

# **Repurposing Drugs for the Rapid Response to Epidemics and Pandemics**

## **Using Batch Active Learning**



**Ross Brown**

Department of Chemical Engineering and Biotechnology  
University of Cambridge

This dissertation is submitted for the degree of  
*Master of Engineering*

Robinson College

May 2022

I would like to dedicate this thesis to the loss of sleep never to be recovered. Its sacrifice in making this project come to fruition will never be forgotten.

## **Declaration**

The work described in this report is the result of my own research, unaided except as specifically acknowledged in the text, and it does not contain material that has already been used to any substantial extent for a comparable purpose. This report contains 39 pages and 9000 words (excluding this page, the title page, and the safety appendix).

Ross Brown

May 2022

## Abstract

The Sars-Cov-2 pandemic saw a high death toll which was reduced as drugs such as Remdesivir were introduced as treatments. This process was slow and few drugs were found capable of reducing the mortality of the virus. We present a solution to this issue: batch active learning on existing drugs. This combined greedy methodologies with clusterisations and uncertainty analysis. Algorithms were compared with each other, with the final algorithm learning the datasets at a 10% faster rate than simple randomly sampling.

# Table of contents

<b>Nomenclature</b>	<b>vi</b>
<b>1 Introduction</b>	<b>2</b>
<b>2 Previous Work</b>	<b>4</b>
2.1 Active Learning . . . . .	4
2.1.1 Current Data . . . . .	4
2.1.2 Estimated Future . . . . .	10
2.2 Batch Active Learning . . . . .	10
2.2.1 BatchBALD . . . . .	14
2.3 Drug Data for Machine Learning . . . . .	14
2.3.1 Physical Properties . . . . .	14
2.3.2 Fingerprints . . . . .	15
<b>3 Methodology</b>	<b>16</b>
3.1 Data . . . . .	16
3.2 Computational Methodology . . . . .	16
3.2.1 Model . . . . .	17
3.2.2 Scoring . . . . .	18
3.2.3 Active Learning Algorithms . . . . .	19
3.2.4 Parallelisation . . . . .	22
3.2.5 Minimisation . . . . .	22
<b>4 Results</b>	<b>23</b>
4.1 Non-Parametric . . . . .	23
4.1.1 Monte Carlo . . . . .	23
4.1.2 Greed . . . . .	24
4.1.3 Region of Disagreement . . . . .	25

4.2	Parametric . . . . .	26
4.2.1	Clusters . . . . .	26
4.2.2	Region of Disagreement with Greed . . . . .	29
4.2.3	RoDGeR . . . . .	30
<b>5</b>	<b>Discussion</b>	<b>32</b>
5.1	Non-Parametric . . . . .	32
5.2	Parametric . . . . .	33
5.3	Problem Sensitivity . . . . .	36
5.4	Refinement . . . . .	36
5.5	Link to Covid . . . . .	37
<b>6</b>	<b>Conclusion</b>	<b>38</b>
<b>References</b>		<b>39</b>

# Nomenclature

## Chapter 2

$N$	Number of features/dimensions of $x$
$s_g$	Sample standard deviation of the predictions
$x$	Data points where $x = \{x_0, x_1, \dots, x_{N-1}\}$
$y$	Labels for the dataset where $y = \{y_0, y_1, \dots, y_{N-1}\}$
$\text{AC}_{50}$	Half maximal effective molar concentration
$\text{EC}_{50}$	Half maximal effective molar concentration
$\text{IC}_{50}$	Half maximal inhibitory molar concentration
$\text{Ki}$	Half maximal molar concentration for half receptor occupancy

---

**Nomenclature****1**

$LD_{50}$  Median lethal dose

$XC_{50}$  Half maximal effective or inhibitory molar concentration

**Chapter 3**

$X_{\text{test}}$  Datasets used to provide a score for the algorithms

$X_{\text{train}}$  Datasets used for training the algorithms

$x_{\text{known}}$  Data points where the true label is available to the algorithms used

$x_{\text{unknown}}$  Data points where the true label is not available to the algorithms used

$y_{\text{known}}$  True labels available to the algorithms used

$y_{\text{unknown}}$  True labels unavailable to the algorithms used

$n$  The number of samples per iteration

**Chapter 4**

$N$  The number of datasets

# <sup>1</sup> Chapter 1

## <sup>2</sup> Introduction

<sup>3</sup> In 2019, human civilisation was on the precipice of a natural disaster: SARS-CoV-2  
<sup>4</sup> (COVID-19). First reported to the World Health Organization (WHO) on December 31st,  
<sup>5</sup> it became officially recognised as a pandemic on March 11th 2020. As of the writing of  
<sup>6</sup> this passage, 515 million cases and 18 million excess deaths have been recorded [Wan+22;  
<sup>7</sup> Wor22]. This, however, is not the first time a pandemic has occurred, with the Black Death  
<sup>8</sup> infamously killing a third of Europe's population and the Spanish Flu causing mass death  
<sup>9</sup> throughout the world. Likewise, it is unlikely to be the last.

<sup>10</sup> When such a disaster does strike, it is important to react quickly. Vaccinations are  
<sup>11</sup> developed and manufactured on accelerated timelines, cutting development time from years  
<sup>12</sup> to months. Trials into potential treatments are encouraged with haste. When speed is not  
<sup>13</sup> achieved with these measures, misinformation rapidly spreads. Within the first stages of the  
<sup>14</sup> pandemic, drugs such as hydroxychloroquine and bleach were amongst several that were  
<sup>15</sup> promoted by the President of the United States of America demonstrating the desperation in  
<sup>16</sup> finding therapeutic drugs against the virus.

<sup>17</sup> In order to facilitate a more robust approach to finding treatments, the FDA instigated the  
<sup>18</sup> Coronavirus Treatment Acceleration Program (CTAP) [Cen22]. Here, over 690 drugs are in  
<sup>19</sup> the development stage with over 450 clinical trials underway to investigate the effectiveness,  
<sup>20</sup> with 15 drugs currently authorised for emergency use and only one drug, remdesivir, with  
<sup>21</sup> approval for use against COVID-19 [Cen22]. These results, and the timescale in which  
<sup>22</sup> they were achieved, is suboptimal. This is due to the slow, labourious, methods used in  
<sup>23</sup> investigations into pre-existing drugs slow. Flawed selection priorities due to an information  
<sup>24</sup> overload on scientists. This resulted in delays in treatment. Time many did not have.

<sup>25</sup> A hopeful fulfilment of this problem is the "Robot Scientist" [Spa+10]; a fully automated  
<sup>26</sup> combination of software and hardware aimed at solving this problem. For the software

side, a form of reinforcement machine learning is proposed: batch active learning. This is a methodology suited to fields with large amounts of unlabelled data which is difficult to label. In this case, the labelling requires chemical and biological experimentation costing both time and money. By using active learning, as few drugs as possible will be labelled within this stage to accurately predict the best drugs for the given problem. From here, accelerated, targetted clinical trials may begin.

Due to the large importance of time, many drugs may be tested in parallel. This becomes even more practically considering the existence of robotic testing facilities. This presents an additional problem: how does one set up a testing scheme for batches? Can the same techniques used in single site learning be transitioned across, or are more inventive methodologies required here?

Thus, the purpose of this thesis. To present an algorithm which may be used to discover effective drugs within a short period of time. Additionally, a framework will be developed that allows for different algorithms to be rigorously compared to each other for increased robustness.

# <sup>1</sup> Chapter 2

## <sup>2</sup> Previous Work

<sup>3</sup> In order to assist the understanding of the methodologies used by others within the field of  
<sup>4</sup> active learning, a toy dataset has been created. It is based upon 2.1 and has been shown  
<sup>5</sup> in Figure 2.1. The  $y$  values used within the algorithms have been combined with errors,  
<sup>6</sup>  $\epsilon \sim \mathcal{N}(0, 0.01)$ .

<sup>7</sup>

$$y = \sin(x_0)^{10} + \cos(10 + x_0 x_1) \cos(x_0) \quad (2.1)$$

<sup>8</sup> In order to assess the algorithms, the mean squared error (mse) has been used. Compar-  
<sup>9</sup> isons are made to the naive approach of random sampling, i.e. Monte Carlo sampling. Each  
<sup>10</sup> algorithm will be given five random starting points, and attempted improvement will follow.

### <sup>11</sup> 2.1 Active Learning

<sup>12</sup> There are several schools of thought regarding active learning. These can be separated  
<sup>13</sup> into two distinct categories: current data and future predictions. The former of these is  
<sup>14</sup> computationally cheaper, more complex to implement, and less adaptable to model changes,  
<sup>15</sup> as will be apparent on description.

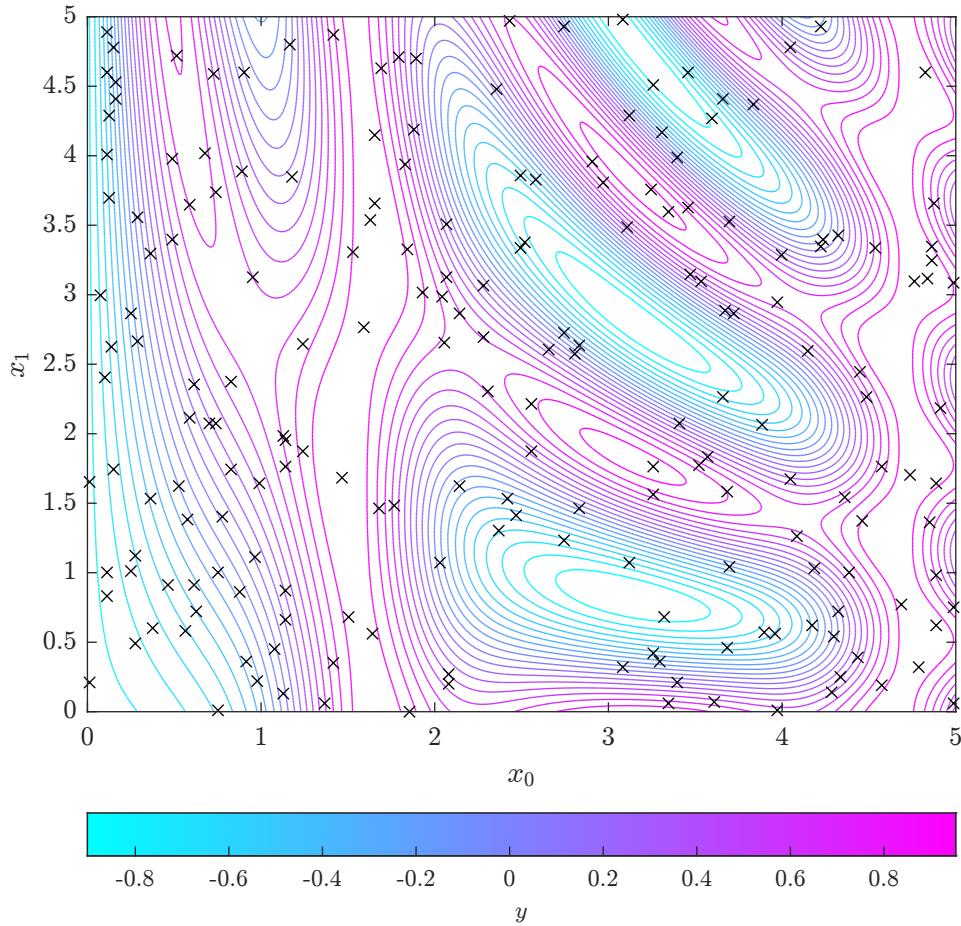
#### <sup>16</sup> 2.1.1 Current Data

##### <sup>17</sup> Uncertainty Sampling and Regions of Disagreements

<sup>18</sup> The simplest is applicable to cases in which a certainty is provided with each prediction.  
<sup>19</sup> Settles [Set09] suggests selecting the data point with the largest uncertainty according to the  
<sup>20</sup> current model. This has been shown with the toy dataset, as demonstrated in Figure 2.2.

## 2.1 Active Learning

## 5

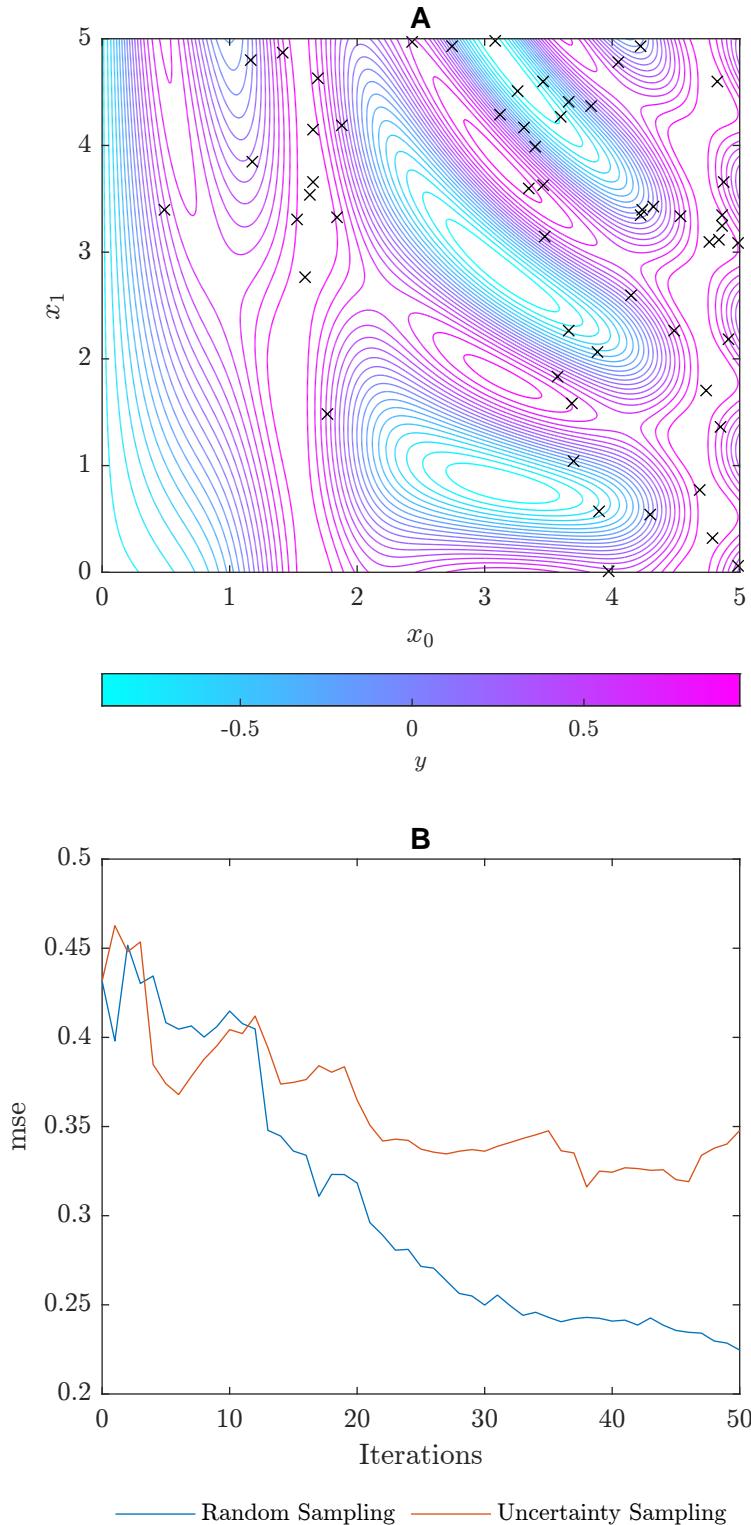


**Fig. 2.1** Contour plot of the function used to demonstrate the algorithms presented in previous work. The crosses have been used to show the location of the 200 test data points used within this example.

Interestingly, Figure 2.2B shows how the mean squared error for the random sampling method performed to worse within the iterations tested. This is likely due to a bias in the use of linear models in fitting leading to large uncertainties surrounding areas with high curvature. Evidence to this is provided in Figure 2.2A with a large proportion of the sampled points at areas of high curvature.

$$x_{\text{next}} = \underset{X}{\operatorname{argmax}} [s_{g(X)}] \quad (2.2)$$

As addressed by Settles [Set09], this can be extended to any probabilistic model through 7  
2.2. Settles [Set09] also notes the use of information theory for probabilistic models(2.3), 8



**Fig. 2.2** The outcome of the investigating the areas of the highest uncertainty. An initial set of 5 random points was provided, and 50 further iterations were then carried out of sample size 1. A) Demonstrates the final set of points tested by the algorithm and B) shows the change in the mean squared error for the algorithm after each iteration.

## 2.1 Active Learning

7

where  $y^* = \operatorname{argmax}_y P(y|x; \theta)$  is the most likely  $y$  for  $x$ . This derives from the principle that the greatest entropy requires the most information to encode, and thus the least certain. However, Settles [Set09] fails to address non-probabilistic models in this instance, instead converting such models into probabilistic ones.

$$x_{\text{next}} = \operatorname{argmax}_x [P(y^*|x; \theta)] \quad (2.3) \quad 5$$

In order to adapt non-probabilistic models into probabilistic ones, composite models may be used. These are an amalgamation of other models where the standard deviation of the individual models can be taken as the degree of certainty for a given point. This is commonly referred to minimising the region of disagreement, referring the spaces of discord within the hypothesis space. By minimising the region of disagreement between various models, a more coherent hypothesis space is sought leading to a more accurate model. Indeed, this was the method used in Figure 2.2. Mathematically, a set of  $n$  models  $M = \{m_0, \dots, m_{n-1}\}$ , with each model offering a prediction of  $\hat{m}_i$ ,  $\hat{M} = \frac{1}{n} \sum \hat{m}_i$ , and the sample standard deviation of  $\hat{m}$  giving the uncertainty.

Settles [Set09] suggests third way of interpreting uncertainty. By taking the approach from information theory, 2.4 is settled upon. This directly states gives the point of the highest entropy, suggesting by knowing the point provides the largest information gain. Notably however, this is difficult to implement with most models, as a probability distribution is required. This could be made simpler by approximating to a normal distribution.

$$x_{\text{next}} = \operatorname{argmax}_x \left[ \phi_A(x) \times \left( \frac{1}{U} \sum \operatorname{sim}(x, x_i) \right)^\beta \right] \quad (2.4) \quad 20$$

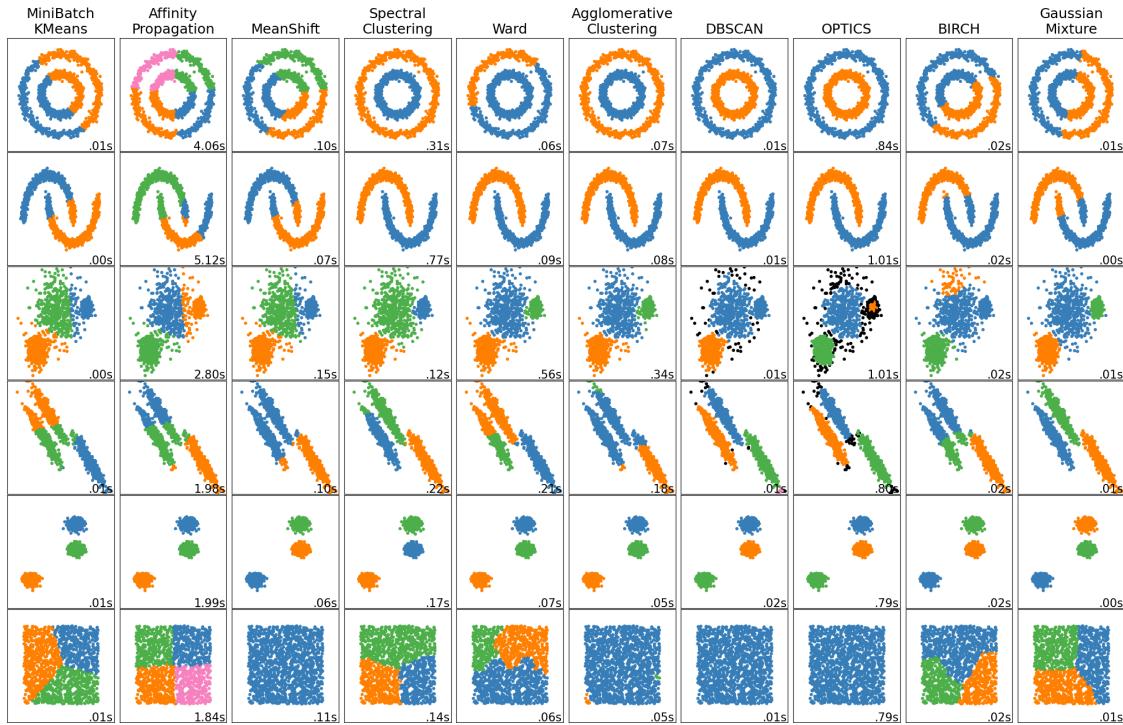
**Density Hotspots**

Conversely, a density weighted model has been suggested, as it escapes the introduction of error from outliers (i.e. data points far away from alternative data points). Settles and Craven [SC08] suggest (2.5) which can be broken down into two parts: a function for selection,  $\phi_A$ , and a function for similarity,  $\operatorname{sim}$ . The former arises from another method described in this section. The latter requires a function to describe the similarity between data points.

$$x_{\text{next}} = \operatorname{argmax}_x \left[ \phi_A(x) \times \left( \frac{1}{U} \sum \operatorname{sim}(x, x_i) \right)^\beta \right] \quad (2.5) \quad 27$$

Settles and Craven [SC08] admit that  $\operatorname{sim}$  is open for interpretation. It must also be recognised that this lays the foundation of a clusterisation algorithm. There exist many forms

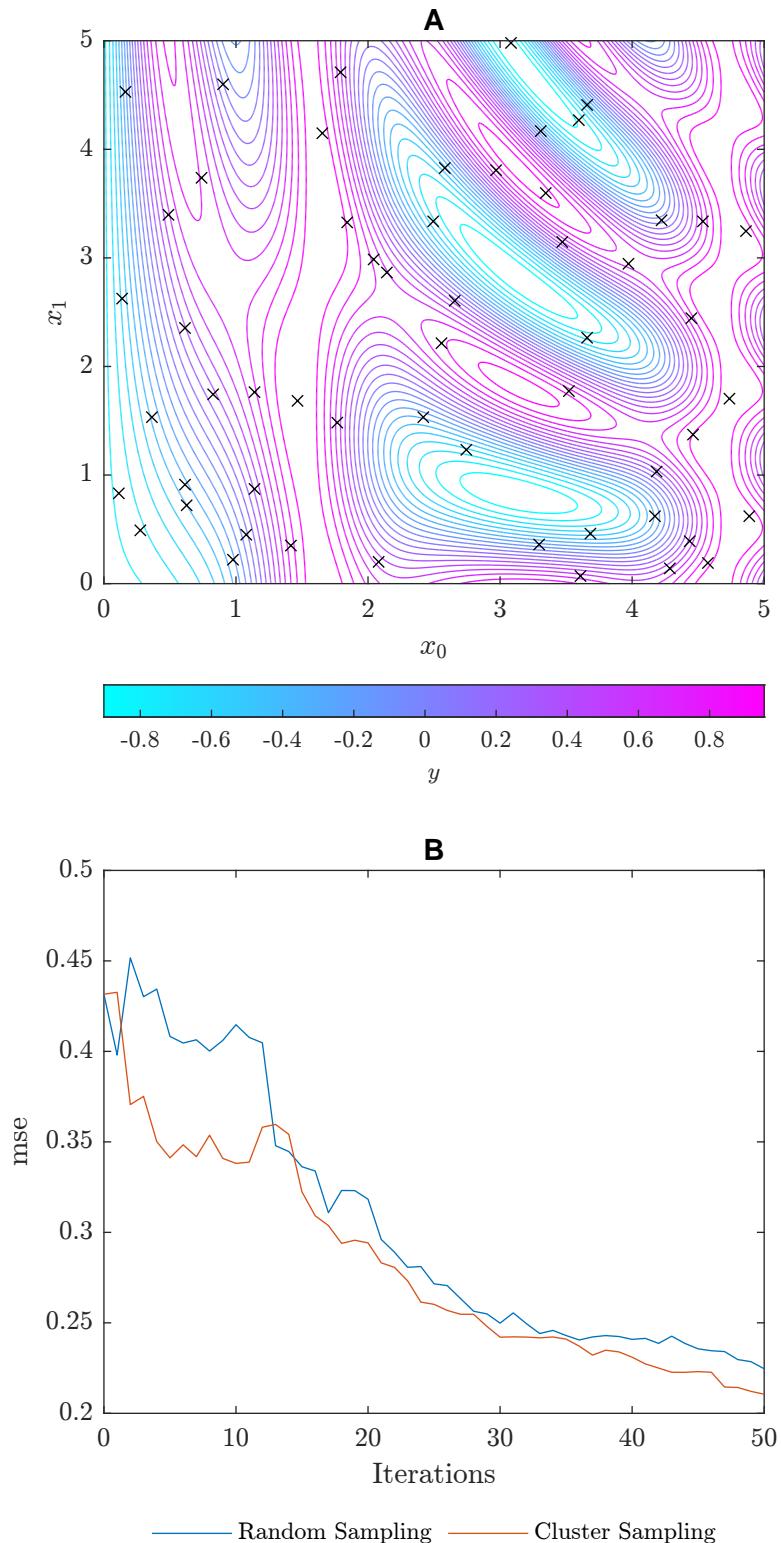
of these algorithms, with the results of several of these algorithms on toy data sets presented in Figure 2.3 [Sci].



**Fig. 2.3** Clusterisation algorithms used on sample two-dimensional data sets to demonstrate resultant clusters.

As Figure 2.3 demonstrates, there are multiple different interpretations of the solution to the problem of clustering. The makers of the Scikit learn package also discuss the scalability of each algorithm [Sci]. In order to prepare a high number of features (beyond the two used within this section for demonstration) and large number of data points, it is required that the algorithm scales accordingly. Further, for an adaptive process, it is more suitable for an algorithm to be adaptive to differing distribution. This limits the suitable algorithms to K-Means, Ward and Birch - columns one, five, and nine of Figure 2.3 respectively. Results for Birch can be seen in Figure 2.4. This appears do well, although it must be noted that this is likely due to the similarity between Monte Carlo (random) sampling, and clusterisation. I.e. areas distant from previously gathered points face a high chance of sampling.

## 2.1 Active Learning



**Fig. 2.4** The outcome of the investigating the areas of using a cluster hotspot sampling methodology. An initial set of 5 random points was provided, and 50 further iterations were then carried out of sample size 1. A) Demonstrates the final set of points tested by the algorithm and B) shows the change in the mean squared error for the algorithm after each iteration.

**2.1.2 Estimated Future**

These methods attempt to minimise a future attribute of the model. This works by predicting changes given with the inclusion of more data with a higher degree f theoretical underpinning that the sampling methods discussed thus far.

**5 Expected Model Change**

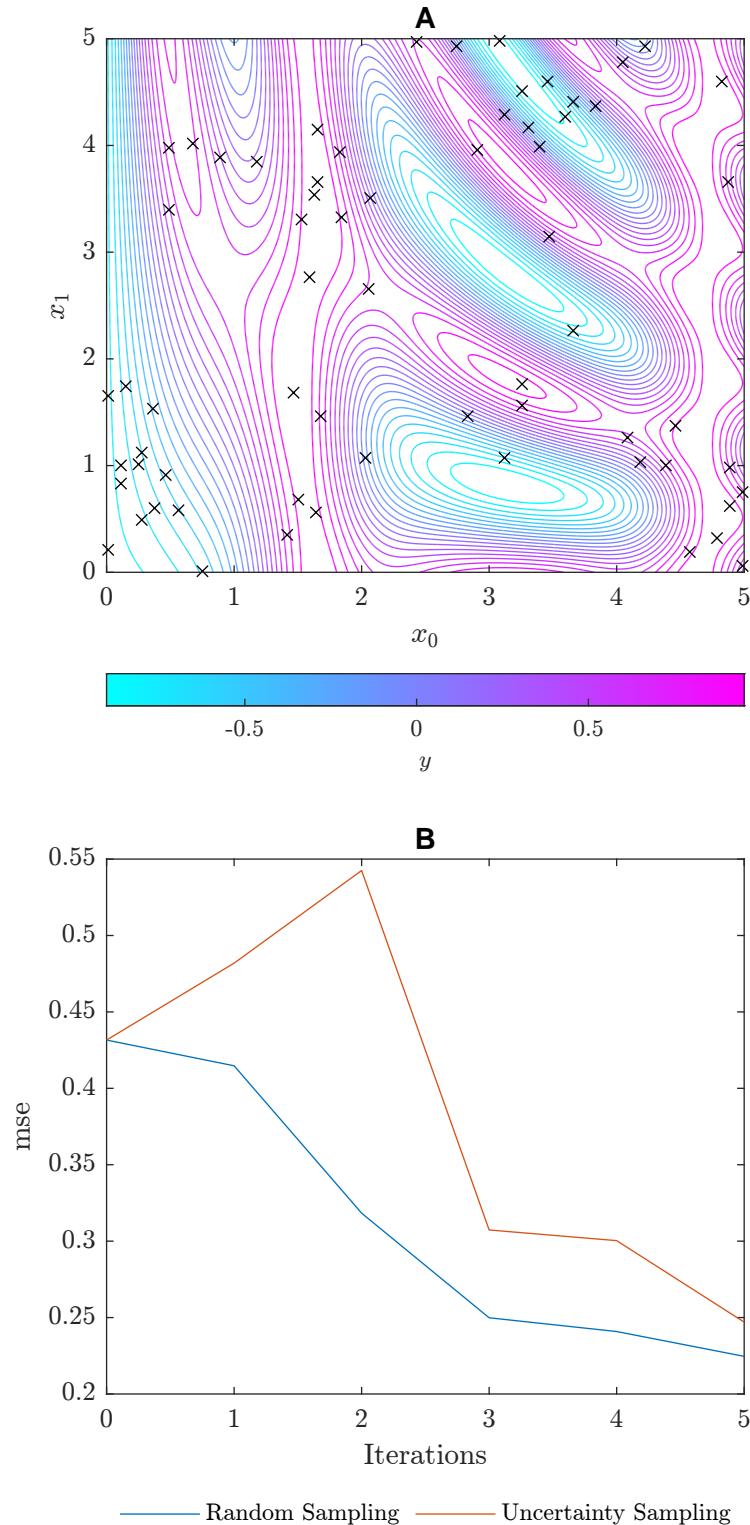
As the name implies, this method chooses points which are likely to have the largest impact on the final model. By instigating each potential point, the impact on the eventual model can be found. However, this requires a method for quantifying the model change.

Settles and Craven [SC08] and Settles [Set09] investigate models which can be trained "online": i.e. models which can use the previous iteration to reduce the time taken for convergence. They present a method called "Expected Gradient Length" (EGL) which has a couple of prerequisites: **1)** A probabilistic model is used **2)** Linear gradient based optimisation is used **3)** The model can be improved from previous iterations. Given these prerequisites, the problem becomes less computationally inexpensive given a small dataset or extensive parallelisation, and scales as  $\mathcal{O}(n)$ . However, it does have the distinct drawback of requiring close control of the data models used. Here, the length of the training gradient (the gradient used in re-fitting the parameters with gradient based optimisation) can be used as a measure of model change. In the case of a small model change, as is expected, the length of the training gradient can be written as  $\|\nabla l(\langle x, y_i \rangle; \theta)\|$ . Combining this with the probability distribution of  $y$ , the next sample to undergo labelling is given by 2.6.

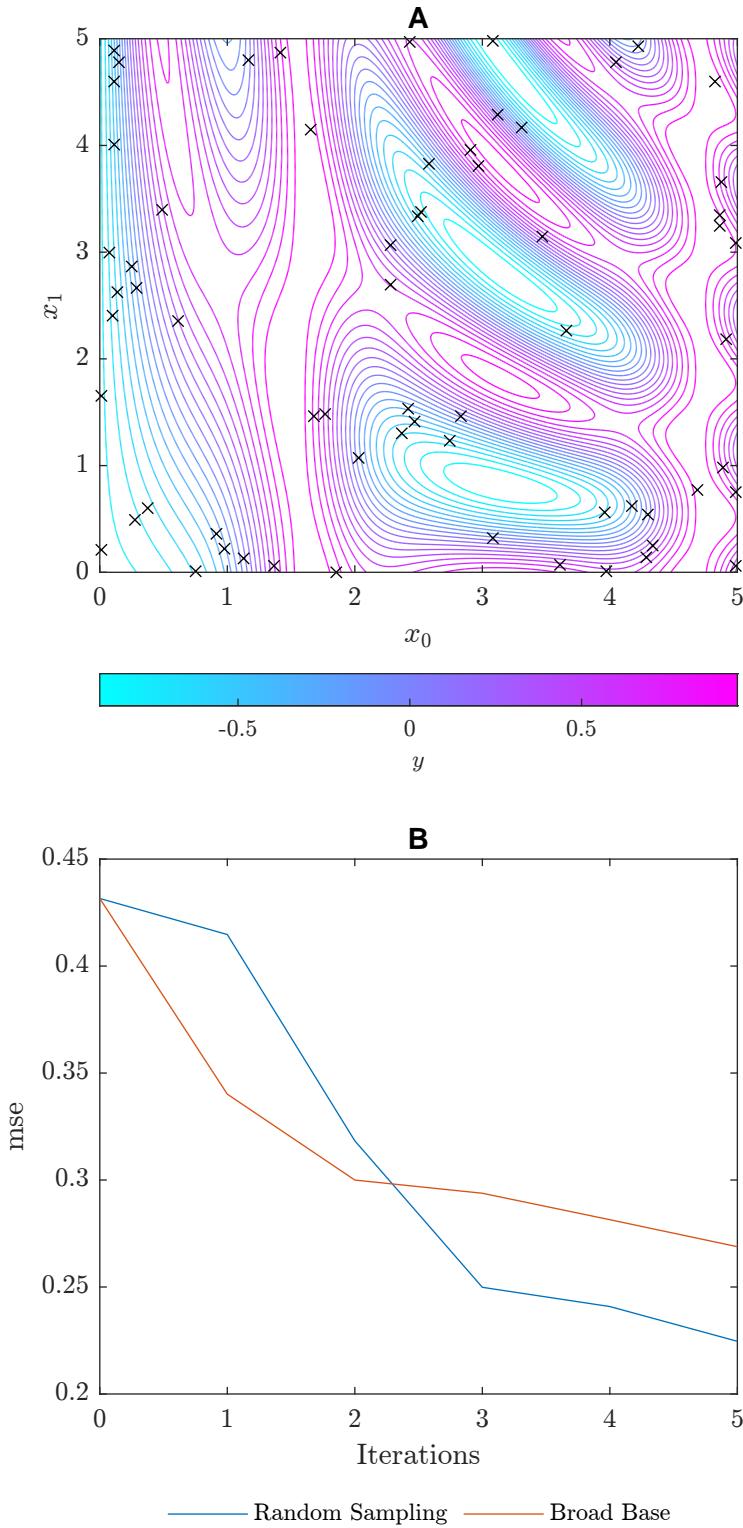
$$x_{EGL}^* = \operatorname{argmax}_x \sum_i P(y_i|x; \theta) \|\nabla l(\langle x, y_i \rangle; \theta)\| \quad (2.6)$$

**2.2 Batch Active Learning**

Little literature exists with respect to batch active learning. Naive implementation exist whereby the methods explored earlier present a stack of data points to be chosen, and the top  $N$  are used. However, this method does not take into account the equivalence of the data points. This can be seen by the formation of clusters within the broad and uncertainty sampling methods, although it is not present within the clusterisation algorithm.



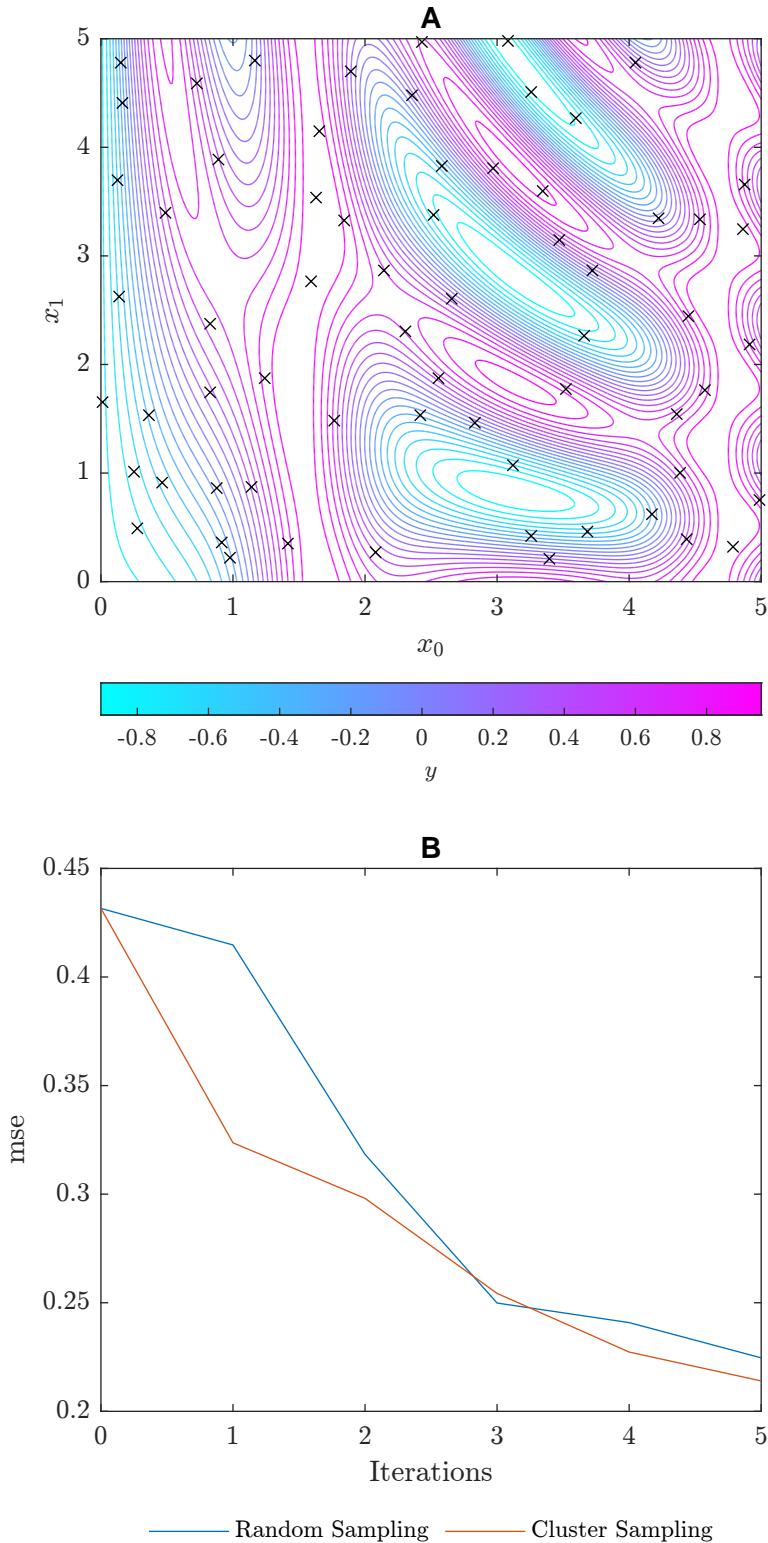
**Fig. 2.5** The outcome of the investigating the areas of using uncertainty sampling. An initial set of 5 random points was provided, and 5 further iterations were then carried out of sample size 10. A) Demonstrates the final set of points tested by the algorithm and B) shows the change in the mean squared error for the algorithm after each iteration.



**Fig. 2.6** The outcome of the investigating the areas of using broad-base sampling. An initial set of 5 random points was provided, and 5 further iterations were then carried out of sample size 10. A) Demonstrates the final set of points tested by the algorithm and B) shows the change in the mean squared error for the algorithm after each iteration.

## 2.2 Batch Active Learning

## 13



**Fig. 2.7** The outcome of the investigating the areas of using cluster sampling. An initial set of 5 random points was provided, and 5 further iterations were then carried out of sample size 10. A) Demonstrates the final set of points tested by the algorithm and B) shows the change in the mean squared error for the algorithm after each iteration.

It stands to reason that the area which has the highest uncertainty will see this for the data points nearest neighbours. Thus, this singular data point suffers the potential of being surrounded by  $N - 1$  other data points. The benefit this provides in fitting the model is thus extremely limited, and only slightly greater than if one data point had been chosen. A simple fix would be to simulate the model after 1 iteration, and select the next point from here. By doing this  $N - 1$  times, a better solution may be found, although this may prove to be computationally expensive.

### 2.2.1 BatchBALD

Kirsch, Amersfoort, and Gal [KAG19] propose an algorithm named BatchBALD (Batch Bayesian Active Learning by Disagreement). Demonstrating for sample size of 10 an improvement compared to random sampling in optical character recognition. In doing so, they use complex Bayesian Neural Networks and apply the problem to categorical data.

## 2.3 Drug Data for Machine Learning

There are numerous data categories that can be used to represent a chemical in a suitable form for machine learning. Indeed, the field of chemoinformatics is dedicated to the pursuit of describing chemicals for computational models. Each of these methods have various strengths and weaknesses. Some are directly based upon the chemical structure whereas others are based upon physical properties. These can be combined to produce models with high predictive capabilities.

### 2.3.1 Physical Properties

A selection of physical properties from chemicals are known, from melting points to solubility. Many of these provide important aspects for consideration and allow human scientists to predict interactions, especially when determining new drugs. These data are often reported in tables within textbooks such as Perry's Chemical Engineering Handbook or provided through software [EMB09; GS18].

Several of these data can be predicted through theoretical models, although the difficulty increases for larger molecules. For example, models exist for density predictions, but predicting the LD<sub>50</sub> of a drug is far more challenging task. Indeed, even with animal testing, this property is deemed difficult to truly assess.

Within drug discovery, physical and biological properties are usually the sought after labels. An example of this is supplied by EMBL-EBI [EMB09] with a custom property named pChEMBL, as defined by 2.7 where "l" is synonymous with "or". Values are expected to be between 2 and 12, although these are not limited. Indeed, values even be negative, although this is rare and unlikely.

$$\text{pChEMBL} = -\log_{10} (\text{IC}_{50} | \text{XC}_{50} | \text{EC}_{50} | \text{AC}_{50} | \text{Ki} | \text{LD}_{50} | \text{Potency}) \quad (2.7)$$

### 2.3.2 Fingerprints

Another methodology is to develop a fingerprint: a unique code based on the chemical structure, either of the atomic arrangement, or by the electron cloud distribution. The latter of these is more fundamental to the activity of molecules but far harder to calculate. Indeed, for accurate representation of the latter, both atomic structure is needed *and* solutions for the Schrödinger equations corresponding to molecule in question.

According to Capecchi, Probst, and Reymond [CPR20], the most popular fingerprint in use are Morgan Fingerprints, a form of Extended Chemical Fingerprint (ECFP). ECFPs use a simple algorithm in order to generate a unique identifier, as described by Rogers and Hahn [RH10]:

1. **Initial Assignment:** Each atom has an integer assigned as an identifier.
2. **Iterative Updating:** Updating the identifier assigned to atoms based on adjacent atoms and structural duplications.
3. **Duplicate Removal:** Duplicate features are removed for hashing.

The iteration process involves each atom and adjacent atoms sharing numbers before in an array. A hash function is applied to this array and becomes the atoms new identifier. Fingerprints of this class are labelled according to the number of iterations,  $n$ , with the final name given as  $\text{ECFP}_{\langle 2n \rangle}$ . Morgan fingerprints, the most common form, are thus also called  $\text{ECFP}_4$  [CPR20; RH10]. Thus, these come under the remit of fingerprints based upon two-dimensional chemical structure, rather than three-dimensional or even electron distribution. Morgan fingerprints are readily available for millions of compounds from the publicly accessible ChEMBL database [EMB09].

# <sup>1</sup> Chapter 3

## <sup>2</sup> Methodology

### <sup>3</sup> 3.1 Data

<sup>4</sup> Each dataset used consists of a 1024-bit Morgan fingerprint for the features and these  
<sup>5</sup> associated pChEMBL values. The sets used for parameter fitting and score reporting make  
<sup>6</sup> up a set of 2094 files from EMBL-EBI [EMB09]. These were filtered to prevent datasets  
<sup>7</sup> with fewer than 1000 entries to be admitted into the main script. Columns were added with  
<sup>8</sup> the scoring limits, as will be discussed later within the chapter. Consideration was given  
<sup>9</sup> to reducing larger datasets to 1000 data points, although this notion was disregarded as the  
<sup>10</sup> data was seen as too valuable to ignore. The data sets used within the scripts is given at  
<sup>11</sup> [https://github.com/rjb255/researchProject/tree/master/data/big/qzar\\_with\\_lims](https://github.com/rjb255/researchProject/tree/master/data/big/qzar_with_lims).

<sup>12</sup> Morgan fingerprints were chosen due to the ease in which it is to calculate the vectors, the  
<sup>13</sup> popularity of them within the chemoinformatics sphere, and the success enjoyed by others  
<sup>14</sup> when using them for predictive purposes. It was decided that physical properties would not  
<sup>15</sup> be used as this could increase the onus on data sanitation and preparation rather than active  
<sup>16</sup> learning, although it is unavoidable using physical data for the labels. Here, pChEMBL, as  
<sup>17</sup> defined in 2.7, is used due to comparability and easy interface with EMBL-EBI [EMB09].

### <sup>18</sup> 3.2 Computational Methodology

<sup>19</sup> The methodology presents a novel means of assessing different parametrised batch active  
<sup>20</sup> learning methods on existing data sets, allowing for a robust answer into the use of active  
<sup>21</sup> learning in drug rediscovery. Results can thus be given with a given belief. This approach  
<sup>22</sup> has taken principles commonly used in machine learning and applied it to more traditional

algorithmic methods. Python was used as the scripting language, with the codebase provided at <https://github.com/rjb255/researchProject/tree/master/purePython>.

Firstly, a collection of pre-existing data sets,  $X$ , are used.  $X$  is then split into two sub sets:  $X_{\text{train}}$  and  $X_{\text{test}}$ . Similarly to classical machine learning methods, the former of these subsets is used in fitting the parameters of the equation, and the latter is used to provide a result without the risk of data leakage into the training set. Parallelisation is used to efficiently train the algorithms, allowing the time for training to be  $\sim \mathcal{O}(c)$  provided an unrestricted number of processors. Datasets used have at least 1000 entries resulting in 164 datasets used for training, and a further 42 used for testing.

Examining the smaller details, each algorithm is provided with the sets  $x_{\text{known}}$ ,  $y_{\text{known}}$ , and  $x_{\text{unknown}}$ . Various algorithms are given these sets and allowed to generate a subset of  $x_{\text{unknown}}$  to be added into  $x_{\text{known}}$  alongside corresponding  $y_{\text{known}}$ . This can then repeat until a predefined stopping point is reached. Scores are reported using a weighted mean squared error [] based upon  $y_{\text{predict}}$  for all  $x$ . This is similar to a standard machine learning methodology with a couple of differences. Firstly, no distinction is made between the training and testing set within a dataset contrary to standard practice. This is due to two reasons. Firstly, the datasets are not large enough for an accurate representation of the data within the testing set, and secondly, the scoring to each dataset is not used within the machine learning algorithms to fit parameters as is usually the case. All algorithms used rely upon a simple custom composite model to allow for flexibility and consistency.

### 3.2.1 Model

The machine learning model is the only custom class used. Here, a similar structure is used when compared with Scikit's machine learning [Ped+], as is demonstrated in Table 3.1. To manage this, it has four methods: `__init__`, `fit`, `predict`, and `predict_error`. The last of these is not seen in all Scikit's machine learning models and is usually reserved for those which can report a certainty of prediction. Here, this was achieved by taking a standard deviation of the models.

		Name	Description
Attributes	Models: List	List of models to be used in composite	
	fit(X: int[][][], Y: double[][])	Fits the models in Models	
Methods	predict(X: int[][][]): double[]	Takes a set of labels and returns mean predicted label from all the models.	
	predict_error(X: int[][][]): double[][][]	Takes a set of labels and returns the mean predicted label from all the models and standard deviations of model predictions.	

**Table 3.1** Schema for the Model Class.

<sup>1</sup> The models used for the composite model were Bayesian-ridge, k-nearest neighbours,  
<sup>2</sup> random forest regressor, stochastic gradient descent regressor with Huber-loss, epsilon-  
<sup>3</sup> support vector regression, and AdaBoost regressor [Ped+]. This was kept consistent during  
<sup>4</sup> testing, allowing for direct comparison of the algorithms without influence from model  
<sup>5</sup> selection.

### <sup>6</sup> 3.2.2 Scoring

<sup>7</sup> This method implements a weighted mean squared error (wmse) given in 3.1 where  $w$  is a  
<sup>8</sup> normalization of the true label such that  $\sum w_i = 1$  and  $0 \leq w_i \leq 1$ . Further modification to  
<sup>9</sup> this ensures the base case with five data points provides a score = 1 and the score if the entire  
<sup>10</sup> dataset is modelled provides a score = 0.

$$\text{wmse} = \frac{1}{n} \sum_{i=0}^{n-1} w_i (y_i - \bar{y})^2 \quad (3.1)$$

<sup>11</sup> This achieves several goals. Firstly, it targets the higher values of pChEMBL, as these  
<sup>12</sup> are the most beneficial for drug development. Secondly, it reduces the natural spread in  
<sup>13</sup> results for datasets, preventing those poorly capable of being predicted the model from  
<sup>14</sup> displacing results from the algorithm. Finally, it allows the results to be given as a fractional  
<sup>15</sup> improvement instead. It allows a target of "85%" prediction to be given for stopping criteria  
<sup>16</sup> if desired.  
<sup>17</sup>

### 3.2.3 Active Learning Algorithms

The algorithms tested are all provided with  $x_{\text{known}}$ ,  $y_{\text{known}}$ ,  $x_{Y_{\text{unknown}}}$ , a model fitted to  $x_{\text{known}}$  and  $y_{\text{known}}$ , and a memory object to allow for information kept over iterations is required. This is useful for clusterisation, where online training is possible. It is within the memory object where parameters may also be provided. As a result, it is impossible for the suppressed  $y_{Y_{\text{known}}}$  to influence an algorithms scoring process. The algorithms then return a list in the same order as  $y_{\text{unknown}}$ , with the lowest scores designating higher priority in sampling. This allows uniformity across algorithms and the amalgamation of different algorithms without the duplication of code.

#### Monte Carlo

The Monte Carlo algorithm employs random sampling. This represents the least computationally expensive approach, and is thus used as a baseline in comparing other algorithms. Since the datasets are shuffled prior to being used, the algorithm is extremely simple, as demonstrated in Algorithm 1.

---

**Algorithm 1:** Monte Carlo Sampling
 

---

**Data:**  $X_{\text{unknown}}$

**Result:** An array of priority-scores for sampling

**return** ones\_like( $X_{\text{unknown}}$ )

---

#### Greed

Since the largest activity is sought, a methodology proposed is to simply seek the predicted highest label. Here, the predict() method (see Table 3.1) was used to return a prediction and a standard deviation. The indices of  $x_{\text{unknown}}$  were then returned, ordered descending with respect to the afore mentioned standard deviations. The algorithm used is given in Algorithm 2.

---

**Algorithm 2:** Greed Sampling Selection
 

---

**Data:**  $X_{\text{known}}$ ,  $Y_{\text{known}}$ ,  $X_{\text{unknown}}$ , Model

**Result:** An array of priority-scores for sampling

Model.fit( $X_{\text{known}}$ ,  $Y_{\text{known}}$ );

prediction = Model.predict\_error( $X_{\text{unknown}}$ );

**return** -prediction

---

---

## **1 Region of Disagreement**

2 Similarly to the Greed algorithm, **Region of Disagreement** (ROD) is a very simple algorithm.  
 3 Here, the predict\_error() method (see Table 3.1) is used to return a prediction and a standard  
 4 deviation. The prediction is ignored, and instead the standard deviation is returned, mul-  
 5 tiplied by  $-1$  to ensure the largest uncertainty has the lowest "score". This is shown with  
 6 Algorithm 3.

---

### **Algorithm 3:** RoD Sampling Selection

---

**Data:**  $X_{\text{known}}$ ,  $Y_{\text{known}}$ ,  $X_{\text{unknown}}$ , Model

**Result:**  $X$  ordered according to priority for sampling

```
7 Model.fit( $X_{\text{known}}$ ,  $Y_{\text{known}}$ );
_, error = Model.predict_error( $X_{\text{unknown}}$ );
return -error
```

---

## **8 Hotspot Clusters**

9 Three clustering algorithms were trialled, all based upon the ideology presented in Sec-  
 10 tion 2.1.1. The function shared by all three algorithms is shown in Algorithm 4. Here,  $c$  is  
 11 the number of clusters sought, and is a parameter that requires fitting. Bounds can be placed  
 12 upon this. The lower limit can be set as the number of known data points, and the upper as  
 13 the total number of data points in the data set, although it is hypothesised that beyond the  
 14 sum of the known points and the samples sought would make little, to no difference. To test  
 15 this hypothesis, the upper limit will be set at  $\text{len}(X_{\text{unknown}}) + 1.5n$ . The combined limits have  
 16 been shown in 3.2.

$$17 \quad \text{len}(X_{\text{known}}) < c < \text{len}(X_{\text{unknown}}) + 1.5n \quad (3.2)$$

**Algorithm 4:** Uncertainty Sampling Selection**Data:**  $z_{\text{known}}$ ,  $z_{\text{unknown}}$ ,  $c$ **Result:** Score of datapoints

```

combined_z = concat(zknown, zunknown);
clusters = cluster(number_of_clusters=c);
clusters.fit(combined_z);
predicted_clusters = clusters.predict(zunknown);
distances = clusters.distance_to_nearest_centroid(zunknown);
indicies = zknown.index;
sorted_indicies = sort(indicies -> By cluster size followed by distance to centroid) ;
high_priority, low_priority = split(sorted_indicies, if cluster contains zknown);
high_priority.riffle();
low_priority.riffle();
order = join(high_priority, low_priority);
return -error

```

Several key steps are involved within the algorithms to fit to the ideology. Firstly, clusters containing samples from  $x_{\text{known}}$  are given lower priority. These are perceived as known clusters so ideally would not undergo further testing. Secondly, the sorting needs to be addressed. Here, the sample is sorted into the relevant cluster groups. These groups are then ordered by size, with larger cluster favoured. Samples within the cluster are sorted by distance to the equivalent centroid. The clusters are then split into those containing sampled points and those that do not. With each of these groups, a riffling procedure is used. Named after the common card shuffling technique, this ensures the priority is given to different clusters, with the highest priority going to the point from the most populated cluster, and closest to the centroid. The two groups of clusters are then concatenated.

The three versions of clusterisation differ by the  $z$  provided. In Cluster I,  $z \equiv x$ , whereas in Cluster II,  $y_{\text{known}}$  and  $y_{\text{unknown}}$  is joined to  $x_{\text{known}}$  and  $x_{\text{unknown}}$  respectively. Cluster III takes this a step further by combining  $s_{g_{\text{unknown}}}$  into  $z_{\text{unknown}}$  with 0 being the equivalent value used for  $z_{\text{known}}$ .

**Region of Disagreement with Greed**

The first composite algorithm explored is **Region of Disagreement with Greed** (RoDG), combining both the greedy sampling, and the uncertainty sampling algorithms. This metric is shown in 3.3.

$$1 \quad \text{score}_{\text{greedy}\&\text{uncertainty}} = \text{score}_{\text{greedy}}^{\alpha} \text{score}_{\text{uncertainty}}^{1-\alpha} \quad (3.3)$$

2        Here,  $\alpha$  is a parameter which needs to be found, bounded as  $0 < \alpha < 1$ . Note here that at  
 3        the limits, the algorithm reduces to the RoD and Greed algorithms.

4        **Region of Disagreement with Greed and Clustering**

5        **Region of Disagreement with Greed and Clustering (RoDGER)** is a second order composite  
 6        function, involving RoD with Greed and Cluster III, as shown in 3.4.

$$7 \quad \text{score}_{\text{RoDGER}} = \text{score}_{\text{ClusterIII}}^{\alpha} \text{score}_{\text{RoDG}}^{1-\alpha} \quad (3.4)$$

8        Both of the constituent algorithms are parameterised, implying a total of three parameters.  
 9        Bounds on initial estimates will be provided by the results of these algorithms taken  
 10      individually.

11      **3.2.4 Parallelisation**

12      The large number of datasets used presents a problem: time. Indeed, each iteration sees a new  
 13      fitting of a machine learning model. Within the training stage, this would correspond to a  
 14      minimum of 1000 models trained: a considerable number. Thus, by exploiting parallelisation,  
 15      the time can be reduced in execution to the case, where given an infinite number of processes,  
 16      the training and testing framework would scale as  $\mathcal{O}(c)$ . This requires circumventing pythons  
 17      global interpreter lock, accomplished using Pathos due to several shortcomings found with  
 18      the default multiprocessing package [McK+12; MA10].

19      **3.2.5 Minimisation**

20      Due to the available parallelisation, only one iteration was performed in minimisation. This  
 21      approach consisted of generating a uniform distribution of test parameters, testing upon the  
 22      datasets in one parallelised step, and selecting the best performing parameter combination.

# Chapter 4

## Results

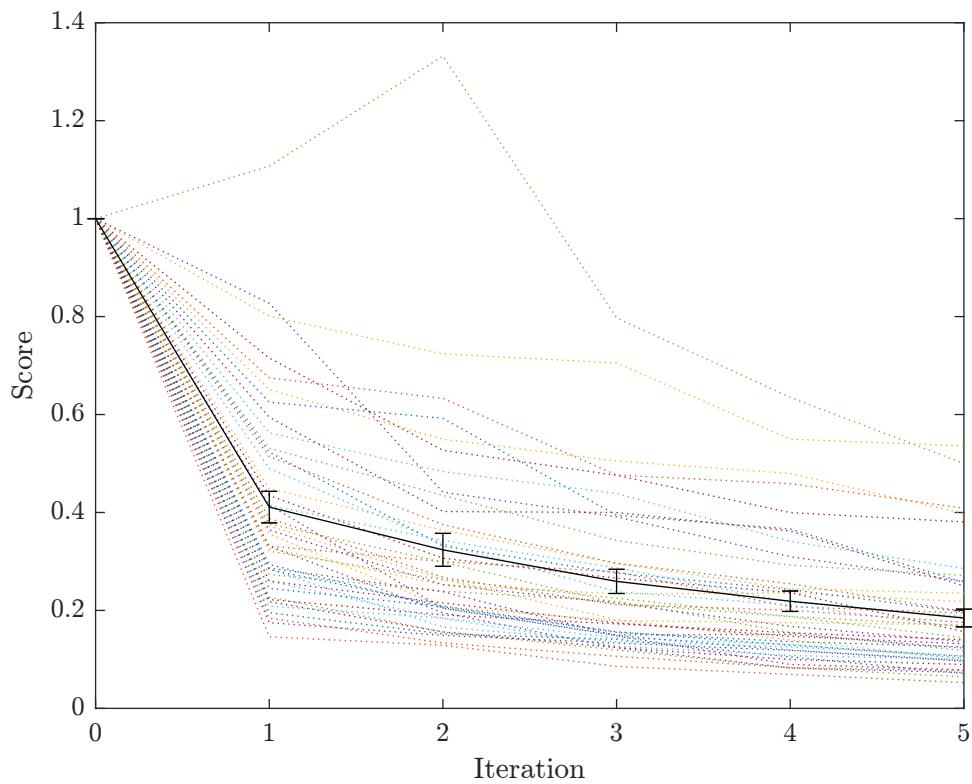
Results are presented for the algorithms discussed in Chapter 3. Where possible, errors have been provided by taking the sample standard deviation of the results provided and dividing by  $\sqrt{N - 1}$ . This allows for robust discussion and comparison of each method used. Within figures, lines are added to guide the eye to changes.

### 4.1 Non-Parametric

Non-parametric equations have the benefit of not requiring the minimisation function. Due to this, all testing of these algorithms were undertaken on a standard laptop. These also tend to be the easiest to implement, as uncovered in Chapter 3. Particularly important is the Monte Carlo method as this allows shows what should be a minimum baseline to achieve.

#### 4.1.1 Monte Carlo

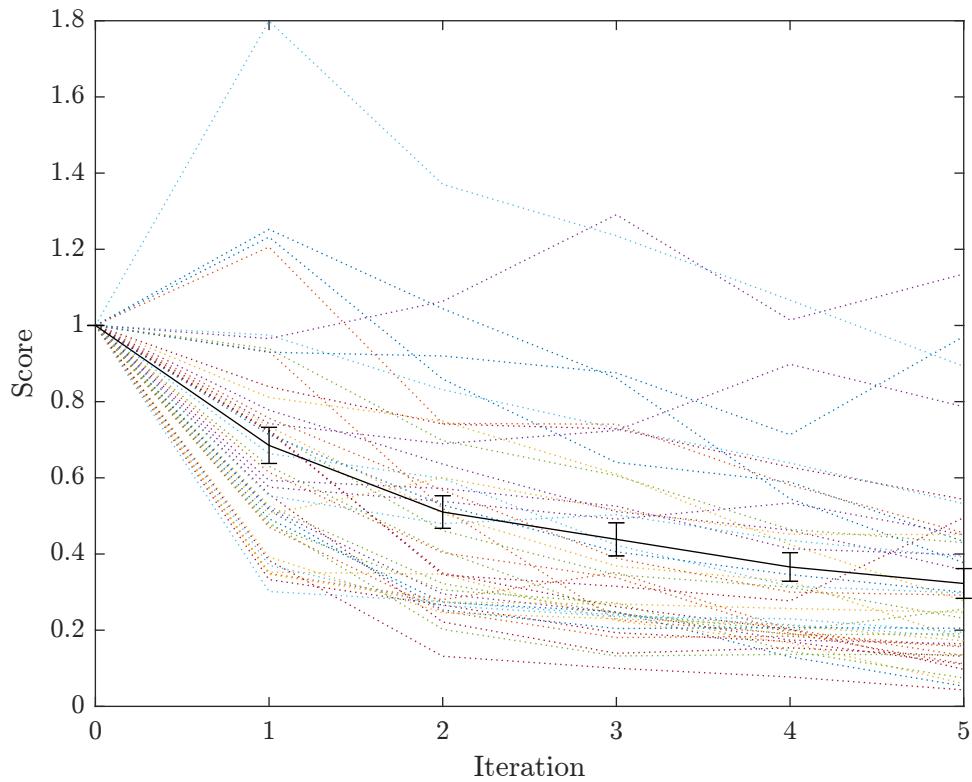
The first non-parametrised algorithm discussed in Chapter 3 was the Monte Carlo method. Due to the non-parametric nature of this algorithm, execution was simply carried out on the test data set. Results are presented in Figure 4.1, demonstrating a final score of  $0.184 \pm 0.018$ .



**Fig. 4.1** Results of Monte Carlo sampling on the test datasets. Dotted lines represent the individual scoring for the data sets and the solid line shows the mean results at each iteration with error bars of  $\frac{\sigma}{\sqrt{n-1}}$ .

### <sup>1</sup> 4.1.2 Greed

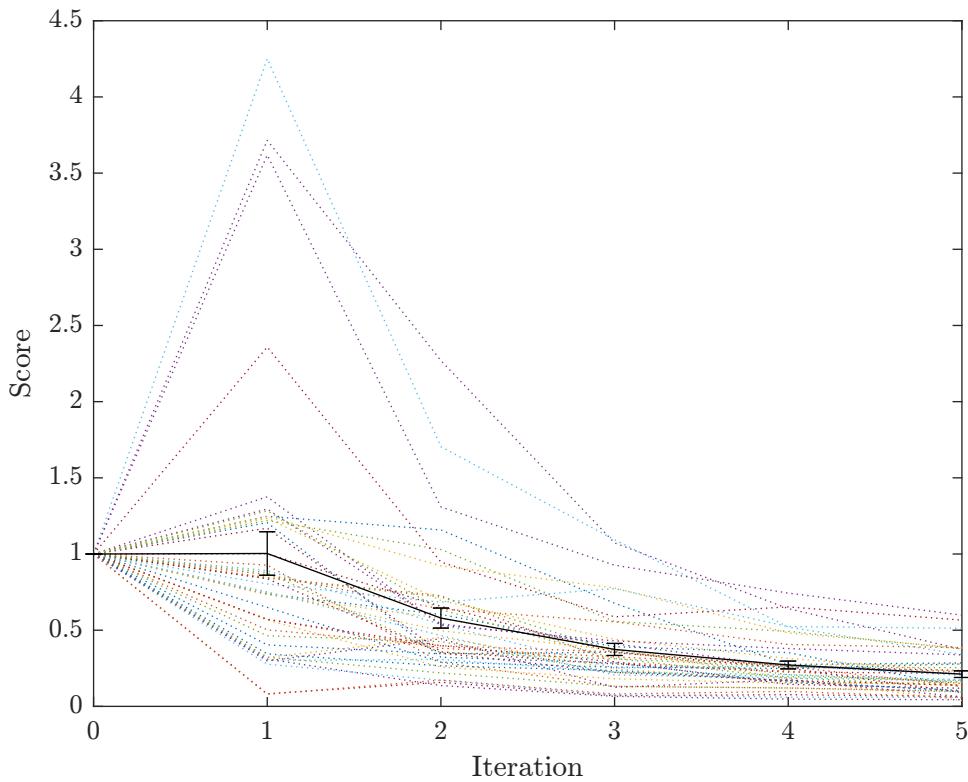
<sup>2</sup> Likewise, the Greedy algorithm was tested, with results presented in Figure 4.2. Here, a final  
<sup>3</sup> score of  $0.323 \pm 0.039$  was found indicating a worse scoring than the base case.



**Fig. 4.2** Results of greedy sampling on the test datasets. Dotted lines represent the individual scoring for the data sets and the solid line shows the mean results at each iteration.

### 4.1.3 Region of Disagreement

The final non-parametric algorithm to be tested was RoD. A final score of  $0.211 \pm 0.022$ , leading to a middling position between the other two parametric algorithms. The improvement in each iteration is shown in Figure 4.3.



**Fig. 4.3** Results of RoD sampling on the test datasets. Dotted lines represent the individual scoring for the data sets and the solid line shows the mean results at each iteration.

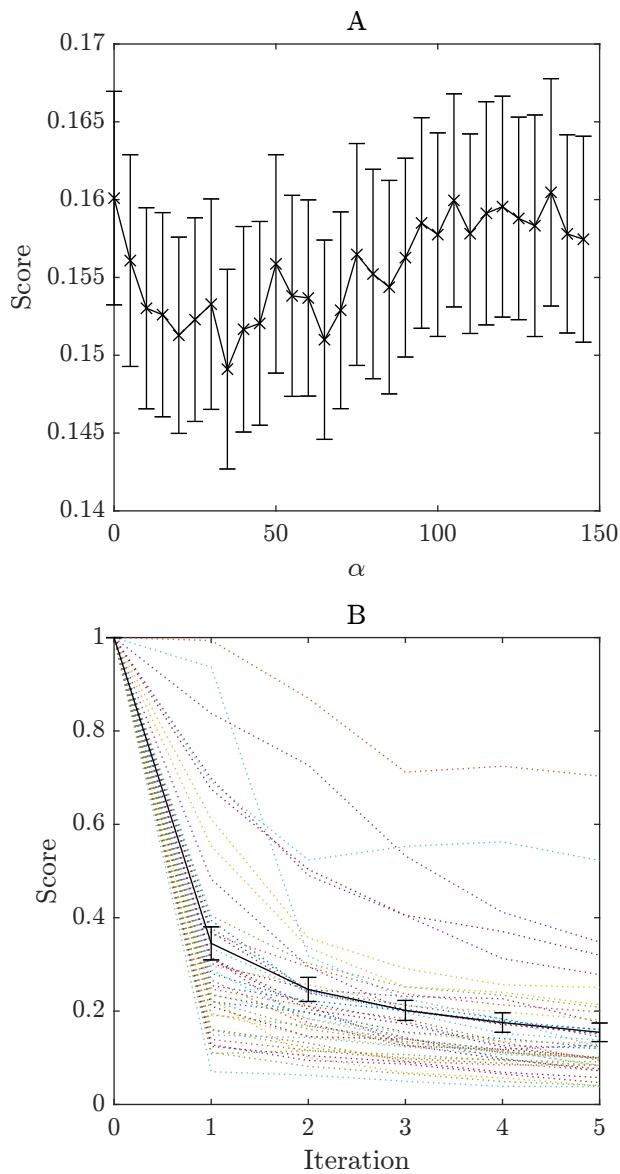
## 4.2 Parametric

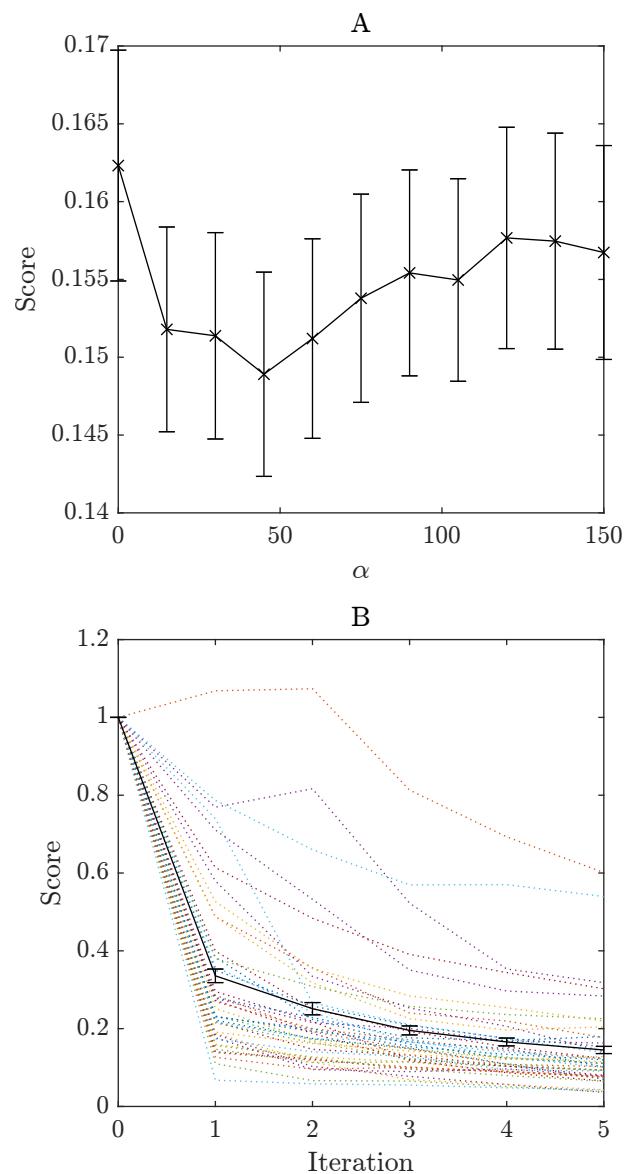
Parametric algorithms require a minimisation procedure on the training set. This leads to a computationally challenging script, and for this the author is grateful for the services provided by the HPC [Uni22].

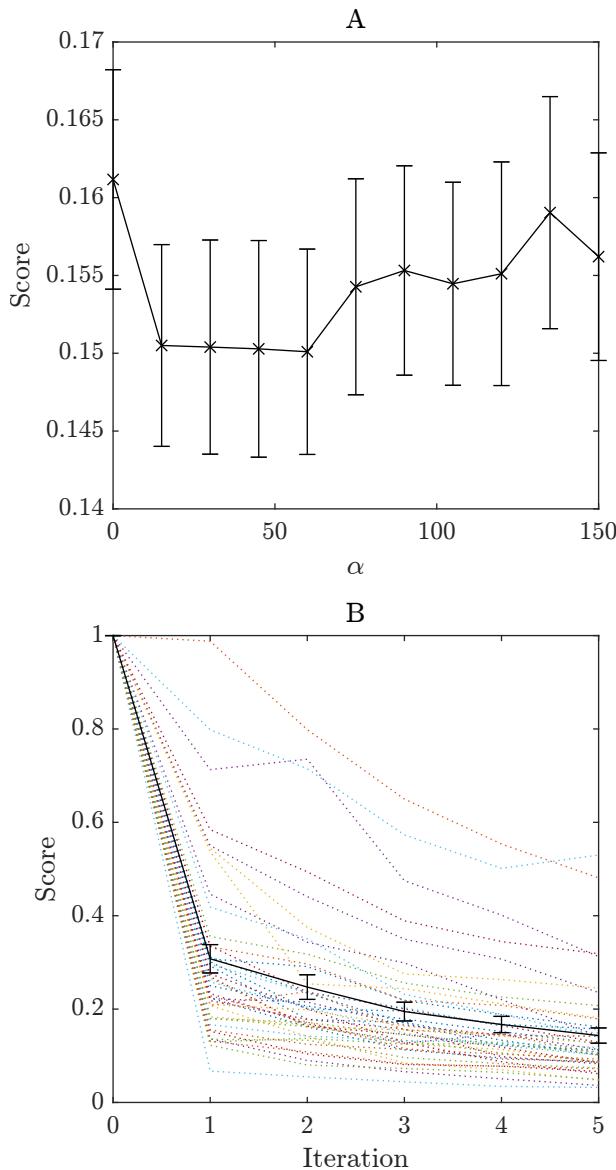
### 4.2.1 Clusters

The first set of algorithms tested were the clusters. Each of these outperformed all three of the other algorithms, with Cluster I, Cluster II, and Cluster III giving scores of  $0.155 \pm 0.020$ ,  $0.145 \pm 0.009$ , and respectively  $0.143 \pm 0.016$ . Due to the results from Cluster III, this is the one that will be used within the Holy Trinity. A variety of optimal  $c$  were found when comparing to Algorithm 4. An additional cluster size of 45, 40, and 60 were found to be optimal for Cluster I, II, and III respectively.

---

4.2 Parametric

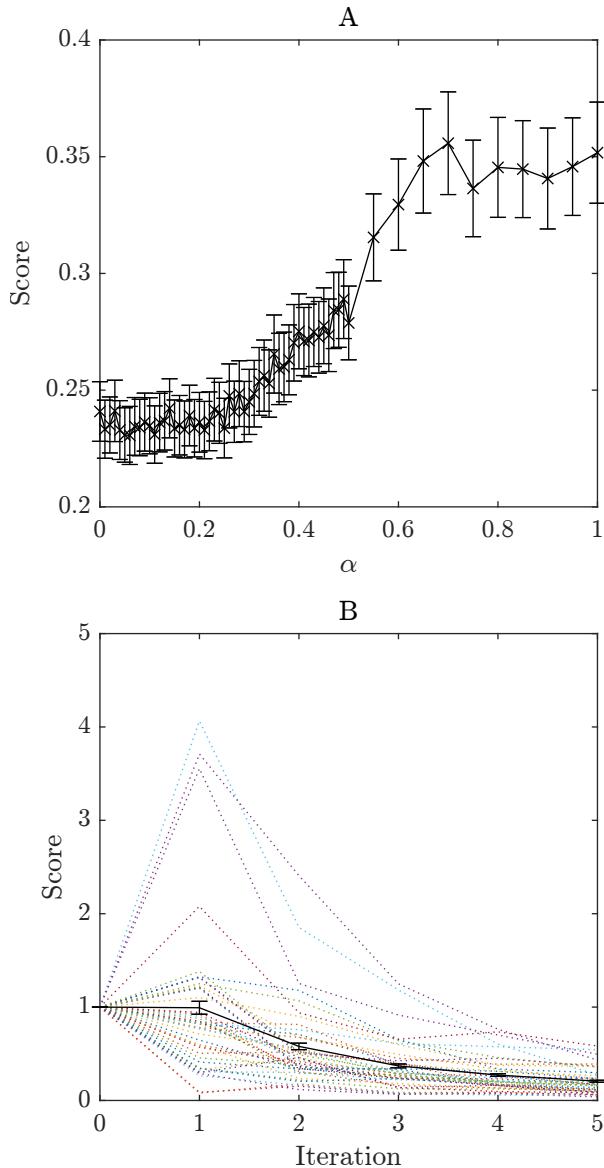




**Fig. 4.4** The results of fitting  $c$  to the Cluster III algorithm. A) shows the results from parameter fitting and B) shows the learning process on the test set.

### 4.2.2 Region of Disagreement with Greed

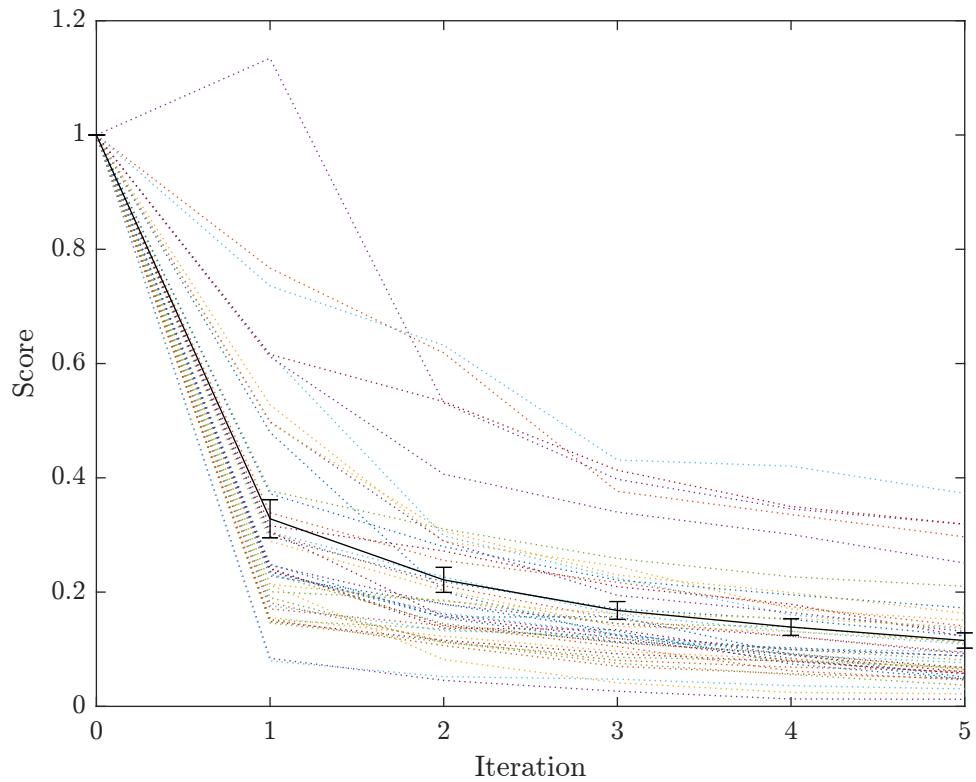
When testing the RoDG sampling algorithm, it was found that despite the weighting towards higher value targets in scoring, no significant improvement was seen over RoD. The minimisation procedure returned  $\alpha = 0.06$ , with  $\alpha$  defined in 3.3. However, the tolerance at small  $\alpha$ , as shown in Figure 4.5A. This method gave a final a score of  $0.206 \pm 0.011$ , a slight improvement over simply using RoD.



**Fig. 4.5** The results of fitting  $\alpha$  to the RoDG algorithm. A) shows the results from parameter fitting and B) shows the learning process on the test set.

### 1 4.2.3 RoDGeR

2 By sampling multiple values for  $\alpha$ , a final set of  $\alpha = [60, 0.47, 0.22]$  was reached where  
 3  $[\alpha_0, \alpha_1, \alpha_2]$  correspond to the constants used in Algorithm 4, 3.3, and 3.4 respectively. When  
 4 validated against the testing datasets, a final score of  $0.115 \pm 0.013$  was found; the best result.



**Fig. 4.6** The results after fitting  $\alpha$  to RoDGER, showing the learning process on the test set. The learning of each data set has been added with dotted lines for illustrative purposes.

# <sup>1</sup> Chapter 5

## <sup>2</sup> Discussion

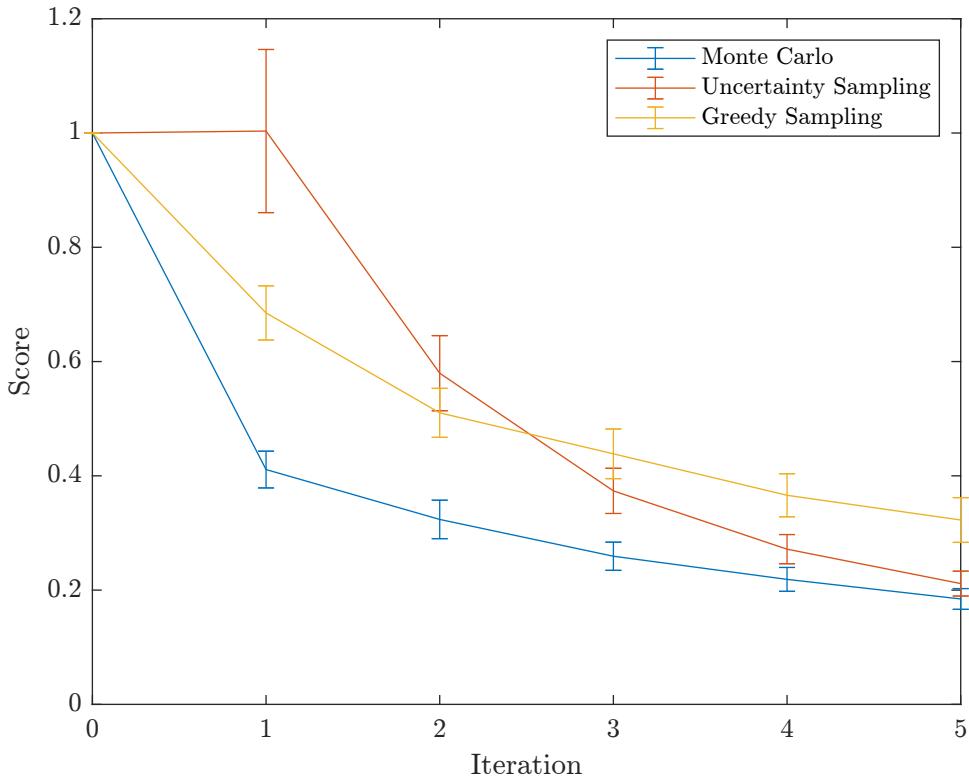
### <sup>3</sup> 5.1 Non-Parametric

<sup>4</sup> Three algorithms tested of non-parametric variety producing several noticeable results. Firstly,  
<sup>5</sup> Monte Carlo sampling outperformed both Greedy and RoD sampling. This is demonstrated  
<sup>6</sup> convincingly through Figure 5.1 where results from the greedy results suggest the worst  
<sup>7</sup> accuracy.

<sup>8</sup> Despite the greedy algorithm demonstrating the worst accuracy, interesting results were  
<sup>9</sup> shown with ROD sampling. Poor selection is evidently present with the first sample set,  
<sup>10</sup> although rapid improvement quickly follows. Indeed, after the first iteration, the learning  
<sup>11</sup> rate is superior to the other two algorithms. An extra iteration may indeed have seen RoD  
<sup>12</sup> surpassing Monte Carlo. This is expected as the ROD algorithm specifically targets regions  
<sup>13</sup> of the model which are challenging causing the largest changes towards proper fitting.

<sup>14</sup> Both ROD and greedy sampling are suspected to suffer from clusterisation whereby  
<sup>15</sup> data points similar to each other in the feature space are sampled within the same batch,  
<sup>16</sup> thus reducing the total information conveyed per batch operation. This is believed to be  
<sup>17</sup> particularly costly with the first iteration as the model will heavily overfit to the new cluster  
<sup>18</sup> it has sampled. The random nature of Monte Carlo reduces this prospect, hence the apparent  
<sup>19</sup> promising performance of a random sampling methodology. Evidence to this is shown in  
<sup>20</sup> Figure 4.1, Figure 4.2, and Figure 4.3.

<sup>21</sup> This demonstrates a danger with Batch Active Learning. It is very easy to produce a  
<sup>22</sup> learning algorithm which actually performs worse than random screening.



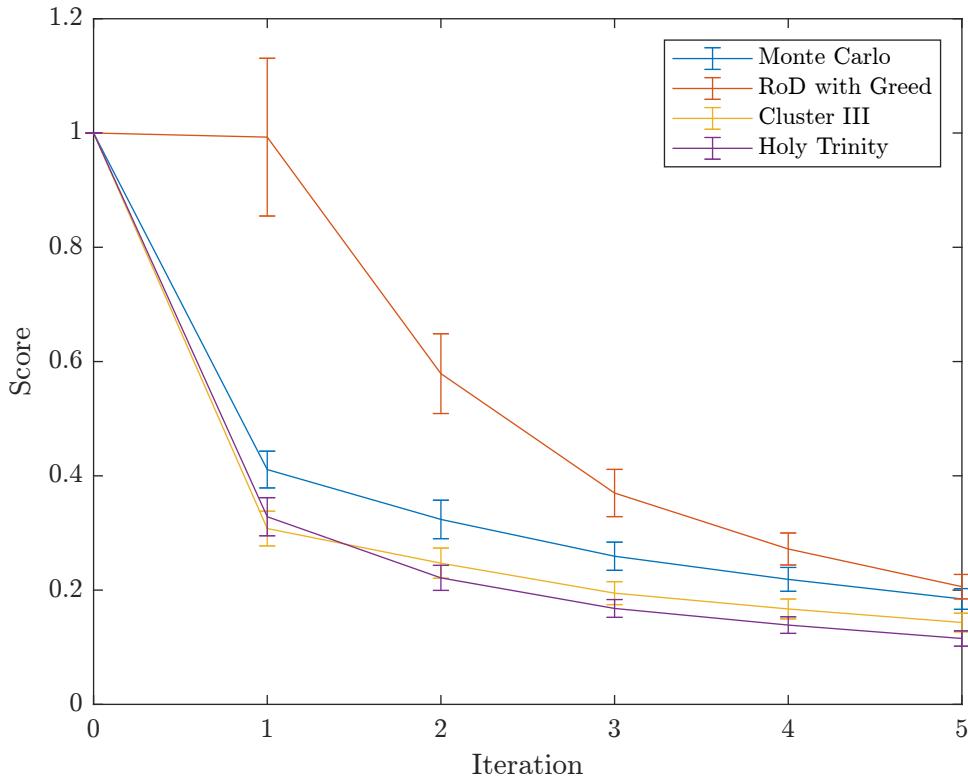
**Fig. 5.1** Comparison of different non-parametric algorithms with standard deviations represented as error bars.

## 5.2 Parametric

Different classes of parametric algorithms were tested. The first of these is a first order composite algorithm, RoD with Greed: i.e. uses different active learning algorithms as a base. The second is a clustering algorithm with the number of clusters left as a parameter. The third is a second order composite active learning algorithm which combines the other two parametric functions, affectionately named the Holy Trinity. A constant improvement is seen throughout these algorithms, with the Holy Trinity performing the best.

Several points of interest are highlighted with these results. Firstly, despite improving upon RoD, RoD with Greed is still beaten by Monte Carlo sampling. Again, the methodology suffers from clustering of points. This is shown with the ability of Cluster III outperforming Monte Carlo. The progression through the different cluster algorithms also sees improvement with progression, as anticipated.

The sampling process of the Cluster III algorithm demonstrates its ability at outperforming the random sampling methodology of Monte Carlo even within the first iteration. The Holy



**Fig. 5.2** Comparison of different parametric algorithms with standard deviations represented as error bars.

1 Trinity algorithm sacrifices some of this initial performance for longer term gain, as shown  
 2 by the worse performance after the first iteration. By the second iteration, the difference  
 3 becomes insignificant, with the error for each algorithm. By the end of the fifth iteration, the  
 4 Holy Trinity algorithm convincingly outperforms the other algorithms.

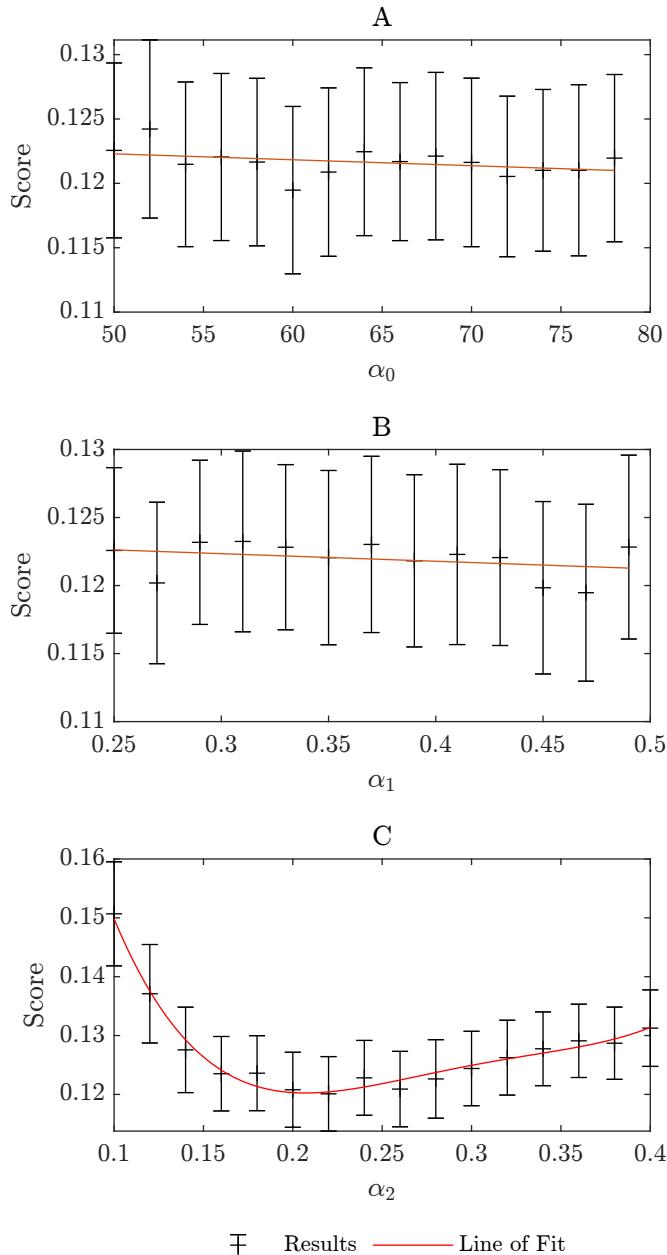
5 Upon investigation of the parameters settled upon within these several points arise. Firstly  
 6 with RoD with Greed, at low  $\alpha$ , the score appears uncorrelated with  $\alpha$ , only experiencing a  
 7 significant rise with  $\alpha > 0.4$ . Thus, it can be surmised that RoD is the driving force, with  
 8 evidence given by the final scores for RoD and RoD with Greed algorithms arising within  
 9 error of each other.

10 On the other hand, the sensitivity of Cluster III is extremely low to cluster size, demon-  
 11 strated by Figure 4.4. Here, no significant change is observed within the significant parameter  
 12 range. It is believed this is due to the highest ranking points remaining within the top clusters  
 13 as large clusters are likely to remain the largest, even with an increased number of clusters.  
 14 Thus, the top candidates are likely to remain in the same region of the feature space.

## 5.2 Parametric

## 35

Most surprising are the parameters found for the Holy Grail, shown in Figure 5.3. Here, it appears the highest sensitivity is based on  $\alpha_2$ , the exponent to the RoD with Greed score. This indeed shows a difference from Rod with Greed, where the Greed aspect appeared to be borderline irrelevant, with final results within error of RoD. Comparatively,  $\alpha_0$  and  $\alpha_1$  appear to have a linear fit.



**Fig. 5.3** Comparison of different parametric algorithms with standard deviations represented as error bars.

1      The use of curve fitting has, up until now been avoided. This is due to the difficulty  
2      in procuring the forms of these curves. Take Figure 4.3 where the first iteration produces  
3      no significant change. By fitting a curve, the results here could be misrepresented, so  
4      interpolation has been used in most cases to guide the eye. In Figure 5.3, it was considered  
5      essential to present the different in form between  $\alpha_0$ ,  $\alpha_1$ , and  $\alpha_2$  so a curve has been added  
6      to guide the reader to the differences in form. Polynomial fits were used for each subfigure,  
7      with A and B using 1st order and C using 4th order.

8      **5.3 Problem Sensitivity**

9      The problem set up provides an estimation of a fixed number of iteration and sample size.  
10     What if these change? Are the parameters overfitted to this specific problem? If deviations  
11     from this are taken, are the intelligent methods worse than Monte Carlo? This is important to  
12     determine, as there is a significant potential cost to such an inefficiency.

13     **5.4 Refinement**

14     There are several points for progression that are worth discussing. Firstly, the training system  
15     requires improvement. Despite the observations of parallelisation leading to a situation of  
16      $\mathcal{O}(c)$  given an infinite number of processing units, an infinite number of processing units  
17     unfortunately do not exist. In the event of three parameters, the current methodology requires  
18      $N_{\text{train}} \prod(n_{\alpha_i})$  executions of the learning algorithm, where  $n_{\alpha_i}$  is the number of different values  
19     tested for  $\alpha_i$ . Even with simply 3 different values tested for each parameter in the Holy Trinity  
20     algorithm, this equates to  $\sim 4500$  executions of the algorithm. Thus, as the maximum number  
21     of CPUs available was 380, the training process became  $\mathcal{O}(N_{\text{train}} \prod n_{\alpha_i})$ . A potential solution  
22     would be segmentation, where the datasets are split into smaller groups with which are tested  
23     on a sample of the parameter space, with results from these smaller groups amalgamated  
24     at the end. Additionally, active learning could be used in the determination of the minima.  
25     Here, the goal would be to find the minima using as few parameter values as possible.

26     The current implementation of the scoring system is simple. Although this would please  
27     Occam's barber, it is believed that this is not satisfactory for the aggressive pursuit of effective  
28     drugs. One possibility is only scoring samples which show a pChEMBL greater than seven.  
29     This puts a greater weight on these samples, although a multidisciplinary discussion is  
30     required here. This could potentially be aided by categorising the data set instead, instead  
31     separating results into  $\text{pChEMBL} > 7$  and  $\text{pChEMBL} \leq 7$ .

## 5.5 Link to Covid

1  
2  
3  
4  
5  
6  
7  
8  
9  
10

Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Etiam lobortis facilisis sem. Nullam nec mi et neque pharetra sollicitudin. Praesent imperdiet mi nec ante. Donec ullamcorper, felis non sodales commodo, lectus velit ultrices augue, a dignissim nibh lectus placerat pede. Vivamus nunc nunc, molestie ut, ultricies vel, semper in, velit. Ut porttitor. Praesent in sapien. Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Duis fringilla tristique neque. Sed interdum libero ut metus. Pellentesque placerat. Nam rutrum augue a leo. Morbi sed elit sit amet ante lobortis sollicitudin. Praesent blandit blandit mauris. Praesent lectus tellus, aliquet aliquam, luctus a, egestas a, turpis. Mauris lacinia lorem sit amet ipsum. Nunc quis urna dictum turpis accumsan semper.

# **Chapter 6**

## **Conclusion**

There are about 20000 drugs approved for pharmaceutical use, with more being trialled every year. However, hesitancy in using these drugs as treatments for emerging diseases. Instead, focus is given to designer drugs which may take years to develop. It is estimated 80% of the cost in drug design and manufacture arises simply from the developing process. This was shown to be ineffective at the time of the Sars-Cov-2 outbreak whereby the use of existing drugs was slow, and often polluted with misinformation.

The solution presented

# References

- 1  
Capecci, Alice, Daniel Probst, and Jean-Louis Reymond (June 12, 2020). “One molecular  
2 fingerprint to rule them all: drugs, biomolecules, and the metabolome”. In: *Journal of*  
3 *Cheminformatics* 12.1, p. 43. ISSN: 1758-2946. DOI: 10.1186/s13321-020-00445-4. URL:  
4 <https://doi.org/10.1186/s13321-020-00445-4> (visited on 05/06/2022).  
5
- Center for Drug Evaluation and Research (Apr. 25, 2022). “Coronavirus Treatment Acceleration Program (CTAP)”. In: *FDA*. Publisher: FDA. URL: <https://www.fda.gov/drugs/coronavirus-covid-19-drugs/coronavirus-treatment-acceleration-program-ctap> (visited  
6 on 05/05/2022).  
7
- EMBL-EBI (2009). *ChEMBL Database*. URL: <https://www.ebi.ac.uk/chembl/> (visited on  
8 05/06/2022).  
9
- Green, Don W. and Marylee Z. Southard (2018). *Perry’s Chemical Engineering Handbook*.  
10 9th. McGraw-Hill.  
11
- Kirsch, Andreas, Joost van Amersfoort, and Yarin Gal (Oct. 28, 2019). “BatchBALD: Efficient and Diverse Batch Acquisition for Deep Bayesian Active Learning”. In: *arXiv:1906.08158 [cs, stat]*. arXiv: 1906.08158. URL: <http://arxiv.org/abs/1906.08158> (visited on  
12 05/12/2022).  
13
- McKerns, Michael and Michael Aivazis (2010). *pathos: a framework for heterogeneous computing*. URL: <http://uqfoundation.github.io/project/pathos>.  
14
- McKerns, Michael M. et al. (Feb. 6, 2012). “Building a Framework for Predictive Science”.  
15 In: *arXiv:1202.1056 [cs]*. arXiv: 1202.1056. URL: <http://arxiv.org/abs/1202.1056> (visited  
16 on 05/07/2022).  
17
- Pedregosa, Fabian et al. (n.d.). “Scikit-learn: Machine Learning in Python”. In: *MACHINE LEARNING IN PYTHON* (), p. 6.  
18
- Rogers, David and Mathew Hahn (Feb. 4, 2010). “Extended-Connectivity Fingerprints | Journal of Chemical Information and Modeling”. In: *Journal of Chemical Information and Modeling* 50.5. DOI: 10.1021/ci100050t. URL: <https://pubs.acs.org/doi/10.1021/ci100050t> (visited on 11/01/2021).  
19
- Scikit Learn (2022). 2.3. *Clustering*. scikit-learn. URL: <https://scikit-learn.org/stable/modules/clustering.html> (visited on 05/05/2022).  
20
- Settles, Burr (2009). *Active Learning Literature Survey*. Technical Report. Accepted: 2012-03-15T17:23:56Z. University of Wisconsin-Madison Department of Computer Sciences.  
21 URL: <https://minds.wisconsin.edu/handle/1793/60660> (visited on 11/01/2021).  
22
- Settles, Burr and Mark Craven (Oct. 25, 2008). “An analysis of active learning strategies for sequence labeling tasks”. In: *Proceedings of the Conference on Empirical Methods in Natural Language Processing*. EMNLP ’08. USA: Association for Computational Linguistics, pp. 1070–1079. (Visited on 05/01/2022).  
23
- 24
- 25
- 26
- 27
- 28
- 29
- 30
- 31
- 32
- 33
- 34
- 35
- 36
- 37

- <sup>1</sup> Sparkes, Andrew et al. (Jan. 4, 2010). “Towards Robot Scientists for autonomous scientific discovery”. In: *Automated Experimentation* 2.1, p. 1. ISSN: 1759-4499. DOI: 10.1186/1759-4499-2-1. URL: <https://doi.org/10.1186/1759-4499-2-1> (visited on 05/09/2022).
- <sup>4</sup> University of Cambridge (2022). *Research Computing Services*. URL: <https://www.hpc.cam.ac.uk/> (visited on 05/07/2022).
- <sup>6</sup> Wang, Haidong et al. (Apr. 16, 2022). “Estimating excess mortality due to the COVID-19 pandemic: a systematic analysis of COVID-19-related mortality, 2020–21”. In: *The Lancet* 399.10334. Publisher: Elsevier, pp. 1513–1536. ISSN: 0140-6736, 1474-547X. DOI: 10.1016/S0140-6736(21)02796-3. URL: [https://www.thelancet.com/journals/lancet/article/PIIS0140-6736\(21\)02796-3/fulltext](https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(21)02796-3/fulltext) (visited on 05/06/2022).
- <sup>11</sup> World Health Organization (May 6, 2022). *WHO Coronavirus (COVID-19) Dashboard*. URL: <https://covid19.who.int> (visited on 05/06/2022).