Optimal Spatial Dominance: An Effective Search of Nearest Neighbor Candidates

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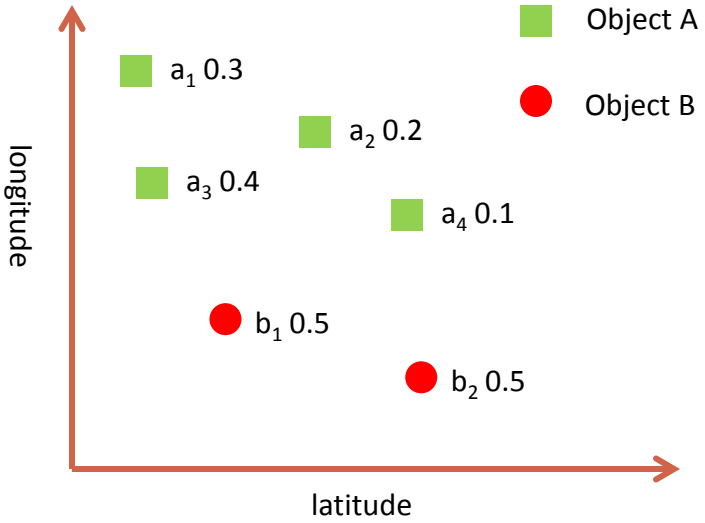
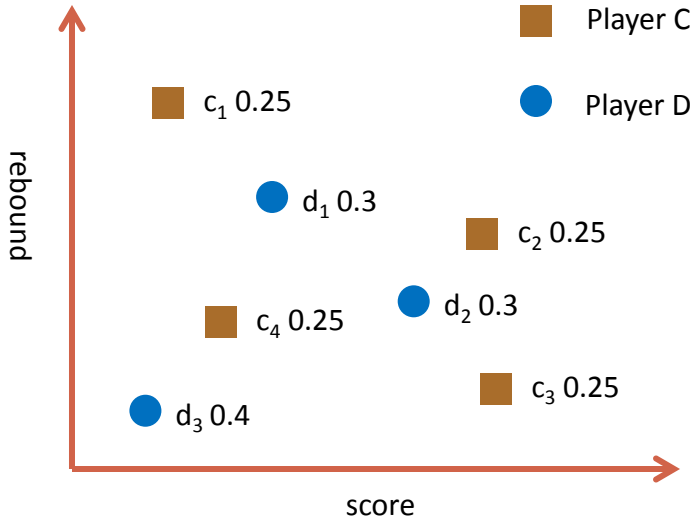
Outline

- Introduction
- Related Work
- Spatial Dominance Operators
- Experiments
- Conclusion

Introduction

- Objects with multiple instances are widely used.
  - Uncertain object (instances are exclusive), e.g., uncertain spatial objects.
  - Multi-valued object (instances are co-occurrence), e.g., NBA player records.





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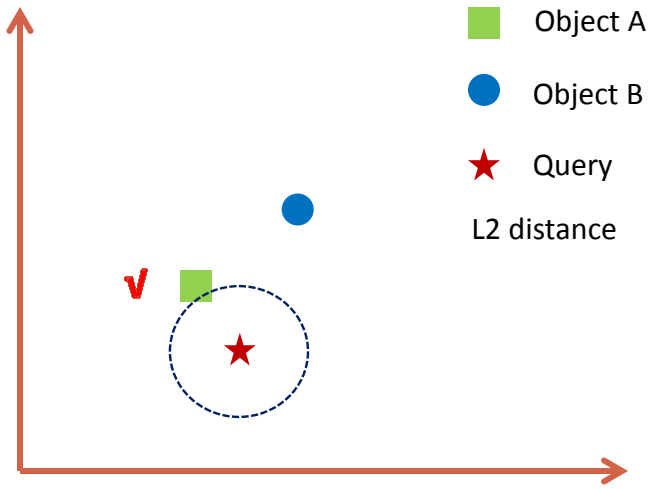
- Easy for objects with single instance when distance metric is given.



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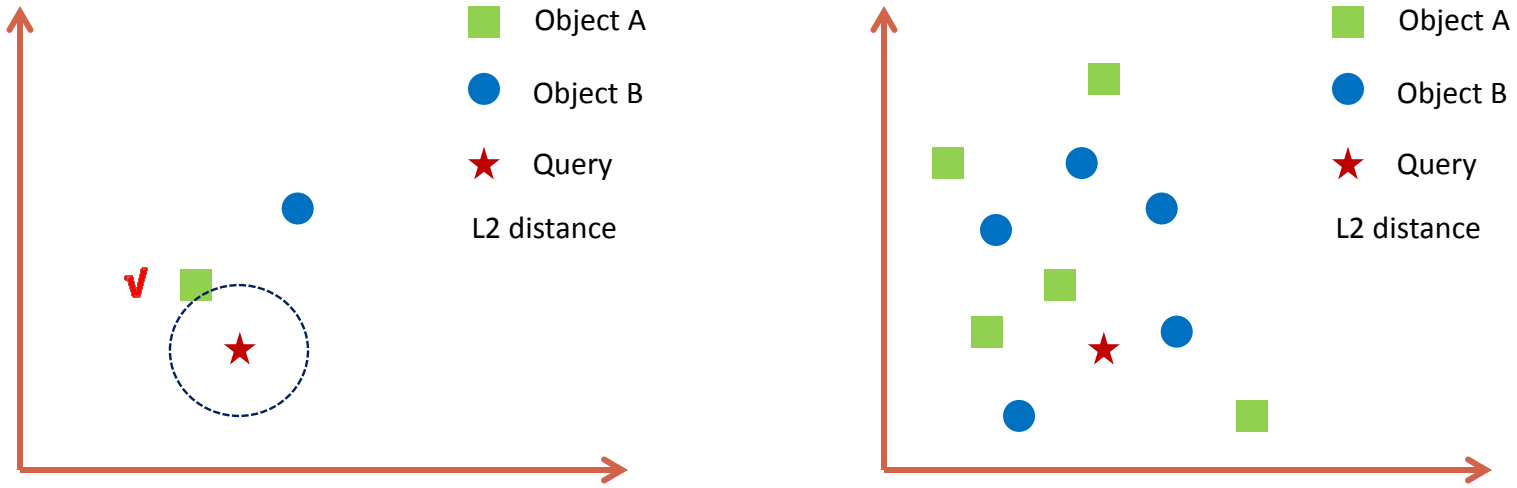

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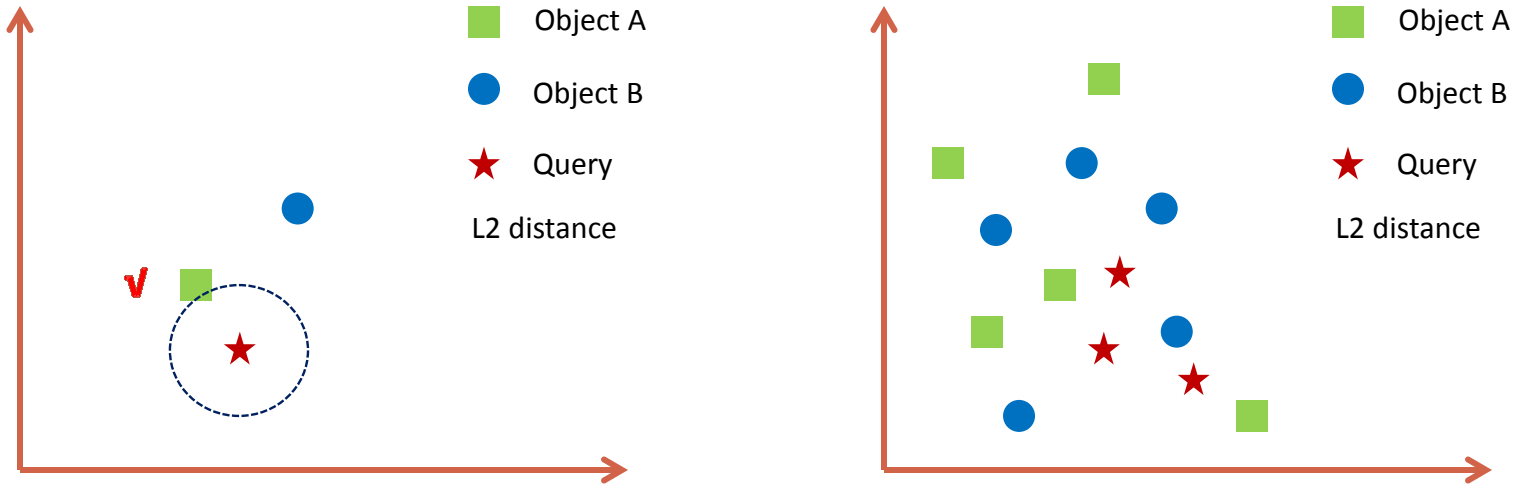

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  - Given a query object *Q*, return the nearest object to the query.
- There are a lot of NN ranking functions for objects with multiple instances.
  - Min/Max, Expected distance, Quantile.
  - NN probability, Expected rank.
  - Earth Mover's distance, Netflow distance.

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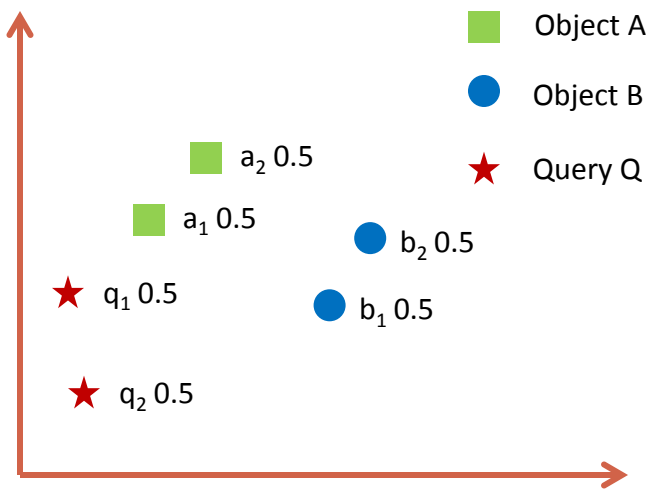
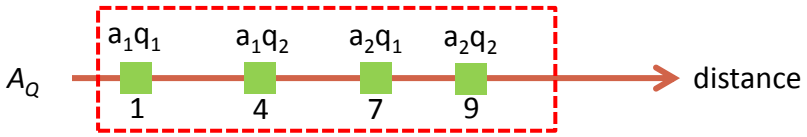
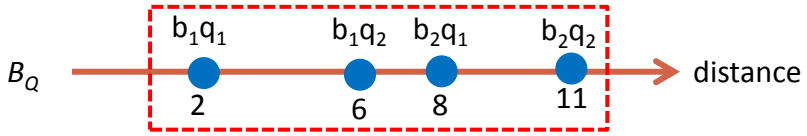


1. Expected distance (all pairs based NN)



$$E_{dis}(A,Q) = 1 * 0.25 + 4 * 0.25 + 7 * 0.25 + 9 * 0.25 = 5.75$$



$$E_{dis}(B,Q) = 2 * 0.25 + 6 * 0.25 + 8 * 0.25 + 11 * 0.25 = 6.75$$

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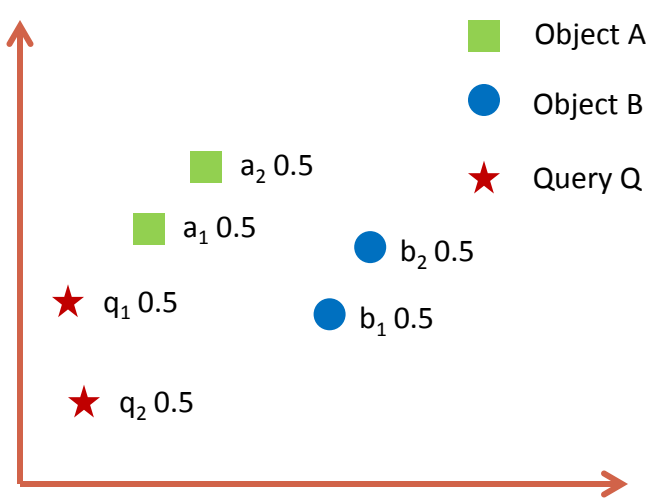

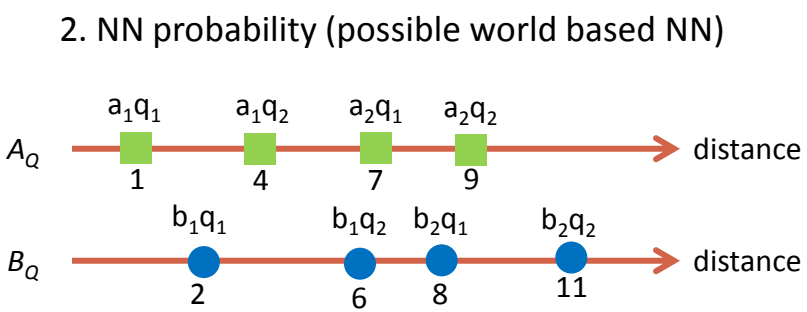

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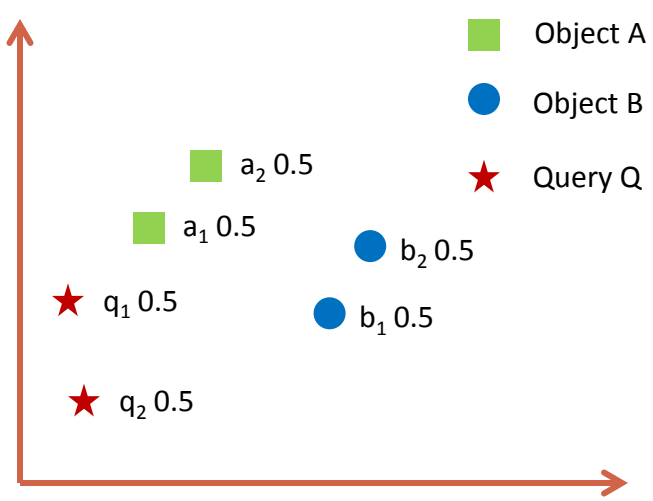

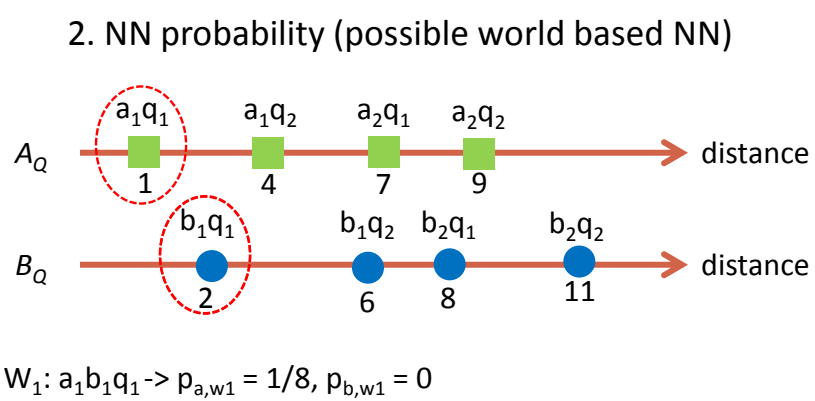

W_1: $a_1b_1q_1$ -> $p_{a,w1} = 1/8$, $p_{b,w1} = 0$

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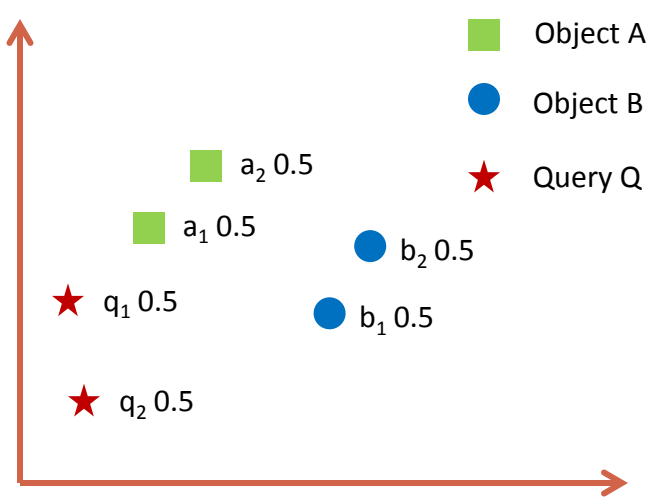
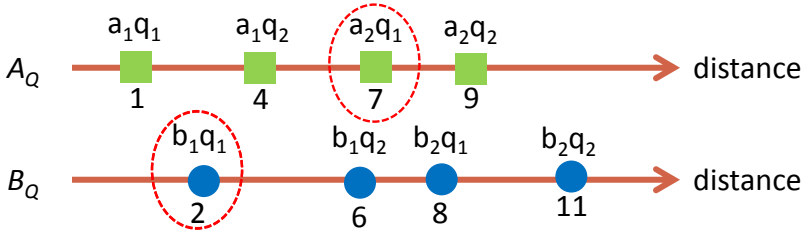


2. NN probability (possible world based NN)



W_1: $a_1b_1q_1$ -> $p_{a,w1} = 1/8$, $p_{b,w1} = 0$

W_2: $a_2b_1q_1$ -> $p_{a,w2} = 0$, $p_{b,w2} = 1/8$

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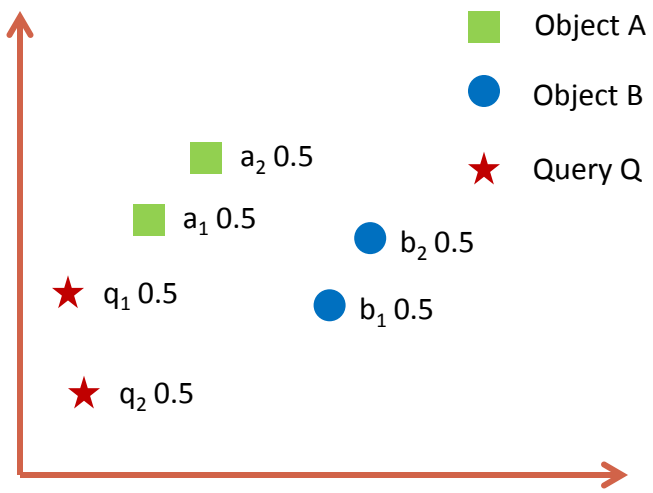

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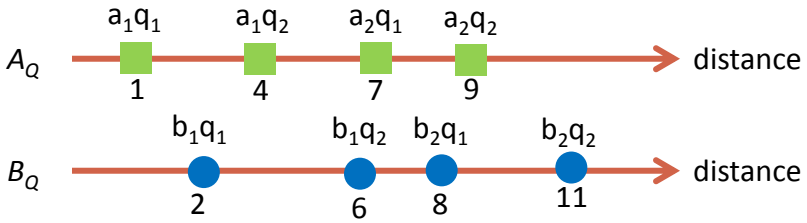

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W_2: $a_2b_1q_1$ -> $p_{a,w2} = 0$, $p_{b,w2} = 1/8$

...

W_8: $a_2b_2q_2$ -> $p_{a,w8} = 1/8$, $p_{b,w8} = 0$

=>

$NN_p(A,Q) = \sum p_{a,wi} = 6/8$

$NN_p(B,Q) = \sum p_{b,wi} = 2/8$

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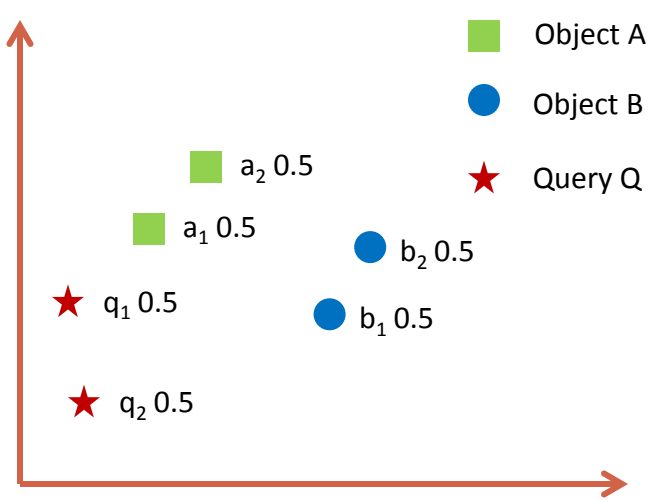
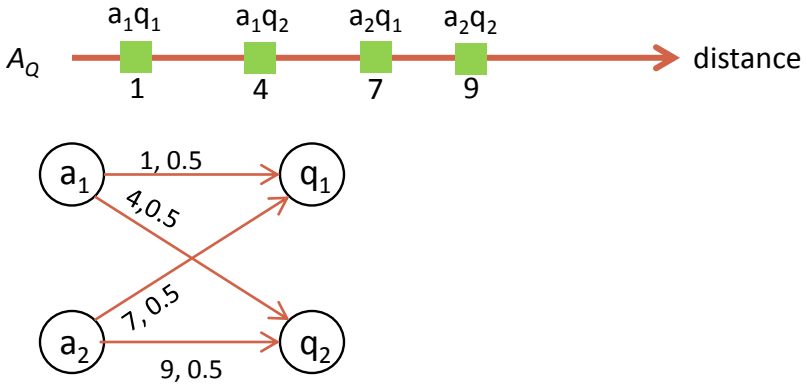


3. Earth Mover's distance (selected pairs based NN)



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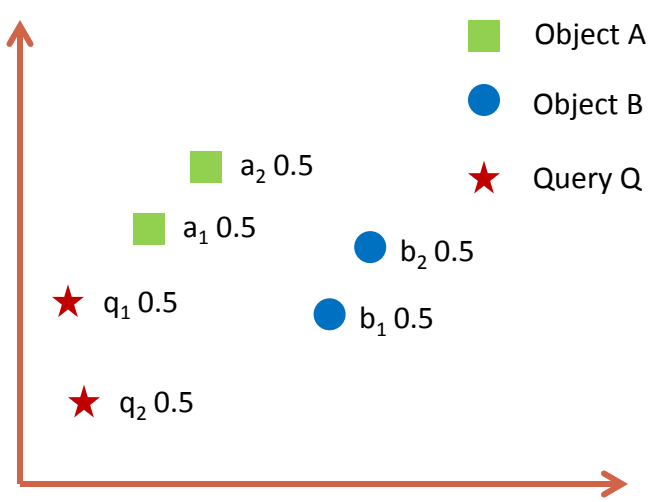

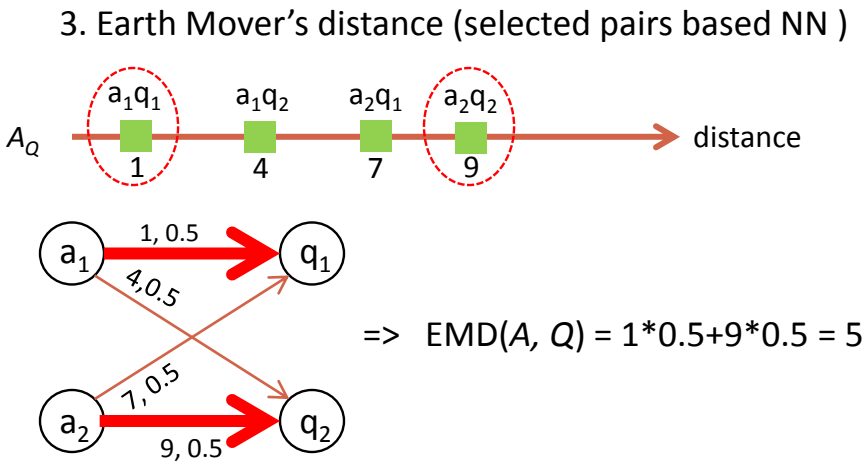

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- There are a lot of NN ranking functions for objects with multiple instances.
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- **Motivation**
  - **A user may not have a specific NN function in mind, it is desirable to provide her with a set of NN candidates.**

Introduction

- A spatial dominate (SD) operator is used to define the partial order between objects regarding a query *Q*, i.e., SD(*A, B, Q*) means *A* dominates *B*, otherwise $\neg$SD(*A, B, Q*).

- Given a SD operator, the NN candidate set consists of the objects that are not dominated by any other objects.

- Optimal SD operator w.r.t a family *F* of NN functions
  - Correctness: SD(*A, B, Q*) $\Rightarrow \forall f \in F$, that $f(A) \leq f(B)$
  - Completeness: $\neg$SD(*A, B, Q*) $\Rightarrow \exists f \in F$, that $f(A) > f(B)$

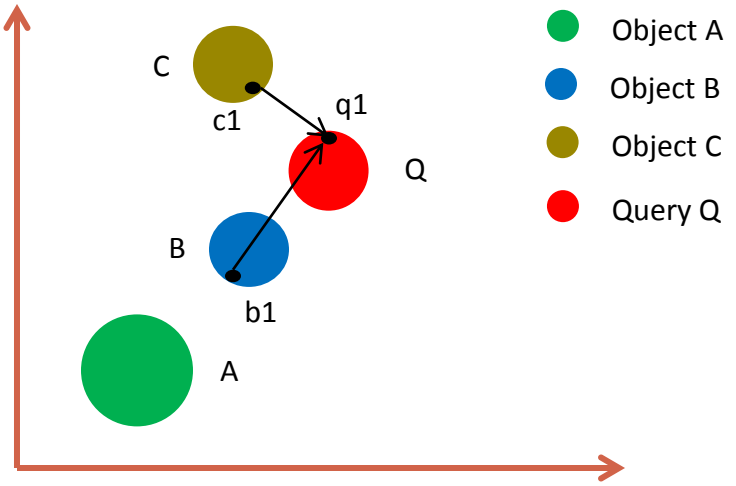
Related Work

- Full dominance operator (F-SD)
  - We have FSD(*A,B,Q*), if and only if $\forall q \in Q, \max(A,q) \leq \min(B,q)$ (SIGMOD10, SIGMOD14)

Cheng Long, et. al, The Hong Kong University of Science and Technology

Tobias Emrich, et. al, Institute for Informatics, Ludwig-Maximilians-Universität München

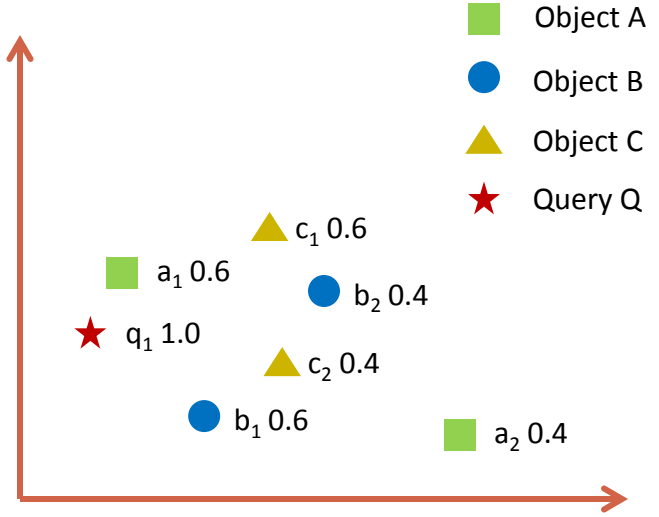
$FSD(B,A,Q)$
$\neg FSD(B,C,Q)$

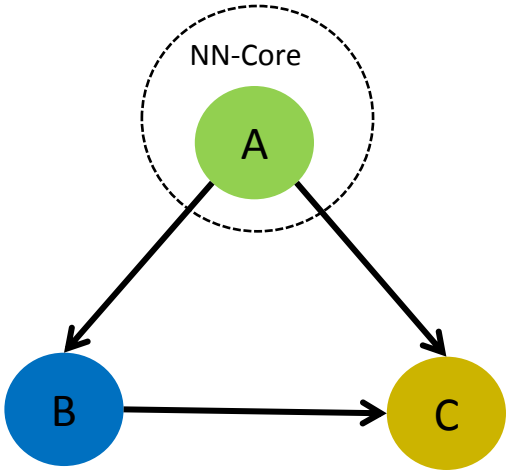


Over pessimistic: contain many redundant objects (no completeness property)

Related Work

- NN Core (TKDE10) ← Sze Man Yuen, et. al, Chinese University of Hong Kong
  - A → B: if A has higher chance to be closer to the query than B;
  - NN candidates : Minimal set of objects, each of which beats any object not in the NN candidates.



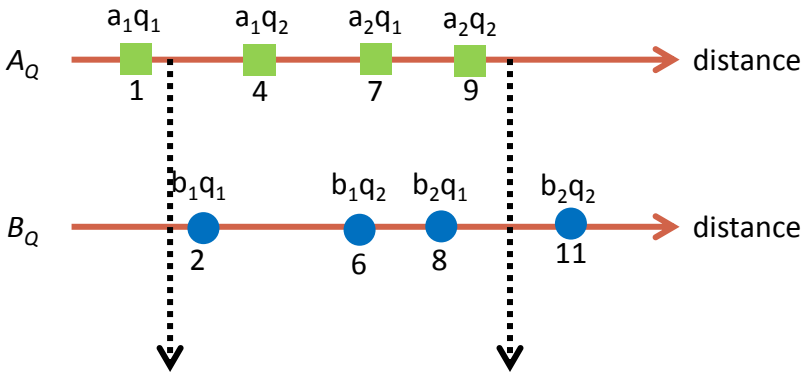


Too aggressive: violate correctness property

Related Work

- Stochastic order has been widely used in various domains to compare the "goodness" of two random variables distributions.

Stochastic Order. Given two independent random variables *X* and *Y* , we say *X* is smaller than *Y* in usual stochastic order, denoted by $X \preccurlyeq_{st} Y$, if $Pr(X \leq \lambda) \geq Pr(Y \leq \lambda)$ for every $\lambda \in R$.



$\Pr(A_Q \leq 1.5) = 0.25; \Pr(B_Q \leq 1.5) = 0$

$\Pr(A_Q \leq 10) = 1; \Pr(B_Q \leq 10) = 0.75$

Problem Definition

- Objects with multiple instances
  - An object *U* consists of a set $\{u_i\}$ of instances, and a discrete probability mass function assigns each instance u_i a probability value, denoted by $p(u_i)$, where $\sum p(u_i) = 1$.
  - The multi-valued objects are treated as discrete random variable if their weight can be normalized.

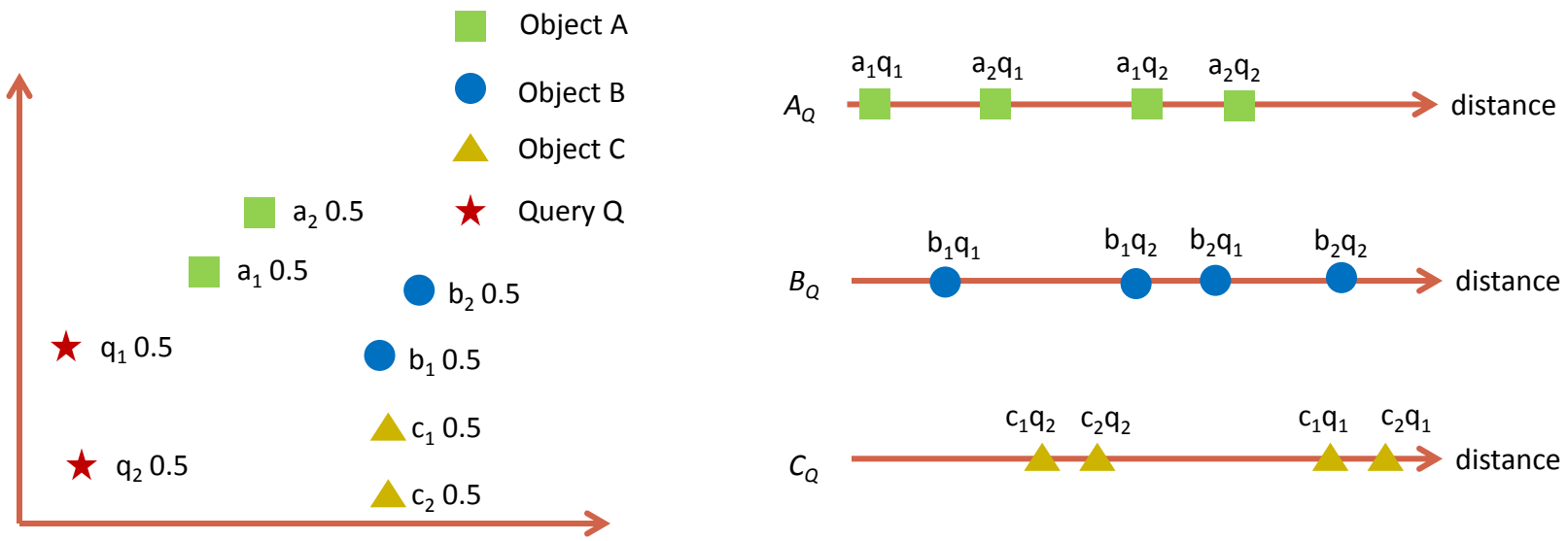
- Problem statement
  - Devise spatial dominance (SD) operators by carefully considering various NN function families.

Classify NN Functions

- N_1: all pairs based NN
  - Aggregation over pair-wise distances g(A_Q), e.g., Min/Max, Expected distance, Quantile.
- N_2: possible world based NN
  - Aggregation over score on each possible world g(A_W), e.g., NN probability, Expected rank.
- N_3: selected pairs based NN
  - Aggregation over selected pairs g(S(A_Q)), e.g., Earth Mover's distance, Netflow distance.

SD Operator

- Stochastic-SD (*S-SD*, opt. w.r.t N_1)
  - Given two objects *U* and *V*, and the query *Q*, we have *SSD*(*U,V,Q*) if and only if $U_Q \preccurlyeq_{st} V_Q$ and $U_Q \neq V_Q$.



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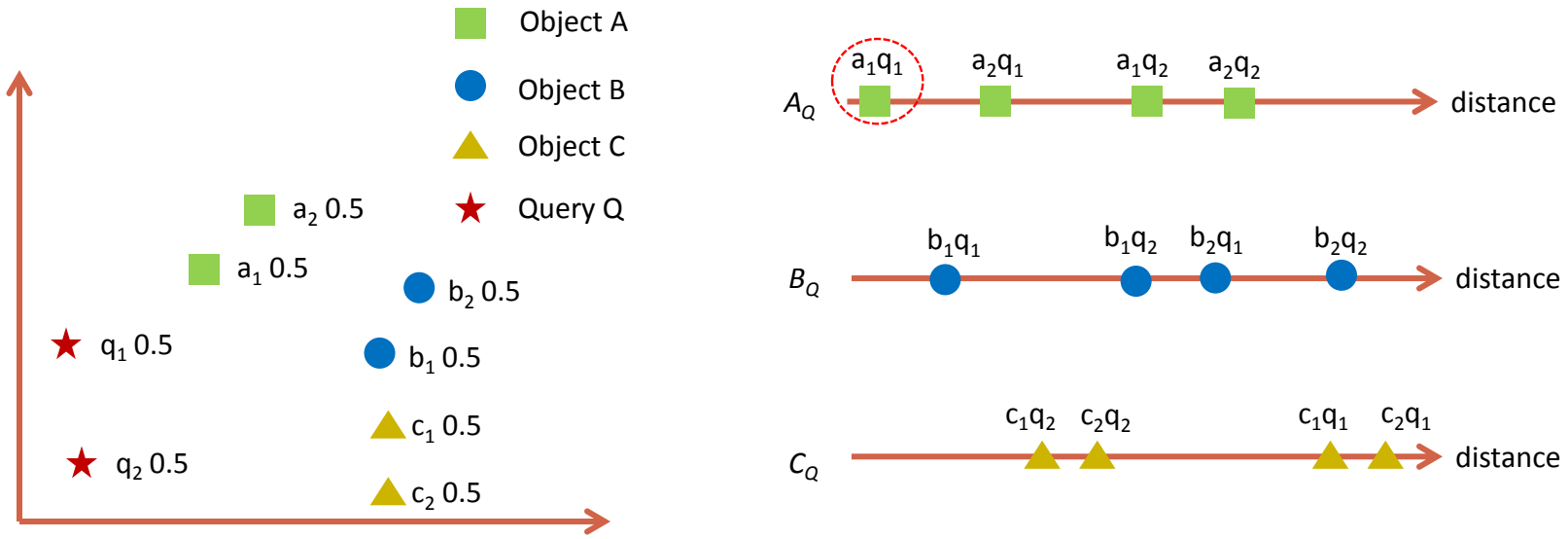

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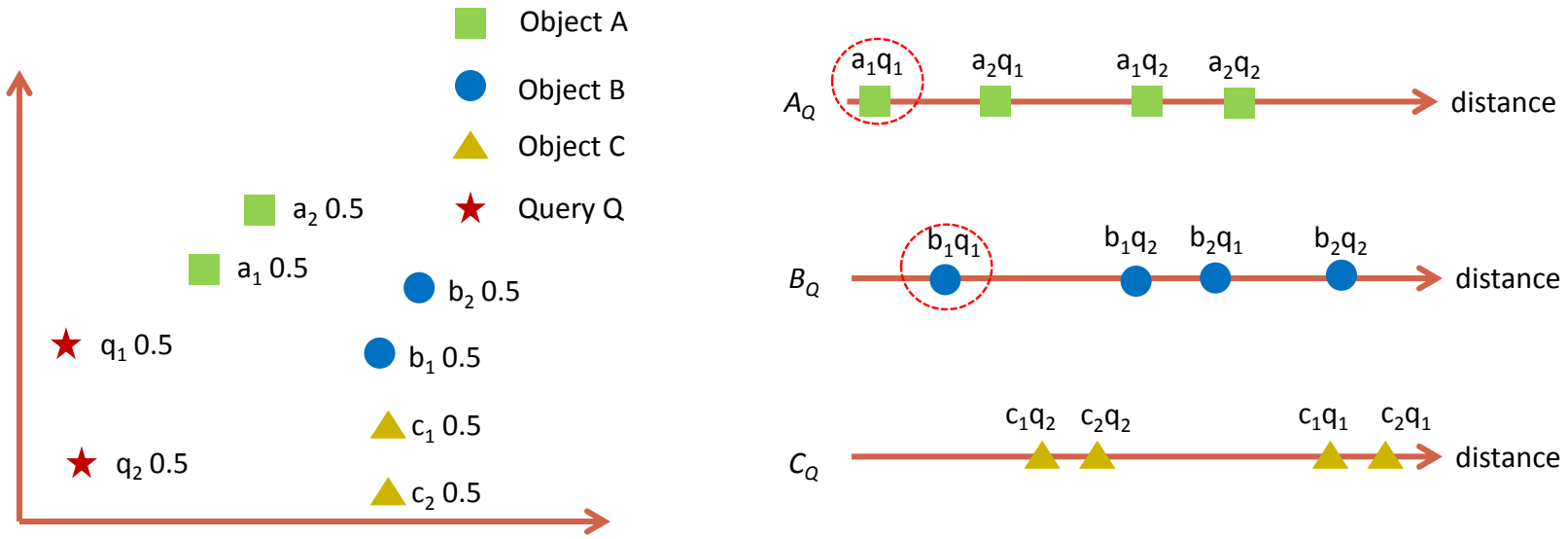

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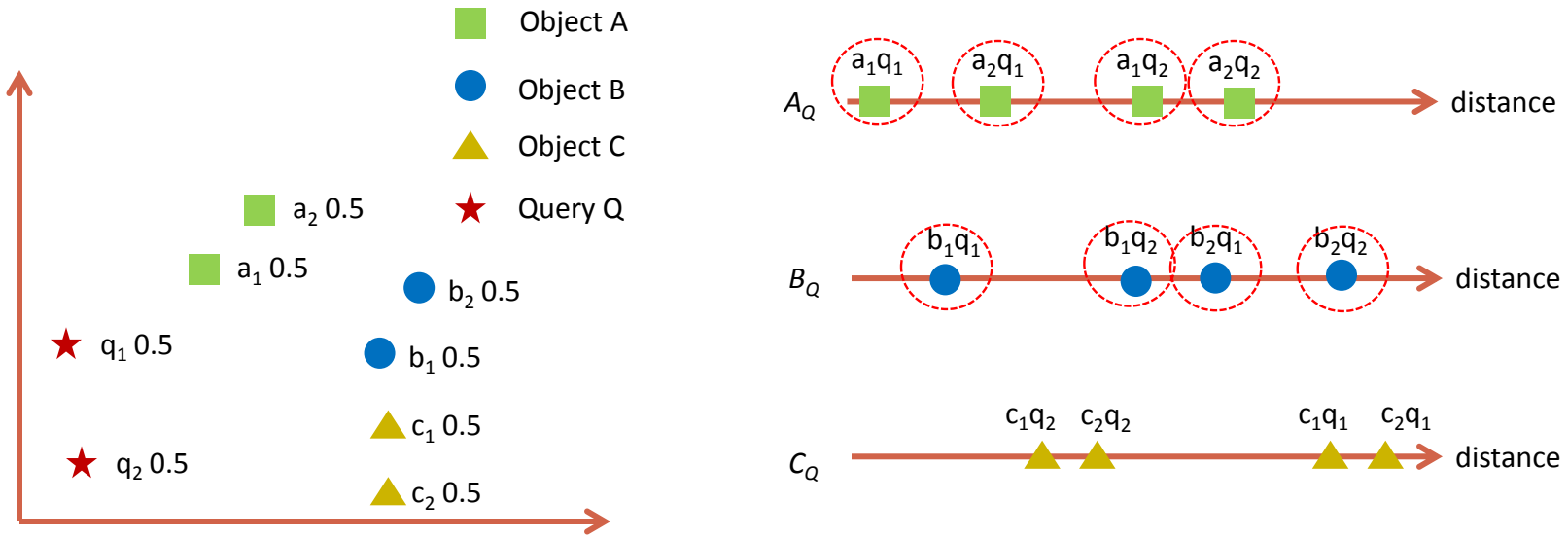
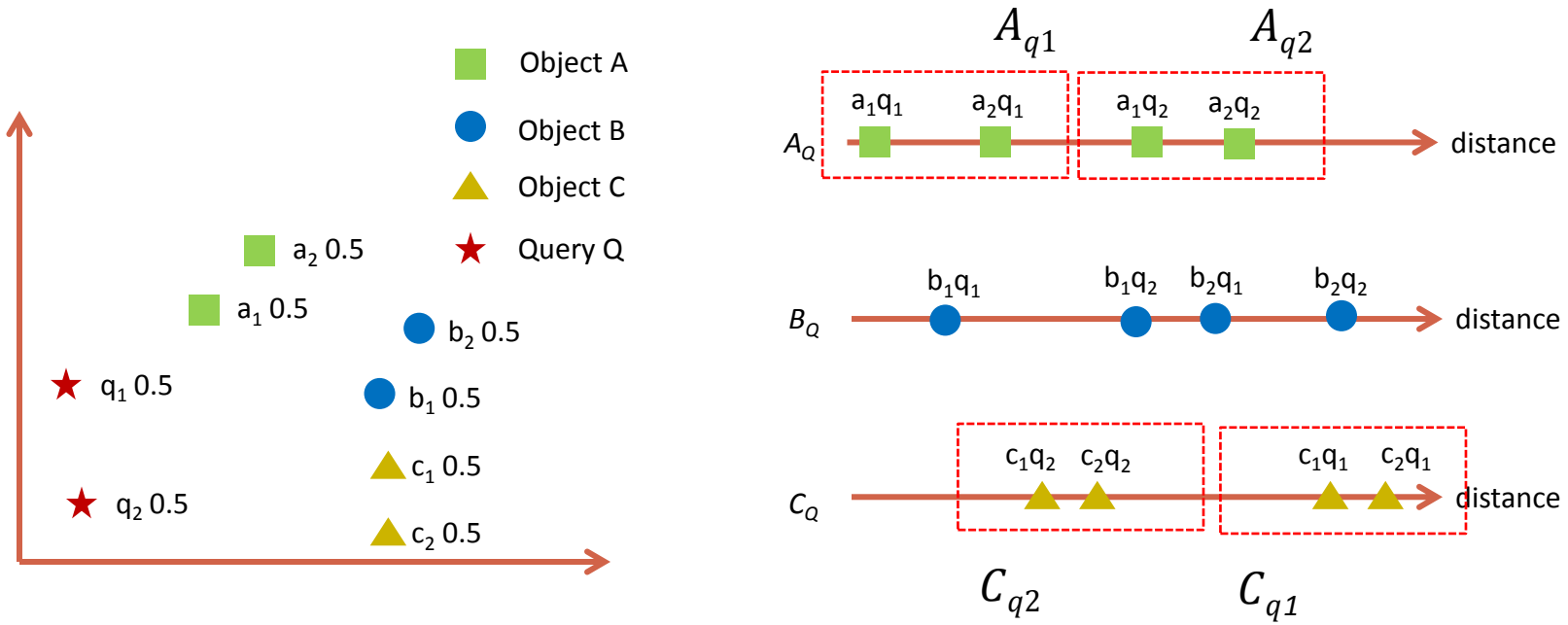


SD Operator

- Strict Stochastic-SD (*SS-SD*, opt. w.r.t $N_{1,2}$)
  - Given two objects *U* and *V*, and the query *Q*, we have *SSSD*(*U*,*V*,*Q*) if and only if $U_q \preccurlyeq_{st} V_q$ for $\forall q \in Q$ and $U_Q \neq V_Q$.



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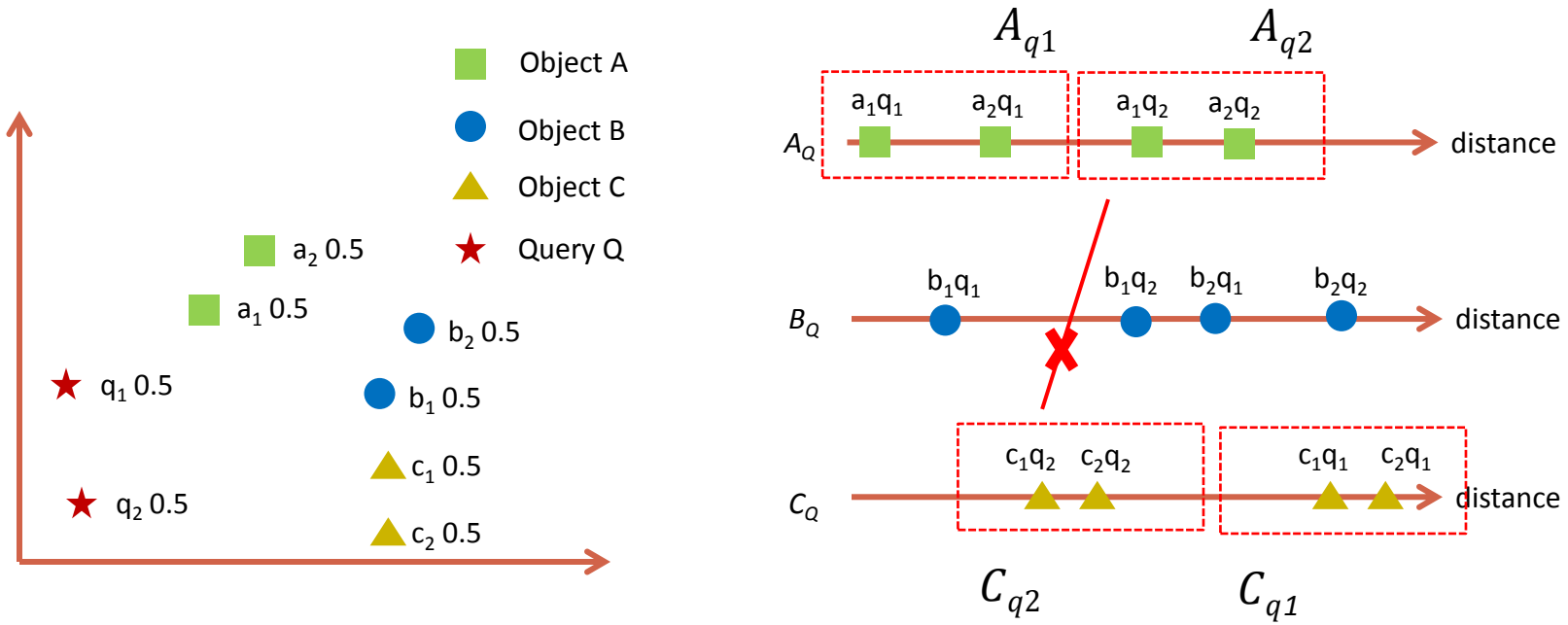
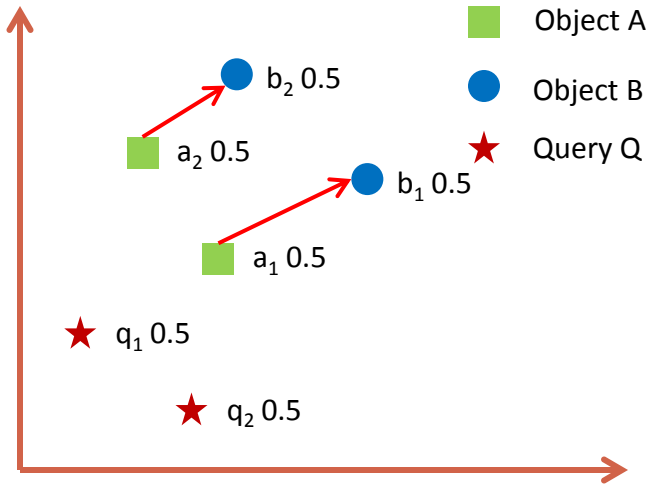
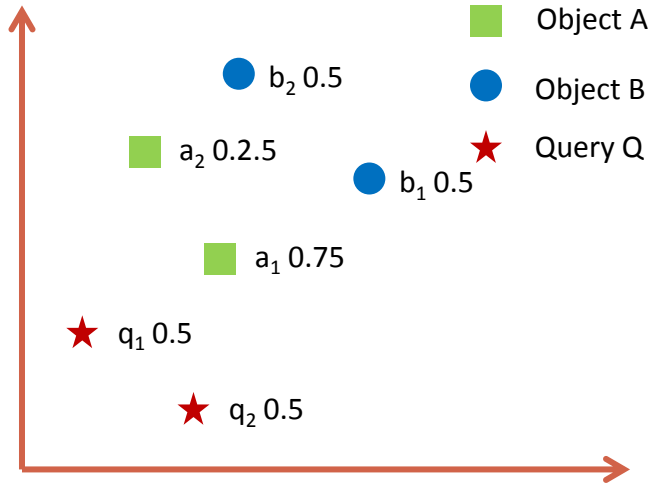


SD Operator

- Peer-SD (*P-SD*, opt. w.r.t $N_{1,2,3}$)
  - Given two objects *U* and *V*, and the query *Q*, we have *PSD*(*U*,*V*,*Q*) if there is a mapping between *U* and *V*, for each pair <*u*,*v*>, *u* is always closer to *Q* than *v* with same weight.





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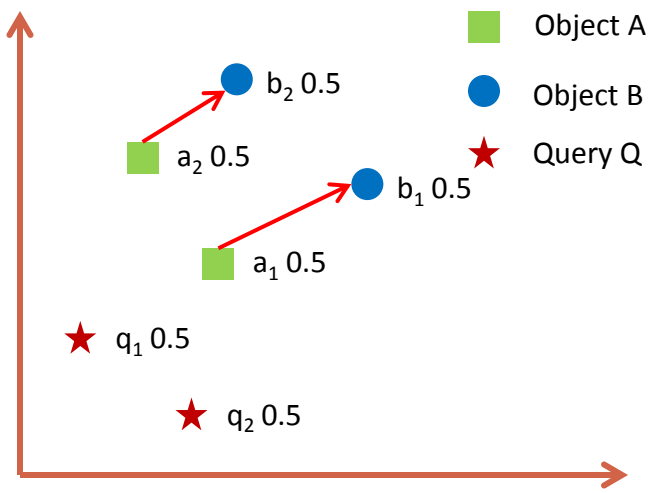

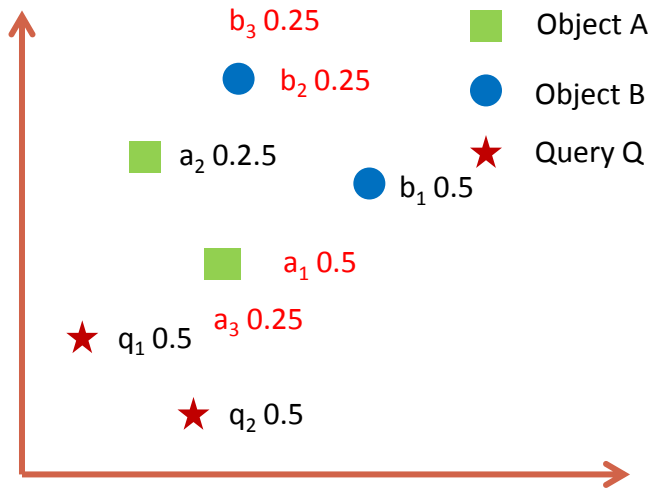

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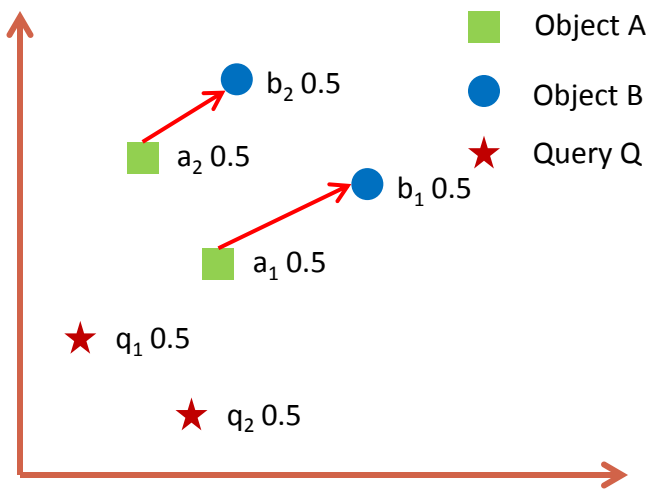
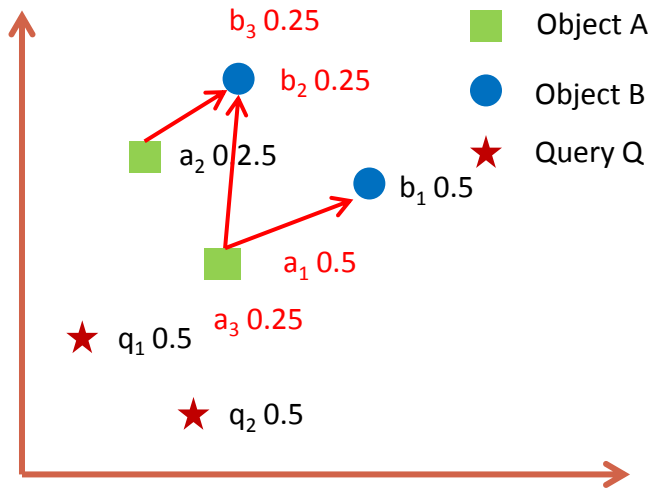
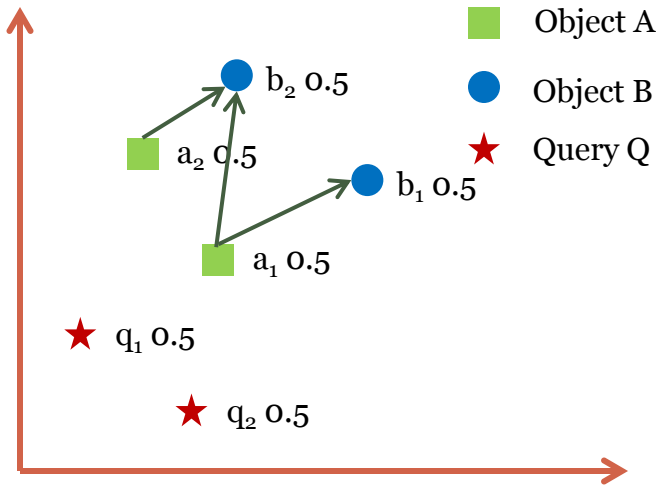
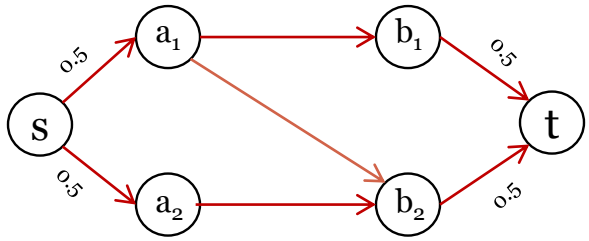




P-SD Check

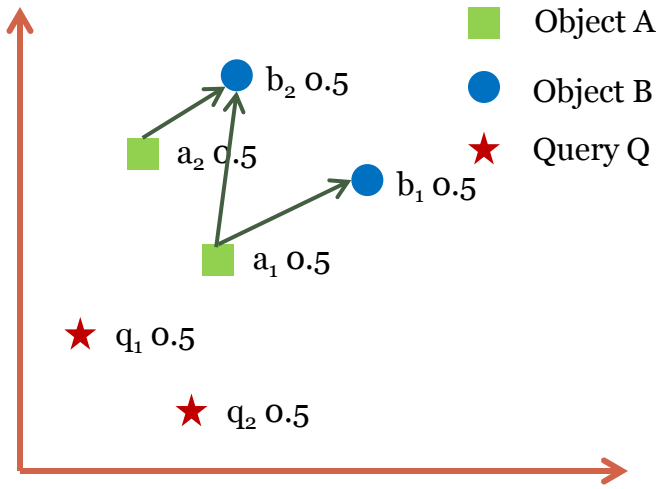
- *P-SD* check
  - Naively have to check all the mapping.
  - The P-SD check between *U* and *V* can be reduced to compute the network flow problem, *PSD*(*U*,*V*,*Q*) iff the network flow is 1

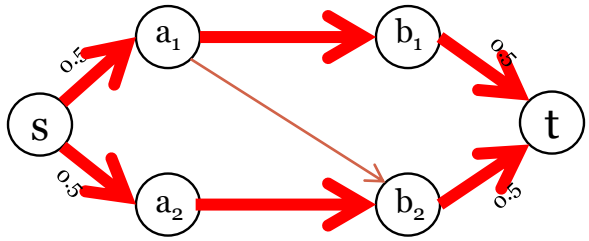




P-SD Check

- *P-SD* check
  - Naively have to check all the mapping.
  - The P-SD check between *U* and *V* can be reduced to compute the network flow problem, *PSD*(*U*,*V*,*Q*) iff the network flow is 1

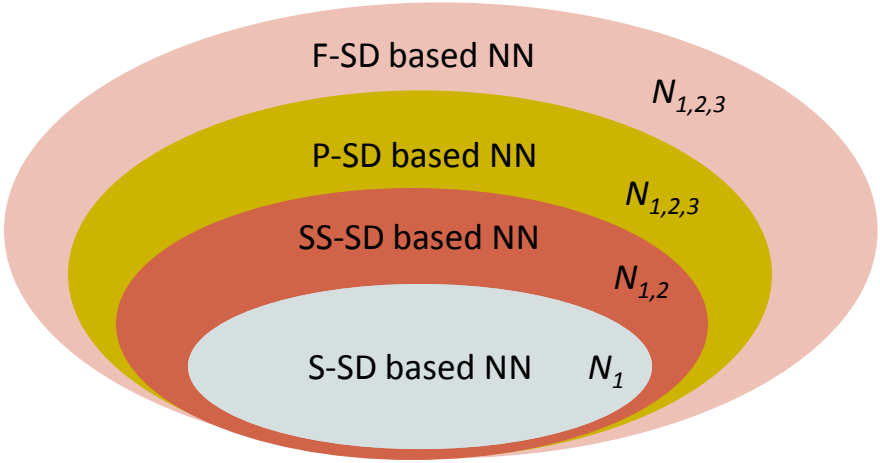




SD Operator Properties

- SD operator containment

$$NNC(O, Q, S\text{-}SD) \subseteq NNC(O, Q, SS\text{-}SD) \subseteq NNC(O, Q, P\text{-}SD) \subseteq NNC(O, Q, F\text{-}SD)$$



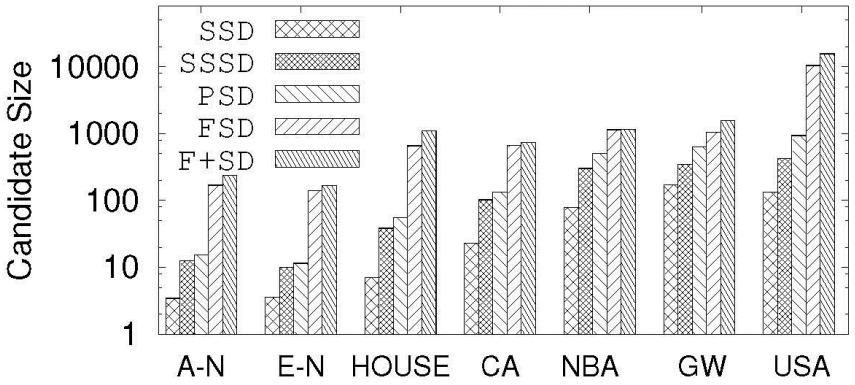
- NN candidate search
  - Based on branch and bound framework like skyline search

Experiments

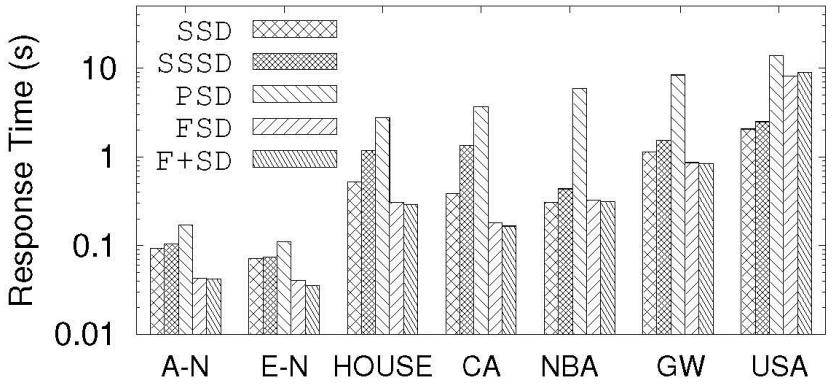
- Compare Algorithm
  - SSD, SSSD, PSD, FSD and F^+SD
- Datasets:
  - real dataset: NBA, Gowalla;
  - semi-real dataset: House, CA, USA;
  - synthetic dataset.

Evaluation parameter	Values
dimensionality d	2, **3**, 4, 5
# of objects n	**100k**, 200k, 400k, 600k, 1M
# of object instances m_d	20, **40**, 60, 80, 100
edge length of object h_d	100, 200, 300, **400**, 500
object center distribution	**anti (A)**, indep (E)
# of query instances m_q	10, 20, **30**, 40, 50
edge length of query h_q	100, **200**, 300, 400, 500

Experiments

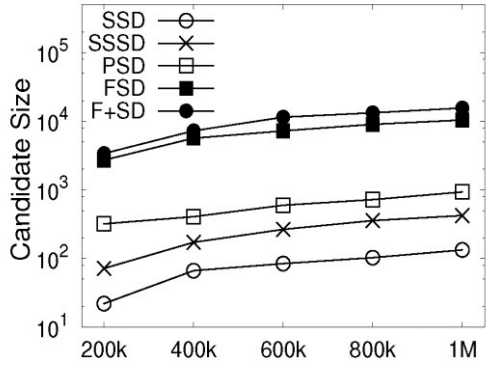


(a) Candidate Size of Different Datasets

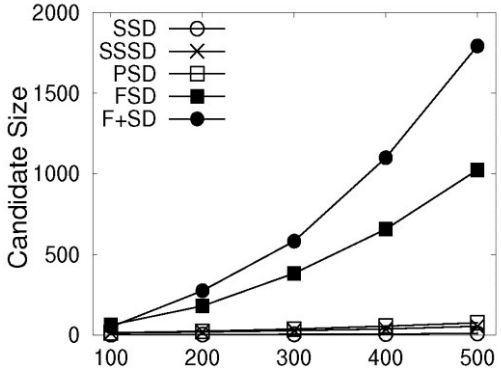


(b) Response Time of Different Datasets

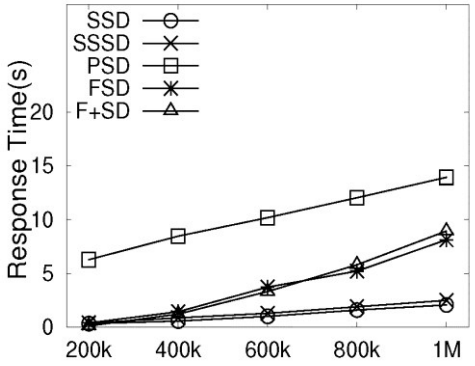
Experiments



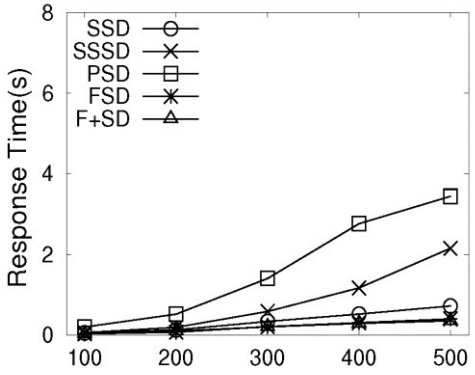
(a) Varying n



(b) Varying h_d



(c) Varying n



(d) Varying h_d

Conclusion

- Formalize three families of NN functions that cover popular NN ranking mechanisms.
- Advocate three SD operator that are optimal to different family of NN functions.
- Propose efficient NN candidate search algorithm for three *SD* operators.

Thanks!
Q&A

Experiments

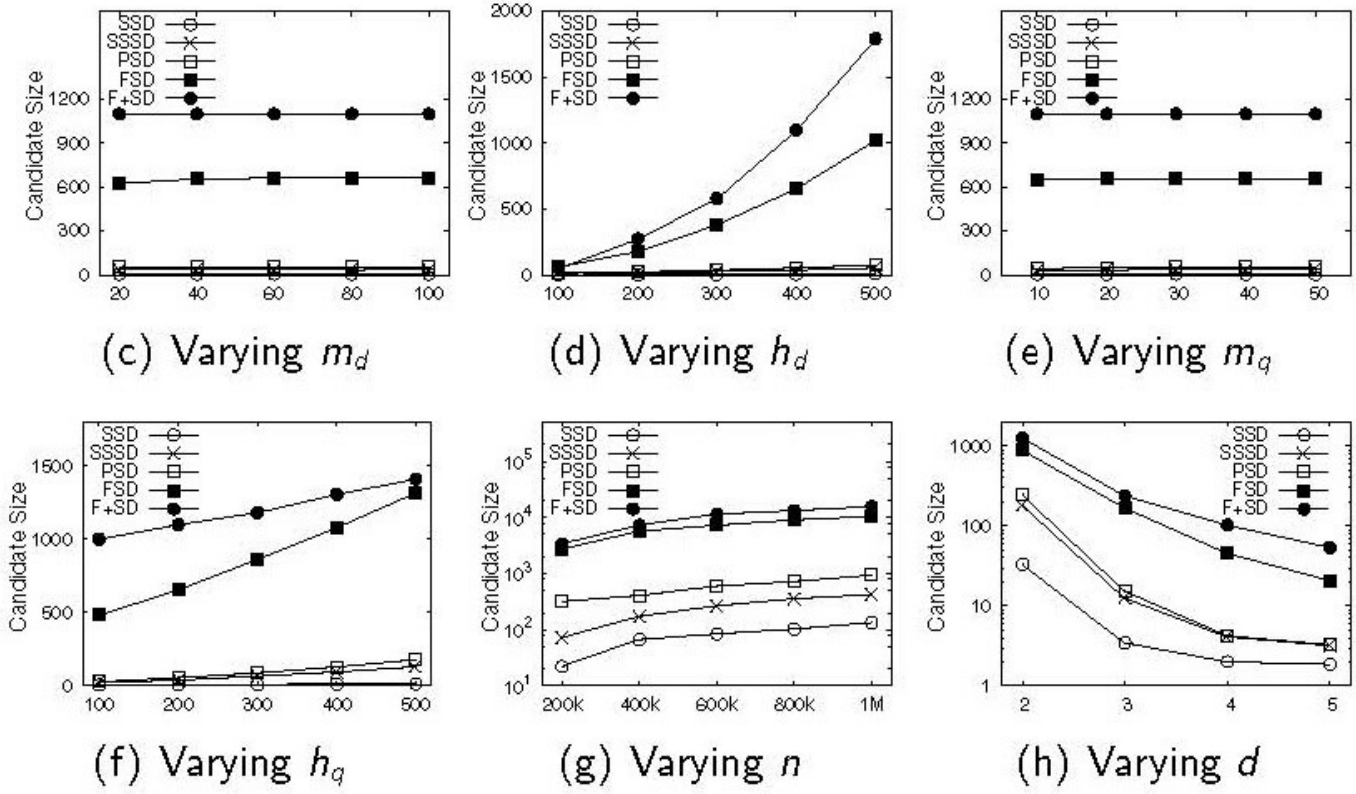


Figure: Impact of Diff. Parameters on Effectiveness

Experiments

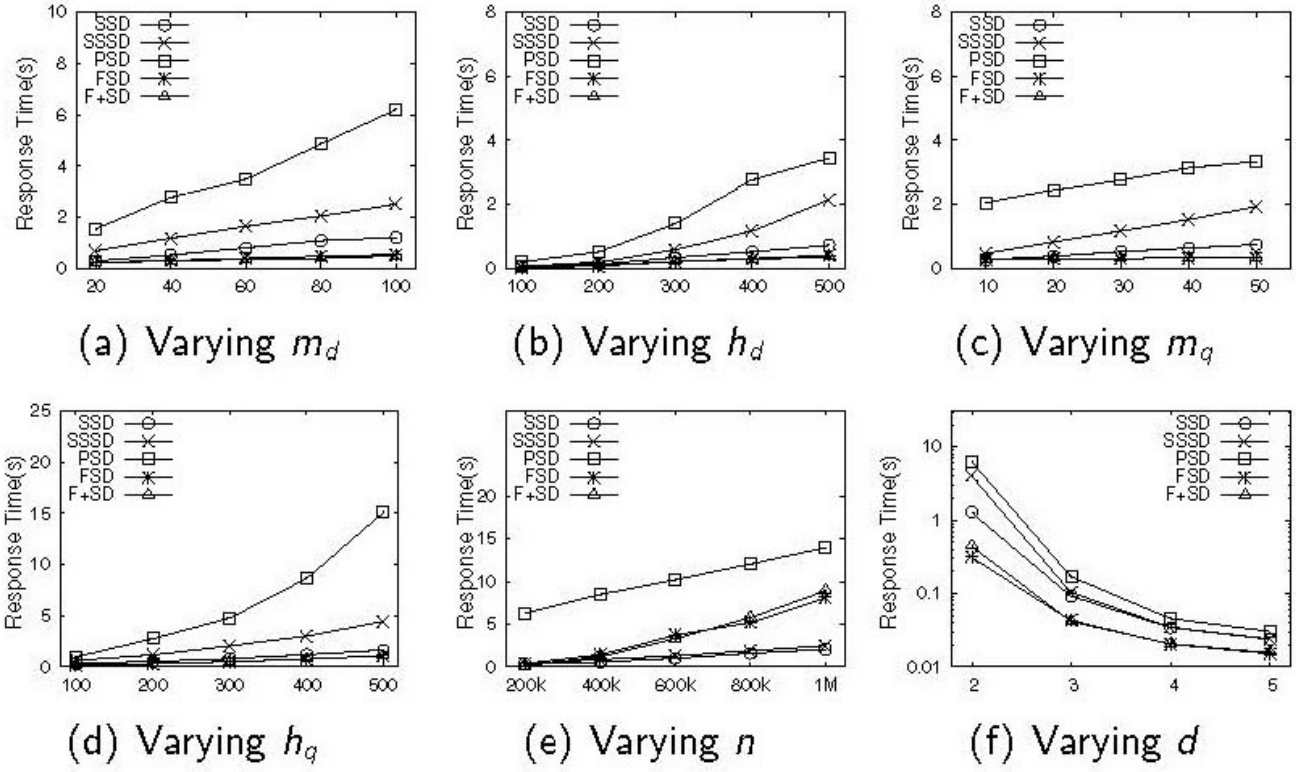


Figure: Impact of Diff. Parameters on Efficiency