Semi-Supervised Learning of Protein Secondary Structure from Single Sequences

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ABSTRACT

Predicting the secondary structure of a single protein sequence in the absence of homology information has remained a challenge for several decades. Although not as performant as their homology-based counterparts, single-sequence methods are not constrained by the requirement of evolutionary information. More accurate single-sequence approaches have the potential to improve structural modelling across the vast majority of sequence space, especially in areas of great scientific interest like viral proteins, the "dark proteome", and *de novo* protein design. Here we introduce S4PRED, the successor to the open-source PSIPRED-Single method, which utilizes semi-supervised learning to achieve a Q_3 score of 75.3% on the standard CB513 test set, taking only single sequences as input. Not only does this result represent a leap in performance for single-sequence methods, it also provides a blueprint for the development of future tools, beyond waiting for larger structural datasets and more powerful neural networks.

Main

Although the protein structure prediction problem has long persisted, the computational prediction of protein secondary structure from sequence has seen significant headway. In the past two decades secondary structure prediction has become an invaluable tool across the cutting edge of protein science, particularly in areas like cryo-electron microscopy[1,2], tertiary structure prediction[3], and protein design[4]. Starting from a three class accuracy (Q_3) of $\sim 76\%$[5] in the late 1990's, our renowned secondary structure prediction tool, PSIPRED, has grown to a current state-of-the-art Q_3 of 84.2%, and is used globally in both experimental and computational research[6].

PSIPRED, along with other methods, is able to produce high accuracy predictions by leveraging valuable homology information found in multiple sequence alignments (MSAs)[7]. This is typically done by constructing a MSA for a given query sequence and then converting it into a PSI-BLAST[8] profile to be used as features for the predictor, along with the original protein sequence[5,7]. This approach is in stark contrast to single-sequence methods, like PSIPRED-Single[6], that are designed to predict secondary structure based only on a single query sequence, without relying on homology information. Unfortunately, over the past decades, single-sequence methods have been slow to improve relative to homology based methods, as can be seen in Figure 1. Currently, the most performant single-sequence methods achieve low Q_3 scores of 71-72%[6,9–11], where homology based methods are achieving scores of $> 84\%$[6,11,12] and are approaching a hypothesized theoretical maximum of 88-90%[13].

In this work we present a major improvement to single-sequence secondary structure prediction with Single-Sequence Secondary Structure PREDictor (S4PRED), the next iteration of PSIPRED-Single, our current method. S4PRED uses recent advances from *semi-supervised learning* (SSL) to achieve a state-of-the-art Q_3 score of 75.3% on the standard CB513 test set[14]. This performance approaches the first version of the homology-based PSIPRED[5] and represents a leap in performance for single-sequence based methods (Figure 1).

Given this success, we put forward S4PRED as a first step in moving the secondary structure prediction field away from utilizing MSAs and towards single-sequence prediction using semi-supervised learning. Accurate single-sequence prediction enables the modelling of any given sequence without the constraints of homology, which, from both a theoretical and practical perspective, represents an incredibly valuable research prospect with a plethora of use cases.

The first and most apparent of these is being able to better model any part of the known protein space, especially given that the vast majority of sequenced natural proteins have no known homologues[3,25]. For example, a particularly important area where this is often the case is viral sequence analysis. The structures of viral proteins are often attractive targets for the development of antiviral drugs or the development of vaccines[26], however, viral

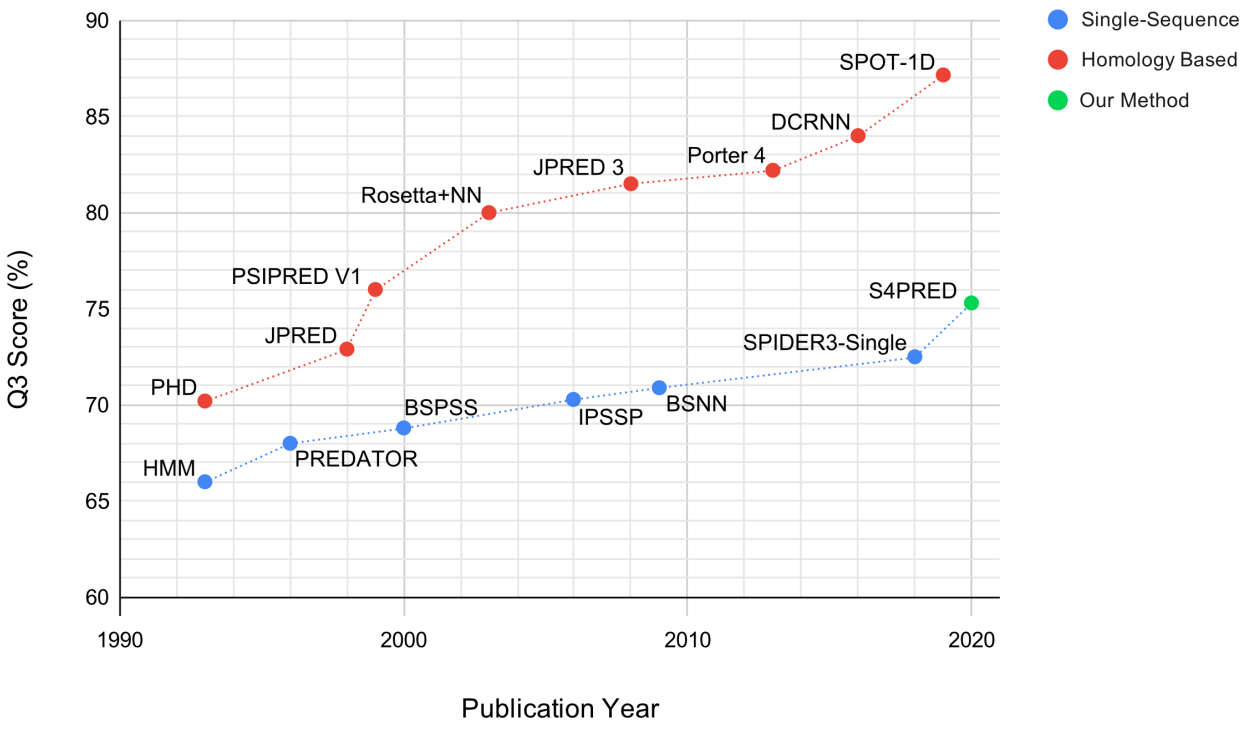

Figure 1. Plot showing reported test Q_3 scores for a range of published secondary structure prediction methods over the previous three decades. This includes single-sequence methods[9,10,15–18] and homology methods[5,12,19–24] separately to provide an illustrative view of how single-sequence methods have improved very slowly, compared to homology methods, over time. We include this work, S4PRED, to demonstrate how it is a step upwards in accuracy. In order to avoid conflation with Rosetta *ab initio*, we use the name Rosetta + Neural Network (Rosetta+NN) in this figure to refer to the work of Meiler & Baker[21].

sequences tend to be highly diverse and typically have no detectable homologues, making structural modelling difficult[26–28]. Another example is being able to better model the homology-poor "dark proteome"[29], the contents of which likely holds yet to be discovered functional and structural biology[3]. The value of single-sequence methods also extends outside of natural proteins to areas like *de novo* protein design[4], where novel sequences and structures typically, by their very design, have no homologues[30].

Even in the case of a sequence having known homologues, single-sequence methods also have many valuable uses. One clear example is in variant effects[28], where methods like PSIPRED that use MSAs are limited because their predictions for a given sequence will be biased towards a family "average"[31]. Single-sequence methods avoid this bias and have the potential to better model the changes in secondary structure across a family even for highly divergent members. This also extends to being able to better model large single-species insertions that intrinsically have no homology information. Being able to avoid the bias of homology methods could also benefit protein engineering tasks[32], where the aim may be to generate a sequence that is highly divergent from its homologues.

Not only do single-sequence methods aid in a variety of scientific problems, they also directly tackle the protein structure prediction problem. Recent advances in tertiary structure prediction demonstrate highly accurate *ab initio* structure modelling when homologous sequences are available, but successful prediction without homology information remains elusive[33,34]. Single-sequence methods directly address the prediction of protein structure sans homology information, and improved predictors have the potential to lay the groundwork for future steps towards the herculean task of single-sequence tertiary structure prediction.

In this work, we show S4PRED provides significant improvements to single-sequence predictive accuracy by taking a semi-supervised approach to prediction. SSL methods represent powerful approaches for developing models that utilize both labelled and unlabelled data. Labelled data can be expensive to acquire, as is the case in determining high resolution protein structure data. Improving predictive performance by utilizing readily available

A

	Accuracy
PSIPRED-Single	70.6%
AWD-GRU	71.6%
S4Pred	**75.3%**

B

	F_1	Precision	Recall	Support
loop	76	73	79	45
α	78	81	76	34
β	66	69	64	21

C

True \ Predicted	loop	α	β
loop	79%	11%	10%
α	20%	76%	4%
β	29%	6%	64%

100% 75% 50% 25% 0%

Figure 2. (**A**) Table showing the difference in final accuracy (Q_3 score) between the improved S4PRED, the AWD-GRU benchmark, and the current version of PSIPRED-Single on the CB513 test set. (**B**) Table of classification metrics for the S4PRED model test set predictions. These are shown for each of the three predicted class; α-helix, β-sheet, and loop (or coil). The support is normalized across classes to 100 for clarity - there are a total of 84484 residue predictions in the test set. (**C**) Confusion matrix for the three classes in the S4PRED model test set predictions.

unlabelled protein sequence data is therefore very advantageous. Where some recent works[35,36] have looked to take advantage of this unlabelled data using unsupervised learning, borrowing from techniques in natural language processing[37,38], we instead look to modern SSL methods like FixMatch[39] for inspiration. These methods have demonstrated that psuedo-labelling, amongst other techniques, can significantly improve model performance[39–41]. Pseudo-labelling techniques use the model to assign artificial labels to unlabelled data which can be incorporated into the training of the model itself[41]. Here we design a pseudo-labelling approach for single-sequence prediction and combine it with a powerful neural network classifier to create S4PRED.

Results

Generating an artificially labelled dataset

For S4PRED, we take inspiration from FixMatch and develop a pseudo-labelling approach that is used to generate a large set of single sequences with highly accurate artificial labels. The first step is taking a large set of unlabelled protein sequences clustered as alignments and then removing the clusters containing a small number of sequences. The MSA-based PSIPRED V4[6] is then used to generate secondary structure predictions for each remaining cluster alignment. The representative sequence for each cluster is used as the target sequence when predicting secondary structure. The target sequence is then kept along with the Q_3 predictions, and the alignment is discarded. In this way, each cluster produces a single training example, constituting a single sequence and its psuedo-labels.

This approach effectively utilizes a homology-based predictor to provide accurate pseudo-labels for individual unlabelled sequences. PSIPRED generates high accuracy predictions, so it can be inferred that it's providing highly plausible secondary structure labels. These labels are, therefore, able to provide valuable biological information to the S4PRED model during training. Because each sequence is sampled from a separate cluster, there is also the added benefit of diversity between individual sequences in the dataset.

In this work we use the Uniclust30 database[42] to generate a training set, which, after a rigorous process of benchmarking and cross-validation, contains 1.01M sequences with pseudo-labels. To accompany the pseudo-labelled sequences, we construct a labelled dataset from protein structures in the PDB[43]. Homology with the test set is evaluated by CATH[44] classification, assessed at the Topology level. The final training and validation sets contain 10143 and 534 sequences respectively.

To train the S4PRED model using both sets of data we adapt the 'fine-tuning' approach from recent work of Devlin and collaborators[38]. In the context of S4PRED, fine-tuning consists of first training on the large pseudo-labelled dataset, after which a small amount of additional training is performed with the labelled dataset. Fine-tuning in this manner provides an effective and regimented training scheme that incorporates both sets of sequences. The S4PRED model itself uses a variant of the powerful AWD-LSTM[45] model, a recurrent neural network model that uses a variety of regularization techniques.

The prediction of secondary structure from a single sequence

The final model achieves an average test set Q_3 score of 75.3%. This improves the Q_3 of PSIPRED-Single by almost 5% (Figure 2A), currently being 70.6%. This is clearly seen in Figure 3A, which shows how the distribution of test set Q_3 scores for S4PRED has improved as a whole from PSIPRED-Single scores. In some cases, this has led to a

large improvement in prediction accuracy, an example of which is visualized in Figure 3B. Although this represents a significant improvement it is not necessarily a fair comparison as PSIPRED-Single uses a much simpler multi-layer perceptron model[5,6].

The most comparable method to date is SPIDER3-Single[10] which uses a bidirectional LSTM[46] trained in a supervised manner. This method predicts secondary structure and other sequence information, like solvent accessibility and torsion angles, from a single sequence. SPIDER3-Single uses one model to make preliminary predictions, which are then concatenated with the original input sequence, to be used as input to a second model that produces the final predictions. It reports a Q_3 score of 72.5%, however, this is on a non-standard test set based on a less stringent definition of homology[47].

To establish an equivalent and informative comparison we provide a second benchmark by training a similar supervised model to SPIDER3-Single which predicts only secondary structure in a standard supervised manner, without a secondary network. This uses the same network architecture as our SSL method but only trains on the labelled sequence dataset. This achieves a Q_3 score of 71.6% on CB513. This is a similar result to that achieved in a recent work[11], which reported a single-sequence Q_3 score of 69.9% and 71.3% on a validation set with a perceptron model and a LSTM-based model respectively. Although the second benchmark used here does not utilize a secondary prediction network like SPIDER3-Single, it is $< 1\%$ less performant than SPIDER3-Single's reported test set performance. Importantly, it provides a direct comparison to S4PRED by using the same model and test set. We use the name AWD-GRU, after the AWD-LSTM variant[45] used herein, to refer to this benchmark model. Although they use the same architecture, S4PRED still exceeds the performance of the AWD-GRU benchmark by a difference in Q_3 of almost 4%. Not only is this a large improvement for single-sequence prediction, it directly demonstrates the benefit of the SSL approach.

To more precisely determine the benefit that fine-tuning contributes to this performance gain, we tested a model trained on only pseudo-labelled sequences. This achieves a test Q_3 score of 74.4%. As is expected, this demonstrates that fine-tuning is a functional approach to combining both datasets that markedly improves prediction by $\sim 1\%$. Aside from the obvious benefit of learning from real labelled data, we speculate that part of the fine-tuning improvement derives from a softening of class decision boundaries. The model trained on only pseudo-labels has a prediction entropy of 0.325, averaged across classes, residues, and sequences. The final model shows a notably higher entropy of 0.548 suggesting that fine-tuning is possibly softening classification probabilities and improving predictions for cases that sit on those boundaries. One clear aspect of S4PRED that should be a focus of future improvement is β-strand prediction. Of the three classes it has the lowest F_1 score by a reasonable margin, 0.66 compared to 0.78 and 0.76 for loop and helix respectively (Figure 2B). This is likely due to a combination of being the least represented class in the training set and the most difficult class to predict.

Data efficiency using the semi-supervised learning approach

Another aspect we wished to investigate was the data efficiency of the SSL approach. We trained the AWD-GRU benchmark model on training sets of different sizes, randomly sampling from the 10143-sequence real-labelled training set. To a good degree, the test set accuracy linearly increases with the logarithm of the real-labelled training set size ($R^2 = 0.92$), as can be seen in Figure 4. This trend suggests that the SSL approach simulates having trained on a real sequence dataset that is $\sim$x7.6 larger. Under the loose assumption that the ratio of PDB structures to labelled

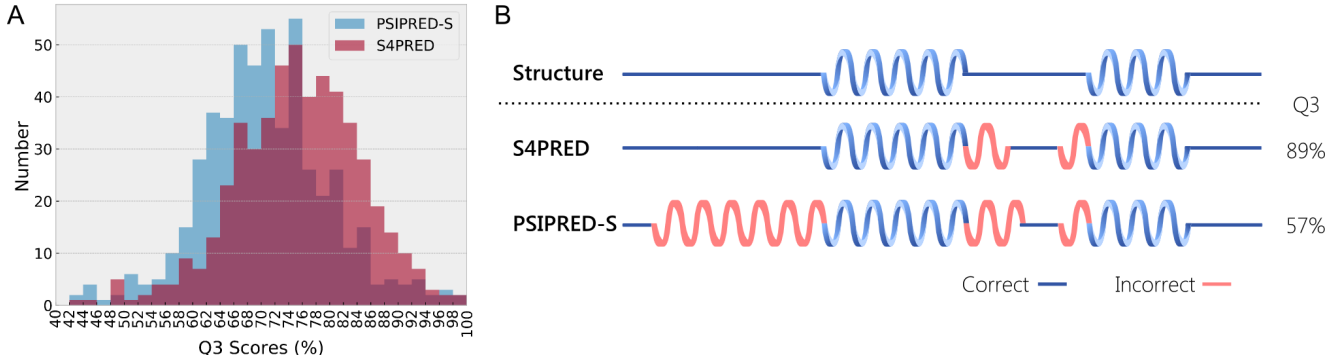

Figure 3. (**A**) Histogram of Q_3 scores on the CB513 test set showing the improved results of S4PRED over PSIPRED-Single (PSIPRED-S). (**B**) Example of S4PRED and PSIPRED-Single secondary structure predictions relative to the true structure for the C terminal domain of pyruvate oxidase and decarboxylase (PDB ID 1POW).

training set size stays the same, there would need to be greater than 1.2M structures in the PDB (as compared to the 162816 entries available as of 04-2020) to achieve the same performance as S4PRED using only real data.

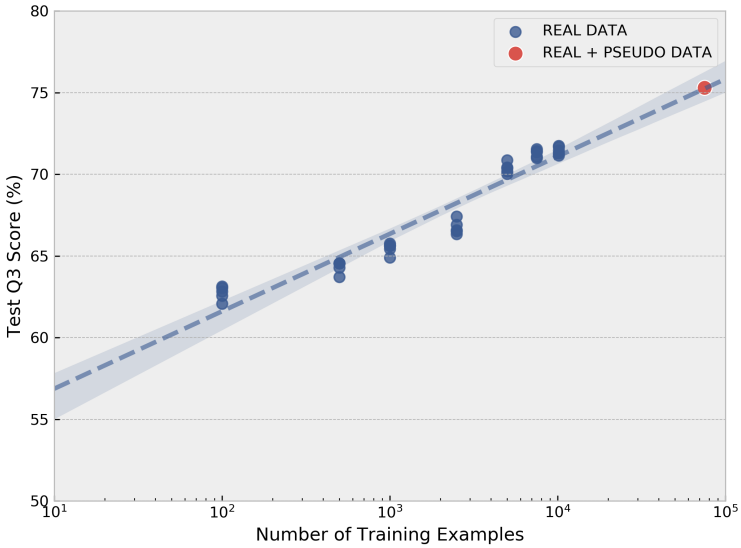

Figure 4. Scatter plot comparing the logarithm of the number of data points compared to trained model accuracy with real labelled sequences. A dashed linear trend line is included. The S4PRED model using real and psuedo-labelled data (75.3%) is included as a single point for comparison.

Single-sequence prediction in context

In this work we consider single-sequence prediction in the strictest sense. This is a model that, for a single example, provides predictions without using information derived from related sequences or evolutionary information. This is an important distinction because using even a small number of homologous sequences improves prediction by several percentage points[18].

The recently published SPOT-1D[12] provides a clear example of this phenomenon. Hanson and collaborators[12] show Q_3 scores of several homology-based models when predicting with low diversity alignments. The criterion for this low diversity is having $N_{eff} < 2$ (a measure of alignment diversity, as provided by HHblits[48]). This is reported as $N_{eff} = 1$, however, all values are rounded down to the nearest integer. This is clearly not a single-sequence approach. It is also further evidenced in the reported Q_3 scores. Of the methods reported, Porter 5[11,49] achieves the highest Q_3 with 78%, followed by SPOT-1D at 77%. Separate to these results, Porter 5 reports a validation set Q_3 of 71.3% when trained on only single sequences without profiles[11]. Ignoring potential training set and test set overlap for the values reported in SPOT-1D, this difference in Q_3 clearly demonstrates that using even low diversity alignments is enough to significantly improve predictive performance, over a purely single-sequence approach.

Information from homologous sequences can also improve results by being present in the bias of a trained model. A subtle example of this is in the recent DeepSeqVec model[36], which trained an unsupervised neural network to produce learned representations of individual sequences from UniRef50[50]. The unsupervised model is subsequently used to generate features which are used to train a second model that predicts secondary structure. This second model achieves a Q_3 score of 76.9% on CB513[36]. Although this two model approach is providing secondary structure predictions for individual sequences, it is not a single-sequence method because the unsupervised model has access to implicit evolutionary information for both the training set and test set sequences. This is partly due to being improperly validated, a split was not performed between the training and test sets. With no split the model is able to learn relationships between test set and training set sequences. It is also due to the training objective of the underlying ELMo language model[51]. The model is able to learn relationships between homologous sequences in a shared latent space, especially given that residue representations are optimized by trying to predict what residue is likely to be found at each position in a given input sequence.

Even if the model uses a small amount of evolutionary information, it still precludes it from being a single-sequence method. The predictions from such a model still benefit from evolutionary information. This not only highlights the difficulty in developing accurate methods that are strictly single-sequence, it also highlights how achieving a Q_3 score of 75.3% with S4PRED represents a step up in performance for single-sequence methods.

Discussion

In this work we have developed S4PRED, a method for predicting protein secondary structure from a single sequence using semi-supervised learning. Single sequence methods are a valuable research prospect with many potential high-impact applications. S4PRED shows that a semi-supervised approach, leveraging the large amount of unlabeled protein sequence data available, is capable of achieving a leap in performance for these methods.

Through this success, S4PRED provides a first step and blueprint for continued work on single-sequence methods in the secondary structure prediction field. One clear avenue for further improvement is expanding the pseudo-labelled set by including the large number of available metagenomic sequences[25,52]. Other potential options include leveraging data augmentation and powerful regularization methods like MixUp[53], and utilizing large self-attention based classifiers[38]. The semi-supervised approach of S4PRED, using homology-based predictors to provide pseudo-labels for single sequences, could also be extended to other similar single-sequence problem domains like the prediction of solvent accessibility[54], or even the challenging field of contact prediction[31]. To foster further development and immediate application we provide S4PRED as an open source state-of-the-art tool and as an option on the PSIPRED web service. Much like homology-based secondary structure prediction heralded later improvements in homology-based tertiary structure prediction, we hope that S4PRED heralds many future improvements in the general prediction of tertiary protein structure from a single sequence.

Methods

Labelled dataset construction

The first stage in our construction of a labelled dataset is generating a non-redundant set of PDB chains using the PISCES server[55] with a maximum identity between structures of 70% and a maximum resolution of 2.6Å. This produces a list of 30630 chains, all with a length of 40 residues or more. At the cost of introducing some noise but retaining more examples we do not remove any chains with unlabelled residues.

From this list we then remove any chains that share homology with the test set. We use the standard test set for secondary structure prediction, CB513. Homology is assessed and qualified as having any overlapping CATH[44] domains at the T-level with any of the sequences in the test set. This removes approximately ⅔ of the chains leaving a total of 10677 from which to generate training and validation sets.

The remaining chains are clustered at 25% identity using `MMseqs2`[56]. From the resulting 6369 clusters, a subset is randomly sampled such that the total sum of their sequences makes up $\sim 5\%$ of the 10677 chains. This is to create a validation set and achieve a 95%/5% split between training and validation sets, as well as keeping the validation and test sets similarly sized. This leaves a final split of 10143/534/513 examples for the training, validation, and test sets respectively.

Secondary structures are specified using DSSP[57]. For each residue in each sequence the eight states (H, I, G, E, B, S, T, -) are converted to the standard 3 classes (Q_3) of strand for E & B, helix for H & G, and loop (coil) for the remainder. Protein sequences are represented as a sequence of amino acids, where each residue is represented by one of 21 integers; twenty for the canonical amino acids and one for "X" corresponding to unknown and non-canonical amino acids. Each integer represents an index to an embedding that is learned during the training of the neural network models.

Pseudo-labelled dataset generation

To assemble a dataset of psuedo-labelled sequences we start with Uniclust30 (Januray 2020 release)[42]. This consists of UniProtKB[58] sequences clustered to 30% identity, making up 23.8M clusters. Each cluster is then considered as a single potential example for the pseudo-labelled training set. Any cluster can be converted into a target sequence and alignment which can then be passed to PSIPRED to generate high accuracy predictions of secondary structure. These predictions are then one-hot encoded and treated as pseudo-labels with the target sequence providing a single example.

Clusters are filtered from the initial 23.8M Uniclust30 set by removing clusters that are either too short or have too few sequence members. If a cluster has a representative sequence with a length of less than 20 residues or contains less than 10 non-redundant sequences in its alignment it is removed. Applying these restrictions leaves a much smaller set of 1.41M clusters. These are the candidate clusters for generating a training set from which homology with the validation and test sets is to be removed.

Removal of test set homology from the pseudo-labelled dataset

Models trained on labelled and pseudo-labelled data use the same CB513[14] test set. This consistency provides a means of directly comparing S4PRED with models trained separately on only labelled data, namely, PSIPRED-Single and the AWD-GRU. The same real-labelled validation set is also used, ensuring that all validation sequences used in this work are structurally non-homologous with the test set.

For the vast majority of clusters, solved structures are not available. This leaves sequence-based approaches to identify and eliminate clusters that share any homology with the test set. It is widely known that using a simple percent identity (e.g. 30%) as a homology threshold between two sequences is inadequate and leads to data leakage[47]. As such we employ a rigorous and multifaceted approach to removing clusters that are homologous to the test set.

The first step is performing HMM-HMM homology searching for each member of CB513 with `HHblits`[48] using one iteration and an E-value of 10 against the remaining clusters. An accurate means of homology detection, using a high E-value also provides an aggressive sweep to capture any positive matches at the expense of a small number of false hits. One iteration was performed as this was broadly found to return more hits. For the validation set, the same procedure is followed, however the default E-value (1×10^{-3}) is used with two iterations. All clusters that are matches to the test and validation sets are then removed.

The remaining clusters are copied and combined to create a single large sequence database which is processed with `pFilt`[59] to mask regions of low amino acid complexity. The test set alignments produced by `HHblits` are used to construct `HMMER`[60] HMMs which are then used to perform HMM-sequence homology searches against the

sequence database using `hmmsearch`. The '–max' flag is used to improve sensitivity and the default e-value is used. All sequences that are positive hits, along with their respective clusters, are removed from the remaining set.

A secondary and overlapping procedure is also performed. Each member of the test set is mapped to one or more Pfam[61] families by pre-existing annotations. These are found by a combination of SIFTS[62] and manual searching. From the test set, 17 structures were not found to belong to any Pfam family. For each Pfam family linked to the remaining members of the test set, a list of UniProt sequence IDs is generated. This is extracted from the family's current UniProt-based Pfam alignment (01-2020) and is used to remove clusters following the same procedure as positive hits from the HMM-sequence search.

In total these methods remove approximately a quarter of the initial 1.41M clusters, leaving a final 1.01M clusters to construct a pseudo-labelled training set. While the fear of data leakage remains ever present, we believe that in the absence of structures this approach constitutes a rigorous and exhaustive approach to homology removal.

Generating pseudo-labels with PSIPRED

A given cluster can provide a sequence with pseudo-labels by first taking its representative sequence as the target sequence and splitting off the remainder of the cluster alignment. This is treated as if it was the target sequence alignment. Both sequence and alignment are then processed using the standard PSIPRED procedure. The Q_3 labels predicted by PSIPRED V4[6] are then kept along with the target sequence as a single example for the training set. The version of PSIPRED used to generate labels is trained on a set of sequences that are structurally non-homologous with the CB513 test set. This ensures that the pseudo-labels contain no information derived from the test set implicitly through PSIPRED. This procedure is repeated to generate a training set of 1.01M sequences each paired with a sequence of pseudo-labels.

Model architecture

We use a state-of-the-art recurrent neural network (RNN) from the language modelling domain as a classification model. More specifically we adapt the AWD-LSTM[45] for secondary structure prediction. The first portion of our model takes a sequence of amino acids encoded as integers and replaces them with corresponding 128-d embeddings that are learned during training and are initialized from $\mathcal{N}(0,1)$. During training a 10% dropout is applied to the embeddings.

The embeddings are fed into a bidirectional gated recurrent unit (GRU)[63] model with 1024 hidden dimensions in each direction. Here the model differs from the AWD-LSTM which utilizes a long short term memory (LSTM) model with DropConnect[64] applied to the hidden-to-hidden weight matrices. Our model does the same but utilizes a GRU which we refer to as an AWD-GRU. Unless specified, the weight dropping is set to 50% during training. This model utilizes three layers of AWD-GRUs with 10% dropout applied between each layer during training.

The output of the final recurrent layer is a 2048-d vector at each time step. This is fed into a final linear layer with a log softmax operation to produce the 3-class probabilities at each residue position. These are then used to calculate a negative log likelihood loss using the corresponding one-hot encoded labels. Unlike the original AWD-LSTM we use another popular stochastic gradient descent (SGD) variant, Adam[65], as an optimizer to minimize the loss and train model parameters.

S4PRED Training with pseudo-labelled data

The first stage in training the S4PRED model is training on the 1.01M pseudo-labelled sequences. For optimization the Adam beta terms are set to $\beta_1,\beta_2 = \{0.9, 0.999\}$ with an initial learning rate of 1×10^{-4} and a mini-batch size of 256. We also perform gradient clipping with a maximum norm of 0.25. To utilize a batch size of greater than 1 all batches are padded on the fly to the length of the longest sequence in a given batch. The padding symbol has a corresponding embedding and the loss is masked at positions that are padded. Training occurs for up to 10 epochs which typically takes between 48 to 72 hours in total. The performance on the validation set is tested every 100 batches and it is used to perform early stopping.

Fine-tuning with labelled data

We adapt the methodology presented by Devlin and collaborators[38] for S4PRED by taking the model trained on pseudo-labelled sequences and performing 1 epoch of training on the 10K labelled sequences. Unlike their method, however, we do not need an additional output layer, having already trained on the semi-supervised secondary structure prediction objective with the psuedo-labelled sequences. For fine-tuning, the batch size is lowered to 32 and the weight drop is set to 0%. All other hyper-parameters are kept the same and the Adam optimizer is reset. The final model is a an ensemble of 5 models fine-tuned with different random seeds, all starting from the same model. Using an ensemble improves prediction by $\sim 0.1\%$.

Performance Benchmarking

Two methods are used to benchmark the results of S4PRED. The first method is the original PSIPRED-Single. Its predictions are generated using the pipeline included with PSIPRED V4. PSIPRED-Single achieves a Q_3 score of 70.6% on CB513. The AWD-GRU model is the second model used for benchmarking. It is trained with the same model architecture and hyper-parameters as S4PRED when it is being trained on the psuedo-labelled set before fine-tuning. However, it only trains on the 10143-sequence set with real labels. This achieves a Q_3 score of 71.6% also on CB513.

The data efficiency of the S4PRED method was investigated to estimate the value of training with pseudo-labelled data. This was done by training five versions of the AWD-GRU model, each with a different random seed, on different sized subsets of the 10143 real labelled data. Models were trained with 100, 500, 1000, 2500, 5000, 7500, & 10143 examples (a total of 35 models). Each model is tested against CB513 and a linear regression model is fit between the logarithm of the number of points and model Q_3 score ($R^2 = 0.92$). This is visualized in Figure S4. By the linear model, a Q_3 score of 75.3% would require 77K real labelled sequences in the dataset.

Software Implementation

All analysis was performed using Python and all neural network models were built and trained using Pytorch[66]. During training, all models used mixed precision which was implemented using the NVIDIA Apex package with the `-O2` flag. This was found to improve training speeds with a negligible effect on results. Individual models were trained on a single compute cluster node using an NVIDIA V100 32GB GPU. Upon publication, the S4PRED model and AWD-GRU model with their weights will be released as open source software on the PSIPRED GitHub repository (https://github.com/psipred/) along with documentation. It will also be provided as a part of the PSIPRED web service (http://bioinf.cs.ucl.ac.uk/psipred/).

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Author contributions statement

L.M. and D.T.J. conceived and designed the study and reviewed the manuscript. L.M. carried out the computational work and drafted the manuscript.

Competing interests

The authors declare no competing interests.

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