

Indian Institute of Technology Bombay

Course: Foundations of Machine Learning CS 725

Experimental Verification of Perceptron Convergence Algorithm

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Abstract

The perceptron is one of the earliest linear classifiers and comes with a classical convergence theorem: if the training data are linearly separable, the perceptron learning algorithm converges in a finite number of updates, with a worst-case mistake bound of order $(\frac{R}{\gamma})^2$, where R is the radius of the dataset and γ is the geometric margin. This project presents an experimental verification of this convergence behaviour.

We first construct two-dimensional synthetic datasets using `make_classification`, controlling class separation to obtain both linearly separable and non-separable scenarios. Labels are encoded in $\{-1, +1\}$ and a standard perceptron with an explicit bias term is implemented. During training, we record the sequence of weight and bias updates and visualize the evolution of the decision boundary over the training samples, including an animation that shows how misclassified points successively rotate and translate the separating hyperplane until a stable separator is reached in the separable case.

For separable datasets, we empirically estimate the radius R and the margin $\hat{\gamma}$ of the final classifier, compute the theoretical upper bound $(\frac{R}{\hat{\gamma}})^2$ on the number of mistakes, and compare it with the actual number of updates observed. Our experiments confirm that the perceptron converges in finitely many steps and that the observed number of updates is significantly smaller than the conservative theoretical bound. Additional experiments on overlapping (non-separable) data and a hinge-loss-based variant further illustrate the limitations of the classical theorem and the behaviour of perceptron-like algorithms beyond the separable setting.

Introduction

The perceptron is a linear classifier that updates parameters using wrongly classified training examples. *Perceptron Convergence Theorem* states that if the training dataset is linearly separable that is, it is clearly separable into two classes by a hyperplane of $n-1$ dimensions in an n dimensional input space, then the perceptron learning algorithm converges to a separating hyperplane in a finite number of updates. The maximum number of updates made during training can be bounded in terms of the radius of the dataset and the geometric margin between the two classes.

This project experimentally verifies this theorem by implementing the perceptron, training it on synthetically generated two-dimensional datasets with controlled separability, recording the number of updates until convergence, and comparing it with the theoretical mistake bound. We also study the perceptron on non-separable data, showing that the algorithm does not converge in this case, confirming the requirement of Linearly Separable Data.

Theory

Perceptron Model

The perceptron is a linear classifier for binary labels $y \in \{-1, +1\}$. Given an input vector $x \in \mathbb{R}^d$, the perceptron predicts

$$\hat{y} = \text{sign}(\langle w, x \rangle + b),$$

where $w \in \mathbb{R}^d$ is the weight vector and $b \in \mathbb{R}$ is the bias term.

Learning Rule

During training, whenever the perceptron misclassifies a sample (x_i, y_i) , the parameters are updated as

$$w \leftarrow w + y_i x_i, \quad b \leftarrow b + y_i.$$

No update is made on correctly classified samples.

Linear Separability

A dataset $\{(x_i, y_i)\}_{i=1}^n$ is called *linearly separable* if there exists some (w^*, b^*) such that

$$y_i(\langle w^*, x_i \rangle + b^*) > 0 \quad \forall i.$$

Define the *margin*

$$\gamma = \min_i \frac{y_i(\langle w^*, x_i \rangle + b^*)}{\|w^*\|}$$

and let the data radius be

$$R = \max_i \|x_i\|.$$

Perceptron Convergence Theorem

Theorem. If the dataset is linearly separable with margin $\gamma > 0$, then the perceptron learning algorithm makes only finitely many mistakes, and the total number of updates T satisfies

$$T \leq \left(\frac{R}{\gamma} \right)^2.$$

Hence, the algorithm converges to a separating hyperplane in a finite number of steps.

Non-Separable Case

If the dataset is not linearly separable, no finite update bound exists and the perceptron may continue updating indefinitely, oscillating without reaching convergence.

Proof of the Perceptron Convergence Theorem

Step 1: The Perceptron Vector Makes Progress Toward the Optimal Separator

Assume the perceptron makes an update on (x_i, y_i) :

$$w^{(t+1)} = w^{(t)} + y_i x_i.$$

Take the dot product with the optimal weight vector w^* (where $\|w^*\| = 1$):

$$w^{(t+1)} \cdot w^* = w^{(t)} \cdot w^* + y_i(x_i \cdot w^*).$$

Since the margin is at least γ , we have

$$y_i(x_i \cdot w^*) \geq \gamma.$$

Thus,

$$w^{(t+1)} \cdot w^* \geq w^{(t)} \cdot w^* + \gamma.$$

By induction, after T updates:

$$w^{(T)} \cdot w^* \geq T\gamma.$$

Step 2: The Norm of the Perceptron Vector Cannot Grow Too Quickly

We compute:

$$\|w^{(t+1)}\|^2 = \|w^{(t)} + y_i x_i\|^2 = \|w^{(t)}\|^2 + \|x_i\|^2 + 2y_i(w^{(t)} \cdot x_i).$$

Since the point is misclassified:

$$y_i(w^{(t)} \cdot x_i) \leq 0.$$

Thus,

$$\|w^{(t+1)}\|^2 \leq \|w^{(t)}\|^2 + \|x_i\|^2 \leq \|w^{(t)}\|^2 + R^2.$$

By induction:

$$\|w^{(T)}\|^2 \leq TR^2.$$

Combining:

$$T^2\gamma^2 \leq TR^2.$$

Divide both sides by $T\gamma^2$:

$$T \leq \frac{R^2}{\gamma^2}.$$

Algorithm

Perceptron Learning Algorithm (with Bias Term)

We implement the standard perceptron learning algorithm with an explicit bias term. The training data are $\{(x_i, y_i)\}_{i=1}^n$ with $x_i \in \mathbb{R}^d$ and $y_i \in \{-1, +1\}$.

Inputs

- Training set $\{(x_i, y_i)\}_{i=1}^n$
- Learning rate $\eta > 0$ (in the code: `lr = 1.0`)
- Maximum number of epochs T_{\max} (in the code: `max_epochs = 1000`)

Outputs

- Final weight vector $w \in \mathbb{R}^d$
- Final bias $b \in \mathbb{R}$
- History of parameters after each update: $(w^{(t)}, b^{(t)})$, used for visualization

Pseudocode

Initialize:

- $w \leftarrow 0 \in \mathbb{R}^d$
- $b \leftarrow 0$
- $\text{history} \leftarrow []$ (empty list to store (w, b) after each update)

For epoch = 1 to T_{\max} :

1. Set **errors** $\leftarrow 0$.
2. **For** $i = 1$ to n :
 - (a) Compute the activation

$$a_i = w \cdot x_i + b.$$

- (b) Predict

$$\hat{y}_i = \begin{cases} +1, & \text{if } a_i \geq 0, \\ -1, & \text{if } a_i < 0. \end{cases}$$

- (c) **If** $\hat{y}_i \neq y_i$ (misclassification), then:

- Update the weights:

$$w \leftarrow w + \eta y_i x_i,$$

- Update the bias:

$$b \leftarrow b + \eta y_i,$$

- Increment **errors** $\leftarrow \text{errors} + 1$,
- Append current (w, b) to **history**.

3. **If** **errors** = 0, then:

- Stop the training (the perceptron has converged).

Return final (w, b) and the full **history** of updates.

Experimental Setup

Dataset Generation

We generate two-dimensional synthetic datasets using `make_classification` from `sklearn.datasets`. The data consist of two classes labeled $+1$ and -1 , and the separability is controlled by the parameter `class_sep`.

- Each dataset contains $n = 200$ samples in \mathbb{R}^2 .

- Labels are converted to $\{-1, +1\}$ after generation.
- We study two settings:
 1. **Linearly separable data:** high `class_sep` value.
 2. **Non-separable data:** overlapping classes (small `class_sep`).

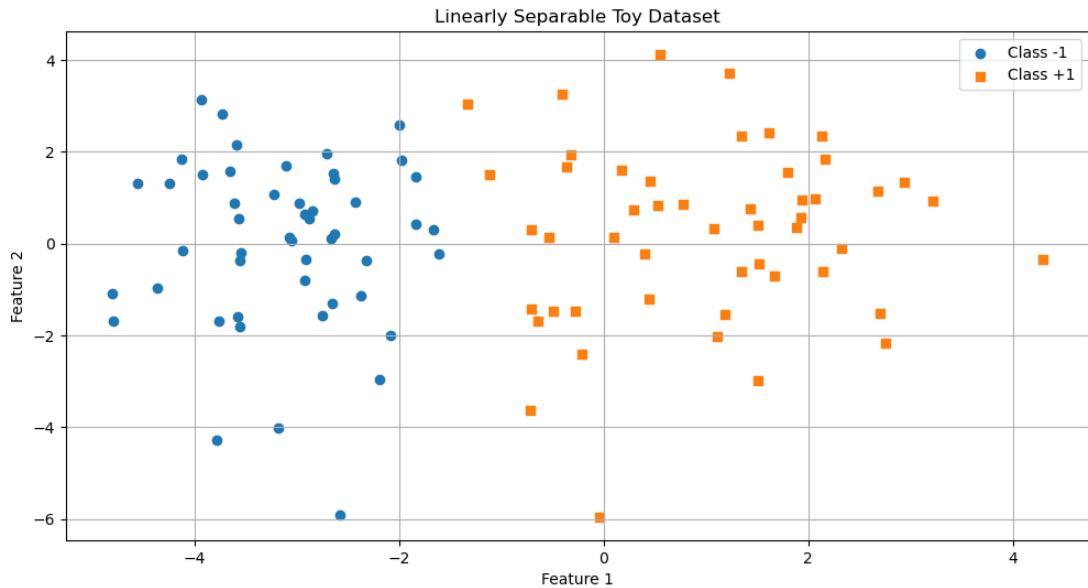


Figure 1: Generated synthetic Linearly separable dataset with two classes in \mathbb{R}^2 .

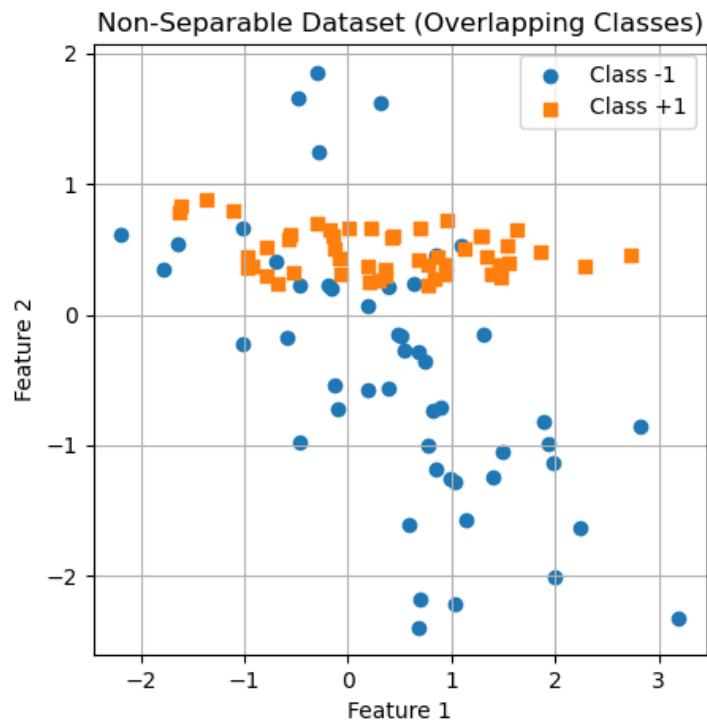


Figure 2: Generated synthetic Non-Linearly separable dataset with two classes in \mathbb{R}^2 .

Data Generation code

Here is the code that we used to generate both linearly separable and non-linearly separable cases

Listing 1: Synthetic Linearly separable dataset generation

```
1 import numpy as np
2 import matplotlib as plt
3
4 X, y = make_classification(
5     n_samples=100,
6     n_features=2,
7     n_informative=1,
8     n_redundant=0,
9     n_classes=2,
10    n_clusters_per_class=1,
11    random_state=41,
12    hypercube=False,
13    class_sep=10
14)
15 y_perc = np.where(y == 0, -1, 1)
16 variance_scale = 2.0
17 X = X * variance_scale
18 plt.figure(figsize=(12, 6))
19 plt.scatter(X[y_perc == -1, 0], X[y_perc == -1, 1], marker='o', label='Class
-1')
20 plt.scatter(X[y_perc == 1, 0], X[y_perc == 1, 1], marker='s', label='Class
+1')
21 plt.xlabel('Feature 1')
22 plt.ylabel('Feature 2')
23 plt.legend()
24 plt.title('Linearly Separable Toy Dataset')
25 plt.grid(True)
26 plt.savefig("D:\Important Subjects\Machine Learning\Project\Report\Media")
27 plt.show()
```

In order to experimentally study the perceptron convergence behavior, a two-dimensional synthetic dataset is generated using the `make_classification` function from `sklearn.datasets`. The dataset consists of two linearly separable classes, where separability is controlled through a large `class_sep` parameter. The resulting labels from `make_classification` are initially encoded as $\{0, 1\}$, which are manually converted to $\{-1, +1\}$ to match the perceptron update rule. To further spread the samples in the feature space, a scaling factor is applied to the feature matrix. Finally, the data are visualized by plotting the two classes with distinct markers, providing a clear view of their separability before applying the perceptron learning algorithm.

Listing 2: Synthetic Non Separable dataset generation

```

1 X_bad, y_bad = make_classification(
2     n_samples=100,
3     n_features=2,
4     n_informative=2,
5     n_redundant=0,
6     n_classes=2,
7     n_clusters_per_class=1,
8     class_sep=0.5,
9     random_state=0
10)
11
12 y_bad_perc = np.where(y_bad == 0, -1, 1)
13 plt.figure(figsize=(5, 5))
14 plt.scatter(X_bad[y_bad_perc == -1, 0], X_bad[y_bad_perc == -1, 1], marker='o',
15             label='Class -1')
16 plt.scatter(X_bad[y_bad_perc == 1, 0], X_bad[y_bad_perc == 1, 1], marker='s',
17             label='Class +1')
18 plt.xlabel('Feature 1')
19 plt.ylabel('Feature 2')
20 plt.legend()
21 plt.title("Non-Separable Dataset (Overlapping Classes)")
22 plt.grid(True)
23 plt.savefig("D:\\Important Subjects\\Machine Learning\\Project\\Report\\Media")
24 plt.show()

```

To illustrate the limitations of the perceptron convergence theorem, a non-separable dataset is generated using the `make_classification` function from `sklearn.datasets`. In this case, the data are constructed in two dimensions with both features being informative, and a small value of `class_sep` is chosen to intentionally produce overlapping classes. As before, the labels originally encoded as $\{0, 1\}$ are converted to $\{-1, +1\}$ to comply with the perceptron update rule. The resulting data are visualized using a scatter plot, where the two classes overlap significantly in the feature space, making it impossible for any linear separator to perfectly classify all points. This visualization highlights that under non-separable conditions, the perceptron fails to converge, which is consistent with the theoretical guarantees.

Training Procedure

We train the perceptron using the update rule described in the Algorithm section. The learning rate is set to $\eta = 1.0$, and training stops early when no misclassification occurs in a full pass over the data.

- Maximum epochs: 1000
- Learning rate: 1.0
- Bias term is updated together with weights
- After every update, the current (w, b) pair is stored to visualize the evolution of the decision boundary

Listing 3: Perceptron Trainning Function

```

1 def perceptron_train(X, y, lr=1.0, max_epochs=1000):
2     n_samples, n_features = X.shape
3     w = np.zeros(n_features)
4     b = 0.0
5     history = []
6
7     for epoch in range(max_epochs):
8         errors = 0
9         for i in range(n_samples):
10            activation = np.dot(w, X[i]) + b
11            y_pred = 1 if activation >= 0 else -1
12            if y_pred != y[i]:
13                w += lr * y[i] * X[i]
14                b += lr * y[i]
15                errors += 1
16            history.append((w.copy(), b))
17        if errors == 0:
18            print(f"Perceptron converged in epoch {epoch + 1}")
19            break
20
21    return w, b, history
22
23 w, b, history = perceptron_train(X, y_perc, lr=1.0, max_epochs=1000)
24 print("Final weights:", w)
25 print("Final bias:", b)
26
27 plot_decision_boundary(X, y_perc, w, b, "Perceptron (Vanilla) on Separable Data
   ")

```

Once we run the code the Algorithm converged within 4 epoches and following was the final result. Using the function that plots graphs for each of the 4 eposches, we plotted the decision boundary on the input space. Here is the code snippet that we used

Listing 4: Generating plots of decision boundary after epoch

```

1 import os
2 def plot_decision_boundary_save(X, y, w, b, title, filename):
3     plt.figure(figsize=(5, 5))
4     plt.scatter(X[y == -1, 0], X[y == -1, 1], marker='o', label='Class -1')
5     plt.scatter(X[y == 1, 0], X[y == 1, 1], marker='s', label='Class +1')
6
7     x_min, x_max = X[:, 0].min() - 1, X[:, 0].max() + 1
8     xs = np.linspace(x_min, x_max, 200)
9
10    if abs(w[1]) > 1e-12:
11        ys = -(w[0] * xs + b) / w[1]
12        plt.plot(xs, ys, linestyle='--', label='Decision boundary')
13    else:
14        x_line = -b / (w[0] + 1e-12)
15        plt.axvline(x_line, linestyle='--', label='Decision boundary')
16
17    plt.xlabel('Feature 1')
18    plt.ylabel('Feature 2')
19    plt.title(title)
20    plt.legend()
21    plt.grid(True)
22
23    plt.savefig(os.path.join("D:\\Important Subjects\\Machine Learning\\Project\\
      Report\\Media\\Convergence plots", filename), dpi=300, bbox_inches='tight
      ')
24    plt.close()

```

Results of Training

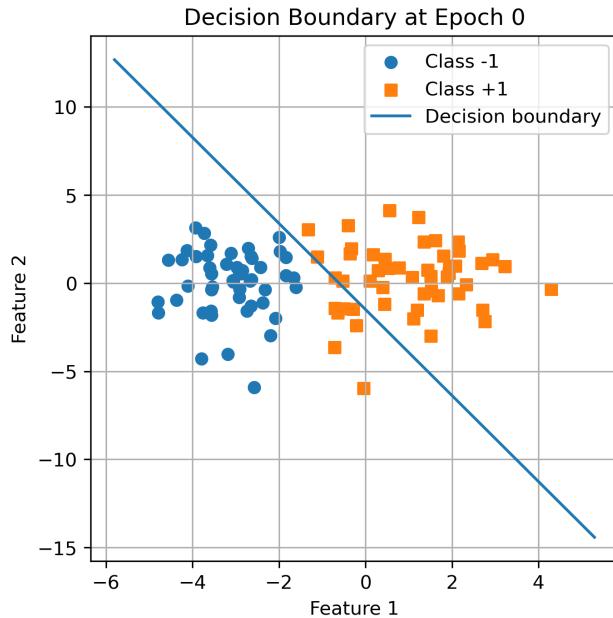
Once the training loop was exited. The following results are obtained

```

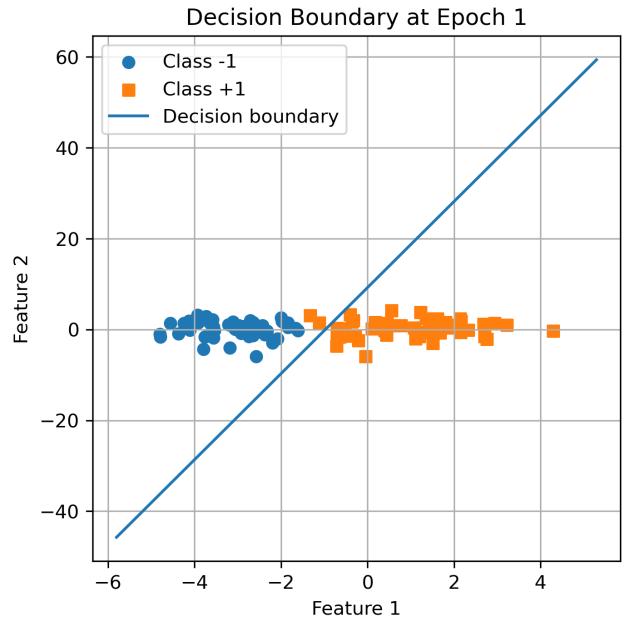
1 Perceptron converged in epoch 4
2 Final weights: [7.09703775 0.62987918]
3 Final bias: 9.0

```

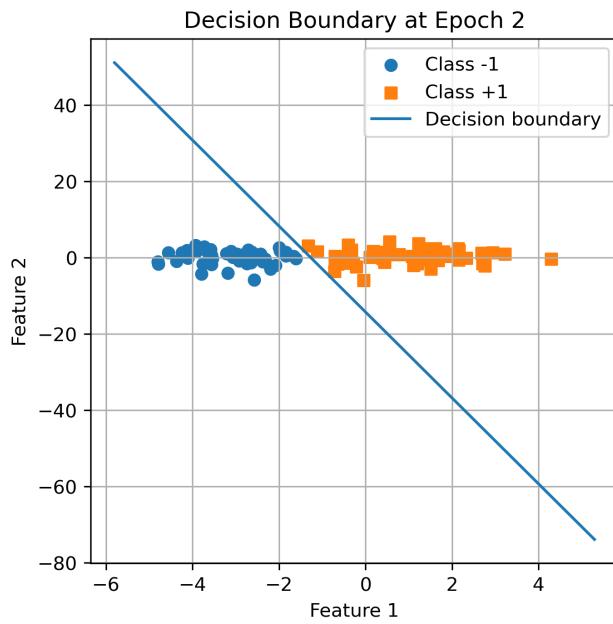
Here are the plots showing decision boundary after every epoch



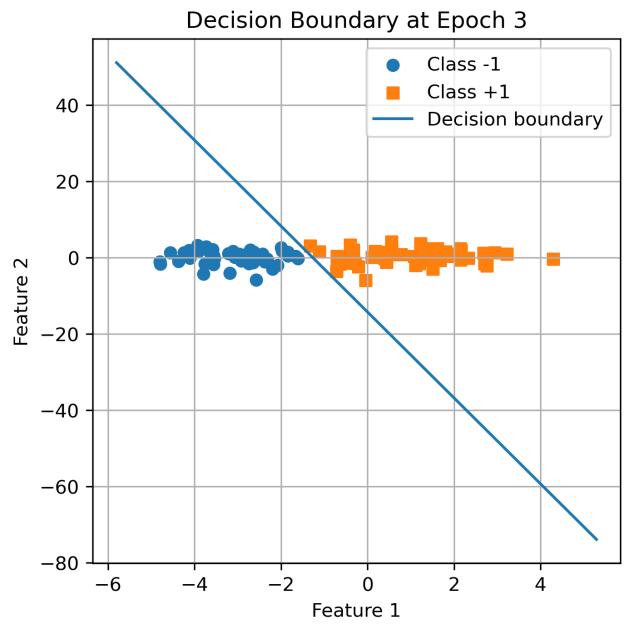
(a) Epoch 1



(b) Epoch 2



(c) Epoch 3



(d) Epoch 4

Figure 3: Evolution of the perceptron decision boundary over training epochs.

Updates in Weights and Bias terms

As we ran the algorithm it converged in 4 epochs but the total number of updates that is mentioned in Convergence theorem is 21. As Updates happens only when we have a mistake

in classification, then only the update rule is called. Our code not only captures the training process but also the update history of the weights the final history array that was created once the algorithm converged is given as

Listing 5: Final History array after the algorithm

```

1   history array at epoch {2}  sample {8} : [(array([3.18173012,
  4.02398429]), -1.0), (array([ 3.1378471 , -1.93786434]), 0.0), (array([
  2.77318887, -0.2633231 ]), 1.0), (array([ 2.12962518, -1.94226489]),
  2.0), (array([4.32446697, 1.01781785]), 1.0), (array([3.62140857,
  1.31221853]), 2.0), (array([ 3.40910773, -1.09605838]), 3.0), (array
  ([2.08122805, 1.95332431]), 4.0), (array([5.18645851, 0.264209 ]),
  3.0), (array([ 4.47104397, -3.36906979]), 4.0), (array([7.04722514,
  2.53839253]), 3.0), (array([6.51581261, 2.66839097]), 4.0), (array
  ([6.01817204, 1.20608633]), 5.0), (array([ 5.30919124, -0.21012546]),
  6.0), (array([4.19188526, 1.28706508]), 7.0), (array([ 4.14800223,
  -4.67478355]), 8.0), (array([ 7.90712105, -2.99617403]), 7.0), (array([
  7.54246282, -1.32163278]), 8.0), (array([6.21458314, 1.72774991]),
  9.0), (array([ 8.21434374, -0.86731136]), 8.0), (array([7.09703775,
  0.62987918]), 9.0)]

```

Why we captured the history of every update?

Capturing the history enabled us to clearly plot the decision boundary after each update. Length of the history array also gives us the total number of updates that the algorithm takes to converge that is 21. For full length updation in weights [please refer to appendix](#) of the report.

Decision Boundary after each update for all the 21 updates are shown [here in appendix](#). Once we plotted the decision boundaries it is quite easy to see how actually the decision boundary changes with updatation rule. As the algorithm converges we get the final plot beyond which the decision boundary will not change.

Margin and Theoretical Bound Estimation

For the separable dataset, we estimate the geometric margin of the learned separator and compute the theoretical mistake bound

$$\left(\frac{R}{\gamma}\right)^2,$$

where R is the maximum norm of the data points. This value is compared with the actual number of perceptron updates recorded during training.

Where R is given mathematically as

$$R = \max_i \|x_i\|$$

and

$$\gamma = \min_i \frac{y_i(\langle w, x_i \rangle + b)}{\|w\|}$$

to calculate the values of R and γ for our dataset we used the following code

Listing 6: Code to calculate Radius and γ

```

1 R = np.max(np.linalg.norm(X, axis=1))
2 print("R (max norm of samples):", R)
3
4 def estimated_margin(X, y, w, b):
5     w_norm = np.linalg.norm(w)
6     margins = y * (X @ w + b) / (w_norm + 1e-12)
7     return np.min(margins)
8
9 gamma_hat = estimated_margin(X, y_perc, w, b)
10 print("Estimated margin gamma_hat:", gamma_hat)

```

To Calculate the bound suggested by Convergence theorem, we used -

```

1 bound = (R / (gamma_hat + 1e-12)) ** 2

```

Finally we get the results of above code blocks as

```

1 R (max norm of samples): 6.4447513916413
2 Estimated margin gamma_hat: 0.21006936522129688
3 Approx. theoretical upper bound on number of updates: 941.2107779492442
4 Actual number of updates until convergence: 21

```

Which is far lesser than the theoretical bound suggested by the Convergence Theorem.

Perceptron Training on Non–Separable Data

Motivation The perceptron Convergence Theorem states that it is guaranteed to find a separating hyperplane only when the data has a linear separation. To verify this limitation experimentally, we train the same perceptron model on a dataset in which the two classes overlap in the input space. as shown in the earlier section that we have generated a non-separable dataset. Using this dataset we aim to verify the limitation enforced by Convergence theorem. Here is the non-separable dataset.

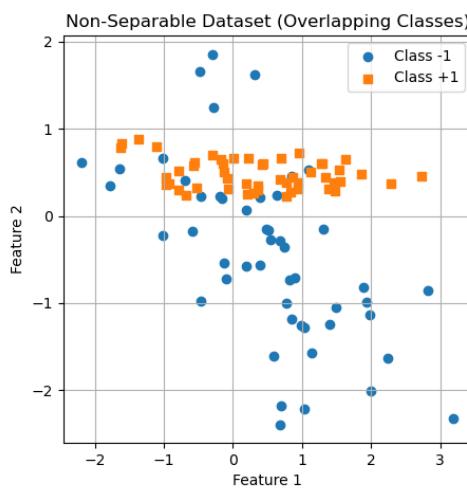


Figure 4: Non–Separable Dataset in \mathbb{R}^2 .

Training Behaviour The dataset is constructed using a small value of `class_sep`, which forces many samples from both classes to lie close to each other. During training, the perceptron attempts to classify each point using a linear decision boundary. Whenever a point is misclassified, the algorithm updates the parameters (w, b) in an attempt to correct the error. However, because some samples cannot be simultaneously separated with a single hyperplane, correcting the classification of one point often causes a mistake on another. As a result, the weight vector keeps shifting without reaching a stable configuration. To support the above claim we conducted training on this dataset with limiting the maximum number of epochs to 50 as shown in the code snippet below

Listing 7: code used to train perceptron on non-linearly separable data

```

1 w_bad, b_bad, history_bad = perceptron_train(X_bad, y_bad_perc, lr=1.0,
      max_epochs=50)
2 print("Number of updates on non-separable data:", len(history_bad))
3 print(history_bad)
4 plot_decision_boundary(X_bad, y_bad_perc, w_bad, b_bad, "Perceptron on Non-
  Separable Data (No Convergence Guarantee)")

```

On running the above code we can see the length of `history_bad` to see the number of updates and we can see the progression of weight updates by simply printing the `history_bad` array but it is unusually long and that will take many pages of this report.

Observed Results Even after multiple epochs of training that were limited to 50, the number of misclassified samples does not drop to zero. The parameters continue to change and the decision boundary keeps oscillating instead of converging to a fixed separator. This behaviour contrasts strongly with the separable case, where only a finite number of updates were required before the boundary stabilized. Here is the result of this training of perceptron on non-linearly separable dataset.

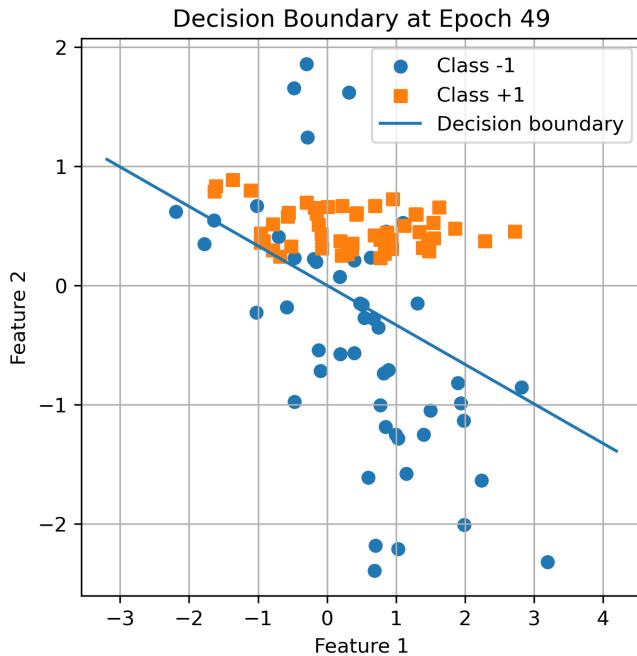


Figure 5: Non-Separable Dataset along with Decision boundary after 50 Epoches.

As of the number of updates at the end of 50 epochs there were 1416 updates and there was no sign of convergence of the algorithm in any case the non-separable case has exceeded the upper limit set by Convergence theorem. As there were many updates it is not a good choice to include

all the plots for all the epoches so for better understading, I am including plots at 10th epoches in the [Appendix](#)

1 Number of updates on non-separable data: 1416

Conclusion The continual fluctuations in the decision boundary are a consequence of the overlapping nature of the classes. Since no linear boundary can correctly classify all samples, the update rule is repeatedly triggered. The perceptron therefore continues to modify the weights indefinitely or until the preset maximum number of epochs is reached. The decision boundary observed during training often swings between correcting different regions of the feature space, producing no stable solution.

Appendix

Appendix A

Perceptron Weight and Bias Updates

Here is the complete result that was obtained after each of 21 updates of the weights and bias stored in the history array as in the code.

Listing A.1: Full history of (w, b) updates used for animation

```
1 history array at epoch {0} sample {3} : [(array([3.18173012, 4.02398429])
2 , -1.0)]
3
4 history array at epoch {0} sample {12} : [(array([3.18173012,
5 4.02398429]), -1.0), (array([ 3.1378471 , -1.93786434]), 0.0)]
6
7 history array at epoch {0} sample {18} : [(array([3.18173012,
8 4.02398429]), -1.0), (array([ 3.1378471 , -1.93786434]), 0.0), (array([
9 2.77318887, -0.2633231 ]), 1.0)]
10
11 history array at epoch {0} sample {35} : [(array([3.18173012,
12 4.02398429]), -1.0), (array([ 3.1378471 , -1.93786434]), 0.0), (array([
13 2.77318887, -0.2633231 ]), 1.0), (array([ 2.12962518, -1.94226489]), 2.0)]
14
15 history array at epoch {0} sample {48} : [(array([3.18173012,
16 4.02398429]), -1.0), (array([ 3.1378471 , -1.93786434]), 0.0), (array([
17 2.77318887, -0.2633231 ]), 1.0), (array([ 2.12962518, -1.94226489]), 2.0),
  (array([4.32446697, 1.01781785]), 1.0)]
18
19 history array at epoch {0} sample {51} : [(array([3.18173012,
20 4.02398429]), -1.0), (array([ 3.1378471 , -1.93786434]), 0.0), (array([
21 2.77318887, -0.2633231 ]), 1.0), (array([ 2.12962518, -1.94226489]), 2.0),
  (array([4.32446697, 1.01781785]), 1.0), (array([3.62140857, 1.31221853]), 2.0)]
22
23 history array at epoch {0} sample {59} : [(array([3.18173012,
24 4.02398429]), -1.0), (array([ 3.1378471 , -1.93786434]), 0.0), (array([
25 2.77318887, -0.2633231 ]), 1.0), (array([ 2.12962518, -1.94226489]), 2.0),
  (array([4.32446697, 1.01781785]), 1.0), (array([3.62140857, 1.31221853]), 2.0),
  (array([ 3.40910773, -1.09605838]), 3.0)]
26
27 history array at epoch {0} sample {65} : [(array([3.18173012,
28 4.02398429]), -1.0), (array([ 3.1378471 , -1.93786434]), 0.0), (array([
29 2.77318887, -0.2633231 ]), 1.0), (array([ 2.12962518, -1.94226489]), 2.0),
  (array([4.32446697, 1.01781785]), 1.0), (array([3.62140857, 1.31221853]), 2.0),
  (array([ 3.40910773, -1.09605838]), 3.0), (array([2.08122805,
30 1.95332431]), 4.0)]
31
32 history array at epoch {0} sample {68} : [(array([3.18173012,
33 4.02398429]), -1.0), (array([ 3.1378471 , -1.93786434]), 0.0), (array([
34 2.77318887, -0.2633231 ]), 1.0), (array([ 2.12962518, -1.94226489]), 2.0),
```

```

18     (array([4.32446697, 1.01781785]), 1.0), (array([3.62140857, 1.31221853]), 2.0), (array([ 3.40910773, -1.09605838]), 3.0), (array([2.08122805, 1.95332431]), 4.0), (array([5.18645851, 0.264209 ]), 3.0)]
19 history array at epoch {0} sample {84} : [(array([3.18173012, 4.02398429]), -1.0), (array([ 3.1378471, -1.93786434]), 0.0), (array([ 2.77318887, -0.2633231]), 1.0), (array([ 2.12962518, -1.94226489]), 2.0), (array([4.32446697, 1.01781785]), 1.0), (array([3.62140857, 1.31221853]), 2.0), (array([ 3.40910773, -1.09605838]), 3.0), (array([2.08122805, 1.95332431]), 4.0), (array([5.18645851, 0.264209 ]), 3.0), (array([ 4.47104397, -3.36906979]), 4.0)]
20 history array at epoch {0} sample {89} : [(array([3.18173012, 4.02398429]), -1.0), (array([ 3.1378471, -1.93786434]), 0.0), (array([ 2.77318887, -0.2633231]), 1.0), (array([ 2.12962518, -1.94226489]), 2.0), (array([4.32446697, 1.01781785]), 1.0), (array([3.62140857, 1.31221853]), 2.0), (array([ 3.40910773, -1.09605838]), 3.0), (array([2.08122805, 1.95332431]), 4.0), (array([5.18645851, 0.264209 ]), 3.0), (array([ 4.47104397, -3.36906979]), 4.0), (array([7.04722514, 2.53839253]), 3.0)]
21 history array at epoch {0} sample {99} : [(array([3.18173012, 4.02398429]), -1.0), (array([ 3.1378471, -1.93786434]), 0.0), (array([ 2.77318887, -0.2633231]), 1.0), (array([ 2.12962518, -1.94226489]), 2.0), (array([4.32446697, 1.01781785]), 1.0), (array([3.62140857, 1.31221853]), 2.0), (array([ 3.40910773, -1.09605838]), 3.0), (array([2.08122805, 1.95332431]), 4.0), (array([5.18645851, 0.264209 ]), 3.0), (array([ 4.47104397, -3.36906979]), 4.0), (array([7.04722514, 2.53839253]), 3.0), (array([6.51581261, 2.66839097]), 4.0)]
22 history array at epoch {1} sample {1} : [(array([3.18173012, 4.02398429]), -1.0), (array([ 3.1378471, -1.93786434]), 0.0), (array([ 2.77318887, -0.2633231]), 1.0), (array([ 2.12962518, -1.94226489]), 2.0), (array([4.32446697, 1.01781785]), 1.0), (array([3.62140857, 1.31221853]), 2.0), (array([ 3.40910773, -1.09605838]), 3.0), (array([2.08122805, 1.95332431]), 4.0), (array([5.18645851, 0.264209 ]), 3.0), (array([ 4.47104397, -3.36906979]), 4.0), (array([7.04722514, 2.53839253]), 3.0), (array([6.51581261, 2.66839097]), 4.0), (array([6.01817204, 1.20608633]), 5.0)]
23 history array at epoch {1} sample {2} : [(array([3.18173012, 4.02398429]), -1.0), (array([ 3.1378471, -1.93786434]), 0.0), (array([ 2.77318887, -0.2633231]), 1.0), (array([ 2.12962518, -1.94226489]), 2.0), (array([4.32446697, 1.01781785]), 1.0), (array([3.62140857, 1.31221853]), 2.0), (array([ 3.40910773, -1.09605838]), 3.0), (array([2.08122805, 1.95332431]), 4.0), (array([5.18645851, 0.264209 ]), 3.0), (array([ 4.47104397, -3.36906979]), 4.0), (array([7.04722514, 2.53839253]), 3.0), (array([6.51581261, 2.66839097]), 4.0), (array([6.01817204, 1.20608633]), 5.0), (array([ 5.30919124, -0.21012546]), 6.0)]
24 history array at epoch {1} sample {8} : [(array([3.18173012, 4.02398429]), -1.0), (array([ 3.1378471, -1.93786434]), 0.0), (array([ 2.77318887, -0.2633231]), 1.0), (array([ 2.12962518, -1.94226489]), 2.0), (array([4.32446697, 1.01781785]), 1.0), (array([3.62140857, 1.31221853]), 2.0), (array([ 3.40910773, -1.09605838]), 3.0), (array([2.08122805, 1.95332431]), 4.0), (array([5.18645851, 0.264209 ]), 3.0), (array([ 4.47104397, -3.36906979]), 4.0), (array([7.04722514, 2.53839253]), 3.0), (array([6.51581261, 2.66839097]), 4.0), (array([6.01817204, 1.20608633]), 5.0), (array([ 5.30919124, -0.21012546]), 6.0), (array([4.19188526, 1.28706508]), 7.0)]
25 history array at epoch {1} sample {12} : [(array([3.18173012, 4.02398429]), -1.0), (array([ 3.1378471, -1.93786434]), 0.0), (array([ 2.77318887, -0.2633231]), 1.0), (array([ 2.12962518, -1.94226489]), 2.0), (array([4.32446697, 1.01781785]), 1.0), (array([3.62140857, 1.31221853]), 2.0), (array([ 3.40910773, -1.09605838]), 3.0), (array([2.08122805, 1.95332431]), 4.0), (array([5.18645851, 0.264209 ]), 3.0), (array([ 4.47104397, -3.36906979]), 4.0), (array([7.04722514, 2.53839253]), 3.0), (array([6.51581261, 2.66839097]), 4.0), (array([6.01817204, 1.20608633]), 5.0), (array([ 5.30919124, -0.21012546]), 6.0), (array([4.19188526, 1.28706508]), 7.0)]

```

```

2.77318887, -0.2633231]), 1.0), (array([ 2.12962518, -1.94226489]), 2.0),
(array([4.32446697, 1.01781785]), 1.0), (array([3.62140857, 1.31221853]),
2.0), (array([ 3.40910773, -1.09605838]), 3.0), (array([2.08122805,
1.95332431]), 4.0), (array([5.18645851, 0.264209 ]), 3.0), (array([
4.47104397, -3.36906979]), 4.0), (array([7.04722514, 2.53839253]), 3.0), (
array([6.51581261, 2.66839097]), 4.0), (array([6.01817204, 1.20608633]),
5.0), (array([ 5.30919124, -0.21012546]), 6.0), (array([4.19188526,
1.28706508]), 7.0), (array([ 4.14800223, -4.67478355]), 8.0)]
```

32

```

33 history array at epoch {1} sample {17} : [(array([3.18173012,
4.02398429]), -1.0), (array([ 3.1378471 , -1.93786434]), 0.0), (array([
2.77318887, -0.2633231]), 1.0), (array([ 2.12962518, -1.94226489]), 2.0),
(array([4.32446697, 1.01781785]), 1.0), (array([3.62140857, 1.31221853]),
2.0), (array([ 3.40910773, -1.09605838]), 3.0), (array([2.08122805,
1.95332431]), 4.0), (array([5.18645851, 0.264209 ]), 3.0), (array([
4.47104397, -3.36906979]), 4.0), (array([7.04722514, 2.53839253]), 3.0), (
array([6.51581261, 2.66839097]), 4.0), (array([6.01817204, 1.20608633]),
5.0), (array([ 5.30919124, -0.21012546]), 6.0), (array([4.19188526,
1.28706508]), 7.0), (array([ 4.14800223, -4.67478355]), 8.0), (array([
7.90712105, -2.99617403]), 7.0)]
```

34

```

35 history array at epoch {1} sample {18} : [(array([3.18173012,
4.02398429]), -1.0), (array([ 3.1378471 , -1.93786434]), 0.0), (array([
2.77318887, -0.2633231]), 1.0), (array([ 2.12962518, -1.94226489]), 2.0),
(array([4.32446697, 1.01781785]), 1.0), (array([3.62140857, 1.31221853]),
2.0), (array([ 3.40910773, -1.09605838]), 3.0), (array([2.08122805,
1.95332431]), 4.0), (array([5.18645851, 0.264209 ]), 3.0), (array([
4.47104397, -3.36906979]), 4.0), (array([7.04722514, 2.53839253]), 3.0), (
array([6.51581261, 2.66839097]), 4.0), (array([6.01817204, 1.20608633]),
5.0), (array([ 5.30919124, -0.21012546]), 6.0), (array([4.19188526,
1.28706508]), 7.0), (array([ 4.14800223, -4.67478355]), 8.0), (array([
7.90712105, -2.99617403]), 7.0), (array([ 7.54246282, -1.32163278]), 8.0)]
```

36

```

37 history array at epoch {1} sample {65} : [(array([3.18173012,
4.02398429]), -1.0), (array([ 3.1378471 , -1.93786434]), 0.0), (array([
2.77318887, -0.2633231]), 1.0), (array([ 2.12962518, -1.94226489]), 2.0),
(array([4.32446697, 1.01781785]), 1.0), (array([3.62140857, 1.31221853]),
2.0), (array([ 3.40910773, -1.09605838]), 3.0), (array([2.08122805,
1.95332431]), 4.0), (array([5.18645851, 0.264209 ]), 3.0), (array([
4.47104397, -3.36906979]), 4.0), (array([7.04722514, 2.53839253]), 3.0), (
array([6.51581261, 2.66839097]), 4.0), (array([6.01817204, 1.20608633]),
5.0), (array([ 5.30919124, -0.21012546]), 6.0), (array([4.19188526,
1.28706508]), 7.0), (array([ 4.14800223, -4.67478355]), 8.0), (array([
7.90712105, -2.99617403]), 7.0), (array([ 7.54246282, -1.32163278]), 8.0),
(array([6.21458314, 1.72774991]), 9.0)]
```

38

```

39 history array at epoch {1} sample {69} : [(array([3.18173012,
4.02398429]), -1.0), (array([ 3.1378471 , -1.93786434]), 0.0), (array([
2.77318887, -0.2633231]), 1.0), (array([ 2.12962518, -1.94226489]), 2.0),
(array([4.32446697, 1.01781785]), 1.0), (array([3.62140857, 1.31221853]),
2.0), (array([ 3.40910773, -1.09605838]), 3.0), (array([2.08122805,
1.95332431]), 4.0), (array([5.18645851, 0.264209 ]), 3.0), (array([
4.47104397, -3.36906979]), 4.0), (array([7.04722514, 2.53839253]), 3.0), (
array([6.51581261, 2.66839097]), 4.0), (array([6.01817204, 1.20608633]),
5.0), (array([ 5.30919124, -0.21012546]), 6.0), (array([4.19188526,
1.28706508]), 7.0), (array([ 4.14800223, -4.67478355]), 8.0), (array([
7.90712105, -2.99617403]), 7.0), (array([ 7.54246282, -1.32163278]), 8.0),
(array([6.21458314, 1.72774991]), 9.0), (array([ 8.21434374, -0.86731136]),
8.0)]
```

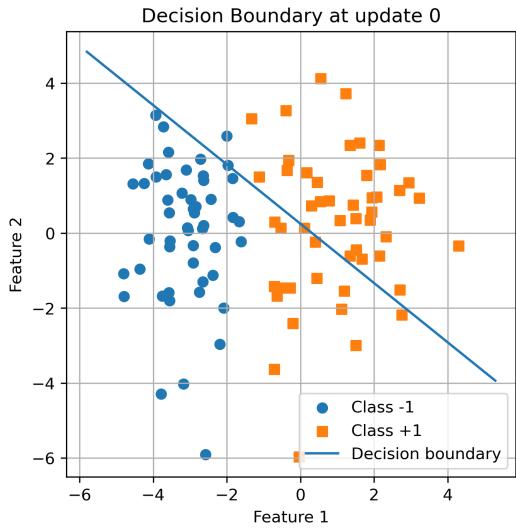
40

```

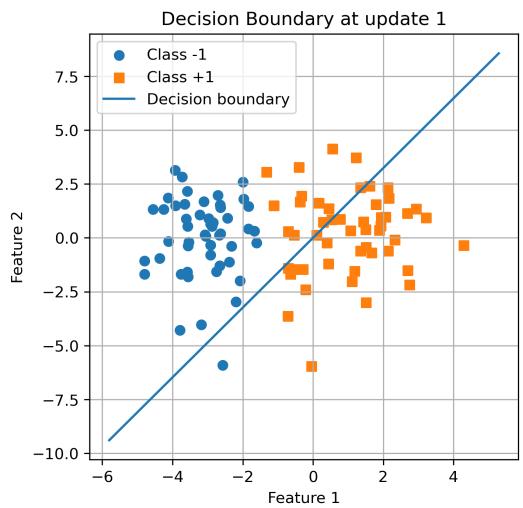
41 history array at epoch {2} sample {8} : [(array([3.18173012, 4.02398429])]
```

```
, -1.0), (array([ 3.1378471 , -1.93786434]), 0.0), (array([ 2.77318887,
-0.2633231 ]), 1.0), (array([ 2.12962518, -1.94226489]), 2.0), (array
([4.32446697, 1.01781785]), 1.0), (array([3.62140857, 1.31221853]), 2.0), (
array([ 3.40910773, -1.09605838]), 3.0), (array([2.08122805, 1.95332431]),
4.0), (array([5.18645851, 0.264209 ]), 3.0), (array([ 4.47104397,
-3.36906979]), 4.0), (array([7.04722514, 2.53839253]), 3.0), (array
([6.51581261, 2.66839097]), 4.0), (array([6.01817204, 1.20608633]), 5.0), (
array([ 5.30919124, -0.21012546]), 6.0), (array([4.19188526, 1.28706508]),
7.0), (array([ 4.14800223, -4.67478355]), 8.0), (array([ 7.90712105,
-2.99617403]), 7.0), (array([ 7.54246282, -1.32163278]), 8.0), (array
([6.21458314, 1.72774991]), 9.0), (array([ 8.21434374, -0.86731136]), 8.0),
(array([7.09703775, 0.62987918]), 9.0)]
```

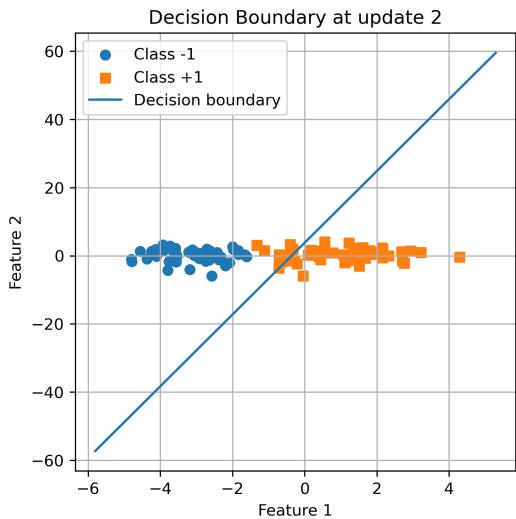
Plots of Decision Boundary



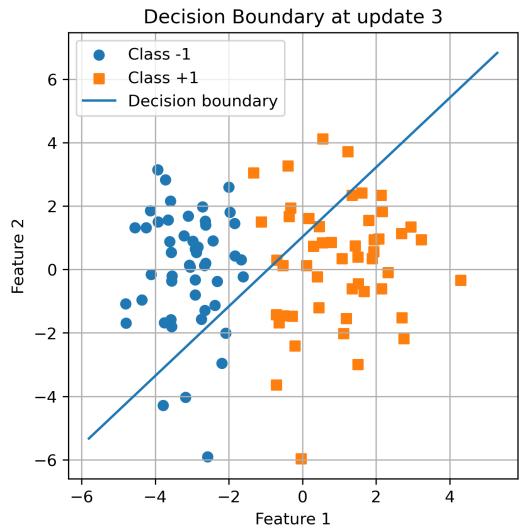
(a) Plot 1



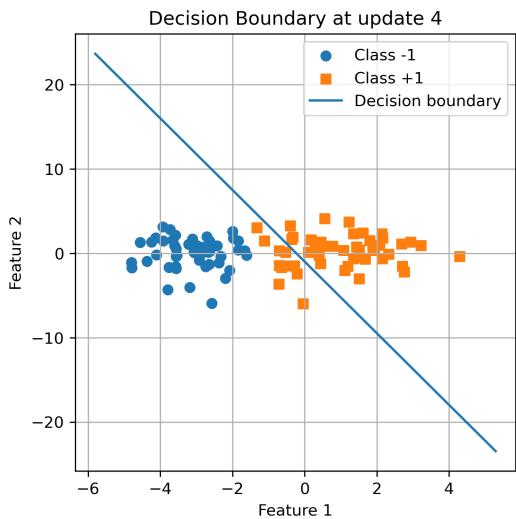
(b) Plot 2



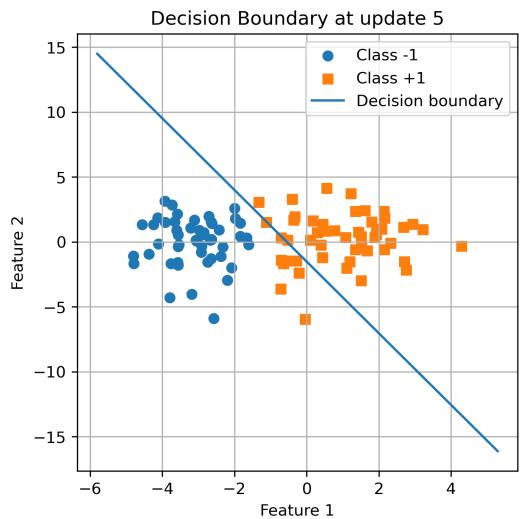
(c) Plot 3



(d) Plot 4

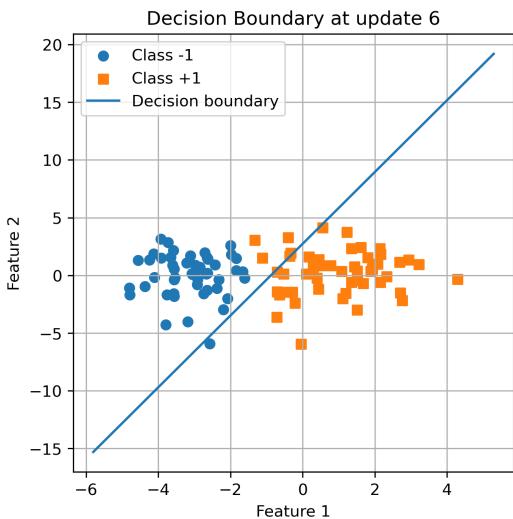


(e) Plot 5

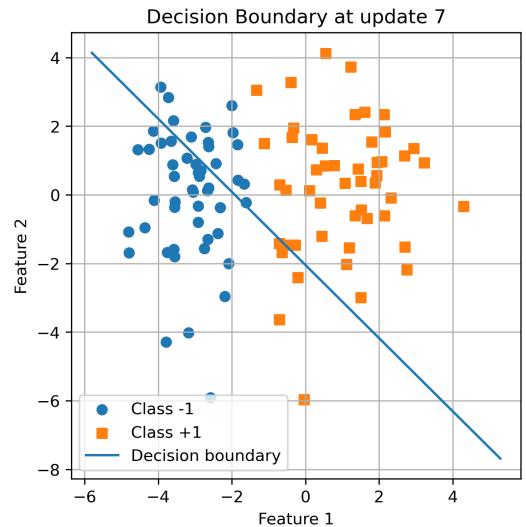


(f) Plot 6

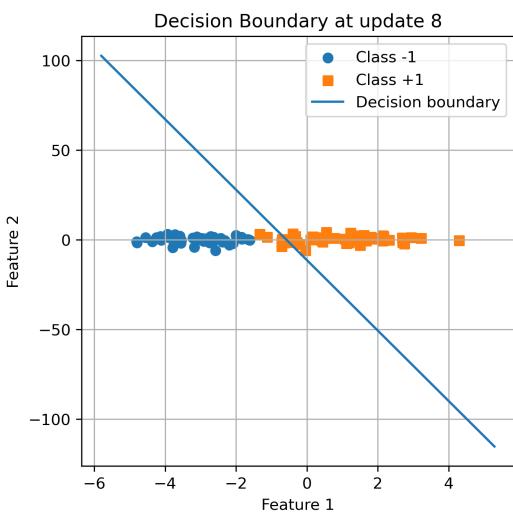
Figure A.1: Evolution of Perceptron Decision Boundary



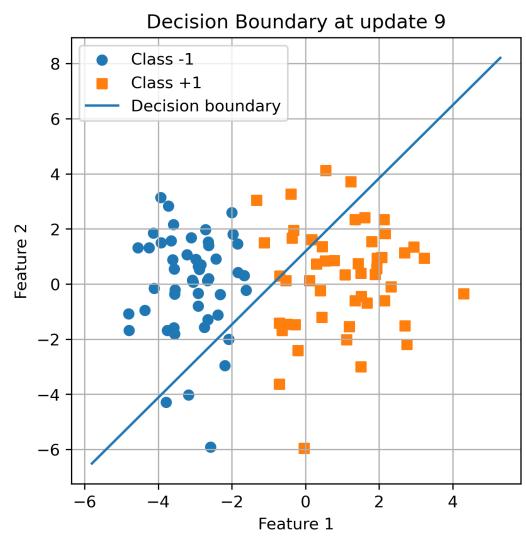
(a) Plot 7



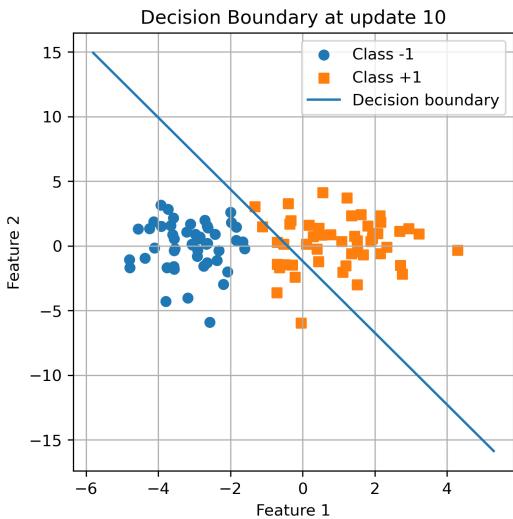
(b) Plot 8



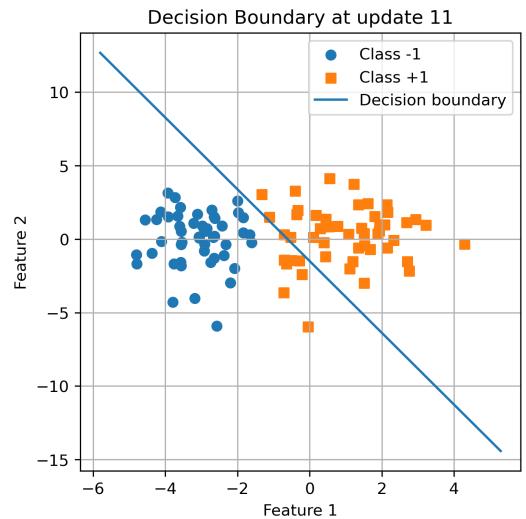
(c) Plot 9



(d) Plot 10



(e) Plot 11



(f) Plot 12

Figure A.2: Evolution of Perceptron Decision Boundary

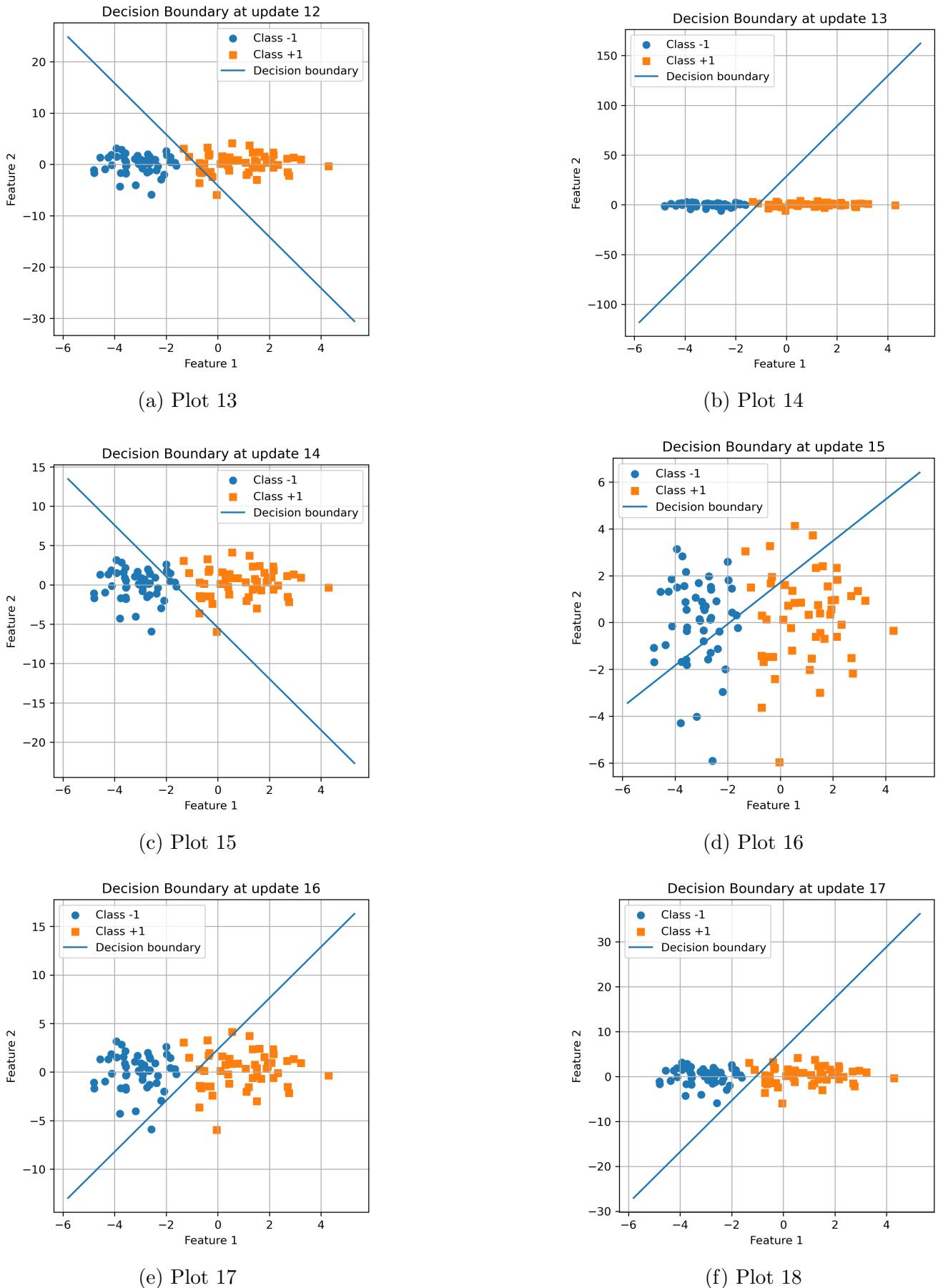


Figure A.3: Evolution of Perceptron Decision Boundary

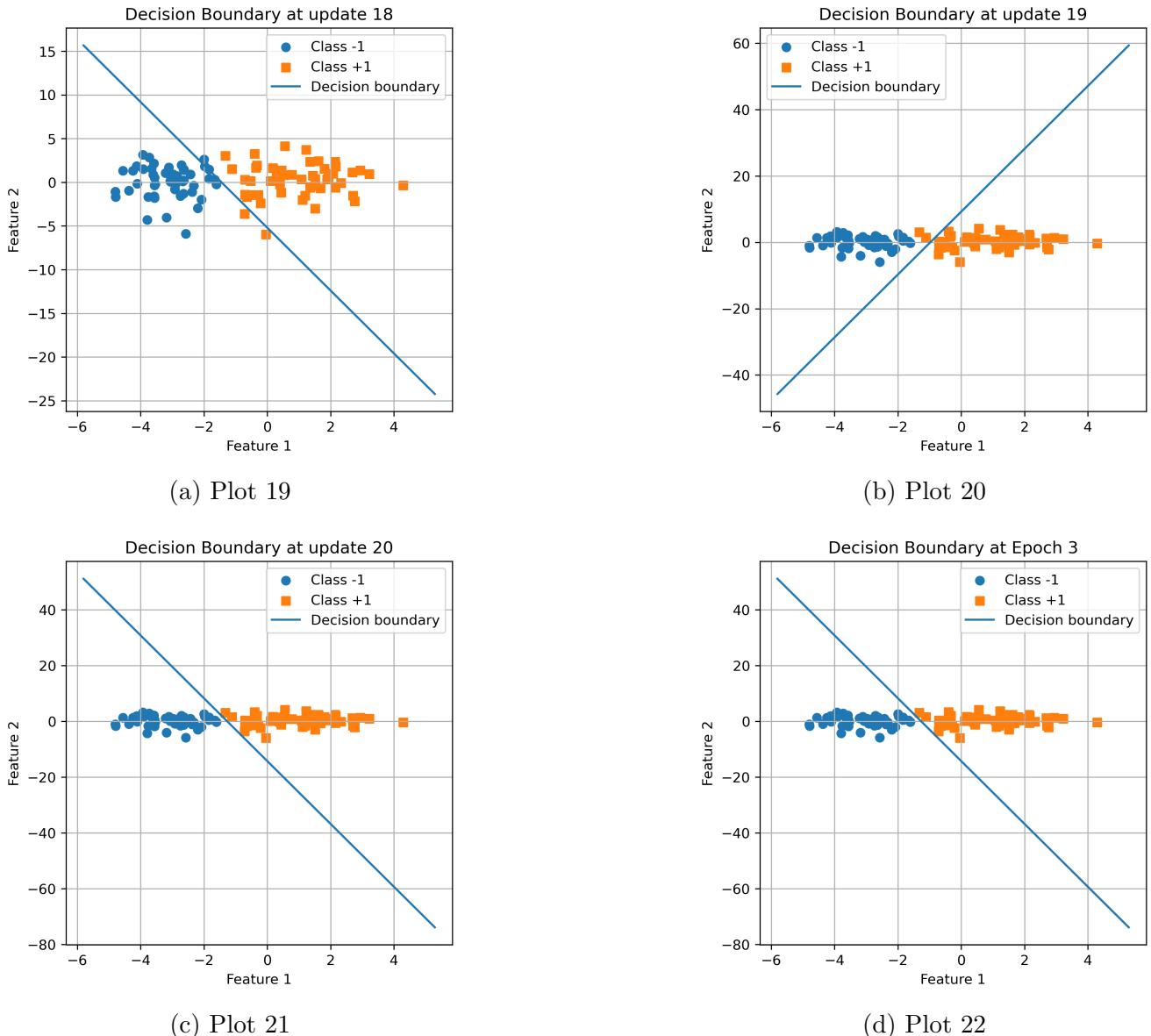
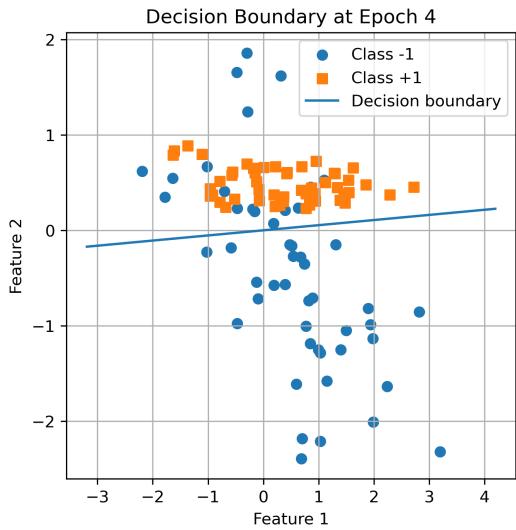
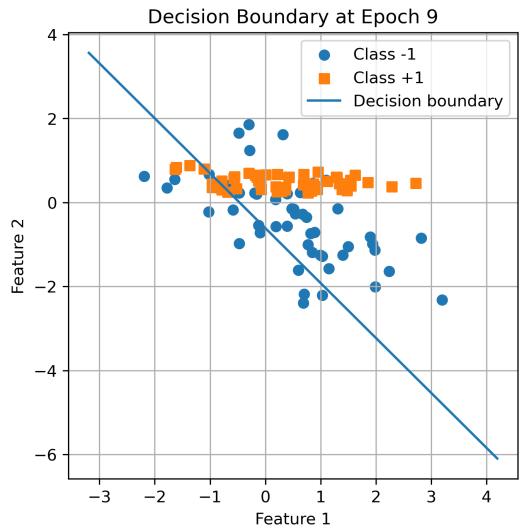


Figure A.4: Evolution of Perceptron Decision Boundary

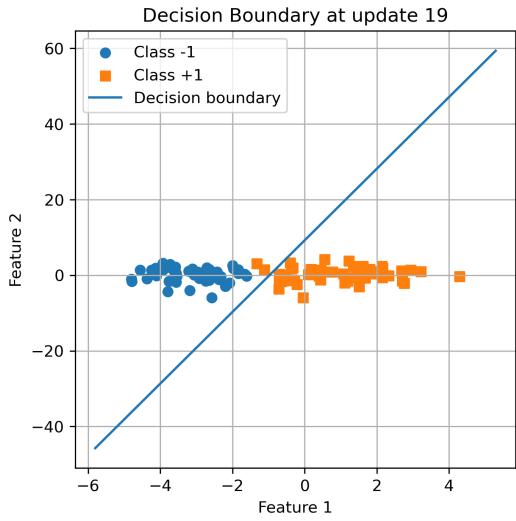
Non-Separable Plots



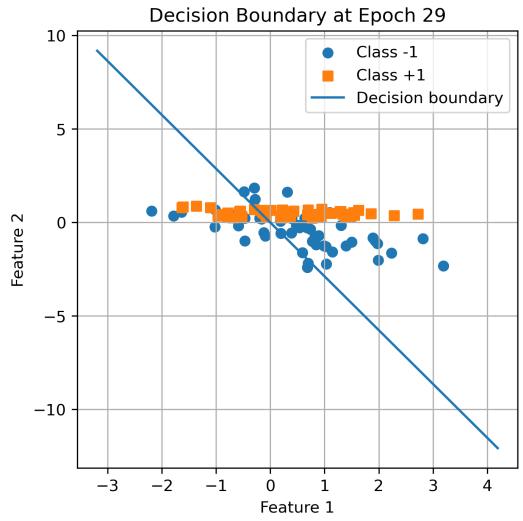
(a) Plot 4



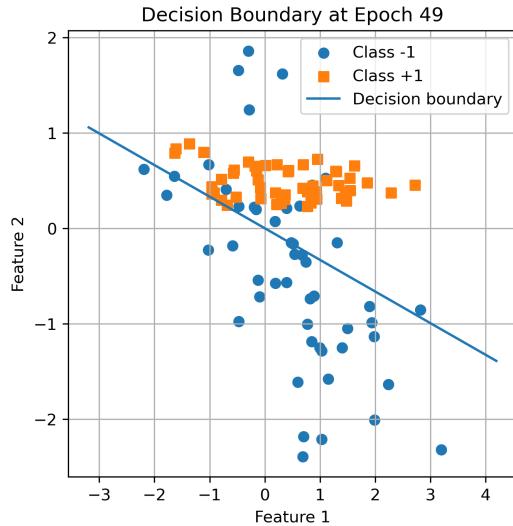
(b) Plot 9



(c) Plot 19



(d) Plot 29



(e) Plot 49

Appendix B

Code and Repository

The complete source code used for data generation, perceptron training, visualization, animation, and theoretical margin computation is available in the official Git repository linked below. The repository also contains:

- Python implementations of the perceptron algorithm (with bias),
- Synthetic dataset generation scripts,
- Plotting utilities for decision boundary evolution,
- Full report L^AT_EX source file,
- Experimental results and saved convergence plots.

GitHub Repository Link:

[Repository Link](#)