Near-Optimal Constrained Padding for Object Retrievals with Dependencies

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Agenda

- Objective
- Algorithm
- Evaluation
- Questions

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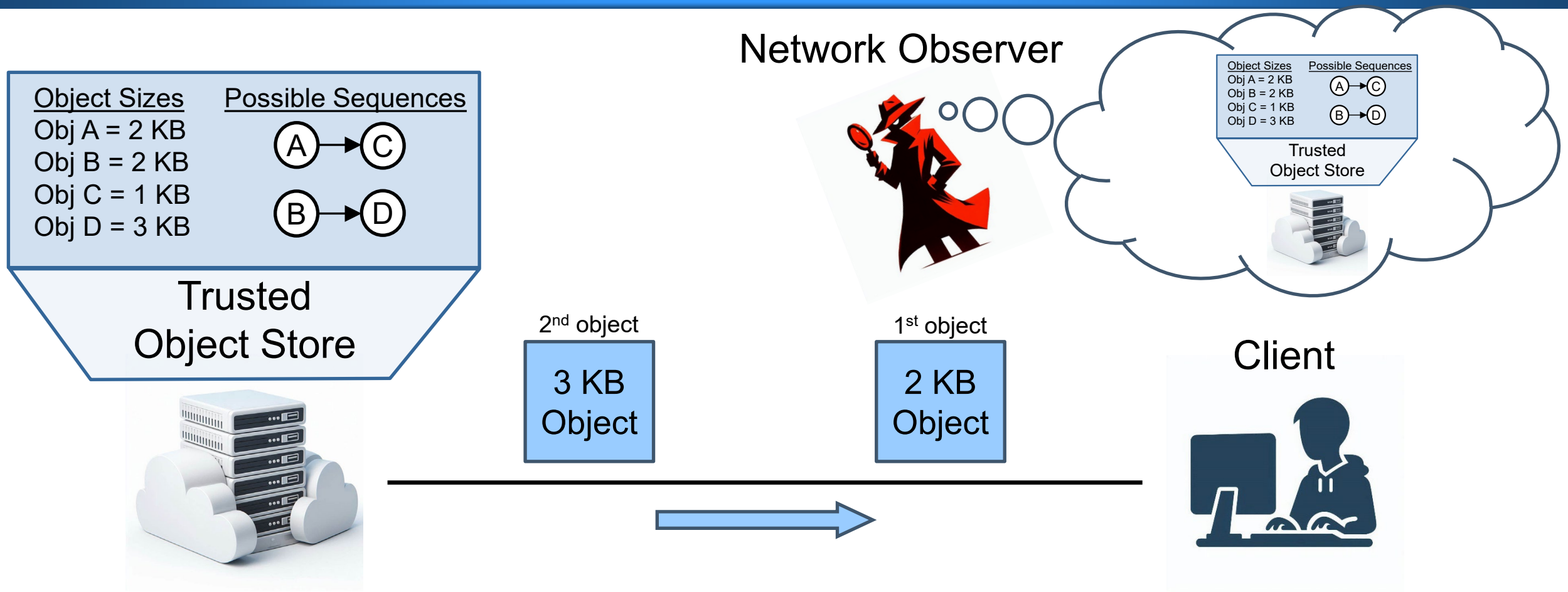
Objective: High Level



- **Client** has retrieved a sequence of objects from **Trusted Object Store**
- **Network Observer's** goal is to identify which objects were requested

All images generated by the authors using Bing Copilot Designer, August 5, 2024.

Objective: High Level

- Threat: A network observer with the following…
  - Capability: discern the sizes of sequentially-retrieved objects
  - Goal: identify which objects were retrieved
  - Knows:
    - every object's size
    - all possible sequences of object retrievals, and how often retrieved
    - the padding defense used by object store
- Trusted Object Store's Goal: Compute a padding scheme $\lceil \cdot \rceil$ that…
  1. Uses padding to best thwart the adversary
  2. Controls the per-object overhead due to padding

Note: The object store is only willing to pad objects, i.e., it will not insert decoy objects.

Objective: Our Approach

- **Objective**: Minimize $\mathbb{I}_\infty\left(\vec{S};\vec{Y}\right)$
  - $\mathbb{I}_\infty$ = Sibson mutual information of order infinity, also referred to as **min-capacity**[1] and **maximal leakage**[2]
  - S = random variable for an object's **identity**
  - Y = random variable for an object's **padded size**
  - $\longrightarrow$ denotes a sequence

Why did we choose $\mathbb{I}_\infty\left(\vec{S};\vec{Y}\right)$?

[1] and [2] advocate for this metric because:

a) $\mathbb{I}\left(\vec{S};\vec{Y}\right) \leq \mathbb{I}_\infty\left(\vec{S};\vec{Y}\right)$ over all distributions of $\vec{S}$.

b) $\mathbb{I}_\infty\left(\vec{S};\vec{Y}\right)$ upper-bounds an adversary's multiplicative gain in correctly guessing any function of $\vec{S}$ after observing $\vec{Y}$, over all distributions of $\vec{S}$.

- **Constraints**: For a given **max pad factor** c_{tgt} :
  - No object is padded by more than a factor of c_{tgt}
  - Each object is served in full

Note: it's possible for some objects to remain isolated in our setting

1. M. Alvim, K. Chatzikokolakis, C. Palamidessi, and G. Smith, "Measuring information leakage using generalized gain functions," *25th IEEE Computer Security Foundations*, Jun. 2012.
2. I. Issa, A. B. Wagner, and S. Kamath, "An operational approach to information leakage," *IEEE Transactions on Information Theory*, vol. 66, no. 3, Mar. 2020.

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Algorithm: Padding For Sequences (PFS)

- Design: a linear program named Padding For Sequences (PFS)

- Inputs:
  - S = the set of objects
  - $\vec{S}$ = the set of possible sequences
  - c_{tgt} = max padding factor per object

- Output:
  - A *memoryless* padding scheme $\lceil \cdot \rceil$ that minimizes an upper bound on $\mathbb{I}_\infty\left(\vec{S};\vec{Y}\right)$ and does not violate c_{tgt} for any object

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Competitors: Overview

- BDK[3]
  - Target metric: $\mathbb{I}\left(\vec{S};\vec{Y}\right)$
- MVMD-D[4]
  - Target metric: ℓ-diversity
- PwoD[5]
  - Target metric: $\mathbb{I}_\infty(S;Y)$

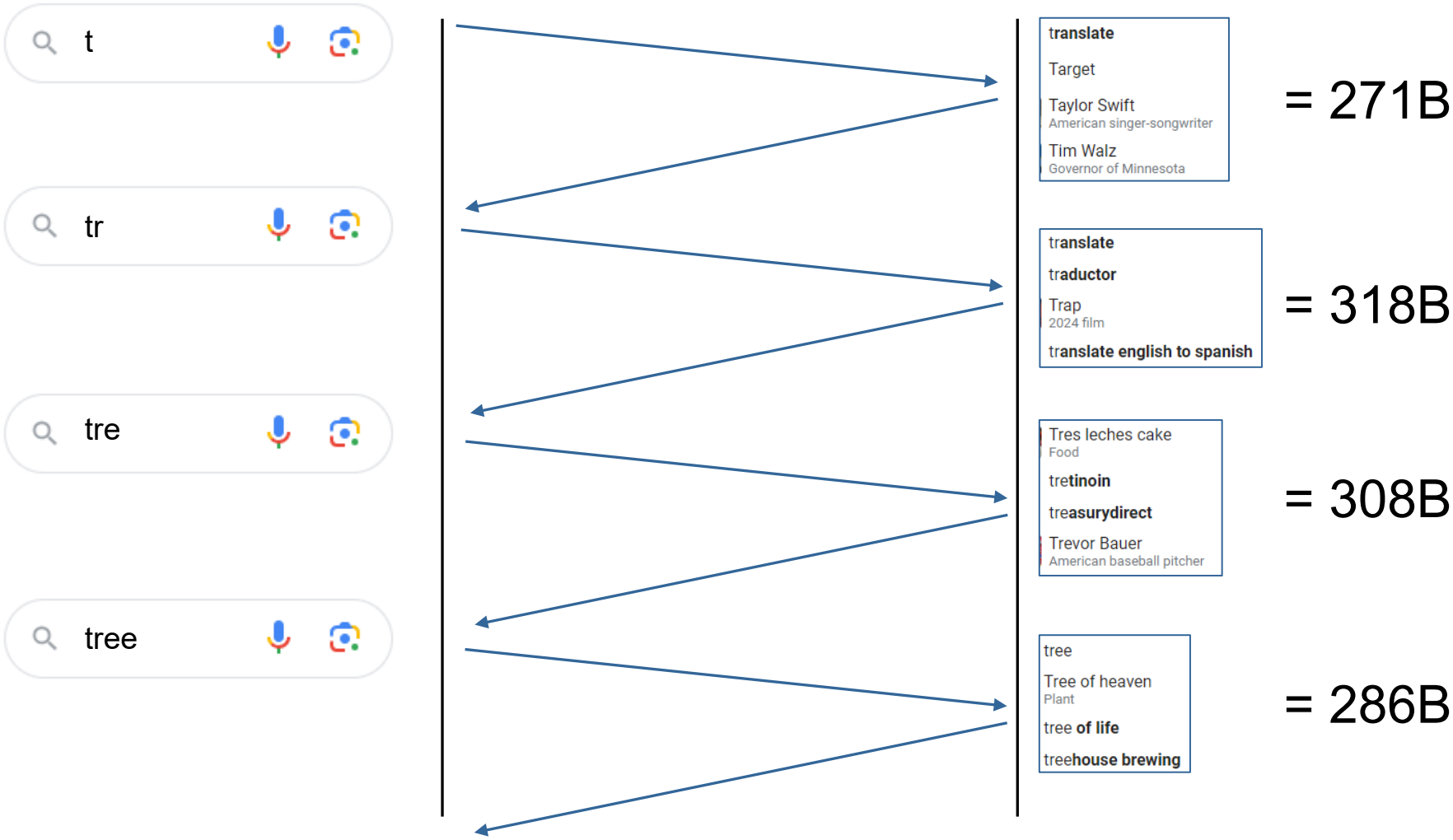
Inputs required per algorithm.

Algorithm	Sets		Distributions			
	S	$\vec{S}$	E	$\mathbb{P}(S=s)$	$\mathbb{P}\left(\vec{S}_{1\ldots i}=\vec{s}_{1\ldots i}\right)$	$\mathbb{P}\left(\vec{S}_{i+1}=s' \middle\| \vec{S}_i=s\right)$
BDK	✓		✓	✓		✓
MVMD-D	✓	✓			✓	
PwoD	✓					
PFS	✓	✓				

3. M. Backes, G. Doychev, and B. Kopf, "Preventing side channel leaks in web traffic: A formal approach," *20th ISOC Network and Distributed System Security Symposium*, February 2013.
4. W. M. Liu, L. Wang, P. Cheng, K. Ren, S. Zhu, and M. Debbabi, "PPTP: Privacy-preserving traffic padding in web-based applications," *IEEE Transactions on Dependable and Secure Computing*, Nov-Dec 2014.
5. A. C. Reed and M. K. Reiter, "Optimally hiding object sizes with constrained padding," *IEEE Computer Security Foundations Symposium*, July 2023.

Dataset: Autocomplete

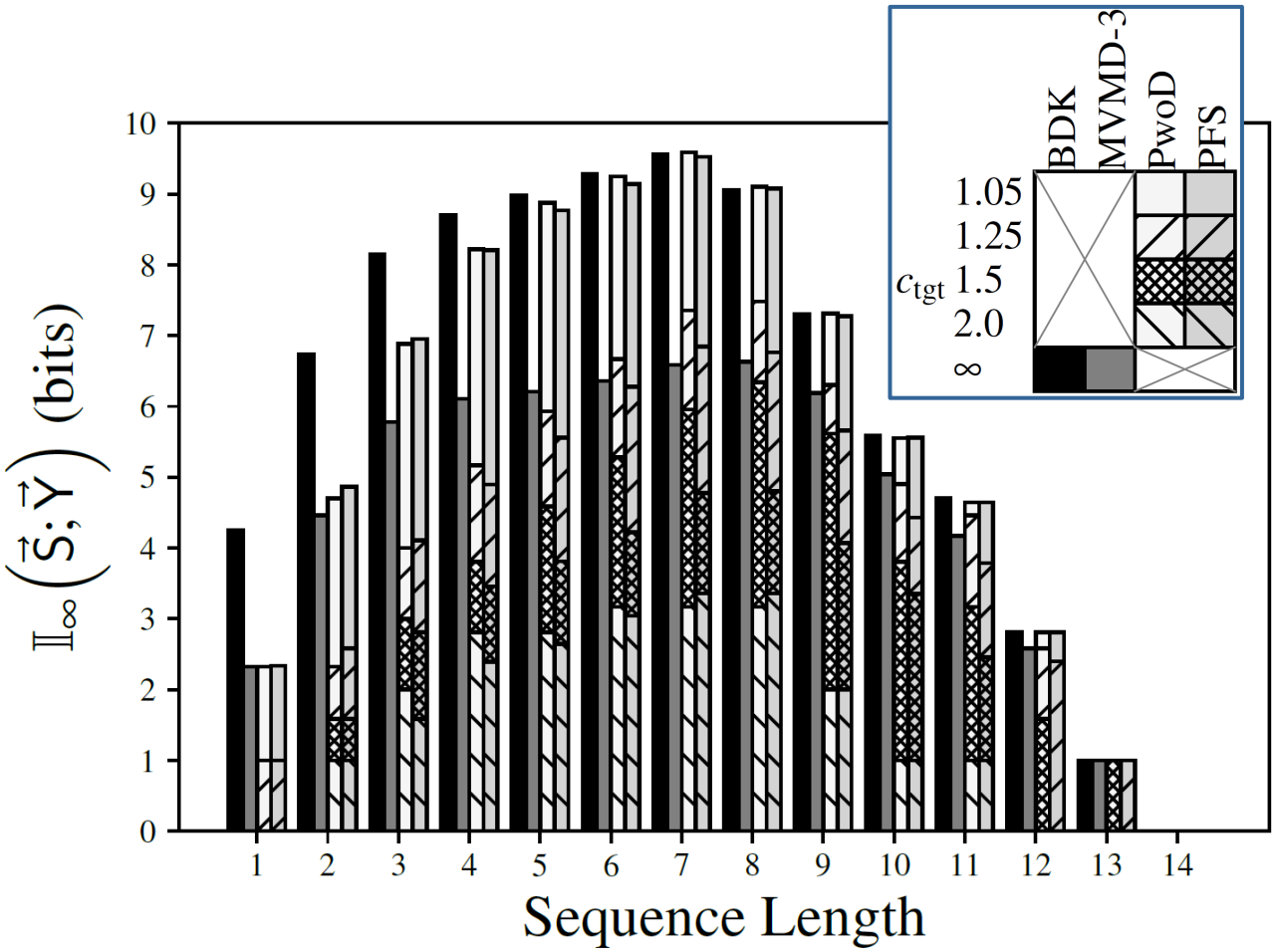
- 899 full words
- 3870 total sequences
- Models a user typing a word into the Google search bar and receiving suggested search terms after each character is typed.



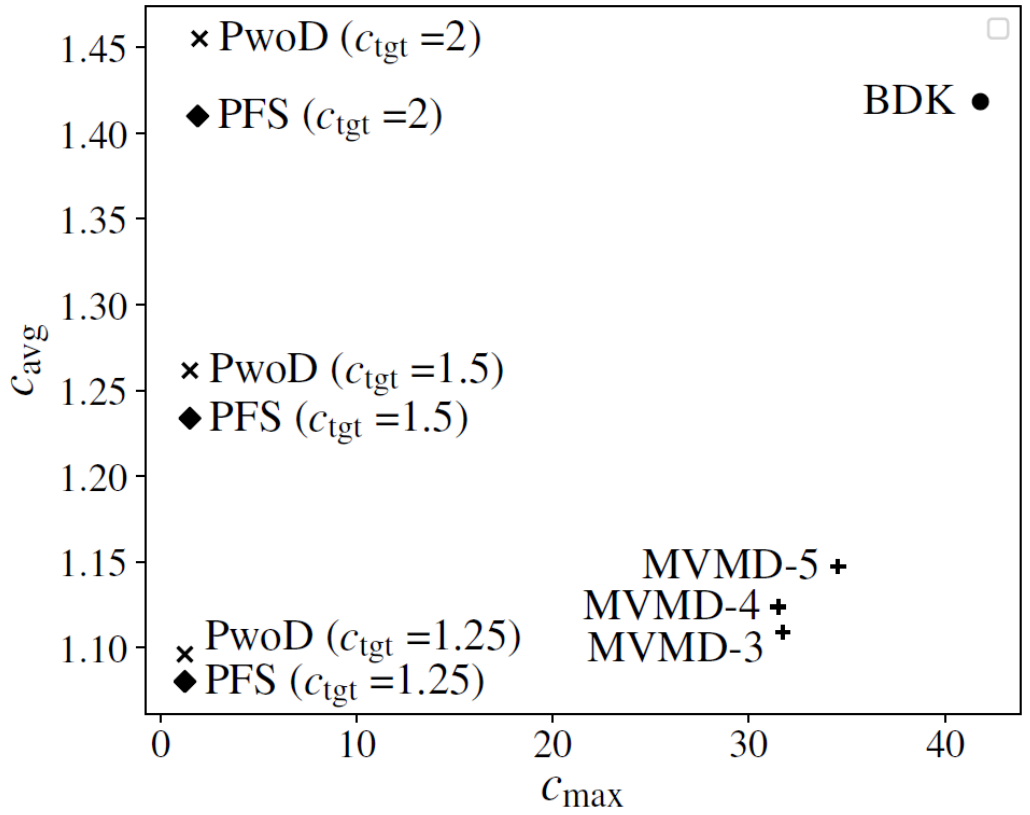
The Autocomplete sequence corresponding to the word “tree” is: (t, tr, tre, tree) = (271, 318, 308, 286)

Note: Screenshots taken Aug 8, 2024 and do not correspond to the sizes in the provided dataset. They are for illustrative purposes only.

Evaluation: Autocomplete - $\mathbb{I}_\infty\left(\vec{S};\vec{Y}\right)$

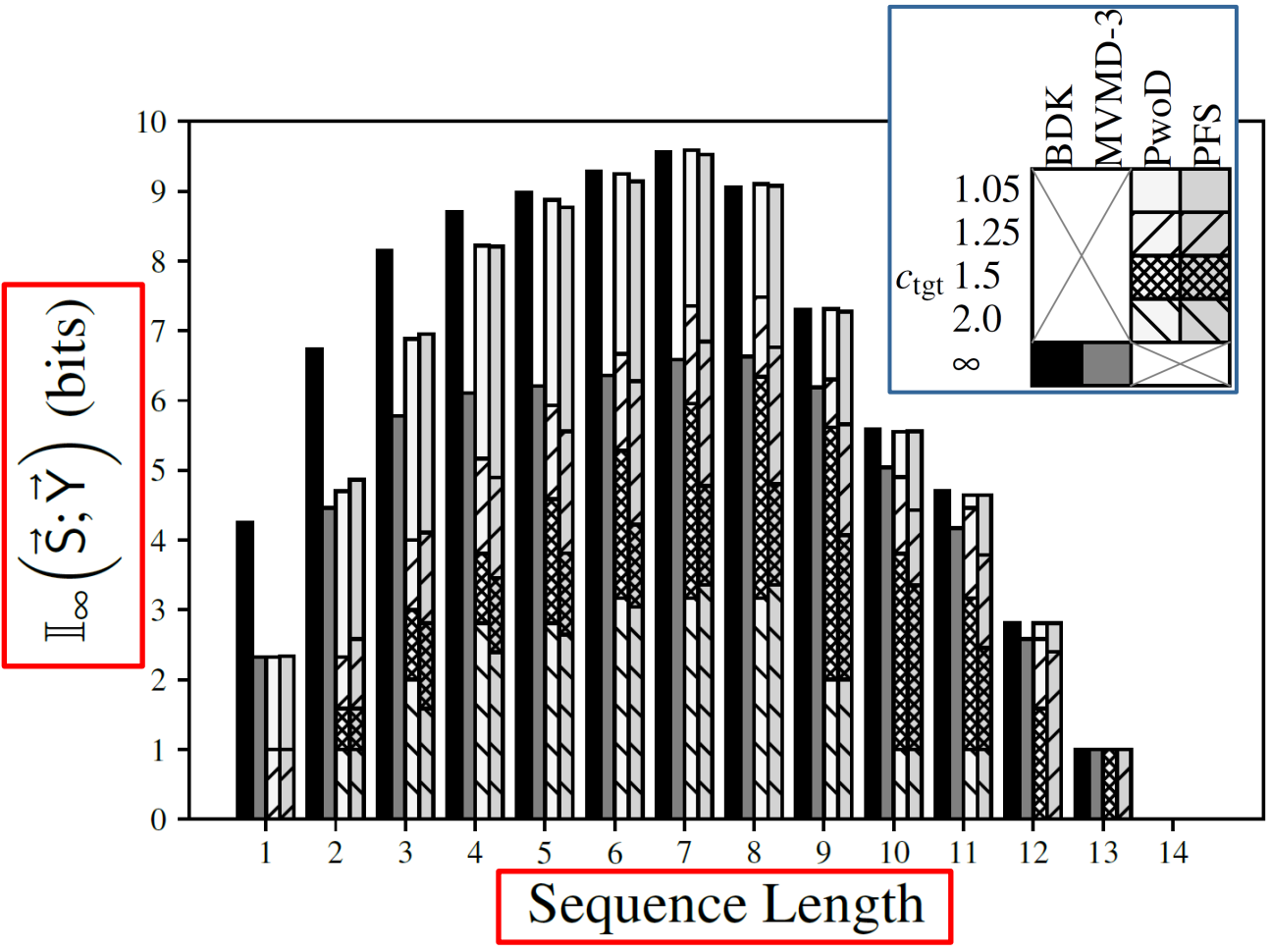


Comparing all algorithms using $\mathbb{I}_\infty\left(\vec{S};\vec{Y}\right)$ as the privacy metric.



Padding overhead factors for each padding algorithm.

Evaluation: Autocomplete - $\mathbb{I}_\infty\left(\vec{S};\vec{Y}\right)$



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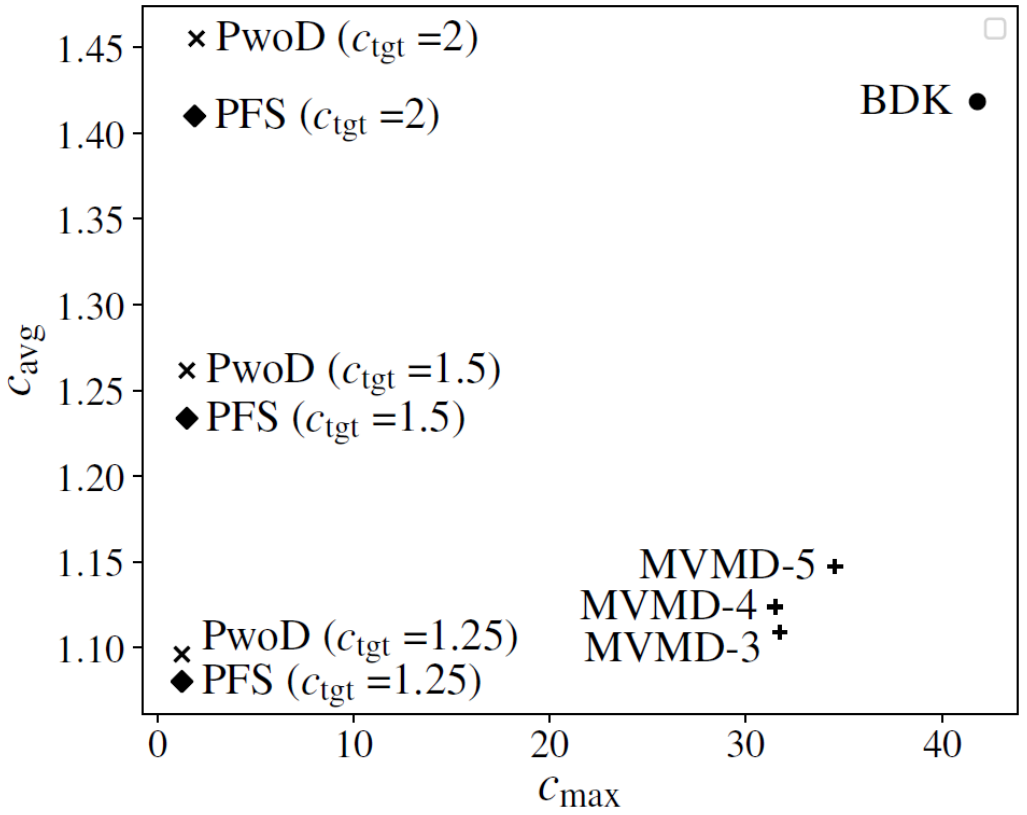

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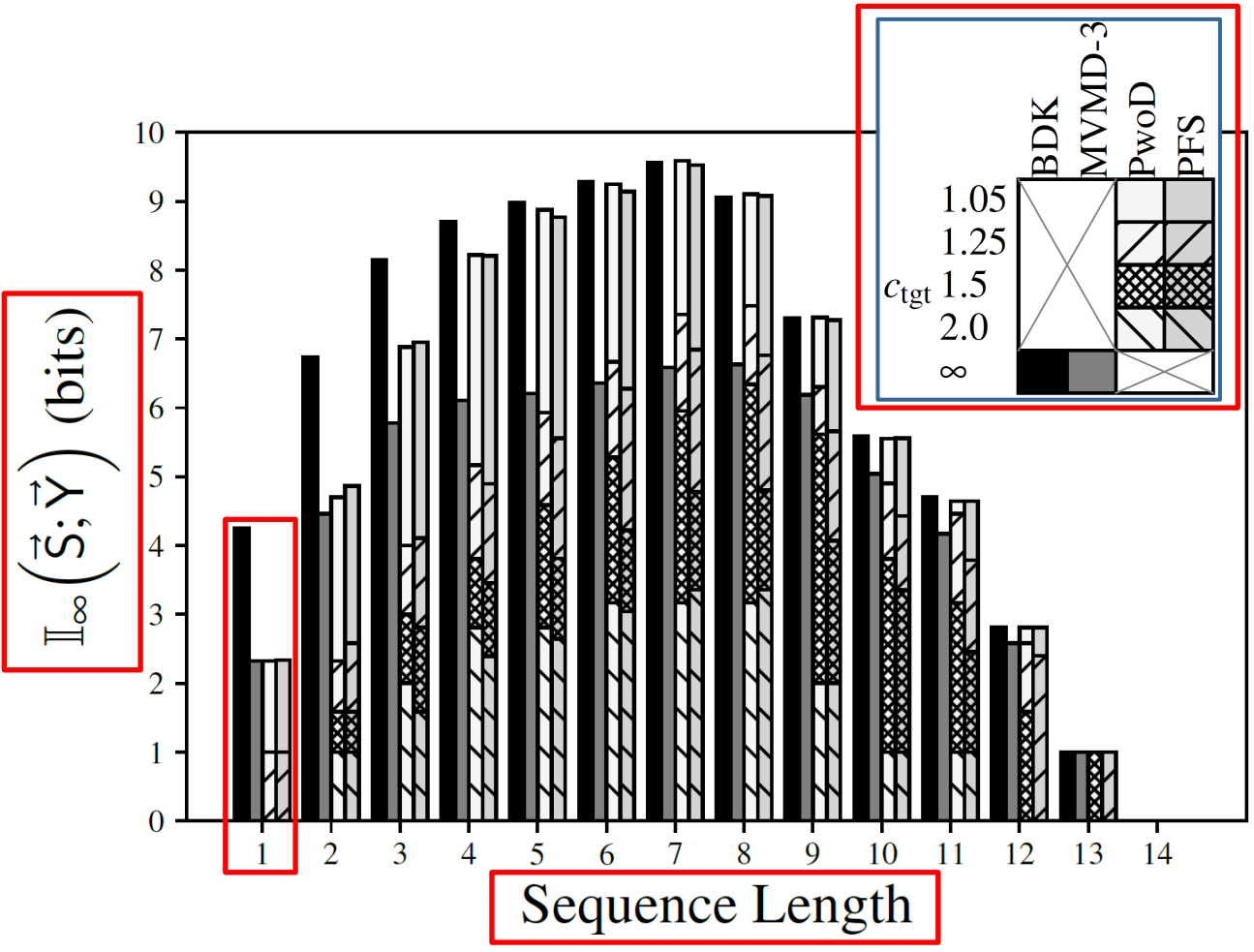

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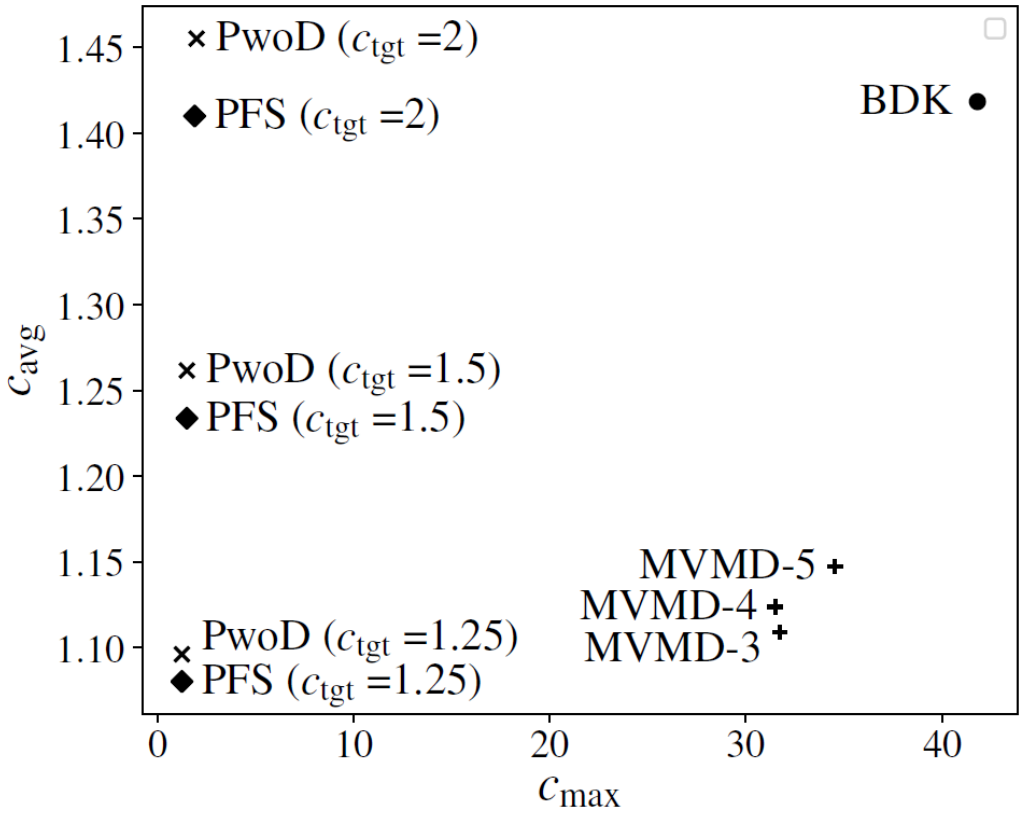

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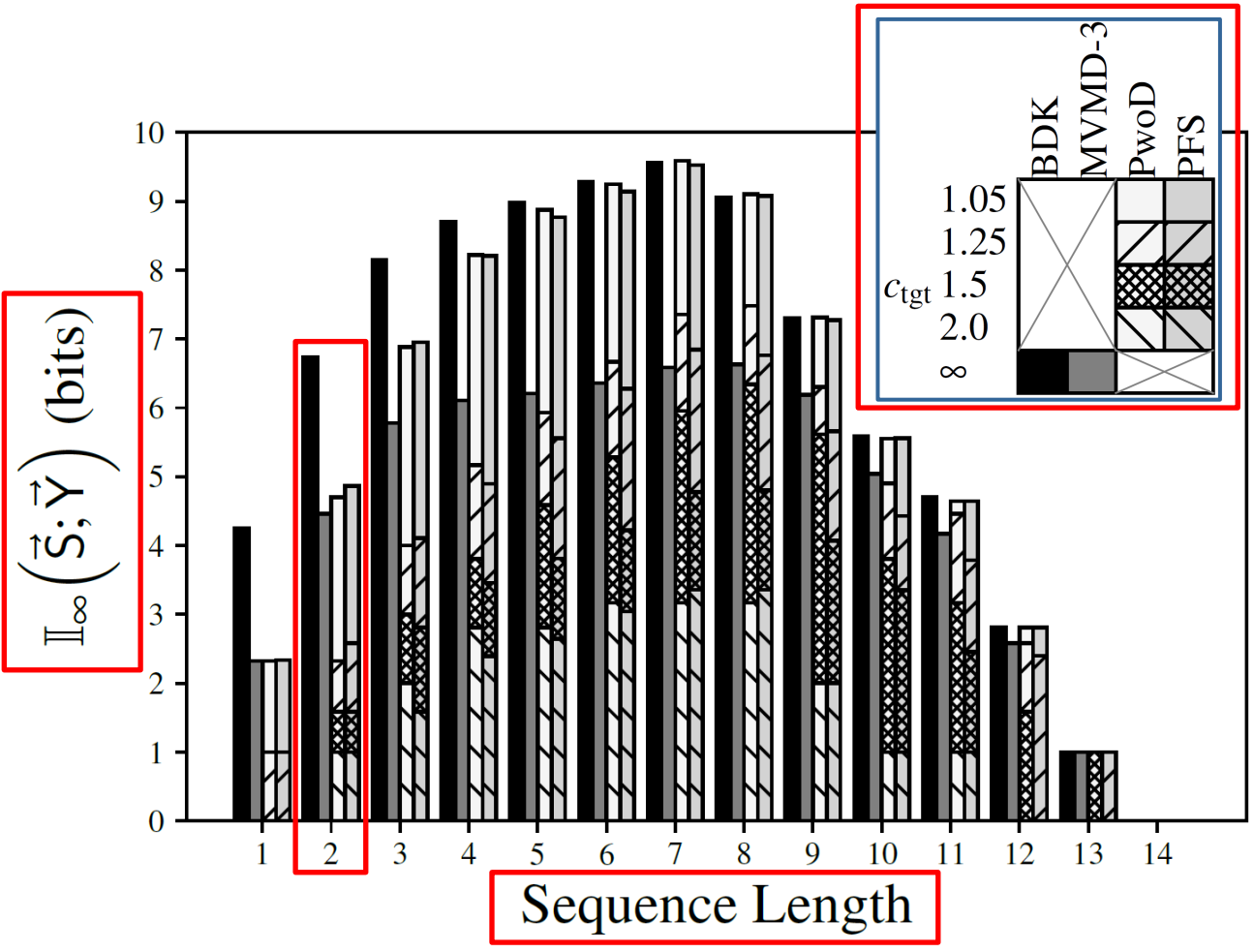

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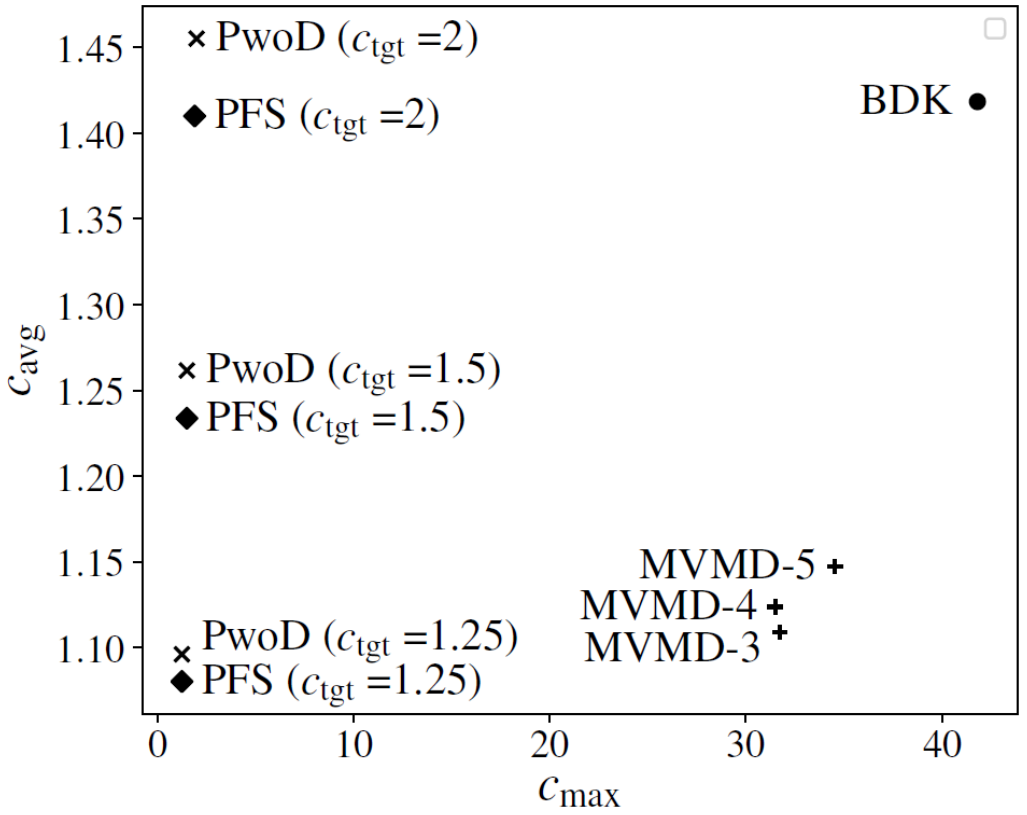

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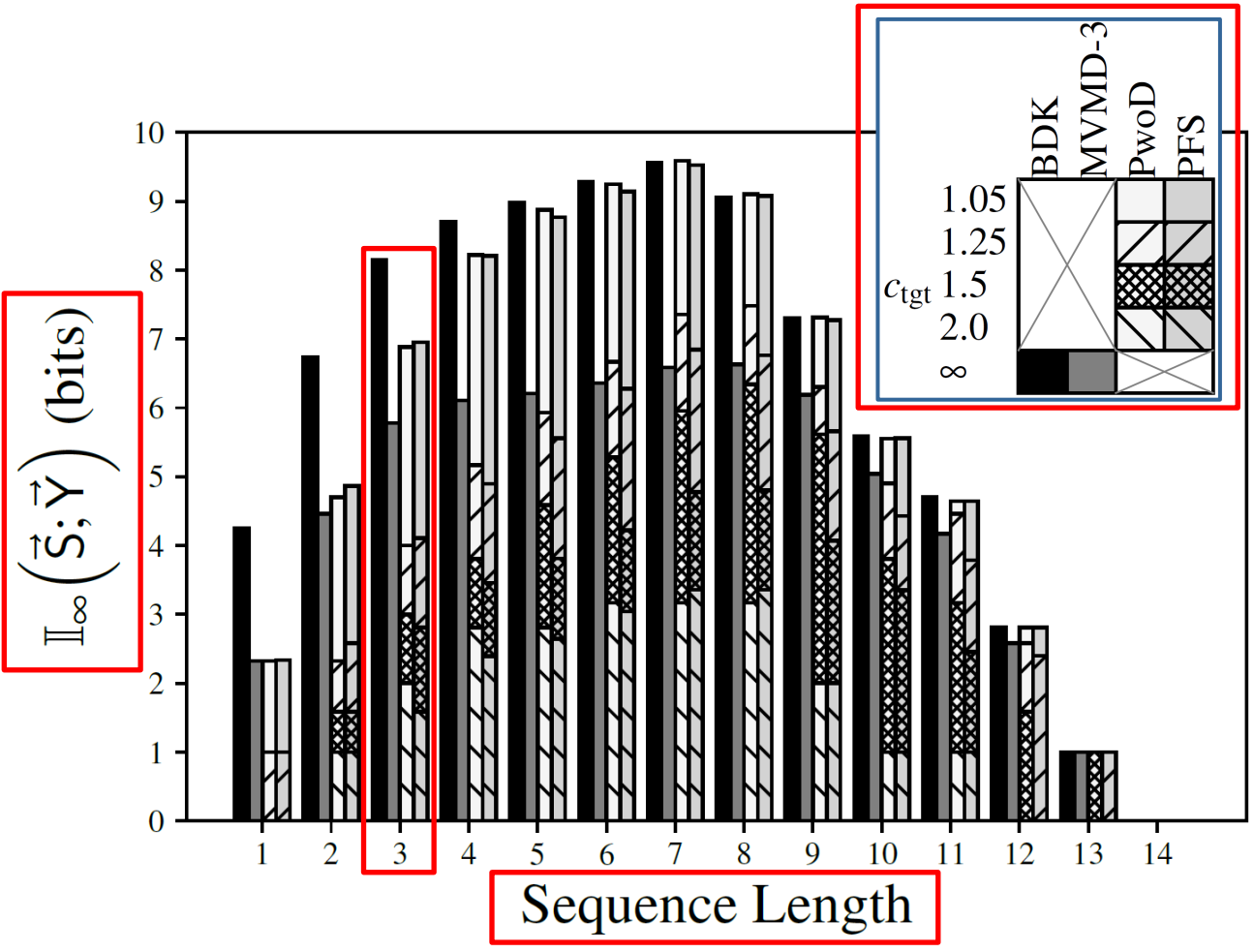

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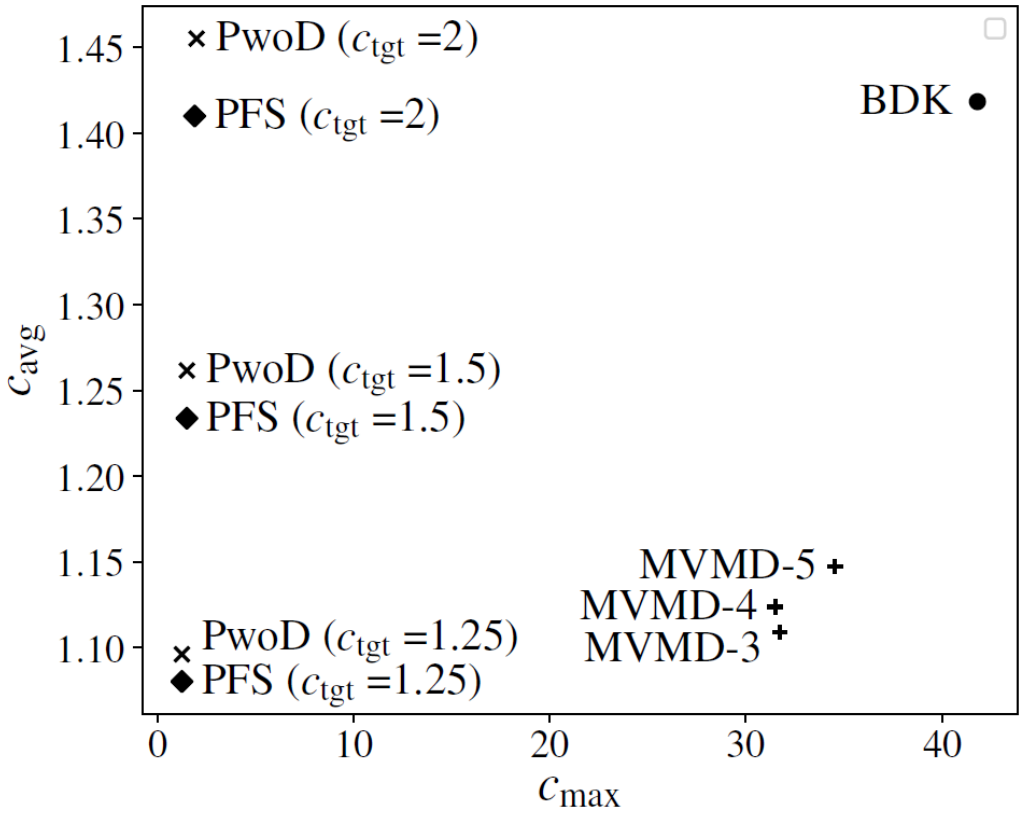

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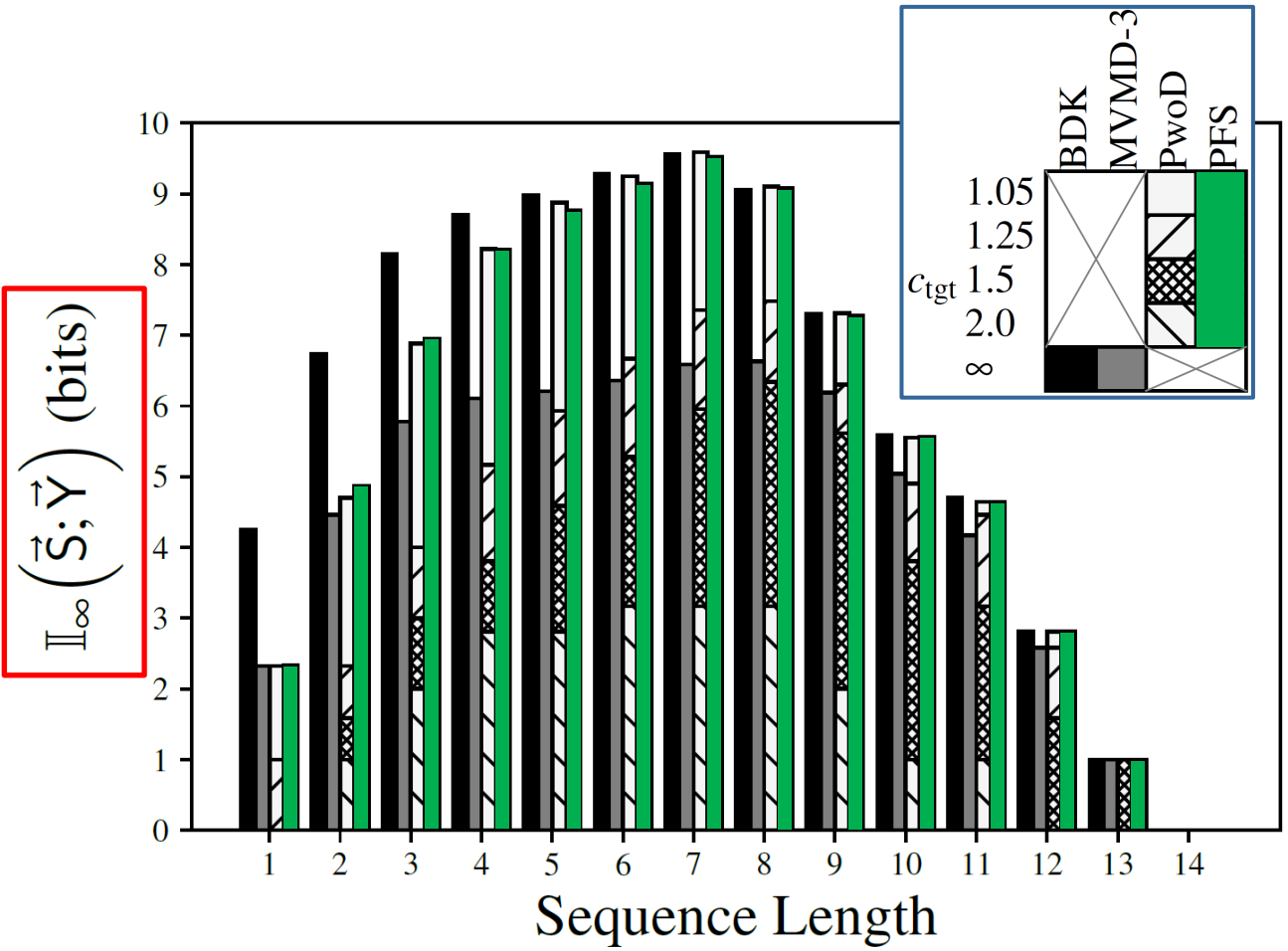

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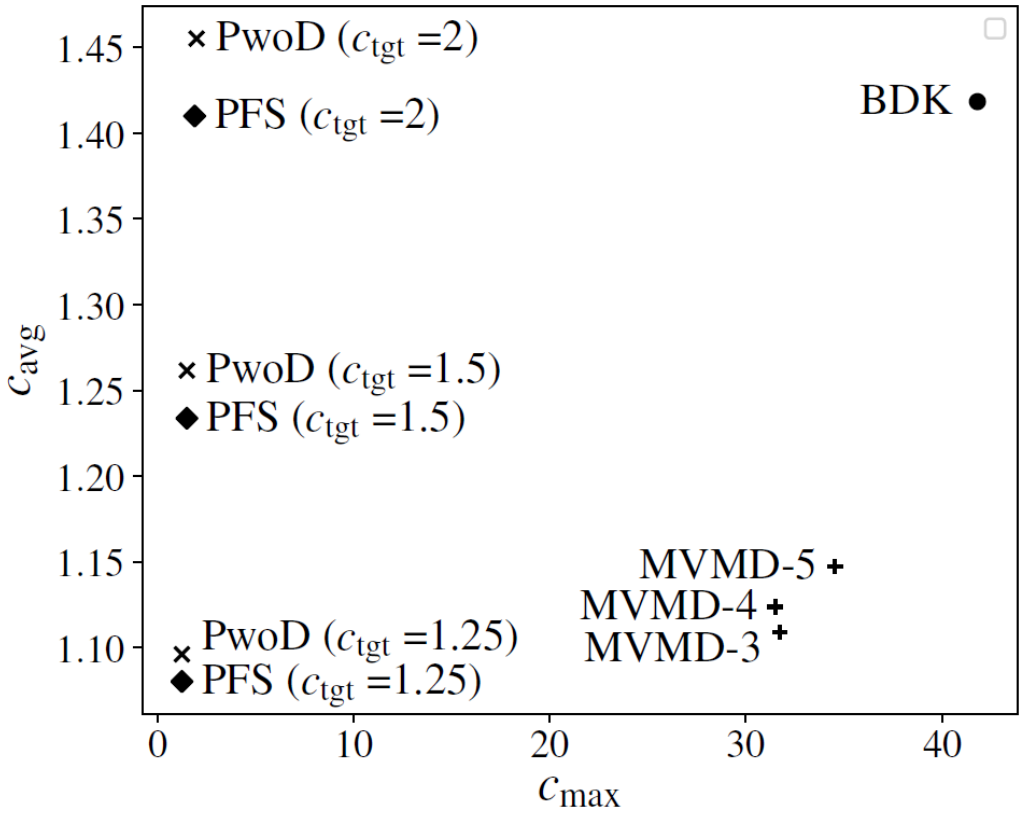

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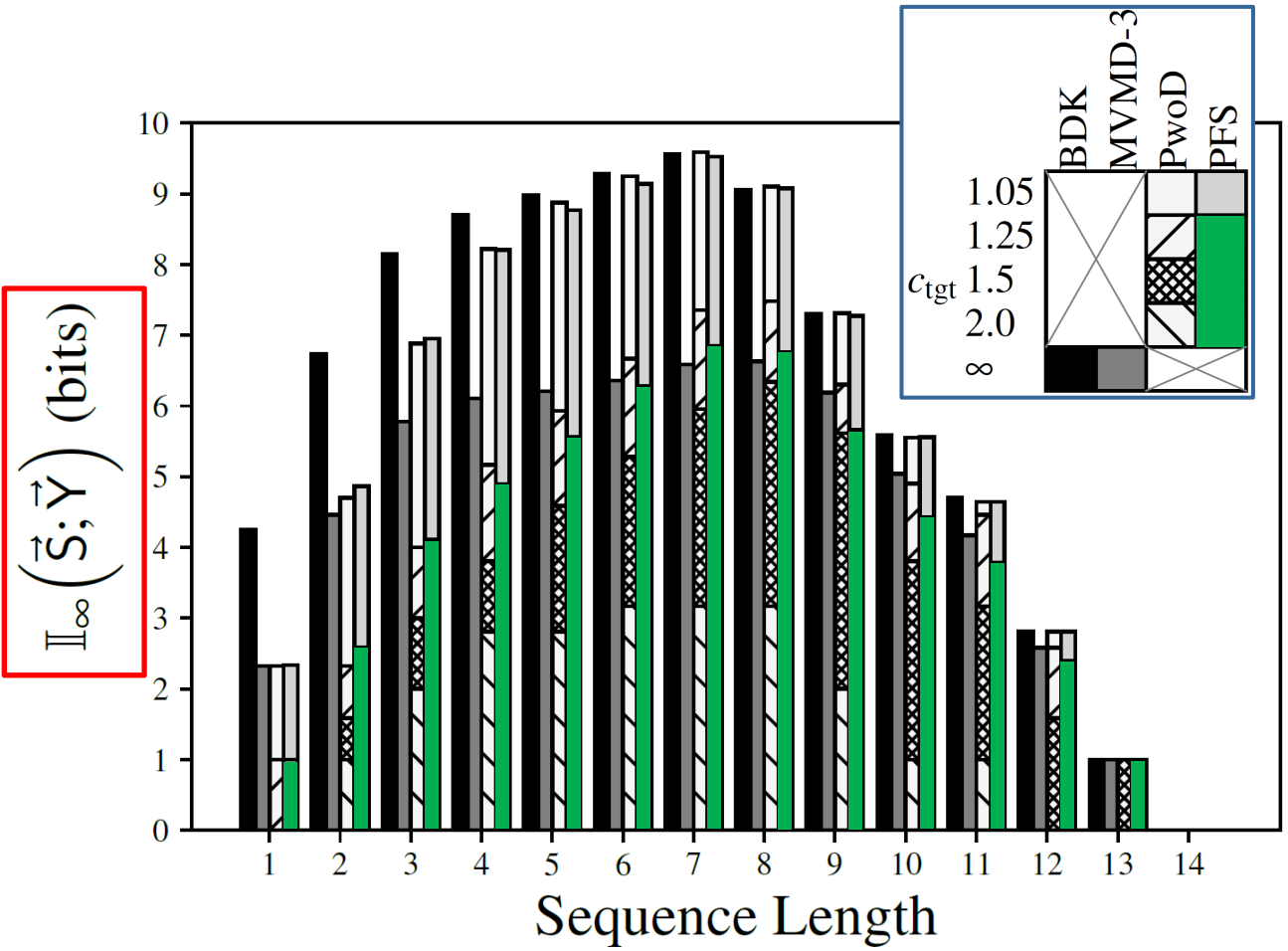

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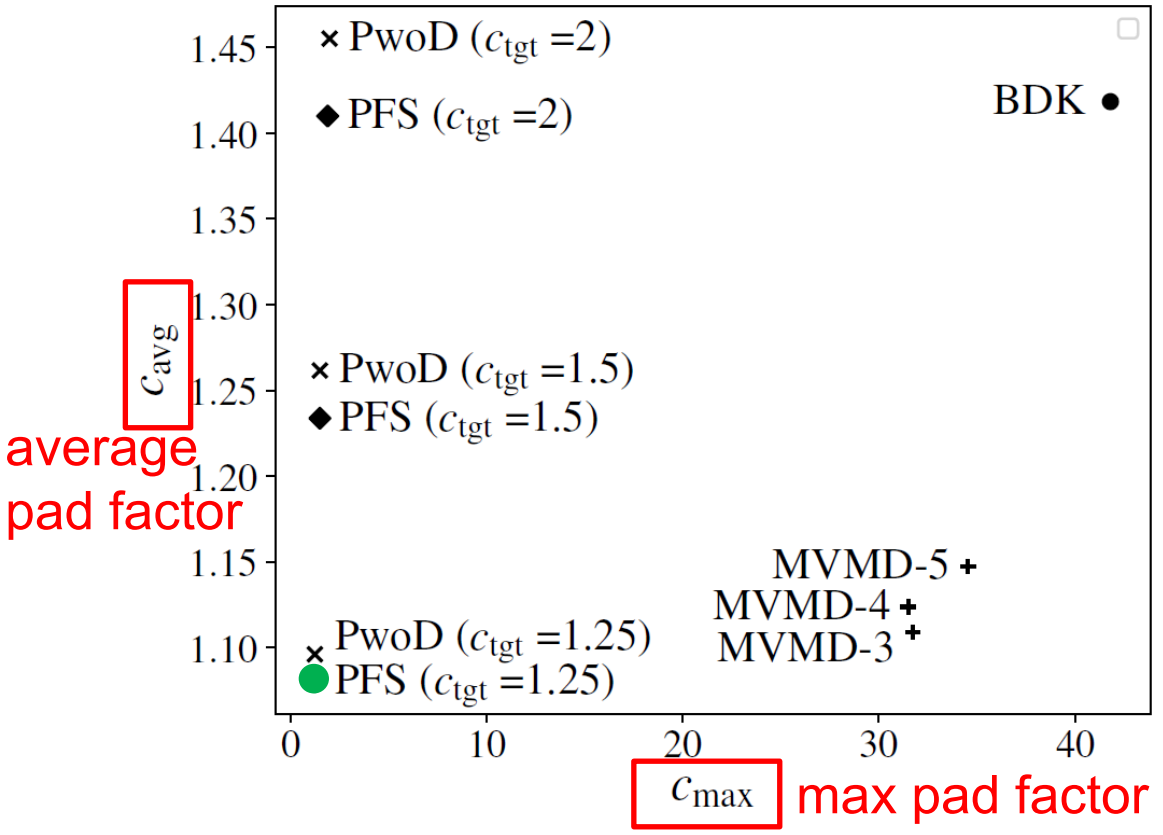

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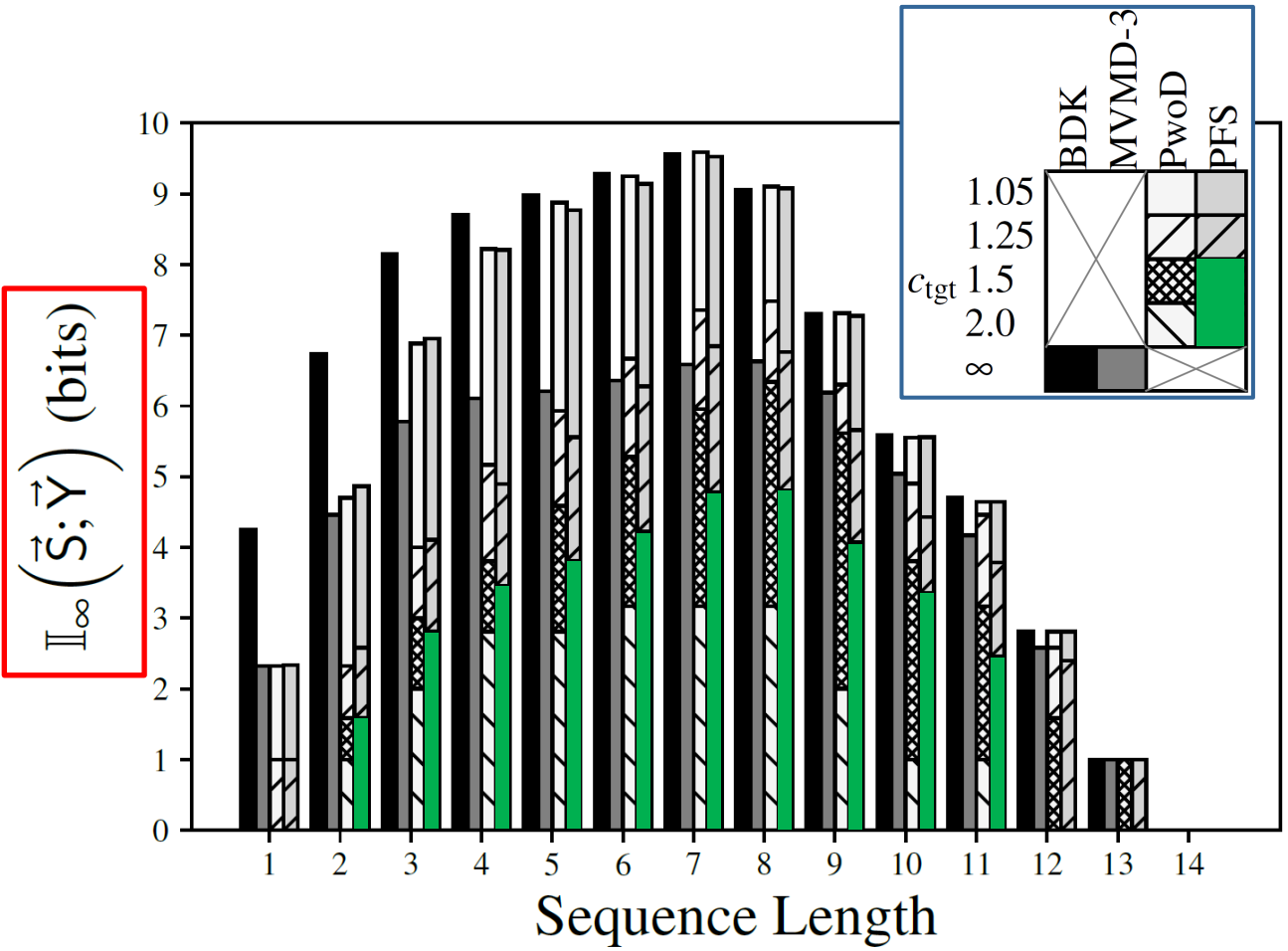

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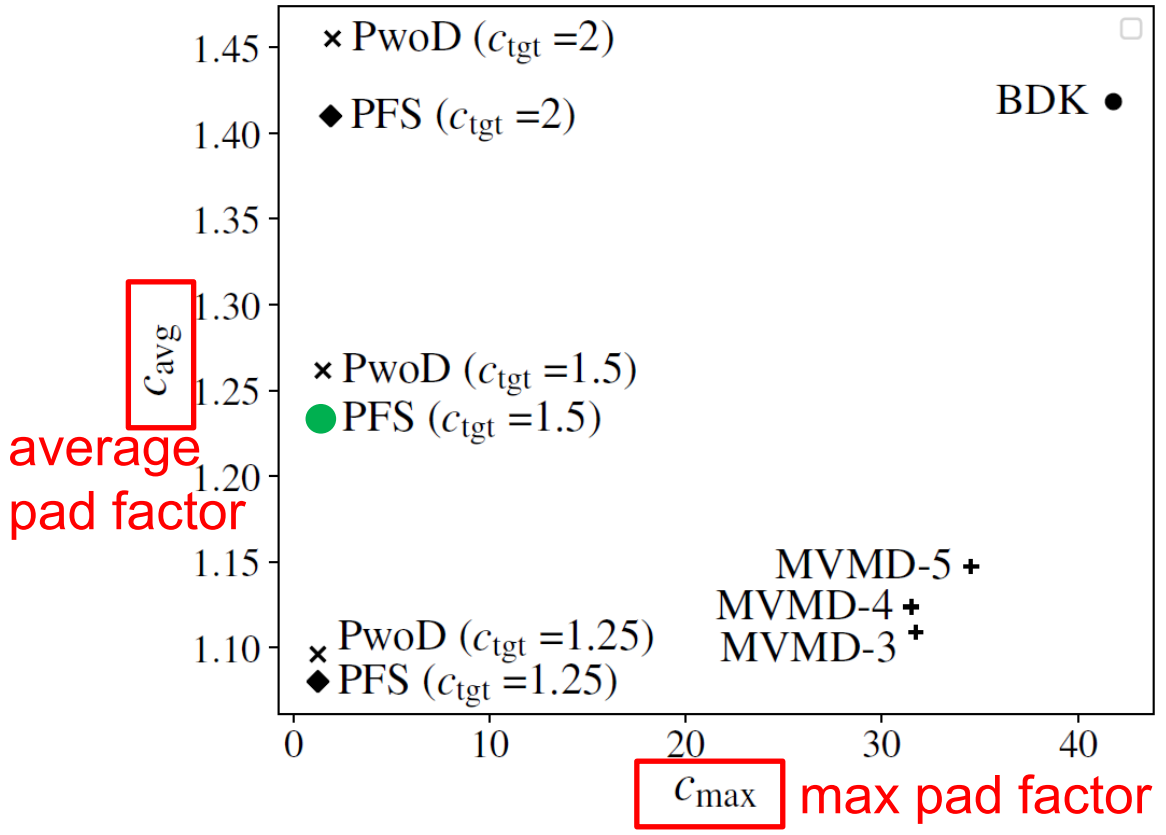

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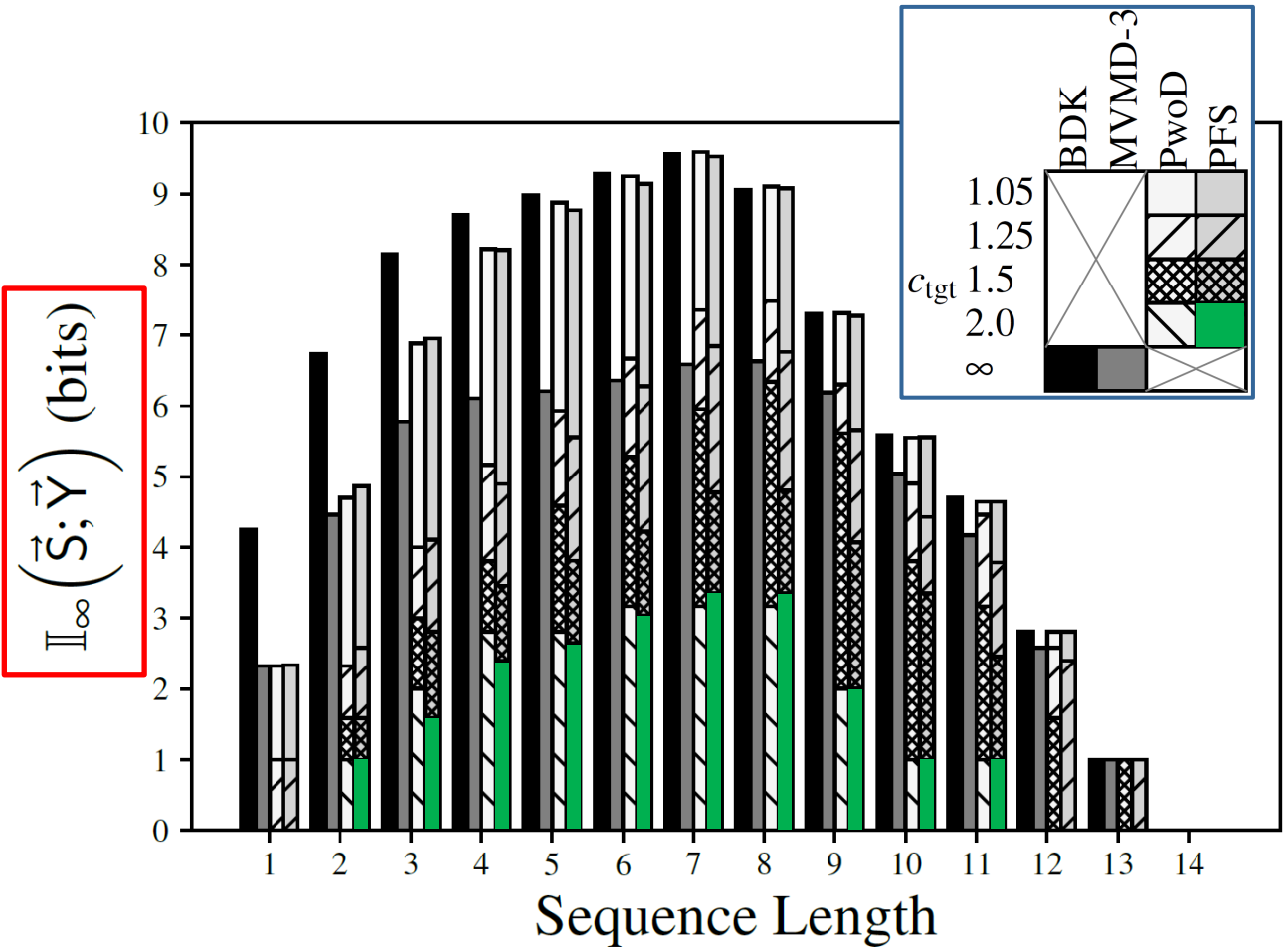

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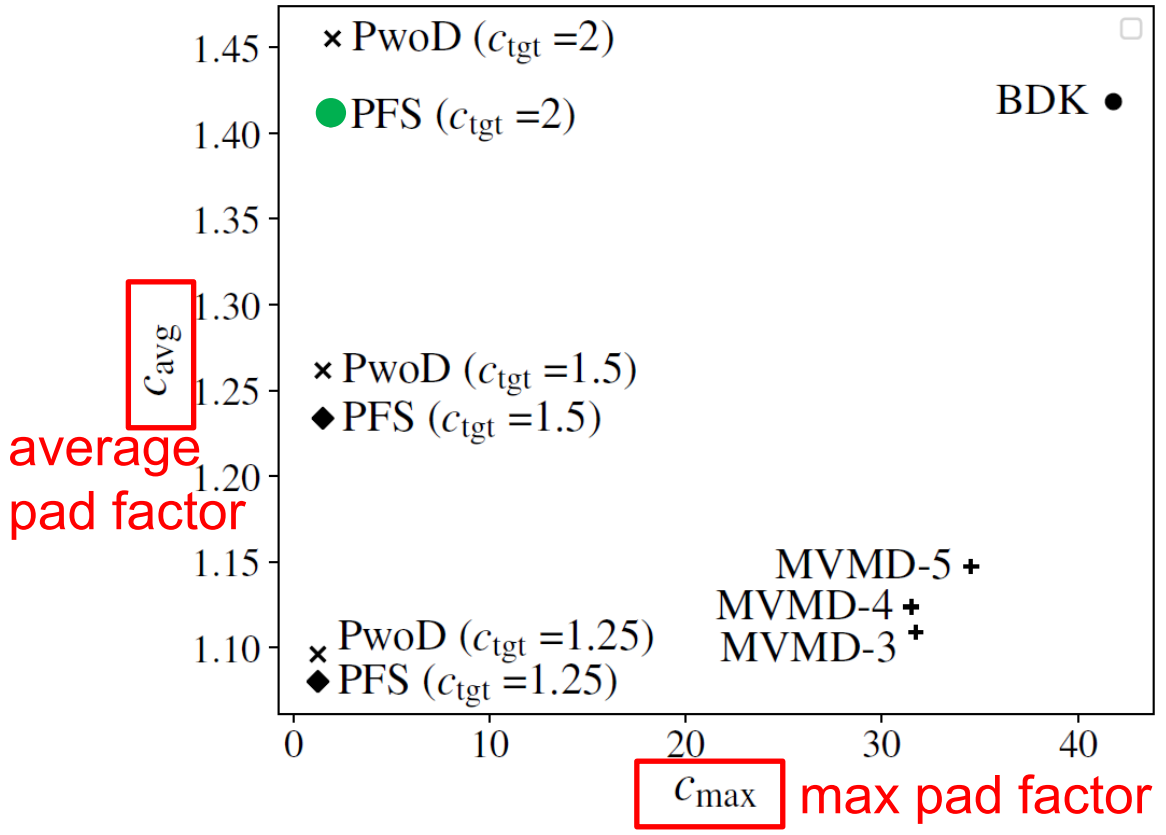

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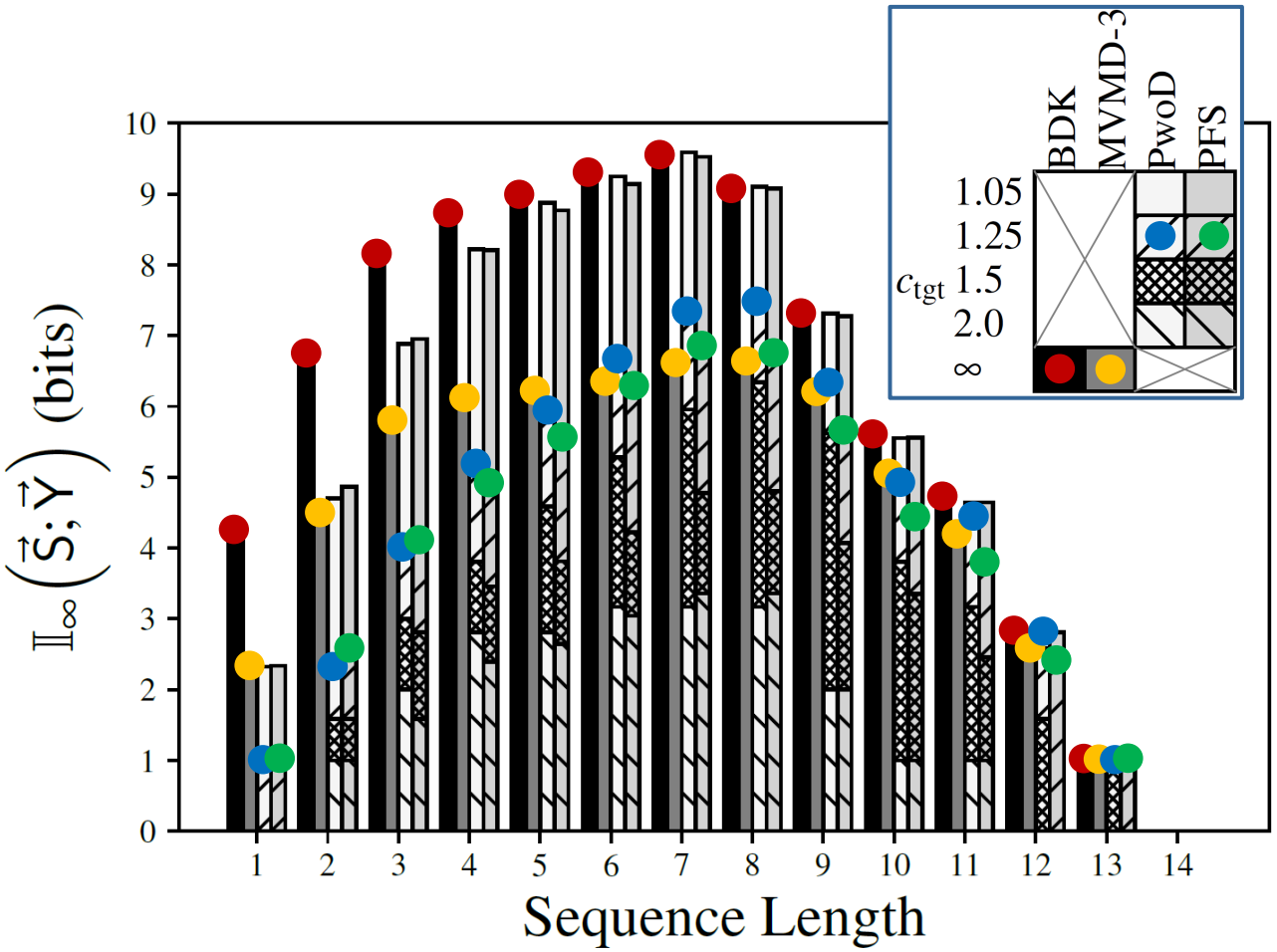

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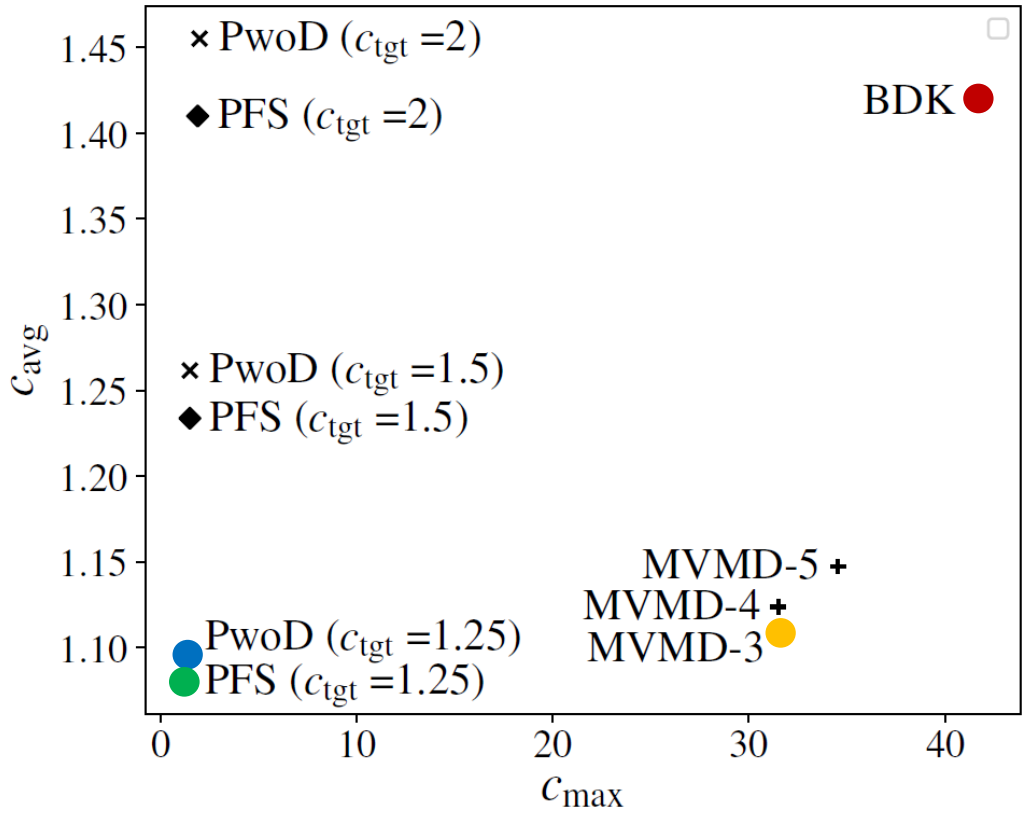


Padding overhead factors for each padding algorithm.

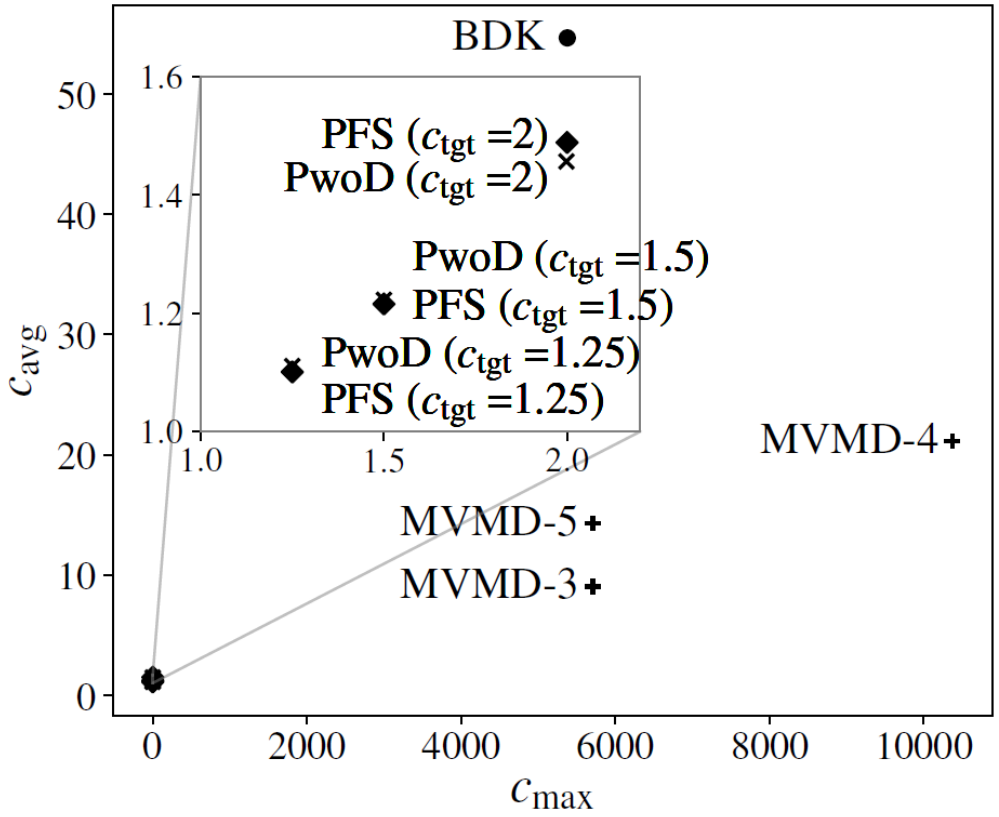
Additional Material in the Paper…

- Compare PFS against BDK and MVMD-D using *their* metrics
- Additional datasets used for evaluation
- Precision-Recall tests that model a network adversary
- Faster alternative to PFS named Padding For Graphs (PFG)

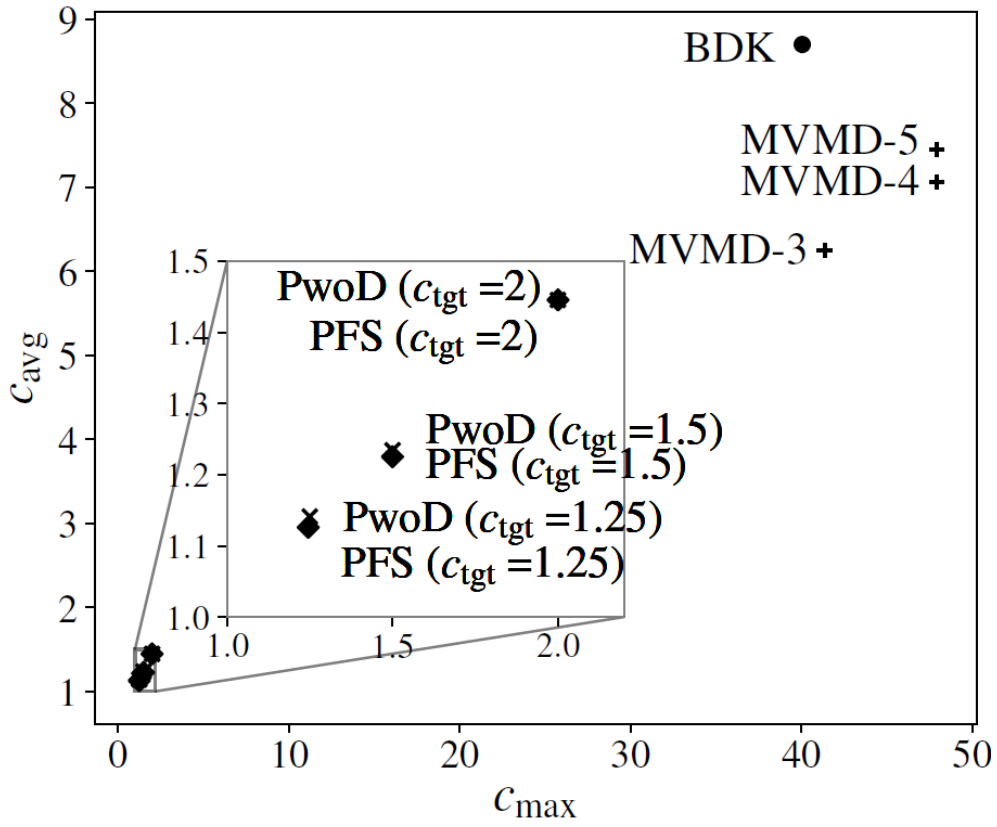
Questions?

Source Code and Datasets available at:
https://doi.org/10.5281/zenodo.13119687

Backup Slide: Padding Overhead



Linode



Wikipedia