CS422A

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Submission Folder Structure

- task_1_5.cpp
    - Contains implementation of direction predictors from part A to E (static, bimodal, SAg, Gag, and gshare)

- task_6.cpp
    - Contains the implementation of the direction predictor in part F, i.e. the Hybrid of SAg and GAg

- task_7a.cpp
    - Contains the implementation of the direction predictor in part G, i.e. the Hybrid of SAg, GAg and gshare with the majority-vote meta predictor

- task_7b.cpp
    - Contains the implementation of the direction predictor in part G, i.e. the Hybrid of SAg, GAg and gshare with the tournament meta-predictor

- task_2a.cpp
    - Contains the implementation of the BTB for indirect branches with indexing using PC

- task_2b.cpp
    - Contains the implementation of the BTB for indirect branches with indexing using a hash of PC and global history

Part A: Directional Predictor for Conditional Branches

1. Static forward not-taken and backward taken

- Results

400.perlbench

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	104154769	64820611	62.23
Backward Conditional Branch Instructions	25939550	11370183	43.83
All branch instructions	191982171	111311051	57.97

401.bzip2

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	63177446	43599287	69.01
Backward Conditional Branch Instructions	66745639	25400415	38.0555
All branch instructions	152805528	88081491	57.6429

403.gcc

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	114543851	78113778	68.1955
Backward Conditional Branch Instructions	31259198	14345546	45.8922
All branch	238818755	135364822	56.681

instructions			

429.mcf

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	89125369	57299758	64.2912
Backward Conditional Branch Instructions	89117609	63995436	71.8101
All branch instructions	211670126	138086547	65.2367

450.soplex

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	35344286	28063754	79.4011
Backward Conditional Branch Instructions	66985245	55667397	83.104
All branch instructions	123117442	98062132	79.6493

456.hmmer

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	120193666	28087505	23.3685
Backward Conditional Branch Instructions	24167758	24005877	99.3302
All branch instructions	144858448	52386530	36.1639

471.omnetpp

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	98390013	65208246	66.2753
Backward Conditional Branch Instructions	18945250	12089984	63.8154
All branch instructions	189558894	116517033	61.4675

483.xalancbmk

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	141970232	130665271	92.0371
Backward Conditional Branch Instructions	46166086	44024585	95.3613
All branch instructions	237445733	200204879	84.3161

2. Bimodal

- Results

400.perlbench

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	104154769	42265423	40.5794
Backward Conditional Branch Instructions	25939550	11784796	45.4318
All branch instructions	191982171	114582909	59.6841

401.bzip2

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	63177446	21220041	33.588
Backward Conditional Branch Instructions	66745639	26190623	39.2395
All branch instructions	152805528	70292886	46.0015

403.gcc

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	114543851	41062896	35.8491
Backward Conditional Branch Instructions	31259198	14542316	46.5217
All branch instructions	238818755	148620775	62.2316

429.mcf

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	89125369	33816201	37.9423
Backward Conditional Branch Instructions	89117609	64768847	72.6779
All branch instructions	211670126	132012163	62.3669

450.soplex

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	35344286	7404823	20.9506
Backward Conditional Branch Instructions	66985245	56031681	83.6478
All branch instructions	123117442	84223687	68.4092

456.hmmer

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	120193666	92474352	76.9378
Backward Conditional Branch Instructions	24167758	24006343	99.3321
All branch instructions	144858448	116977164	80.7527

471.omnetpp

	Total	Correct Predictions	Prediction Accuracy

			(%)
Forward Conditional Branch Instructions	98390013	36949439	37.5541
Backward Conditional Branch Instructions	18945250	12116168	63.9536
All branch instructions	189558894	120858879	63.758

483.xalancbmk

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	141970232	14140661	9.9603
Backward Conditional Branch Instructions	46166086	44238232	95.8241
All branch instructions	237445733	106890225	45.0167

3. SAg

- Results

400.perlbench

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	104154769	42227576	40.5431
Backward Conditional Branch Instructions	25939550	11784810	45.4318
All branch instructions	191982171	114548161	59.666

401.bzip2

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	63177446	21220041	33.588
Backward Conditional Branch Instructions	66745639	26190623	39.2395
All branch instructions	152805528	70292886	46.0015

403.gcc

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	114543851	41062896	35.8491
Backward Conditional Branch Instructions	31259198	14542316	46.5217
All branch instructions	238818755	148620775	62.2316

429.mcf

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	89125369	33816201	37.9423
Backward Conditional Branch Instructions	89117609	64768847	72.6779
All branch instructions	211670126	132012163	62.3669

450.soplex

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	35344286	7404764	20.9504
Backward Conditional Branch Instructions	66985245	56031698	83.6478
All branch instructions	123117442	84223792	68.4093

456.hmmer

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	120193666	92474352	76.9378
Backward Conditional Branch Instructions	24167758	24006343	99.3321
All branch instructions	144858448	116977164	80.7527

471.omnetpp

	Total	Correct Predictions	Prediction Accuracy

			(%)
Forward Conditional Branch Instructions	98390013	36949392	37.554
Backward Conditional Branch Instructions	18945250	12116171	63.9536
All branch instructions	189558894	120859082	63.7581

483.xalancbmk

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	141970232	14141271	9.96073
Backward Conditional Branch Instructions	46166086	44238379	95.8244
All branch instructions	237445733	106891309	45.0172

4. GAg

- Results

400.perlbench

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	104154769	44804516	43.0172
Backward Conditional Branch Instructions	25939550	12800563	49.3477
All branch instructions	191982171	116846067	60.863

401.bzip2

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	63177446	22153938	35.0662
Backward Conditional Branch Instructions	66745639	28869148	43.2525
All branch instructions	152805528	73345737	47.9994

403.gcc

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	114543851	45544584	39.7617
Backward Conditional Branch Instructions	31259198	17520632	56.0495
All branch instructions	238818755	151475573	63.427

429.mcf

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	89125369	36712631	41.1921
Backward Conditional Branch Instructions	89117609	65633773	73.6485
All branch instructions	211670126	135623115	64.0729

450.soplex

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	35344286	28063754	79.4011
Backward Conditional Branch Instructions	66985245	55667397	83.104
All branch instructions	123117442	98062132	79.6493

456.hmmer

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	120193666	94203730	78.3766
Backward Conditional Branch Instructions	24167758	23863848	98.7425
All branch instructions	144858448	118557753	81.8439

471.omnetpp

	Total	Correct Predictions	Prediction Accuracy (%)

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	98390013	40799142	41.4668
Backward Conditional Branch Instructions	18945250	12531435	66.1455
All branch instructions	189558894	123034963	64.9059

483.xalancbmk

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	141970232	14934671	10.5196
Backward Conditional Branch Instructions	46166086	44011379	95.3327
All branch instructions	237445733	106723186	44.9463

5. gshare

- Results

400.perlbench

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	104154769	44174381	40.5794
Backward Conditional Branch Instructions	25939550	12526987	48.293
All branch instructions	191982171	116975073	60.9302

401.bzip2

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	63177446	21987567	33.588
Backward Conditional Branch Instructions	66745639	27202225	40.7551
All branch instructions	152805528	71927021	47.071

403.gcc

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	114543851	41982693	35.8491
Backward Conditional Branch Instructions	31259198	15878259	50.7955
All branch instructions	238818755	149488101	62.5948

429.mcf

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	89125369	36312130	37.9423
Backward Conditional Branch Instructions	89117609	65388735	73.3735
All branch instructions	211670126	135002784	63.7798

450.soplex

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	35344286	7532880	20.9506
Backward Conditional Branch Instructions	66985245	56463395	84.2923
All branch instructions	123117442	98062132	68.8546

456.hmmer

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	120193666	94654962	76.9378
Backward Conditional Branch Instructions	24167758	23858053	98.7185
All branch instructions	144858448	119000589	82.1496

471.omnetpp

	Total	Correct Predictions	Prediction Accuracy (%)

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	98390013	39759750	37.5541
Backward Conditional Branch Instructions	18945250	12512011	66.043
All branch instructions	189558894	123158036	64.9709

483.xalancbmk

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	141970232	16010268	9.9603
Backward Conditional Branch Instructions	46166086	44110381	95.5472
All branch instructions	237445733	107784113	45.3932

6. Hybrid of SAg and GAg

- Results

400.perlbench

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	104154769	38551682	37.0139
Backward Conditional Branch Instructions	25939550	10970989	42.2946
All branch instructions	191982171	97089831	50.5724

401.bzip2

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	63177446	15884983	25.1434
Backward Conditional Branch Instructions	66745639	18835648	28.22
All branch instructions	152805528	49888496	32.6484

403.gcc

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	114543851	9073107	31.2822
Backward Conditional Branch Instructions	31259198	98212426	94.1313
All branch instructions	238818755	120193236	81.0371

429.mcf

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	89125369	24329617	27.2982
Backward Conditional Branch Instructions	89117609	36819228	41.3153
All branch instructions	211670126	77629438	36.6747

450.soplex

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	35344286	4527867	13.3337
Backward Conditional Branch Instructions	66985245	29599813	42.7847
All branch instructions	123117442	46176180	37.6918

456.hmmer

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	120193666	82218873	68.4053
Backward Conditional Branch Instructions	24167758	20091695	83.1343
All branch instructions	144858448	102746077	70.9286

471.omnetpp

	Total	Correct Predictions	Prediction Accuracy (%)

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	98390013	33994657	34.5509
Backward Conditional Branch Instructions	18945250	11461772	60.4994
All branch instructions	189558894	109898140	57.9757

483.xalancbmk

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	141970232	14605517	10.2877
Backward Conditional Branch Instructions	46166086	38462271	83.3128
All branch instructions	237445733	91019315	38.3327

7a. Hybrid of SAg, GAg and gshare (majority vote meta-predictor)

- Results

400.perlbench

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	104154769	41969202	40.3117
Backward Conditional Branch Instructions	25939550	11898966	45.8267
All branch instructions	191982171	114933613	59.8859

401.bzip2

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	63177446	21150907	33.4786
Backward Conditional Branch Instructions	66745639	26143611	39.169
All branch instructions	152805528	70114839	45.885

403.gcc

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	114543851	78113778	68.1955
Backward Conditional Branch Instructions	31259198	14345546	45.8922
All branch instructions	238818755	135364822	56.681

429.mcf

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	89125369	34048908	38.2034
Backward Conditional Branch Instructions	89117609	62675408	70.3289
All branch instructions	211670126	130051138	61.4405

450.soplex

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	35344286	6931409	20.4117
Backward Conditional Branch Instructions	66985245	58596692	84.6979
All branch instructions	123117442	84892615	69.2945

456.hmmer

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	120193666	93468351	77.7648
Backward Conditional Branch Instructions	24167758	23997391	99.2951
All branch instructions	144858448	117961215	81.4321

471.omnetpp

	Total	Correct Predictions	Prediction Accuracy (%)

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	98390013	35859628	36.4464
Backward Conditional Branch Instructions	18945250	12224043	64.523
All branch instructions	189558894	119766545	63.1817

483.xalancbmk

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	141970232	14062049	9.90493
Backward Conditional Branch Instructions	46166086	44236609	95.8206
All branch instructions	237445733	106839460	44.9953

7b. Hybrid of SAg, GAg and gshare (tournament meta-predictor)

- Results

   400.perlbench

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	104154769	33791014	32.4431
Backward Conditional Branch Instructions	25939550	9880229	38.0894
All branch instructions	191982171	92628027	48.2482

401.bzip2

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	63177446	16813546	26.6132
Backward Conditional Branch Instructions	66745639	18570600	27.8229
All branch instructions	152805528	51288940	33.5648

403.gcc

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	114543851	9323436	32.0164
Backward Conditional Branch Instructions	31259198	98969727	94.9007

	Total	Correct Predictions	Prediction Accuracy (%)
All branch instructions	238818755	121103896	81.5826

429.mcf

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	89125369	27411159	30.7557
Backward Conditional Branch Instructions	89117609	38254620	42.926
All branch instructions	211670126	89557309	42.3098

450.soplex

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	35344286	3894613	11.4689
Backward Conditional Branch Instructions	31266403	31266403	45.1936
All branch instructions	123117442	47448802	38.7306

456.hmmer

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	120193666	84669007	70.4438
Backward Conditional Branch Instructions	24167758	20386826	84.3555
All branch	144858448	105514555	72.8398

instructions			

471.omnetpp

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	98390013	34490366	35.0547
Backward Conditional Branch Instructions	18945250	10781238	56.9073
All branch instructions	189558894	110796025	58.4494

483.xalancbmk

	Total	Correct Predictions	Prediction Accuracy (%)
Forward Conditional Branch Instructions	89998672	5896303	6.55154
Backward Conditional Branch Instructions	81048075	57888668	71.4251
All branch instructions	226046586	115828417	51.2409

Observations:

- In general, the backward conditional branches result in a higher prediction accuracy as compared to the forward conditional branches. This might be due to the usage of loops where the pattern is of type: 1111….0 and hence, the direction is fixed for the duration of execution of the loop.

- This difference is more visible for the bimodal predictor since these predictors usually fail for branches having alternate patterns and work properly for branches having loop-like patterns

- For the static predictor, the behavior is a bit unpredictable and depends on the application. For some applications (for example, applications prefixed 456 and 471), the prediction accuracy is poor when compared to the dynamic predictors. However, for others (for example, the applications prefixed 450 and 483), the prediction accuracy overtakes the accuracies from the dynamic predictors. This might be due to the specificity of the application where some applications follow the forward not-taken and backward taken execution which matches our direction prediction policy. Hence, this fails for other applications which have a different execution flow.

- The hybrid of SAg and GAg doesn't have any significant improvement in results over the individual SAg and GAg predictors. However, when we use SAg, GAg, and GAg together using the majority-vote and tournament predictors, the prediction accuracy improves for most of the applications significantly, even reaching 99% for the backward conditional branches for some of the applications.

- Prediction of forward conditional branches remains a major bottleneck since it brings down the overall prediction accuracy. Specifically, for the application prefixed 483, the forward conditional branch prediction accuracy is in the range of 9-11%, whereas the same range for backward conditional branches is around 95-99%.

Part B: Target Predictors for Indirect Control Flow Instructions

1. BTB Indexed with PC

- Results

400.perlbench

Total No. of BTB accesses	Number of BTB Misses	BTB Miss Rate (%)	BTB Prediction Accuracy (%)
28134252	2234711	7.94303	58.7743

401.bzip2

Total No. of BTB accesses	Number of BTB Misses	BTB Miss Rate (%)	BTB Prediction Accuracy (%)
791919	63	0.00795536	51.7062

403.gcc

Total No. of BTB accesses	Number of BTB Misses	BTB Miss Rate (%)	BTB Prediction Accuracy (%)
34739347	1661274	4.78211	26.2528

429.mcf

Total No. of BTB accesses	Number of BTB Misses	BTB Miss Rate (%)	BTB Prediction Accuracy (%)
12556327	9	7.1677×10^{-5}	99.3865

450.soplex

Total No. of BTB accesses	Number of BTB Misses	BTB Miss Rate (%)	BTB Prediction Accuracy (%)
6315969	332	0.00525652	99.9918

456.hmmer

Total No. of BTB accesses	Number of BTB Misses	BTB Miss Rate (%)	BTB Prediction Accuracy (%)
201570	2628	1.30377	92.6884

471.omnetpp

Total No. of BTB accesses	Number of BTB Misses	BTB Miss Rate (%)	BTB Prediction Accuracy (%)
30294701	6334154	20.9085	53.9806

483.xalancbmk

Total No. of BTB accesses	Number of BTB Misses	BTB Miss Rate (%)	BTB Prediction Accuracy (%)
31362362	10230472	32.6202	50.5857

2. BTB Indexed with a hash of PC and global path history

- Results

400.perlbench

Total No. of BTB accesses	Number of BTB Misses	BTB Miss Rate (%)	BTB Prediction Accuracy (%)
28134252	4949389	17.592	67.642

401.bzip2

Total No. of BTB accesses	Number of BTB Misses	BTB Miss Rate (%)	BTB Prediction Accuracy (%)
791919	210	0.0265179	49.5053

403.gcc

Total No. of BTB accesses	Number of BTB Misses	BTB Miss Rate (%)	BTB Prediction Accuracy (%)
7075497	833525	11.7804	72.4498

429.mcf

Total No. of BTB accesses	Number of BTB Misses	BTB Miss Rate (%)	BTB Prediction Accuracy (%)
12556327	78549	0.625573	98.89

450.soplex

Total No. of BTB accesses	Number of BTB Misses	BTB Miss Rate (%)	BTB Prediction Accuracy (%)
6333800	3222	0.0508699	99.9288

456.hmmer

Total No. of BTB	Number of BTB	BTB Miss Rate (%)	BTB Prediction

accesses	Misses		Accuracy (%)
201570	7569	3.75502	94.0284

471.omnetpp

Total No. of BTB accesses	Number of BTB Misses	BTB Miss Rate (%)	BTB Prediction Accuracy (%)
30294701	10611631	35.028	56.1884

483.xalancbmk

Total No. of BTB accesses	Number of BTB Misses	BTB Miss Rate (%)	BTB Prediction Accuracy (%)
31362362	13489937	43.0131	48.9359

Observations:

- When we index the BTB with a hash of PC and global history, we have a relatively higher BTB miss rate as compared to the case when we are indexing simply using the PC. One possible reason might be that since we are using XOR of PC and global history, it introduces more entropy due to the number of possibilities of the global history and hence, the index obtained after XOR might not be present in the BTB. For example, if we have an index for PC p, it will result in a hit if indexed simply using the PC, but, might lead to different index when XOR-ed with the global history, resulting into a BTB miss

- In general, the prediction accuracy is either almost comparable or slightly higher in the second case, i.e. when indexed using hash of PC and global history. A possible reason might be that global history enhances the possibilities of capturing cross-relation between branches since after XOR-ing, multiple indices might collide even though their PC's are different.