
Exploiting Dynamic Sparsity in Einsum (Technical Appendices)

submitted to Neurips 2025

Here we provide additional plots and extensive data tables for the experiments in the main paper.

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1 Proof of Lemma 2

Lemma 2. *Contracting the tensor hypernetwork encoding of GRID_n needs at least 2^n flops, when using multidimensional arrays.*

Proof. In Proposition 4.2 in Markov and Shi [2], it is shown that the size of the largest intermediate tensor, in terms of the number of axes, for any tensor (hyper-)network contraction order is lower bounded by the treewidth of the dual graph of the (hyper-)network. The dual graph of the tensor hypernetwork encoding of GRID_n is the $(n \times n)$ -grid graph, whose vertices correspond to the variables $x_{i,j}$ and whose edges correspond to the clauses. The dual graph of the tensor hypernetwork encoding of GRID_3 is shown in Figure 1 of the main paper, where its vertices are represented by small gray bullets. Since the treewidth of an $(n \times n)$ -grid graph is n and all axes are of length 2, the largest intermediate tensor has 2^n entries, all of which need to be computed explicitly when using multidimensional arrays for the tensor encoding. \square

2 Synthetic data

Median runtimes for the synthetic data for selected values of n are shown in Table 1. The runtime in the dense case grows exponentially with grid size, while the sparse case grows only quadratically. We stopped recording dense runtimes after $n = 30$ due to excessive runtime. The sparse runtime remains low even at $n = 128$.

Table 1: Synthetic Data

Grid Site Length (n)	Dense Runtime (s)	Sparse Runtime (s)
2	0.000632	0.001335
5	0.001317	0.001469
8	0.003559	0.004170
11	0.006530	0.009026
14	0.017364	0.015918
17	0.114016	0.028419
20	0.213142	0.035368
23	6.945333	0.032761
26	61.066411	0.044847
29	594.365473	0.058783
30	1267.657151	0.064903
32	NaN	0.075265
44	NaN	0.141794
56	NaN	0.254500
68	NaN	0.431774
80	NaN	0.678623
92	NaN	0.991301
104	NaN	1.407768
116	NaN	1.778932
128	NaN	2.480547

3 Density evolution

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Because Figure 3 of the main paper is rather small, we include a larger version of the same plot in Figure 7. In addition, we modified the colors and line styles for Group 3b to improve distinguishability.

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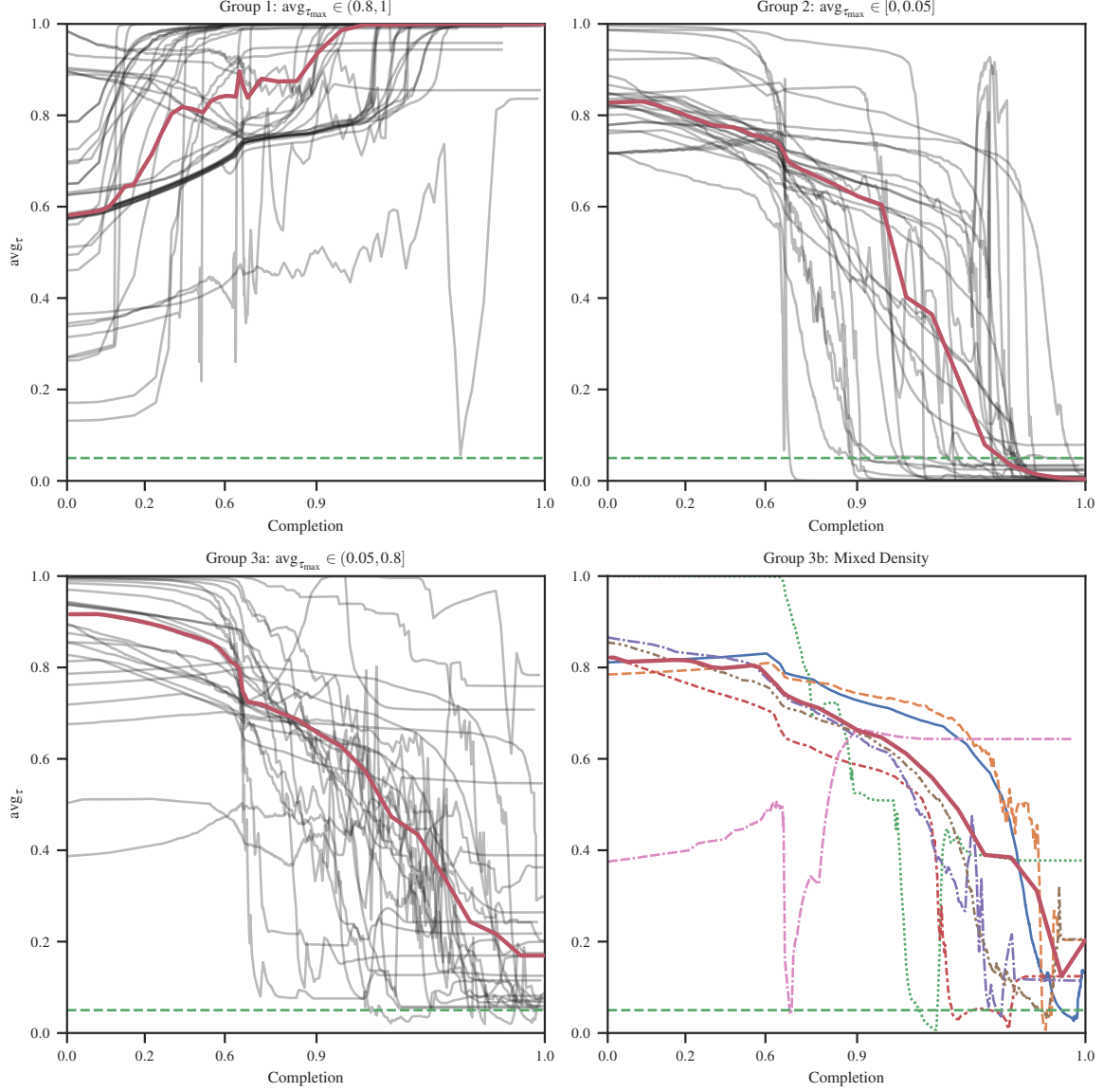


Figure 7: Evolution of average tensor density across instances, grouped by their final values. Within each group, a bold red line indicates the median density. The last group comprises instances transitioning from sparse ($< 5\%$) to dense ($> 10\%$). An exponential scaling at both ends is used along the x-axis to show the fraction of completed contractions. A green dashed line marks the 5% density threshold.

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33 4 Runtime comparison

34 Table 2 shows the median runtimes for the dense, sparse, and hybrid implementations, as well as for the
35 density estimation, on all benchmark einsum expressions compiled by Blacher et al. [1]. The bench-
36 mark includes one contraction order optimized for minimal intermediate size and one for minimal
37 floating-point operations (flops). We indicate which order was used in the *Path* column. Additionally,
38 we report whether the hybrid implementation switched to the sparse tensor format, along with some
39 instance metadata.

Table 2: Runtimes of the different implementations on the benchmark instances. The flops are reported as \log_{10} , the size as \log_2 .

Name	Flops	Size	Path	Average Density	Dense (s)	Sparse (s)	Hybrid (s)	Density (s)	Switched	DType
gm_1fas	11.03	28.53	flops	0.91	3.66	218.15	3.87	7.96e-04	No	float64
gm_1kp6	10.40	27.77	flops	0.97	1.60	67.87	1.62	7.78e-04	No	float64
gm_BN_13	11.42	32.00	flops	1.00	87.83	1914.03	90.48	5.81e-04	No	float64
gm_Promedas_33	13.26	30.00	size	0.08	16.39	185.09	16.35	7.19e-02	No	float64
gm_mastermind_03_08_05-0000	11.27	30.00	flops	0.07	37.71	38.95	42.30	9.07e-03	Yes	float64
gm_myciel5g_3_wcsp	10.71	30.11	flops	1.00	22.67	438.57	23.70	4.84e-04	No	float64
gm_pedigree38	10.35	27.57	flops	0.17	2.29	7.38	2.32	2.92e-03	No	float64
gm_pedigree50	10.95	29.26	flops	0.84	4.14	90.07	4.01	4.76e-03	No	float64
gm_queen5_5_3.wcsp	9.75	26.94	flops	1.00	1.21	30.16	1.21	3.94e-04	No	float64
lm_batch_likelihood_brackets_3_16d	10.40	29.88	flops	1.00	3.34	75.88	3.38	2.14e-03	No	float64
lm_batch_likelihood_brackets_4_12d	10.99	28.11	flops	1.00	3.36	212.78	3.58	5.56e-03	No	float64
lm_batch_likelihood_brackets_4_16d	11.70	29.77	flops	1.00	9.28	993.96	9.95	7.32e-03	No	float64
lm_batch_likelihood_brackets_4_4d	8.37	18.96	flops	1.00	0.02	1.17	0.03	2.27e-03	No	float64
lm_batch_likelihood_sentence_3_12d	9.20	20.86	flops	1.00	0.35	3.53	0.24	1.75e-03	No	float64
lm_batch_likelihood_sentence_4_12d	11.07	25.23	flops	1.00	1.92	215.30	1.72	5.17e-03	No	float64
lm_batch_likelihood_sentence_4_14c	11.43	29.58	flops	1.00	14.83	568.80	14.76	7.55e-03	No	complex128
lm_batch_likelihood_sentence_4_16c	11.82	26.89	flops	1.00	7.67	1199.84	7.91	7.15e-03	No	complex128
lm_batch_likelihood_sentence_4_16d	11.82	26.89	flops	1.00	4.22	1205.42	4.11	4.61e-03	No	float64
lm_batch_likelihood_sentence_4_18c	12.12	27.57	flops	1.00	12.04	2319.38	12.19	6.94e-03	No	complex128
lm_batch_likelihood_sentence_4_20c	12.34	31.64	flops	1.00	34.83	3947.27	35.60	8.67e-03	No	complex128
lm_batch_likelihood_sentence_4_20d	12.34	31.64	flops	1.00	25.38	4012.05	25.42	5.50e-03	No	float64
lm_batch_likelihood_sentence_4_20d	12.34	31.64	flops	1.00	25.38	4012.05	25.42	5.50e-03	No	float64

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Name	Flops	Size	Path	Average Density	Dense (s)	Sparse (s)	Hybrid (s)	Density (s)	Switched	DType
__4d	8.46	18.89	flops	1.00	0.07	1.22	0.05	1.81e-03	No	float64
lm_batch_likelihood_sentence_4_										
__8d	10.04	22.89	flops	1.00	0.62	24.59	0.57	3.92e-03	No	float64
lm_first_last_brackets_4_16d	12.75	29.61	flops	1.00	8.34	9648.99	8.29	1.33e-03	No	float64
lm_first_last_sentence_4_14c	12.28	26.65	flops	1.00	5.51	3194.48	5.44	1.77e-03	No	complex128
lm_first_last_sentence_4_16c	12.85	30.92	flops	1.00	35.56	12026.60	36.35	2.32e-03	No	complex128
lm_first_last_sentence_4_16d	12.85	30.92	flops	1.00	16.89	12169.89	17.36	1.69e-03	No	float64
mc_2020_017	9.65	22.00	flops	0.05	4.23	1.77	2.58	1.09e-02	Yes	int32
mc_2020_062	10.41	25.00	flops	0.13	13.17	9.74	10.48	5.45e-02	Yes	int64
mc_2020_082	10.59	24.00	flops	0.09	7.07	9.87	11.46	8.25e-02	Yes	float64
mc_2020_175	12.85	32.00	size	0.20	46.17	460.45	481.97	5.40e-03	Yes	float64
mc_2020_arjun_042	10.28	28.00	flops	0.02	19.92	3.55	10.73	1.60e-02	Yes	int64
mc_2020_arjun_046	9.08	24.00	flops	0.22	0.86	1.62	1.09	4.80e-03	No	int64
mc_2020_arjun_057	9.01	24.00	flops	0.06	0.76	0.38	0.84	3.72e-03	No	int32
mc_2020_arjun_061	10.62	28.00	flops	0.55	2.36	38.29	2.30	2.69e-03	No	float64
mc_2020_arjun_102	10.07	26.00	flops	0.07	0.95	2.70	0.93	6.76e-03	No	float64
mc_2020_arjun_115	11.13	30.00	flops	0.13	79.21	210.94	77.87	2.17e-01	No	float64
mc_2021_027	8.62	23.00	flops	0.00	0.20	0.02	0.16	4.93e-04	Yes	int16
mc_2021_036	11.64	30.00	flops	0.00	124.67	1.28	0.41	3.78e-03	Yes	float64
mc_2021_065	9.37	26.00	flops	0.06	2.57	0.66	2.59	7.63e-03	No	int64
mc_2021_074	10.33	28.00	flops	0.17	16.20	17.86	16.59	3.64e-02	No	int32
mc_2021_075	9.70	27.00	flops	1.00	2.44	44.66	2.61	6.45e-04	No	float64
mc_2021_arjun_007	13.58	31.00	size	0.17	43.09	6580.91	46.17	3.83e-03	No	float64
mc_2021_arjun_031	12.77	32.00	flops	0.38	131.48	7337.47	138.82	2.82e-03	No	float64
mc_2021_arjun_171	9.68	25.00	flops	0.36	0.50	4.36	0.56	7.73e-03	No	float64
mc_2021_arjun_179	10.15	28.00	flops	0.76	4.47	51.02	4.70	1.99e-02	No	float64
mc_2022_025	9.85	27.00	flops	0.01	0.90	0.25	0.28	1.64e-03	Yes	float64
mc_2022_029	10.11	27.00	flops	0.01	1.92	0.37	0.31	2.34e-03	Yes	float64
mc_2022_079	6.63	12.00	flops	0.04	0.13	0.06	0.09	0.00e+00	No	float64
mc_2022_085	11.49	29.00	size	0.20	197.36	175.87	193.23	2.11e-01	No	int64
mc_2022_087	10.90	27.00	flops	0.00	18.54	0.30	0.29	3.12e-03	Yes	float64
mc_2022_167	6.86	6.00	flops	0.56	9.57	6.42	10.76	0.00e+00	No	int16
mc_2022_arjun_037	12.04	28.00	size	0.78	1.73	121.21	2.11	4.84e-03	No	float64
mc_2022_arjun_069	12.95	31.00	size	0.12	715.55	88.67	88.23	2.68e-03	Yes	int64

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Name	Flops	Size	Path	Average Density	Dense (s)	Sparse (s)	Hybrid (s)	Density (s)	Switched	DType
mc_2023_002	7.19	17.00	flops	0.25	0.39	0.31	0.42	3.26e-03	No	float64
mc_2023_075	11.57	29.00	flops	0.00	103.34	0.21	0.36	4.06e-03	Yes	float64
mc_2023_151	12.47	33.00	flops	0.12	168.54	324.54	325.05	8.00e-03	Yes	float64
mc_2023_186	11.21	28.00	flops	0.02	30.42	15.45	14.50	6.39e-03	Yes	float64
mc_2023_188	9.21	20.00	flops	0.06	0.66	1.10	0.66	7.05e-03	No	float64
mc_2023_199	10.73	30.00	flops	0.24	25.21	56.61	25.95	5.89e-02	No	int64
mc_2023_arjun_071	12.43	29.00	size	0.03	263.95	41.82	269.42	8.72e-02	No	int64
mc_2023_arjun_117	9.79	23.00	flops	0.20	1.09	4.15	1.09	1.25e-02	No	float64
mc_2023_arjun_133	11.60	32.00	flops	0.39	76.25	524.98	69.68	2.30e-01	No	float64
mc_rw_32.sk_4_38	11.38	30.00	flops	0.00	158.72	0.36	0.44	3.25e-03	Yes	int32
mc_rw_blasted_TR_b14_1_linear	11.85	32.00	flops	0.08	148.01	230.04	230.83	1.02e-02	Yes	float64
mc_rw_blasted_case1_b14_even3	9.79	23.00	flops	0.01	1.71	0.57	1.20	6.10e-03	Yes	float64
mc_rw_blasted_case3	10.43	29.00	flops	0.11	16.40	4.75	4.65	2.06e-03	Yes	int32
mc_rw_blasted_squaring12	12.87	33.00	flops	0.21	743.14	383.79	354.24	4.07e-02	Yes	int64
mc_rw_blockmap_05_01.net	11.11	30.00	flops	0.03	36.34	5.19	5.50	3.91e-03	Yes	int16
mc_rw_c1908.isc	12.66	31.00	size	0.05	371.38	53.10	59.11	1.94e-02	Yes	int64
mc_rw_c7552.isc	10.31	26.00	flops	0.08	1.66	3.19	3.03	6.37e-03	Yes	float64
mc_rw_log-1	12.31	35.00	flops	0.00	509.55	0.63	0.67	5.01e-03	Yes	float64
mc_rw_or-70-20-4	10.30	29.00	flops	1.00	10.60	191.04	10.61	3.76e-04	No	float64
mc_rw_or-70-5-6-UC-10	10.60	30.00	flops	0.71	30.10	176.21	29.74	2.91e-04	No	int64
mc_rw_s510.bench	11.33	32.00	flops	0.01	132.42	5.70	6.12	2.40e-03	Yes	int32
mc_rw_s510_15_7	11.49	32.00	flops	0.00	298.14	3.31	3.57	1.39e-03	Yes	int32
mc_rw_sat-grid-pbl-0020	12.34	28.00	flops	0.85	4.71	3008.33	4.74	3.08e-02	No	float64
qc_circuit_n47_m14_s0_e0_pEFGH	11.46	30.00	flops	1.00	75.23	1101.99	77.69	1.04e-03	No	complex128
qc_circuit_n49_m14_s9_e6_pEFGH_...simplified	9.81	25.00	flops	1.00	3.24	26.57	3.25	1.01e-03	No	complex128
qc_circuit_n53_m12_s2_e8_pABCD_...CDAB_simplified	9.88	25.00	flops	1.00	3.61	35.78	3.68	9.33e-04	No	complex128
qc_circuit_n53_m20_s5_e22_pABC_...DCDAB	11.03	27.00	flops	1.00	32.62	436.79	33.34	8.50e-04	No	complex128
qc_circuit_patch_n53_m16_s10_e_...28_pABCD_...CDAB	10.63	27.00	flops	1.00	24.08	253.03	24.27	1.25e-03	No	complex128
qc_circuit_patch_n53_m16_s19_e_...28_pABCD_...CDAB_simplified	10.63	27.00	flops	1.00	23.17	246.13	23.42	1.18e-03	No	complex128

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Table 2: Runtimes of the different implementations on the benchmark instances. The flops are reported as \log_{10} , the size as \log_2 .

Name	Flops	Size	Path	Average Density	Dense (s)	Sparse (s)	Hybrid (s)	Density (s)	Switched	DType
qc_circuits-1	8.84	20.00	flops	1.00	0.16	2.84	0.15	8.29e-04	No	complex128
qc_circuits-14	11.03	27.00	flops	1.00	18.68	423.88	18.77	9.99e-04	No	complex64
qc_circuits-18	11.99	31.00	flops	1.00	190.66	4670.79	190.87	1.07e-03	No	complex64
qc_circuits-2	10.98	27.00	flops	1.00	18.85	408.10	19.10	1.61e-03	No	complex64
qc_circuits-35	9.69	25.00	flops	1.00	1.17	14.88	1.18	1.02e-03	No	complex128
qc_circuits-42	10.29	26.00	flops	1.00	4.01	63.69	4.81	7.12e-04	No	complex128
qc_circuits-7	10.29	26.00	flops	1.00	2.49	64.10	2.49	8.62e-04	No	complex64
qc_circuits-8	8.43	20.00	flops	1.00	0.14	1.43	0.10	7.56e-04	No	complex128
qc_maxcut_n18_r17_p100	10.50	18.00	flops	1.00	9.10	222.84	8.95	5.78e-02	No	complex128
qc_maxcut_n24_r20_p10	11.46	24.00	flops	1.00	226.95	1678.78	225.57	1.13e-02	No	complex128
qc_maxcut_n25_r4_p4	10.42	25.00	flops	1.00	10.56	95.25	10.49	2.57e-03	No	complex128
qc_maxcut_n27_r6_p5	11.43	27.00	flops	1.00	180.83	1730.15	181.20	2.66e-03	No	complex128
qc_maxcut_n28_r3_p3	9.29	23.00	flops	0.64	1.04	3.78	3.69	1.56e-03	Yes	complex128
qc_maxcut_n29_r4_p10	12.29	29.00	flops	0.99	1109.70	12467.45	1106.18	9.04e-03	No	complex128
qc_qft_27	9.13	27.00	flops	1.00	1.37	25.06	1.34	1.92e-03	No	complex128
qc_qft_28	9.43	28.00	flops	1.00	1.48	45.32	1.42	1.97e-03	No	complex64
qc_qft_30	10.03	30.00	flops	1.00	5.21	194.04	5.08	2.24e-03	No	complex64
qc_rand_google53_25_50	10.97	25.00	flops	1.00	30.29	491.44	31.16	1.53e-03	No	complex64
qc_rand_google53_26_15	10.54	26.00	flops	1.00	12.52	154.53	13.44	6.72e-04	No	complex128
qc_rand_google53_27_20	11.07	27.00	flops	1.00	20.03	490.17	21.18	4.30e-04	No	complex64
qc_rand_supremacy2d_1_12_400	10.11	25.00	flops	1.00	9.31	65.05	9.68	1.27e-03	No	complex128
qc_rand_supremacy2d_4_4_100	11.28	29.00	flops	0.97	107.12	1836.30	108.99	1.09e-03	No	complex64
qc_rand_supremacy2d_7_2_800	10.16	23.00	flops	1.00	5.33	104.70	4.32	6.45e-03	No	complex64
qc_variational_29	10.11	29.00	flops	0.00	5.85	4.50	4.57	4.74e-04	Yes	complex128
qc_variational_30	10.41	30.00	flops	0.00	3.61	4.67	5.23	2.23e-04	Yes	complex64
qc_variational_31	10.73	31.00	flops	0.00	14.59	9.11	9.45	2.61e-04	Yes	complex64
rnd_mixed_01	11.29	31.68	flops	1.00	56.87	1356.80	60.23	2.44e-04	No	float64
rnd_mixed_02	11.72	31.57	flops	1.00	91.44	2352.18	92.70	3.62e-04	No	float64
rnd_mixed_03	11.68	30.82	flops	1.00	68.34	1665.60	70.49	5.56e-04	No	float64
rnd_mixed_05	11.73	31.21	flops	1.00	36.39	1614.23	38.69	7.36e-04	No	float32
rnd_mixed_06	10.65	29.29	flops	1.00	6.41	195.38	6.60	1.71e-03	No	float32
rnd_mixed_07	11.63	31.18	flops	1.00	39.40	1527.21	42.11	2.33e-03	No	float32
rnd_mixed_08	10.27	25.69	flops	1.00	1.12	50.03	1.14	2.25e-03	No	float32
rnd_mixed_09	11.11	31.15	flops	1.00	6.71	373.56	7.06	1.90e-03	No	float32

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Name	Flops	Size	Path	Average Density	Dense (s)	Sparse (s)	Hybrid (s)	Density (s)	Switched	DType
rnd_mixed_10	10.68	27.01	flops	1.00	7.30	196.16	7.25	2.63e-03	No	float32
rnd_mixed_11	10.93	29.66	flops	1.00	15.79	478.69	16.19	1.80e-03	No	float32
rnd_oe_01	10.90	28.04	flops	1.00	2.48	177.13	2.49	4.54e-04	No	float32
rnd_oe_02	11.86	27.30	flops	1.00	0.97	1150.62	0.96	5.51e-04	No	float32
rnd_oe_03	11.84	31.03	flops	1.00	40.45	1795.40	40.93	9.14e-04	No	float64
rnd_oe_04	11.01	29.26	flops	1.00	26.35	508.69	26.49	5.60e-04	No	float64
str_ctg_lattice_01	12.31	30.51	flops	1.00	37.94	4066.06	38.51	1.49e-03	No	float32
str_ctg_lattice_02	11.17	27.51	flops	1.00	11.14	431.40	11.25	2.26e-03	No	float32
str_ctg_lattice_03	12.76	32.63	flops	1.00	157.10	12769.82	161.48	1.56e-03	No	float32
str_ctg_lattice_04	12.58	32.02	flops	1.00	312.65	12332.65	315.69	2.19e-03	No	float32
str_ctg_regular_01	11.63	31.15	flops	1.00	11.85	940.26	12.02	3.59e-04	No	float32
str_ctg_regular_02	11.68	31.85	flops	1.00	34.09	1465.70	34.97	2.81e-04	No	float32
str_ctg_regular_03	11.69	31.17	flops	1.00	26.09	1307.57	26.56	6.28e-04	No	float32
str_ctg_regular_04	11.37	30.34	flops	1.00	21.58	774.26	21.31	4.57e-04	No	float32
str_matrix_chain_multiplicatio_										
_n_100	8.48	17.26	flops	1.00	0.02	1.98	0.02	4.17e-03	No	float64
str_matrix_chain_multiplicatio_										
_n_1000	8.32	12.11	flops	1.00	0.05	2.88	0.06	2.80e-04	No	float64
str_mps_varying_inner_product_										
_200	8.31	15.48	flops	1.00	0.05	2.27	0.06	7.12e-03	No	float64
str_mps_varying_inner_product_										
_2000	8.66	13.45	flops	1.00	0.18	7.15	0.31	2.04e-02	No	float64
str_nw_ftps_open_28	9.05	28.00	flops	1.00	0.19	14.76	0.19	1.47e-04	No	float64
str_nw_ftps_open_30	9.65	30.00	flops	1.00	0.96	58.16	0.98	1.61e-04	No	float64
str_nw_ftps_open_32	10.24	32.00	flops	1.00	3.62	238.03	3.67	1.21e-04	No	float64
str_nw_mera_closed_120	10.66	25.02	flops	1.00	2.46	91.56	2.49	2.18e-03	No	float64
str_nw_mera_closed_247	12.39	31.98	flops	1.00	39.15	4824.67	39.15	5.14e-03	No	float64
str_nw_mera_open_26	10.49	25.36	flops	1.00	0.23	80.47	0.24	8.72e-04	No	float64
str_nw_peps_closed_325	12.56	32.41	flops	1.00	153.82	8540.10	160.78	1.74e-03	No	float64
str_nw_peps_closed_333	10.05	23.37	flops	1.00	0.37	27.53	0.34	1.62e-03	No	float64
str_nw_peps_open_30	11.98	31.32	flops	1.00	29.57	2153.93	29.47	2.85e-04	No	float64
wmc_2021_061	11.01	28.00	flops	0.00	30.62	0.64	0.99	4.94e-03	Yes	float64
wmc_2021_130	5.88	12.00	flops	0.86	0.08	0.07	0.11	0.00e+00	No	float64
wmc_2021_145	11.85	31.00	flops	0.00	134.45	1.02	1.23	7.02e-03	Yes	float64

Continued on next page

Table 2: Runtimes of the different implementations on the benchmark instances. The flops are reported as \log_{10} , the size as \log_2 .

Name	Flops	Size	Path	Average Density	Dense (s)	Sparse (s)	Hybrid (s)	Density (s)	Switched	DType
wmc_2021_183	9.88	28.00	flops	1.00	4.50	82.71	4.59	3.96e-04	No	float64
wmc_2021_187	10.93	31.00	flops	1.00	21.86	564.82	22.29	6.69e-04	No	float64
wmc_2022_004	10.33	29.00	flops	1.00	8.04	150.34	8.30	6.05e-04	No	float64
wmc_2022_038	10.14	28.00	flops	0.00	9.49	0.28	0.35	1.54e-03	Yes	float64
wmc_2022_051	11.22	30.00	flops	0.03	18.46	17.85	19.83	5.91e-03	Yes	float64
wmc_2022_060	10.38	26.00	flops	0.01	16.52	3.35	3.38	5.85e-03	Yes	float64
wmc_2022_082	11.15	31.00	flops	0.00	68.30	0.15	0.16	8.43e-04	Yes	float64
wmc_2023_035	6.96	12.00	flops	0.24	0.17	0.12	0.19	0.00e+00	No	float64
wmc_2023_036	10.93	27.00	flops	0.01	26.48	20.20	3.35	5.22e-03	Yes	float64
wmc_2023_141	10.38	24.00	flops	0.01	6.06	12.59	6.70	6.32e-02	Yes	float64
wmc_2023_152	6.46	15.00	flops	0.65	0.54	0.37	0.61	4.00e-03	No	float64

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