**Imperial College London**

IMPERIAL COLLEGE LONDON

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# Title

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**Abstract**

Your abstract.

# Acknowledgments

Comment this out if not needed.

# Contents

# Chapter 1

# Introduction

The application of remote learning in higher education has increased massively since the explosion of COVID-19 [1]. Many institutions including Imperial College London moved their courses online during lockdowns. These courses are taught based on online systems. However, some online systems are not capable of conducting the digitalisation of teaching tasks such as lecture recording/playing and assignment marking etc. For example, some departments of Imperial College London were using Möbius for online assignment and assessment, but it was complained by students and staffs that the system was hard to use. This thus leads to a demand of updating or developing new systems so that students and teachers can get better experience.

Therefore, the college has decided to develop a new online learning system named Lambda Feedback. This system is a web application which allows students to do assignments posted by teachers and get feedback immediately. Comparing to its predecessor Möbius, Lambda Feedback has modern user interface, friendly interaction and much more features. One of the features is the expression input. In many assignment questions, solutions are math expressions. In Lambda Feedback, users can input math expressions in a text field, and the system is able to understand the expression and check if it is correct. Figure 1.1 is a screenshot of a demo in Lambda Feedback. The webpage displays a navigation sidebar, the question, and the answer area, where users can input the expression.

However, the current system only supports keyboard input for math expressions. Users need to type the whole expression including symbols and operators, which can be very inconvenient and complex especially for complicated equations. Consequently, an extension with a new method of input is needed for the system.

Handwriting input is considered appropriate for the system because of its convenience and simplicity. Although there are other input methods such as equation editor and image upload, they either require users to learn how to use, or need some extra steps. This means they are not suitable as the major approach of expression input, but can be a good supplement to handwriting input in some special situations.

This project thus aims to develop a component with handwriting input and equa-
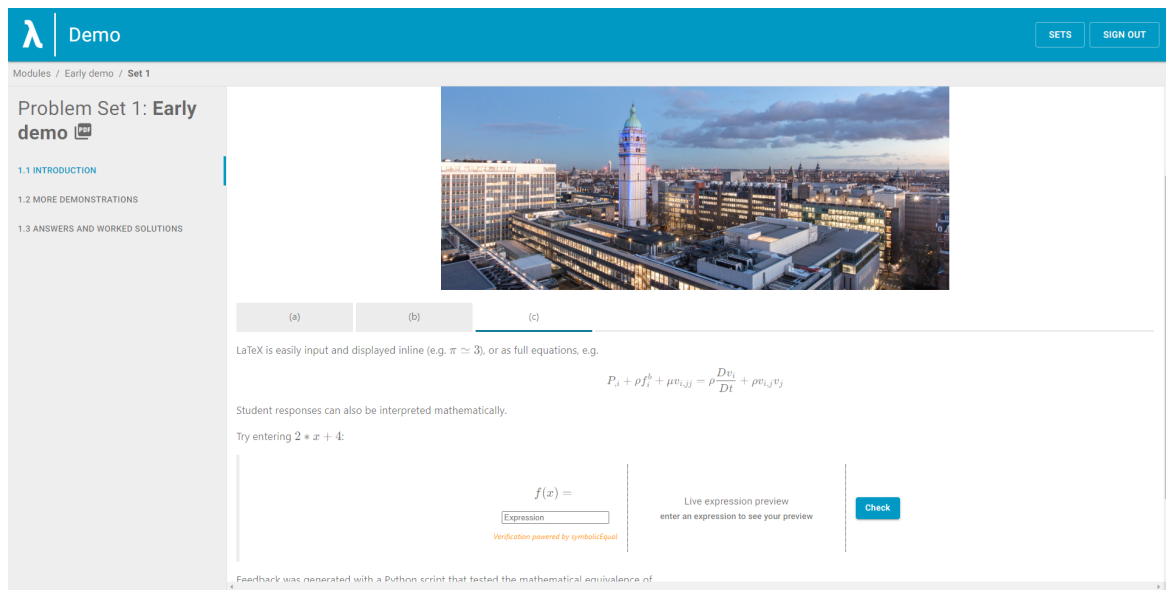
**Figure 1.1:** Screenshot of a Demo in Lambada Feedback System

tion recognition, and integrate it to the Lambda Feedback system. The component shall enable the users to write on it either via mouse/touchpad on computers or fingers/pens on mobile devices. After users finish a stroke, it should be able to recognize the equation and display the result alongside the writing area. Integration with the Lambda Feedback system should be carried out after the component is tested available.

This report records the development of the project. Chapter 2 investigates several approaches to realise the software component and analyses their advantages and drawbacks. Chapter 3 states the process of development and explains the implementation of the software component. In Chapter 4, progressive results are demonstrated and the final achievement is shown. An evaluation of the results are included in this chapter as well. Finally, in chapter 5, a conclusion of the project is drawn, and possible future improvements are listed.

# Chapter 2

# Background

This chapter records the background research, which includes general reviews on articles, tutorials and existing projects that have helped the development of this project, as well as potential choices that could be taken and why they were discarded, along with the reasons of selecting current tools. An overview of the project is made below before diving into details.

## Overview

The component to develop is a TypeScript (strong typed version of JavaScript) web application which has two major functionalities:

1. Have a canvas where users can write equation

2. Ability to recognise the equation written on canvas and display the result

In addition, the application should include some functions for editing the user's drawing, such as undo, redo, delete all and remove stroke.

Moreover, the component should be integrated into Lambda Feedback, so it is necessary to introduce the system because they will use same frameworks and language.

Lambda Feedback is a web application which has a frontend and a backend. The frontend is built upon NextJS (a framework built on React), and the backend is built upon NestJS. Both are written in Typescript (These frameworks will be introduced in Chapter 2.1). Most code of the project will be installed in a component of the frontend named `ResponseArea`, which is responsible for receiving input and giving result to users.

It is difficult to develop the component directly upon Lambda Feedback, as it already had much code when this project launched. Therefore, it was decided to build a web application independent of Lambda Feedback to save time on reading code and testing functionality.

Although the final independent web application must be written under the same framework with Lambda Feedback, i.e. React, there is another way, Vanilla JavaScript (also referred to as plain JS), to start with. Table 2.1 compares the two methods:

**Table 2.1:** Comparison of Two Methods for Independent Web Application

| Method | Advantages | Disadvantages |
|---|---|---|
| Vanilla JS | Easy to start & Require no extra configuration | Does not fit Lambda Feedback |
| React | Uses same framework as Lambda Feedback - does not need extra steps for integration | Need to study React before start |

After careful consideration, it was decided to start by using Vanilla JS to get familiar with functionalities, and then converting the application to React. This makes the procedure more fluent and only need to focus on one emphasis for every update.

Overall, the procedure of the project is:

1. Develop a web application with Vanilla JS which enables users to draw equations, and recognise the equation

2. Move the web application under React framework

3. Integrate the application as a component to Lambda Feedback

Despite using different frameworks during the procedure, the approaches to realise functionalities are the same. Hence, the background research mainly focuses on three parts:

- React framework and integration with the Lambda Feedback

- A canvas where users can draw stuffs

- Functionality of mathematical equation recognition

Therefore, the remaining part of this chapter is divided into three sections, each introducing one part.

## 2.1   React and Lambda Feedback

Lambda Feedback's frontend is built upon NextJS, a framework based on React. Distinct features of NextJS mainly focus on page level optimization, and the method of building a component remains the same as React. Therefore, it is necessary to learn React framework before building the component for Lambda Feedback, but only need to have a general understanding of NextJS.

React is an open-source frontend library deployed to develop reusable user interface (UI) components. Unlike Vanilla JS which structures all the layouts of a webpage in one file, React focuses on the idea of components [2].

In Vanilla JS, layouts, functions and styles of a webpage are written in HTML, JS and CSS file respectively.  However, in React, the webpage is assembled by React components.  This makes component the basic unit in React.  Layout and functions of a component are in the same file whose type is JSX. Even styles can be embedded in it as well.  This means only one file is needed for one component [2].  Figure 2.1 shows the design pattern of VanillaJS and React.  It can be found from Figure 2.1
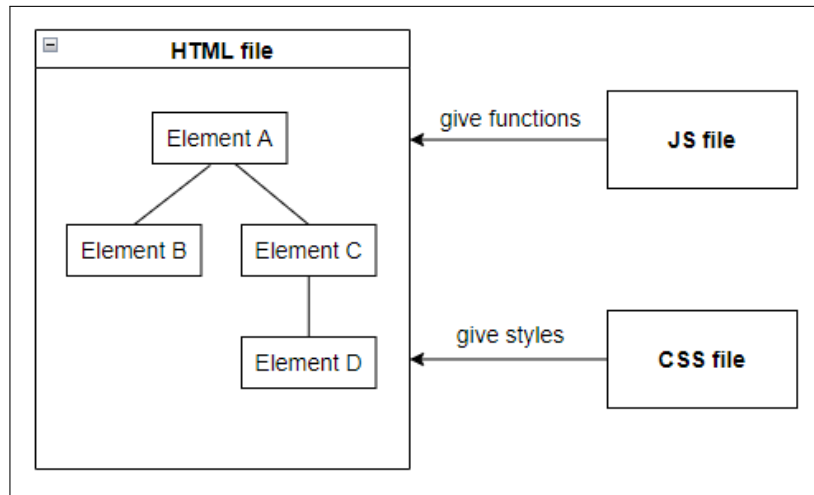


**(a)** Design Pattern of Vanilla JS
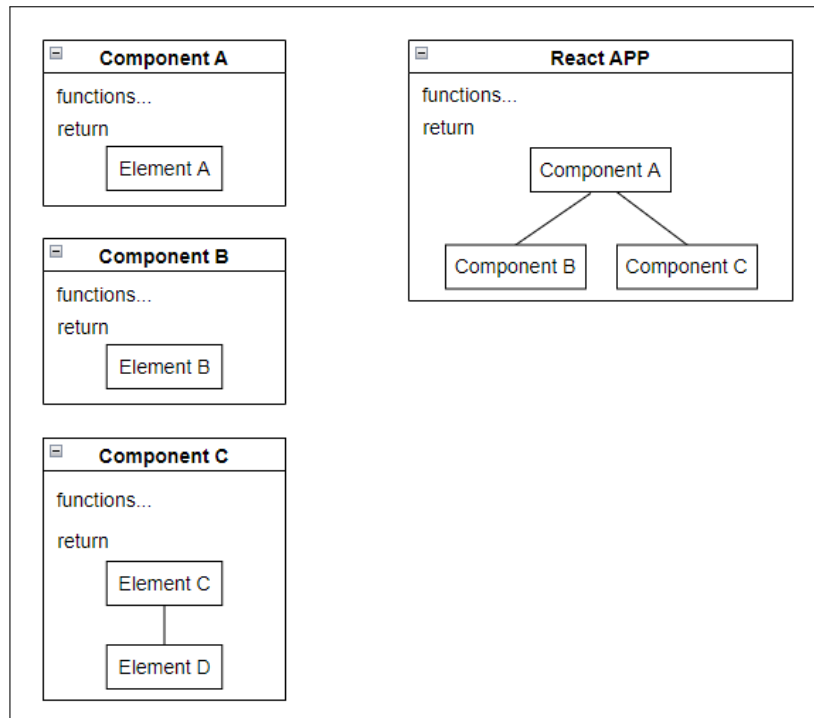


**(b)** Design Pattern of React

**Figure 2.1:** Comparison of Vanilla JS and React

that React is more flexible than Vanilla JS as its components can be plugged into other React APPs conveniently, whereas the structure of Vanilla JS is fixed.

The method of writing a React component in JSX is similar with writing a class. The class contains functions needed for the component, and has a return function which returns the layout of the component in HTML. Styles can either be imported from a CSS file, or specified in the JSX file.

A React component can have attributes, which can either be constants or functions (presented as function typed constant). Attributes of a component are defined by external classes, normally its parent component, when the component is used. Examples of attribites can be:

- Height, width. . .

- onClick - function happened in parent component when this component is clicked

The class can be simplified to a function typed constant when feature Hooks is introduced. The constant behaves exactly the same as a function but can be exported so that other components can use it.

Apart from the idea of JSX and component, Hooks is another important feature used in this project.

Without Hooks, React components were written in classes and had to contain many React features, which had made the development complicated. To solve this, Hooks were published. Hooks are essentially functions which encapsulate React features by using existing JavaScript features, so that developers do not need to learn extra syntaxes of React, but only need to focus on functions needed for the component [3].

There are three Hooks used in the project: `useState`, `useEffect` and `useRef`.

## Hook: `useState`

`useState` function declares a state variable. An example of `useState` is as following:

```
const [count, setCount] = useState(0)
```

In this line of code, variable `count` is declared as a state of the component, and it can only be modified using function `setCount`. It is initialised to 0 which is a parameter of `useState`.

The state variables are useful in the component they are monitored by React, so that the component can 'react' to any change of a state variable. For example, the `count` variable is used in an element:

```
return (<div>{count}</div>)
```

This line returns the structure of the component, which simply displays the `count` variable. When `count` changes, React will automatically re-render this element so that the updated `count` is displayed.

## Hook: `useEffect`

`useEffect` allows the developer to add side effect to the change of a state variable. An example is as following:

$$\texttt{useEffect(() => \{do something\}, [state])}$$

When `state` changes, function in `useEffect` is invoked.

## Hook: `useRef`

`useRef` creates a reference to an element in the component, so that APIs of the element can be used, and other functions can refer to this element.

These are the main React features of that will be utilised in this project for the React component.

To integrate the component into Lambda Feedback, context in Lambda Feedback should be examined.

The component is a handwriting input tool. In Lambda Feedback, there is a component `ResponseArea`, where users can input their result and get feedback from backend. Inside `ResponseArea`, there is a type folder containing all the types of input. One of them is `ExpressionInput`. The handwriting input component will be installed inside the `ExpressionInput` component as an extension input method of expression input. It was considered firstly to add a new input type in `ResponseArea`, but this needs to change 15 files in frontend and 15 files in backend and can be difficult testing as well. Therefore, it was dicided to install it upon an existing type, `ExpressionInput`, so that minimal changes will be done to the big project, and is much easier to test.

Details of `ExpressionInput` and the process of integration will be presented in Chapter 3.2.

Chapter 2.1 has investigated features of React and the component where this project is installed in Lambda Feedback. The next section will then discover different choices to realise a handwriting canvas.

## 2.2 Canvas

A handwriting canvas is needed for the component, which should do the following:

- Users can draw and edit stuffs

- The canvas can output the content, either by image or stroke data

Here, stroke data means positions that represent points on the strokes. For example, stroke `{1, 1}, {2, 2}, {3, 3}` means a line starting at point (1, 1), passing point

(2, 2) and ends at (3, 3). All paths drawn on the canvas can be expressed as stroke data.

Two HTML elements - `canvas` and `SVG` - were investigated for this part.

The `canvas` element is an HTML container used to draw graphics on web page. Graphics are drawn by APIs, which has several methods for drawing, including paths, boxes, circles, text, and adding images [4].

The component can utilize its paths method to display the user's strokes: once the user drags the pointer, the component fetches its position in the canvas, and draws a path to the next position the pointer moves to.

The `canvas` element also provides APIs to output content as images, while stroke data is generated when recording positions of the pointer.

Drawing on `canvas` is easy because all graphics is drawn by APIs, so the component only needs to 'tell' `canvas` how to draw. However, there are two drawbacks of this element:

1. To use `canvas` APIs, the HTML element should be referred. This in React will be using `React Refs`. Unlike in Vanilla JS, API callings in React should be carefully considered with *React Component Lifecycle* [5]. This will affect the performance of the component and brings extra work.

2. The `canvas` element is represented as a Bitmap in webpage. This means when transforming the size of the canvas, graphics might look blurry [6]. This will be further discussed in Chapter 3.

Figure 2.2 is a good example showing how graphics get blurry in `canvas` element when zooming in.
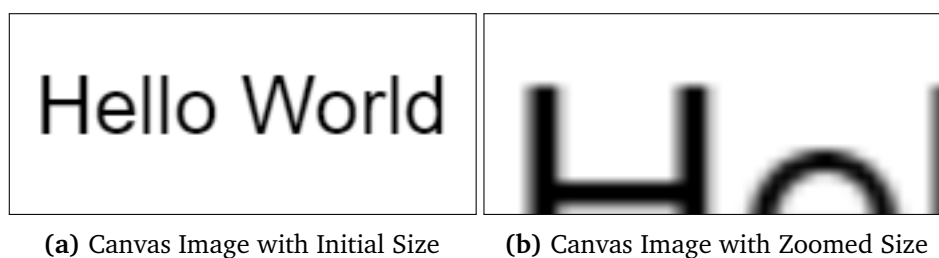


(a) Canvas Image with Initial Size          (b) Canvas Image with Zoomed Size

**Figure 2.2:** Comparison of Unzoomed and Zoomed Canvas

In contrast with `canvas`, the `SVG` element does not have listed problems. The term SVG (Scalable Vector Graphics) means an XML based vector image format for defining 2D graphics. Therefore, as an element in HTML, `SVG` simply represents a container for SVG graphics.

Because it is 'vector graphic', regardless of the ratio of rendered size and programmed size, users can always get a clear graph of what they draw. This thus solve the blurry problem of `canvas`.

`SVG` has several sub-element including `Path` . Data of a `Path` is a string containing commands and points, and is attached to its property 'd'.

To show strokes that a user draws, instead of containing them in one `canvas` element, multiple `Path`s are used to display the user's drawing, each for one stroke. It is more flexible for the programme to monitor and control them.

This feature fits *React Component Lifecycle* perfectly as any change of path data causes React to 'react' to it, and render the path with updated data.

Overall, `SVG` is more suitable than `canvas` for this project due to its vector property and compatibility with React.

Before converting the Vanilla JS application to React component, an existing React component, *React-Sketch-Canvas* [7], was investigated. It has most features this project needs as a canvas, and can be directly installed in Lambda Feedback. However, it only allows the user to erase on a stroke but cannot remove the whole stroke the pointer points. The remove stroke function is considered important as the canvas focuses more on writing than on drawing, and operations on strokes are more important than on the graph. Besides, the existing component has many functions that are not needed but still need to be configured when invoking. Therefore, it was decided to develop a custom canvas with `SVG` so that necessary functions are included and the size of the component is minimised.

## 2.3   Equation Recognition

An equation recognition function is required for the project. The function needs to correctly recognize the content which users draw as an equation. High accuracy is required for this project to ensure good user experience. In addition, response to recognition request should be quick so that live update is available.

Initially, building a model with machine learning was considered, and some tools such as TensorFlow and Pytorch were preliminarily explored. It then turned out that this approach is excessively time-consuming if a high-accuracy model is wanted. Wenqi Zhao, etc.'s project *Handwritten Mathematical Expression Recognition with Bidirectionally Trained Transformer* [8] in 2021 shows that after 8 months of development and training, their model achieved scores of 57.91%, 54.49%, and 56.88% on three different datasets. This apparently does not meet the high accuracy requirement. Although improvements can be made upon existing projects, it is still impossible to train a model with sufficient accuracy within 2 months, and this approach is discarded as a consequence.

As a result, the project finally uses an existing service for mathematical equation recognition: *Mathpix*.

*Mathpix* is a company that focuses on mathematical equation recognition. It provides OCR (Optical Charactor Recognition) APIs for developers so that they can embed this feature in their project. Figure 2.3 shows the pricing of the service.

**Figure 2.3:** Mathpix OCR API Pricing [9]

*Mathpix* receives image data and recognizes the content in the image. If one or multiple equations are found, it can return the result in several styles like Latex, MathML and Asciimath etc. There are also options such as `confidence`, `data type` to assist the user for further process on the reponse data. In addition, it provides complete error messages which is helpful for development.

Although there are other companies providing similar services such as *MyScript*, *Mathpix* is advantageous at its *App Token* and *digital ink* method.

To request recognition, *Mathpix* requires the *API Key* to verify if the access is authorised. Therefore, the *API Key* must not be included in the client end, or they can easily be stolen by hackers by inspecting the app binary. This means that *API Key* and corresponding functions should be implemented in backend, and every time a recognition request is made by client end, it is passed to the backend. The backend then makes the request to *Mathpix* server and returns the response to the client end. This could waste time transmitting data, and bring much load to the backend server when multiple client ends make requests at the same time.

To solve the problem, *Mathpix* provides an *App Token* function, which creates a short live client side token so that client apps can make request directly to *Mathpix* server. In this approach, the clients no longer need to proxy their requests through the backend, but only need to request an *App Token* from the backend. It largely reduces the time on data transmission and load of the backend server.

Figure 2.4 illustrates the procedures of two methods mentioned above.

While other services require the image to be uploaded in their API call, *Mathpix*'s *digital ink* method allows users to upload stroke data, i.e. coordinates of points on strokes, in their API call in order to reduce network load and response time. More-

over, a live processing session for 5 minutes can be created in *digital ink* method. In a session, users can invoke APIs as many times as they but only counts once in pricing, which is much more cost-effective.

In conclusion, *Mathpix* is the best choice regarding accuracy, cost and time and development.

Another thing to be noted is the equation rendering. *Mathpix* can return a latex styled string of the result, but the string cannot be displayed as an equation in web page. Therefore, a rendering tool is needed to parse the latex string and display the equation in the web page.

This project uses `Katex`, which is the same tool used in *Mathpix*. It can render a latex styled equation in one line of code [10]. Details will be

This chapter records the background research on React framework, handwriting canvas to use and method of equation recognition, and givs reasons why `SVG` element and *Mathpix* are used in the project. In Chapter 3, the implementation of the Vanilla JS application, conversion to React component and integration with Lambda Feedback is explained.
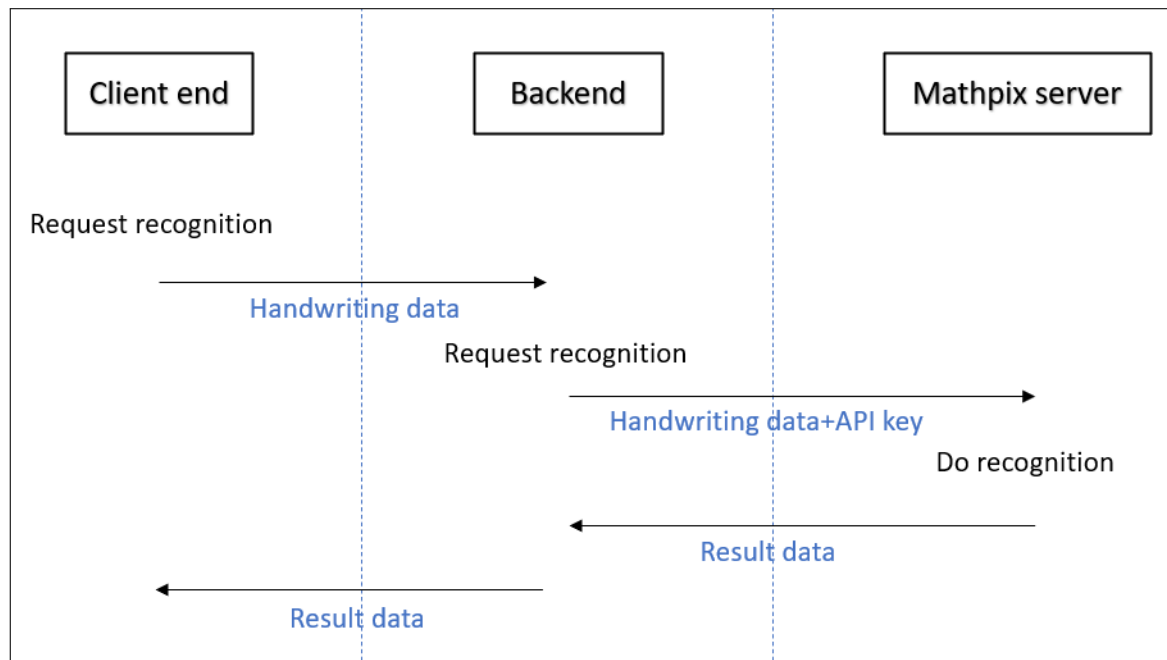
**(a)** Use API Key for Recognition
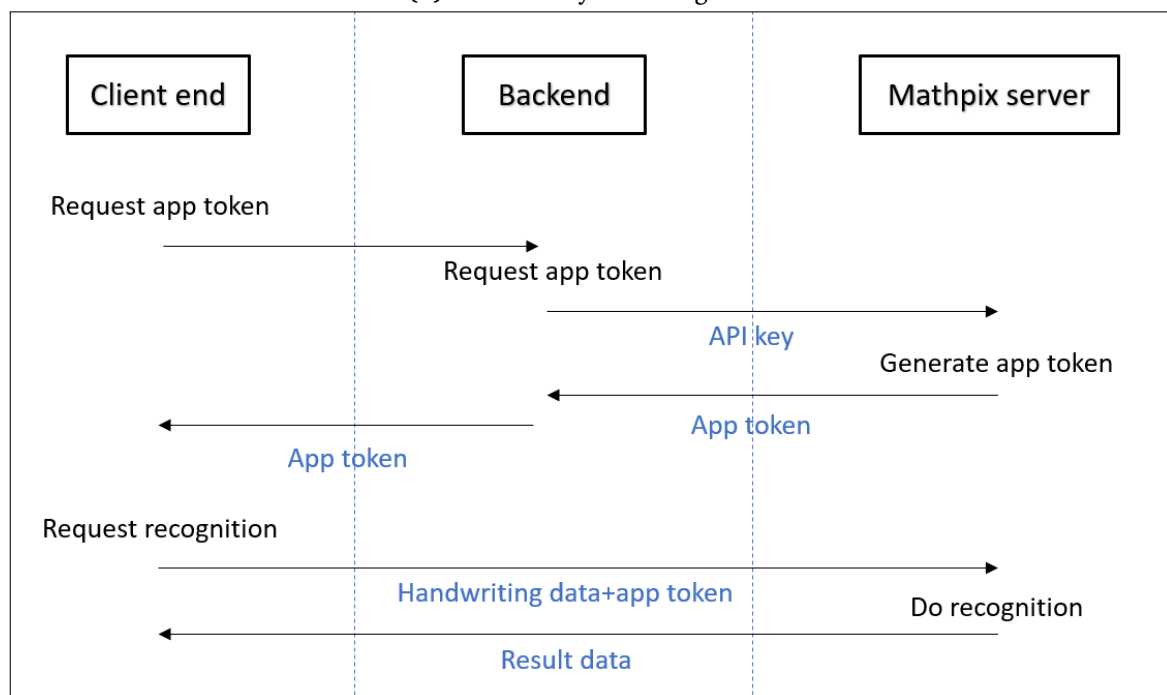


**(b)** Use App Token for Recognition

**Figure 2.4:** Comparison of Using API Key and App Token for Recognition

# Chapter 3

# Implementation

Following the three steps mentioned in Chapter 2, this chapter is divided into three sections as well, each explaining the implementation of one step.

It should be noted that before installing the component into Lambda Feedback, the frontend part and backend part are not seperated for the purpose of the convenience of development and test. This means that the Vanilla JS web application and React component contain the *API Key* for requesting *App Token*.

## 3.1   Vanilla JS Web Application

The first objective of the project is to develop a web application in Vanilla JS. The application requests an *App Token* when being launched. It has a handwriting area for the user to draw, and when the user finishes a stroke, i.e. the pointer goes up, it should automatically send the stroke data to *Mathpix* server. After receiving response from the serverm it should display the equation recognised in text format. In addition, there should be a toolbar to edit the content.

This application consisits of three parts:

- Structure of the web pate (HTML)

- Functions (JavaScript)

- Styles of the web page (css file)

In this application, styles are not concerned as they will be specified in another approach in React.

The structure of the web page is designed as Figure 3.1

The HTML code can thus be written easily based on the structure. It should be noted that this application uses `canvas` element because `SVG` element was not discovered yet when building this prototype. The next step is to add functions to the application.
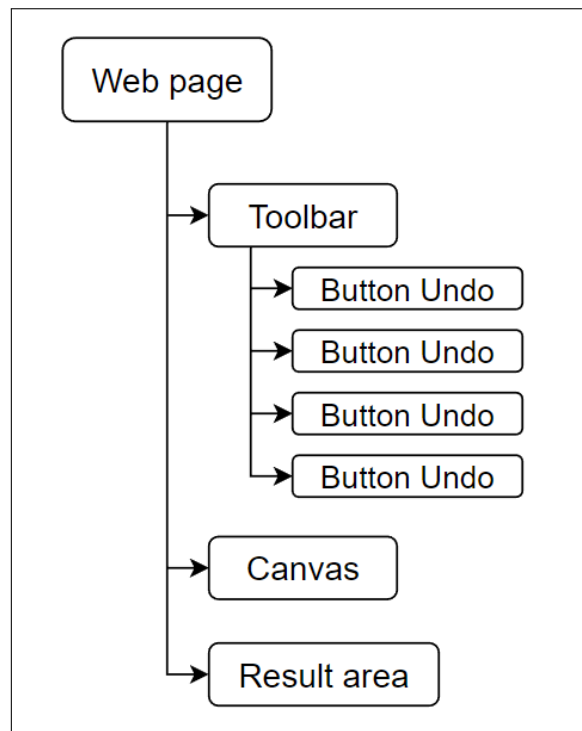
**Figure 3.1:** Structure of Vanilla JS Web Page

Different from developing in other languages such as Python and C++, test functions are normally not available for frontend development with JavaScript/TypeScript. Tests are usually carried in the console of a browser. Therefore, the application was developed progressively. Functions were divided into several parts and each part was added after previous part passed tests:

1. Users can draw on the canvas, and stroke data is recorded

2. The application can send stroke data to *Mathpix* and display the result

3. Undo, redo, delete and remove functions are available

Following sections will explain how each function was implemented.

### 3.1.1 Drawing on the canvas

Before start, the `canvas` should be initialised and referred. This is done in a `setupCanvas` function, which sets up variables such as size, stroke color and stroke width etc.

To let the users draw on the canvas and display the strokes they draw, function `addEventListener` was used. This function can detect specified HTML event (e.g. `onClick`, `onMouseDown` etc.) on an HTML element, and bind the event to a custom function so that once the event happens on the element, the corresponding function is called. The function is used in `setupCanvas` as well.

In `canvas` element, three events are being detected:

- `onMouseDown` : the mouse button is pressed down

- `onMouseMove` : the mouse is moving

- `onMouseUp` : the mouse is released

In this application, three events are connected to function `handleMouseDown` , `handleMouseMove` and `handleMouseUp` respectively. Operations in each function are shown in flowchart in Figure 3.2.
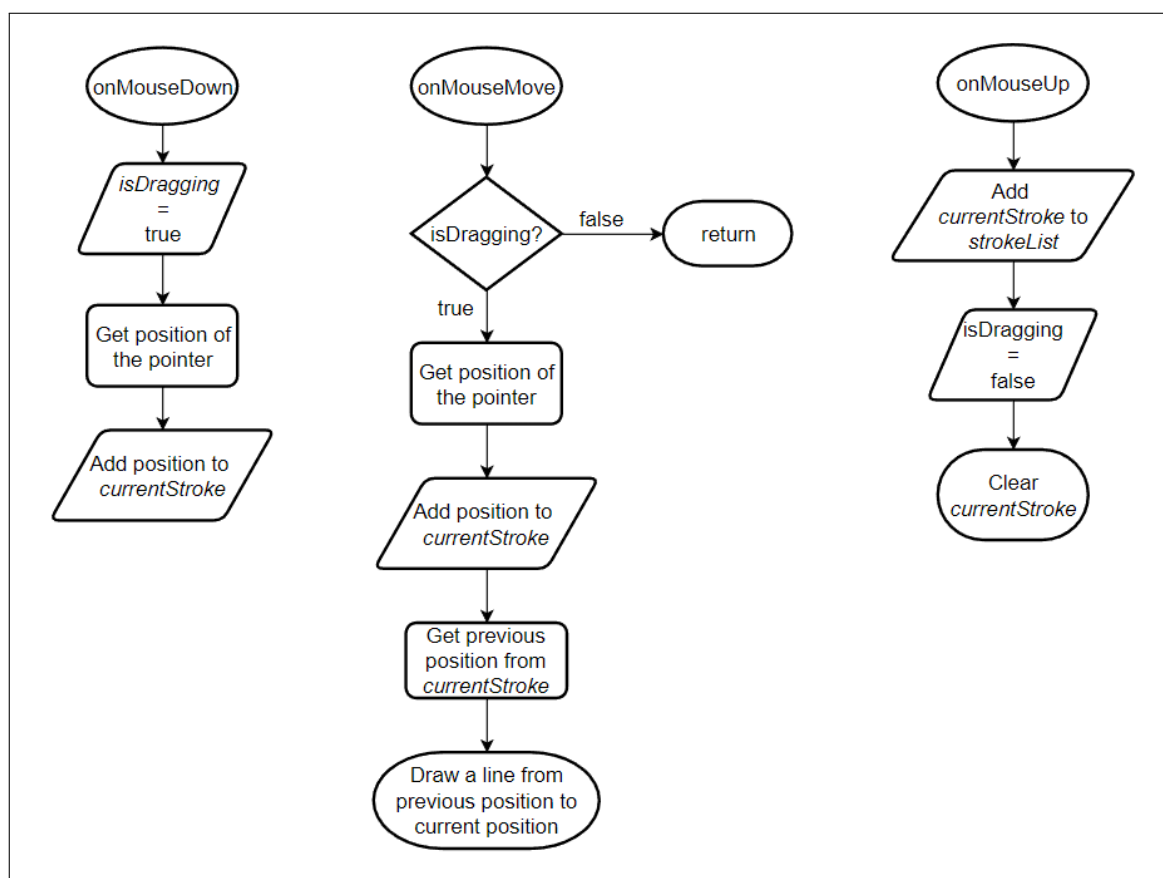


**Figure 3.2:** Event Flowcharts for Drawing on Canvas and Data Recording

Where:

- `isDragging` is a state flag checking if the mouse is down

- `currentStroke` is a list of points representing the current stroke the user is drawing

- `strokeList` is a list of strokes representing all content the user has drawn, i.e. the stroke data

The function for `onMouseDown` sets a start point for the canvas to draw, and marks the pointer state down. Event `onMouseMove` is checked every browser's event loop.

When it is detected, and mouse is down, the position of the pointer is recorded to `currentStroke` and the `canvas` draws a line from the previous point obtained from `currentStroke` and the current position. This is done by methods `moveto(previousPoint)` and `lineto(currentPoint)` of element `canvas`.

The user can now draw paths on the canvas, and stroke data is recorded in this process. The next section will explain how stroke data is sent to *Mathpix* and how result is fetched and displayed.

### 3.1.2   Send stroke data and display result

In this application, there are two requests to *Mathpix*: *App Token* request and recognition request. Both requests are made by `cURL`. In JS/TS, this can be done by `fetch` function. It can send a request through HTTP pipeline and fetch response asynchronously across the network [11]. Using `fetch`, it is easy to make requests for *App Token* and recognition.

*App Token* should be obtained when the web page launches. Therefore, the request is added in `setupCanvas` function. According to *Mathpix* document [12], the request header should include the *API Key* for authorisation and content type of `application/json` for data transmission. The data to transmit is to ask the server to return session ID so that a live session is created. The *Mathpix* server will then return an object containing *APP Token* and *session id*. The object is then parsed and data is stored.

As to recognition request, to realise live update, the content should be recognised every time the user finishes a stroke, which corresponds to the event `onMouseUp`. Therefore, the request is added to function `handleMouseUp`.

Instead of *API Key*, recognition request uses *APP Token*. This is for seperation of backend and frontend in further development. The data to submit is the stroke data (`strokeList`) and *session id*. Moreover, options for the response can be specified in the data as well. In this application, `latex_styled` is included in the option so that a latex styled string is included in the result. *Mathpix* will process the data and return the result as an object containing required data format. The object is then parsed and the `latex_styled` result is stored.

After the result is obtained, it has to be displayed. As introduced in Chapter 2.3, `Katex` can render a latex styled string to equation in a specified element. In this application, it is rendered in the element `result area`. This is done after the result is obtained, which is in function `handleMouseUp` as well.

Now, the flowchart of function `handleMouseUp` becomes Figure 3.3

This section records the implementation of recognition and render. The next section will explain how undo, redo, delete and remove functions are implemented.
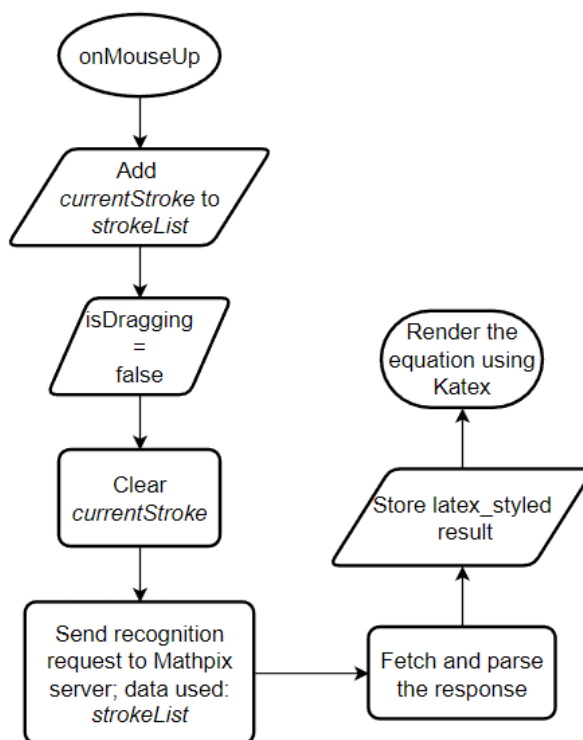
**Figure 3.3:** Flowchart of `handleMouseUp` for Recognition

### 3.1.3 Toolbar functions

Four edit functions, `undo`, `redo`, `delete` and `remove` are implemented in the toolbar. As `remove` function affects the development of `undo` and `redo` functions, it is implemented firstly.

The `remove` function is bound to the remove button. When the button is clicked, the application enters the 'remove' mode: when the pointer presses on or is dragged over a stroke, the stroke is removed. This is done by traversing all points in all strokes, and compare them to the position where the pointer is down. If horizontal and vertical difference is below a specific value, typically `3*stroke width`, the stroke is moved from `strokeList` to `undoStrokeList`, the canvas redraws all strokes and stroke data is submitted for recognition. This function is named `checkCollision`, and the flowchart is shown in Figure 3.4:
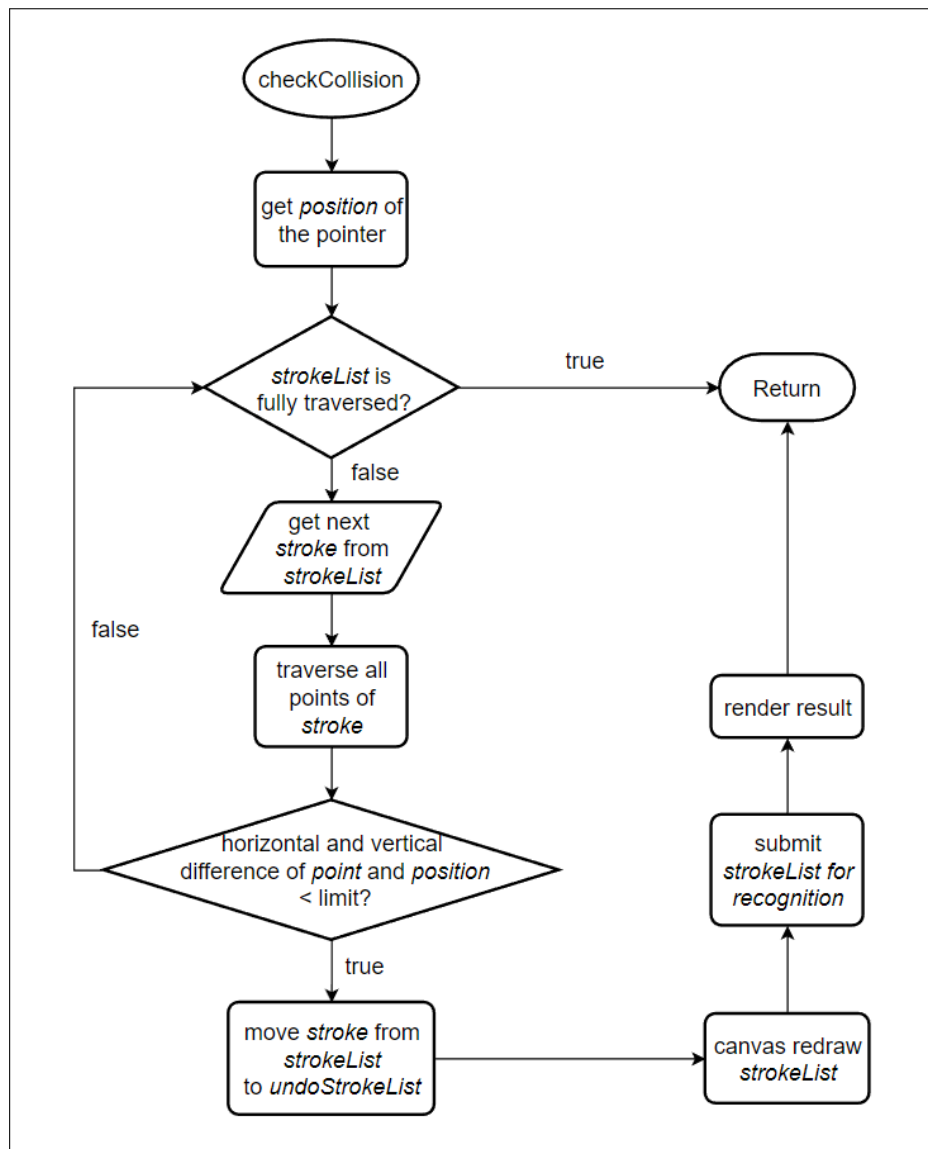
**17**

**Figure 3.4:** Flowchart of Function `checkCollision`

It should be noted that when 'remove' mode is added to the application, a state flag `isDrawing` is added to check if it is in 'remove' mode. Every time `handleMouseDown` or `handleMouseMove` is invoked, `isDrawing` is checked to determine following operations. The flowchart of `handleMouseDown` and `handleMouseMove` thus becomes Figure 3.5:
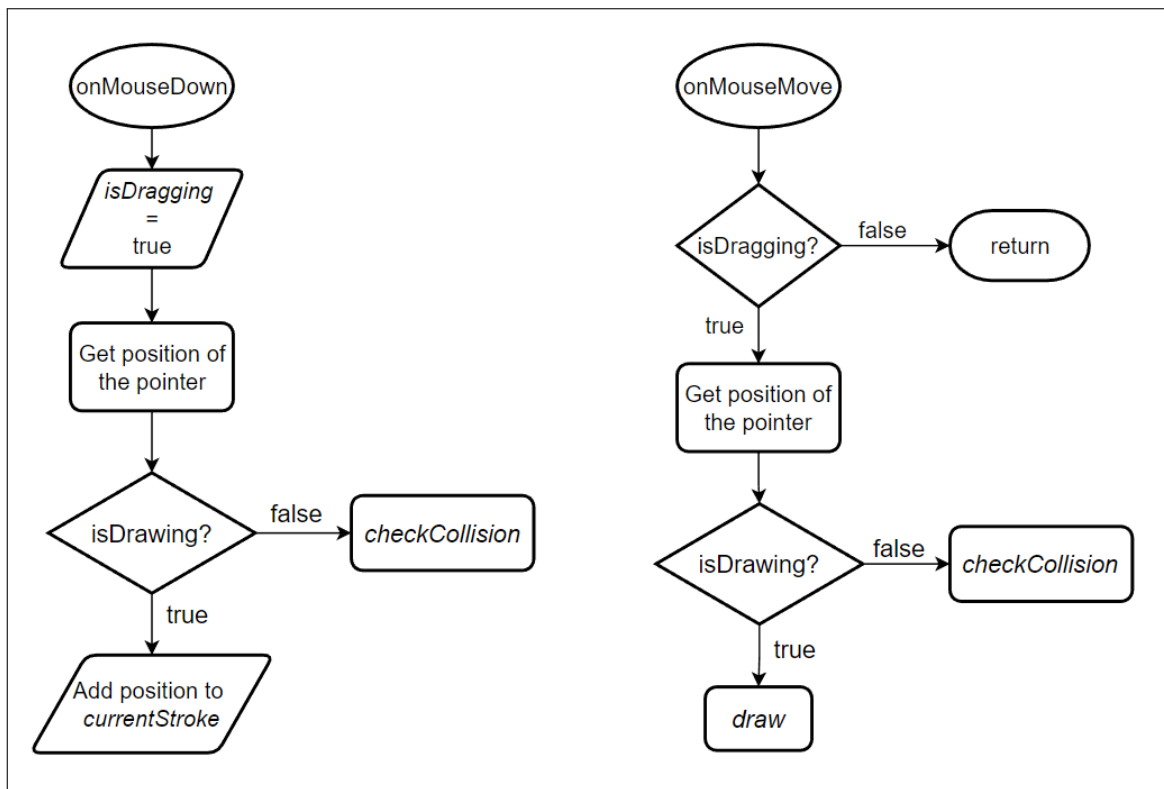
**Figure 3.5:** Flowchart of `handleMouseDown` and `handleMouseMove` with 'remove' mode

Where `draw` is illustrated in Figure 3.2

Function `delete` simply clears the canvas and the stroke data, i.e. `strokeList`. Note that the result area is cleared as well.

Function `undo` depends on the operation done to determine whether to remove or restore a stroke. Therefore, a variable named `operations` is needed to record all operations. When a stroke is added to `strokeList`, string 'draw' is added to `operations`; when a stroke is removed from `strokeList`, string 'remove' is added to `operations`. When `undo` is invoked, it checks the last operation in `operations` and moves it to `undoOperations`. If the last operation is 'add', the last stroke in `strokeList` is moved to `undoStrokeList`; else, the last stroke in `undoStrokeList` is moved to `strokeList`.

Two assist functions, `removeLastStroke` and `restoreLastStroke`, are used. Flowcharts are shown in Figure 3.6.

Function `redo` has opposite logic of `undo`, and can be easily implemented from it. Flowchart of `undo` and `redo` is shown in Figure 3.7
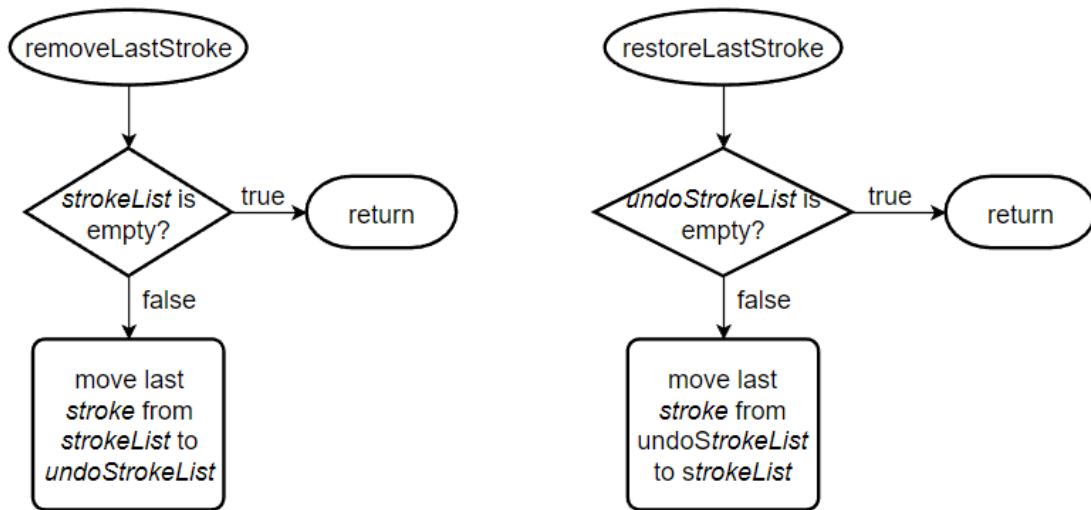
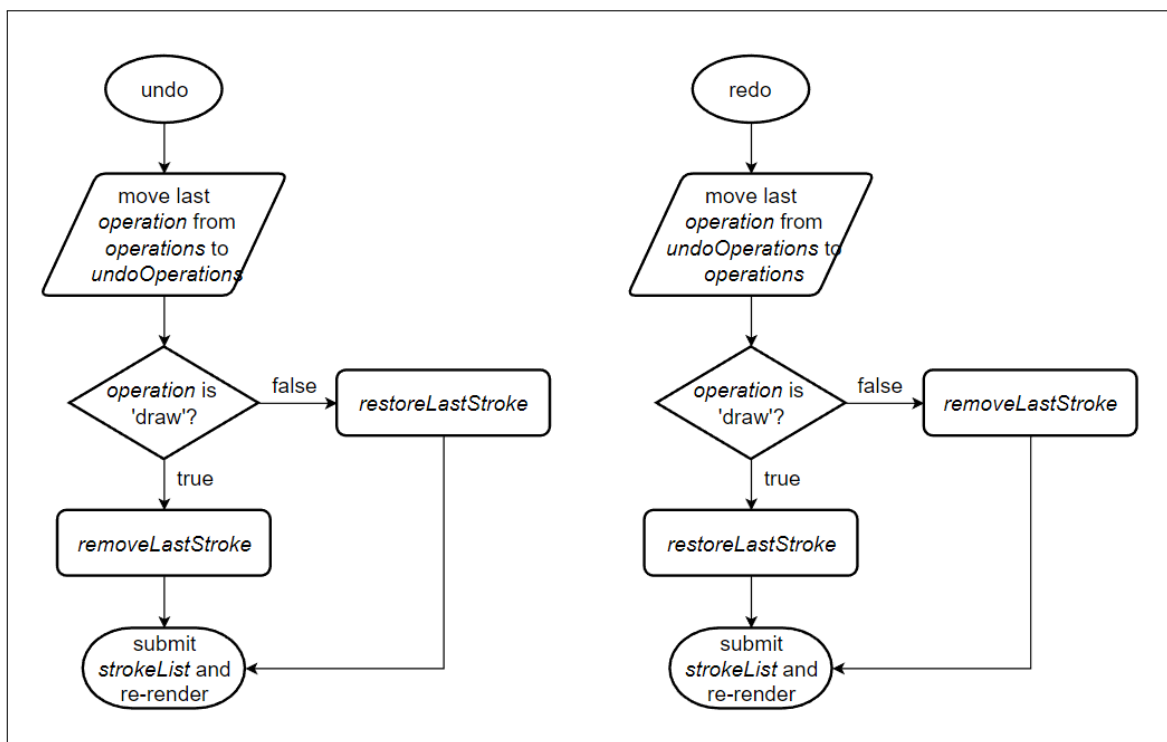**Figure 3.6:** Flowchart of `removeLastStroke` and `restoreLastStroke`



**Figure 3.7:** Flowchart of `undo` and `redo`

The implementation of the Vanilla JS web application is completed, and the result and evaluation will be demonstrated in Chapter 4. The next section will focus on the conversion from Vanilla JS application to React component.

## 3.2  Convert to React component

To convert from Vanilla JS to React component, the programme is restructured into sub-components according to functions:

- `Canvas`

- `FullScreenDialog`

- `Navbar`

- `Path`

All sub-components are wrapped in a parent component `HandwritingInput`, where most functions are deployed.

It should be noted that for the handwriting canvas of the React component, the `canvas` element is replaced with `SVG` element. This thus leads to a new sub-component `Path`, which will be explained later in this section.

# Chapter 4

# Experimental Results

# Chapter 5

# Conclusion

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# Chapter 6

# Appendices