SGDP: A Stream-Graph Neural Network Based Data Prefetcher

Yiyuan Yang*
University of Oxford
Huawei Noah's Ark Lab
Oxford, UK
yiyuan.yang@cs.ox.ac.uk

Rongshang Li*
University of Sydney
Huawei Noah's Ark Lab
Sydney, Australia
roli5128@uni.sydney.edu.au

Qiquan Shi
Huawei Noah's Ark Lab
Huawei
Shenzhen, China
shiqiquan@huawei.com

Xijun Li
MIRA Lab, USTC
Huawei Noah's Ark Lab
Shenzhen, China
xijun.li@huawei.com

Gang Hu
Huawei
Chengdu, China
hugang27@huawei.com

Xing Li
Huawei Noah's Ark Lab
Hongkong, China
li.xing2@huawei.com

Mingxuan Yuan
Huawei Noah's Ark Lab
Hongkong, China
Yuan.Mingxuan@huawei.com

*Both authors contributed equally to this research. Work done as interns in Huawei Noah's Ark Lab

Background

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IJCNN2023
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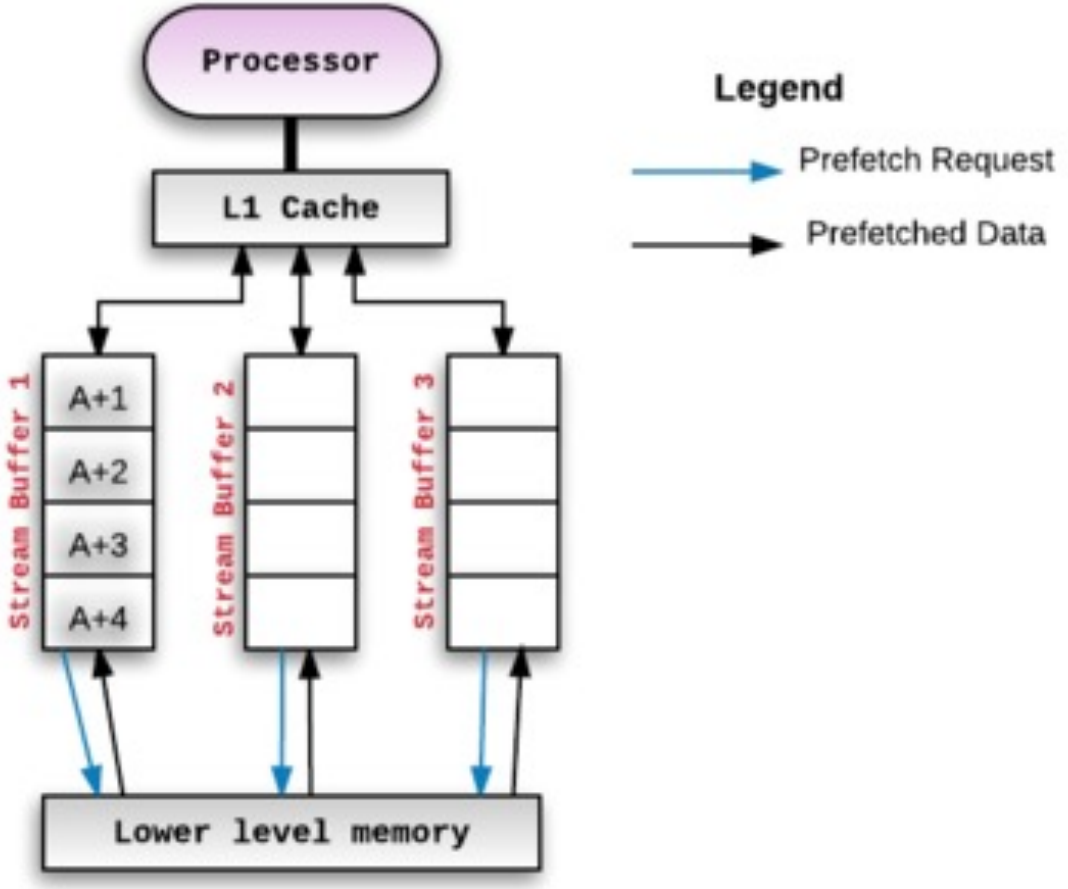

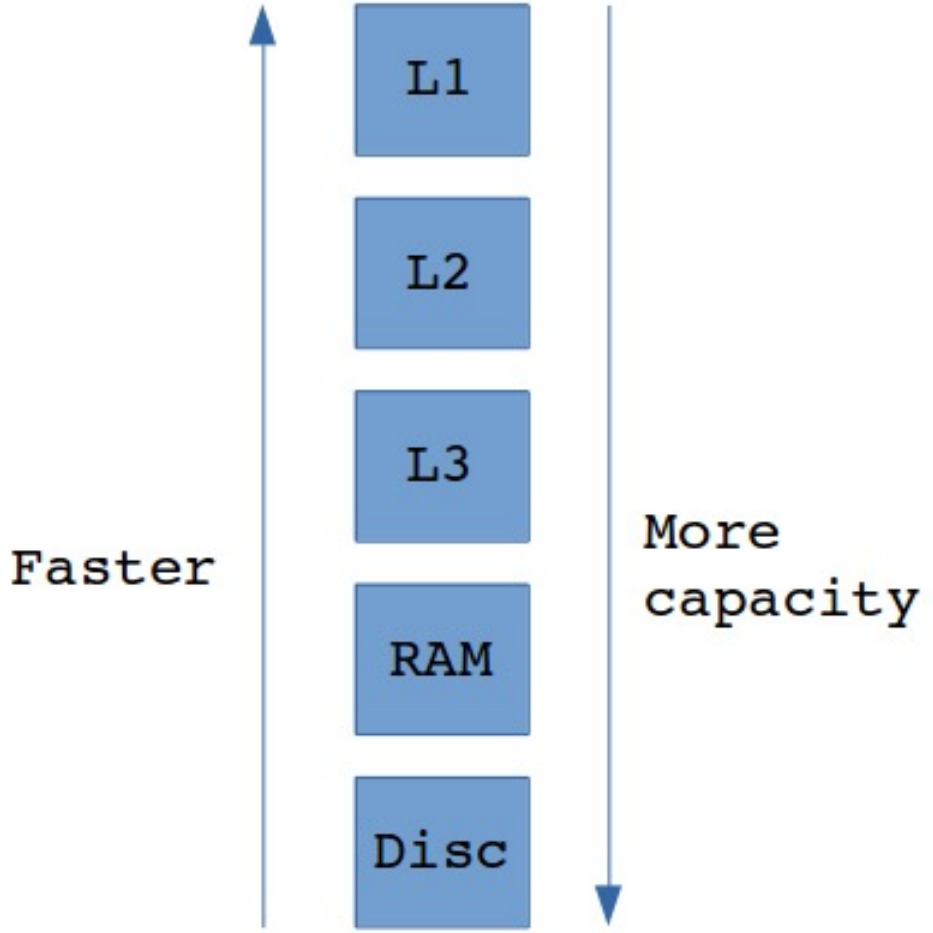

Contribution

1. SGDP can accurately learn complex access patterns by capturing the relations of LBA deltas in each stream. The relations are represented by sequential connect matrices and full-connect matrices using graph structures.

2. SGDP is the first work that utilizes the stream-graph structure of the LBA delta in the data prefetching problem. Using gated graph neural networks and attention mechanisms, we extract and aggregate sequential and global information for better prefetching.

3. As a novel solution in the hybrid storage system, SGDP can be generalized to multiple variants by different stream construction methods, which further enhances its robustness and expands its application to various real-world scenarios.

4. SGDP outperforms SOTA by 6.21% on hit ratio, 7.00% on effective prefetching ratio, and speeds up inference time by 3.13X. It has been verified in commercial hybrid storage systems in the experimental phase and will be deployed in the future product series.

Preliminaries

$$\langle lba_i \rangle_{i=1}^{n} = \langle lba_1, lba_2, \ldots, lba_n \rangle, \tag{1}$$

$$ld_i = lba_{i+1} - lba_i, \tag{2}$$

$$\langle ld_i \rangle_{i=1}^{n-1} = \langle ld_1, ld_2, \ldots, ld_{n-1} \rangle. \tag{3}$$

$$\widehat{lba}_{n+1} = lba_n + \widehat{ld}_n. \tag{4}$$

Methodology

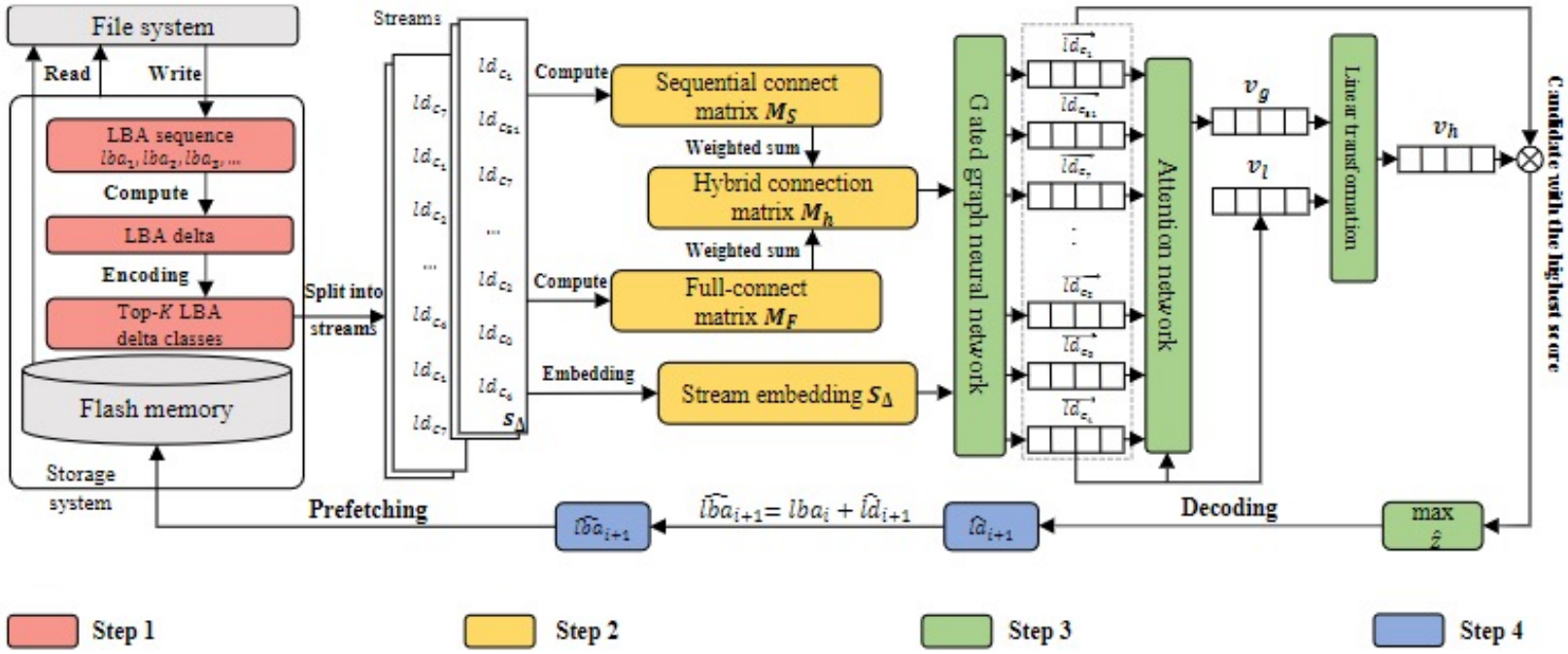

Fig. 1. The workflow of the SGDP framework. In Step 1, we compress the search space and reduce the learning complexity. In Step 2, we compute the hybrid connection matrix $\mathbf{M}_h$ with sequential and global information and embed the LBA delta stream into a matrix $\mathbf{S}_\Delta$. In Step 3, using gated graph neural networks to update the latent node vectors. Each stream is represented as the combination of the local preference $\mathbf{v}_l$ and global interaction $\mathbf{v}_g$ by an attention network. In Step 4, we predict the candidate with the highest score and decode it to get the next accessed LBA for prefetching. This framework corresponds to the four steps of **Algorithm 1**.

Methodology

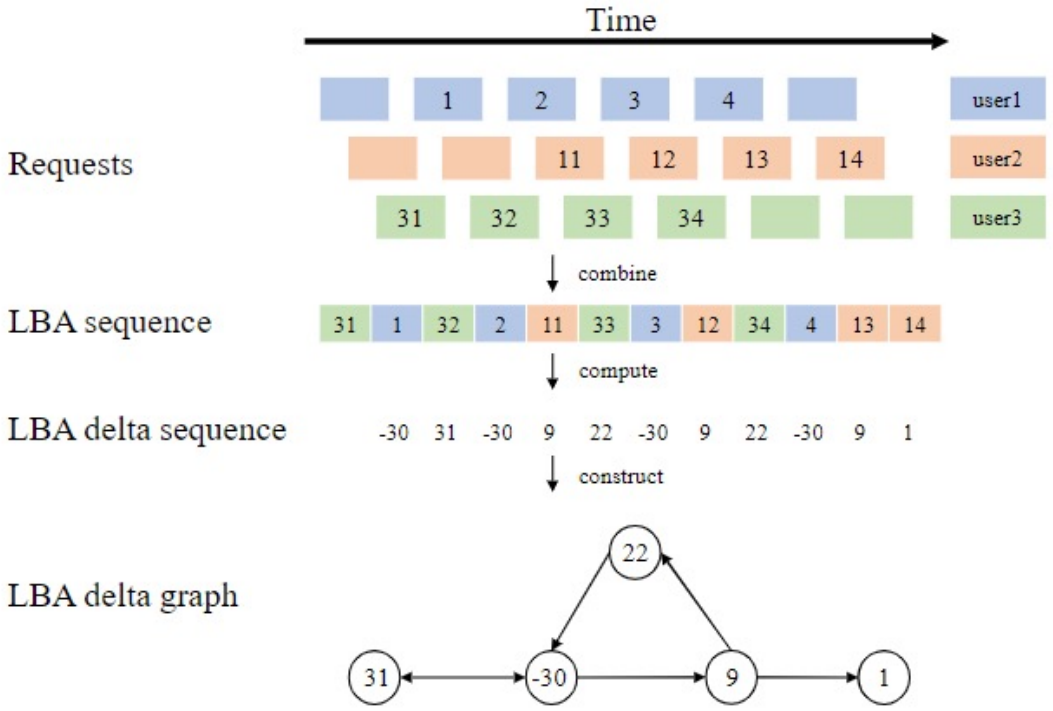

Fig. 2. Example of LBA delta and graph.

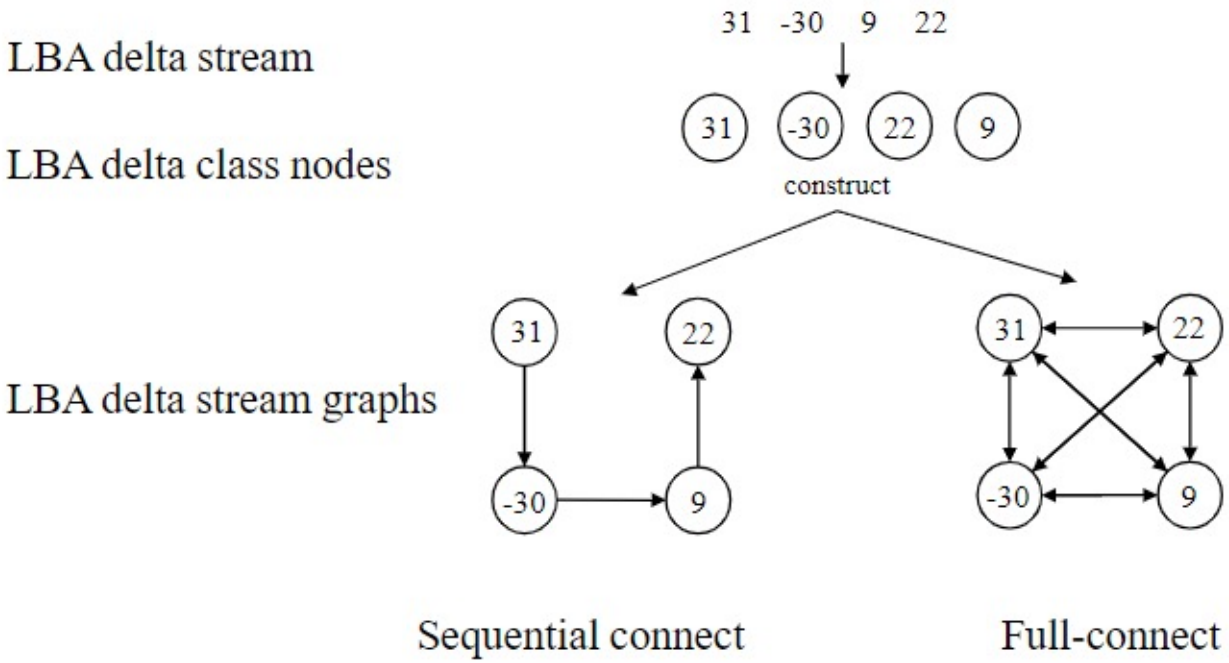

Fig. 3. Example of two kinds of graphs.

Experimental settings

TABLE I
DATASETS DESCRIPTION

Source	Dataset	Length	Memory (GB)	Function	Sequential (%)
MSRC	hm_1	1.08×10^6	6.36	Hardware monitoring	39.9
	mds_0	4.23×10^5	8.48	Media server	65.2
	proj_0	1.17×10^6	4.056	Project directories	57.3
	prxy_0	4.03×10^5	5.18	Firewall/web proxy	37.6
	src1_2	1.15×10^6	2.0	Source control	58.5
HW	hw_1	1.39×10^6	930.29	hybrid storage system	55.8
	hw_2	2.58×10^5	600.46	hybrid storage system	95.1
	hw_3	1.73×10^5	902.22	hybrid storage system	43.7

$$\mathrm{HR} = \frac{\text{Cache Hits}}{\text{Cache Hits} + \text{Cache Misses}} \times 100\%.$$

$$\mathrm{EPR} = \frac{\text{Correct Prefetchings}}{\text{All Prefetchings}} \times 100\%.$$

Performance & result

TABLE II

SINGLE-STEP RESULTS. THE RESULTS ARE IN PERCENTAGE, THE BEST RESULTS ARE IN **BOLD**, THE SECOND ONES ARE UNDERLINED, N IS CACHE SIZE.

Dataset	hw_1						hw_2						hw_3						hm_1					
Metric	HR@N			EPR@N			HR@N			EPR@N			HR@N			EPR@N			HR@N			EPR@N		
Method	10	100	1000	10	100	1000	10	100	1000	10	100	1000	10	100	1000	10	100	1000	10	100	1000	10	100	1000
No_pre	0.0	0.3	54.2	0.0	0.0	0.0	1.0	1.1	1.1	0.0	0.0	0.0	0.0	0.1	1.3	0.0	0.0	0.0	2.7	25.3	98.3	0.0	0.0	0.0
Naïve	57.5	58.0	63.2	63.3	64.5	64.5	92.5	92.6	92.7	93.3	93.7	94.0	47.7	47.9	48.8	48.0	48.3	48.7	31.7	43.8	97.4	30.5	31.2	5.6
Stride	43.7	44.0	65.8	80.5	81.1	80.6	91.0	91.1	91.1	**99.1**	**99.2**	**99.2**	38.4	38.6	39.6	81.6	82.0	82.3	27.1	47.0	99.1	82.3	84.4	**88.4**
ARIMA	1.9	4.0	8.8	1.9	4.3	6.2	82.8	82.9	83.0	85.9	86.2	86.4	0.3	0.3	1.3	0.2	0.3	0.3	3.5	19.0	95.2	2.7	5.2	2.5
Informer	0.2	0.9	5.8	0.3	0.9	2.9	1.0	1.1	1.1	0.0	0.0	0.0	0.0	0.0	0.9	0.0	0.0	0.0	1.1	14.0	90.4	0.1	0.7	0.7
DeepPrefetcher	74.3	74.6	79.2	75.4	75.9	76.5	92.2	92.5	92.8	93.4	94.0	94.5	50.4	50.7	51.7	50.4	50.7	51.2	38.5	59.1	99.3	38.5	56.0	46.1
Delta-LSTM	74.4	74.8	79.3	75.5	76.0	76.6	92.5	92.8	93.1	93.7	94.2	94.7	56.4	56.8	57.9	66.2	66.8	67.2	30.0	50.6	99.3	57.7	72.8	87.6
SGDP	**79.2**	**79.5**	**85.8**	**82.9**	**83.5**	**81.6**	93.0	93.0	93.1	97.5	97.7	97.8	76.0	76.6	77.5	**88.9**	**89.5**	**90.1**	38.1	55.7	**99.4**	**87.8**	**90.1**	86.2
$SGDP_l$	78.5	78.8	84.9	82.1	82.7	80.6	92.9	93.1	93.2	97.0	97.2	97.4	**78.5**	**79.0**	**79.8**	83.6	84.2	84.7	43.1	61.4	99.1	46.3	60.8	24.4
$SGDP_p$	75.7	78.2	83.6	77.6	80.4	79.6	**93.7**	**94.0**	**94.2**	94.4	95.0	95.4	48.1	48.3	49.6	72.1	73.1	75.1	**43.9**	**62.9**	99.4	46.8	63.8	34.8
Dataset	mds_0						proj_0						prxy_0						src1_2					
Metric	HR@N			EPR@N			HR@N			EPR@N			HR@N			EPR@N			HR@N			EPR@N		
Method	10	100	1000	10	100	1000	10	100	1000	10	100	1000	10	100	1000	10	100	1000	10	100	1000	10	100	1000
No_pre	13.2	35.0	61.0	0.0	0.0	0.0	6.1	28.7	35.2	0.0	0.0	0.0	20.1	40.7	48.8	0.0	0.0	0.0	3.9	34.8	48.2	0.0	0.0	0.0
Naïve	54.3	68.2	85.2	47.8	51.1	52.2	61.1	70.1	74.3	58.7	59.7	60.8	46.4	64.3	72.7	35.1	38.5	40.9	60.5	73.0	80.8	59.9	63.1	66.3
Stride	47.3	62.2	79.8	**82.3**	**90.6**	**89.8**	51.0	61.1	65.4	82.5	**88.1**	**88.3**	40.3	56.5	63.8	69.6	81.1	81.4	48.3	63.8	73.4	81.0	**89.6**	**92.0**
ARIMA	16.6	37.4	58.3	8.6	9.2	12.0	12.9	33.5	39.3	12.0	10.1	10.4	19.9	42.2	52.3	6.5	7.2	8.2	14.6	42.0	54.8	19.5	17.7	19.2
Informer	9.6	28.3	54.5	0.3	1.2	5.2	3.9	19.8	34.7	0.1	0.5	2.3	13.7	32.1	46.9	0.0	0.0	0.2	1.7	22.5	45.3	0.0	0.1	0.6
DeepPrefetcher	60.7	73.7	88.5	66.9	77.5	83.3	72.6	79.1	82.8	75.0	78.6	81.5	57.0	70.2	77.4	63.5	70.4	73.9	74.5	82.9	89.0	76.2	80.9	87.0
Delta-LSTM	57.3	69.6	86.2	80.2	87.8	89.8	62.3	69.1	73.3	**84.3**	86.2	87.4	52.2	64.2	71.3	75.7	79.3	80.9	70.0	79.6	86.2	77.5	81.3	87.2
SGDP	66.0	76.3	91.6	80.2	87.0	88.4	73.4	78.5	82.1	84.0	87.6	88.2	62.2	73.2	79.9	**76.3**	**83.3**	**84.1**	75.4	83.1	88.8	**82.5**	88.5	90.8
$SGDP_l$	66.1	77.5	92.1	65.4	73.9	79.6	**75.5**	81.1	84.6	79.8	83.6	85.6	**64.1**	**76.5**	83.0	65.7	74.3	78.4	**76.3**	83.9	89.4	81.5	87.4	89.3
$SGDP_p$	**67.4**	**79.8**	**92.6**	68.7	81.9	87.9	73.7	**81.3**	**85.2**	74.5	80.2	83.9	63.9	76.2	**83.0**	64.9	72.6	76.1	74.9	**84.8**	**89.8**	76.1	84.0	87.3

TABLE III

AVERAGE RESULTS OF MULTI-STEP PREFETCHING. THE RESULTS ARE IN PERCENTAGE, THE BEST RESULTS ARE IN **BOLD**, AND THE CACHE SIZE IS 100.

Metric	HR@100										EPR@100									
Method \ Step	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
DeepPrefetcher	74.0	76.1	76.7	77.1	77.2	77.1	77.1	77.0	77.0	76.9	73.1	60.7	52.5	46.5	42.0	38.3	35.3	32.8	30.7	28.8
Delta-LSTM	70.2	74.9	77.1	78.0	78.5	78.9	79.3	79.6	79.8	80.0	81.5	72.3	65.9	60.6	56.3	52.6	49.5	46.8	44.5	42.3
SGDP	77.0	78.3	78.9	79.3	79.6	79.8	80.0	80.1	80.3	80.3	**88.4**	**80.5**	**74.0**	**68.9**	**64.6**	**60.9**	**57.7**	**54.9**	**52.7**	**50.5**
$SGDP_l$	**78.9**	**80.7**	**81.4**	**81.8**	**82.2**	**82.4**	**82.5**	**82.6**	**82.7**	**82.7**	80.5	70.2	62.9	57.5	53.1	49.6	46.6	44.0	41.8	39.8
$SGDP_p$	75.7	77.4	78.1	78.6	78.9	79.1	79.2	79.3	79.5	79.5	78.9	68.3	60.8	55.1	50.6	46.8	43.7	41.1	38.8	36.7

Performance & result

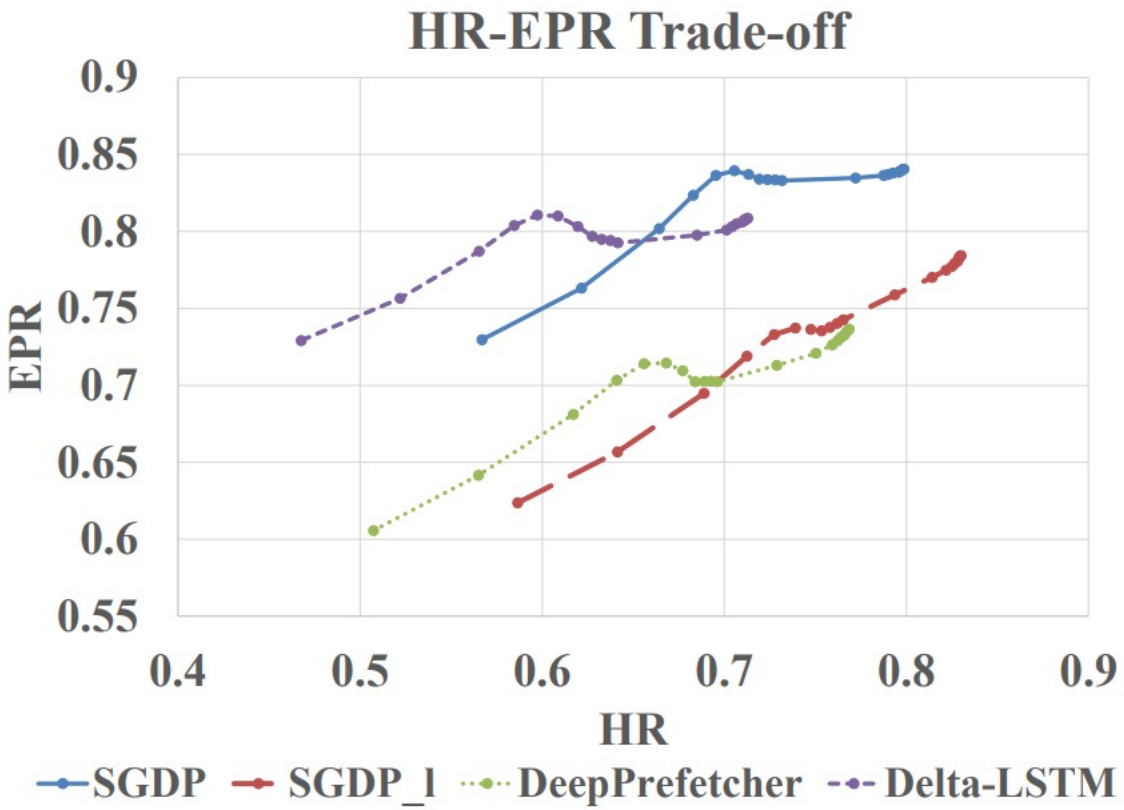

Fig. 4. HR-EPR trade-off.

TABLE IV
THE NUMBER OF PREDICTIONS INFERRED PER SECOND BY LEARNING-BASED METHODS.

Method \ Dataset	hw_1	hw_2	hw_3	hm_1	mds_0	proj_0	prxy_0	src1_2	avg
Delta-LSTM	89.4	87.4	94.5	92.4	90.7	91.5	88.4	95.1	91.2
DeepPrefetcher	208.2	154.5	194.2	160.1	248.4	178.4	187.9	249.6	197.7
SGDP	**644.5**	**692.4**	**666.1**	515.2	543.5	553.3	470.0	550.7	579.5
$SGDP_l$	634.7	686.9	614.7	500.1	**651.4**	**663.9**	526.3	**670.7**	**618.6**
$SGDP_p$	599.5	645.6	593.9	**567.0**	491.7	529.3	**574.8**	558.7	570.1

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Many Thanks

Yiyuan Yang*
University of Oxford
Huawei Noah's Ark Lab
Oxford, UK
yiyuan.yang@cs.ox.ac.uk

Rongshang Li*
University of Sydney
Huawei Noah's Ark Lab
Sydney, Australia
roli5128@uni.sydney.edu.au

Qiquan Shi
Huawei Noah's Ark Lab
Huawei
Shenzhen, China
shiqiquan@huawei.com

Xijun Li
MIRA Lab, USTC
Huawei Noah's Ark Lab
Shenzhen, China
xijun.li@huawei.com

Gang Hu
Huawei
Chengdu, China
hugang27@huawei.com

Xing Li
Huawei Noah's Ark Lab
Hongkong, China
li.xing2@huawei.com

Mingxuan Yuan
Huawei Noah's Ark Lab
Hongkong, China
Yuan.Mingxuan@huawei.com