

# Hypergraph Motif Representation Learning

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## Abstract

Hypergraphs have emerged as a powerful tool for representing high-order connections in real-world complex systems. Similar to graphs, local structural patterns in hypergraphs, known as high-order motifs (h-motifs), play a crucial role in network dynamics. In this work, we aim to advance our understanding of such complex high-order dynamics by introducing and formalizing the problem of h-motifs prediction. To address this task, we propose a novel solution that leverages both high-order and pairwise to capture hyperedges correlation within h-motifs. A key component of our solution is the generation of non-trivial negative samples. designed to generate close-to-positive negative samples.

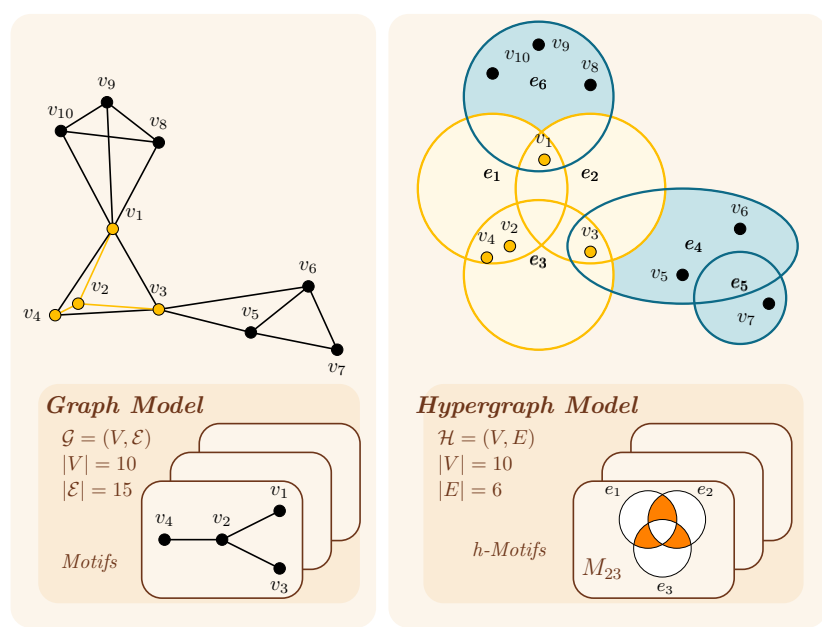


**Figure 1.** Differences between the graph and the hypergraph models.

## Datasets

We conducted our experiments on the following four real-world networks:

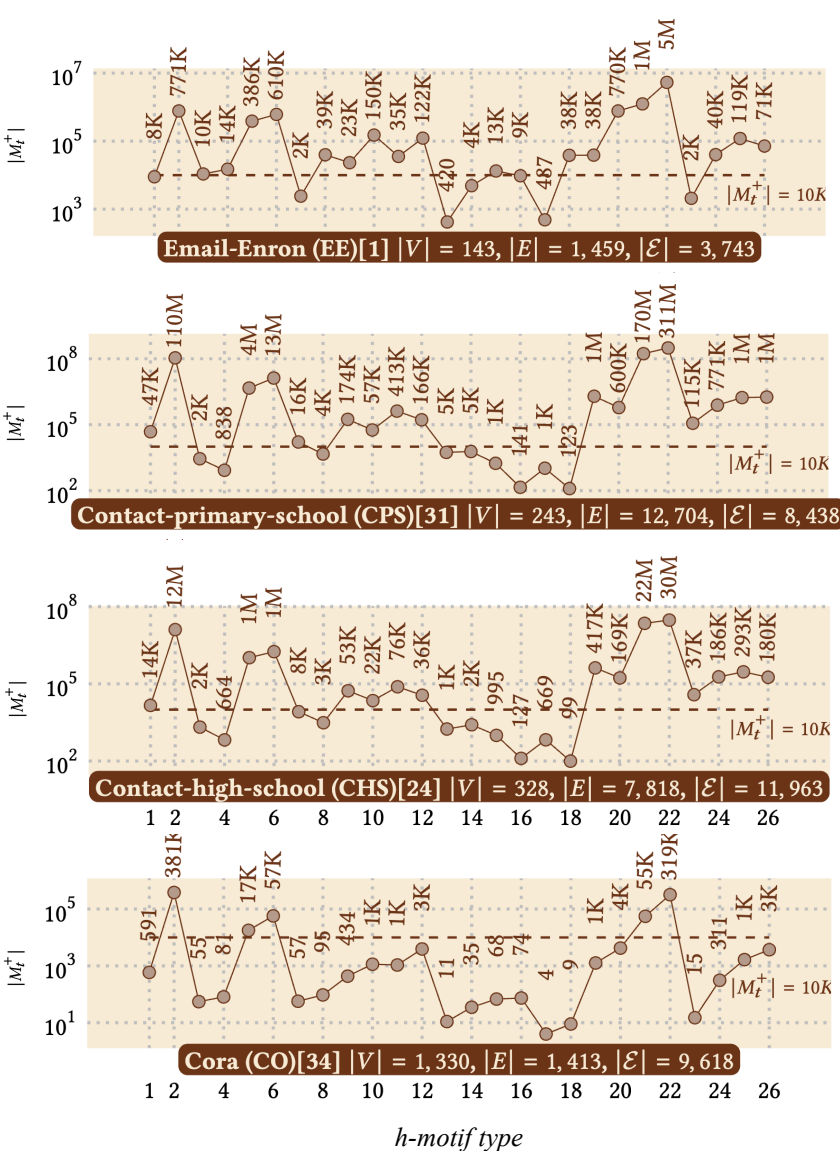


**Figure 4.** Dataset statistics - # Nodes, # Hyperedges, # Clique expansion edges and h-motifs distribution on the chart.

## Problem Formulation

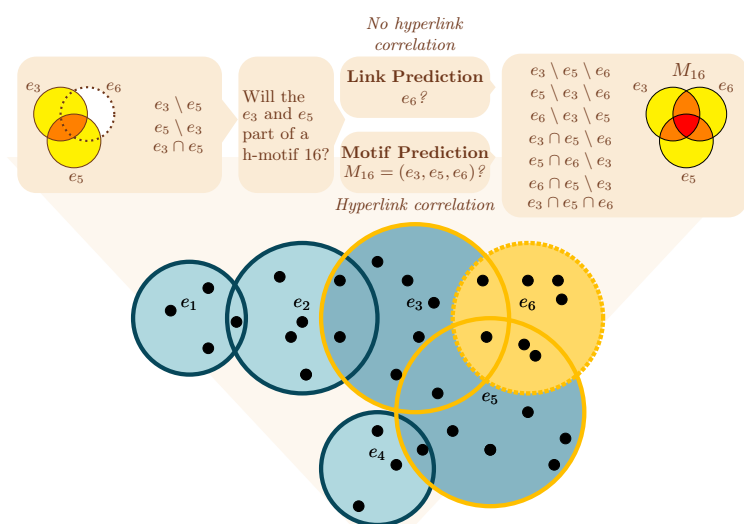


**Figure 2.** A high-level description of the h-motif prediction problem.

## End-to-end Architecture

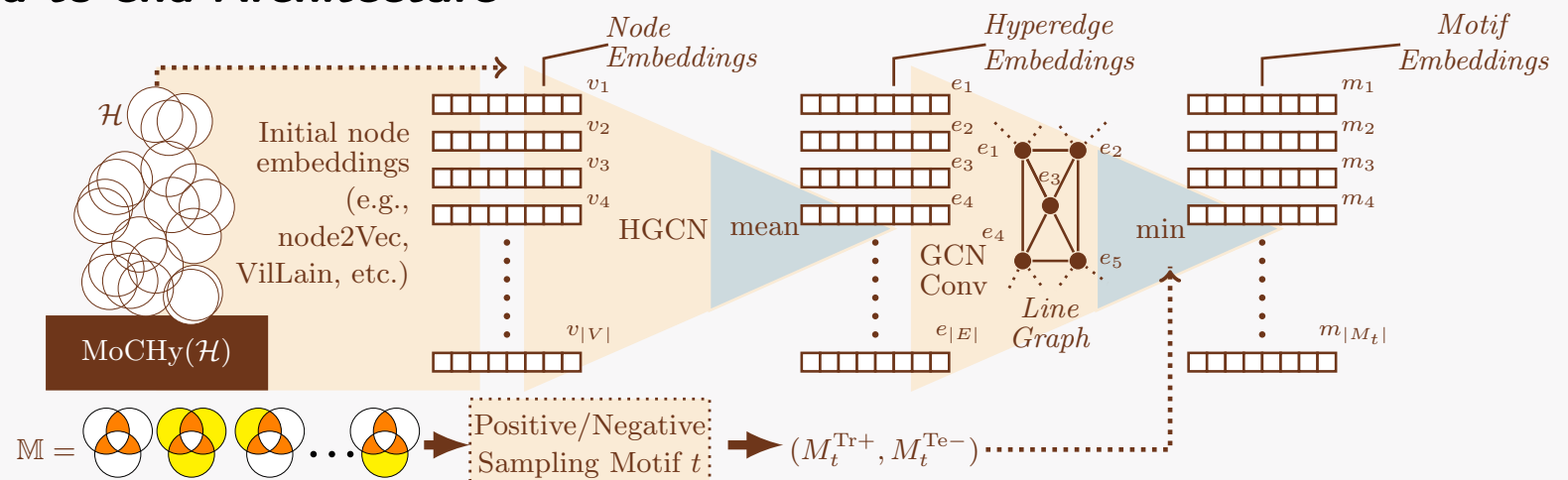


**Figure 3.** The deep neural network architecture employed in the proposed h-motif framework.

## Evaluation

In our experiments, networks were divided over hyperedges, allocating 80% of the data for the training set and the remaining 20% for the test set. Due to computational constraints, we limited the h-motif positive sampling algorithm to a maximum of  $|M_t^+| \leq 10K$  h-motifs selected at random.

| EE<br>$\eta = 0.01$ |           |             |             |             |             |             |             |             |             |             |           |             |             | CPS<br>$\eta = 0.01$ |             |             |             |             |             |             |  |  |  |  |  |  |  |
|---------------------|-----------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-----------|-------------|-------------|----------------------|-------------|-------------|-------------|-------------|-------------|-------------|--|--|--|--|--|--|--|
| $t$                 | $ M_t^+ $ | CC          | AA          | JC          | HPRA        | N2V         | N2V<br>HGCN | VL          | HM<br>N2V   | HM<br>VL    | $ M_t^- $ | CC          | AA          | JC                   | HPRA        | N2V         | N2V<br>HGCN | VL          | HM<br>N2V   | HM<br>VL    |  |  |  |  |  |  |  |
| 1                   | 771K      | 0.45 ± 0.01 | 0.60 ± 0.01 | 0.70 ± 0.01 | 0.68 ± 0.02 | 0.74 ± 0.05 | 0.79 ± 0.01 | 0.88 ± 0.01 | 0.97 ± 0.01 | 0.96 ± 0.00 | 47K       | 0.40 ± 0.01 | 0.73 ± 0.01 | 0.70 ± 0.03          | 0.60 ± 0.03 | 0.91 ± 0.01 | 0.96 ± 0.01 | 0.94 ± 0.03 | 0.97 ± 0.01 | 0.97 ± 0.00 |  |  |  |  |  |  |  |
| 2                   | 8K        | 0.38 ± 0.00 | 0.53 ± 0.01 | 0.51 ± 0.01 | 0.64 ± 0.04 | 0.82 ± 0.02 | 0.84 ± 0.01 | 0.89 ± 0.04 | 0.85 ± 0.08 | 0.95 ± 0.00 | 110M      | 0.29 ± 0.01 | 0.62 ± 0.02 | 0.45 ± 0.01          | 0.61 ± 0.02 | 0.95 ± 0.01 | 0.97 ± 0.00 | 0.95 ± 0.04 | 0.97 ± 0.01 | 0.98 ± 0.01 |  |  |  |  |  |  |  |
| 3                   | 10K       | 0.44 ± 0.04 | 0.61 ± 0.04 | 0.73 ± 0.07 | 0.71 ± 0.03 | 0.77 ± 0.03 | 0.84 ± 0.00 | 0.90 ± 0.02 | 0.96 ± 0.03 | 0.98 ± 0.01 | 72K       | 0.37 ± 0.04 | 0.72 ± 0.03 | 0.66 ± 0.05          | 0.67 ± 0.04 | 0.84 ± 0.05 | 0.96 ± 0.01 | 0.95 ± 0.03 | 0.98 ± 0.01 | 0.97 ± 0.02 |  |  |  |  |  |  |  |
| 4                   | 14K       | 0.53 ± 0.02 | 0.67 ± 0.00 | 0.77 ± 0.01 | 0.71 ± 0.01 | 0.73 ± 0.02 | 0.77 ± 0.01 | 0.95 ± 0.01 | 0.90 ± 0.07 | 0.97 ± 0.01 | 938       | 0.38 ± 0.03 | 0.76 ± 0.03 | 0.66 ± 0.03          | 0.64 ± 0.01 | 0.79 ± 0.06 | 0.93 ± 0.01 | 0.96 ± 0.02 | 0.97 ± 0.01 | 0.96 ± 0.03 |  |  |  |  |  |  |  |
| 5                   | 386K      | 0.44 ± 0.01 | 0.59 ± 0.01 | 0.63 ± 0.01 | 0.66 ± 0.01 | 0.80 ± 0.01 | 0.82 ± 0.01 | 0.95 ± 0.01 | 0.94 ± 0.04 | 0.97 ± 0.01 | 91M       | 0.32 ± 0.00 | 0.70 ± 0.02 | 0.55 ± 0.01          | 0.60 ± 0.01 | 0.95 ± 0.01 | 0.98 ± 0.01 | 0.95 ± 0.03 | 0.97 ± 0.01 | 0.98 ± 0.01 |  |  |  |  |  |  |  |
| 6                   | 610K      | 0.47 ± 0.00 | 0.64 ± 0.00 | 0.67 ± 0.00 | 0.71 ± 0.03 | 0.80 ± 0.01 | 0.82 ± 0.01 | 0.95 ± 0.01 | 0.94 ± 0.04 | 0.97 ± 0.01 | 136M      | 0.35 ± 0.02 | 0.69 ± 0.02 | 0.61 ± 0.03          | 0.72 ± 0.04 | 0.85 ± 0.02 | 0.97 ± 0.01 | 0.95 ± 0.03 | 0.97 ± 0.00 | 0.97 ± 0.00 |  |  |  |  |  |  |  |
| 7                   | 2K        | 0.33 ± 0.02 | 0.50 ± 0.03 | 0.67 ± 0.06 | 0.64 ± 0.06 | 0.87 ± 0.04 | 0.96 ± 0.01 | 0.92 ± 0.01 | 0.98 ± 0.01 | 0.98 ± 0.01 | 136K      | 0.36 ± 0.01 | 0.78 ± 0.01 | 0.64 ± 0.03          | 0.58 ± 0.01 | 0.96 ± 0.01 | 0.96 ± 0.01 | 0.92 ± 0.03 | 0.96 ± 0.03 | 0.95 ± 0.03 |  |  |  |  |  |  |  |
| 8                   | 39K       | 0.48 ± 0.01 | 0.66 ± 0.02 | 0.72 ± 0.01 | 0.72 ± 0.04 | 0.76 ± 0.01 | 0.77 ± 0.03 | 0.92 ± 0.07 | 0.86 ± 0.10 | 0.96 ± 0.01 | 74K       | 0.37 ± 0.01 | 0.75 ± 0.03 | 0.65 ± 0.02          | 0.57 ± 0.02 | 0.81 ± 0.02 | 0.95 ± 0.01 | 0.96 ± 0.03 | 0.96 ± 0.01 | 0.96 ± 0.02 |  |  |  |  |  |  |  |
| 9                   | 23K       | 0.39 ± 0.03 | 0.55 ± 0.01 | 0.70 ± 0.06 | 0.65 ± 0.02 | 0.89 ± 0.01 | 0.91 ± 0.00 | 0.90 ± 0.01 | 0.95 ± 0.04 | 0.98 ± 0.00 | 174K      | 0.36 ± 0.01 | 0.76 ± 0.02 | 0.65 ± 0.01          | 0.64 ± 0.01 | 0.96 ± 0.01 | 0.97 ± 0.01 | 0.94 ± 0.01 | 0.98 ± 0.01 | 0.98 ± 0.01 |  |  |  |  |  |  |  |
| 10                  | 150K      | 0.54 ± 0.01 | 0.68 ± 0.02 | 0.75 ± 0.01 | 0.74 ± 0.01 | 0.74 ± 0.02 | 0.76 ± 0.03 | 0.97 ± 0.01 | 0.87 ± 0.08 | 0.95 ± 0.04 | 357K      | 0.37 ± 0.02 | 0.72 ± 0.03 | 0.68 ± 0.01          | 0.66 ± 0.05 | 0.90 ± 0.01 | 0.96 ± 0.00 | 0.95 ± 0.03 | 0.97 ± 0.02 | 0.97 ± 0.02 |  |  |  |  |  |  |  |
| 11                  | 35K       | 0.45 ± 0.03 | 0.68 ± 0.04 | 0.76 ± 0.02 | 0.77 ± 0.03 | 0.81 ± 0.02 | 0.84 ± 0.02 | 0.88 ± 0.01 | 0.99 ± 0.01 | 0.98 ± 0.00 | 713K      | 0.36 ± 0.01 | 0.71 ± 0.03 | 0.70 ± 0.02          | 0.75 ± 0.04 | 0.94 ± 0.01 | 0.98 ± 0.01 | 0.95 ± 0.03 | 0.98 ± 0.02 | 0.98 ± 0.02 |  |  |  |  |  |  |  |
| 12                  | 122K      | 0.58 ± 0.01 | 0.73 ± 0.02 | 0.81 ± 0.01 | 0.82 ± 0.02 | 0.75 ± 0.02 | 0.79 ± 0.02 | 0.92 ± 0.01 | 0.95 ± 0.04 | 0.96 ± 0.02 | 1666K     | 0.39 ± 0.01 | 0.73 ± 0.03 | 0.73 ± 0.01          | 0.74 ± 0.03 | 0.87 ± 0.03 | 0.97 ± 0.00 | 0.97 ± 0.02 | 0.98 ± 0.01 | 0.99 ± 0.01 |  |  |  |  |  |  |  |
| 13                  | 48K       | 0.31 ± 0.01 | 0.52 ± 0.04 | 0.71 ± 0.04 | 0.68 ± 0.05 | 0.83 ± 0.03 | 0.96 ± 0.01 | 0.91 ± 0.05 | 0.98 ± 0.01 | 0.97 ± 0.00 | 5K        | 0.37 ± 0.02 | 0.77 ± 0.01 | 0.71 ± 0.01          | 0.78 ± 0.01 | 0.87 ± 0.06 | 0.98 ± 0.01 | 0.96 ± 0.01 | 0.97 ± 0.01 | 0.98 ± 0.01 |  |  |  |  |  |  |  |
| 14                  | 4K        | 0.39 ± 0.01 | 0.58 ± 0.02 | 0.75 ± 0.01 | 0.73 ± 0.05 | 0.85 ± 0.02 | 0.88 ± 0.00 | 0.86 ± 0.02 | 0.96 ± 0.03 | 0.98 ± 0.00 | 75K       | 0.37 ± 0.02 | 0.77 ± 0.01 | 0.71 ± 0.01          | 0.78 ± 0.01 | 0.87 ± 0.06 | 0.98 ± 0.01 | 0.96 ± 0.01 | 0.97 ± 0.01 | 0.98 ± 0.01 |  |  |  |  |  |  |  |
| 15                  | 13K       | 0.56 ± 0.01 | 0.71 ± 0.01 | 0.81 ± 0.01 | 0.79 ± 0.03 | 0.72 ± 0.05 | 0.78 ± 0.01 | 0.93 ± 0.02 | 0.98 ± 0.02 | 0.98 ± 0.01 | 71K       | 0.37 ± 0.03 | 0.70 ± 0.05 | 0.67 ± 0.03          | 0.79 ± 0.04 | 0.88 ± 0.03 | 0.98 ± 0.01 | 0.97 ± 0.01 | 0.98 ± 0.00 | 0.98 ± 0.01 |  |  |  |  |  |  |  |
| 16                  | 9K        | 0.70 ± 0.02 | 0.76 ± 0.01 | 0.88 ± 0.02 | 0.81 ± 0.01 | 0.68 ± 0.12 | 0.83 ± 0.02 | 0.87 ± 0.03 | 0.96 ± 0.03 | 0.97 ± 0.01 | 14K       | 0.36 ± 0.03 | 0.70 ± 0.05 | 0.69 ± 0.04          | 0.77 ± 0.03 | 0.89 ± 0.04 | 0.90 ± 0.04 | 0.97 ± 0.01 | 0.95 ± 0.03 | 0.95 ± 0.04 |  |  |  |  |  |  |  |
| 17                  | 48K       | 0.35 ± 0.03 | 0.53 ± 0.03 | 0.67 ± 0.02 | 0.59 ± 0.04 | 0.86 ± 0.03 | 0.96 ± 0.01 | 0.91 ± 0.04 | 0.96 ± 0.01 | 0.97 ± 0.01 | 913K      | 0.34 ± 0.01 | 0.64 ± 0.01 | 0.61 ± 0.02          | 0.74 ± 0.03 | 0.94 ± 0.01 | 0.98 ± 0.01 | 0.96 ± 0.01 | 0.99 ± 0.00 | 0.99 ± 0.01 |  |  |  |  |  |  |  |
| 18                  | 38K       | 0.66 ± 0.04 | 0.80 ± 0.02 | 0.80 ± 0.04 | 0.68 ± 0.04 | 0.69 ± 0.05 | 0.72 ± 0.04 | 0.94 ± 0.03 | 0.87 ± 0.09 | 0.92 ± 0.04 | 723       | 0.46 ± 0.04 | 0.76 ± 0.13 | 0.81 ± 0.04          | 0.69 ± 0.04 | 0.76 ± 0.08 | 0.95 ± 0.03 | 0.98 ± 0.02 | 0.98 ± 0.01 | 0.98 ± 0.02 |  |  |  |  |  |  |  |
| 19                  | 38K       | 0.36 ± 0.02 | 0.51 ± 0.02 | 0.62 ± 0.06 | 0.57 ± 0.01 | 0.90 ± 0.02 | 0.93 ± 0.01 | 0.86 ± 0.03 | 0.95 ± 0.03 | 0.97 ± 0.01 | 1M        | 0.32 ± 0.00 | 0.69 ± 0.01 | 0.55 ± 0.00          | 0.60 ± 0.01 | 0.96 ± 0.01 | 0.97 ± 0.02 | 0.93 ± 0.03 | 0.97 ± 0.02 | 0.97 ± 0.03 |  |  |  |  |  |  |  |
| 20                  | 770K      | 0.59 ± 0.02 | 0.71 ± 0.02 | 0.74 ± 0.03 | 0.70 ± 0.01 | 0.74 ± 0.02 | 0.76 ± 0.02 | 0.97 ± 0.00 | 0.96 ± 0.01 | 0.95 ± 0.02 | 600K      | 0.42 ± 0.01 | 0.60 ± 0.03 | 0.59 ± 0.01          | 0.62 ± 0.01 | 0.93 ± 0.02 | 0.97 ± 0.01 | 0.98 ± 0.02 | 0.99 ± 0.01 | 0.99 ± 0.01 |  |  |  |  |  |  |  |
| 21                  | 1M        | 0.38 ± 0.01 | 0.54 ± 0.01 | 0.54 ± 0.04 | 0.58 ± 0.01 | 0.86 ± 0.00 | 0.87 ± 0.01 | 0.88 ± 0.04 | 0.96 ± 0.02 | 0.97 ± 0.00 | 170M      | 0.27 ± 0.01 | 0.61 ± 0.03 | 0.43 ± 0.01          | 0.58 ± 0.04 | 0.96 ± 0.00 | 0.98 ± 0.00 | 0.95 ± 0.02 | 0.97 ± 0.02 | 0.97 ± 0.01 |  |  |  |  |  |  |  |
| 22                  | 5M        | 0.52 ± 0.03 | 0.67 ± 0.02 | 0.68 ± 0.04 | 0.71 ± 0.01 | 0.79 ± 0.01 | 0.81 ± 0.01 | 0.95 ± 0.01 | 0.95 ± 0.02 | 0.96 ± 0.00 | 111M      | 0.28 ± 0.01 | 0.64 ± 0.03 | 0.50 ± 0.02          | 0.63 ± 0.02 | 0.94 ± 0.01 | 0.97 ± 0.00 | 0.96 ± 0.02 | 0.98 ± 0.01 | 0.99 ± 0.01 |  |  |  |  |  |  |  |
| 23                  | 2K        | 0.33 ± 0.01 | 0.45 ± 0.01 | 0.53 ± 0.02 | 0.58 ± 0.09 | 0.86 ± 0.04 | 0.96 ± 0.01 | 0.91 ± 0.04 | 0.96 ± 0.01 | 0.97 ± 0.01 | 351K      | 0.29 ± 0.01 | 0.68 ± 0.01 | 0.49 ± 0.02          | 0.56 ± 0.03 | 0.97 ± 0.01 | 0.98 ± 0.01 | 0.94 ± 0.01 | 0.97 ± 0.01 | 0.97 ± 0.01 |  |  |  |  |  |  |  |
| 24                  | 40K       | 0.44 ± 0.02 | 0.59 ± 0.03 | 0.64 ± 0.04 | 0.62 ± 0.01 | 0.86 ± 0.02 | 0.94 ± 0.03 | 0.93 ± 0.06 | 0.93 ± 0.06 | 0.96 ± 0.01 | 41K       | 0.43 ± 0.04 | 0.65 ± 0.07 | 0.89 ± 0.02          | 0.99 ± 0.01 | 0.99 ± 0.01 | 0.99 ± 0.01 | 0.99 ± 0.01 | 0.99 ± 0.01 | 0.99 ± 0.01 |  |  |  |  |  |  |  |
| 25                  | 119K      | 0.52 ± 0.00 | 0.68 ± 0.00 | 0.72 ± 0.01 | 0.73 ± 0.01 | 0.79 ± 0.02 | 0.81 ± 0.02 | 0.96 ± 0.00 | 0.94 ± 0.07 | 0.98 ± 0.00 | 1M        | 0.34 ± 0.01 | 0.70 ± 0.02 | 0.63 ± 0.00          | 0.63 ± 0.03 | 0.95 ± 0.02 | 0.97 ± 0.01 | 0.96 ± 0.02 | 0.97 ± 0.01 | 0.97 ± 0.01 |  |  |  |  |  |  |  |
| 26                  | 71K       | 0.62 ± 0.01 | 0.75 ± 0.01 | 0.84 ± 0.02 | 0.80 ± 0.02 | 0.75 ± 0.01 | 0.81 ± 0.02 | 0.92 ± 0.01 | 0.94 ± 0.06 | 0.98 ± 0.00 | 1M        | 0.37 ± 0.02 | 0.77 ± 0.01 | 0.71 ± 0.01          | 0.78 ± 0.01 | 0.87 ± 0.06 | 0.98 ± 0.01 | 0.96 ± 0.01 | 0.97 ± 0.01 | 0.98 ± 0.01 |  |  |  |  |  |  |  |
| avg                 |           | 0.47        | 0.62        | 0.71        | 0.69        | 0.79        | 0.84        | 0.92        | 0.94        | 0.97        |           | 0.35        | 0.71        | 0.63                 | 0.66        | 0.90        | 0.96        | 0.95        | 0.97        | 0.97        |  |  |  |  |  |  |  |

| CHS<br>$\eta = 0.01$ |           |             |             |             |             |             |             |             |             |             |           |             |             | CO<br>$\eta = 0.0001$ |             |             |             |             |             |             |  |  |  |  |  |  |  |
|----------------------|-----------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-----------|-------------|-------------|-----------------------|-------------|-------------|-------------|-------------|-------------|-------------|--|--|--|--|--|--|--|
| $t$                  | $ M_t^+ $ | CC          | AA          | JC          | HPRA        | N2V         | N2V<br>HGCN | VL          | HM<br>N2V   | HM<br>VL    | $ M_t^- $ | CC          | AA          | JC                    | HPRA        | N2V         | N2V<br>HGCN | VL          | HM<br>N2V   | HM<br>VL    |  |  |  |  |  |  |  |
| 1                    | 141K      | 0.69 ± 0.02 | 0.80 ± 0.02 | 0.90 ± 0.01 | 0.68 ± 0.02 | 0.79 ± 0.04 | 0.97 ± 0.01 | 0.94 ± 0.00 | 0.98 ± 0.01 | 0.98 ± 0.01 | 791       | 0.66 ± 0.02 | 0.70 ± 0.02 | 0.87 ± 0.02           | 0.16 ± 0.04 | 0.71 ± 0.10 | 0.80 ± 0.05 | 0.79 ± 0.05 | 0.93 ± 0.04 | 0.90 ± 0.07 |  |  |  |  |  |  |  |
| 2                    | 381K      | 0.66 ± 0.01 | 0.71 ± 0.01 | 0.80 ± 0.01 | 0.73 ± 0.02 | 0.89 ± 0.05 | 0.97 ± 0.00 | 0.93 ± 0.01 | 0.98 ± 0.01 | 0.99 ± 0.00 | 71K       | 0.33 ± 0.03 | 0.58 ± 0.03 | 0.51 ± 0.01           | 0.45 ± 0.01 | 0.95 ± 0.01 | 0.97 ± 0.01 | 0.70 ± 0.06 | 0.96 ± 0.03 | 0.98 ± 0.01 |  |  |  |  |  |  |  |
| 3                    | 2K        | 0.67 ± 0.02 | 0.79 ± 0.01 | 0.87 ± 0.01 | 0.71 ± 0.01 | 0.80 ± 0.07 | 0.98 ± 0.00 | 0.97 ± 0.01 | 0.98 ± 0.01 | 0.99 ± 0.00 | 755       | 0.68 ± 0.06 | 0.76 ± 0.06 | 0.95 ± 0.03           | 0.07 ± 0.04 | 0.79 ± 0.02 | 0.82 ± 0.03 | 0.96 ± 0.05 | 0.94 ± 0.03 | 0.93 ± 0.01 |  |  |  |  |  |  |  |
| 4                    | 760K      | 0.77 ± 0.03 | 0.84 ± 0.02 | 0.93 ± 0.01 | 0.78 ± 0.01 | 0.76 ± 0.01 | 0.97 ± 0.01 | 0.95 ± 0.01 | 0.99 ± 0.00 | 0.99 ± 0.00 | 781       | 0.73 ± 0.01 | 0.74 ± 0.08 | 0.95 ± 0.00           | 0.09 ± 0.02 | 0.71 ± 0.01 | 0.71 ± 0.02 | 0.93 ± 0.02 | 0.95 ± 0.02 | 0.93 ± 0.01 |  |  |  |  |  |  |  |
| 5                    | 1M        | 0.68 ± 0.01 | 0.78 ± 0.01 | 0.85 ± 0.01 | 0.68 ± 0.01 | 0.82 ± 0.01 | 0.98 ± 0.00 | 0.92 ± 0.01 | 0.99 ± 0.00 | 0.99 ± 0.00 | 141K      | 0.49 ± 0.01 | 0.64 ± 0.02 | 0.88 ± 0.01           | 0.16 ± 0.01 | 0.86 ± 0.03 | 0.90 ± 0.02 | 0.80 ± 0.05 | 0.97 ± 0.03 | 0.98 ± 0.01 |  |  |  |  |  |  |  |
| 6                    | 40K       | 0.44 ± 0.02 | 0.59 ± 0.03 | 0.64 ± 0.04 | 0.62 ± 0.01 | 0.86 ± 0.02 | 0.94 ± 0.03 | 0.93 ± 0.06 | 0.93 ± 0.06 | 0.96 ± 0.01 | 71K       | 0.42 ± 0.04 | 0.65 ± 0.07 | 0.89 ± 0.02           | 0.99 ± 0.01 | 0.99 ± 0.01 | 0.99 ± 0.01 | 0.99 ± 0.01 | 0.99 ± 0.01 | 0.99 ± 0.01 |  |  |  |  |  |  |  |
| 7                    | 78K       | 0.66 ± 0.01 | 0.79 ± 0.01 | 0.87 ± 0.01 | 0.64 ± 0.03 | 0.86 ± 0.03 | 0.99 ± 0.00 | 0.93 ± 0.01 | 0.99 ± 0.00 | 0.99 ± 0.00 | 57        | 0.70 ± 0.06 | 0.85 ± 0.04 | 0.90 ± 0.00           | 0.21 ± 0.01 | 0.88 ± 0.01 | 0.94 ± 0.02 | 0.96 ± 0.02 | 0.92 ± 0.02 | 0.90 ± 0.02 |  |  |  |  |  |  |  |
| 8                    | 38K       | 0.68 ± 0.02 | 0.81 ± 0.01 | 0.87 ± 0.01 | 0.65 ± 0.01 | 0.86 ± 0.04 | 0.98 ± 0.01 | 0.97 ± 0.01 | 0.99 ± 0.00 | 0.99 ± 0.01 | 795       | 0.65 ± 0.07 | 0.77 ± 0.06 | 0.84 ± 0.08           | 0.21 ± 0.03 | 0.85 ± 0.03 | 0.84 ± 0.06 | 0.96 ± 0.02 | 0.90 ± 0.02 | 0.90 ± 0.02 |  |  |  |  |  |  |  |
| 9                    | 523K      | 0.71 ± 0.01 | 0.83 ± 0.00 | 0.89 ± 0.00 | 0.77 ± 0.03 | 0.81 ± 0.01 | 0.98 ± 0.00 | 0.94 ± 0.01 | 0.99 ± 0.01 | 0.99 ± 0.01 | 434       | 0.58 ± 0.03 | 0.68 ± 0.04 | 0.86 ± 0.03           | 0.21 ± 0.01 | 0.77 ± 0.02 | 0.89 ± 0.00 | 0.81 ± 0.01 | 0.93 ± 0.02 | 0.92 ± 0.01 |  |  |  |  |  |  |  |
| 10                   | 22K       | 0.76 ± 0.02 | 0.85 ± 0.01 | 0.90 ± 0.00 | 0.77 ± 0.03 | 0.83 ± 0.02 | 0.98 ± 0.00 | 0.95 ± 0.01 | 0.99 ± 0.00 | 0.99 ± 0.00 | 71K       | 0.63 ± 0.03 | 0.71 ± 0.04 | 0.87 ± 0.03           | 0.13 ± 0.04 | 0.79 ± 0.02 | 0.88 ± 0.02 | 0.80 ± 0.03 | 0.97 ± 0.01 | 0.96 ± 0.02 |  |  |  |  |  |  |  |
| 11                   | 760K      | 0.79 ± 0.01 | 0.86 ± 0.01 | 0.93 ± 0.00 | 0.85 ± 0.03 | 0.83 ± 0.03 | 0.98 ± 0.00 | 0.95 ± 0.01 | 0.99 ± 0.00 | 0.98 ± 0.01 | 71K       | 0.61 ± 0.01 | 0.67 ± 0.03 | 0.87 ± 0.01           | 0.12 ± 0.01 | 0.77 ± 0.04 | 0.92 ± 0.01 | 0.64 ± 0.03 | 0.96 ± 0.00 | 0.95 ± 0.00 |  |  |  |  |  |  |  |
| 12                   | 8K        | 0.82 ± 0.02 | 0.87 ± 0.01 | 0.95 ± 0.01 | 0.80 ± 0.02 | 0.83 ± 0.04 | 0.99 ± 0.00 | 0.96 ± 0.01 | 0.99 ± 0.00 | 0.99 ± 0.00 | 71K       | 0.64 ± 0.04 | 0.65 ± 0.07 | 0.89 ± 0.02           | 0.09 ± 0.01 | 0.89 ± 0.06 | 0.95 ± 0.01 | 0.99 ± 0.01 | 0.99 ± 0.01 | 0.98 ± 0.00 |  |  |  |  |  |  |  |
| 13                   | 13K       | 0.70 ± 0.01 | 0.81 ± 0.01 | 0.91 ± 0.01 | 0.82 ± 0.01 | 0.88 ± 0.07 | 0.99 ± 0.02 | 0.97 ± 0.00 | 0.99 ± 0.00 | 0.99 ± 0.00 | 71K       | 0.71 ± 0.08 | 0.78 ± 0.07 | 0.99 ± 0.01           | 0.05 ± 0.04 | 0.73 ± 0.05 | 0.64 ± 0.09 | 0.87 ± 0.06 | 0.95 ± 0.01 | 0.80 ± 0.08 |  |  |  |  |  |  |  |
| 14                   | 72K       | 0.77 ± 0.03 | 0.85 ± 0.02 | 0.93 ± 0.01 | 0.85 ± 0.01 | 0.85 ± 0.04 | 0.99 ± 0.00 | 0.96 ± 0.01 | 0.99 ± 0.00 | 0.99 ± 0.00 | 35        |             |             |                       |             |             |             |             |             |             |  |  |  |  |  |  |  |

**Table 1.** Performance comparison of prediction methods across all 26 h-motif types.