIP model and two classical classifiers (RF and LR) trained on ProtT5 and BioGPT embeddings.

As shown in Figure 2C, CLASP outperformed all baselines (yet modestly), achieving the highest mean F1 score (0.948) and mean MCC (0.895). CLASP also achieved the highest mean accuracy (0.949) and AUROC (0.986), and the second highest mean AUPRC (0.984), lagging only slightly behind ProteinCLIP (0.987) (Supplementary Table S1). We should point out that all tested models here (including ProteinCLIP and ProtST) utilize pLLMs to obtain sequence embeddings and natural LLMs to obtain description embeddings (Methods). The rich embeddings used by these models as inputs are likely the reason why all models (even RF and LR) perform well in this task. While modest, CLASP's consistent advantage compared to alternative models likely arises from the additional tri-modal supervision, where structural constraints implicitly regularize the relationship between sequence and description embeddings. This is particularly evident from comparing CLASP with CLIP, which uses identical description and sequence inputs and a bimodal contrastive objective instead of a tri-modal one (Figure 2C and Supplementary Table S1).

Given its good performance in aligning natural language descriptions and proteins, we next evaluated CLASP's performance in retrieving the correct amino acid sequence from a large set of 35,911 candidate sequences, given only a textual description as a query. Crucially, we designed this evaluation to probe not only retrieval performance on proteins held out from training but also robustness to variations in description types. To that end, we used three distinct types of descriptions for four proteins, each reflecting different levels of complexity: (1) curated entries from UniProt (the style which was also used during CLASP's training phase); (2) literature-style descriptions sourced from external materials such as academic papers and Wikipedia; and (3) freehand descrip-

tions written by a domain expert in our lab. These categories are intended to span a gradient of increasing difficulty in terms of linguistic variability and alignment with training data: UniProt entries are structured and formulaic, resembling the text seen during training; literature-style descriptions introduce more diverse phrasing and context-dependent language; and freehand inputs are the most variable, often informal and unconstrained by standard annotation guidelines. The full set of descriptions used in this experiment is available in Supplementary Note 1.

As can be seen in Figure 2D-E, CLASP achieved strong retrieval performance. Specifically, for UniProt and Literature descriptions, the corresponding sequence was ranked consistently higher than 98th percentile (Supplementary Table S2). While performance degraded with increasing linguistic complexity (as expected), CLASP retained high-rank percentiles for freehand with a mean percentile of 97.56% ± 2.44%. These results suggest that CLASP's shared embedding space meaningfully aligns sequences and descriptions.

2.5 CLASP's embeddings cluster protein structures by family

Next, we asked whether the structure embeddings learned by the EGNN and fine tuned using CLASP's tri-modal contrastive learning captures information regarding protein families. For this purpose, we evaluated how well CLASP's structure embeddings cluster PDBs by their corresponding protein families. We focused on PDBs corresponding to five protein families of kinases (n = 9,997 PDBs), GPCRs (G protein-coupled receptors, n = 3,613 PDBs), ion channels (n = 1,083 PDBs), HSPs (heat shock proteins, n = 775 PDBs), and ABC transporters (n = 189 PDBs), due to their distinct functional and structural characteristics and their role in various biological processes.

Compared to Progres and COLLAPSE, CLASP's embeddings showed a better clustering performance based on the silhouette score [21], Calinski–Harabasz (CH) index [22], Kullback–Leibler (KL) divergence [23], Jensen–Shannon (JS) [24] divergence, and Davies–Bouldin index [25] (Figure 3A, Supplementary Table S3). These results suggest that embedding of PDBs corresponding to proteins of the same family are placed closer to each other in the latent space by CLASP compared to alternative models, capturing biologically meaningful patterns.

This is further confirmed by comparing the distribution of distances of embeddings of a family to their family centroid (i.e., "intra-cluster" distances) against embeddings of other families to the same centroid ("inter-cluster" distances) (Figure 3B, Supplementary Table S4). This clear separation of intra-cluster and inter-cluster distance distributions is also evident from their KL and JS divergence values, with HSPs showing the highest degree of divergence (Supplementary Table S4).

These results suggest that CLASP's EGNN encoder combined with its tri-modal contrastive training that aligns structure embeddings with sequence and description embeddings produce functionally relevant and biologically meaningful representations with clearer family-level separation compared to other approaches.

2.6 Analysis of CLASP's architectural choices

First, we investigated whether CLASP's amino acid sequence projection layer, which is trained to align ProtT5 sequence embeddings with structure and description modalities in a contrastive manner, enhances the separation of embeddings by protein families. Using the same five protein families as before (see Supplementary Table S5 for the number of sequence embeddings in each family), we assessed the clustering performance of the original ProtT5 embeddings and the projected CLASP embeddings.

Visually, the CLASP embeddings show a more distinct separation by protein families, based on the top two principal components, compared to the original ProtT5 embeddings (Figure 3C-D). This was also confirmed quantitatively using clustering metrics (Figure 3C-D, Supplementary Table S6). For example, the Silhouette score was approximately 14-fold higher based on CLASP embeddings, while the CH index was approximately higher by a factor of two (Figure 3E). These results suggest that the contrastive projection layer further refines the rich ProtT5 embeddings to add important, biologically-relevant information to the model's latent representations.

Next, we performed an ablation study to assess the contribution of the EGNN and the tri-modal objective function. First, we trained a variant of CLASP in which the EGNN was replaced with a standard graph neural network (GNN) (Table 2). On both structure-to-sequence and structure-to-description tasks, this model performed worse than CLASP, showcasing the importance of using EGNN in obtaining structure embeddings from PDBs.

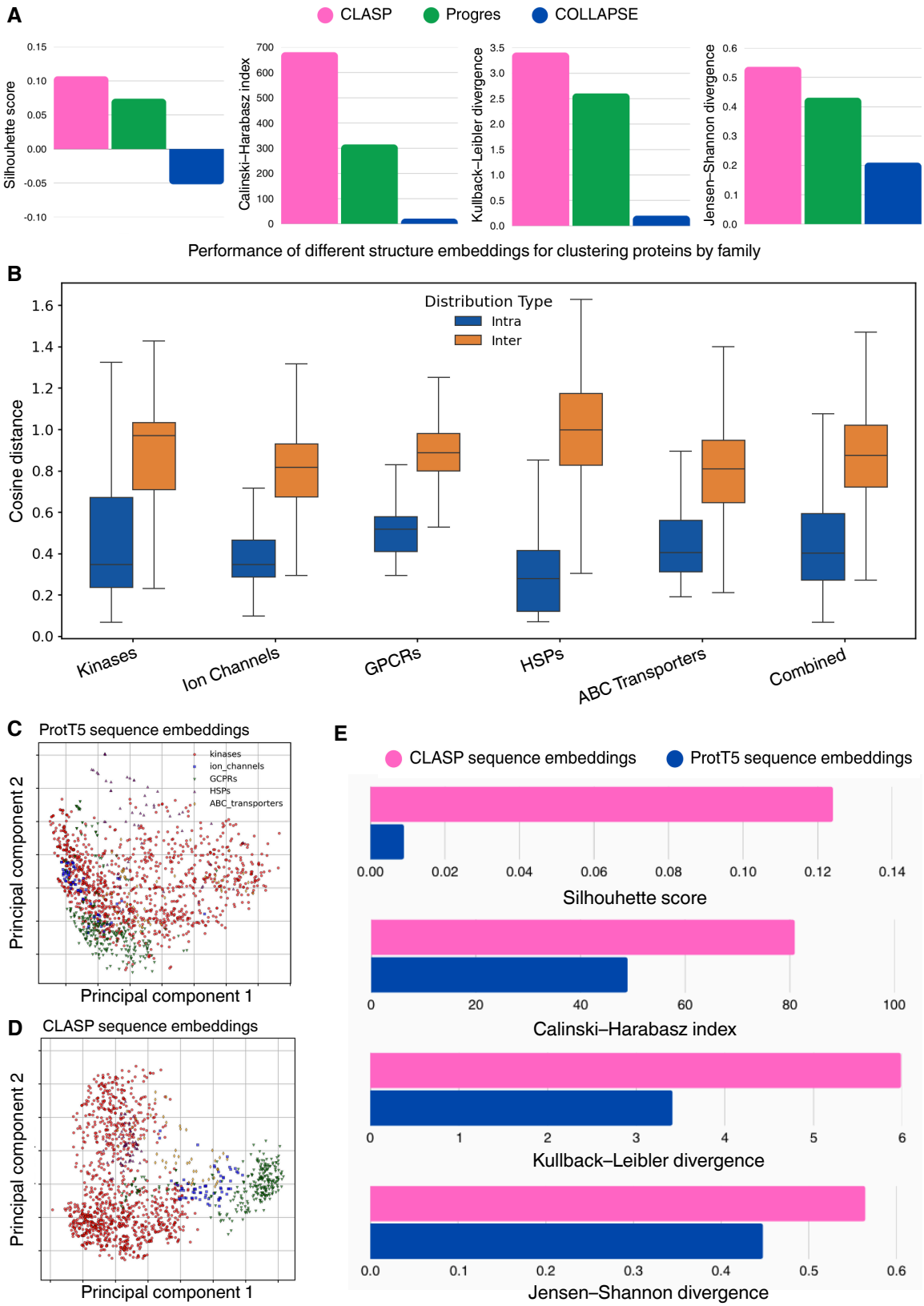

Figure 3. ***(Caption on next page.)***

Figure 3. ***(Previous Page).*** **Performance of latent embeddings in clustering by protein family. (A)** Bar plots showing the performance of structure embeddings of CLASP (pink), Progres (green), and COLLAPSE (blue) based on four clustering metrics: Silhouette score (far left), Calinski–Harabasz index (middle left), Kullback–Leibler divergence (middle right), and Jensen–Shannon divergence (far right). A larger value shows a better separation of clusters. **(B)** Box plots depicting the distribution of cosine distances between CLASP's structure embeddings and a protein family centroid. Intra-cluster distances (blue) are measured from each point to its own cluster centroid, while inter-cluster distances (orange) are measured from points in other families to the same centroid. "Combined" shows the merged distribution of intra-cluster and inter-cluster distances for all families. **(C–D)** Principal component analysis (PCA) of amino acid sequence embeddings of ProtT5 (C) and CLASP (D). CLASP embeddings are those obtained after the projection layer. Each point represents an amino acid sequence and is colored and shaped by protein family: kinases (red circles), ion channels (blue squares), GPCRs (green triangles), HSPs (purple upward triangles), and ABC transporters (orange diamonds). **(E)** Bar plots comparing the clustering performance of ProtT5 sequence embeddings (blue) and CLASP sequence embeddings (pink) using the same four metrics as in panel A.

To assess the role of tri-modal contrastive training, we trained two variations of CLASP, in which the original EGNN encoder was used, but the tri-modal objective function was replaced by a two-modality CLIP objective. Both models showed an inferior performance compared to CLASP in their respective tasks of structure-to-sequence or structure-to-description alignment (Table 2). Interestingly, a larger drop in the performance was observed when we replaced the EGNN with GNN compared to when we changed the tri-modal objective function, further emphasizing the importance of structure encoder in CLASP's performance.

Table 2. Performance of CLASP and its variants in structure-to-sequence and structure-to-description tasks

Task	Model	Accuracy	F1 Score	AUROC	AUPRC	MCC
PDB–AAS	CLASP	**0.929 ± 0.003**	**0.929 ± 0.002**	**0.979 ± 0.001**	**0.981 ± 0.001**	**0.858 ± 0.005**
	CLASP (w GNN)	0.876 ± 0.004	0.875 ± 0.004	0.944 ± 0.002	0.948 ± 0.002	0.753 ± 0.008
	CLIP (w EGNN)	0.902 ± 0.009	0.902 ± 0.009	0.963 ± 0.006	0.968 ± 0.005	0.805 ± 0.018
PDB–DESC	CLASP	**0.804 ± 0.005**	**0.816 ± 0.007**	**0.894 ± 0.004**	**0.886 ± 0.004**	**0.614 ± 0.012**
	CLASP (w GNN)	0.730 ± 0.008	0.760 ± 0.004	0.823 ± 0.003	0.815 ± 0.003	0.475 ± 0.014
	CLIP (w EGNN)	0.775 ± 0.023	0.794 ± 0.018	0.853 ± 0.018	0.829 ± 0.013	0.559 ± 0.045

Note: Values are reported as mean ± standard deviation across three random seeds. AUROC = Area Under the Receiver Operating Characteristic Curve, AUPRC = Area Under the Precision–Recall Curve, MCC = Matthews Correlation Coefficient. Bold indicates the best value in each column.

3 Discussion

CLASP is a unified tri-modal framework that integrates protein structure, sequence, and natural language description into a shared representation space through contrastive pretraining. By jointly aligning structural embeddings generated by an E(3)-invariant graph neural network with precomputed amino acid sequence and language embeddings, CLASP captures complementary views of a protein and significantly improves cross-modal alignment tasks without requiring task-specific supervision.

We demonstrate that CLASP enables accurate zero-shot classification across all modality pairs, outperforming baselines on structure-to-sequence, structure-to-description, and sequence-to-description alignment tasks. In particular, its significant improvement compared to its own variations in which only two data modalities were used along with a CLIP objective function signifies the added value of a joint tri-modal contrastive training to obtain rich embeddings.

We showed that CLASP also enables sequence retrieval from over 35,000 candidates using descriptions written in multiple styles (including freehand summaries, curated UniProt entries, and literature-style prose) with mean retrieval percentiles above 97% across all categories. This robustness to language variability reflects the model's ability to generalize beyond the structured training data, suggesting potential applications in semantic protein search engines or literature-driven protein design.

In addition to its cross-modal alignment capabilities, CLASP produces embeddings that better reflect protein family structure. Structural embeddings obtained from CLASP cluster into functionally coherent groups, as demonstrated by various clustering metrics. These trends hold for both structure and sequence embeddings, suggesting that CLASP's contrastive objective encourages alignment not only across modalities but also within each individual modality. The inclusion of natural language descriptions during training appears to act as a functional regularizer, encouraging structural and sequential encoders to capture biologically meaningful features that reflect known family-level distinctions. This multi-modal supervision leads to more discriminative and functionally informative representations, outperforming structure-only baselines on all clustering metrics.

Ablation studies confirm that both the tri-modal training objective and the E(3)-invariant architecture are essential to CLASP's performance. Replacing the EGNN with a standard GNN reduces MCC by over 10 points, while training with a bi-modal CLIP-style objective leads to consistently worse performance in both structure-to-sequence and structure-to-description tasks. Interestingly, the performance degradation was more pronounced in the structure-to-description task, where removing either component led to larger drops in AUPRC and MCC. This may reflect the inherently noisier and more semantically diffuse nature of protein descriptions, which benefit disproportionately from structural grounding and regularization via the third modality. These findings emphasize that CLASP's architecture gains do not come from any single component in isolation but from the interaction between its geometry-aware encoder and its tri-modal alignment objective. The symmetry and shared supervision across all modality pairs are particularly important, as they allow information from one modality (such as descriptive language) to inform representations in another (such as structure), resulting in a unified embedding space with enhanced generalization capacity.

CLASP does, however, face limitations. The coverage of proteins with structural data in the training dataset is constrained by the availability of high-confidence PDB entries, which can introduce bias against certain protein classes, such as intrinsically disordered regions or membrane proteins. The model also operates with frozen LLM backbones (ProtT5 and BioGPT), and although this reduces computational overhead, it may limit deeper cross-modal synergy. Joint fine-tuning or adapter-based approaches could further enhance performance, but require careful calibration to prevent overfitting or catastrophic forgetting.

Despite these constraints, CLASP establishes a strong foundation for tri-modal protein representation learning and opens new directions for multi-modal biological modeling. By embedding structure, sequence, and natural language into a single, biologically grounded space, CLASP unifies molecular and semantic information, enabling tasks that bridge mechanistic and functional domains. The model's ability to align and retrieve proteins across modalities (without retraining) suggests applications in protein annotation, drug discovery, and automated literature synthesis. Future extensions may incorporate additional modalities such as evolutionary context or tissue-specific expression, and conditional generation models may allow users to synthesize candidate structures from textual prompts or functional targets.

4 Methods

4.1 Data acquisition and preprocessing

The main CLASP dataset consists of $n = 35,918$ unique UniProt Knowledgebase (UniProtKB) [8] accession numbers (UPKB ACs), each linked to at least one Protein Data Bank (PDB) entry. For each UPKB AC, we collected the corresponding structural information, including PDB ID, chain identifier, raw chain sequence, and annotated residue start and end positions. On average, each protein was associated with 8.61 PDB entries (median = 2), reflecting structural variation due to conformational changes or crystallization conditions. These associations were extracted programmatically from the reviewed (Swiss-Prot) UniProtKB XML archive (https:

//www.uniprot.org/downloads) using custom parsers.

The dataset was split by protein into disjoint subsets for training (80%), validation (10%), and testing (10%), ensuring no overlap of UPKB ACs across the splits. This split was repeated independently across three random seeds to evaluate stability and reproducibility. For each training set associated with a seed, we generated five variations, each containing a different randomly selected PDB entry for the training proteins (when multiple PDB entries were available). This was done to introduce structural diversity during training. During training, we cycled through these five sets across epochs, ensuring that each protein was paired with a distinct structure every fifth epoch, thereby enriching the training distribution.

For evaluation, we constructed 3,592 positive and 3,592 negative test pairs (7,184 total) using the test set proteins. For tasks involving structure, each positive pair was created by selecting a protein sequence or description and randomly sampling one of its associated PDBs. A corresponding negative pair was formed by pairing the same sequence or description with a PDB belonging to a different protein from the test set. For sequence-description tasks, the same approach was used except that the negative pair was generated by sampling a description associated with a different protein in the test set. The same data splits were used across all models to ensure a fair comparison.

For the sequence modality, we used 1024-dimensional per-protein amino acid embeddings generated by the ProtT5-XL-UniRef50 model [2], a protein language model trained using a masked language modeling objective on large-scale protein sequence databases. These embeddings were directly downloaded from the UniProt website's embedding repository at https://www.uniprot.org/help/embeddings. The provided embeddings are precomputed by the UniProt consortium using the bio_embeddings framework, specifically the prottrans_t5_xl_u50 model. Only canonical sequences from the UniProtKB/Swiss-Prot database were retained.

For the natural language modality, protein descriptions were curated from UniProt's structured annotations, specifically the "Protein names" and "Function" fields [8]. These text descriptions included formal protein names, synonyms, and functional summaries. Descriptions were tokenized and embedded using BioGPT [19], a transformer-based language model fine-tuned on biomedical corpora. We used the official HuggingFace implementation (https://huggingface.co/microsoft/BioGPT) to generate 1024-dimensional embeddings for each description. For the sequence retrieval task, the protein descriptions (whether UniProt, Literature, or Freehand styles) were processed in a similar manner.

4.2 Protein structure graph representation

In CLASP, protein structures are represented as graphs, enabling the model to capture intricate geometric and biochemical information. These graphs are constructed using Graphein [18], a specialized library for protein structural data. Each graph encodes atoms as nodes, annotated with biochemical and spatial features, and edges representing spatial relationships or biochemical interactions. Graphs were generated using Graphein's default "ProteinGraphConfig", with no custom parameters modified during construction.

Proteins were matched with their corresponding three-dimensional structures using the Uniprot SWISS-PROT Knowledgebase. More precisely, the Uniprot knowledgebase contains information linking proteins to Protein Data Bank (PDB) files in which they are present, as well as the relevant polypeptide chain. Graphein was used to download PDB files, construct structure graphs from them, and filter all but the relevant polypeptide chains.

Each node in the graph was annotated with features that capture a range of biochemical properties, including hydrophobicity, polarity, charge, and size [26]. These descriptors offer a compact yet comprehensive characterization of the biochemical nature of each residue. Additionally, the 3-dimensional (3D) spatial coordinates of each node are preserved, providing geometric information.

Edges in the graph were defined based on spatial proximity, capturing relationships between nodes within a certain distance threshold. Each edge was weighted by the Euclidean distance between the 3D coordinates of its connected nodes, reflecting the protein's spatial arrangement. These weights are essential for tasks involving geometric analysis, as they allow the model to consider both local and global structural relationships.

These graphs were converted into PyTorch Geometric Data objects for integration with the downstream encoder. The nodes were indexed to ensure consistency, and tensors were generated for node features, edge

indices, edge attributes (distances), and node positions (coordinates). This ensures that the graphs are optimized for efficient processing in the EGNN.

4.3 E(3)-invariant graph neural network architecture

Graph neural networks (GNNs) are a class of deep learning models that operate on graph-structured data, allowing information to propagate along edges between nodes. In molecular settings, GNNs are commonly used to model interactions between atoms or molecules, where the graph topology reflects the spatial or chemical connectivity of the nodes. However, conventional GNNs typically ignore the geometric symmetries of 3D space, making them suboptimal for tasks where spatial configuration is biologically meaningful.

To address this limitation, CLASP employs an E(3)-invariant graph neural network (EGNN) [11] that incorporates spatial geometry while remaining insensitive to the protein's absolute orientation or position in space. This invariance is achieved by encoding pairwise squared Euclidean distances between nodes, quantities that are mathematically invariant under rotations, translations, and reflections in 3D. These distance-based edge features enable the model to capture biologically relevant internal geometric relationships while discarding extraneous coordinate information. Such invariance ensures that structurally identical proteins yield identical embeddings [11]. Our implementation closely follows the implementation described in TeachOpenCADD [27].

The EGNN begins by transforming node features into an initial embedding space. Each node i in the graph has features $\mathbf{f}_i \in \mathbb{R}^k$ (here $k = 7$), which are mapped to an embedding $\mathbf{h}_i^{(0)} \in \mathbb{R}^2$ using a learnable linear transformation

$$\mathbf{h}_i^{(0)} = \psi_0(\mathbf{f}_i), \tag{1}$$

where ψ_0 is a linear projection. A central component of the EGNN is its invariant message-passing mechanism, which iteratively updates node embeddings based on their relationships with neighboring nodes. At each layer l, pairwise distances d_{ij}^2 between nodes i and j are computed from their 3D coordinates $\mathbf{c}_i$ and $\mathbf{c}_j$

$$d_{ij}^2 = \|\mathbf{c}_i - \mathbf{c}_j\|^2. \tag{2}$$

These distances serve as edge attributes, capturing geometric relationships between nodes. Using the embeddings of the source node $\mathbf{h}_i^{(l)}$ and target node $\mathbf{h}_j^{(l)}$, along with the distance d_{ij}^2, the model computes a message $\mathbf{m}_{ij}$ through a learnable function ϕ_l. The messages from all neighbors of a node are aggregated via summation, yielding the total message for node i:

$$\mathbf{M}_i = \sum_{j \neq i} \phi_l(\mathbf{h}_i^{(l)}, \mathbf{h}_j^{(l)}, d_{ij}^2). \tag{3}$$

This aggregated message $\mathbf{M}_i$ is combined with the node's current embedding $\mathbf{h}_i^{(l)}$ to compute the updated embedding $\mathbf{h}_i^{(l+1)}$. A residual connection ensures stable training and preserves information from earlier layers according to

$$\mathbf{h}_i^{(l+1)} = \psi_l(\mathbf{h}_i^{(l)}, \mathbf{M}_i) + \mathbf{h}_i^{(l)}, \tag{4}$$

where ψ_l is a learnable multi-layer perceptron (MLP) that integrates the node embedding with the aggregated message.

After L message-passing layers (here we used $L = 3$), the final node embeddings $\mathbf{h}_i^{(L)}$ are aggregated using a sum pooling operation to produce a graph-level embedding. This embedding is then processed through a two-layer feedforward neural network ψ_{readout}, defined as

$$\mathbf{e}_{\text{pdb}} = \psi_{\text{readout}}\left(\sum_i \mathbf{h}_i^{(L)}\right) = \mathbf{W}_2 \cdot \text{ReLU}\left(\mathbf{W}_1 \cdot \left(\sum_i \mathbf{h}_i^{(L)}\right)\right), \tag{5}$$

where $\mathbf{W}_1$ and $\mathbf{W}_2$ are learnable weight matrices corresponding to linear layers. All non-linearities throughout the model, including the initial embedding layer ψ_0, the message and update functions ϕ_l and ψ_l, and the readout function ψ_{readout}, use the ReLU activation function. Residual connections are employed in each message-passing layer to stabilize training and facilitate the flow of gradients.

4.4 Alignment module architecture - 3D CLIP

The Contrastive Language-Image Pretraining (CLIP) model [13] provides a mechanism for aligning representations from two distinct modalities (typically images and text) into a shared embedding space. A central aspect of CLIP's training procedure is its employment of contrastive learning, where the embeddings of matched pairs are "pulled" closer together, and those of mismatched pairs are "pushed" apart. This is to say that the distance between pairs of embeddings which match the same protein are minimized, while the distance of mismatched pairs are maximized. This framework enables tasks such as cross-modal retrieval and zero-shot classification by learning to map semantically related content closer in the embedding space [13]. The CG3D model (CLIP goes 3D) [17] extends this approach by introducing a dedicated 3D encoder trained to align point cloud representations with CLIP's image and text embeddings, thereby enabling zero-shot understanding directly from geometric data. This extension yields significant performance benefits in 3D recognition, retrieval, and scene querying tasks [17].

In CLASP, the CG3D methodology has been adapted to align protein natural language descriptions, amino acid sequences, and structures (PDBs). The model first processes each modality independently through a modality-specific linear projection layer. These projection heads map each input vector to a unified 512-dimensional embedding space. Formally, let $\mathbf{e}_{\text{pdb}}, \mathbf{e}_{\text{aas}}, \mathbf{e}_{\text{desc}}$ be the input embeddings for a given protein's structure (from the EGNN), sequence (from ProtT5), and description (from BioGPT), respectively. These are first transformed via independently parameterized modality-specific linear projection layers and then L^2-normalized to unit length, represented as $\mathbf{x}_{\text{pdb}}$, $\mathbf{y}_{\text{aas}}$, and $\mathbf{z}_{\text{desc}}$ ($\mathbf{x}$, $\mathbf{y}$, $\mathbf{z}$, for brevity) (Figure 1B-C).

Given a batch of n proteins, three pairwise cross-modality similarity matrices $\mathbf{S}_{\text{mod1, mod2}} \in \mathbb{R}^{n \times n}$ are formed. Specifically, the (i, j)-th entry of each such matrix captures the cross-modality similarity of protein i and protein j, calculated as

$$\mathbf{S}_{\text{pdb, aas}}(i,j) = \langle \mathbf{x}_i, \mathbf{y}_j \rangle, \qquad \mathbf{S}_{\text{pdb, desc}}(i,j) = \langle \mathbf{x}_i, \mathbf{z}_j \rangle, \qquad \mathbf{S}_{\text{aas, desc}}(i,j) = \langle \mathbf{y}_i, \mathbf{z}_j \rangle, \tag{6}$$

where $\langle \cdot, \cdot \rangle$ denotes the dot product (Figure 1C). These similarity matrices are used to calculate the loss function during training and serve as the foundation for downstream tasks during inference such as cross-modal retrieval and classification.

4.5 Training process and loss function

CLASP is trained end-to-end using a tri-modal contrastive learning objective inspired by the CG3D framework [17], extended to protein data. The core idea is to align embeddings from three modalities - structure, sequence, and description - by maximizing similarity between matched pairs and minimizing similarity between mismatched pairs. For each modality pair, a symmetric cross-entropy loss is computed across the pairwise similarity matrices $\mathbf{S}_{\text{pdb, aas}}$, $\mathbf{S}_{\text{pdb, desc}}$, and $\mathbf{S}_{\text{aas, desc}}$. Specifically,

$$\mathscr{L}_{\text{mod1, mod2}} = \text{CE}\left(\text{softmax}\left(\frac{\mathbf{S}_{\text{mod1, mod2}}}{\tau}\right), \mathbf{I}\right) \tag{7}$$

where $\text{mod1}, \text{mod2} \in \{\text{pdb}, \text{aas}, \text{desc}\}$, τ is a temperature parameter controlling the sharpness of the softmax distribution, CE is the cross-entropy, and $\mathbf{I}$ is the identity matrix representing the correct alignment between corresponding pairs in the batch. The cross-entropy loss encourages the diagonal entries of the similarity matrix (representing correctly matched pairs) to have the highest similarity scores, while suppressing scores of mismatched (off-diagonal) pairs.

The total contrastive loss is computed as the average of the pairwise losses across all modality pairs. To prevent overfitting and encourage generalization, an L^2 regularization term is applied to the parameters of the structure encoder. The final objective is

$$\mathscr{L}_{\text{total}} = \frac{1}{3}\left(\mathscr{L}_{\text{pdb, desc}} + \mathscr{L}_{\text{desc, aas}} + \mathscr{L}_{\text{pdb, aas}}\right) + \lambda \|\theta_{\text{enc}}\|_2^2, \tag{8}$$

where θ_{enc} denotes the encoder parameters, and λ is the regularization weight. Training is performed with the Adam optimizer using early stopping based on validation loss. Hyperparameters (τ and λ) were selected based

on performance on the held-out validation set. Models are trained across three distinct random seeds to ensure reproducibility and robustness.

4.6 Baseline methods

We chose two state of the art PDB embedding methods to serve as baseline comparisons: Progres [6], which generates structure-aware protein embeddings by encoding local atomic environments using a hierarchical graph convolutional network and contrastive learning on protein graph pairs; and COLLAPSE [20], a self-supervised framework that learns local structure-function representations by aligning residue-centered 3D environments across homologous proteins using evolutionary conservation signals from multiple sequence alignments. To assess structure alignment quality, we trained separate alignment modules on these fixed structure embeddings using the same amino acid sequence and natural language description embeddings employed in CLASP. For each structure embedding method (Progres [6] and COLLAPSE [20]), we trained a standard CLIP [13] (including trainable projection layers) and two conventional classifiers, Random Forest and logistic regression, trained on concatenated structure–sequence or structure–description embedding pairs. All models were evaluated on the same training, validation, and test splits, ensuring a fair comparison.

For sequence-to-description tasks, we considered two alternative baselines: ProteinCLIP [14], which contrasts amino acid sequences with functional text using frozen pretrained language models and lightweight projection heads; and ProtST [15], a multi-modal framework that jointly trains protein and biomedical text representations using a combination of masked language modeling and cross-modal alignment tasks. We re-trained ProteinCLIP [14] on our data split using their ProtT5 [2] sequence and OpenAI text-embedding-3-large (`https://platform.openai.com/docs/models/text-embedding-3-large`) description embeddings. For ProtST [15], we fine-tuned a CLIP-style [13] alignment model on their zero-shot classification setup by projecting their ESM-1b [28] sequence embeddings and PubMedBERT [29] description embeddings into a shared embedding space using a contrastive InfoNCE loss. Finally, we trained a standard CLIP [13] model (with trainable projection layers) and two conventional classifiers - Random Forest and logistic regression (on concatenated sequence-description embedding pairs) - using the same frozen BioGPT [19] and ProtT5 [2] embeddings as in CLASP. All models were evaluated on the same training, validation, and test splits to ensure a fair comparison.

4.7 Implementation details

CLASP was implemented in the Python programming language using the PyTorch deep learning framework. Training was performed for up to 500 epochs using the Adam optimizer (learning rate 0.001), batch size 8, and early stopping with a patience of 40. All models were trained and evaluated on an NVIDIA RTX 3090 GPU with 32 CPU cores. Each seed-specific run took approximately 13.08 hours (~2 minutes per epoch). The structure encoder used in CLASP was an EGNN with 3 message passing layers, 7 input node features, hidden dimensionality of 16, and output embedding size of 512. Final graph-level representations were produced using sum pooling followed by a two-layer MLP with ReLU activations. Tri-modal supervision was applied using a multi-modal contrastive loss with a temperature of 0.07 and L2 regularization (λ = 0.01) on the EGNN parameters.

4.8 Clustering evaluation and metrics

Quantitative metrics include the silhouette score (measuring cohesion versus separation using cosine distances where higher is better) [21], Davies–Bouldin index (assessing average cluster similarity where lower is better) [25], and Calinski–Harabasz index (ratio of between- to within-cluster dispersion where higher is better) [22]. Additionally, we calculated intra-cluster cosine distances from each point to its family centroid and inter-cluster distances from points of other families to the same centroid; we evaluated distributional divergence between intra- and inter-cluster distances with Kullback–Leibler [23] and Jensen–Shannon [24] divergences computed on normalized histograms.

Data Availability

All datasets and embeddings used in the analyses herein are made available under a the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International license. Data can be accessed via Internet Archive: https://archive.org/details/clasp_data

Code Availability

The CLASP source code is made available under the GNU Affero General Public License v3. The code-base can be accessed via GitHub: https://github.com/Emad-COMBINE-lab/clasp.

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Competing Interests

The authors have no competing interests to declare.

References

1. Thomas Hayes, Roshan Rao, Halil Akin, Nicholas J. Sofroniew, Deniz Oktay, Zeming Lin, Robert Verkuil, Vincent Q. Tran, Jonathan Deaton, Marius Wiggert, Rohil Badkundri, Irhum Shafkat, Jun Gong, Alexander Derry, Raul S. Molina, Neil Thomas, Yousuf A. Khan, Chetan Mishra, Carolyn Kim, Liam J. Bartie, Matthew Nemeth, Patrick D. Hsu, Tom Sercu, Salvatore Candido, and Alexander Rives. Simulating 500 million years of evolution with a language model. *Science*, 387(6736):850–858, 2025.
2. Ahmed Elnaggar, Michael Heinzinger, Christian Dallago, Ghalia Rehawi, Yu Wang, Llion Jones, Tom Gibbs, Tamas Feher, Christoph Angerer, Martin Steinegger, Debsindhu Bhowmik, and Burkhard Rost. Prottrans: Toward understanding the language of life through self-supervised learning. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 44(10):7112–7127, 2022.
3. Joseph Szymborski and Amin Emad. A flaw in using pre-trained pllms in protein-protein interaction inference models. *bioRxiv*, 2025.
4. Feng Hu, Ying Hu, Wen Zhang, Hao Huang, Yi Pan, and Peng Yin. A multimodal protein representation framework for quantifying transferability across biochemical downstream tasks. *Advanced Science*, 10(22):e2301223, 2023.
5. Gabriele Mayr, Francisco S. Domingues, and Philipp Lackner. Comparative analysis of protein structure alignments. *BMC Structural Biology*, 7:50, 2007.
6. Joe G Greener and Kiarash Jamali. Fast protein structure searching using structure graph embeddings. *Bioinformatics Advances*, 5(1):vbaf042, 03 2024.
7. Helen M. Berman, John Westbrook, Zukang Feng, Gary Gilliland, Tamilmani N. Bhat, Helge Weissig, Ilya N. Shindyalov, and Philip E. Bourne. The protein data bank. *Nucleic Acids Research*, 28(1):235–242, 2000.
8. The UniProt Consortium. Uniprot: the universal protein knowledgebase in 2025. *Nucleic Acids Research*, 53(D1):D609–D617, 11 2024.
9. Hanjing Zhou, Mingze Yin, Wei Wu, Mingyang Li, Kun Fu, Jintai Chen, Jian Wu, and Zheng Wang. Protclip: Function-informed protein multi-modal learning. *Proceedings of the AAAI Conference on Artificial Intelligence*, 39(21):22937–22945, Apr. 2025.
10. Michail Chatzianastasis, Yang Zhang, George Dasoulas, and Michalis Vazirgiannis. Geometric self-supervised pretraining on 3d protein structures using subgraphs, 2024.

11. Victor Garcia Satorras, Emiel Hoogeboom, and Max Welling. E(n) equivariant graph neural networks. In *Proceedings of the 38th International Conference on Machine Learning*, volume 139 of *Proceedings of Machine Learning Research*, pages 9323–9332. PMLR, 2021.
12. Ningyu Zhang, Zhen Bi, Xiaozhuan Liang, Siyuan Cheng, Haosen Hong, Shumin Deng, Qiang Zhang, Jiazhang Lian, and Huajun Chen. Ontoprotein: Protein pretraining with gene ontology embedding. In *International Conference on Learning Representations*, 2022.
13. Alec Radford, Jong Wook Kim, Chris Hallacy, Aditya Ramesh, Gabriel Goh, Sandhini Agarwal, Girish Sastry, Amanda Askell, Pamela Mishkin, Jack Clark, Gretchen Krueger, and Ilya Sutskever. Learning transferable visual models from natural language supervision. In Marina Meila and Tong Zhang, editors, *Proceedings of the 38th International Conference on Machine Learning*, volume 139 of *Proceedings of Machine Learning Research*, pages 8748–8763. PMLR, 18–24 Jul 2021.
14. Kevin E. Wu, Howard Chang, and James Zou. Proteinclip: enhancing protein language models with natural language. *bioRxiv*, 2024.
15. Minghao Xu, Xinyu Yuan, Santiago Miret, and Jian Tang. ProtST: Multi-modality learning of protein sequences and biomedical texts. In Andreas Krause, Emma Brunskill, Kyunghyun Cho, Barbara Engelhardt, Sivan Sabato, and Jonathan Scarlett, editors, *Proceedings of the 40th International Conference on Machine Learning*, volume 202 of *Proceedings of Machine Learning Research*, pages 38749–38767. PMLR, 23–29 Jul 2023.
16. Shengchao Liu, Yanjing Li, Zhuoxinran Li, Anthony Gitter, Yutao Zhu, Jiarui Lu, Zhao Xu, Weili Nie, Arvind Ramanathan, Chaowei Xiao, Jian Tang, Hongyu Guo, and Anima Anandkumar. A text-guided protein design framework. *Nature Machine Intelligence*, 7(4):580–591, 2025.
17. Deepti Hegde, Jeya Maria Jose Valanarasu, and Vishal M Patel. Clip goes 3d: Leveraging prompt tuning for language grounded 3d recognition. *arXiv preprint arXiv:2303.11313*, 2023.
18. Arian R. Jamasb, Ramon Viñas, Eric J. Ma, Charlie Harris, Kexin Huang, Dominic Hall, Pietro Lió, and Tom L. Blundell. Graphein - a python library for geometric deep learning and network analysis on biomolecular structures and interaction networks. In *Proceedings of the 36th International Conference on Neural Information Processing Systems*, NIPS '22, Red Hook, NY, USA, 2022. Curran Associates Inc.
19. Renqian Luo, Liai Sun, Yingce Xia, Tao Qin, Sheng Zhang, Hoifung Poon, and Tie-Yan Liu. Biogpt: generative pre-trained transformer for biomedical text generation and mining. *Briefings in Bioinformatics*, 23(6):bbac409, 09 2022.
20. Alexander Derry and Russ B. Altman. Collapse: A representation learning framework for identification and characterization of protein structural sites. *Protein Science*, 32(2):e4541, 2023.
21. Peter J Rousseeuw. Silhouettes: a graphical aid to the interpretation and validation of cluster analysis. *Journal of Computational and Applied Mathematics*, 20:53–65, 1987.
22. Tadeusz Caliński and Jerzy Harabasz. A dendrite method for cluster analysis. *Communications in Statistics*, 3(1):1–27, 1974.
23. Solomon Kullback and Richard A Leibler. On information and sufficiency. *The Annals of Mathematical Statistics*, 22(1):79–86, 1951.
24. Jianhua Lin. Divergence measures based on the shannon entropy. *IEEE Transactions on Information Theory*, 37(1):145–151, 1991.
25. David L Davies and Donald W Bouldin. A cluster separation measure. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, PAMI-1(2):224–227, 1979.
26. Jens Meiler, Markus Müller, Alexander Zeidler, and Frank Schmäschke. Generation and evaluation of dimension-reduced amino acid parameter representations by artificial neural networks. *Journal of Molecular Modeling*, 7(9):360–369, 2001.
27. Jonas Groß. An introduction to e(3)-invariant graph neural networks. `https://projects.volkamerlab.org/teachopencadd/talktorials/T036_e3_equivariant_gnn.html`, 2022. Chair for Modelling and Simulation, NextAID project, Saarland University. TeachOpenCADD.
28. A Rives, J Meier, T Sercu, S Goyal, Z Lin, J Liu, D Guo, M Ott, C L Zitnick, J Ma, and R Fergus. Biological structure and function emerge from scaling unsupervised learning to 250 million protein sequences. *Proc*

Natl Acad Sci U S A, 118(15):e2016239118, Apr 13 2021.

29. Yu Gu, Robert Tinn, Hao Cheng, Michael Lucas, Naoto Usuyama, Xiaodong Liu, Tristan Naumann, Jianfeng Gao, and Hoifung Poon. Domain-specific language model pretraining for biomedical natural language processing. *ACM Trans. Comput. Healthcare*, 3(1), October 2021.