Graphs Are Not Enough: Using Interactive Visual Analytics in Storage Research

11th USENIX Workshop on Hot Topics in Storage and File Systems (HotStorage'19)

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Outline

- **Motivation**
- Related Work
- Data Collection
- Design of ICE
- Case Study
- Future Work
- Conclusions

Motivation

- Analyzing storage systems is important and challenging
  - Statistics, machine learning, etc.
  - 2-D visualization.
- Key challenge
  - Storage systems are often affected by many factors
    - Tunable parameters, workloads, hardware, etc.

A Partial Example

#	Workload	I/O Size (KB)	HDD Results		SSD Results	
			Base (% Diff)	Optimized (% Diff)	Base (% Diff)	Optimized (% Diff)
1	seq-rd-1th-1f	4	- 2.5	+ 1.7	- 0.5	- 0.9
2		32	- 0.2	- 2.2	+ 0.8	+ 0.3
3		128	- 0.9	- 2.1	+ 0.4	+ 1.7
4		1024	- 0.9	- 2.2	+ 0.2	- 0.3
5	seq-rd-32th-32f	4	- 36.9	- 26.9	- 0.1	- 0.2
6		32	- 41.5	- 30.3	- 0.1	- 1.8
7		128	- 41.3	- 29.8	- 0.1	- 0.2
8		1024	- 41.0	- 28.3	- 0.0	- 2.1

- Workload
- I/O size
- HDD vs. SSD
- Base vs. Optimized

[FAST'17 & TOS'18]

#	Workload	I/O Size (KB)	HDD Results			SSD Results		
			EXT4 (ops/sec)	StackfsBase (%Diff)	StackfsOpt (%Diff)	EXT4 (ops/sec)	StackfsBase (%Diff)	StackfsOp (%Diff)
1	seq-rd-1th-1f	4	38382	- 2.45^{+}	+ 1.7^{+}	30694	- 0.5^{+}	- 0.9^{+}
2		32	4805	- 0.2^{+}	- 2.2^{+}	3811	+ 0.8^{+}	+ 0.3^{+}
3		128	1199	- 0.86^{+}	- 2.1^{+}	950	+ 0.4^{+}	+ 1.7^{+}
4		1024	150	- 0.9^{+}	- 2.2^{+}	119	+ 0.2^{+}	- 0.3^{+}
5	seq-rd-32th-1f	4	1228400	- 2.4^{+}	- 3.0^{+}	973450	+ 0.02^{+}	+ 2.1^{+}
6		32	153480	- 2.4^{+}	- 4.1^{+}	121410	+ 0.7^{+}	+ 2.2^{+}
7		128	38443	- 2.6^{+}	- 4.4^{+}	30338	+ 1.5^{+}	+ 1.97^{+}
8		1024	4805	- 2.5^{+}	- 4.0^{+}	3814.50	- 0.1^{+}	- 0.4^{+}
9	seq-rd-32th-32f	4	11141	- 36.9$^{\#}$	- 26.9$^{\#}$	32855	- 0.1^{+}	- 0.16^{+}
10		32	1491	- 41.5$^{\#}$	- 30.3$^{\#}$	4202	- 0.1^{+}	- 1.8^{+}
11		128	371	- 41.3$^{\#}$	- 29.8$^{\#}$	1051	- 0.1^{+}	- 0.2^{+}
12		1024	46	- 41.0$^{\#}$	- 28.3$^{\#}$	131	- 0.03^{+}	- 2.1^{+}
13	rnd-rd-1th-1f	4	243	- 9.96*	- 9.95*	4712	- 32.1$^{\#}$	- 39.8$^{\#}$
14		32	232	- 7.4*	- 7.5*	2032	- 18.8*	- 25.2$^{\#}$
15		128	191	- 7.4*	- 5.5*	852	- 14.7*	- 12.4*
16		1024	88	- 9.0*	-3.1^{+}	114	- 15.3*	-1.5^{+}
17	rnd-rd-32th-1f	4	572	- 60.4$^{!}$	-23.2*	24998	- 82.5$^{!}$	-27.6$^{\#}$
18		32	504	- 56.2$^{!}$	-17.2*	4273	- 55.7$^{!}$	-1.9^{+}
19		128	278	- 34.4$^{\#}$	-11.4*	1123	- 29.1$^{\#}$	-2.6^{+}
20		1024	41	- 37.0$^{\#}$	-15.0*	126	- 12.2*	-1.9^{+}
21	seq-wr-1th-1f	4	36919	-26.2$^{\#}$	- 0.1^{+}	32959	- 9.0*	+ 0.1^{+}
22		32	4615	- 17.8*	- 0.16^{+}	4119	- 2.5^{+}	+ 0.12^{+}
23		128	1153	- 16.6*	- 0.15^{+}	1030	- 2.1^{+}	+ 0.1^{+}
24		1024	144	- 17.7*	-0.31^{+}	129	- 2.3^{+}	- 0.08^{+}
25	seq-wr-32th-32f	4	34370	- 2.5^{+}	+ 0.1^{+}	32921	+ 0.05^{+}	+ 0.2^{+}
26		32	4296	- 2.7^{+}	+ 0.0^{+}	4115	+ 0.1^{+}	+ 0.1^{+}
27		128	1075	- 2.6^{+}	- 0.02^{+}	1029	- 0.04^{+}	+ 0.2^{+}
28		1024	134	- 2.4^{+}	- 0.18^{+}	129	- 0.1^{+}	+ 0.2^{+}
29	rnd-wr-1th-1f	4	1074	- 0.7^{+}	- 1.3^{+}	16066	+ 0.9^{+}	- 27.0$^{\#}$
30		32	708	- 0.1^{+}	- 1.3^{+}	4102	- 2.2^{+}	- 13.0*
31		128	359	- 0.1^{+}	- 1.3^{+}	1045	- 1.7^{+}	- 0.7^{+}
32		1024	79	- 0.01^{+}	- 0.8^{+}	129	- 0.02^{+}	- 0.3^{+}
33	rnd-wr-32th-1f	4	1073	- 0.9^{+}	- 1.8^{+}	16213	- 0.7^{+}	- 26.6$^{\#}$
34		32	705	+ 0.1^{+}	- 0.7^{+}	4103	- 2.2^{+}	- 13.0*
35		128	358	+ 0.3^{+}	- 1.1^{+}	1031	- 0.1^{+}	+ 0.03^{+}
36		1024	79	+ 0.1^{+}	- 0.3^{+}	128	+ 0.9^{+}	- 0.3^{+}
37	files-cr-1th	4	30211	- 57$^{!}$	- 81.0$^{!}$	35361	- 62.2$^{!}$	- 83.3$^{!}$
38	files-cr-32th	4	36590	- 50.2$^{!}$	- 54.9$^{!}$	46688	- 57.6$^{!}$	- 62.6$^{!}$
39	files-rd-1th	4	645	+ 0.0^{+}	- 10.6*	8055	- 25.0*	- 60.3$^{!}$
40	files-rd-32th	4	1263	- 50.5$^{!}$	-4.5^{+}	25341	- 74.1$^{!}$	-33.0$^{\#}$
41	files-del-1th	-	1105	- 4.0^{+}	- 10.2*	7391	- 31.6$^{\#}$	- 60.7$^{!}$
42	files-del-32th	-	1109	- 2.8^{+}	- 6.9*	8563	- 42.9$^{\#}$	- 52.6$^{!}$
43	file-server	-	1705	- 26.3$^{\#}$	-1.4^{+}	5201	- 41.2$^{\#}$	-1.5^{+}
44	mail-server	-	1547	- 45.0$^{\#}$	-4.6^{+}	11806	- 70.5$^{!}$	-32.5$^{\#}$
45	web-server	-	1704	- 51.8$^{!}$	+6.2^{+}	19437	- 72.9$^{!}$	-17.3*

[FAST'17]

#	Workload	I/O Size (KB)	HDD Results			SSD Results		
			Ext4 (%)	SBase (%Diff)	SOpt (%Diff)	Ext4 (%)	SBase (%Diff)	SOpt (%Diff)
9	seq-rd-32th-32f	4	28	- 35.7$^{\#}$	- 28.6$^{\#}$	95	0.0‡	0.0‡
10		32	30	- 43.3$^{\#}$	- 30.0$^{\#}$	98	0.0‡	- 1.0†
11		128	30	- 43.3$^{\#}$	- 30.0$^{\#}$	98	0.0‡	- 1.0†
12		1024	30	- 43.3$^{\#}$	- 30.0$^{\#}$	98	0.0‡	- 1.0†
13	rnd-rd-1th-1f	4	1	0.0‡	0.0‡	13	- 30.8$^{\#}$	- 38.5$^{\#}$
14		32	4	0.0‡	0.0‡	45	- 17.8*	- 24.4*
15		128	14	0.0‡	0.0‡	75	- 13.3*	- 12.0*
16		1024	59	+ 3.4‡	0.0‡	89	- 3.4†	0.0‡
17	rnd-rd-32th-1f	4	1	0.0‡	0.0‡	69	- 82.6$^{!}$	- 24.6*
18		32	10	- 60.0$^{!}$	- 20.0*	94	- 55.3$^{!}$	- 1.1†
19		128	21	- 33.3$^{\#}$	- 9.5*	98	- 27.6$^{\#}$	0.0‡
20		1024	27	- 33.3$^{\#}$	- 11.1*	98	- 9.2*	0.0‡
21	seq-wr-1th-1f	4	92	- 26.1$^{\#}$	- 1.1†	95	- 7.4*	0.0‡
22		32	92	- 17.4*	- 1.1†	95	- 2.1†	0.0‡
23		128	92	- 16.3*	- 1.1†	95	- 1.0†	0.0‡
24		1024	92	- 17.4*	- 1.1†	95	- 1.0†	0.0‡
25	seq-wr-32th-32f	4	86	- 2.3†	- 1.2†	95	0.0‡	0.0‡
26		32	86	- 2.3†	- 1.2†	95	0.0‡	0.0‡
27		128	85	- 1.2†	0.0‡	95	0.0‡	0.0‡
28		1024	85	- 1.2†	0.0‡	95	0.0‡	0.0‡
29	rnd-wr-1th-1f	4	2	0.0‡	0.0‡	46	0.0‡	- 26.1$^{\#}$
30		32	14	0.0‡	0.0‡	93	0.0‡	- 9.7*
31		128	28	0.0‡	0.0‡	95	0.0‡	0.0‡
32		1024	50	0.0‡	0.0‡	95	0.0‡	- 1.0†
33	rnd-wr-32th-1f	4	2	0.0‡	0.0‡	46	0.0‡	- 26.1$^{\#}$
34		32	14	0.0‡	0.0‡	93	0.0‡	- 12.9*
35		128	28	0.0‡	0.0‡	95	0.0‡	0.0‡
36		1024	50	0.0‡	- 2.0†	95	0.0‡	- 1.0†
37	files-cr-1th	4	31	- 58.1$^{!}$	- 80.6$^{!}$	42	- 61.9$^{!}$	- 83.3$^{!}$
38	files-cr-32th	4	37	- 48.6$^{\#}$	- 59.5$^{!}$	54	- 57.4$^{!}$	- 61.1$^{!}$
39	files-del-1th	4	2	0.0‡	- 50.0$^{!}$	21	- 23.8*	- 57.1$^{!}$
40	files-del-32th	4	3	- 33.3$^{\#}$	0.0‡	66	- 74.2$^{!}$	- 33.3$^{\#}$
41	files-rd-1th	-	5	0.0‡	0.0‡	42	- 33.3$^{\#}$	- 61.9$^{!}$
42	files-rd-32th	-	5	0.0‡	0.0‡	48	- 39.6$^{\#}$	- 54.2$^{!}$
43	file-server	-	25	- 24.0*	0.0‡	95	- 41.0$^{\#}$	- 2.1†
44	mail-server	-	11	- 45.4$^{\#}$	- 9.1*	76	- 60.5$^{!}$	- 17.1*
45	web-server	-	7	- 42.9$^{\#}$	0.0‡	81	- 74.1$^{!}$	- 9.9*

[TOS'18]

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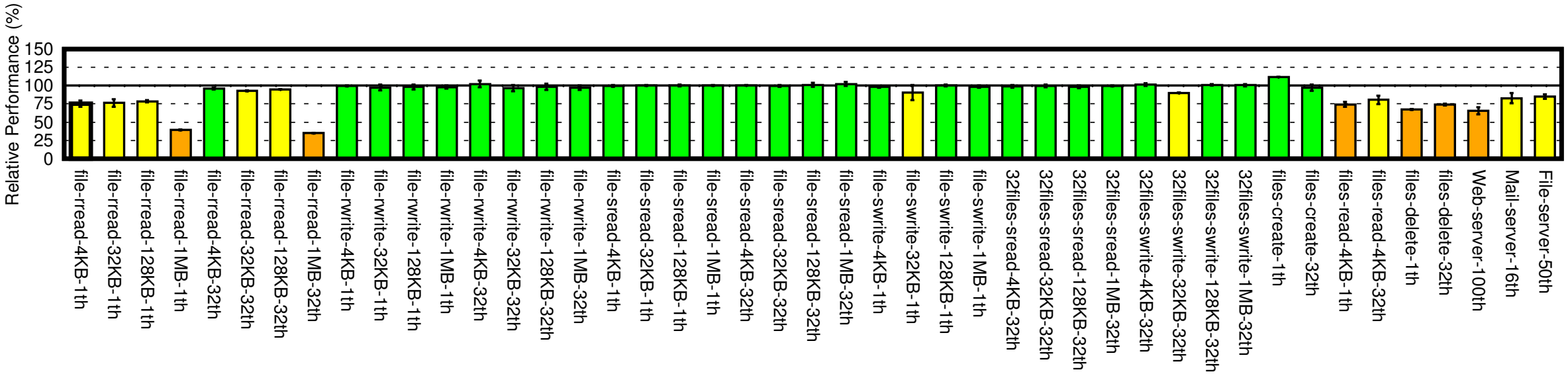
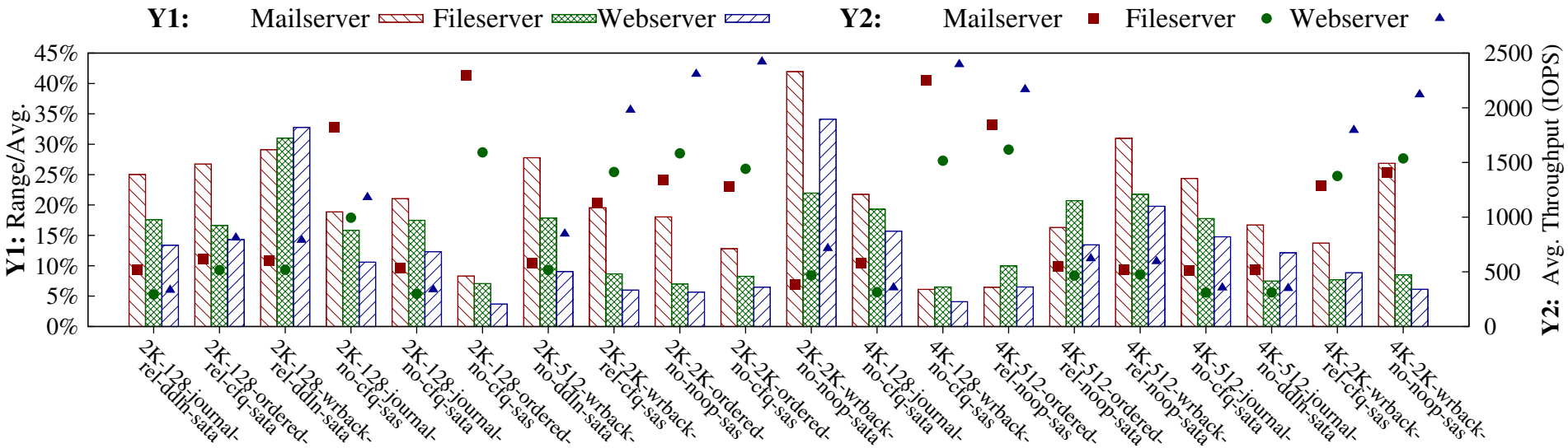


[HotStorage'15]



[FAST'17]

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Challenges

- Storage systems are often affected by many factors
  - Tunable parameters, workloads, hardware, etc.
- Lack of interpretability
- Difficult to infuse domain knowledge

Proposed solution: Interactive Visual Analytics

Key Contributions

- Prototyped Interactive Configuration Explorer (**ICE**)
- Demonstrate ICE can help the analysis of storage performance
- ICE will be open-sourced

Related Work

- Interactive visual analytics have been successfully applied in exploring and analyze real-world datasets
  - Plotly, Tableau, etc.
  - Parallel Coordinates, Parallel Sets, Data Context Maps, etc.
- Visualization in storage research
  - Mostly 2D techniques such as histograms, box plots, etc., and 3D versions such as surface plots
  - Visualizing block I/O workloads [Rodeh et al.]
- Other domains
  - Network
  - Database query optimization

Data Collection

- Settings
  - Hardware: 1 Intel Xeon quad-core 2.4GHz CPU, 24GB RAM, 4 drives
  - Benchmarks: Filebench
    - Dbserver, mailserver, fileserver, webserver
- Parameter spaces
  - file system, inode size, block size, block group, journal options, mount options, special options, I/O schedulers
    - **6,222** unique combinations (over 500k data points collected)
  - 4 workload × 4 devices
    - Datasets published (link)

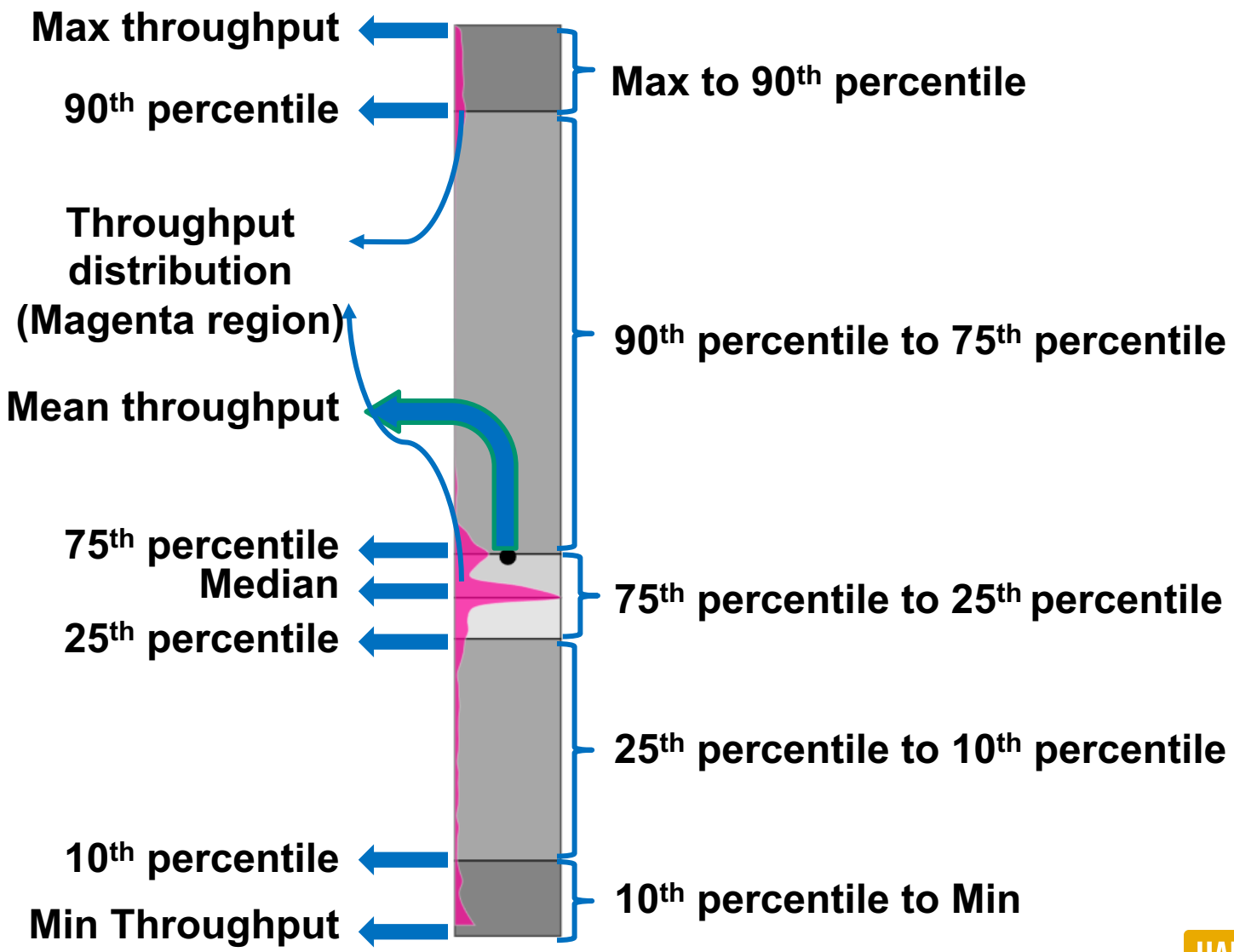
Outline

- Motivation
- Related Work
- Data Collection
- **Design of ICE**
- Case Study
- Future Work
- Conclusions

Design of ICE

- Lessons from common 2D visualization
  - Difficult to analyze multiple factors simultaneously
  - Difficult to infuse domain knowledge
- Lessons from existing interactive visual analytics
  - Difficult to visualize categorical parameters [ATC'18]
- Design principles
  - Designed for storage analysis
  - Easy to use

Design of ICE (1 of 3)



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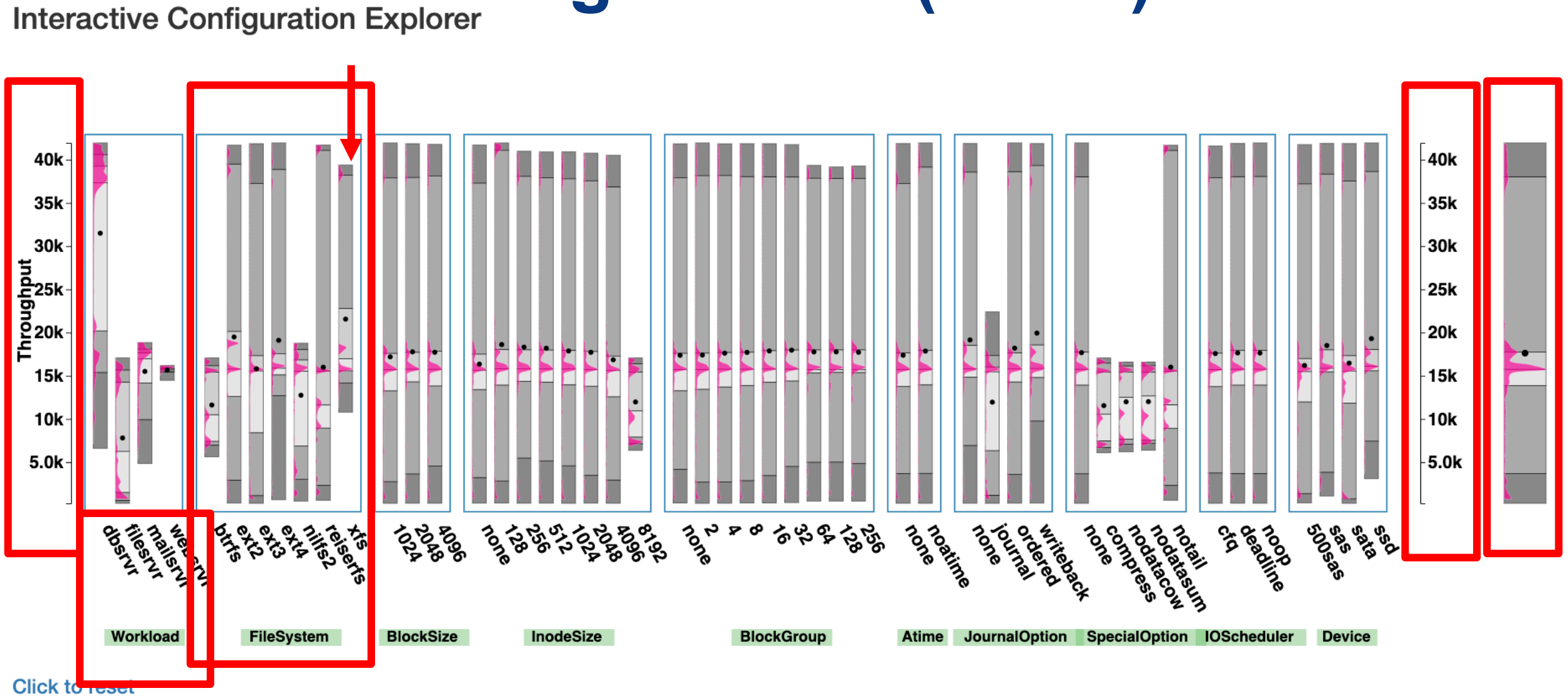
Design of ICE (2 of 3)



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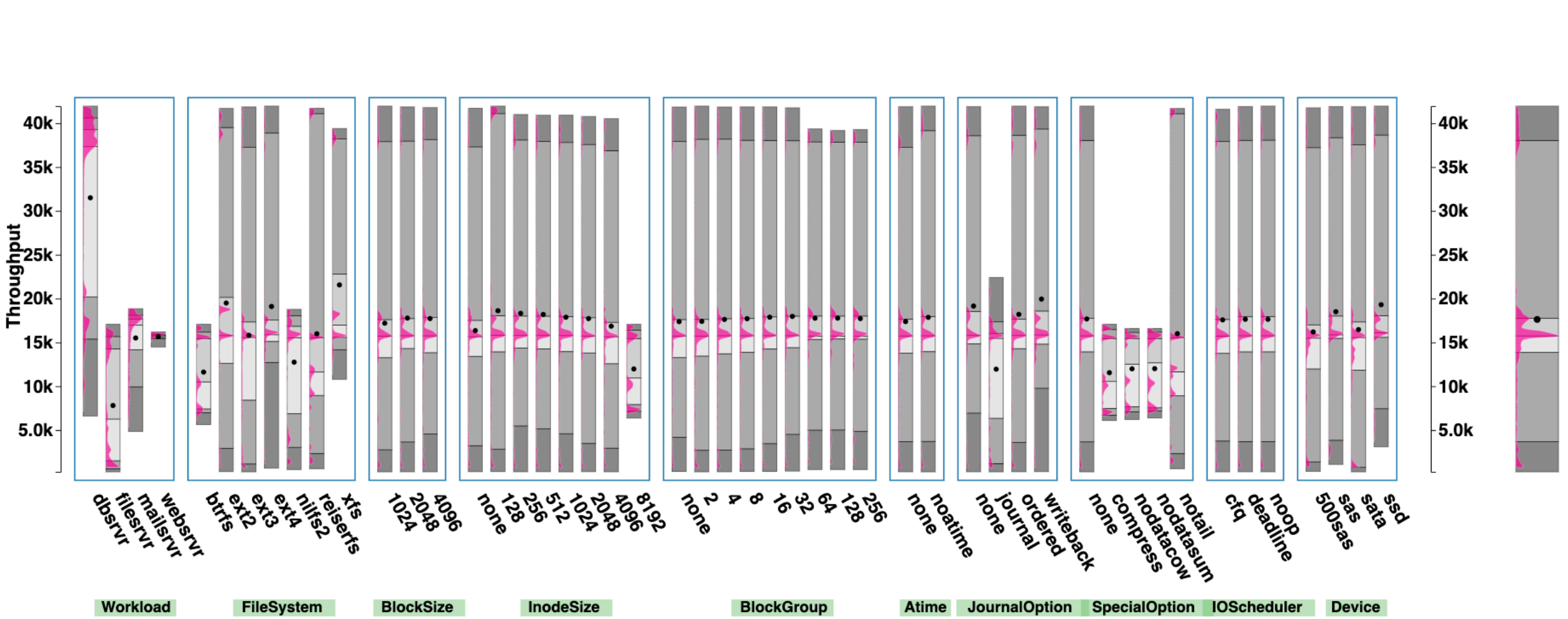
Design of ICE (3 of 3)



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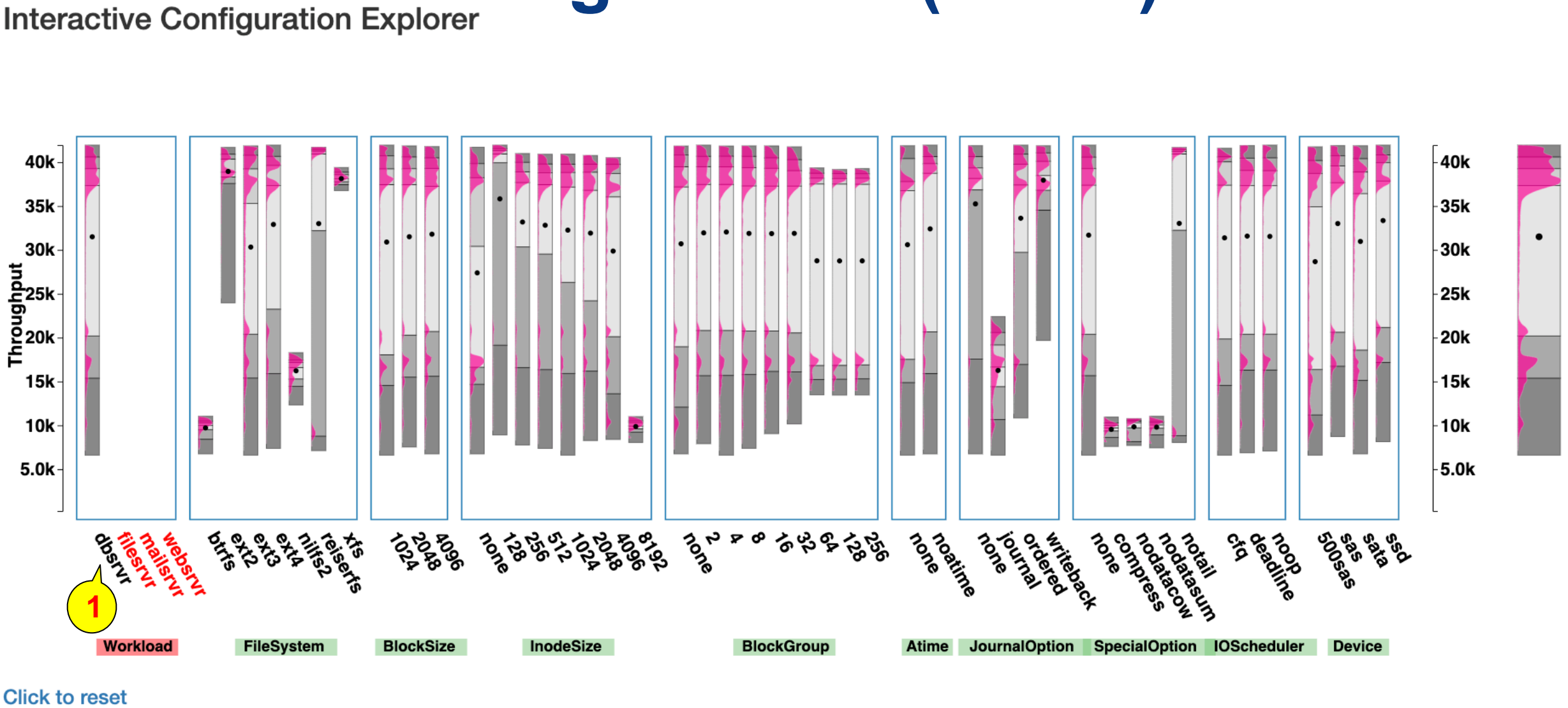
Design of ICE (3 of 3)



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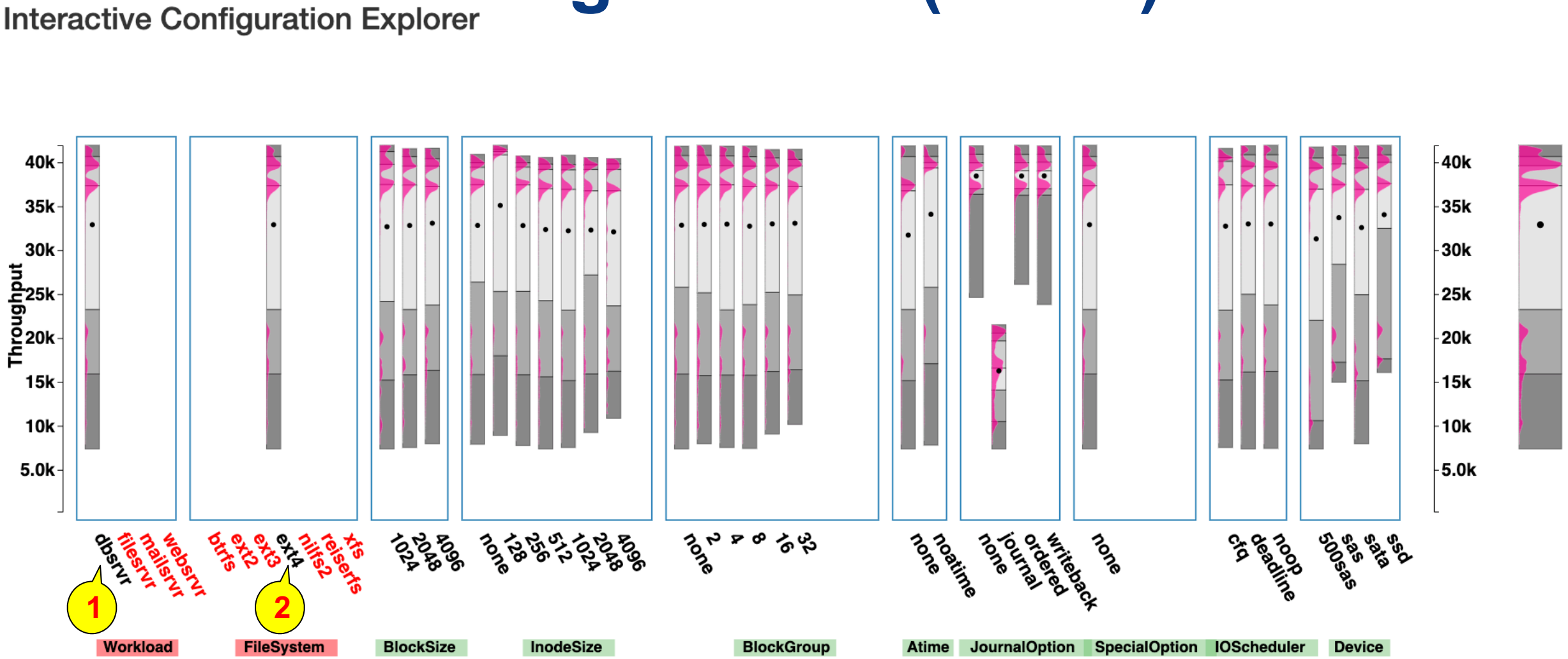
Design of ICE (3 of 3)



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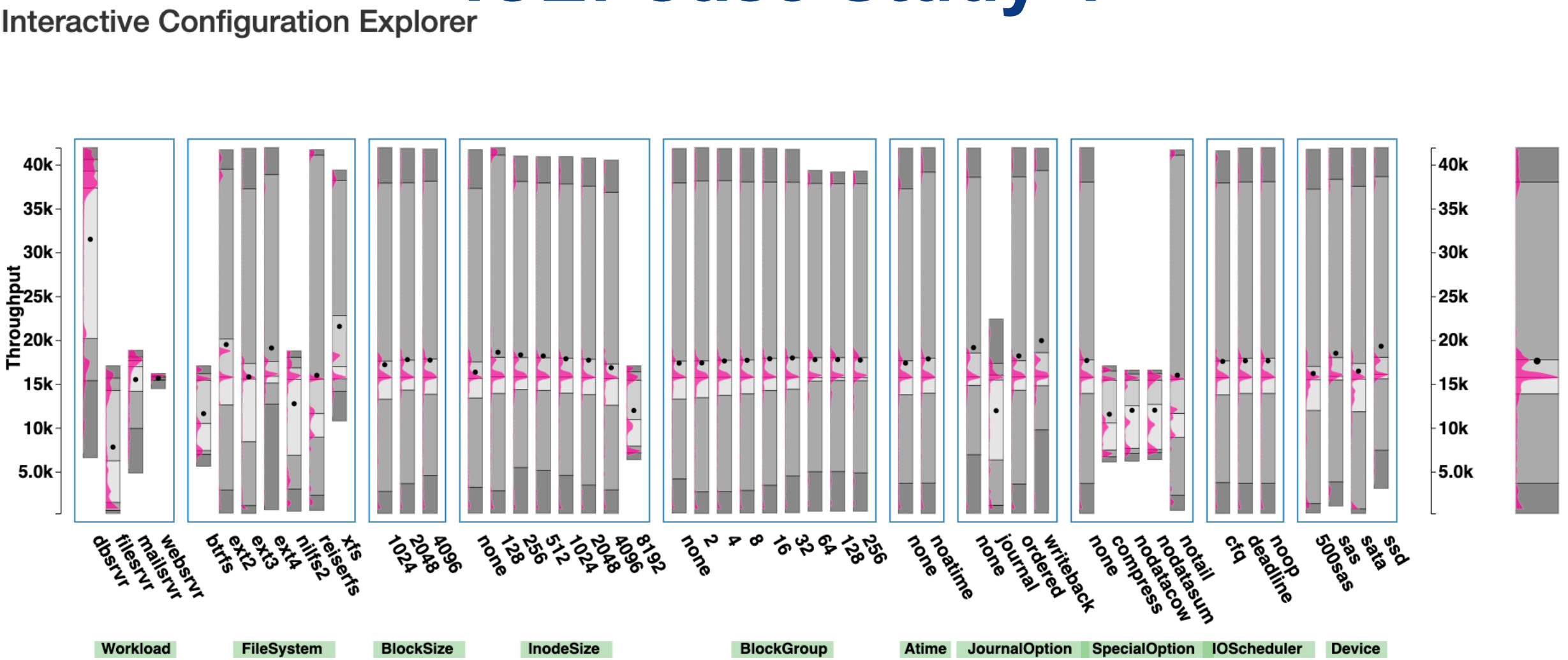
ICE Case Studies

- Case Study 1: optimize throughput under a fixed workload
- Case Study 2: optimize performance stability
- Case Study 3: optimize with constraints
- **Case Study 4: optimize performance stability & achieve good throughput**

ICE: Case Study 4



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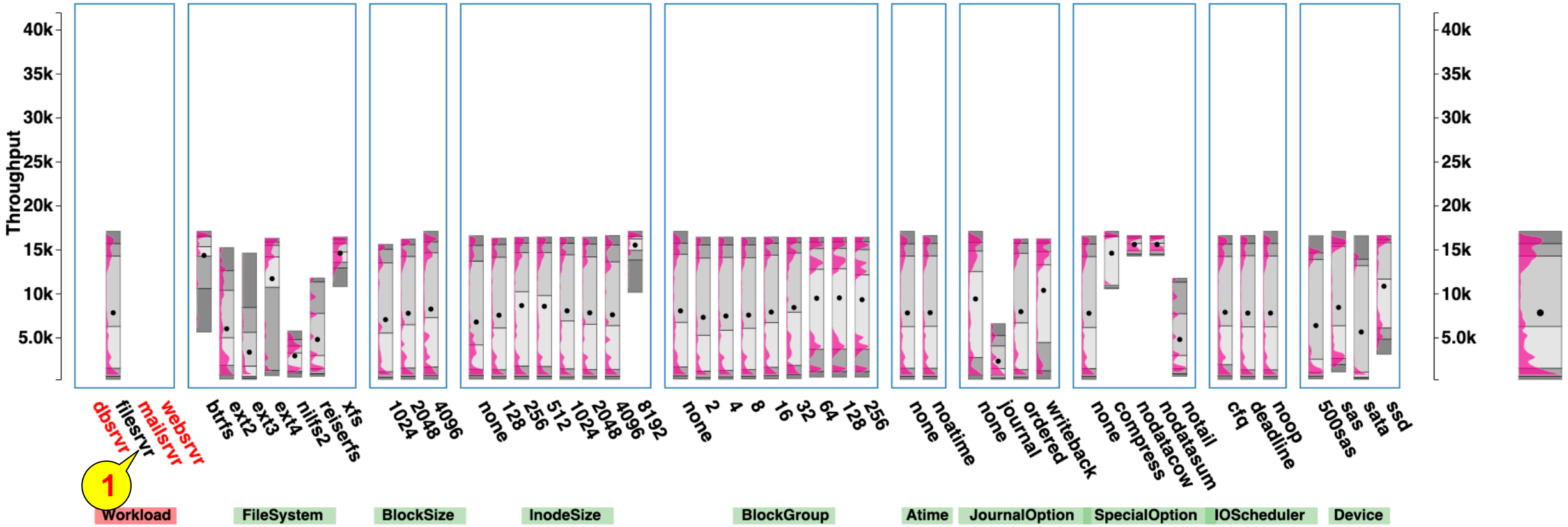
ICE: Case Study 4

Interactive Configuration Explorer



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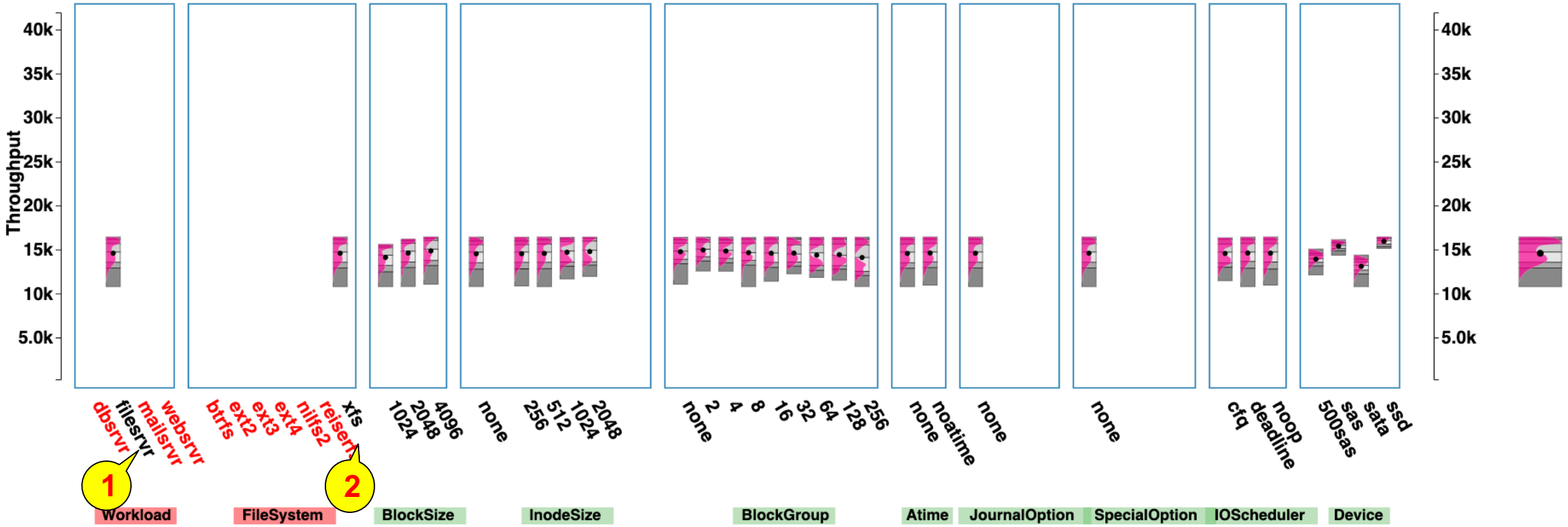
ICE: Case Study 4

Interactive Configuration Explorer



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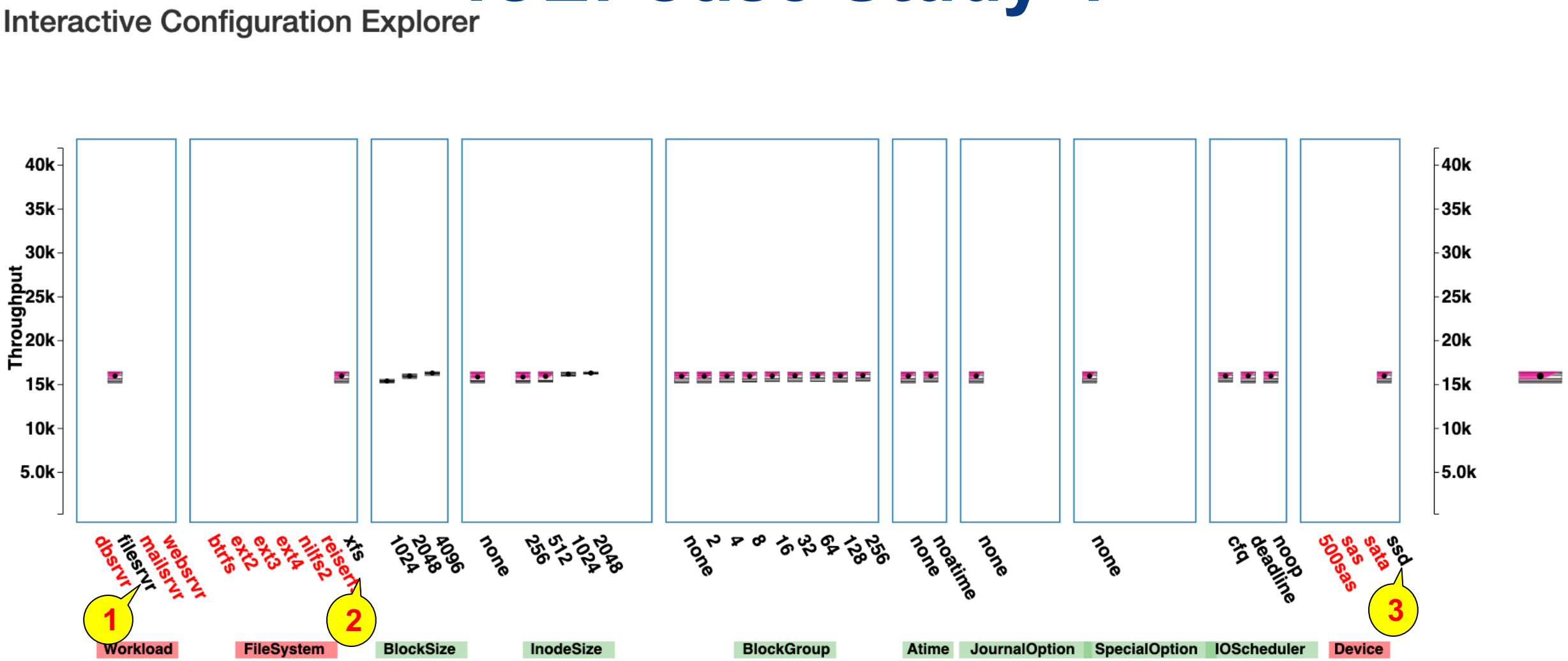
ICE: Case Study 4



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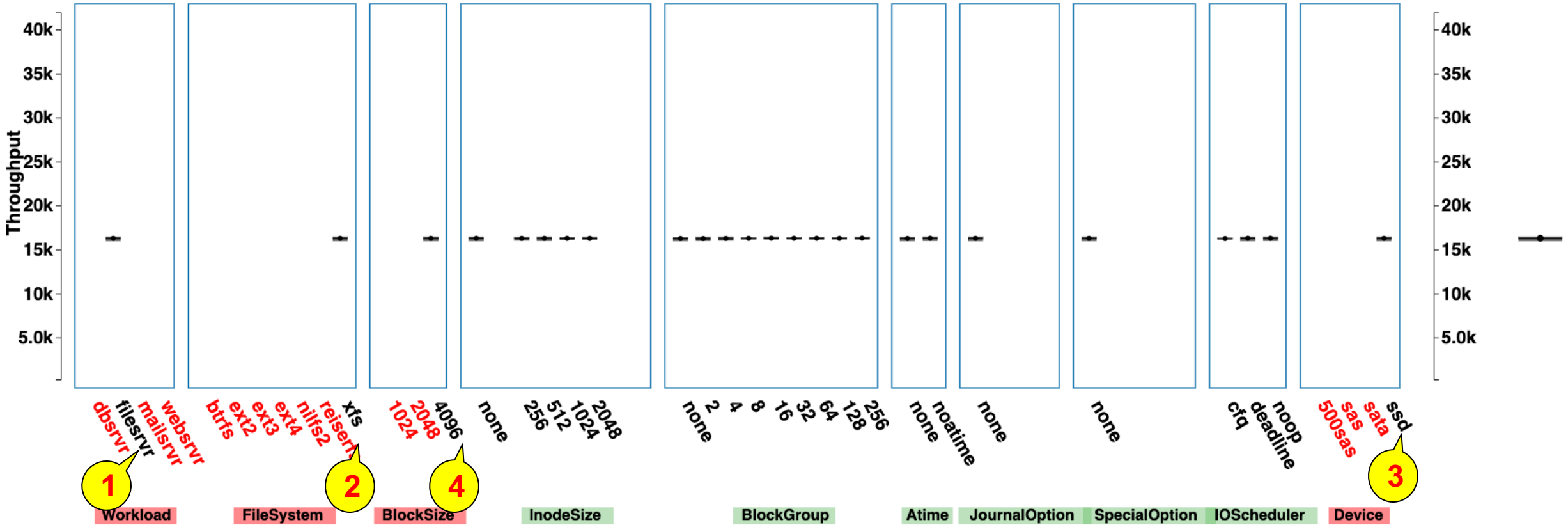
ICE: Case Study 4

Interactive Configuration Explorer



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Future Work

- Scale ICE with hundreds of dimensions
- Support multi-objective analysis
- Aid data collection and performance tuning
- Apply other visualization techniques for storage and system analysis
  - E.g., Context Maps

Conclusions

- Propose to utilize interactive visual analytics in storage research
- Prototyped Interactive Configuration Explorer (**ICE**)
- Demonstrated effectiveness of ICE
- Make ICE open-source

Graphs Are Not Enough: Using Interactive Visual Analytics in Storage Research

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Thank You

Q&A

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