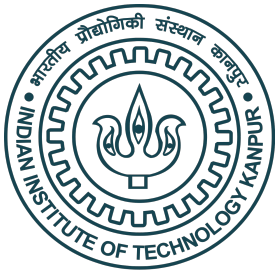


# CS422 Computer Architecture

Assignment 2

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# 1 PART A: DIRECTION PREDICTORS FOR CONDITIONAL BRANCHES

## 1.1 perlbench

| Direction Predictor | Misprediction Fraction | | |
|---|---|---|---|
| | Forward | Backward | Total |
| FNBT | 37.5699 | 56.1758 | 41.3026 |
| BIM | 9.96035 | 7.88675 | 9.54435 |
| SAG | 3.749 | 3.32712 | 3.66437 |
| GAG | 12.427 | 9.1189 | 11.7633 |
| GSHARE | 10.3103 | 9.72903 | 10.1937 |
| SAG_GAG_HYBRID | 3.18185 | 2.76472 | 3.09817 |
| MAJ | 5.08555 | 4.77508 | 5.02326 |
| TOURNAMENT_MP | 2.90099 | 2.38271 | 2.79701 |

## 1.2 bzip2

| Direction Predictor | Misprediction Fraction | | |
|---|---|---|---|
| | Forward | Backward | Total |
| FNBT | 30.9892 | 61.9445 | 46.892 |
| BIM | 10.7903 | 9.24878 | 9.99839 |
| SAG | 11.4242 | 8.92617 | 10.1409 |
| GAG | 14.7518 | 10.389 | 12.5105 |
| GSHARE | 12.1152 | 10.5467 | 11.3094 |
| SAG_GAG_HYBRID | 10.8428 | 8.38938 | 9.58242 |
| MAJ | 10.201 | 8.45028 | 9.30162 |
| TOURNAMENT_MP | 10.0766 | 8.21679 | 9.12114 |

## 1.3 gcc

| Direction Predictor | Misprediction Fraction | | |
|---|---|---|---|
| | Forward | Backward | Total |
| FNBT | 31.9047 | 4.55539 | 10.453 |
| BIM | 12.6277 | 1.9919 | 4.28541 |
| SAG | 7.60393 | 1.31804 | 2.67353 |
| GAG | 11.9516 | 1.87172 | 4.04535 |
| GSHARE | 11.8776 | 1.70902 | 3.90177 |
| SAG_GAG_HYBRID | 5.74565 | 1.01943 | 2.03859 |
| MAJ | 7.02809 | 1.23017 | 2.48044 |
| TOURNAMENT_MP | 5.11418 | 0.937427 | 1.83811 |

## 1.4 mcf

| Direction Predictor | Misprediction Fraction | | |
|---|---|---|---|
| | Forward | Backward | Total |
| FNBT | 35.7088 | 28.19 | 31.9496 |
| BIM | 16.2883 | 19.7519 | 18.02 |
| SAG | 15.0981 | 11.002 | 13.0502 |
| GAG | 9.22753 | 9.34422 | 9.28587 |
| GSHARE | 10.3481 | 10.0909 | 10.2195 |
| SAG_GAG_HYBRID | 8.94988 | 8.60069 | 8.77529 |
| MAJ | 8.76091 | 8.60215 | 8.68154 |
| TOURNAMENT_MP | 8.5454 | 8.26083 | 8.40312 |

## 1.5 cactusADM

| Direction Predictor | Misprediction Fraction | | |
|---|---|---|---|
| | Forward | Backward | Total |
| FNBT | 0.459441 | 24.9282 | 12.6912 |
| BIM | 0.14132 | 24.8116 | 12.4738 |
| SAG | 0.0934394 | 0.482263 | 0.28781 |
| GAG | 0.193938 | 0.520965 | 0.357417 |
| GSHARE | 0.171832 | 24.3423 | 12.2545 |
| SAG_GAG_HYBRID | 0.0853122 | 0.469301 | 0.277266 |
| MAJ | 0.109415 | 0.497131 | 0.303232 |
| TOURNAMENT_MP | 0.0808538 | 0.465258 | 0.273015 |

## 1.6 leslie3D

| Direction Predictor | Misprediction Fraction | | |
|---|---|---|---|
| | Forward | Backward | Total |
| FNBT | 3.82682 | 0.851498 | 0.884765 |
| BIM | 3.39932 | 0.851231 | 0.879721 |
| SAG | 0.506928 | 0.832854 | 0.82921 |
| GAG | 18.9296 | 0.941208 | 1.14234 |
| GSHARE | 6.60664 | 0.852528 | 0.916865 |
| SAG_GAG_HYBRID | 0.453975 | 0.828935 | 0.824743 |
| MAJ | 4.97715 | 0.82977 | 0.876142 |
| TOURNAMENT_MP | 0.453975 | 0.82895 | 0.824757 |

## 1.7 soplex

| Direction Predictor | Misprediction Fraction | | |
|---|---|---|---|
| | Forward | Backward | Total |
| **FNBT** | 19.9305 | 15.5134 | 16.9548 |
| **BIM** | 0.912735 | 6.72012 | 4.82514 |
| **SAG** | 0.658447 | 5.64174 | 4.01566 |
| **GAG** | 0.850962 | 5.22952 | 3.80077 |
| **GSHARE** | 1.30071 | 5.26466 | 3.9712 |
| **SAG_GAG_HYBRID** | 0.651763 | 4.99313 | 3.57652 |
| **MAJ** | 0.821522 | 5.21704 | 3.78276 |
| **TOURNAMENT_MP** | 0.650605 | 4.99224 | 3.57554 |

## 1.8 hmmer

| Direction Predictor | Misprediction Fraction | | |
|---|---|---|---|
| | Forward | Backward | Total |
| **FNBT** | 76.6315 | 0.669822 | 63.9146 |
| **BIM** | 10.2041 | 0.353847 | 8.55503 |
| **SAG** | 10.8637 | 0.480342 | 9.12541 |
| **GAG** | 13.6193 | 2.56574 | 11.7688 |
| **GSHARE** | 11.7958 | 2.7062 | 10.2741 |
| **SAG_GAG_HYBRID** | 10.2256 | 0.77008 | 8.64262 |
| **MAJ** | 10.3101 | 0.62554 | 8.68882 |
| **TOURNAMENT_MP** | 9.94742 | 0.416836 | 8.35189 |

## 1.9 libquantum

| Direction Predictor | Misprediction Fraction | | |
|---|---|---|---|
| | Forward | Backward | Total |
| **FNBT** | 86.2244 | 0.985879 | 55.6545 |
| **BIM** | 11.7074 | 0.492961 | 7.68548 |
| **SAG** | 1.24813 | 0.493088 | 0.977343 |
| **GAG** | 9.30406 | 0.493255 | 6.14416 |
| **GSHARE** | 9.12447 | 0.49331 | 6.029 |
| **SAG_GAG_HYBRID** | 1.18141 | 0.493041 | 0.934531 |
| **MAJ** | 8.06685 | 0.4932 | 5.35064 |
| **TOURNAMENT_MP** | 1.1814 | 0.493041 | 0.934528 |

## 1.10 lbm

| Direction Predictor | Misprediction Fraction | | |
|---|---|---|---|
| | Forward | Backward | Total |
| **FNBT** | 47.2961 | 90.5521 | 62.0235 |
| **BIM** | 0.0376736 | 3.32815 | 1.15798 |
| **SAG** | 0.0154314 | 1.31342 | 0.457357 |
| **GAG** | 0.0210357 | 1.30018 | 0.456548 |
| **GSHARE** | 0.202009 | 1.30037 | 0.57597 |
| **SAG_GAG_HYBRID** | 0.0153536 | 1.2951 | 0.451068 |
| **MAJ** | 0.0198876 | 1.29917 | 0.455444 |
| **TOURNAMENT_MP** | 0.015373 | 1.29506 | 0.451068 |

## 1.11 omnetpp

| Direction Predictor | Misprediction Fraction | | |
|---|---|---|---|
| | Forward | Backward | Total |
| **FNBT** | 33.7247 | 36.1846 | 34.1219 |
| **BIM** | 9.72772 | 13.8898 | 10.3997 |
| **SAG** | 4.36209 | 8.3315 | 5.003 |
| **GAG** | 11.8266 | 14.3424 | 12.2328 |
| **GSHARE** | 10.3791 | 13.2551 | 10.8435 |
| **SAG_GAG_HYBRID** | 3.584 | 6.89711 | 4.11894 |
| **MAJ** | 4.76364 | 9.22605 | 5.48415 |
| **TOURNAMENT_MP** | 3.3828 | 6.58434 | 3.89973 |

## 1.12 sphinx3

| Direction Predictor | Misprediction Fraction | | |
|---|---|---|---|
| | Forward | Backward | Total |
| **FNBT** | 59.551 | 7.35363 | 27.8501 |
| **BIM** | 6.93516 | 4.88766 | 5.69166 |
| **SAG** | 6.81008 | 4.52059 | 5.41961 |
| **GAG** | 6.73407 | 5.16692 | 5.78229 |
| **GSHARE** | 7.56273 | 5.25844 | 6.16327 |
| **SAG_GAG_HYBRID** | 5.3523 | 4.37221 | 4.75706 |
| **MAJ** | 5.46445 | 4.8121 | 5.06826 |
| **TOURNAMENT_MP** | 5.26672 | 4.36976 | 4.72197 |

### 1.13 xalancbmk

| Direction Predictor | Misprediction Fraction | | |
|---|---|---|---|
| | Forward | Backward | Total |
| **FNBT** | 9.80271 | 5.33882 | 8.5914 |
| **BIM** | 4.66085 | 2.25203 | 4.0072 |
| **SAG** | 2.41469 | 1.24981 | 2.09859 |
| **GAG** | 5.8463 | 3.3471 | 5.16812 |
| **GSHARE** | 4.99449 | 3.20164 | 4.50798 |
| **SAG_GAG_HYBRID** | 1.76962 | 1.0967 | 1.58702 |
| **MAJ** | 2.68197 | 1.78191 | 2.43773 |
| **TOURNAMENT_MP** | 1.63322 | 0.965019 | 1.4519 |

## 2 OBSERVATIONS

- **FNBT** gives more than 90% accurate predictions for benchmark applications like xalancbmk, leslie3D, gcc etc. This shows that these programs are **loop-intensive**.
- In other cases, **FNBT** performs very poorly compared to other direction predictors. This is because in a program rich in conditional if-else type branches which shows multiple varying patterns over the timeline of the program, a static predictor like FNBT will give worse performance than dynamic predictors which learns the pattern during the execution of the program.
- All the other dynamic direction predictors gives approximately more than 90% accurate predictions.
- Performance of **GAg** and **SAg** on various benchmarks differs. In programs like perlbench, bzip2, gcc, leslie3D etc, SAg performs better than GAg showing greater local correlation over global correlation. In programs like mcf, soplex etc, GAg performs better than SAg showing greater global correlation. Overall, SAg perfoms better than GAg in most cases.
- Misprediction rate of **gshare** lies in between SAg and GAg for most programs. This is because gshare is indexed using **GHR XOR PC**, which contains both local(PC) and global components (GHR). Hence gshare to some extent is able to capture both local and global correlation. The Misprediction rate is much closer to the GAg showing dominance of global component over local component.
- **Hybrid Predictors** performs much better than individual GAg, SAg, and gshare. This is because they adaptively combine local and global predictions. Hence branches with local correlation will get trained to use prediction from SAg whereas branches with global correlation will get trained to use prediction from GAg or gshare. Tournament meta predictor works at par with GAg_SAg_Hybrid and much better than majority voter.

# 3 PART B: TARGET PREDICTORS FOR INDIRECT CONTROL FLOW INSTRUCTIONS

| BenchMark Applications | Indexing By PC | | Indexing By PC XOR GHR | |
|---|---|---|---|---|
| | Misprediction Rate | BTB Miss Rate | Misprediction Rate | BTB Miss Rate |
| perlbench | 35.3423 | 0.0114141 | 10.418 | 1.55463 |
| bzip2 | 48.2937 | 0.00745013 | 47.5235 | 0.0270225 |
| gcc | 35.5979 | 0.00674459 | 12.0902 | 0.796392 |
| mcf | 0.613493 | 0.0000716 | 0.409914 | 0.000836234 |
| **cactusADM** | **0.376885** | **0.0218048** | **0.252823** | **0.0473691** |
| **leslie3D** | **39.6728** | **11.5542** | **40.8998** | **19.0184** |
| soplex | 0.00535151 | 0.00148829 | 0.0104655 | 0.00539901 |
| hmmer | 6.38537 | 0.056556 | 2.64077 | 0.42169 |
| **libquantum** | **0.0123952** | **0.00161677** | **0.0138324** | **0.00449103** |
| **lbm** | **38.5714** | **16.1905** | **41.9048** | **35.2381** |
| omnetpp | 29.361 | 0.0188284 | 11.6377 | 0.878609 |
| **sphinx3** | **54.5317** | **0.00472665** | **12.6454** | **0.146099** |
| xalancbmk | 28.6954 | 2.46549 | 29.1813 | 16.1178 |

# 4 OBSERVATIONS

- **Misprediction Rate** decreases when using indexing by **PC XOR GHR** over using indexing by **PC**. This is because the indirect branches have a path correlation. Indexing by just **PC** just not encode path information at all contrary to **PC XOR GHR**. GHR encodes the global history of conditional branches, and hence in certain way the information about the path taken to reach the indirect branch instruction.

- **BTB Miss Rate** increases when using indexing by **PC XOR GHR** over using indexing by **PC**. This is because, in both cases, the BTB size(sets and ways) remains the same. In the first case, there are multiple entries for a single indirect branch instruction in the BTB depending on the path taken contrary to the second case, where there is a single entry per indirect instruction in the BTB. This, in turn, increases the number of conflicts and hence replacements in the BTB leading to a larger miss rate.

- Less BTB Miss Rate in some benchmark programs(mcf, soplex, libquantum) shows the **localization** of the program in certain areas for most of the duration and thus BTB is able to store all the targets for indirect instruction without replacements.

- In some benchmark applications(leslie3D, soplex, lbm, xalancbmk), BTB performs better when indexed by using **PC** over **PC XOR GHR**. This is because as seen from the data, BTB Miss Rate significantly increases in **PC XOR GHR** for these programs meaning that BTB is not able to hold all valid indirect targets(for different paths) and thus leading to higher mispredictions and BTB misses. This can be improved by increasing the size of BTB.