Finding Time Period-Based Most Frequent Path in Big Trajectory Data[1]

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Summary

Overview

- The main task: find *the most frequent*(MFP) during user-specified time periods in large-scale historical trajectory data.
- They refer to this query as *time period-based MFP*(TPMFP).
- Specifically, given a time peroid T, a source v_s and a destination v_d, TPMFP searchs the MFP from v_s to v_d during T.

Overview

- None of the previous work can well reflect people's common sense notion which can be described by the following key properties:
  - *suffix-optimal*
  - *length-insensitive*
  - *bottleneck-free*
- The first task is to give a TPMFP definition that satisfies the above three properties.
- The next task is to find TPMFP over huge amount of trajectory data efficiently.(over $11,000,000$ trajectories.)

Summary

Key Properities

Property (Suffix-Optimal)

Let P^* denote the $v_s - v_d$ MFP. For any vertex $u \in P^*$, the sub-path (suffix) of P^* from u to v_d should be the u–v_d MFP.

Property (Length-Insensitive)

The length of any path should not be a deciding factor of whether it is the $v_s - v_d$ MFP.

Property (Bottleneck-Free)

The MFP P^* should not contain infrequent edges(i.e., bottlenecks).

Summary

Definations

Defination (Road Network)

A road network is a directed graph $G = (V, E)$ where V is a set of vertices representing road intersections and E is a set of edges representing road segments.

Defination (Path)

Given G, an x_1–x_k path is a non-empty graph $P = (V_p, E_p)$ of the form $Vp = x_1, x_2, \ldots, x_k$ and $E_p = (x_1, x_2), \ldots, (x_{k-1}, x_k)$ such that P is a sub-graph of G and the x_i are all distinct.

Defination (Trajectory)

Given G, a trajectory Y is a sequence $((x_1, t_1), (x_2, t_2), \ldots, (x_k, t_k))$ such that there exists a path $x_1 \to x_2, \to, \ldots, \to x_k$ on G and t_i is a timestamp indicating the time when Y passes x_i.

Definations

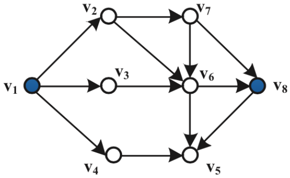
Defination (Footmark)

Given $\Omega = (G, \Upsilon, v_s, v_d, T)$ *and a trajectory* $Y = ((x_1, t_1), \ldots, (x_k, t_k)) \in \Upsilon$, *if there exists a non-empty sub-trajectory* Y' *of* Y *from* $Y[i]$ *to* $Y[j]$ *such that:*

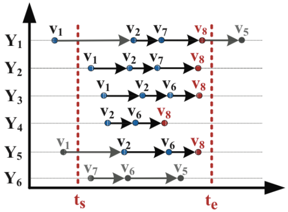
- $Y'.d = v_d$, *i.e.*, $Y'[j].v = v_d$,
- $[Y'.t_s, Y'.t_e] \subseteq T$, *i.e.*, $[Y[i].t, Y[j].t] \subseteq T$,
- $Y[i{-}1].t \notin T$, *if* $i > 1$,

then path $Y'.P$ *is the footmark of* Y *w.r.t.* v_d *and* T *, denoted as* $\widetilde{Y}(v_d, T)$.

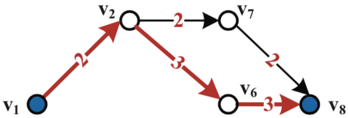
Definations



(a) Road network G



(b) Footmarks in $\widetilde{\Upsilon}$



(c) Footmark graph G_f

Definations

Defination (Edge Frequency)

Given G, $\widetilde{\Upsilon}_{(v_d,T)}$, *and an edge* $(u, v) \in G$, *the edge frequency* $F(u, v)$ *is the number of the footmarks in* $\widetilde{\Upsilon}_{(v_d,T)}$ *containing*(u, v).

Defination (Footmark Graph)

Given G *and* $\widetilde{\Upsilon}_{(v_d,T)}$, *a footmark graph* G_f *is a weighted sub-graph of* G *such that:*

- *for any edge* $(u, v) \in G$, $w_{uv} = F(u, v)$;
- *edge* $(u, v) \in G_f$, *if and only if* $(u, v) \in G$*and* $w_{uv} > 0$.

Definations

Defination (Path Frequency)

Given G_f *, the frequency of path* $P(to\ v_d)$ *is a sequence* $F(P) = (f_1, ..., f_k)$ *where:*

- $\{f_i | i \in 1, \dots, k\} = \{w_{uv} | (u, v) \in E(P)\}$,
- $f_1 \leq f_2 \leq \dots \leq f_k$.

Definations

Defination (More-Frequent-Than Relation)

Given two path frequencies $F(P) = (f_1, \ldots, f_m)$ *and* $F(P') = (f'_1, \ldots, f'_n)$ *w.r.t. the same* G_f *,* $F(P)$ *is more-frequent-than* $F(P')$*, denoted as* $F(P) \succeq F(P')$*, if one of the following statements holds:*

- $F(P)$ *is a prefix of* $F(P')$*;*
- *there exists a* $q \in \{1, \ldots, min(m, n)\}$ *such that 1)* $f_i = f'_i$ *for all* $i \in \{1, \ldots, q-1\}$*, if* $q > 1$*, and 2)* $f_q > f'_q$*.*

Particularly, $F(P)$ *is strictly-more-frequent-than* $F(P')$*, denoted as* $F(P) \succ F(P')$*, if* $F(P) \succeq F(P')$ *and* $F(P) \neq F(P')$*.*

Problem Statement

Theorem

The more-frequent-than relation is a total order.

Defination (MPF)

Given G_f and a v_s–v_d path $P_* \subseteq G_f$, if $F(P_*) \succeq F(P)$ holds for every v_s–v_d path $P \subseteq G_f$, then P_* is the v_s–v_d MFP w.r.t. G_f.

Problem Statement: Given $\Omega = (G, \Upsilon, v_s, v_d, T)$ where Υ is a very large set of historical trajectories, we need to find the TPMFP which is the MFP w.r.t. G_f . Note that G_f is the footmark graph derived from Ω.

Summary

Overview Algorithm

Algorithm 1: Two major steps for the TPMFP query

Input: $\Omega = (G, \Upsilon, v_s, v_d, T)$
Output: the TPMFP w.r.t. Ω
begin
  step 1: build the footmark graph G_f w.r.t. Ω ;
  step 2: find the MFP P^* from v_s to v_d on G_f ;
  return P^* ;

Theorem

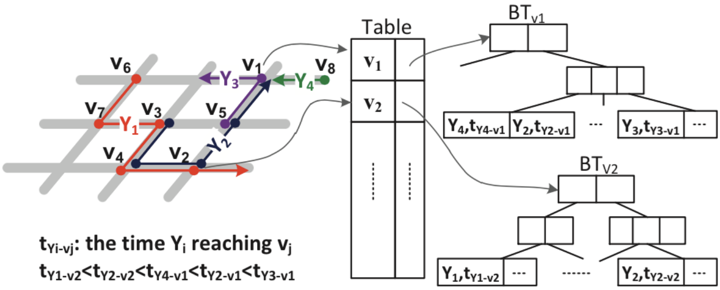
Given $\Omega = (G, \Upsilon, v_s, v_d, T)$, let P_* be the v_s–v_d TPMFP w.r.t. Ω. Then, for every vertex $u \in V(P)$, the sub-path of P_* from u to v_d is the u–v_d TPMFP.

Footmark Index

They design an index called Footmark Index (FMI):

- Build a $B^+ - tree\ BT_{v_i}$ for each vertex $v_i \in V(G)$
- BT_{v_i} indexes the time of the trajectories reaching v_i and stores the corresponding trajectory id's
- Each leaf entry of BT_{v_i} is of the form $< tid, t_a >$
- Given v_d and T , FMI-Search(v_d, T) returns the id's of all the trajectories in $\Upsilon(v_d, T)$ via searching BT_{v_d}

Footmark Index



$t_{Y_i\text{-}v_j}$: the time Y_i reaching v_j

$t_{Y1\text{-}v2} < t_{Y2\text{-}v2} < t_{Y4\text{-}v1} < t_{Y2\text{-}v1} < t_{Y3\text{-}v1}$

Footmark Index

Algorithm 2: FMI-FG(v_d, T)

begin

$FG \leftarrow |V(G)| \times |V(G)|$ matrix with all entries zeros ;

$TRID \leftarrow$ FMI-Search(v_d, T) ;

for *each* $tid \in TRID$ **do**

  $Y \leftarrow$ GetTraj(tid) ;

  $(vid, t) \leftarrow$ the first element of Y ;

  while $t \notin T$ **do**

    $(vid, t) \leftarrow$ the next element of Y ;

  while $vid \neq v_d$ **do**

    $(vid', t') \leftarrow$ the next element of Y ;

    $FG[vid][vid'] \leftarrow FG[vid][vid'] + 1$;

    $(vid, t) \leftarrow (vid', t')$;

return FG ;

Containment-Based Footmark Index

- FMI incurs $|\Upsilon(v_d, T)|$ page accesses
- Organizing the involved trajectories into different groups
- In each group, the front part of each trajectory Y before reaching v_d (including v_d), denoted as Y_{*-v_d} , is 'contained' by a unique 'dominant' trajectory
- Only need to fetch the 'dominant' trajectory
- They refer to this new index as Containment-Based Footmark Index (CFMI)

Containment-Based Footmark Index

Defination (v_d-Containment)

For two trajectories Y and Y' in Υ_{v_d} , if $Y_{*-v_d}.P$ is a sub-path of $Y'_{*-v_d}.P$, then Y is v_d-contained by Y'. In particular, if $Y_{*-v_d}.P \neq Y'_{*-v_d}.P$, then Y is stickly $v - d$-contained by Y'.

Defination (v_d-Dominant)

A trajectory $Y \in \Upsilon_{v_d}$ is v_d-dominant if there exists no $Y' \in v_d$ such that Y is strictly v_d-contained by Y'.

Containment-Based Footmark Index

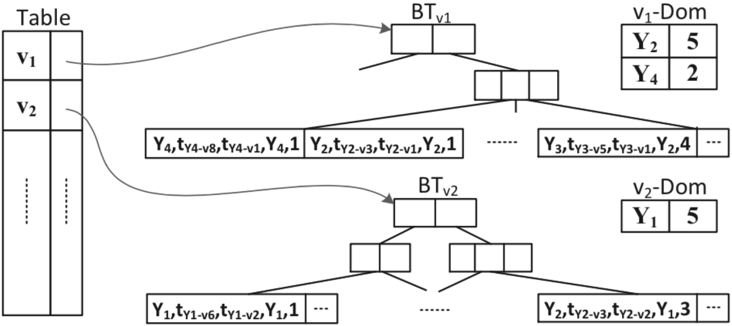
- CFMI improves the structure of each $B^+ - tree$ in FMI. Specifically, each leaf entry of BT_{v_i} is in the following new form: $< tid, t_s, t_a, did, sloc >$
- Besides, we keep a table $v_i - Dom$ for each BT_{v_i} , in which we record the length of $Y_{*-v_i}.P$ for each v_i-dominant trajectory Y

Containment-Based Footmark Index

For each query (v_i, T), CFMI returns two sets:

1. $TRREC = \{(tid, t_s, did, sloc)\}$, which records the information of trajectories in $\Upsilon(v_d, T)$
2. $DOM = \{(did, len)\}$, which records the did's appeared in TRREC and their corresponding values in $v_i - Dom$

Containment-Based Footmark Index



Containment-Based Footmark Index

Algorithm 3: CFMI-FG(v_d, T)

begin

  $FG \leftarrow |V| \times |V|$ matrix with all entries zeros ;

  $(TRREC, DOM) \leftarrow$ CFMI-Search(v_d, T) ;

  $DA \leftarrow \emptyset$;

  for *each* $(did, len) \in DOM$ **do**

    create array $DA.did[len]$ with all entries zeros ;

    $DA \leftarrow DA \cup DA.did[len]$;

  for *each* $(tid, t_s, did, sloc) \in TRREC$ **do**

    if $t_s \notin T$ **then**

      Modify-FG(tid) ;

    else

      $DA.did[sloc] \leftarrow DA.did[sloc] + 1$;

Containment-Based Footmark Index

for *each* $(did, len) \in DOM$ **do**
    $Y \leftarrow \mathrm{GetTraj}(did)$;
    $vid \leftarrow$ the first location of $Y.P$;
    $k \leftarrow 1, w \leftarrow 0$;
    while $vid \neq v_d$ **do**
        $vid' \leftarrow$ the next location of $Y.P$;
        if $DA.did[k] \neq 0$ *or* $w \neq 0$ **then**
            $w \leftarrow w + DA.did[k]$;
            $FG[vid][vid'] \leftarrow FG[vid][vid'] + w$;
        $k \leftarrow k + 1$;
        $vid \leftarrow vid'$;
return FG ;

MFP-Search

Lemma

Let $u \rightsquigarrow v$ denote a path from u to v. Suppose $P^c = v_s \rightsquigarrow v_k \rightsquigarrow v_k \rightsquigarrow v_d$ is a path with cycles on G_f. We have $F(P) \succ F(P^c)$, where P is the resulting path after removing the portion of P^c between consecutive visits to v_k.

Lemma

Given G_f w.r.t. Ω, there exists an MFP from v_s to v_d that is simple, i.e., has at most $|V_f|-1$ edges.

MFP-Search

Define '$+$' as follows:

- If the two inputs are non-decreasing sequences of positive integers, "$+$" merges them into a non-decreasing sequence. For example: $(20) + (5, 20) = (5, 20, 20)$;
- If one input is $\emptyset$, then the other input is returned. If both inputs are $\emptyset$'s, then $\emptyset$ is returned. For example: $\emptyset + (5, 20) = (5, 20)$;
- If one input is $\#$, then $\#$ is returned. For example: $\# + (5, 20) = \#$.

MFP-Search

Let $F^*(v_s, i)$ be the frequency of the v_s–v_d MFP using at most i edges.

Lemma

Given $G_f = (V_f, E_f)$, if $i > 0$, then we have

$$F^*(v_s, i) = \max(F^*(v_s, i{-}1), \max_{(v_s,v)\in E_f}((w_{v_s v}) + F^*(v, i{-}1))).$$

MFP-Search

Algorithm 4: MFP($v_s, G_f = (V_f, E_f)$)

begin
  for *each* $u \in V_f$ **do**
    if $u = v_d$ **then**
      $u.\xi \leftarrow \emptyset$;
    else
      $u.\xi \leftarrow \#, u.suc \leftarrow null$;
  $P^* \leftarrow null$;
  if $v_s \in V_f$ **then**
    for $i \leftarrow 1$ *to* $|V_f| - 1$ **do**
      for *each edge* $(u, v) \in E_f$ **do**
        if $(w_{uv}) + v.\xi \succeq u.\xi$ **then**
          $u.\xi \leftarrow (w_{uv}) + v.\xi$;
          $u.suc \leftarrow v$;
    create P^* by following the successors from v_s to v_d ;
  return P^* ;

Summary

Dataset & Environment

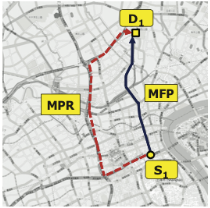
Dataset

Dataset Name	No. of Trajectories	Total Length	Size (MB)
Year Dataset	11,547,611	245,276,717	3,335
Month Dataset	1,650,134	35,619,454	484
Day Dataset	54,579	1,217,890	17

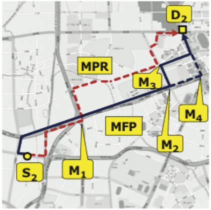
Environment

- Intel(R) Xeon(R) E5506 CPU (2.13GHz)
- 12GB memory
- 10,000RPM sever-level hard disks
- Linux 2.6.32 x86_64
- Jre 1.7.0_4 64-Bit

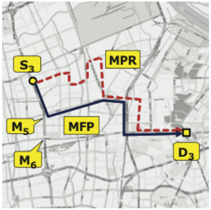
Effectiveness



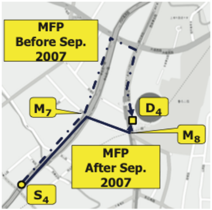
(a) Case 1



(b) Case 2

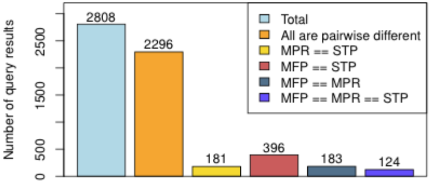


(c) Case 3

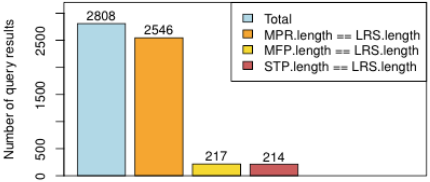


(d) Case 4

Effectiveness



(a) vs. shortest path



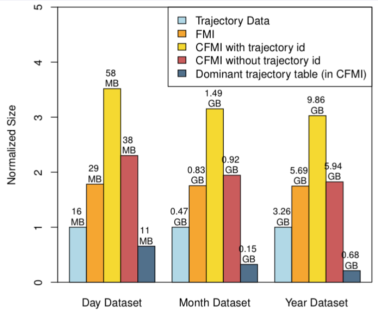
(b) vs. least road segments

Index Creation and Size

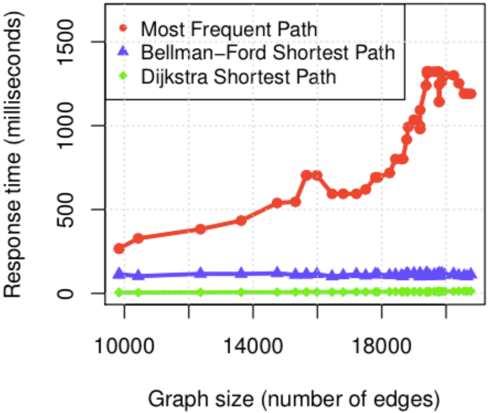
Index Creation

For Year Dataset, the index creation time of FMI and CFMI is 72 minutes and 127 minutes, respectively.

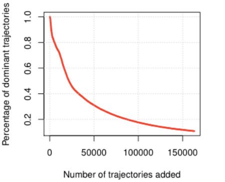
Index Size

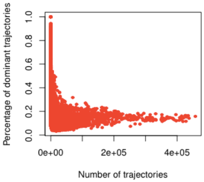


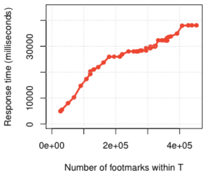
Effciency of MFP-Search

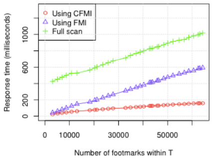


Effciency

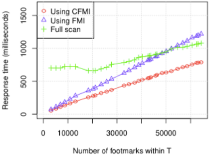




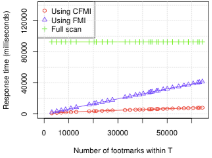




(a) Tiny-Dataset Mode



(b) Small-Dataset Mode



(c) Big-Dataset Mode

Any Questions?

End

Thanks For Attention!