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**COVID-19 Digital Contact Tracing: A Privacy-preserved Sequence Embedding Solution**

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# Abstract

This project aims to propose a novel digital contact tracing solution TracingwPrivacy with privacy preserved for users, and deliver a Proof of Concept for the solution.

The current contact tracing apps and QR code solutions are either centralised systems which sends every users’ data to the government database, or partially decentralised systems where the government maintain COVID-19 patients’ and all their contacts’ data. Different from the current solutions, this project proposes a completely decentralised system, where the government only get the embeddings of users’ trajectories, not the original data. TracingwPrivacy addresses the rising concern of data privacy in digital contact tracing.

Firstly, existing embedding algorithms were researched, and SGT (Sequence Graph Embedding) was found suitable. Then a multi-agent simulation of mobile system was built since we could not take data from the real world. The simulation generated data, which were embedded by SGT and sent to a server. The server would compute the distances between the embeddings and return similar ones upon the frontend’s request.

# Acknowledgements

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# Introduction

## Background

The Coronavirus pandemic which is caused by the SARS-CoV-2 virus (Covid-19), has been a global scale disaster. As reported by the WHO, until February, there were more than 100 million confirmed cases of COVID-19, including more than two million deaths[1].

Contact tracing has been one of the top priorities in controlling the spread of Covid-19. As the number of cases continued to surge and soon exceeded the capacity of public health services, most governments turned to digital contact tracing.

There are various existing or proposed digital contact tracing solutions. From the sensor technology used, they can be categorised into QR code and Big data based, GPS based or Bluetooth based systems. From the software architecture, they are either centralised or decentralised systems. In centralised systems, personal data are collected through the sensor technology chosen and send to a central server cluster, which is controlled by the government authority. In decentralised systems, the data are stored on individuals’ devices. However, the current decentralised solutions are not complete decentralised since the government maintains a special database only for covid-19 patients and their close contacts.[2]

A typical example is Singapore’s TraceTogether app, a Bluetooth based decentralised system. It does not require every user’s data. However, the data of a infected user and his/her close contacts can still be seen by the government officials. If the virus affects a larger population in Singapore, the MOH can get more people’s data[2,3]. Beside TraceTogether app, there is another QR based centralised system SafeEntry, which stores every single data entry in a server owned by the government[4]. There has been debate and negative news towards TraceTogether and SafeEntry, including tracing data made available to police[5].

The trajectory of a contract tracing app user during a certain time period *[T1, T2]* can be regarded as a sequence. A sequence is defined as a string of ordered discrete alphabets. An alphabet can be an event, a value or in our case, the location. The feature embedding of a sequence is the representation of the sequence in vector space[6]. Embeddings are not human readable. Therefore, a tracing app preserves total privacy if it only sends the embeddings to the central server. The feature of users’ trajectories is preserved in vector space so similarities between them could be computed[7].

## Scope and Objective

This project aims to propose a Singapore digital contact tracing solution with complete privacy preserved by combining existing sequence embedding function[7] and the current mobile app solution like SafeEntry, and develop a Proof of Concept(PoC) for it. The scope of the project includes:

A. Developing a system with:

(1) A real-time multi-agent mobile simulation, which records user’s trajectory and perform sequence embedding at client’s side. Only the embeddings are sent to the central server, not data itself.

(2) A server which computes the similarity between sequence embeddings upon the request from the frontend.

(3) A frontend that allows a MOH staff to search close contacts with a patient’s sequence embedding.

B. Show that the system can distinguish between similar and different trajectory pairs.

## Potential Issues, Limitations and Challenges

### Scaling

### Accuracy

## Report Outline

This report consists five sections.

Section 1, the current section, introduces the background, motivations, scope and objectives, the potential issues, limitations and challenges.

Section 2 is the literature review. In this section, the current apps and solutions which are mentioned in the introduction are explained in detail.

Section 3 describes the design of the proposed system, the core algorithm (SGT) used in the PoC and the tools and packages used.

Section 4 shows the experimental results and discuss how the algorithm helps search close contacts of a patient.

Section 5 draws the conclusion from all previous sections, and states possible future work recommendations.

# Literature Review

## Existing Digital Contact Tracing Solutions

### Absolute Location vs Relative Location

In digital contact tracing systems, the goal is to find close contacts of the infected patient. The process to decide whether two users are close contact or not is often based on geo information. We can categorize location data into two kinds: relative location data, and absolute location data [3].

Typical example of absolute location data is GPS system. Relative location data can be collected through Bluetooth. If two smartphones with Bluetooth on gets into a certain range, it can be recorded down. Both absolute location data and relative location data is widely applied in digital contact tracing.

### Centralized vs Decentralized Architecture

In centralized architecture, the software resides at a central location. In digital contact tracing, it refers to the data and the algorithm resides in a server or server cluster owned by the government. In decentralized architecture, the software resides on each client machine.[8]

### TraceTogether and How It Works

There are plenty of existing contact tracing systems globally. This project proposes a solution for Singapore. Therefore, TraceTogether, the current solution in Singapore, is discussed in detail here.

The typical process of digital contacting tracing can be divided into four phases in a workflow[3]:

(1) Initialization phase: the system is set up by individuals and other parties.

(2) Sensing phase: the system records down each user’s relevant data, relative location or absolute location.

(3) Reporting phase: an infected user reports his/her data to Ministry of Health.

(4) Tracing phase: a third party, such as MOH, will collect the infected user’s data and search the close contact based on the data.

For TraceTogether, the following is the entire process of contact tracing:

(1) Initialization phase: the user installs the TraceTogether app on his/her smartphone. The app sends the user’s phone number N to MoH. MoH server generates a pseudonym PID and store (N, PID) in the database. Then MoH encrypts the PID and a certain time interval T with secret key K, and sends INFO = Encryption(PID, T, K) to the user’s smartphone.

(2) Sensing phase: In the time interval T, if two users i and j come into a certain Bluetooth range, they will store (INFOi , INFOj , Signal Strength) locally on their phones.

(3) Reporting phase: A user diagnosed with covid-19 have to give MoH all the locally stored pairs (INFOi , INFOj , Signal Strength).

(4) Tracing phase: MoH decrypts all the encrypted pairs and obtain PID of all users who came close with the patient. Then MoH obtain the phone number from the PID and contact them.[3]

## Data Regulation and Technology Protocols

## PDPA

Personal Data Protection Act (PDPA) is a framework that gives a baseline for data protection and privacy in Singapore. Similar to other personal data regulations, such as GDPR in Europe, PDPA consists of various requirements in storing, governing and transmitting user’s personal data.

## PEPP-PT

Pan-European Privacy-Preserving Proximity Tracing (PEPP-PT) is a technology protocol mainly for centralized contact tracing systems, where the App and personal data are controlled by the government health agency. It is a framework that adheres to GDPR and based on Bluetooth technology. The framework was released in April 2020 and soon adapted by many EU countries, such as Germany, France and Italy. It consists of four layers and three protocols, including data protection, secure communication and proximity measurement. [9]

## DP-3T

Decentralized Privacy-Preserving Proximity Tracing (DP-3T) is a technology protocol mainly for decentralized contact tracing systems. Compared to PEPP-PT, DP-3T makes effort to largely reduce the privacy risk. It was released in April 2020 shortly after PEPP-PT. Different from PEPP-PT, the users’ data are stored locally and only collected anonymously to a central database if the user gets infected.[10]

## Decentralized System and Feature Embeddings

As mentioned in 2.1.2, in decentralized architecture, the software resides in each client’s machine. In digital contact tracing, currently there is no completely decentralized app. TraceTogether is a partially decentralized solution, where the Bluetooth information is stored locally on the client’s machine, while MoH maintains a central database of the infected user’s data.

In TraceTogether, the user’s data is encrypted. Therefore, the app protects users from data attack. However, MoH could see the data of infected users and their contacts. This requires people put trust into the MoH, which raised doubt in general public.

The core question in maintain data privacy even against the government is that how to encrypt raw data while maintain the properties so that two sets of data could be compared. It naturally leads to a existing solution: feature embeddings.

Feature embedding is the process of transforming the data from original space into a new vector space, and extract data feature in the process[11]. There are various embedding algorithm on different types of data. For instance, Word2Vec for text embedding. Feature extraction of text or a sequence is challenging because of the arbitrary nature of data. There is a new sequence embedding algorithm called Sequence Graph Embedding (SGT), which is used as the embedding algorithm in this project.[7]

Suppose there is an GPS based, centralized mobile app which records down user’s trajectory. Each place, such as a shopping mall or an MRT station, can be regarded as a node on the map. The trajectory in a specific time period T can be regarded as a sequence of nodes. And the vocabulary is the set of nodes. Using the SGT algorithm, sequence embeddings can be obtained in decentralized manner. The information sent to the central server is unreadable embeddings. This way, data privacy against the authority is ensured.

# Methodology

## Algorithm: SGT

### Advantages and Limitations

Sequence Graph Transform (SGT) is a novel method for sequence data mining. SGT is a algorithm that deals with both long term and short term dependencies without significant increase in computation. It transforms a sequence to a vector in finite dimensional feature space so that the result can be used in many tasks, such as similarity computation, Neural Network and so on.

The limitations are:

(1) The alphabet set cannot be small. For example, for DNA sequence, the alphabet set is {A ,C G, T}. The size is only 4. When applying the algorithm, the effectiveness will be diminished.

(2) The alphabets of the sequence need to be a single item. Eg. ABBCDEE is a valid sequence, <A><BB><CD><EE> is not.

The limitations of the algorithm do not affect this project.

### Intuition and Algorithm

As the name suggests, the intuition of Sequence Graph Transform comes from the structure of graph. The features are extracted from the relative position of alphabets in the sequence. The alphabet can be an event, in this project, a location. The reason of using relative position to represent the feature is that the similarity between two sequences is usually measured from the positional patterns.

The input of SGT is a sequence *S* where. The alphabet set is denoted as *V*. The sequence *S* is a feed-forward sequence.

The quantitative measure of the effect on the relative position of the alphabets are denoted as where are the positions of two alphabets, and is a distance measure.

Figure 1 shows a high level overview of SGT. As shown in the figure, if interpreted as a graph, each alphabet is a node, and the feature is the edges between them. For example, in sequence , the relative position for pair is denoted as . Similarly, the relative position between all alphabets can be extracted to get features in vector space.

There are two algorithms proposed in SGT. One is sequence embedding via sequence parsing. The other is sequence embedding via alphabets parsing. The sequence parsing method is faster for shorter sequences that length of the sequence . In our case, the length of sequence is the number of times per day that the device records the user’s location. In the PoC, . is the total number of locations. In the PoC, locations are the MRT station in Singapore. However, when applied to real life, the number of location will be much larger. The two algorithm are attached in the appendix.

Diagram

Description automatically generated

1. A High Level Overview of SGT

### Example of Using the Package

* parameters and methods related to the project:

|  |  |
| --- | --- |
| alphabets | Alphabet set , optional, will be computed by the algorithm if not input |
| kappa | Tuning the degree of long term dependency extraction, higher value means lesser long term dependency |
| flatten | Default true. If flatten, a vector is returned. Else a matrix is returned. |
| fit(sequence) | Input: one sequence  Output: SGT embedding of the sequence |
| transform(corpus) | Input: new sequence which belongs to a previously fitted corpus  Output: SGT embedding of the sequence |
| fit\_transform(corpus) | Input: a list of sequences  Output: SGT embedding of the corpus |

1. SGT class definition

* Example

Graphical user interface, text, application

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1. Basic Example of SGT

Suppose we have a corpus where each number is the id of the location and the sequence is the trajectory of the user.

As seen in Figure 3, sequence 0 and sequence 1 have 3 common locations in consecutive manner. Sequence 0 and sequence 2 are similar in the beginning and end. Sequence 3 are different from the previous three.

Text

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1. Experiment with a Corpus

After getting the embedding, a simple calculation of Euclidean distance is done:

Graphical user interface, text, application

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1. Calculating Euclidean Distance

As shown in figure 4, sequence 0 is indeed similar to sequence 1 and sequence 2. Comparing distance(0, 1) with distance(0, 2), it is clear that the SGT embedding has captured the long term relations between the alphabets. Comparing distance(0, 1) and distance(0, 2) with distance(0, 3), the difference is also captured by the algorithm.

## System Design

### Tools and Packages Used

#### React.js

React is a javascript library for building web frontend. It allows the developer to decompose a complex UI into smaller pieces of code called “component”. Each piece of UI can be written as a subclass of React.Component. A component takes in properties, which can be passed from higher level components, and returns a hierarchical view by the render method. The structure of components in this project will be showed in 3.2.3.

With the components and state, a frontend built by react is highly responsive, reusable and has a clear structure.

[https://reactjs.org/docs/getting-started.html]

#### MapboxGL

MapboxGL JS is a javascipt library for displaying interactive maps on the frontend. In this project, it is used to display a map of Singapore.

#### Flask

Flask is a micro framework written in Python for developing backend. It does not have components like database abstraction layer and validations which are included in many other frameworks. However, it is flexible and supports many extensions, such as Flask-PyMongo used in this project.

A simple mock server is needed in this project. Therefore, Flask is chosen as the framework for its simplicity.

[https://flask.palletsprojects.com/en/1.1.x/]

#### MongoDB

MongoDB is a open source document database that stores JSON like data. In this project, MongoDB Atlas is used for the simplicity of set up compare to local database. As stated in 3.2.1.3, Flask supports many extensions. Flask-PyMongo is a bridge between flask and PyMongo, which is a Python distribution for using MongoDB.

[https://flask-pymongo.readthedocs.io/en/latest/]

#### Threading and concurrent.futures

In the implementation of the mobile simulation, threading is used for creating multi-agents. In Python threading, the threads are not actually executed in parallel. In this project, we only need a simulation where the events seem to happen at the same time, not speeding up the program. Thus Python threading module is suitable.

concurrent.futures is a module for managing threads in Python. It is a high-level interface compared to threading for asynchronous execution of callables.

[https://docs.python.org/3/library/concurrent.futures.html]

#### Shapely, Geopandas and pyproj

Shapely is a Python library for dealing with geometries. The Points are created and calculated using Shapely.geometry in this project.

Geopandas is an open source project for handling geospatial data. Pyproj is a Python interface to do coordinate transformations and cartographic projections. Earth has no precise geometric shape. There are plenty of coordinate reference systems, such as epsg:3414 for Singapore, epsg:3112 for Australia. Pyproj is used to transform the coordinates between different standards.

[https://geopandas.org/]

[https://epsg.io/]

### System Overview

Diagram

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1. Use Case Diagram

Diagram, schematic

Description automatically generated

1. System Architecture Overview

Diagram

Description automatically generated

1. System Flow Overview

### Frontend

Diagram, schematic

Description automatically generated

1. Detailed Frontend Design

### Simulation

#### File Structure

.

A picture containing table

Description automatically generated

1. File Structure in Mobile Simulation

|  |  |
| --- | --- |
| File Name | Explanation |
| main.py | The starting point of the simulation, create and run multiple threads of agents |
| mapfiles/\* | The folder containing maps of Singapore |
| node\_data/\* | A json file of geospatial data of MRT stations in Singapore. This is the mock data used in PoC. In real life applications, this would be SafeEntry checkpoints in Singapore. |
| simulator/\* | The package containing all classes for the building simulation |
| Agent.py | Simulate an agent (with mobile app) randomly roaming in Singapore boundary. The program records down the trajectory, do embeddings and send them to the server. |
| Map.py | Containing methods of handling the mapfiles |
| Env.py | Create an environment for the agent |
| constants.py | containing some constants while running the simulation (modifiable for the next round of simulation) |

1. Explanation of Files

#### Simulation Parameters

|  |  |
| --- | --- |
| constants | usage |
| FILE\_LOC, NODE\_DATA\_LOC, SERVER\_URL | the location of mapfiles and node data  server url to make http request, in the PoC we use localhost |
| SG\_CRS | set to 3414 (epsg:3414):  the spatial reference system for Singapore  unit: meter |
| UPDATE\_PERIOD | the time period for the agent to update its location |
| SIMU\_TIMESCALE | the timescale of simulation time/real time |
| DEBUG | debug mode that will only instantiate one agent and output some logs |
| SIMU\_DAYS | simulation time length  unit: s |
| min\_speed, max\_speed | will be used in generating random speed of the agent  by default, min\_speed = 0, max\_speed = 14 (driving and MRT)  unit: m/s |
| record\_range | The GPS coordinate might not be exactly on the nodes. The simulation records coordinate (long, lat) as on node N if (long, lat) is within record\_range of node N  In the experiment part, this parameter will be tuned. |

1. Simulation Parameters

#### Algorithm

Diagram

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1. Simulation Flowchart

Graphical user interface, text

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1. Pseudocode for Random Location Generation

Text

Description automatically generated

1. Pseudocode for Updating Agent’s Location

### Server

Diagram

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1. Server Overview

|  |  |  |
| --- | --- | --- |
| endpoint | method | function |
| /upload | POST | receive a file (json) from request, save it to the database |
| /users/validate | POST | validate a user’s information |
| /users/signin | POST | business logic of sign in |
| /users/signout | POST | business logic of sign out |
| /embedding | POST | called by the simulation  save the embedding sent by simulation into the database |
| /search | GET POST | retrieve other user’s embeddings from the database, compute the distance with patient’s vector, then return the top n most similar user id. |

1. Server Endpoints

## Hardware

The experiment of this PoC uses the following hardware:

MacBook Pro (13-inch, 2018, Four Thunderbolt 3 Ports)

Processor: 2.3 GHz Quad-Core Intel Core i5

Memory: 16 GB 2133 MHz LPDDR3

Graphics: Intel Iris Plus Graphics 655 1536 MB

Simulation, mock server and frontend all will be run on this laptop.

# Experiment Result

## Mobile Simulation

### Simulate a Trajectory

The simulation of one agent is done with the following parameters:

SIMU\_DAYS = 14

DEBUG = True

UPDATE\_PERIOD = 3600 # unit: s, meaning update the server every hour

SIMU\_TIMESCALE = 36000 # simulation time / real time

record\_range = 2000 # unit: meter

Calendar

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1. Trajectory Array

Chart, scatter chart

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1. Trajectory Map

The number in the array is the id of each node in the map. In the map, the MRT stations are marked as blue plus signs. The red dot is the places the agent has been to. The ‘-1’ means that the coordinate of the agent is not near any node.

As shown by the map, the simulation system is a rather random simulation aims to generate the trajectory data rather than simulating mobile users in real life. In real life cases, the user is unlikely to go out at midnight, will only go to a few places on working days. Different groups of users have different behavior patterns etc. These can be considered as possible future improvements of the simulation.

Another problem is that there are some coordinates that are not near any node. In the real application, this is unlikely to happen. In a real application such as SafeEntry, the nodes cover every shop and residential buildings. Large number of undefined nodes will also affect the accuracy of embeddings.

There are two solutions. One is to introduce more nodes (such as bus stops, shopping malls) into the simulation. Another one is to tune the record\_range parameter so that there are less undefined locations.

### Tuning Parameters

|  |  |
| --- | --- |
| record\_range (m) | number of undefined locations out of 14x24 = 336 recorded points |
| 500 | 294 |
| 1000 | 212 |
| 2000 | 88 |
| 3000 | 36 |
| 4000 | 35 |

1. Tuning record\_range

The record\_range in the simulation is set to 3000.

This is for simulation in the PoC only. In real life scenario, the number of record locations are much bigger. The recording is done by GPS. The number of undefined locations in a user’s records will be low.

### Embedding

Embeddings are done once a day in simulation time. Locations are recorded once an hour in simulation time. In total, every embedding is done on array of length 24. Every user has an array of 14 embeddings kept in the database. The record frequency can be further changed, for example every 30 minutes, depends on the real life scenario.

The following steps show how an individual agent does the embedding in a jupyter notebook. The exact same method is applied to the simulation. The two sequences are taken from user trajectories randomly generated by the simulation.

Graphical user interface, text, application

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1. embedding of two trajectories

The embeddings show the limitations of the solution. When we have 157 locations, the length of one embedding is 24964 (excluding the id column).

For the number of locations

As the number of locations increases, the length of embeddings increases exponentially. In addition, the vector or the matrix before flattening is very sparse. To save the storage, several techniques can be used to compress the vectors (see future improvement).

## Server and Frontend: Use Cases

### Homepage (entry point)

Entering the homepage, there’s an interactive map which can be used to display covid19 infected area in future implementations. There’s a menu bar, and a sign in option.

Click on “Search” in the menu bar or “Start search” button without being logged in will bring the user to the login page.

Graphical user interface, website

Description automatically generated

1. Homepage UI

### Login page

The frontend web page has responsive web design. This Sign In page is screenshotted with 50% web page width.

Graphical user interface, text, application

Description automatically generated

1. Sign In page

Graphical user interface, application

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1. After Sign In

### Search

To search the users with similar trajectories with the patient, the government official needs to upload the patient’s trajectory embedding. It is assumed they can retrieve patient’s embedding from the mobile app.

Then the government official needs to key in the search terms. The search date range can be omitted, the system will compute according to the past 14 days data if omitted.

The field “entry to display” is the number of search result to return.

Graphical user interface, application

Description automatically generated

1. Search Page

Graphical user interface, application

Description automatically generated

1. Uploading and Filling In Search Terms

Graphical user interface, application

Description automatically generated

1. Loading Page while Searching

Table

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1. Search Results Displayed

Text

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1. Response by the Server

# Conclusion and Future Improvements

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