



University
of Glasgow | School of
Computing Science

Honours Individual Project Dissertation

PEP2PATH v2

Ross McBride
March 27, 2019

Abstract

Education Use Consent

I hereby grant my permission for this project to be stored, distributed and shown to other University of Glasgow students and staff for educational purposes. **Please note that you are under no obligation to sign this declaration, but doing so would help future students.**

Signature: Ross McBride Date: 27 March 2019

Contents

1	Introduction	1
1.1	Aims	1
1.2	Motivation	1
2	Background	4
2.1	Mass Spectrometry	4
2.2	BGCs	5
2.2.1	NRPs and antiSMASH	5
2.2.2	RiPPs, their six-frame translation and RiPPQuest	5
2.3	Pep2Path	6
2.3.1	NRP2Path	6
2.3.2	RiPP2Path	8
3	Analysis/Requirements	9
3.1	Problem Analysis	9
3.2	Requirements	11
3.2.1	Must Have	11
3.2.2	Should Have	11
3.2.3	Could Have	11
3.2.4	Won't Have	11
3.2.5	Non-Functional Requirements	12
4	Design	13
4.1	Software Structure	13
4.2	Algorithms	13
4.2.1	Mass Spectra Sequencing	13
4.2.2	NRP2Path	16
4.2.3	RiPP2Path	17
5	Implementation	18
5.1	Language Choice	18
6	Evaluation	19
6.1	Unit Tests	19
6.2	Scoring Functions	19
6.3	Original Pep2Path Experiments	21
6.4	Fulfilment of Project Requirements	21
7	Conclusion	22
	Appendices	23
A	Appendices	23
	Bibliography	24

1 | Introduction

One particular problem of interest for biologists is the identification of new biological products with novel properties. Until relatively recently, this process was done manually by trained experts. But with the recent advent of the field of bioinformatics, we can now bring immense computational resources to bear on problems like this, saving precious expert time.

Pep2Path (Medema et al. 2014) is a tool that aims to accelerate drug identification by matching mass-spectrometry outputs to identified biosynthetic gene clusters and in the original paper the authors demonstrate robust benchmarking results. However, despite the utility of Pep2Path, it is implemented as a few monolithic scripts, with little room to revise elements of it in accordance with new developments and research without a complete rewrite. In this paper we present a small suite of software tools implementing a platform for functionality like Pep2Path, and the software process by which this software was designed and created.

1.1 Aims

The aims of the project are to:

- Implement a set of software tools that can achieve similar functionality to the original Pep2Path, subject to correctness testing.
- Achieve a degree of flexibility in the implementation such that this software can be responsively updated to changes in its environment.
- Follow good software practises in the implementation such as loose coupling such that we can achieve software reuse, a cornerstone of software development.

1.2 Motivation

Various classes of biological compounds are formed from assembly-chains of smaller compounds, such as *peptides*, which are formed from amino acids. If we look at this problem as a computer scientist might, the first thing to come to mind in identifying useful drugs within this space might be an exhaustive search of all combinations of molecule. (Of course, for some molecules questions of topology and structure come into question...) This quite quickly runs into problems, as with the addition of each component to a chain of biological molecules, the chemical space grows exponentially. For example, if we consider the relatively limited case of the twenty *proteinogenic* (those involved in the synthesis of proteins, essential for organic life) amino acids and a peptide of length 4, there are 20^4 possible combinations... Around 160,000! We would then have to identify which, if any, of these have useful properties.

Without some heuristic (for example being able to infer properties from chemical composition), an exhaustive search of the chemical space is impossible. Instead we identify biological products produced in the wild, by living organisms – so-called '*natural products*', which have seen a recent resurgence in study. (A.Khan 2018) From an evolutionary perspective, we expect that if organisms are expending resources on producing a particular biological product, then it confers a survival advantage. For example, a strain of bacteria might produce an antibiotic that kills another

competitor species of bacteria – which we can then use ourselves to kill a potentially deadly strain of bacteria. Natural products produced in this way to fulfil an auxiliary function not directly related to the growth or reproduction of the organism are known as ‘*secondary metabolites*’. (Breitling et al. 2013)

To identify potentially interesting natural products we could, for example, analyse chemical structure for similarity to other interesting compounds, or by observing similar behaviour across several species which produce a particular product. However, we also want to match this natural product to the gene cluster – a Biosynthetic Gene Cluster, henceforth **BGC** – which encodes it. One way of achieving this is to cluster together species that share a BGC and produce the natural product in question – this is a good indication that the pattern is meaningful and the BGC produces the natural product.

Mass spectrometry allows us to identify the chemical composition of compounds – by breaking up molecules and then measuring the mass lost, we can infer the *potential* composition of a compound by the masses of its components using a mass-translation table. Mass spectrometry readings, or amino acid **sequence tags** (short listings of consecutive compounds), are one of the key inputs to Pep2Path. Although there are many classes of natural product for which mass spectrometry can be used effectively, (Smith et al. 2014) here we focus on two particular classes, for which Pep2Path provides an algorithm each: Non-Ribosomal Peptides (henceforth **NRPs**) and Ribosomally-synthesized and Post-translationally-modified Peptides (henceforth **RiPPs**).

The other key input to each of the two Pep2Path algorithms is the gene sequence we are attempting to match our compound to. As their name suggests, RiPPs are synthesised by *ribosomes*, the cell organelle responsible for translating gene sequences to proteins and then modified post-translation by enzymes. As a result, they are precisely encoded in an organism’s gene sequence and we can retrieve their composition directly, as Pep2Path does, by obtaining their ‘**six translation frames**’ (the six ways the gene sequence can be potentially be read). NRPs, by contrast, are instead synthesised by Non-Ribosomal Peptide Synthetases (henceforth **NRPSes**) which are independent of the ribosome and can introduce non-proteinogenic amino acids. These consist of several NRPS modules which form an assembly-line of amino acids, and are controlled by three domains – *A* (*Adenylation*), *T* (*Thiolation*) and *C* (*Condensation*). Of particular interest to us is the **Adenylation** domain, which controls which substrate is added to the chain of amino acids. These are not directly encoded into the gene and are therefore harder to predict, so we rely on an external tool – **antiSMASH** (Blin et al. 2017) – for this purpose.

Taking these two sets of inputs, **NRP2Path** matches the potential chemical compositions generated by mass spectrometry analysis to BGC predictions using antiSMASH, whereas **RiPP2Path** matches these potential chemical compositions to the six-frame translation extracted from the genetic sequence data of the RiPP-producing BGCs. Pep2Path can then automatically score these two sets of data against one another, filling a key part in an automated drug-identification pipeline, where previously investigation of natural products would be based on hand-identification.

However, the original Pep2Path is written almost entirely using singular scripts, one for each algorithm. As a result, it breaches some important software design principles, by mixing concerns such as parsing input and generating sequence tags, and at times relies on data structures passed around the entire script. This design makes Pep2Path difficult to update, but there are a number of reasons why it might be advantageous to do so. For one, the scoring method the authors use is based on antiSMASH 2.0 (Blin et al. 2013) the current version at the time. Since the release of Pep2Path, there have been antiSMASH versions up to 4. (Blin et al. 2017) While the original Pep2Path scoring method is backwards-compatible, antiSMASH version 4.0 offers the **SANDPUMA** ensemble algorithm (Chevrette et al. 2017) which collates the **Stachelhaus Code** and **SVM** predictors that antiSMASH 2.0 uses along with several others to offer a more accurate BGC prediction.

Furthermore, we may want to investigate product classes other than NRPS and RiPP, the classes

of biological product on which Pep2Path operates - there are many others, including *polyketides* and *alkaloids*. (For an example as to why this might be useful, the pain-medication morphine is an alkaloid extracted from the opium poppy.) It would also be useful to integrate different algorithms for identifying biological products from sequence data (such as the **RiPPQuest** (Mohimani et al. 2014) method for *lanthipeptides* - a subtype of RiPP), decouple the mass spectrometry process from the Pep2Path process or otherwise update the scoring mechanism with new developments. We also expect more generally that having a more transparent and modular software design might lead to easier discovery of bugs or integration with other codebases.

2 | Background

The motivation for Pep2Path comes from the recent technology of **Peptidogenomics**. (Kersten et al. 2011) In this original paper the authors propose the method of comparing mass spectrometry sequence tags to translated/predicted genomes for ribosomally-synthesised and non-ribosomally synthesised peptides respectively in order to mine for interesting natural products. However, while there were computational tools for aspects of this process, such as the interpretation of mass spectra and the interpretation of genomes, there was no end-to-end tool automating Peptidogenomics – until Pep2Path. During this section we discuss the background behind Peptidogenomics and Pep2Path, and some of the relevant literature.

2.1 Mass Spectrometry

Mass spectrometry is a common technique in chemistry for the identification of the chemical composition of a molecule by ionising it, causing it to break into fragments. There are multiple approaches to mass spectrometry, and multiple ways to interpret the data – for interpretation, there exist dereplicator tools like *iSNAP* (Ibrahim et al. 2012) and *Dereplicator+* (Mohimani et al. 2018) which attempt to statistically match mass spectra output to *known* molecules in a database. *Dereplicator+* for example, functions by comparing them to sample mass-spectra generated from a known database of chemicals, by simulating how the molecules of those spectra will fragment.

However, for our purposes we have a series of ordered readings of mass and intensity – gaps in mass peaks correspond to fragmented parts of a molecule, and we can then translate the mass being broken off into a chemical composition using knowledge of molecular weights stored in a dedicated mass translation table. (The so-called ‘*de novo*’ mass spectrometry technique – alternative methods are an active area of research.) Traditionally, this was a problem hand-solved by chemists, but has long been a target for computational processes due to the ease of translation of these numerical processes.

Once mass shifts have been translated to potential compounds, these can be joined together, end-to-end into longer sequences of compounds – ‘sequence tags’. Then, computational resources can be used to easily mine a group of mass spectrometry readings for sequence tags. However, there will inevitably be noise in mass spectrometry readings, whether from measurement error or the breaking off of small fragments that don’t represent a significant part of the molecule. For this reason, two variables are introduced: an *intensity threshold* and a *mass tolerance*. We can firstly cut out all low-quality readings by cutting out all readings below a certain intensity; secondly, we can account for slight discrepancies in mass measurements by measuring mass shifts within some interval rather than taking the exact values from the mass table. Good values for these variables depend on the dataset in question, and a good general pair of values is currently unknown, but processing mass spectra in this way is standard across most approaches.

2.2 BGCs

2.2.1 NRPs and antiSMASH

antiSMASH (antibiotics and Secondary Metabolite Analysis Shell) (Blin et al. 2017) is a widely-used piece of bioinformatics software used for the automated labelling of BGCs and genome-mining of secondary metabolites from raw sequence genome sequence data extracted from bacteria, fungi or plants. It is usable both as a standalone program on MacOS or Linux and as a web-server and has gone through several revisions and is, at the time of writing, currently up to version 4.0. Therefore, it aggregates many of the latest developments in natural product research and offers many features for the handling of such sequence data and the annotation of its BGCs, outputting data in the standard GenBank format.

For the purposes of this paper, we are interested in antiSMASH's ability to predict the substrate specificity of an NRPS' adenylation domains, that is, give us a prediction for the chemical makeup of a particular NRP given the sequence data of the organism that produces it. The current version of antiSMASH uses the SANDPUMA ensemble algorithm to do this, which aggregates the results of several other predictive algorithms, including those in previous versions of antiSMASH (maintaining backwards-compatibility), to produce significantly better results. However SANDPUMA and antiSMASH 4.0 are relatively recent compared to Pep2Path, and instead we are interested in two key predictors of antiSMASH 2.0: the Stachelhaus Code, a set of rules for comparing different adenylation domains created from empirical observation (Stachelhaus et al. 1999) and a machine learning Support Vector Machine (SVM) based method.

Machine learning is frequently used in bioinformatics to extrapolate underlying trends from the vast quantities of data often involved, learning from a provided dataset useful understandings of programmer-selected features by performing some optimisation task. SVMs in particular are a classifier (that is, assign inputs to one of a set of discrete classes, in this case a substrate prediction) and attempt to draw a decision boundary separating those classes so as to minimise the distance between a certain number of the training datapoints plotted in a hyperplane. The SVM implementation for antiSMASH is provided by **NRPSPredictor2**, (Röttig et al. 2011) a standalone piece of software which has since been integrated into the antiSMASH pipeline. One of the things that makes the original Pep2Path results robust is that it was tested on datasets NRPSPredictor2 had *not* been trained on, avoiding the introduction of bias and showing the generalisability of the Pep2Path method.

2.2.2 RiPPs, their six-frame translation and RiPPQuest

For RiPPs, the translation process is more direct than with NRPs, and does not require an external platform like antiSMASH to make substrate predictions. This process can be done via the 'six-frame translation'. DNA strands are made of long strings of four *nucleotide* bases (*Adenine, Glycine, Thymine and Cytosine*) which can easily be represented and processed in computer systems in large numbers, and which bind in A-T and G-C pairs across the two strands. These bases, in groups of three known as *codons*, reliably encode amino acids in ways we can extract. However, when looking at a genome, we do not know where the first codon begins – it could begin at any of three positions. Then, the encoding could be done by either strand – we only store one strand, but we can retrieve its *reverse complement* by converting the base to its corresponding base and reversing the strand – for a total of six different encodings. This is the six-frame translation method we use for RiPPs.

Among RiPPs, there are many subtypes. One particular subclass of interest is the lanthipeptide, which is specifically targeted by the bioinformatics software RiPPQuest. (Mohimani et al. 2014) A successor to the original Peptidogenomics paper, the RiPPQuest method centres on the prediction of the '*LANC-like*' domain in the genome, which is important for the biosynthesis

of lanthipeptides in particular. It then centres its translation window around the LANC-like domain and begins searching using the six translation frames.

One particular note is that as sequence data gets larger, so will the probability of random matches to our sequence tag. This method’s performance improves as we have either longer sequence tags, or shorter sequence data. If we assume (as a purely illustrative exercise) that there is uniform probability for each sequence tag across the chemical space, for the 20 proteinogenic amino acids (the alphabet for RiPPs) then the probability of any given sequence tag of length 2 is $\frac{1}{400}$. Relatively likely, even in small data. However, a peptide of length 4 would have the probability $\frac{1}{160000}$. Of course, longer genome sequences may contain enough data to appear to have several million peptides and *still* randomly match tags of length 4, 5 or even upwards, but it gets exponentially less likely as sequence tag length increases.

One of the motivations for RiPPQuest is that lanthipeptides have relatively short sequence tags, and thus it is necessary to target the sequence length. By targeting the translation window around a LANC-like domain, RiPPQuest searches less of the genome and provides more accurate results, but consequently only operates on lanthipeptides in particular. (These are some of the features relevant for comparison to our method – there are other complexities to their method which we will not remark on here.) We do not implement the RiPPQuest method here, and instead implement a more general method with looser assumptions in order to target all classes of RiPP, but we highlight this method as a point of comparison and possibility for future extension.

2.3 Pep2Path

Pep2Path (Medema et al. 2014) provides two algorithms, NRP2Path and RiPP2Path. Both rely on the same principles of mass spectrometry. In the original Pep2Path source program, mass search tags can either be given directly or can be derived from a mass-shift sequence. They then extract relevant BGC information from a sequence, and compare potential sequence tags to potential BGCs using a different scoring function for each algorithm in order to enable finding the best match.

2.3.1 NRP2Path

NRP2Path first takes potential sequence tags and antiSMASH substrate specificity predictions. These sequence tags can be arranged either forwards or backwards, and within the prediction there are several different NRPS modules, which themselves can either be arranged forwards or backwards and can be arranged in any order to make up the full BGC sequence. So in order to test all possible gene sequences, Pep2Path must generate all permutations of the cartesian products of the forwards and backwards modules (a total of $n! \cdot 2^n$ different orderings for n modules). A sequence tag and an ordering of a gene sequence are then aligned with one another and scored for their match, testing every possible alignment in order to find the best score.

In order to compare a sequence tag to a BGC, NRP2Path uses its own scoring function loosely inspired by *Bayes’ Rule*. We omit the details of its derivation here for brevity’s sake, but they are available in the original paper.

$$S(C|T) = \sum_{A \in T} \ln \left(\frac{P(A) + c \cdot (I_{A,M}^\eta + x \cdot P(A))}{P(A) \cdot (1 + c \cdot (\sum_{A \in \mathbb{A}} (I_{A,M}^\eta + x)))} \right) \quad (2.1)$$

$S(C|T)$ is the score of a gene cluster given the sequence tag, A is the amino acid making up part of a tag, and \mathbb{A} is the total amino acid alphabet being used. c and x are parameters that express

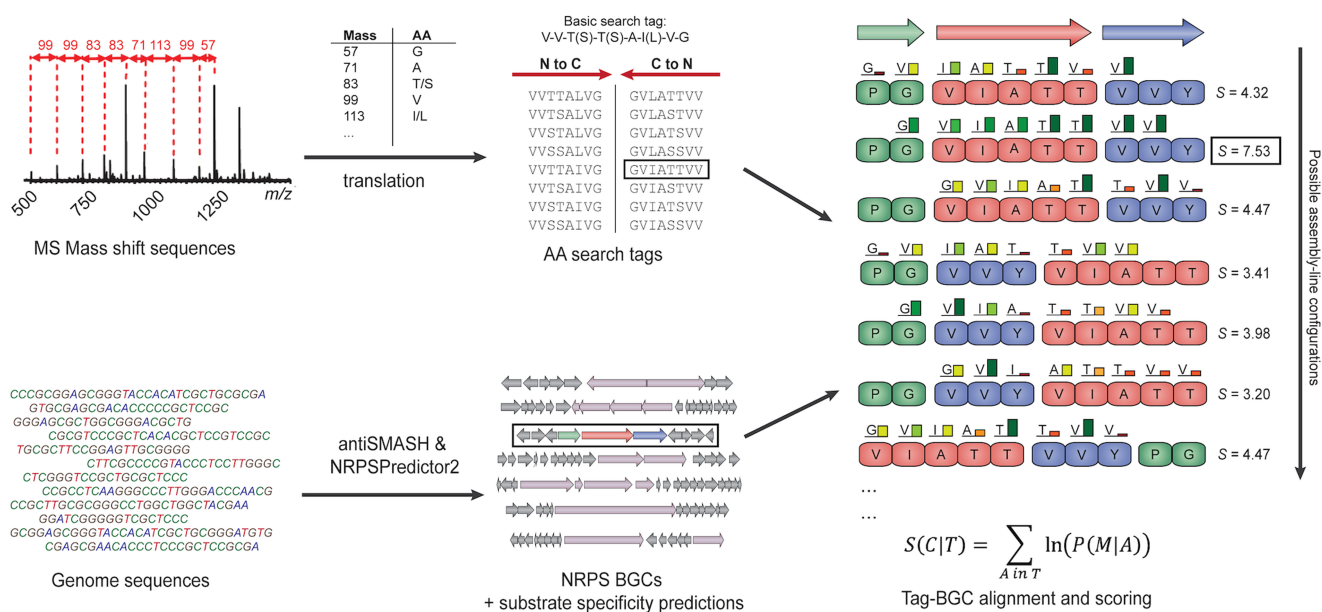


Figure 2.1: An illustration of the NRP2Path algorithm. On the top is a mass spectrometry output being put through a mass translation table to produce a comprehensive list of potential sequence tags. On the bottom is BGC substrate specificity being extracted from raw sequence data by antiSMASH. These two sets of data are then used to compare every alignment of every sequence tag to every possible ordering of NRP blocks extracted from the BGC. using the abbreviated scoring function shown below. Figure adapted from Medema et al. (2014).

the degree of confidence that final probability relies on substrate specificity rather than prior probability, and a pseudo-count to correct for small sample size, with default values $c = 1$ and $x = 0.01$, respectively. η is a regularisation term allowing for the exponential penalisation of repeated mismatches.

$I_{A,M}$ is the average of two values calculated separately for the Stachelhaus Code and SVM predictions. The Code prediction is based on the closeness to the closest known NRPS module for NRPSPredictor2, whereas the SVM value is assigned between five evenly-spaced thresholds between 0 and 1 based on how closely the classes of the amino acid match (0 for no relation, 1 for exact match).

$P(A)$ is the prior probability of A , calculated like so:

$$P(A) = \frac{n(A) + \frac{k}{|A|}}{\sum_{A \in \mathbb{A}} n(A) + k} \quad (2.2)$$

where k is another pseudocount with $k=1$ and $n(A)$ is the number of appearances within the NORINE database. (Caboche et al. 2008)

Finally, the degree of matching between any gene sequence and mass spectrometry output is defined as the maximum of its scores across any alignment.

2.3.2 RiPP2Path

While RiPPQuest provides a method for the matching of BGCs to mass spectrometry readings in lanthipeptides, it does not cover all RiPPs. Following RiPPQuest, Pep2Path introduced RiPP2Path, a simple accessory tool for more broad matching of RiPPs. It functions by running a sliding window containing the sequence tag over every position of every translation frame in a gene sequence, computing the number of amino acid matches over the total length of the tag and then returning the highest scores.

Unlike RiPPQuest, this algorithm is naively targeted and processes a score for each gene subsequence, distinguishing them only by the score they receive. This does have penalties for accuracy where any identified sequence is more likely to have appeared purely by random chance, especially in larger data, and costs more processing power inasmuch as it searches more, but it comes with the benefits of a very simple algorithm and is capable of applying the technology of peptidogenomics to all classes of RiPP, not just lanthipeptides.

3 | Analysis/Requirements

3.1 Problem Analysis

For this project, the supervisor acted as a client, proposing the software for eventual integration into a larger codebase, and due to greater domain experience provided requirements implicitly as the project progressed.

Firstly, we wanted a set of tools to implement the original Pep2Path functionality. This meant implementing NRP2Path and RiPP2Path. Secondly, the client had their own dataset for which the alignment comparison of NRP2Path might prove particularly cumbersome. This then meant being able to read the formats of the data available, and implement a simpler algorithm comparing the overlap between components. We also desired these implementations to be flexible with respect to future advances in bioinformatics and allow the integration of custom scoring functions, and to, as far as possible, allow space for future algorithms for other chemical classes to be implemented within the same framework, as we outlined in the introduction. (1.2) We implement both of these described NRP-comparison algorithms both to solve the more proximal problem of extracting useful information from the client's dataset, and also to demonstrate the flexibility of our implementation and its potential for various algorithms to be incorporated within. Note however that while we also follow this procedure for scoring functions (i.e. we implement a trivial scoring function and the original Pep2Path scoring) producing a more up-to-date scoring function – for example one that takes advantage of the SANDPUMA predictor – is a research endeavour unto itself and is outwith the scope of this project – we only aim to provide a *platform* for more modern techniques.

Furthermore, for Pep2Path to function, it requires both the previously-mentioned mass spectrometry and biological inputs to function. Logically, then, the software must be able to source this input from somewhere. Where the A-domain predictions are concerned, we outsource this work to antiSMASH as the original Pep2Path does – it is well-maintained and the leading piece of software in this area. Additionally, the client's data was already in antiSMASH-produced Genbank form – although this also contains the raw sequence data, accurately predicting A-domains is a problem unto itself, and entirely outside the scope of this project. Where RiPP2Path is concerned, it only takes raw sequence data – so in both cases, on the gene side of things, the software needs only parse antiSMASH-generated Genbank output.

Mass spectrometry, however, is more complicated. We have data from mass spectra, but not sequence tags. This obviously creates a requirement to deruplicate these spectra. However while this problem has been thoroughly studied (and continues to be thoroughly studied) and has an incredible breadth of software solutions available, the breadth of such solutions presents a challenge in itself, and hitherto much of the field has focused on protein-identification, (Smith et al. 2014) as seen in software such as Mascot. (Perkins and Pappin 1999) Rather than trying to find a tool that best fits our needs, we instead propose that the software should have a simple *de novo* mass spectrometry algorithm, focusing on no specific mass table, and usable for any peptide sequence. This violates the software engineering principle of software reuse, but eliminates the need for biochemistry research as a prerequisite, and potentially issues with of software licensing, allowing us to package Pep2Path as a standalone piece of software, with only the open-source

antiSMASH as a dependency. Additionally, we can mitigate the effect of ‘reimplementing the wheel badly’ by having a modular structure such that the mass spectrometry component can be replaced by any implementation an interested party thinks would suit their use-case and the only real drawback in this case is processing speed.

The software has to handle some very large search spaces, so efficiency *is* a concern. However, the client had a preliminary stage of screening for data reducing the data our implementation would have to process. Additionally, it would also be run on powerful hardware dedicated to processing very large bioinformatics data, so whilst it was necessary for our implementation to be efficient enough to terminate in reasonable time (and not, say, have unnecessary orders of complexity included within algorithms), the absolute highest degree of efficiency was not an aim for this project. Particularly, we are interested in a reasonable running-time for *Pep2Path*. This means not concerning ourselves overly with the efficiency of the mass spectrometry derplication – for which efficient algorithms are a different area of study.

It is also important to note that RiPP2Path, while it is a desirable inclusion, is a rather simple accessory tool and is lower-priority than a full implementation of NRP2Path – the highest priority is to deliver an end-to-end *flexible* implementation of NRP2Path to the client, and preferably, implement it in the client codebase, but the simplicity of RiPP2Path also makes it an easy inclusion. Some other useful features to include are (in descending order of significance); the ability to compare a group of spectra to a group of genomes and return some group-matching statistics; an accessory tool to plot the mass spectrum and visualise an identified sequence tag along it; and a CLI in order to run the program as a standalone application.

Moreover, while the full method of RiPPQuest for collecting RiPPs from a genome is its own algorithm, orthogonal to anything we are implementing here, and we leave the complexities of this method to software like RiPPQuest – however, it might be possible, and relatively simple, to use the basic idea of restricting the genome to a subsection around a LANC-like domain for a lanthipeptide, offering faster and less noisy predictions for this specific case of RiPP2Path with a simple alteration to the algorithm.

While the top priority is to deliver functional software to the client, we also wish to contribute to the bioinformatics ecosystem more broadly. One of the major issues facing bioinformatics research is the necessity of two different fields of domain-specific knowledge – biology and computer science, and their associated subfields (organic chemistry, software engineering...). Although attempts are being made to more broadly disseminate the domain-specific knowledge necessary, (Smith et al. 2014) solving these issues will likely require interdisciplinary efforts. Then for our software to *meaningfully* contribute to the bioinformatics ecosystem, it should be accessible to outside experts. This means a clear and transparent design, and to use the established software tools where we use tools. Additionally, in order to be as accessible as possible, the software should be as platform-independent and as portable as possible.

These are some more advantages of using a simple home-brewed MS package in lieu of trying to find a specific tool – a lack of dependencies makes *Pep2Path* easier to configure and get started, and the design should be (in theory) clearer to an observer, especially when compared to proprietary software. antiSMASH, our only external dependency, is only supported for Linux and MacOS, but our intent is to rely on its output files rather than the software itself, where these files can be produced either on a compatible system, or by the web server version. End-users should be concerned as little as possible with the configuration of the software on their system.

Finally we wish to deliver a software that we can *demonstrate* to be correct, and provide a baseline for which future additions to it can be measured against. For this reason we implement unitary testing across our implementation, where we demonstrate adherence to some invariant that should in principle guarantee the implementation correctly maps from the design. As a practical test, to prove that scoring functions meet our expectations, we also implement some tests on synthetic – known – data to see if our scoring functions behave as we would expect. We additionally would

preferably have software that can replicate the original experimental results of Pep2Path using the datasets they provide; this would allow us to show both that our implementation of the Pep2Path scoring mechanism was correct, but also that we have provided a platform that supports scoring functions such as Pep2Path’s scorer.

3.2 Requirements

In this section, we list functional requirements using the MoSCoW method, and then non-functional requirements as their own following list.

3.2.1 Must Have

- A simple *de novo* mass spectrometry tool capable of converting mass/intensity readings to sequence tags.
- Various small tools to be able to read in input data from standard file formats. Particularly, the ability to read the domain-standard antiSMASH-produced Genbank file formats.
- A software base allowing the integration of custom scoring functions, and allows the provision of custom mass tables/alphabets for the compounds being operated on, with a simple scoring method and the original NRP2Path scoring method implemented to demonstrate its capacity in this regard.
- Implementation of a simpler BGC/mass-spectrometry comparison equivalent to taking the set overlap of the components in both, more suited to datasets with shorter sequence tags.
- A full implementation of NRP2Path.
- A suite of unit tests verifying the behaviour of the implementations of the various algorithms and improving future maintainability.
- Practical tests showing the behaviour of the scoring function.

3.2.2 Should Have

- Integration with the client’s codebase.
- A full implementation of RiPP2Path.
- The ability to run a ‘many-to-many’ comparison between BGC-predictions and mass spectrometry.
- Replications of the original experimental results for Pep2Path (not necessarily exact, but on-target) to demonstrate functional correctness by practical test.

3.2.3 Could Have

- An accessory visualisation tool to plot mass spectra with predicted sequence tags over them.
- A simple CLI to run as a standalone.
- An adaptation of the RiPPQuest method to narrow down the translation down to just the region around the LANC-like domain for lanthipeptides.

3.2.4 Won’t Have

- Implementations of novel scoring functions, such as one that takes advantage of antiSMASH 4’s use of the SANDPUMA ensemble.
- A full implementation of the RiPPQuest method for genome mining on lanthipeptides.
- Any attempt to predict A-domains – this should be left to antiSMASH.

3.2.5 Non-Functional Requirements

- Should maintain strong separation of concerns and loose coupling, so components can be reused.
- Platform-independence (portability).
- Transparency of design.
- Reasonable efficiency - not a priority, especially where MS-sequencing is concerned, but the software should avoid wasting time where possible.
- Accessible to outside experts - using established tools where it is necessary to use tools.

4 | Design

4.1 Software Structure

Examining our proposed software, a natural design emerges. There are three important concerns: mass spectrometry, sequence handling, and the implementation of the two Pep2Path algorithms themselves, reliant on the two prior concerns. Therefore we propose a design to separate our software into corresponding packages along these lines.

One module must handle the parsing of any relevant MS data file formats from our client's data, the extraction of sequence tags from such data and a possible accessory tool to plot the sequence tag along its corresponding spectrum. Another must handle the extraction of useful information from sequence data – that is, adenylation domain predictions and raw sequence data from antiSMASH-produced Genbank files, for NRP2Path and RiPP2Path respectively. Finally, the last module must have both of these as dependencies, receiving sequence tags from the spectra module and A-domain predictions and raw sequence data from the Genbank module, and then implement NRP2Path and RiPP2Path. Then, each of these modules should have its own set of tests. Additionally, if a standalone CLI were to be implemented, this would then wrap around the outside of the software, treating the entire Pep2Path and its dependencies as its own dependency.

This design permits us to separate our implementation of the Pep2Path algorithms from the data fed into them, whilst still providing an end-to-end implementation from raw MS data and antiSMASH data to match scoring. For example, one would be able to entirely remove the MS package, replace it with another that provides the same interfaces and sequence tags as output (perhaps using a different algorithm for MS-sequencing) and Pep2Path should function unchanged.

4.2 Algorithms

During this section, we describe precisely the various algorithms we use for this project – note that for MS-sequencing and NRP2Path, we do not specify a mass table/alphabet respectively, and allow the user to provide this. In the case of mass spectra this is totally context-dependent on the molecules being fragmented – in the case of NRP2Path, different predictors may use different alphabets, and so different alphabets will be provided implicitly with the provision of different scoring functions.

4.2.1 Mass Spectra Sequencing

The input to the *de novo* mass spectrometry algorithm is a list of mass spectrometry readings, each with a mass value and an intensity value, where mass gaps represent a potential compound. We then want to convert these values into all potential *sequence tags*, end-to-end lists of possible components. (That is, in a sequence tag, each component must have its gap begin where the previous gap ended.)

Therefore, first, we preprocess our peaks to remove all low-intensity readings, according to some user-chosen threshold (perhaps 5% of the maximum value in a spectrum, for example), and sort

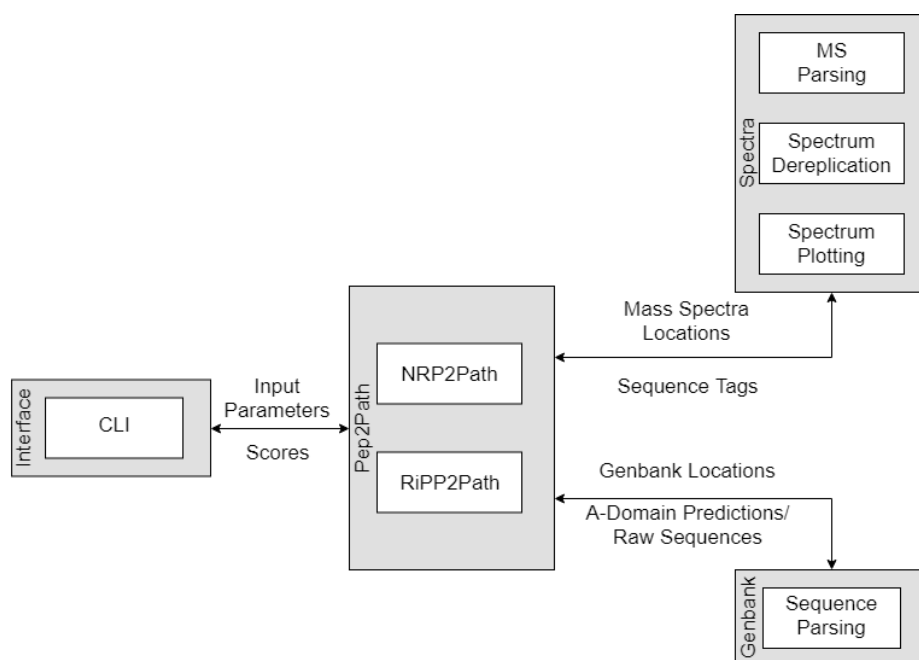


Figure 4.1: An illustration of the largest version of our proposed system layout. The CLI and Spectra Plotting are not as high-priority as the other components. We write input on the top of arrows, and output on the bottom.

them so that they are increasing order of mass. We then want to find gaps in the masses that correspond to the masses in some table of compounds (with some tolerance, either percentile or absolute) and find all end-to-end sequence tags from this.

We can formally model this problem as a **DAG** (Directed Acyclic Graph), a digraph with a topological ordering – that is, each vertex is enumerated and vertices can only have edges to vertices with higher numbers. (There may be multiple topological orderings – for example consider the case where there are multiple *sources* – nodes with no ingoing edges – in the graph. Either could be labelled as the first node! We specifically use an ordering by increasing mass and direct edges towards higher masses.) Furthermore, edges have a label, which is a list of all potential compounds that could be between the peaks the vertices represent, and these edges and their labels are unknown, but discoverable. In this model, vertices are individual mass spectrometry readings (mass and intensity), and edges are potential compounds from gaps between mass peaks. The problem of finding a sequence tag then corresponds to finding a path through this graph. (Boecker 2019)

We partition this algorithm into two stages: **edge discovery** and **path discovery**. Edge discovery is the process of searching the raw numerical mass values of each peak for gaps corresponding to components in the mass table, in order to build the graph’s edge set. Path discovery is then traversing the edges in the edge set in order to form a complete path – and therefore a sequence tag.

To perform edge discovery, we begin by allowing a value to be specified for a mass tolerance. This might be a static value measured in *Da* (Unified Atomic Mass Unit or Dalton), a percentage applied to each mass in the mass table, or a percentage of the maximum mass in the spectra readings. We can then transform each mass in the mass table into an interval ($mass - mass_tolerance, mass + mass_tolerance$). Finally, we iterate through each reading, and subtract it from subsequent readings. If the result lies within the interval, then an edge exists between the peaks with a label

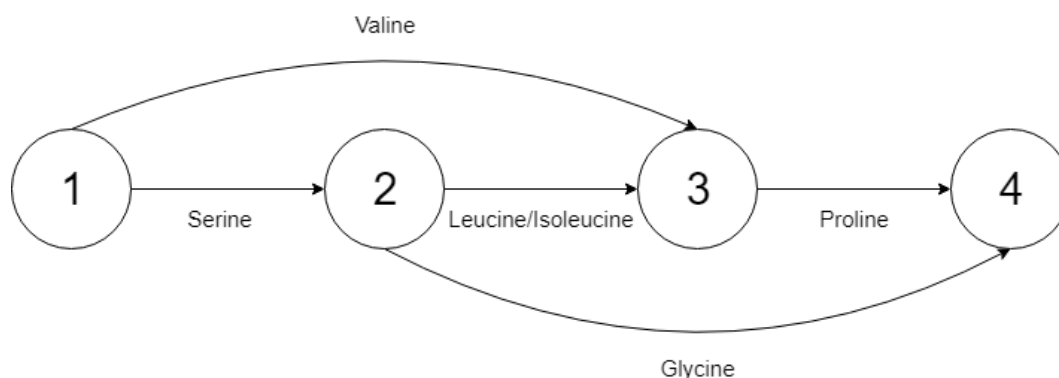


Figure 4.2: An example illustration of some mass spectra peaks represented as a DAG, with arbitrarily chosen amino acid names for the edges. From this graph there would be the tags (without subtags) Ser-Leu/Ile-Pro, Val-Pro, Ser-Gly.

corresponding to the compound which the interval belongs to. We repeat this for all values in the mass table in order to find all possible edges.

<note to include edge discovery pseudocode>

To perform path discovery, we perform an exhaustive depth-first search for every peak in the vertex set. (A breadth-first search would also be possible but depth-first is conceptually simpler to understand.) First, we choose a vertex, and denote it our current vertex. So long as our current vertex has edges we haven't yet explored, we choose one of those edges, marking it as explored, and make the other vertex involved in the edge our current vertex, and push our previous vertex onto a stack. We continue this process until we reach a vertex with no unexplored edges. At this point we pop the vertex at the top of our stack, marking it as our current vertex and resume searching for edges. Once we have also exhausted our stack, we choose another vertex we have not already performed this process for, and repeat until we have exhausted all vertices, to get all possible sequence tags.

There are a few obvious optimisations we can make on this process: firstly, we do not need to check for cycles as we normally might in our depth-first search, as by definition our DAG has no cycles. Secondly, the solution space for our tags is very large - $\sum_{len=1}^n alphabet_size^{len}$ specifically, for all tags up to length n , ignoring for now how these tags might be arranged along our peaks. Rather than storing each tag as we find it, we can instead store the longest tag containing this tag as a substring (we refer to such substrings as *subtags* here).

This is done for two reasons: under normal circumstances, we assume if we have found an edge, then unless the data is exceptionally noisy the edge itself is likely meaningful, and furthermore any subtags can be reconstructed by taking n -grams of the parent tag. For each parent tag, this saves us having to store $\frac{n}{2}(n+1)$ subtags. (Consider that a sliding window of length m has $m-n+1$ possible alignments across a sequence tag of length n , and that we wish to consider the sum of all $1 \leq m \leq n$ and apply the standard formula for the sum of an arithmetic sequence.) For our algorithm, this means saving a sequence tag *only if* we have exhausted all edges and we haven't just popped something from the stack. Additionally, if we visit a vertex as part of path discovery for another vertex, there is no need to begin a tag search beginning from that vertex - any tags discovered this way would be subtags of the tags we have already discovered.

<note to include path discovery pseudocode>

<note: should i move (parts of) this somewhere? the comparison to our method is useful...>

However, note again that this is a relatively naive solution to a well-established problem. We include it here so as to have a complete, end-to-end software pipeline for NRP2Path, but due to our proposed modular structure, it would be relatively easy to replace it with another, more sophisticated mass-spectrometry module and still take advantage of Pep2Path. For example, some approaches include: using a scoring mechanism to measure the fit between a predicted sequence tag and the real data during edge discovery, eliminating impossible sequences early or by completely different approaches such as optimising a scoring function over the entire scoring space using a genetic algorithm or using a Hidden Markov Model. (Colinge and Bennett 2007)

However, perhaps most interestingly, it has been known for quite some time that finding the longest sequence tag is an instance of the *Antisymmetric Longest Path Problem*, an NP-hard problem that is a variation of the *Longest Path Problem* (the classical problem of finding the longest path in a graph, also NP-hard). (Pevzner 2000) (And therefore under the assumption that our result is not generated by noise, that it returns the true value.) However, recent work suggests both tighter bounds on the problem (and its inapproximability) (Song and Yu 2015) but also that under certain restrictions, a linear-time algorithm may be applied to solve the antisymmetric path problem (and particularly, has been tested on spectral data). (Song and Chi 2015) With some fairly lax assumptions this potentially offers a massive theoretical performance improvement over our naive algorithm. Note, however, that our goal was primarily to implement *Pep2Path* – mass spectrometry is neither a priority nor performance bottleneck, so we did not include such sophisticated algorithms in our design.

4.2.2 NRP2Path

<note: small intro to what exactly the problem is, again>

In order to provide a simple scoring mechanism, we measure the overlap between the component subpredictions in a sequence tag, T and gene cluster C . We treat both of these as sets, and use the Jaccard Similarity Index shown in equation 4.1 to measure their similarity. This is a standard similarity metric often used in document analysis, and has a number of nice properties; for one, it is simple and can be used as an effective baseline for more complicated measures. Secondly, it is bounded by the interval $[0, 1]$, with 0 for no match and 1 for an exact match; this makes all scores immediately comparable without reference to details (i.e. we know scores close to 1 are always ‘good’ scores). Thirdly, the score is normalised and weights each individual component less heavily in longer tags; this helps us discount very long tags with many mismatches but many matches (by random chance). Even if a tag contains a perfect match, it will get a lower score than other perfect matches without superfluous components. We adopt this method for these properties.

$$S = \frac{|C \cup T|}{|C \cap T|} \quad (4.1)$$

There are a few immediate restrictions on this method that should be mentioned, however. We note that this method does not account for repeated components; so if *Glycine* appears twice in a tag, the score won’t reflect this. Perhaps most importantly, it also does not account for ordering of the components sequence tags. Most sequence tags are quite small, so the effect of these biases should be minimal, especially in shorter data, where there will be fewer orderings, and less chance of repeated components. We attempt to overcome these limitations by the more complicated method of Pep2Path, but should one wish to extend this method, a simple solution to the problem of repeated components is the generalisation of the Jaccard Similarity Index for multisets.

In order to account for ordering, however, we do what Pep2Path does, and score alignments of sequence tags and gene clusters against one another.

<note to include NRP2Path pseudocode>

<note to make it clear that we can check both directions of sequence tag in the NRPS algorithm by checking all module configurations against one sequence tag>

Note that there are alternative metrics we could have used for this process; for example, for Jaccard similarity a suitable alternative might have been the Dice Coefficient, which is very similar but might justify itself by better empirical performance. Additionally rather than attempting an alignment scoring we might use Levenshtein distance, (?) (perhaps normalised by tag length) which measures edit distance between two strings, for the operations insertion, deletion and substitution. Suppose a tag and a set of BGC predictions are identical, other than one component inserted directly in the middle. Then an alignment comparison will only be able to match half as many components (it will be displaced by one for all others) but the Levenshtein distance will only score one mismatch. If our data were to often miss or insert entire components, then the Levenshtein distance would be a much better predictor.

4.2.3 RiPP2Path

This algorithm first takes as input a sequence tag to search for, and raw sequence data to search for it in (probably retrieved from a GenBank file). It then translates the raw sequence data into its six-frame translation by sampling the sequence and its reverse complement at starting indices 0, 1 and 2 and translating the bases into amino acids – the translation is done via standard tables, and we omit the details here. Then for each of these translation frames, we align the sequence tag with the frame for every possible position and score the match, using the number of exact matches between the two normalised by the tag length $\frac{\text{no_matches}}{\text{len}}$ as a simple scoring mechanism. We then sort our matches, best scores first, and report the strand and position (in nucleotide bases) for the n th best matches (we allow n to be supplied as a parameter).

<note to include ripp2path pseudocode>

This algorithm bears some resemblance to brute-force string search, but whilst brute force string search searches for an exact match, this algorithm attempts to score every possible substring. We do this so as to provide as much information on the data as possible. For example, suppose that our search tag was one amino acid off, and we could not find it in the data. Then when attempting to find an exact match, we would only have a ‘not found’ result. But given this extra granularity, a near-total match would show up as the highest score found.

<note: should i move (parts of) this somewhere? the comparison to our method is useful...>

However, as a result, this algorithm can’t improve on the $O(n^2)$ complexity of the most naive forms of brute-force string search (i.e. ones without early termination on the first mismatch when aligning a substring with the query string), because improvements work by skipping some substrings. However, should we wish to search for exact matches, this is a solved problem with standard solutions, such as the linear-time Knuth-Morris-Pratt algorithm (Knuth et al. 1977), the empirically performant Boyer-Moore algorithm (Boyer and Moore 1977) or algorithms such as hybrid KMP/BM algorithms. (Franek et al. 2007) (Baeza-Yates 1989) String search algorithms such as these are also of more use in other areas of bioinformatics more generally as seen in the use of a hybrid KMP/Boyer-Moore in genome profiling in the recent PATSIM (P.Manikandan and D.Ramyachitra 2018) or an alternative exact string-searching algorithm TVSBS, (Thathoo et al. 2006) designed specifically for biological sequence data. However, for most cases of exact string-matching GNU/Linux provides a standard, optimised implementation of Boyer-Moore as part of the *grep* utility, and other operating systems provide similar tools.

Alternatively, since we are only searching for high scores, it would be possible to implement an algorithm that searches only for *good* matches and skips bad matches by some means – suggesting how one might do this is beyond the scope of this paper, however.

5 | Implementation

5.1 Language Choice

We chose to use Python for our implementation, as it is the *lingua franca* of scientific computing. It offers highly expressive language constructs and useful libraries, such as *itertools* (Python 3 2008) offering many convenient ways to iterate through combinations, permutations and more, *NumPy* (NumPy 2006) for high-speed numerical operations and *BioPython* (BioPython 2000) for bioinformatics. All of these were used in the course of implementing our design. Additionally, a great volume of scientific software is already implemented in Python (indeed, the original *Pep2Path* is implemented using Python) and many scientists are familiar with Python already, making it easier to interface with the already extant body of work. Particularly, the client's codebase was implemented in Python, so this choice made for easier integration without the need for a language-spanning gateway. Other options like *Julia* (JuliaLang 2012) exist, but given their lack of maturity when compared to Python we elected not to explore these options.

Additionally, like most modern high-level languages, Python is also platform-independent, so properly-written software can consequently be run without concern for platform, reaching more potential end-users.

<note to talk about *itertools* simplifying much of combinatorial maths involved – particularly much of the work of *nrp2path* can be reduced to two lines (three with optimisation)>

<note to talk about use of *numpy* in mass spectrometry – standard methods for a lot of processing, and vectorisation in edge discovery specifically (this is not the performance bottleneck however) – we use a list of dictionaries for path discovery>

<note to talk about use of *bio* for *genbank* sections and *ripp2path* – std implementation of biological utilities>

<note to discuss ambiguities in original design, and how we implemented them>

<note to mention constant-time lookup tables for amino acid matches>

<note on how unit tests were implemented>

<note on sequence tag notation, particularly the [A, B, C] case and how this affects default implementations of sequence tag comparison>

<note to specify the flexibility of scoring mechanisms via curried functions (to do)>

<note on simplifying assumptions in *Pep2Path*, and particularly how alphabets affect things>

<note to refer back to requirements for other things we implemented>

<note on performance of algorithms>

<note: would it be faster operating on strings? threads would help>

<note: there are *sklearn* implementations of jaccard similarity, hamming distance, etc; these are implemented in C and so might be faster>

6 | Evaluation

6.1 Unit Tests

<note to include unit tests – this proves not necessarily ultimate correctness, but that they adhere to certain invariants we expect from our conceptual understanding – particularly notable is the generation of synthetic data and the extraction of the correct pregenerated results from random noise, for all our algorithms>

6.2 Scoring Functions

<note to include scoring function test results – we wish to demonstrate that the maximum value is for a perfect match, and that scores generally get worse as random mutations are introduced into – we also wish to show how it varies for different lengths of tag, and maybe how well we can predict things with unexpected alphabets?>

There are three properties of our scoring functions we would like to demonstrate:

1. That the function is bounded above by the score for an exact match.
2. That the function is generally decreasing as we move further away from an exact match.
3. That the function is proportional; i.e. if the tag being compared is longer, then a mismatch causes a larger drop in score than it would for a shorter tag.

In order to test these properties, we designed an experiment. In order to test these properties, we start with an identical sequence tag and set of genbank predictions. Then we want to repeatedly randomly mutate one of these (the choice should be arbitrary; we choose to mutate the sequence tag because it's slightly easier to implement) and measure the score as we do so. This should be sufficient to demonstrate properties one and two – if we plot the results, we should see that the highest point is the first value, and that the graph trends down towards some baseline. In order to demonstrate property 3, we need to repeat this procedure multiple times for multiple different tag lengths and compare how many mutations it takes for the function to approximately reach its baseline (note that this process is random, so the basal value we converge to may be different).

To carry out this procedure, firstly, we generate a synthetic sequence tag from a given alphabet. Then, we create an exact copy for for the Genbank predictions, which we partition at random into smaller blocks analogous to NRPS modules, rearrange these modules and for each module choose at random whether it should be reversed or not. This creates a set of Genbank predictions which is expected to be identical, and tests the rearrangement portions of scoring function for the alignment-based scoring functions. We then measure the score between these two pieces of synthetic data.

From this set of genbank predictions, we generate b mutants, where b is an arbitrary parameter defining batch size. A mutant of a tag is the tag with one randomly-chosen component replaced by another randomly-chosen component from its alphabet with uniform probability (it may be the same one; it depends on the size of the alphabet chosen, but we repeat this process so it should in general converge to produce mismatches). Then at each time step, we take the previous

batch of mutants, and mutate them again to produce a set of mutants which randomly move progressively further from being a total match. We then plot these data.

note for algorithmic layout of experimental procedure

For this procedure, there are four parameters: *alphabet*, *batch size*, *number of mutations* and *tag length*. *Alphabet* defines the components we can draw from when randomly generating both the original tags and mutants; in general, this should have little effect other than that a small alphabet would have greater chance (with uniform probability) to draw the same amino acids repeatedly, and hence this procedure would not converge easily. For our experiments, we simply use the alphabet of proteinogenic amino acids.

Batch size defines how many mutants are generated at each stage. In order to make the trend clearer, we average the score of the mutants in each batch, and plot each average score as an individual point. So in general as batch size increases, these points should converge to their 'true' expected score values for that many mutations, and the graph should get 'smoother'. We try to use batch values of at least a few points and higher where we can, but there is an associated linear performance cost to doing so.

The *number of mutations* controls the total number of batches of mutations we generate; this must be long enough enough that we generate enough mutations to see the score decay to some baseline (and stay there), but it again has an associated linear performance cost. In general we aim for 100 mutations, which suffices to see the whole decay for shorter tags. We also attempt to keep this and batch size fixed within experiments conducted on a single scoring function, and fix the bottom of the axis to 0, for ease of comparison.

Tag length is simply the length of the tags (and all subsequent mutants) that we generate. This is necessary to demonstrate property 3; we vary this to see the decrease in score. It's worth noting that the proportionality effect will be compounded by the fact that as a tag gets longer, when choosing which component to mutate, then over time it is increasingly likely we will choose an element that we have already mutated, and thus is likely to already be a mismatch, and so our position in the tag space does not meaningfully move away from perfect match. In other words, for longer tags we are likely to take longer to converge at baseline and may converge at a higher point not only because of the result we expect, but also due to a *bias in the testing procedure*.

This doesn't make our testing procedure infeasible, however; this effect becomes more pronounced as we go through more mutations, whereas proportionality should be observable throughout. We can determine if a scoring function is proportional by checking its behaviour *at the start* and seeing how quickly it decays. In fact, while this effect becomes more pronounced overall for longer tags, it is *less* pronounced towards the start, due to the fact that we are much more likely to pick a new component to mutate – it is only *convergence* behaviour it affects, and this doesn't come into question for property 3. (And we are concerned with property 2 independently of tag length.)

Alternatively, another experimental design would be to choose which component to mutate next deterministically, or to choose randomly but only choose components that haven't already been mutated. However, an exhaustive search of the scoring space is impossible – or at least very computationally expensive for longer tags, as it will be exponential with the size of the alphabet – so to take these approaches would be to encode certain assumptions about the order we perform mutations in. This bias is unlikely to matter, but we choose to avoid it in favour of exploring the scoring space more randomly at the cost of having a more meandering procedure. We *do* still encode these assumptions to a certain extent by iteratively mutating the same group of mutants, but this enables us to 'walk' the scoring space, and have each group of mutants immediately comparable to the previous, so it is an acceptable compromise here.

note: results go here

Note also that checks on these properties can be implemented as unit tests for the scoring functions; we implement a check on property 1 by performing the iterative mutation process, taking the scores sorted in non-decreasing order by number of mutations, and then use a sorting algorithm to sort in non-increasing order of score; the first value should be the score for no mutations in this case. It would also be possible to enforce properties 2 (by iteratively generating certain mismatches in the tag and checking if the score decreases) and 3 (by performing the same process but instead comparing the drops in score between tag lengths as mismatches are added) but we do not currently implement these at this time.

6.3 Original Pep2Path Experiments

<note to include original pep2path results(?) - this shows that we have a platform capable of implementing various kinds of scoring function, and our implementations themselves are (partially) correct but I may not have time to actually collect these results, so in this case I should just outline the procedure>

6.4 Fulfilment of Project Requirements

<note to refer back to requirements - such as implementation within the client's codebase - in order to justify why the project is a success>

7 | Conclusion

A | Appendices

7 | Bibliography

- R. A.Khan. Natural products chemistry: The emerging trends and prospective goals. *Elsevier Science*, 2018.
- R. A. Baeza-Yates. String searching algorithms revisited. In *Proceedings of the Workshop on Algorithms and Data Structures, WADS '89*, pages 75–96, London, UK, UK, 1989. Springer-Verlag. ISBN 3-540-51542-9. URL <http://dl.acm.org/citation.cfm?id=645928.672525>.
- BioPython. Biopython official webpage, 2000. URL <https://biopython.org/>.
- K. Blin, M. H. Medema, M. Kazempour, M. A. Fischbach, R. Breitling, E. Takano, and T. Weber. antiSMASH 2.0—a versatile platform for genome mining of secondary metabolite producers. *Oxford Academic*, 2013.
- K. Blin, T. Wolf, M. G. Chevrette, X. Lu, C. J. Schwalen, S. A. Kautsar, H. G. S. Duran, E. L. C. de Los Santos, H. U. Kim, M. Nave, J. S. Dickschat, D. A. Mitchell, E. Shelest, R. Breitling, E. Takano, S. Y. Lee, T. Weber, and M. H. Medema. antiSMASH 4.0-improvements in chemistry prediction and gene cluster boundary identification. *Oxford Academic*, 2017.
- S. Boecker. Algorithmic mass spectrometry version 0.6.0, 2019. URL <https://bio.informatik.uni-jena.de/script-algoms/>.
- R. S. Boyer and J. S. Moore. A fast string searching algorithm. *Commun. ACM*, 20(10):762–772, Oct. 1977. ISSN 0001-0782. doi: 10.1145/359842.359859. URL <http://doi.acm.org/10.1145/359842.359859>.
- R. Breitling, A. Cenicerros, A. Jankevics, and E. Takano. Metabolomics for Secondary Metabolite Research. *MDPI*, 2013.
- S. Caboche, M. Pupin, V. Leclère, A. Fontaine, P. Jacques, and G. Kucheroov. NORINE: a database of nonribosomal peptides. *Oxford Academic*, 2008.
- M. G. Chevrette, F. Aicheler, O. Kohlbacher, C. R. Currie, and M. H. Medema. SANDPUMA: ensemble predictions of nonribosomal peptide chemistry reveal biosynthetic diversity across Actinobacteria. *Oxford Academic*, 2017.
- J. Colinge and K. L. Bennett. Introduction to Computational Proteomics. *PLOS Computational Biology*, 2007.
- F. Franek, C. G.Jennings, and W.F.Smyth. A simple fast hybrid pattern-matching algorithm. *Elsevier Science*, 2007.
- A. Ibrahim, L. Yang, C. Johnston, X. Liu, B. Ma, and N. A. Magarvey. Dereplicating nonribosomal peptides using an informatic search algorithm for natural products (iSNAP) discovery. *Proceedings of the National Academy of Sciences of the United States of America*, 2012.
- JuliaLang. Julia language official webpage, 2012. URL <https://julialang.org/>.

- R. D. Kersten, Y.-L. Yang, Y. Xu, P. Cimermancic, S.-J. Nam, W. Fenical, M. A. Fischbach, B. S. Moore, and P. C. Dorrestein. A mass spectrometry-guided genome mining approach for natural product peptidogenomics. *Nature Chemical Biology*, 2011.
- D. E. Knuth, J. H. Morris, and V. R. Pratt. Fast Pattern Matching in Strings. *Society for Industrial and Applied Mathematics*, 1977.
- M. H. Medema, Y. Paalvast, D. D. Nguyen, A. Melnik, P. C. Dorrestein, E. Takano, and R. Breitling. Pep2Path: Automated Mass Spectrometry-Guided Genome Mining of Peptidic Natural Products. *PLOS Computational Biology: Software*, 2014.
- H. Mohimani, R. D. Kersten, W. T. Liu, M. Wang, S. O. Purvine, S. Wu, H. M. Brewer, L. Pasa-Tolic, N. Bandeira, B. S. Moore, P. A. Pevzner, and P. C. Dorrestein. Automated Genome Mining of Ribosomal Peptide Natural Products. *American Chemical Society*, 2014.
- H. Mohimani, A. Gurevich, A. Shlemov, A. Mikheenko, A. Korobeynikov, L. Cao, E. Shcherbin, L.-F. Nothias, P. C. Dorrestein, and P. A. Pevzner. Dereplication of microbial metabolites through database search of mass spectra. *Nature Communications*, 2018.
- NumPy. Numpy official webpage, 2006. URL <http://www.numpy.org/>.
- D. Perkins and D. Pappin. Mascot, 1999. URL <http://www.matrixscience.com/>.
- P. Pevzner. *Computational Molecular Biology: An Algorithmic Approach*. MIT Press, 2000.
- P. Manikandan and D. Ramyachitra. PATSIM: Prediction and analysis of protein sequences using hybrid Knuth-Morris Pratt (KMP) and Boyer-Moore (BM) algorithm. *Elsevier Science*, 2018.
- Python 3. Python 3 official itertools documentation, 2008. URL <https://docs.python.org/3/library/itertools.html>.
- M. Röttig, M. H. Medema, K. Blin, T. Weber, C. Rausch, , and O. Kohlbacher. Automated Genome Mining of Ribosomal Peptide Natural Products. *American Chemical Society*, 2011.
- R. Smith, A. D. Mathis, D. Ventura, and J. T. Prince. Proteomics, lipidomics, metabolomics: a mass spectrometry tutorial from a computer scientist’s point of view. *BioMed Central*, 2014.
- Y. Song and A. Y. Chi. Peptide sequencing via graph path decomposition. *Elsevier Science*, 2015.
- Y. Song and M. Yu. On finding the longest antisymmetric path in directed acyclic graphs. *Elsevier Science*, 2015.
- T. Stachelhaus, H. D. Mootz, and M. A. Marahiel. The specificity-conferring code of adenylation domains in nonribosomal peptide synthetases. *Elsevier Science*, 1999.
- R. Thathoo, A. Virmani, S. S. Lakshmi, N. Balakrishnan, and K. Sekar. TVSBS: A fast exact pattern matching algorithm for biological sequences. *Current Science*, 2006.