



Finding
TPMFP in
BTD

Ziyang Chen

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MFP-Search

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End

Finding Time Period-Based Most Frequent Path in Big Trajectory Data¹

Ziyang Chen

Fudan University

13307130148@fudan.edu.cn

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¹powered by Xe₃La₃TeX



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- 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 period T , a source v_s and a destination v_d , TPMFP searches the MFP from v_s to v_d during T .



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- 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.)



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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).*



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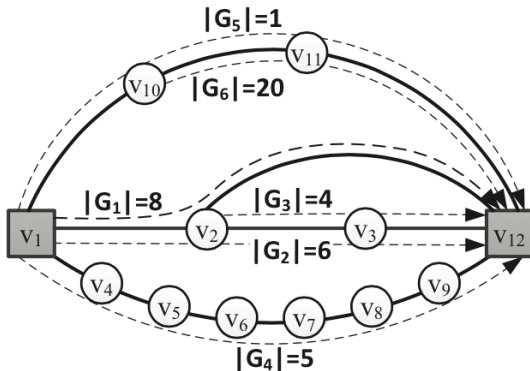
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DEFINATION (ROAD NETWORK)

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 $V_p = x_1, x_2, \dots, x_k$ and $E_p = (x_1, x_2), \dots, (x_{k-1}, x_k)$ 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 $((x_1, t_1), (x_2, t_2), \dots, (x_k, t_k))$ such that there exists a path $x_1 \rightarrow x_2 \rightarrow \dots \rightarrow x_k$ on G and t_i is a timestamp indicating the time when Y passes x_i .



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DEFINITION (FOOTMARK)

Given $\Omega = (G, \Upsilon, v_s, v_d, T)$ and a trajectory $Y = ((x_1, t_1), \dots, (x_k, t_k)) \in \Upsilon$, 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 $\tilde{Y}(v_d, T)$.



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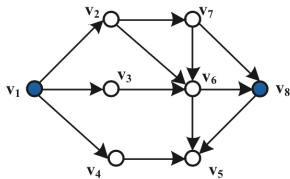
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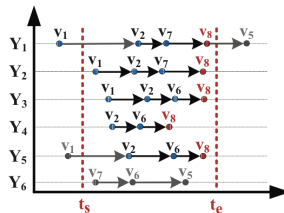
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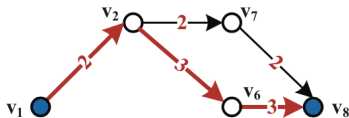
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(a) Road network G



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



(c) Footmark graph G_f



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DEFINATION (EDGE FREQUENCY)

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

DEFINATION (FOOTMARK GRAPH)

Given G and $\tilde{\Upsilon}_{(v_d, T)}$, 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 $w_{uv} > 0$.*



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DEFINATION (PATH FREQUENCY)

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

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



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DEFINITION (MORE-FREQUENT-THAN RELATION)

Given two path frequencies $F(P) = (f_1, \dots, f_m)$ and $F(P') = (f'_1, \dots, f'_n)$ 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 $q \in \{1, \dots, \min(m, n)\}$ such that 1) $f_i = f'_i$ for all $i \in \{1, \dots, q-1\}$, 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

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THEOREM

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

DEFINITION (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 footprint graph derived from Ω .



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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

- 1 step 1: build the footprint graph G_f w.r.t. Ω ;
 - 2 step 2: find the MFP P^* from v_s to v_d on G_f ;
 - 3 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.*



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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 $\langle tid, t_a \rangle$
- Given v_d and T , $FMI\text{-}Search(v_d, T)$ returns the id's of all the trajectories in $\Upsilon(v_d, T)$ via searching BT_{v_d}



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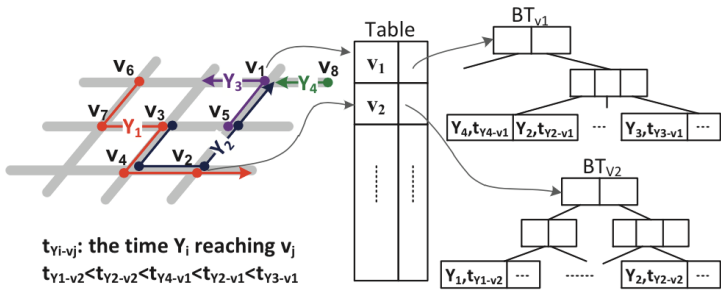
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Algorithm 2: FMI-FG(v_d, T)

begin

```
1   $FG \leftarrow |V(G)| \times |V(G)|$  matrix with all entries zeros ;
2   $TRID \leftarrow \text{FMI-Search}(v_d, T)$  ;
3  for each  $tid \in TRID$  do
4       $Y \leftarrow \text{GetTraj}(tid)$  ;
5       $(vid, t) \leftarrow$  the first element of  $Y$  ;
6      while  $t \notin T$  do
7           $(vid, t) \leftarrow$  the next element of  $Y$  ;
8      while  $vid \neq v_d$  do
9           $(vid', t') \leftarrow$  the next element of  $Y$  ;
10          $FG[vid][vid'] \leftarrow FG[vid][vid'] + 1$  ;
11          $(vid, t) \leftarrow (vid', t')$  ;
12  return  $FG$  ;
```



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- 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)



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DEFINITION (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' .*

DEFINITION (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' .



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- CFMI improves the structure of each $B^+ - tree$ in FMI. Specifically, each leaf entry of BT_{v_i} is in the following new form: $\langle tid, t_s, t_a, did, sloc \rangle$
- 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



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

- ① $TRREC = \{(tid, t_s, did, slot)\}$, 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 $v_i - Dom$



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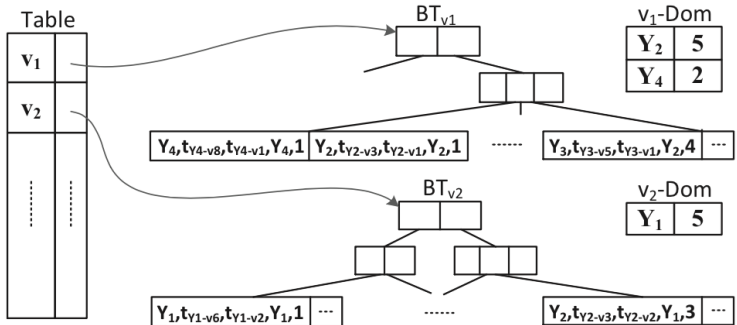
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Algorithm 3: CFMI-FG(v_d, T)

```
begin
1   $FG \leftarrow |V| \times |V|$  matrix with all entries zeros ;
2   $(TRREC, DOM) \leftarrow \text{CFMI-Search}(v_d, T)$  ;
3   $DA \leftarrow \emptyset$  ;
4  for each  $(did, len) \in DOM$  do
5      create array  $DA.did[len]$  with all entries zeros ;
6       $DA \leftarrow DA \cup DA.did[len]$  ;
7  for each  $(tid, t_s, did, sloc) \in TRREC$  do
8      if  $t_s \notin T$  then
9          Modify-FG( $tid$ ) ;
      else
10          $DA.did[sloc] \leftarrow DA.did[sloc] + 1$  ;
```



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```
11  for each (did, len)  $\in$  DOM do
12      Y  $\leftarrow$  GetTraj(did) ;
13      vid  $\leftarrow$  the first location of Y.P ;
14      k  $\leftarrow$  1, w  $\leftarrow$  0 ;
15      while vid  $\neq$  vd do
16          vid'  $\leftarrow$  the next location of Y.P ;
17          if DA.did[k]  $\neq$  0 or w  $\neq$  0 then
18              w  $\leftarrow$  w + DA.did[k] ;
19              FG[vid][vid']  $\leftarrow$  FG[vid][vid'] + w ;
20              k  $\leftarrow$  k + 1 ;
21              vid  $\leftarrow$  vid' ;
22  return FG ;
```



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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.



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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: $\# + (5, 20) = \#$.



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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

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



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Algorithm 4: $\text{MFP}(v_s, G_f = (V_f, E_f))$

```
begin
1  for each  $u \in V_f$  do
2      if  $u = v_d$  then
3           $u.\xi \leftarrow \emptyset$ ;
4      else
5           $u.\xi \leftarrow \#, u.suc \leftarrow null$ ;
6   $P^* \leftarrow null$ ;
7  if  $v_s \in V_f$  then
8      for  $i \leftarrow 1$  to  $|V_f| - 1$  do
9          for each edge  $(u, v) \in E_f$  do
10             if  $(w_{uv}) + v.\xi \succeq u.\xi$  then
11                  $u.\xi \leftarrow (w_{uv}) + v.\xi$ ;
12                  $u.suc \leftarrow v$ ;
13         create  $P^*$  by following the successors from  $v_s$  to  $v_d$ ;
14 return  $P^*$ ;
```



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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



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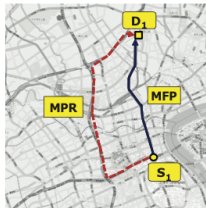
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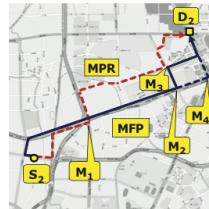
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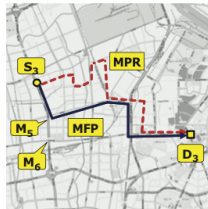
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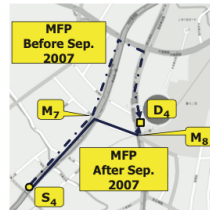
(a) Case 1



(b) Case 2



(c) Case 3



(d) Case 4



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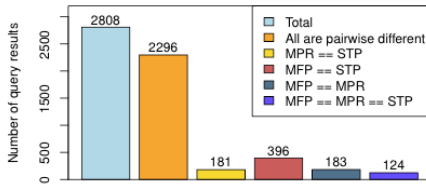
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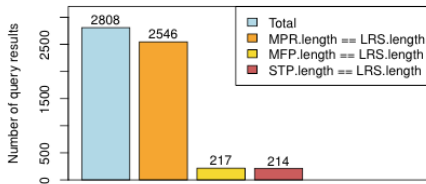
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(a) vs. shortest path



(b) vs. least road segments



Index Creation and Size

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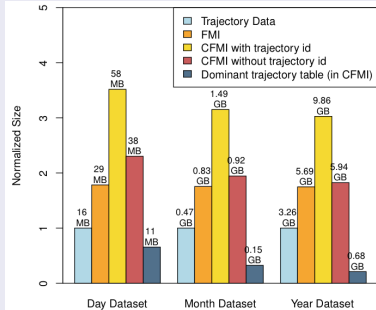
Q&A

End

Index Creation

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

Index Size





Efficiency of MFP-Search

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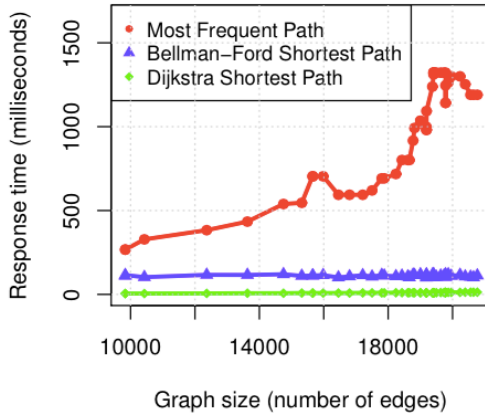
D&E

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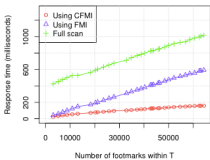
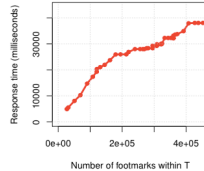
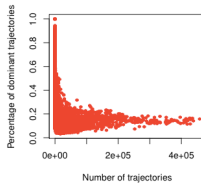
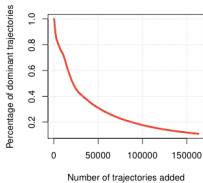
D&E

Effectiveness

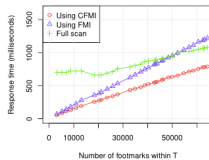
Efficiency

Q&A

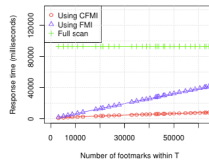
End



(a) Tiny-Dataset Mode



(b) Small-Dataset Mode



(c) Big-Dataset Mode



Q&A

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Any Questions?



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Thanks For Attention!