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A New Algorithm for Protein-Protein Interaction Prediction

Yiwei Li

The University of Western Ontario

Supervisor

Dr. Lucian Ilie

The University of Western Ontario

Graduate Program in Computer Science

A thesis submitted in partial fulfillment of the requirements for the degree in Master of Science

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A NEW ALGORITHM FOR PROTEIN-PROTEIN INTERACTION
PREDICTION

(Thesis format: Monograph)

by

Yiwei Li

Graduate Program in Computer Science

A thesis submitted in partial fulfillment
of the requirements for the degree of
Masters of Science

The School of Graduate and Postdoctoral Studies
The University of Western Ontario
London, Ontario, Canada

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Abstract

Protein-protein interactions (PPI) are vital processes in molecular biology. However, the current understanding of PPIs is far from satisfactory. Improved methods of predicting PPIs are very much needed. Since experimental methods are labour and time consuming and lack accuracy, the improvement is expected to come from the area of computational methods.

We designed and implemented a new algorithm based on protein primary structure to predict PPIs using C++ and OpenMP for parallel computing. We compared our method with four leading methods. Our results are better than the competition for most of the important values. Furthermore, it succeeds in surpassing the consensus of the other methods.

Keywords: protein-protein interaction, PPI prediction, domain-domain interaction

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Chapter 1

Introduction

Proteins are essential molecules in organisms. It is quite often that proteins perform their functions by interacting with other proteins, binding into a stable or temporary complex. It is reported that humans have a similar number of genes with a worm [44], which implies that the differences between organisms are not solely given by the protein numbers, but also by the relations between proteins. A more complicated protein-protein interaction network makes an organism like human more sophisticated.

Currently, the understanding of protein-protein interaction (PPI) networks is far from satisfactory. Even for very small organisms, the ratio between known and potential PPIs is about 1:500 [15, 40]. Obtaining a more complete PPI network for different organisms would help to identify proteins that have the same functions. Additionally, we can have a broader view of which proteins interact more often or with what kinds of other proteins. Therefore, a significant amount of research has been done in the area of protein-protein interaction prediction. Both experimental and computational methods have been developed.

Yeast two-hybrid (Y2H) [8] and tandem affinity purification (TAP) [32] are two widely used experimental methods. Y2H attaches DNA-binding domains (DBD) and activation domains (AD) to proteins, and tell whether a pair of proteins interact or not by detecting a reporter generated by DBD and AD. The TAP method detects protein interaction complexes by adding a “tag” to that complex. After tandem affinity purification, all proteins involved are assumed to interact.

Though experimental methods can make valuable predictions, they are labour and time consuming. In addition, their false positive and false negative rates are high.

Due to the limitations of experimental methods, many types of computational methods have been proposed. Genomic methods [27] detect PPIs by detecting gene neighbourhood conservations, evolutionary relationship methods [27, 44] use phylogenetic profiles, protein structure methods [23, 18, 39] use 3D structures of proteins to find docking areas, domain methods [6] employ conserved domain occurrences, network analysis methods [4] make prediction possible using graph theory and machine learning, and primary protein structure methods [4, 24, 44, 24, 30, 38, 10] use protein sequences, usually along with machine learning techniques.

Although computational methods have advantages over experimental methods, most of them are still inefficient and can not run the whole proteome of advanced organisms like human within an affordable time.

Among those computational methods, four leading methods have being widely used. The algorithm of Martin et al. [24] uses support vector machines (SVM) on signature products, PIPE [30] computes a prediction matrix based on similarities between proteins, Shen et al. [38] use SVM and kernel functions, and Guo et al. [10] employs covariance as the input of SVM.

Park [26] evaluated the above mentioned four methods and implemented a consensus method which integrated all four. The result of the consensus method outperforms all other four methods consistently, which implies a high possibility for designing a more reliable program.

We designed and implemented a new sequence-based PPI prediction algorithm. We compare our program with the four programs in Park's paper. Our method is better than the others for most of the important values. Moreover, for a good part, it succeeds in surpassing the consensus of the other methods.

The thesis is organised as follows. Chapter 2 introduces some biological background, followed by a review of protein-protein interaction prediction methods. Two experimental and six computational methods are introduced and then four leading primary structure approaches are described. A detailed explanation of the design and implementation of

our approach follows in Chapter 3. The evaluation of the new method is performed in Chapter 4 by comparing it with the four leading methods. We conclude in Chapter 5 with ideas for further research.

Chapter 2

Background

This chapter introduces some prerequisite knowledge in molecular biology. Then basic concepts of protein interactions are provided. Protein-protein interaction prediction can be done by both experimental and computational approaches. Both types are introduced, and four leading computational programs are described.

2.1 Molecular biology primer

DNA is the code of life. All living organisms are coded by four nucleotides: adenine (A), thymine (T), guanine (G), and cytosine (C). DNA has a double helix structure which is composed of sugar molecules, phosphate group, and bases (A, G, C, T). In DNA strands, A is always matched with T and G is always matched with C ([16]).

DNA can copy itself via replication. It can also transcript into RNA. During transcription, the information in DNA pairs is passed to corresponding RNA, which will use uracil (U) instead of thymine (T) to match adenine. After transcription, RNA will be translated into protein. In the process of transcription, every three nucleotides (codon) will determine one kind of amino acid. A string of amino acids forms one kind of protein. Figure 2.1 shows the transcription and translation process in a cell. Figure 2.2 shows a protein sequence.

Proteins are made of twenty kinds of amino acids. The function of proteins varies. The main functions of proteins can be working as antibodies, contractile proteins, en-

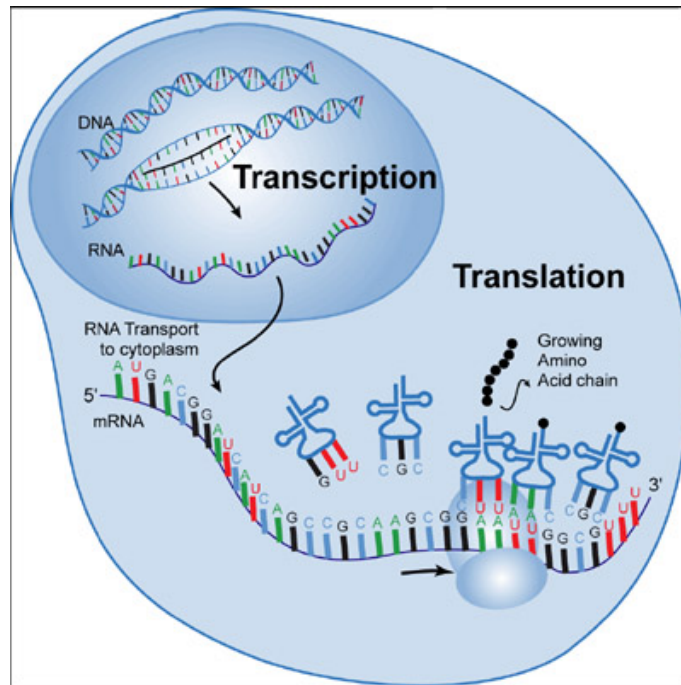


Figure 2.1: Transcription and Translation. From: tokresource.org

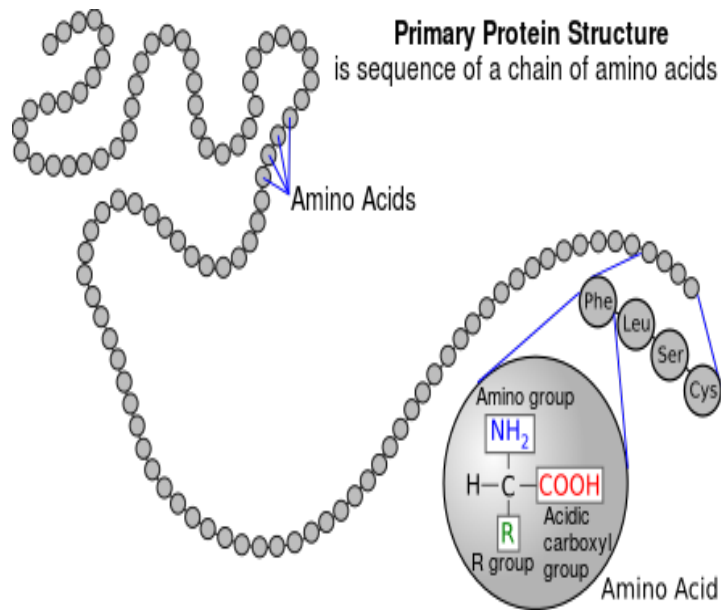


Figure 2.2: Protein sequence. From: wikimedia.org

zymes, hormonal proteins, structural, storage proteins, transport proteins, etc. ([45]). In bioinformatics, we usually use FASTA format files to represent the amino acid sequences of proteins in an organism.

```

> Y P R 1 6 1 C
T T G A C M T T G A C M T T G A C M V V V R N M
A C M T T G A C T T G A C M T T G M T T G A C M
Q S D A V M T T G A C M T T G A C M T T G A C M
A C M T T G A C M T T G A C M T T G T T G A C M
T T G A C M T T G A C M T T

```

Figure 2.3: A protein in FASTA format.

A FASTA file consists of protein or DNA names, description and sequences. Identifiers are preceded by a greater-than symbol “>” and the rest of the line is a description (optional). The next lines up to the next greater-than symbol contain the actual DNA or protein sequence. Figure 2.3 shows an example of a FASTA format. The protein name “YPR161C” follows the “>” sign. The protein sequence is given in the next five lines.

2.2 Proteins, domains, and interactions

The proteins are some of the most important molecules in cells ([34]). They carry out most of the cellular processes. Quite often, they keep the cells functioning by interacting with other proteins in stable or transient protein complexes ([5]). This process is called protein-protein interaction (PPI). This is a vital process because of the accepted idea that PPIs are responsible for cell’s behaviour and different stimuli ([2, 25, 35]). From this point of view, scientists believe the reason that advanced organisms like humans are more complicated than lower organisms like the worms is not only because of large number of genes, but also because of sophisticated PPI networks [29]. Figure 2.4 shows the map of human PPI network. Understanding the potential of unknown proteins is becoming possible by looking into their PPI information [37]. As well, knowing PPI information helps improve the system-level understanding of molecular processes [19]. Therefore, understanding and mapping PPIs is an important current area of research.

A domain refers to a sub-sequences in a protein which has distinct functions or structure. Figure 2.5 shows two proteins interacting with each other. The connecting parts of two proteins are two domains. In 3D structure view, it is quite often a docking structure,

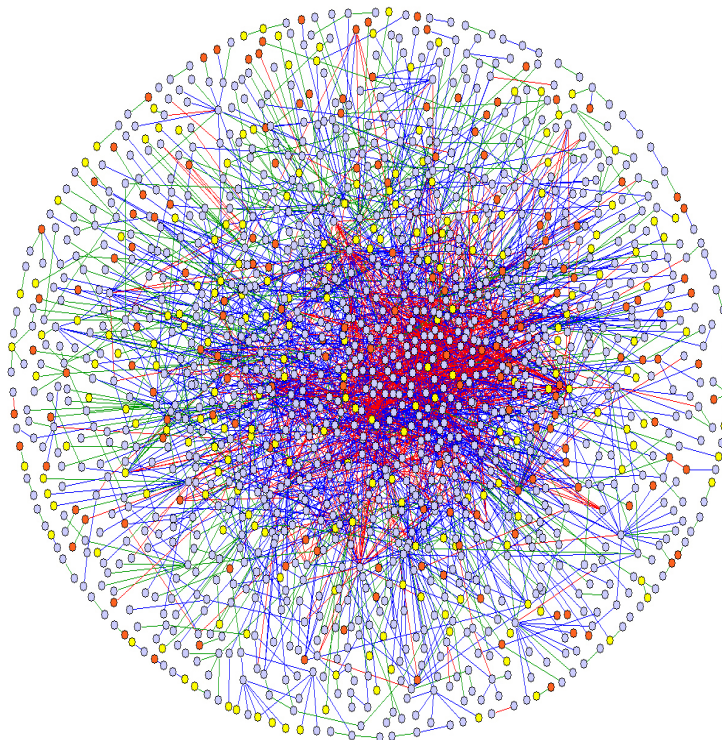


Figure 2.4: The protein-protein interaction network of human. From: www.mdc-berlin.de

where a part of one protein complements a part of another protein.

One commonly accepted assumption is that the same domain in different proteins functions the same, and protein-protein interactions are conducted via domain-domain interactions (DDIs) [43]. Thus, finding the conserved similar domains in each protein would help understand PPIs. Also, based on DDIs, we can design computational methods to predict PPIs.

However, there are a lot of unknown facts about PPIs to be discovered. For example, in a simple organism such as *Saccharomyces cerevisiae*, there are less than 40,000 estimated PPIs. Comparing with 19,000,000 potential interacting pair, it is believed that there is still a significant gap between known PPIs and real ones [15, 40]. Precise, fast and affordable protein-protein interaction prediction methods are needed.

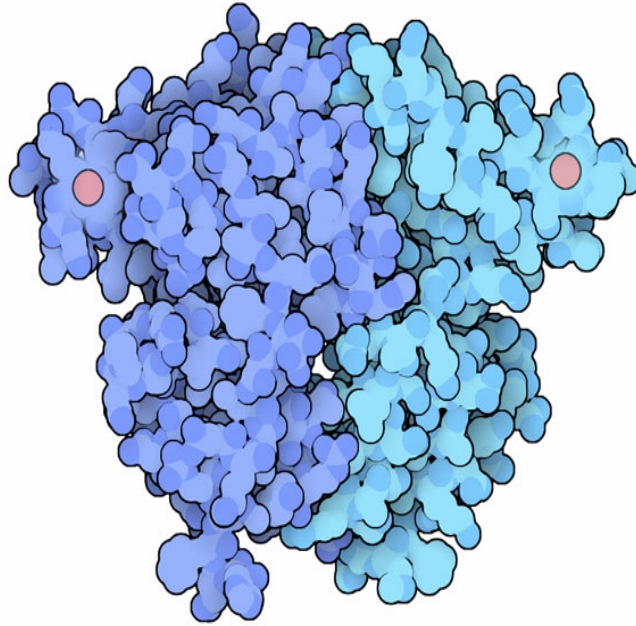


Figure 2.5: Domain-Domain Interaction. From: [31]

2.3 Experimental approaches

Some widely known experimental approaches are designed and employed by biologists. Two of them will be briefly introduced in this section, yeast two-hybrid (Y2H) and tandem affinity purification (TAP).

2.3.1 Yeast two-hybrid (Y2H)

The yeast two-hybrid (Y2H) approach was proposed by Suter et al. [8]. It detects a protein interaction by telling the signal generated by the DNA-binding domain (DBD) and the activation domain (AD) [42].

Figure 2.6 shows the basic procedure of the Y2H approach. If the user wants to detect whether protein 1 (green) and protein 2 (red) are interacting or not, then DBD and AD are bound, each to one of the proteins. The DBD and AD will connect together only when protein 1 and protein 2 interact with each other. When DBD and AD connect, a reporter will be generated. Thus, protein 1 and protein 2 are interacting if a reporter is detected, and vice versa [42].

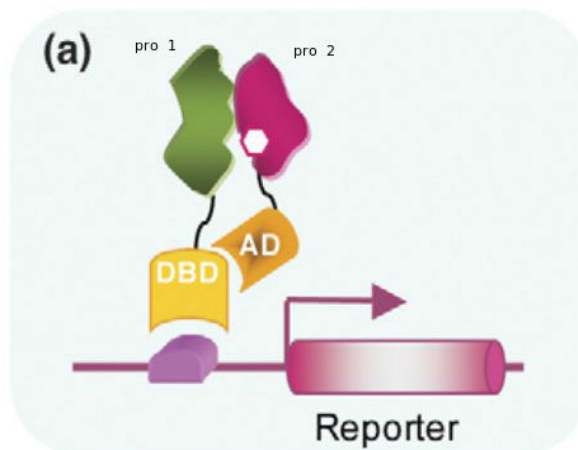


Figure 2.6: The Y2H approach. From: [42]

Although Y2H is able to detect many protein-protein interactions, the drawbacks of this approach are obvious. First, it can only detect PPIs within the nucleus. Second, it can only detect one interaction at a time, which is quite inefficient. Also, the false positive and false negative rates are high [41, 36].

2.3.2 Tandem affinity purification (TAP)

Another widely used experimental approach is tandem affinity purification, which was invented by Rigaut et al. [32]. It can detect protein complex interaction by adding a “tag” to target proteins.

Figure 2.7 shows the general process of TAP. If we want to test whether interaction exists between protein *A* and protein *B*, a tag is added to protein *A*. After tagging, the complex is washed twice to remove the tag and unstable bindings. Isolated interacting proteins can be found if there are some. After washing, the mass spectrometry or other methods will be used to detect remaining proteins. The remaining ones are marked as interacting proteins [32].

A major advantage of the TAP approach is that it can detect interactions of protein complexes (more than two proteins), even without the interacting pattern. However, the “tag” added to proteins is itself a disadvantage. It might become a confounding factor in

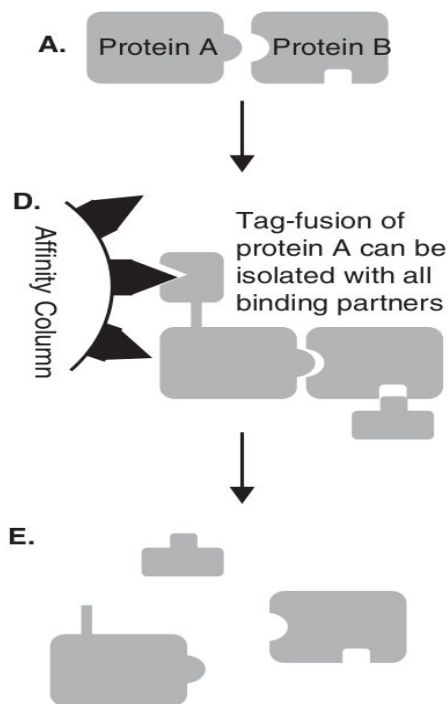


Figure 2.7: Tandem affinity purification. From: [15]

a way that changes the interacting process. Also, some real interactions can be washed away during two times of washing, thus increasing the false negative rate [15].

2.4 Computational approaches

The experimental approaches are time and labour consuming. Also, they have the limitation of being unable to detect some protein complexes. In addition, the false positive rate and false negative rate of those approaches are high ([30]).

Due to the limitations of experimental approaches, we have imperative demanding for efficient, affordable, and more precise computational approaches.

Currently, there are mainly six kinds of computational PPI prediction approaches: genomic approach, evolutionary relationship approach, protein structure approach, domain approach, network analysis approach, and primary protein structure approach [15].

The basis of genomic approach is that proteins whose genes are close in different

genomes are predicted to interact (gene neighbourhood conservation) [27, 44]. In Figure 2.8, there are four different genomes, *A*, *B*, *C*, and *D*. Proteins 1, 2, and 3 appear in those genomes, and we can predict that protein 1 will interact with protein 2 because in genomes *A*, *B* and *D*, their genes occur in close physical proximity [15].

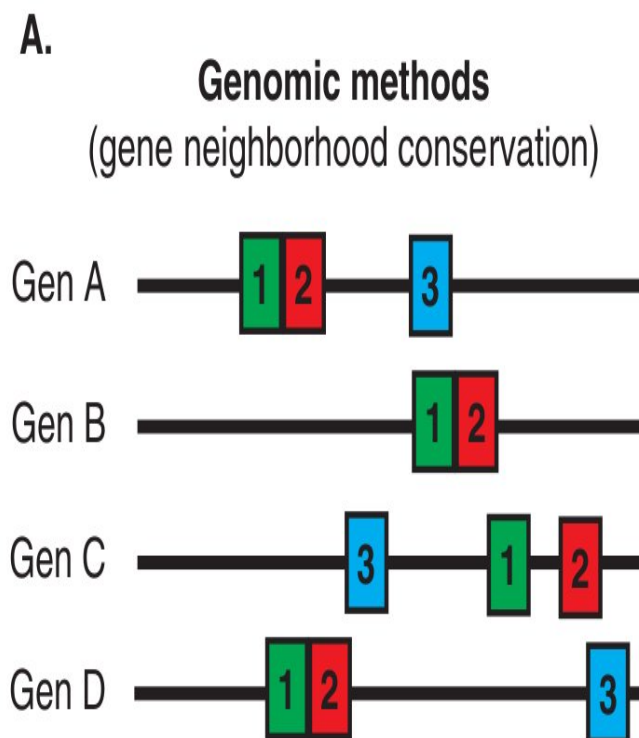


Figure 2.8: Genomic approach. From: [15]

Phylogenetic profiles approach suggests that during the process of evolution, interacting pairs of proteins will be preserved in order to function together ([27, 44]). Figure 2.9 shows four proteins along with their phylogenetic profiles in four genomes. The interaction between protein 1 and protein 4 can be predicted because both appear in genome A and genome D ([15]).

However, phylogenetic profiles approach needs accurate phylogenetic information being provided so that it can predict new interactions. In addition, it can be only applied to complete genomes. This way interactions that only occur in one organism can not be predicted, even if they are essential interactions [9].

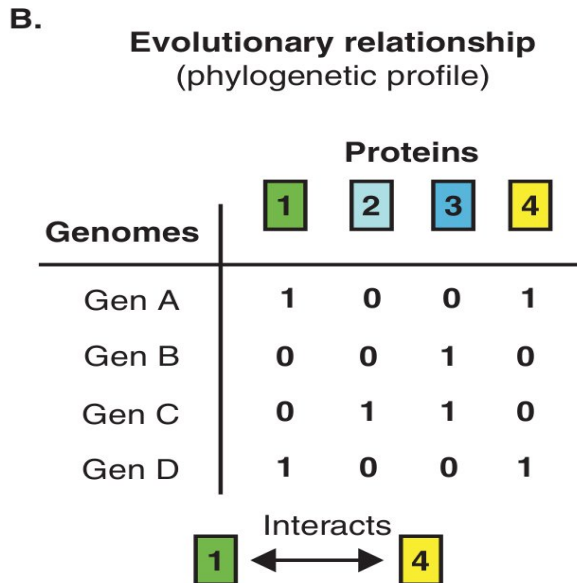


Figure 2.9: Phylogenetic profiles approach. From: [15]

Protein structure approach uses techniques such as X-ray crystallography or NMR spectroscopy to obtain 3D structure of proteins. If two proteins are homologous and share similar sequence, they should interact in a similar way ([23, 18, 39]).

Figure 2.10 shows a simple model of predicting PPIs using protein structure approach. Protein 1 and protein 4 are predicted to be interacting since the docking parts of those proteins fit the best [15].

Domain based approach detects occurrences of sub-sequences (domain) in a protein sequence. It is accepted that protein-protein interactions happen via domain-domain interactions. If conserved domains are found, we can use those domains to predict new interactions [6].

In Figure 2.11, protein *A* and protein *B* are a known interacting pair. Domain 1 and domain 2 are estimated as conserved domains. We predict that protein *C* and protein *D* interact because protein *C* contains a region that is similar to domain 1 and protein *D* contains a region is similar to domain 2 ([15]).

Network analysis approach uses graphs produced by experimental or computational methods and other algorithms to predict new PPIs. A simple way to predict based on PPI network is to add the missing edges. For example, by adding that missing edge, the

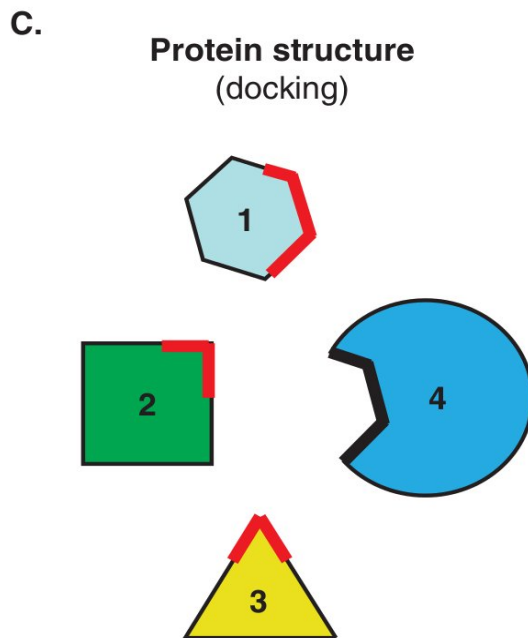


Figure 2.10: Protein structure approach. From: [15]

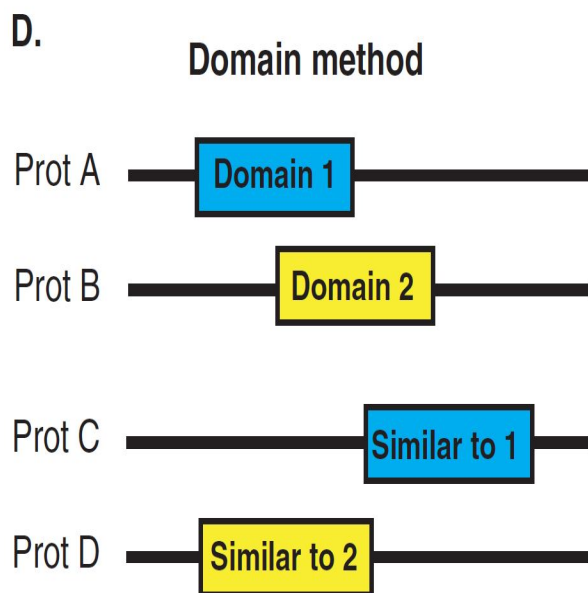


Figure 2.11: Domain based approach. From: [15]

sub-graph can form a clique ([15]).

E. Network analysis

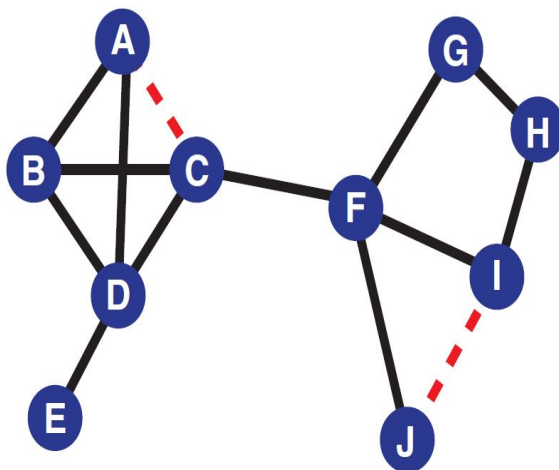


Figure 2.12: Network analysis approach. From: [15]

Figure 2.12 shows an simple instance of network analysis approach. Each node denotes a protein and each solid line denotes a known interaction between two proteins. Proteins A , B , C and D can form a clique by adding the edge $A-C$. So we predict that proteins A and C interact.

An advantage of network analysis approach is that we can visually see the interaction network. We can tell the connections of a certain protein. We can tell as well how often a protein interacts with others. The detailed algorithm is more complicated than simply adding edges, otherwise the false positive rate would be too high [15].

The primary protein structure approach is proposed under the hypothesis that PPIs are conducted via polypeptide sequences. They usually use machine learning techniques such as support vector machines (SVM) or Random Forest (RF) to find binding regions of PPIs ([4, 24, 44]).

Primary protein structure approach will be discussed in detail in the next part.

2.5 Leading programs

Despite the fact that many computational approaches have their own advantages comparing with experimental ones, most of them are too expensive regarding computation time. They cannot run on the entire human proteome because it takes unreasonably long time [15]. Park [26] published an assessment of the current leading PPI prediction methods. He compared in details four leading computational methods.

The characteristics of these four methods is that they are all sequence based (no evolutionary information required). Those four methods are described below. Our own method will be compared with those later.

2.5.1 Method 1

Martin et al. [24] proposed a predicting method using signature products. In this method, an amino acid sequence is represented as a signature, which is a combination of three letters. For example, the amino acid sequence LVMTTM, trimers are: LVM, VMT, MTT and TTM. They are made of a root (middle letter) and two neighbours (side letters). Then the signatures of those trimers are V (LM), V (MT), T (MT), T (MT), respectively. By adding those vectors together, the signature of the sequence is $V(LM) + V(MT) + 2T(MT)$ [24]. Note that $2T(MT)$ comes from $T(MT) + T(TM)$.

The signature will be classified by support vector machines (SVM). Then, using machine learning methods, predictions will be made.

2.5.2 Method 2

The Protein-protein Interaction Prediction Engine (PIPE) series was initiated by Pitre et al. [30]. It is one of the most widely known methods. PIPE can successfully predict new interactions based on re-occurring short sub-sequences in an existing interaction database. The major four steps of PIPE are shown in Figure 2.13. Given an interaction database, an interaction graph (G) is built. Given a query protein pair (A, B), a window w is first slid across A and, for each position, the peptide a_i in the window is searched for in the database of proteins. The neighbours of all proteins found to contain regions

similar with a_i are stored in a list R of neighbours. In Figure 2.13, proteins V and W are hit and their neighbours, X, Y, Z , are added to R . A similar window is then slid across B and any time a neighbour from R is hit, that is, it is found to contain a sequence similar to the current window content b_j , a counter for (a_i, b_j) is incremented, where a_i is the initial segment of A that was used to find the neighbour in R . This way a matrix is obtained, whose (i, j) value is the counter for (a_i, b_j) mentioned above. The highest score of that matrix (if higher than a threshold) is where interaction most likely happens between proteins A and B ([30]). In Figure 2.13, this procedure finds a sub-sequences in A that is similar with, V , for example. Meanwhile, a sub-sequences of B is similar with a sub-sequences of X , Since X and V interact, we predict, based on highest score in the matrix, that the same conserved interaction will happen as well between A and B .

The second version of PIPE was published in 2008 [28]. The improvement of this version is the increase of sensitivity and reduction of running time. Also, prediction of whole yeast proteins are made possible in this version.

PIPE3 changes the architecture to parallel and reduces the memory usage so that it can predict human protein-protein interactions, though it still takes a very long time. On 50 nodes, and a total of 12,800 multiple threads, prediction on human proteome will take more than three months using PIPE3.

2.5.3 Method 3

Shen et al. [38] proposed a sequenced-based PPI prediction method. This method uses also machine learning techniques to make predictions. Their program uses protein sequences and PPIs as training data. Then it classifies new pairs of proteins with support vector machines (SVM) and a kernel function.

SVMs are used for classifying PPIs into two different sets, interacting or non-interacting. The kernel function is used for mapping training data into a higher dimension, in order to classify it linearly. A detailed introduction about SVM and kernel function can be found for instance in [11].

A key point in machine learning is how to “learn” more useful information from training data. Shen et al. first represent amino acids by vectors (see Figure 2.14). Every

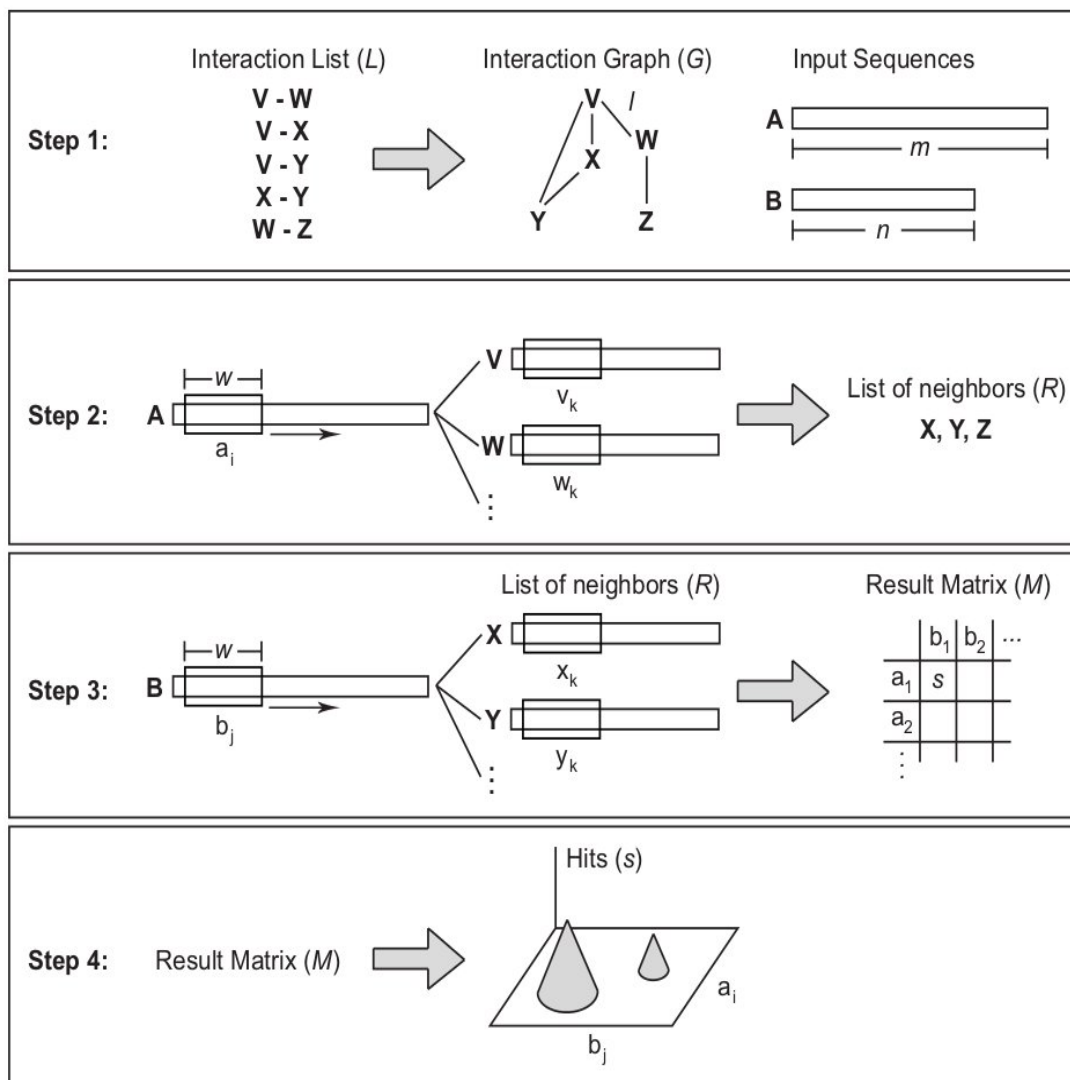


Figure 2.13: Algorithm of PIPE. From: [30]

three amino acids are grouped as a vector space (V, F) , where V is the encoded value, from 1 to 343, and F is the frequency with which those three amino acids appear. For example, the first three amino acids are encoded as $(342, 1)$, because this combination has only appeared once. The 20 amino acids are classified into 7 classes based on the dipoles and volumes of side chain. A detailed classification is shown in Figure 2.15.

This method is claimed to be the first solely sequence-based application to successfully predict PPIs ([38]).

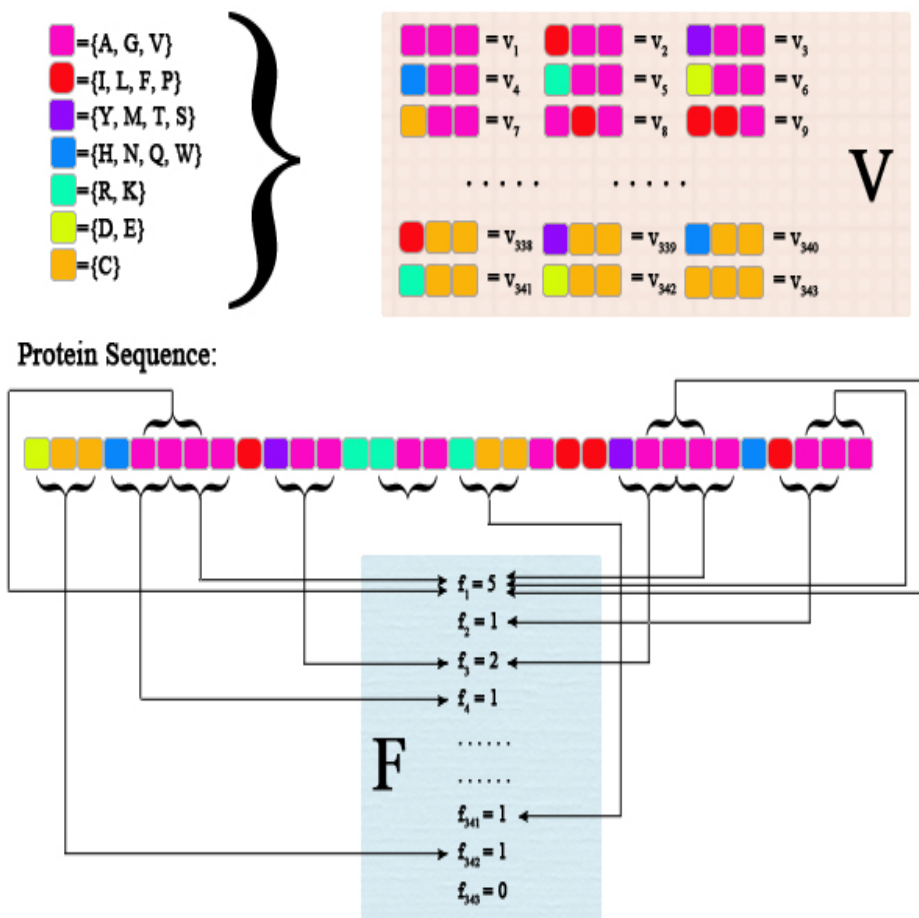


Figure 2.14: Constructing the vector space (V, F) of a protein sequence. From: [38]

No.	Dipole scale ^a	Volume scale ^b	Class
1	-	-	Ala, Gly, Val
2	-	+	Ile, Leu, Phe, Pro
3	+	+	Tyr, Met, Thr, Ser
4	++	+	His, Asn, Gln, Tpr
5	+++	+	Arg, Lys
6	+'+'+'	+	Asp, Glu
7	+ ^c	+	Cys

Figure 2.15: Classification of amino acids. From: [38]

2.5.4 Method 4

Guo et al. [10] proposed another PPI prediction approach. This method uses SVMs and auto covariance (AC) to make predictions.

Similarly with the methods mentioned in 2.5.1 and 2.5.3, SVMs are used for classifying new pairs of proteins into interacting or non-interacting sets. Each amino acid in a protein sequence is represented as neighbouring effects and physicochemical properties (shown in Figure 2.16). According to their optimization experiment, for each amino acid, they take into account 30 neighbour amino acids of it. This neighbouring effect is then translated into a numerical value. The physicochemical properties of each amino acids are shown in Figure 2.17 where H1 = hydrophobicity, H2 = hydrophilicity, V = volume of side chains, P1 = polarity, P2 = polarizability, SASA = solvent accessible surface area, NCI = net charge index of side chains. Variables of neighbouring effect and physicochemical properties be will used to calculate AC variables. SVM will take these AC variables as input to make predictions.

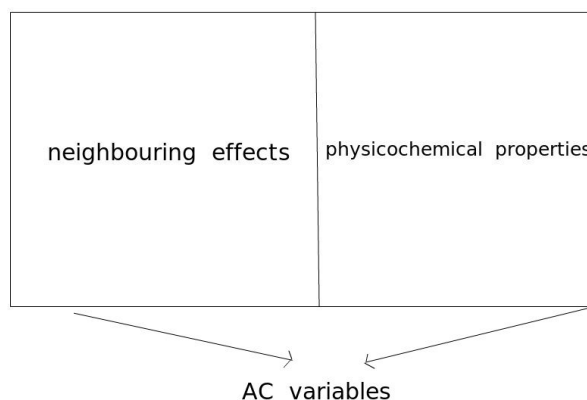


Figure 2.16: Representation of each amino acid

code	H ₁	H ₂	V	P ₁	P ₂	SASA	NCI
A	0.62	-0.5	27.5	8.1	0.046	1.181	0.007187
C	0.29	-1	44.6	5.5	0.128	1.461	-0.03661
D	-0.9	3	40	13	0.105	1.587	-0.02382
E	-0.74	3	62	12.3	0.151	1.862	0.006802
F	1.19	-2.5	115.5	5.2	0.29	2.228	0.037552
G	0.48	0	0	9	0	0.881	0.179052
H	-0.4	-0.5	79	10.4	0.23	2.025	-0.01069
I	1.38	-1.8	93.5	5.2	0.186	1.81	0.021631
K	-1.5	3	100	11.3	0.219	2.258	0.017708
L	1.06	-1.8	93.5	4.9	0.186	1.931	0.051672
M	0.64	-1.3	94.1	5.7	0.221	2.034	0.002683
N	-0.78	2	58.7	11.6	0.134	1.655	0.005392
P	0.12	0	41.9	8	0.131	1.468	0.239531
Q	-0.85	0.2	80.7	10.5	0.18	1.932	0.049211
R	-2.53	3	105	10.5	0.291	2.56	0.043587
S	-0.18	0.3	29.3	9.2	0.062	1.298	0.004627
T	-0.05	-0.4	51.3	8.6	0.108	1.525	0.003352
V	1.08	-1.5	71.5	5.9	0.14	1.645	0.057004
W	0.81	-3.4	145.5	5.4	0.409	2.663	0.037977
Y	0.26	-2.3	117.3	6.2	0.298	2.368	0.023599

Figure 2.17: Values of the seven physicochemical properties for each amino acid. From supplementary material of [10]

Chapter 3

A new algorithm

Our new algorithm to predict PPIs, based on protein sequence only, is described in this chapter. It is implemented in C++ and uses OpenMP for parallelization.

3.1 Domains are responsible for interactions

As discussed in Chapter 2, domain-domain interactions (DDIs) imply protein-protein interactions (PPIs). And because one domain can appear in different proteins, the same DDI can happen between different interacting protein pairs.

Since protein interactions are essential to protein functions, they have to be well preserved during evolution. It is therefore expected that the domains responsible for these interactions are preserved as well. Indeed, it is the 3D structure that requires conservation, but that implies that the amino acid structure should be well conserved as well. That means that different occurrences of the same domain should have a high degree of sequence similarity. Therefore, our starting point will be sequence similarity identification.

The main steps of the algorithm are shown below:

- Detect similarities
- Identify domains
- Attach scores to domain pairs

- Attach scores to protein pairs
- Predict PPIs

3.2 Spaced seeds

Our first problem is finding the similar sub-sequences within protein sequences of an organism. The classic similarity search tool is BLAST (Basic Local Alignment Search Tool) [1]. The basic idea of BLAST is called “hit and extend”. When identifying similarity, BLAST requires several consecutive matches between two strings; the default number for DNA is 11 consecutive matches. Denoting the matches by 1’s we obtain what is called a consecutive seed: 11111111111. A pair of identical consecutive matches is called a hit.

Figure 3.1 shows the basic idea of BLAST. When a hit is detected by the consecutive seed, marked with red color, BLAST extends this hit towards both sides. If the score increases, it continues extending. If the score drops below a threshold, it stops. The blue part is where BLAST extends.

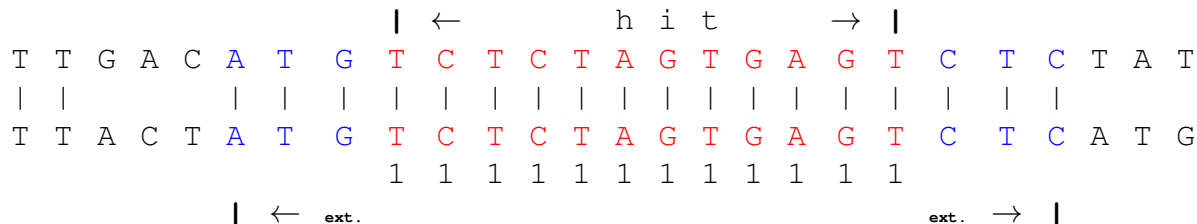


Figure 3.1: Hit and extend in BLAST.

The consecutive seed of BLAST is not very sensitive and we are going to use a much better solution. It has been identified earlier that non-consecutive matches have a higher chance of finding similarities but it was in [22] where optimal arrangements of non-consecutive matches were proposed. A spaced seed is a combination of matches (1’s) and don’t care positions (*’s), such as 111*1**1*1**11*111. Figure 3.2 illustrates the main concept of those two seeds.

C G T C A A G A C T T ? ? C G T C A A G A C T T ? 1	G A G ? C ? ? T ? G ? ? A C ? T T C ? ? ? ? ? ? ? ? ? G A G ? C ? ? T ? G ? ? A C ? T T C ? 1 1 1 * 1 * * 1 * 1 * * 1 1 * 1 1 1 1 1 1 * 1 * * 1 * 1 * * 1 1 * 1 1 1
---	---

Figure 3.2: Consecutive seed (left) and spaced seed (right). The red 1's are new matches required for a hit at the next position; it is much easier for the consecutive seed to have consecutive hits, hence its hits are more clustered than those of the spaced seed.

While consecutive seeds suffer from hit clustering (Figure 3.2 left), spaced seeds have their hits much better distributed (Figure 3.2 right). The number of 1's in a seed defines the weight of the seed, whereas 1's and *'s together are its length. The probability of a hit depends only on the weight of the seed. Therefore, two seeds, one consecutive and one spaced, of the same weight have the same number of expected hits. Because the hits of a spaced seed are less clustered together, more regions will be hit, thus increasing the probability of finding similarities. This probability is called the sensitivity of the seed.

Using several spaced seeds [20] dramatically improves sensitivity. The only problem is that computing optimal seeds is a hard problem. Even the heuristic algorithms are exponential, except for SpEED [13, 14]. We have thus used SpEED to compute the multiple spaced seeds to be used in our PPI prediction program. They are given below:

$$\text{seed}_1 = 11^*111$$

$$\text{seed}_2 = 111^{**}1^*1$$

$$\text{seed}_3 = 11^{***}1^*11$$

$$\text{seed}_4 = 1^*1^{***}111$$

$$\text{seed}_5 = 1^*1^*1^{**}11$$

$$\text{seed}_6 = 11^{*****}1^*11$$

$$\text{seed}_7 = 11^*1^{**}1^{***}1$$

$$\text{seed}_8 = 11^{**}1^{****}11$$

3.3 Detecting domains as similarities

After having computed the seeds, we need to find a way to detect domains fast. In agreement with other methods, we are going to use BLOSUM80 [12] as our similarity matrix (see Figure 3.3).

	A	R	N	D	C	Q	E	G	H	I	L	K	M	F	P	S	T	W	Y	V
A	5	-2	-2	-2	-1	-1	-1	0	-2	-2	-2	-1	-1	-3	-1	1	0	-3	-2	0
R	-2	6	-1	-2	-4	1	-1	-3	0	-3	-3	2	-2	-4	-2	-1	-1	-4	-3	-3
N	-2	-1	6	1	-3	0	-1	-1	0	-4	-4	0	-3	-4	-3	0	0	-4	-3	-4
D	-2	-2	1	6	-4	-1	1	-2	-2	-4	-5	-1	-4	-4	-2	-1	-1	-6	-4	-4
C	-1	-4	-3	-4	9	-4	-5	-4	-4	-2	-2	-4	-2	-3	-4	-2	-1	-3	-3	-1
Q	-1	1	0	-1	-4	6	2	-2	1	-3	-3	1	0	-4	-2	0	-1	-3	-2	-3
E	-1	-1	-1	1	-5	2	6	-3	0	-4	-4	1	-2	-4	-2	0	-1	-4	-3	-3
G	0	-3	-1	-2	-4	-2	-3	6	-3	-5	-4	-2	-4	-4	-3	-1	-2	-4	-4	-4
H	-2	0	0	-2	-4	1	0	-3	8	-4	-3	-1	-2	-2	-3	-1	-2	-3	2	-4
I	-2	-3	-4	-4	-2	-3	-4	-5	-4	5	1	-3	1	-1	-4	-3	-1	-3	-2	3
L	-2	-3	-4	-5	-2	-3	-4	-4	-3	1	4	-3	2	0	-3	-3	-2	-2	-2	1
K	-1	2	0	-1	-4	1	1	-2	-1	-3	-3	5	-2	-4	-1	-1	-1	-4	-3	-3
M	-1	-2	-3	-4	-2	0	-2	-4	-2	1	2	-2	6	0	-3	-2	-1	-2	-2	1
F	-3	-4	-4	-4	-3	-4	-4	-4	-2	-1	0	-4	0	6	-4	-3	-2	0	3	-1
P	-1	-2	-3	-2	-4	-2	-2	-3	-3	-4	-3	-1	-3	-4	8	-1	-2	-5	-4	-3
S	1	-1	0	-1	-2	0	0	-1	-1	-3	-3	-1	-2	-3	-1	5	1	-4	-2	-2
T	0	-1	0	-1	-1	-1	-1	-2	-2	-1	-2	-1	-1	-2	-2	1	5	-4	-2	0
W	-3	-4	-4	-6	-3	-3	-4	-4	-3	-3	-2	-4	-2	0	-5	-4	-4	11	2	-3
Y	-2	-3	-3	-4	-3	-2	-3	-4	2	-2	-2	-3	-2	3	-4	-2	-2	2	7	-2
V	0	-3	-4	-4	-1	-3	-3	-4	-4	3	1	-3	1	-1	-3	-2	0	-3	-2	4

Figure 3.3: The BLOSUM80 matrix

We encode each amino acid with 5 bits. Blocks of 5 bits can have $2^5 = 32$ different values. So 5 bits are more than enough for encoding twenty amino acids. Table 3.1 shows in detail the encoding of every amino acid. Twelve consecutive amino acids will be stored into one unsigned 64-bit integer (4 bits will remain unused) using bitwise operations. The whole sequence will be stored in an array of unsigned 64-bit integers. For example the sequence “MFSELINFQNEG” is encoded as “0000 00111 00110 00010 00101 01101 00010 01001 01010 00110 01111 01101 01100” inside 64 bits. The value of this integer is 259033294012890540.

Amino acid name	Notation in FASTA format	5-bit encoding
Alanine	A	00000
Arginine	R	00001
Asparagine	N	00010
Aspartic acid	D	00011
Cysteine	C	00100
Glutamine	Q	00101
Glutamic acid	E	00110
Glycine	G	00111
Histidine	H	01000
Isoleucine	I	01001
Leucine	L	01010
Lysine	K	01011
Methionine	M	01100
Phenylalanine	F	01101
Proline	P	01110
Serine	S	01111
Threonine	T	10000
Tryptophan	W	10001
Tyrosine	Y	10010
Valine	V	10011

Table 3.1: Amino acid encoding

The eight seeds will be encoded as eight unsigned 64-bit integers. In a spaced seed, “1” is encoded as “11111” in 5 bits, while “0” is encoded as “00000”. For instance, the seed “11010011” is encoded as “11111 11111 00000 11111 00000 00000 11111 11111” in an unsigned 64-bit integer. The longest seed has length 11, which will fit into 55 bits.

For a seed s , an s -mer is a sequence of amino acids interspersed with spaces, of the same length as the seed, such that the amino acids correspond to the 1 positions in s . For instance, if the seed is $s = 11010011$, than an s -mer could be MF_E_L_NF. Spaces are implemented as 0’s, so this s -mer is in fact MF0E00NF. Similar to the consecutive case, a hit consists of a pair of sub-sequences that match to the positions corresponding to the 1’s in the seed (see again Figure 3.2 right); that is, matching s -mers. Therefore, we need a fast way of extracting the s -mers from protein sequences.

We use the encoded seed as a mask on top of encoded protein sequences, and shift the mask from the beginning to the end of each protein sequence. Figure 3.4 shows an

example how seed 11010011 is extracting s -mers from a protein sequence. The 0 position will always extract 0 because 0 means don't care. Amino acids in other positions (1's in seed) will be extracted as in the original sequence. So, for the sequence "MFSELIN-FQNEG", the seed "11010011" will extract the first s -mer "MF0E00NF". After shifting one position, the second s -mer "FS0L00FQ" will be extracted.

	M	F	S	E	L	I	N	F	Q	N	E	G
	1	1	0	1	0	0	1	1				
	M	F	0	E	0	0	N	F				
→	1	1	0	1	0	0	1	1				
→	F	S	0	L	0	0	F	Q				
	→	1	1	0	1	0	0	1	1			
	→	S	E	0	I	0	0	Q	N			
		.	.	.								

Figure 3.4: Extracting s -mers.

The way we extract s -mer is doing "bitwise and" for encoded seed and encoded proteins. In this way, one "and operation" will extract a whole s -mer from the sequence. It is much faster than using characters or strings.

As mentioned earlier, finding similar sub-sequences start with finding hits, that is, matching s -mers. In order to do this fast, we use a hash table. All extracted s -mer will be stored in the hash table. For each seed, we have one hash table. The hash function is:

$$entry_index = s_mer_value \% hash_size \quad (3.1)$$

where the hash size is determined when encoding proteins. For each seed, the maximum number of s -mers is:

$$number_of_smers = \sum_{i=1}^{num_of_pro} (protein_length - seed_length + 1).$$

The program automatically chooses the smallest prime number which is bigger than the number of s -mers, from a list of precomputed large prime numbers, as hash size. Hash collisions are solved using linear probing. In each entry of the hash table, we store its s -mer value along with a pointer to an array of positions, which keeps a record of

protein ids and starting positions of that s -mer. The pseudocode for computing the eight hash tables is given in Algorithm 1. Algorithm 2 shows the insertion into hash table in detail. We use OpenMP to parallel this part so that eight hash tables can be built simultaneously.

Algorithm 1: Algorithm for computing hash tables

input : encoded_proteins EP , 8 encoded_seeds S
output: 8 hash tables HT

```

1 for each seed  $s \in S$  do
2   | - initialize  $ht \in HT$ 
3   | - for each protein  $p \in EP$  do
4   |   | -  $temp\_protein\_sequence = p$ 
5   |   | - for position  $\in [0, (pro\_length - seed\_length + 1)]$  do
6   |   |   | -  $s\text{-mer} = s \ \& \ temp\_protein\_sequence$ 
7   |   |   | -  $temp\_protein\_sequence$  shift one position
8   |   |   | - insert_into_hash_table ( $s\text{-mer}, position, ht$ )
9   |   |   end
10  |   end
11 end

```

Algorithm 2: Algorithm for inserting s -mer into hash table

input : $s\text{-mer}, s\text{-mer_position}, hash_table$
output:

```

1 position  $p = s\text{-mer} \% hash\_size$ 
2 if  $hash\_table[p] == \emptyset$  then
3   | insert ( $s\text{-mer}, s\text{-mer\_position}$ ) into  $hash\_table[p]$ 
4 end
5 else if  $s\text{-mer} == hash\_table[p].s\text{-mer}$  then
6   | add ( $s\text{-mer\_position}$ ) into  $hash\_table[p]$  as a linked list
7 end
8 else if  $s\text{-mer} \neq hash\_table[p].s\text{-mer}$  then
9   | insert_s-mer_into_hashtable( $s\text{-mer}, p + 1, hash\_table$ )
10 end

```

After having the eight hash tables, we start investigating hits as indicated by Algorithm 3. For every s -mer x in the hash table, we compute all s -mers y that are similar enough to x . Here similar enough means that the score between x and y is greater than T_{hit} (hit threshold). The score between two strings of the same length is computed as the sum of the scores of corresponding letters according to the given scoring matrix, in

our case, BLOSUM80. That is, if $x = x_1x_2\dots x_n$, $y = y_1y_2\dots y_n$, then

$$score(x, y) = \sum_{i=1}^n score_{B80}(x_i, y_i) \quad (3.2)$$

Algorithm 3: Algorithm for investigating hits

input : eight seeds and corresponding hash tables
output: a record of domains in each protein

```

1 for each seed  $s \in S$  do
2   for each  $s$ -mer  $x$  do
3     compute  $H(x) = \{y \mid y \geq x, score(x,y) \geq T_{hit}\}$  (Algorithm 4)
4     for all  $y \in H(x)$  do
5       - investigate all hits between occurrences of  $x$  and occ. of  $y$  with
           min-score  $T_{dom}$ 
6       - ignore pairs appearing within already discovered similarity
7       - extend until score drops  $T_{ext}$  or more
8       - merge and mark domains as detecting
9     end
10  end
11 end

```

We notice here that a hit is now a pair of s -mers (x,y) appearing in different places in our protein sequences (maybe the same protein) such that x and y are no longer identical but sufficiently similar. The two s -mers are assumed identical when searching for similarities in DNA sequences, because matches have a high probability with the 4-letter DNA alphabet. We search however for similarities in protein sequences, over a 20-letter alphabet, and matches appear with much lower probability, thus the need for similar s -mers to be investigated as hits.

Fast computation of the $H(x)$ sets is very important for the speed of Algorithm 3. In order to speed up this computation, we start by sorting the rows of the BLOSUM80 matrix. We build an array $S_{B80}[20][20]$ such that $S_{B80}[i]$ is the same row as the i^{th} row of BLOSUM80 but sorted in decreasing order of the scores. For instance, we will always have $S_{B80}[i][0] = B_{80}[i][i]$ since the score of any amino acid with itself is the highest. We need the order of the amino acids in each $S_{B80}[i]$. This will be given by the array $AA[20][20]$. The row $AA[i]$ gives the amino acids in the order of $S_{B80}[i]$. For example,

$AA[i][0] = i$. The computation of the $H(x)$ sets can now be done in optimal time, since we try only those y 's that are good. Starting with $y = x$, we attempt to change each position of y , in the order given by S_{B80} , such that the score between x and y is still above T_{hit} . In the code of Algorithm 4, we sacrificed some elegance for speed.

We then search every y in a hash table. If that y exists, it means that we have a sub-sequence which is similar to x in the protein sequence. Using the information in the hash table, the protein id and the positions of x and y can be retrieved.

A hit (x, y) is investigated further to produce two domain occurrences if the score of the sub-sequences of length 11 extend on x and y , respectively, have a score of at least T_{dom} (domain threshold). In this case, we extend the similarity both ways, until the score drops more than T_{ext} (extension threshold). The two similar regions we found is what we call domain occurrences.

It is possible that two detected domain occurrences are within the same protein and overlap with each other. In this case, we merge those two occurrences if the length of the overlap is longer than half of the shorter one. The reason we do this is that if the overlap of two domain occurrences is long enough, it means that these two domain occurrences are similar enough so they should belong to the same domain. Figure 3.5 gives an example of merging domains. Domain 1 (red, from G to Q) has already been detected. Then domain 2 (blue, from N to N) is detected. The overlap length of domain 1 and domain 2 is 11, which is longer than half of the shorter one's length ($12/2 = 6$). So all amino acids will be merged into the new domain 1 (shows in green). Also, we need to mark all occurrences of domain 2 as domain 1 occurrences everywhere else. The long overlap of two occurrences of different domains is used to indicate that the two domains involved are in fact parts of the same domain.

3.4 Scoring domain pairs

After detecting similarities, we have computed the domains D_1, D_2, \dots, D_k . Each domain is a set of occurrences in our proteins. Consider a given set I of protein-protein interactions. For a protein p and a domain D_i , we say that D_i intersects p if D_i has at least one

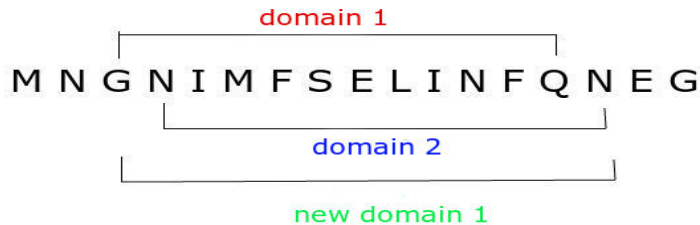


Figure 3.5: Domain merging. The red and blue occurrences overlap and become a single occurrence of the same domain

occurrence in p .

For each pair of domains (D_i, D_j) , we keep a counter d_{ij} , initially equal to 0. For each pair of interacting proteins (p, q) in I such that D_i intersects p and D_j intersects q , we increment d_{ij} by 1.

For each domain D_i , we denote its number of occurrences by d_i . The score associated with the pair (D_i, D_j) is the log-odds:

$$S(D_i, D_j) = \log_2\left(\frac{d_{ij}}{d_i d_j}\right) \quad (3.3)$$

If $d_{ij} = 0$, then the score is set as a negative number, smaller than all the other ones. The pseudocode of scoring domain pairs is given in Algorithm 5.

3.5 Predicting PPIs

The prediction of PPIs is based on the score of domain pairs. The score associated with a pair of proteins (p, q) is:

$$S(p, q) = \max\{S(D_i, D_j) \mid D_i \text{ intersects } p, D_j \text{ intersects } q\}. \quad (3.4)$$

A record of which protein contains which domains is kept. For each protein pair, we look for a domain pair, one from protein 1 and one from protein 2, which realizes the maximum score as in (3.4). That maximum score is the score of the protein pair. We then sort all protein pairs in descending order of $S(p, q)$. A threshold T_{ppi} (protein-protein interaction threshold) will be set so that the protein pairs (p, q) with $S(p, q) \geq T_{ppi}$ are predicted as interacting pairs. The pseudocode is given in Algorithm 6.

3.6 Improving the results

During implementation, we notice that, after the merging process, there will be a very large domain that is too large to be useful. To alleviate this problem, we designed a splitting procedure, based on given interactions, as follows.

Assume the set of proteins is P and the set of interactions in the training dataset is I . As interactions are not oriented, that is, $(p, q) \in I$ and $(q, p) \in I$ mean the same, we shall denote them as sets: $\{p, q\}$. For a domain D , $\text{neigh}(D)$ is the set of its neighbours:

$$\text{neigh}(D) = \{p \in P \mid \{p, q\} \in I \text{ for some } q \text{ such that } D \text{ has occurrences in } q\} \quad (3.5)$$

Each domain D we detected can be partitioned as $D = D_1 \cap D_2$ such that $\text{neigh}(D_1) \cap \text{neigh}(D_2) \neq \emptyset$. We then remove D and create new domains D_1 and D_2 . Figure 3.6 shows the process of splitting domains. All the occurrences of one domain are shown as black dots inside the circle, from occ. 1 to occ. 6. Both occ. 1 and occ. 2 are interacting with protein 1 (red dot outside the circle). We connect occ. 1 and occ. 2 with an edge. After going through all occurrences in a domain, we group the connected occurrences

into new domains. In Figure 3.6, occ. 1, 2 and 3 are grouped into a new domain and occ. 4, 5 and 6 into another domain.

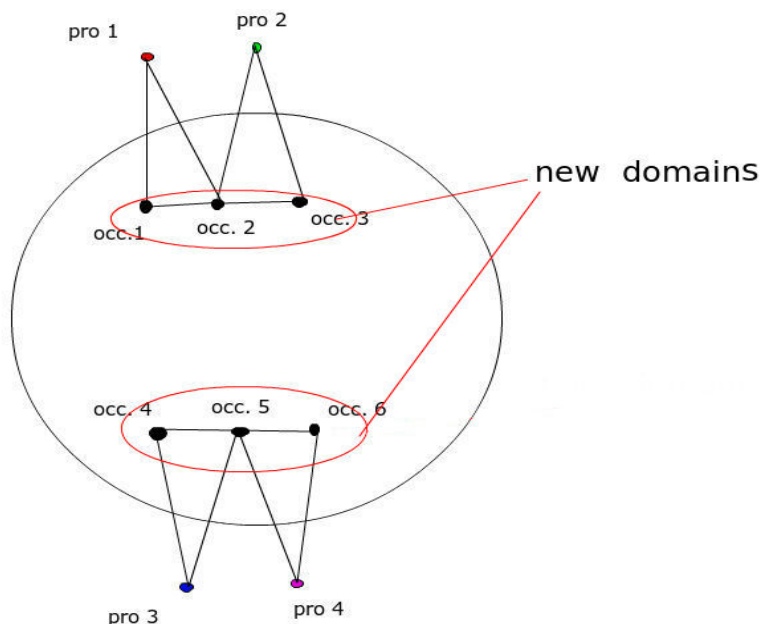


Figure 3.6: Splitting domain.

During implementation, for each D , a graph with the occurrences of D as vertices is built. We add an edge between occurrences d_1 and d_2 whenever $\text{neigh}(d_1) \cap \text{neigh}(d_2) \neq \emptyset$. Then we split every D according to the connected components of the associated graph.

The refined domains are scored and used to predict interaction in the same way as before (see Algorithm 5 and 6). The results we report in the next chapter are based on this procedure.

Algorithm 4: Algorithm for computing $H(x)$

```

input :  $x = x_1x_2x_3x_4x_5, T_{hit}$ 
output:  $H(x)$ 
1  $\Delta S_1 = T_{hit} - score(x, x) + B80[x_1][x_1]$ 
2 for  $i_1 \in [0, 19]$  do
3   if  $S_{B80}[x_1][i_1] \geq \Delta S_1$  then
4      $y_1 = AA[x_1][i_1]; H = H \cup y$ 
5      $\Delta S_2 = \Delta S_1 - S_{B80}[x_1][i_1] + B80[x_2][x_2]$ 
6     for  $i_2 \in [0, 19]$  do
7       if  $S_{B80}[x_2][i_2] \geq \Delta S_2$  then
8          $y_2 = AA[x_2][i_2]; H = H \cup y$ 
9          $\Delta S_3 = \Delta S_2 - S_{B80}[x_2][i_2] + B80[x_3][x_3]$ 
10        for  $i_3 \in [0, 19]$  do
11          if  $S_{B80}[x_3][i_3] \geq \Delta S_3$  then
12             $y_3 = AA[x_3][i_3]; H = H \cup y$ 
13             $\Delta S_4 = \Delta S_3 - S_{B80}[x_3][i_3] + B80[x_4][x_4]$ 
14            for  $i_4 \in [0, 19]$  do
15              if  $S_{B80}[x_4][i_4] \geq \Delta S_4$  then
16                 $y_4 = AA[x_4][i_4]; H = H \cup y$ 
17                 $\Delta S_5 = \Delta S_4 - S_{B80}[x_4][i_4] + B80[x_5][x_5]$ 
18                for  $i_5 \in [0, 19]$  do
19                  if  $S_{B80}[x_4][i_4] \geq \Delta S_5$  then
20                     $y_5 = AA[x_4][i_4]; H = H \cup y$ 
21                  end
22                else
23                  break
24                end
25              end
26            end
27          else
28            break
29          end
30        end
31      end
32    else
33      break
34    end
35  end
36  end
37  else
38    break
39  end
40 end
41 end
42 else
43   break
44 end
45 end

```

Algorithm 5: Algorithm for scoring domain pairs

input : protein-protein interaction set I , protein information set P ,
domain occurrences, domain number k

output: score for domain pairs S

```

1 for each  $p \in P$  do
2   | for each domain occurrences of  $D_j$  in  $p$  do
3   |   |  $d_j = d_j + 1$ 
4   | end
5 end
6 for each  $(p, q) \in I$  do
7   | for each  $(i, j)$  with  $D_i$  intersecting  $p$  and  $D_j$  intersecting  $q$  do
8   |   |  $d_{ij} = d_{ij} + 1$ 
9   | end
10 end
11 for  $i \in [1, k]$  do
12   | for  $j \in [1, k]$  do
13   |   | if  $d_{ij} == 0$  then
14   |   |   |  $S(D_i, D_j) = -\infty$ 
15   |   | end
16   |   | else
17   |   |   |  $S(D_i, D_j) = \log_2(\frac{d_{ij}}{d_i d_j})$ 
18   |   | end
19   | end
20 end

```

Algorithm 6: Algorithm for scoring and predicting PPIs

input : protein information set P , domain pair matrix D , threshold T_{ppi}

output: a list of predicted *PPIs*

```

1 for each protein  $p_i \in P$  do
2   | for each protein  $p_j \in P$  do
3   |   |  $S(p, q) = \max\{S(D_i, D_j) \mid D_i \text{ intersects } p, D_j \text{ intersects } q\}$ 
4   | end
5 end
6 sort  $P \times P$  decreasingly by  $S(p, q)$ 
7 for each protein pair  $(p, q)$  do
8   | if  $S(p, q) > T_{ppi}$  then
9   |   | output  $(p, q)$ 
10  | end
11 end

```

Chapter 4

Evaluation

We evaluate the prediction accuracy of our program by comparing it with the four methods we have described earlier. ROC curves are drawn to show how well each method performs. Our method is better than the others for most of the important values. Moreover, for a good part, it succeeds in surpassing the consensus of the other methods.

4.1 Datasets

In order to compare with existing leading programs, we refer to Park's evaluation paper [26]. In that paper, Park compared the four leading PPI prediction programs M1-M4 that we described in Chapter 2. We use the same datasets from [26].

Some of the methods require both positive and negative training sets.

The positive protein interaction data of yeast is from Database of Interacting Proteins (DIP) [33]. It has been refined by CD-HIT [21] first for removing redundant sequences. Then, proteins with 50 amino acids or less are removed. In total, we have 3867 positive interactions.

The negative protein interaction data is generated by the method of Ben-Hur and Noble [3]. It is reported as one of the best ways to construct negative PPI data. Protein pairs are randomly generated from an organism and those known to be positive are discarded. The generation process continues until the ratio between negative and positive interactions is 100:1. We have around 400,000 negative pairs in total.

Both positive and negative datasets can be downloaded from Park’s website <http://www.marcottelab.org/users/yungki/>.

In order to avoid over fitting, 4-way cross-validation [17] has been used for testing. Both positive and negative sets are divided into four equal parts and three are used for training and the fourth for testing. The process is repeated four times and the result combined. See also Figure 4.1.

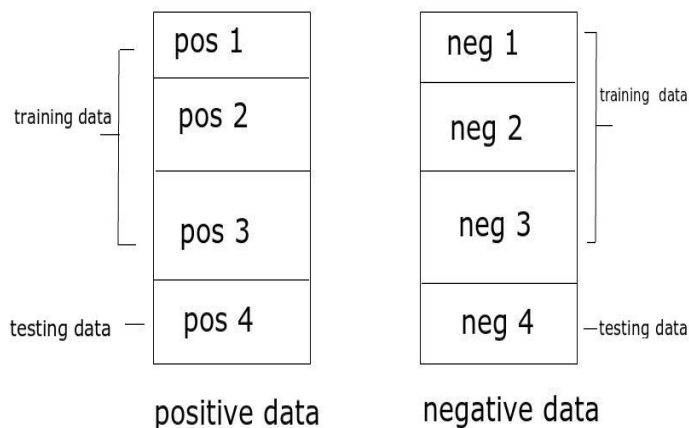


Figure 4.1: Cross validation.

4.2 Competing programs

The programs we compete against are described in Chapter 2. We used the same terminology as Park [26]: Method 1 by Martin et al. [24], Method 2 by Pitre et al.[30], Method 3 by Shen et al. [38], and Method 4 by Guo et al. [10]. Note that method 2 is the second version of PIPE, that is PIPE2. It is reported more accurate than PIPE. Since PIPE3 is focusing on parallelism and a reduction of memory usage, PIPE2 stands for the most accurate version of PIPE.

We also compare our method with the consensus approach proposed by Park [26]. The consensus approach integrates all four methods and clearly outperforms all four, which implies that better approaches can be proposed.

4.3 Comparison

The comparison is done using ROC (Receiver Operating Characteristics) curves generated from each method. The ROC curve shows a coordinate system with false positive rate (1 - specificity) as x-axis and true positive rate (sensitivity) as y-axis. The basic concept of a binary classifier's performance is explained in Figure 4.2.

		True class		
		p	n	
<u>Hypothesized</u> class	Y	True Positives	False Positives	false positive rate = $\frac{FP}{N}$ = 1 - specificity
	N	False Negatives	True Negatives	
Column totals:		P	N	

Figure 4.2: Binary classification. From [7]

Figure 4.3 shows basic concepts about discrete classifiers. A point closer to the north-west corner is better than a point closer to south-east, because it has higher true positive rate and lower false positive rate. For example, D is perfect, both A and B are better than C, and E is the worst.

Conceptually speaking, each test corresponding to some values of our parameters will generate a true positive rate and false positive rate, that is, one point of the ROC curve. This method is however not practical and we used the algorithm of Fawcett [7]. Figure 4.4 shows an example of drawing ROC curve points. Suppose we have 20 results sorted by descending order. We check them one by one, if they belong to the positive set, we

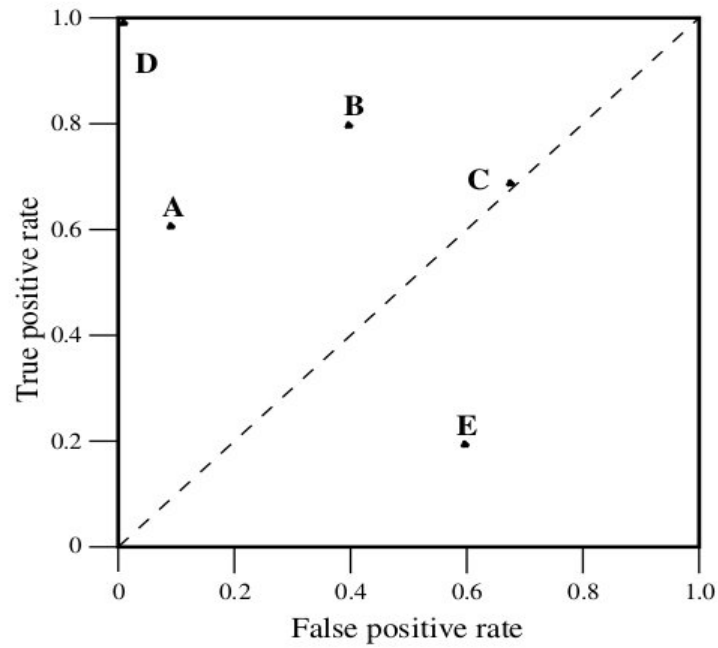


Figure 4.3: Discrete classifiers in ROC curve. From [7]

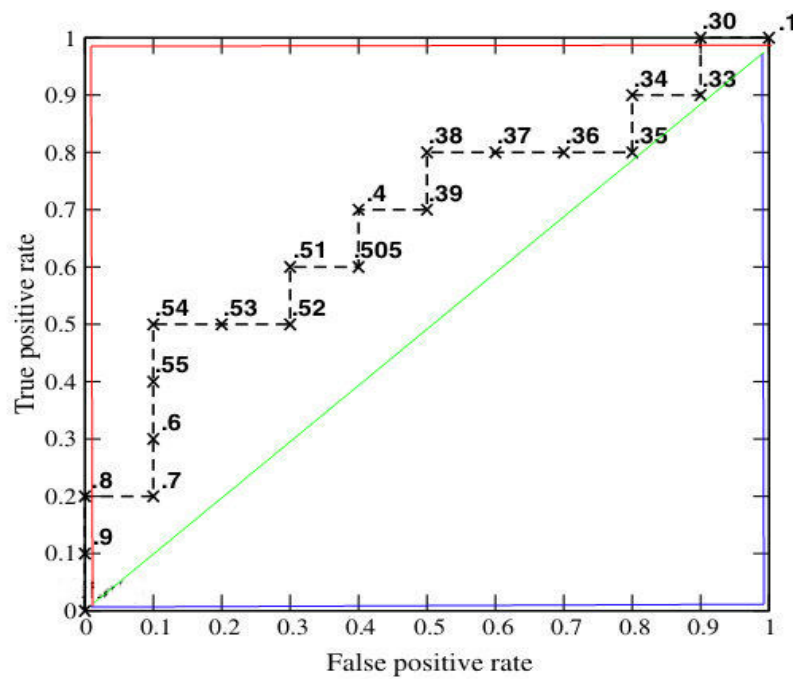


Figure 4.4: Generating ROC points. From [7]

create a point of the ROC curve by going up by 1/10 distance. If they belong to the negative set, we create a point going right by 1/10 distance. In this graph, the first result has score 0.9 and belongs to positive set, so the first point in this curve is (0, 0.1). The same thing happens to the second point. The third point with score 0.7, belongs to negative set, so the third point is (0.1, 0.2). The optimal case is shown as the red line, which means all the positive result have higher score than negative ones. The worst approach is shown as the blue line. A green line shows a theoretical result of randomly guessing approach. If a ROC curve is below the random curve, it is of little usage.

Fawcett's fast algorithm [7] for generating ROC points is shown in Figure 4.5 . We have implemented this algorithm in R.

Inputs: L , the set of test examples; $f(i)$, the probabilistic classifier's estimate that example i is positive; P and N , the number of positive and negative examples.

Outputs: R , a list of ROC points increasing by fp rate.

Require: $P > 0$ and $N > 0$

```

1:  $L_{\text{sorted}} \leftarrow L$  sorted decreasing by  $f$  scores
2:  $FP \leftarrow TP \leftarrow 0$ 
3:  $R \leftarrow \langle \rangle$ 
4:  $f_{\text{prev}} \leftarrow -\infty$ 
5:  $i \leftarrow 1$ 
6: while  $i \leq |L_{\text{sorted}}|$  do
7:   if  $f(i) \neq f_{\text{prev}}$  then
8:     push  $\left(\frac{FP}{N}, \frac{TP}{P}\right)$  onto  $R$ 
9:      $f_{\text{prev}} \leftarrow f(i)$ 
10:  end if
11:  if  $L_{\text{sorted}}[i]$  is a positive example then
12:     $TP \leftarrow TP + 1$ 
13:  else /*  $i$  is a negative example */
14:     $FP \leftarrow FP + 1$ 
15:  end if
16:   $i \leftarrow i + 1$ 
17: end while
18: push  $\left(\frac{FP}{N}, \frac{TP}{P}\right)$  onto  $R$  /* This is (1,1) */
19: end

```

Figure 4.5: Fawcett's fast algorithm for generating ROC curves. From [7]

We compare the ROC curve of our program to the ones of the other four methods as well as the consensus method. Since accurate prediction of PPIs requires very high specificity, we focus on the initial part of the ROC curve. The comparison with the other four methods is shown in Figure 4.6. For specificity 0.886, we reach the sensitivity of 0.674, which is higher than any other program. At the beginning of our curve, method 2 (PIPE2) is slightly better but later on (after specificity 0.976), our ROC curve is the best.

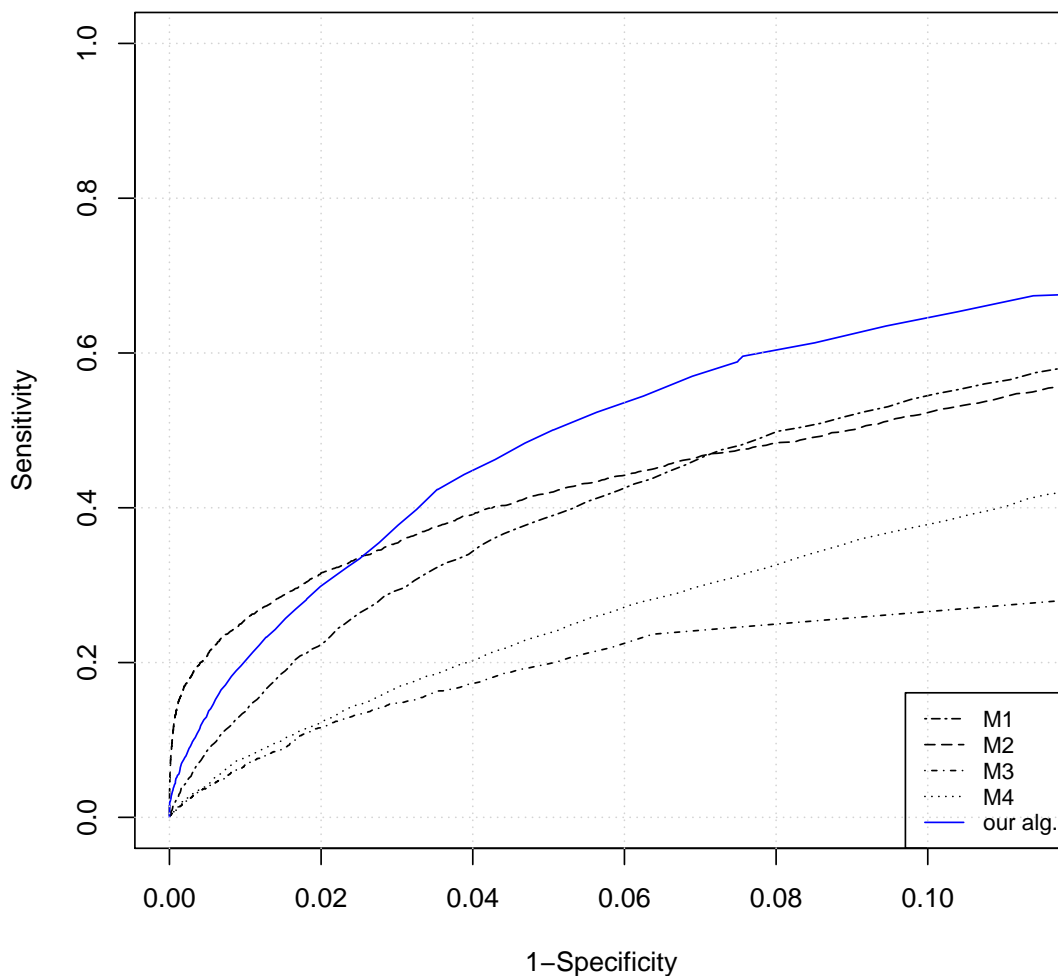


Figure 4.6: ROC curve comparison with other four methods

The comparison with the consensus method is shown in Figure 4.7. At first, the

consensus method is ahead but after specificity 0.95, our method outperforms even the consensus method.

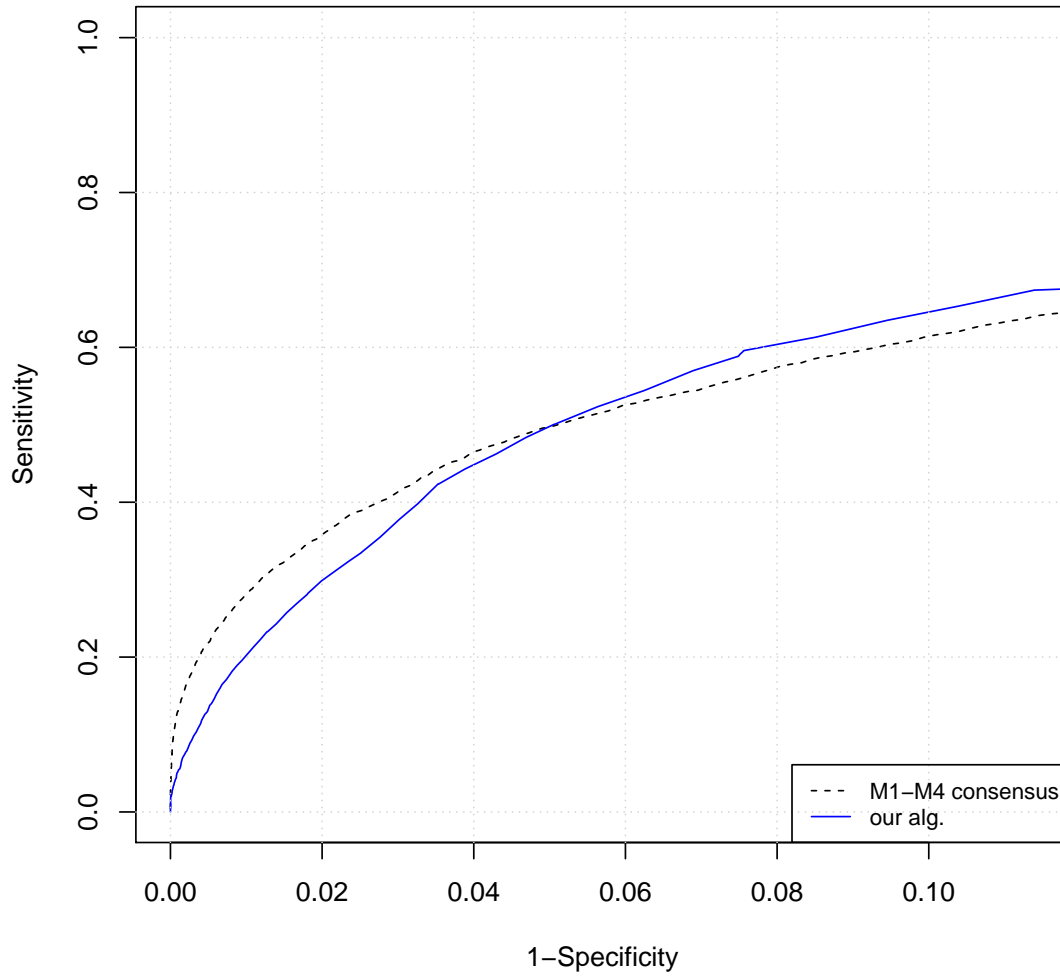


Figure 4.7: ROC curve comparison with consensus method

Chapter 5

Conclusion

In this thesis, we have studied the topic of protein-protein interaction prediction. After a molecular biology primer, we have given an overview of existing approaches for protein-protein interaction prediction, including two experimental methods and six kinds of computational methods.

We proposed a new algorithm and implemented it using C++ and OpenMP. An overview description and some detailed implementation have been illustrated.

We have tested our program on the yeast proteome. We have compared our result with four leading programs and a consensus program that integrates all those four methods, using the same yeast dataset. ROC curves have been used to compare our algorithm with other methods. It has been shown that the new algorithm exceeds other four methods in regard of accuracy. We have even outperformed the consensus method after 0.05 in false positive rate.

A lot of research remains to be done. Our results are good but we hope to improve them. First, at the very beginning of the ROC curve, PIP2 is better and we hope to improve that part. Better identification of domains will be necessary. Second, we may want to improve the entire ROC curve, not only the high specificity region. Finally, our method is expected to run much faster than PIPE3. We will improve the parallelization such that a very convenient PPI prediction tool is obtained.

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Curriculum Vitae

Name: Yiwei Li

Post-Secondary Education and Degrees: University of Western Ontario
London, Ontario, Canada
2012 - present M.Sc. candidate

Anhui University
Hefei, Anhui, China
2008 - 2012 B.Eng.

Honours and Awards: Scholarship for Distinguished Undergraduates in Academic and Science
Anhui University, China, 2011-2012

First Prize in “Challenge Cup” National Undergraduate Curricular
Academic Science and Technology Contest
Dalian, China, 2011

Related Work Experience: Teaching Assistant
The University of Western Ontario
2012 - present

Research Assistant
The University of Western Ontario
2012 - present

Lab Member
National University Student Innovation Program
Anhui University, China, 2010 - 2012

Software Developer Intern
NeuSoft Corporation
China, 2011