Improved Basic Block Reordering[1]

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Introduction

PGO: Profile-Guided Binary Optimization

- Function and **Basic Block Reordering**
- Identical Code Folding
- Function Inlining
- Unreachable Code Elimination
- Register Allocation
- ……

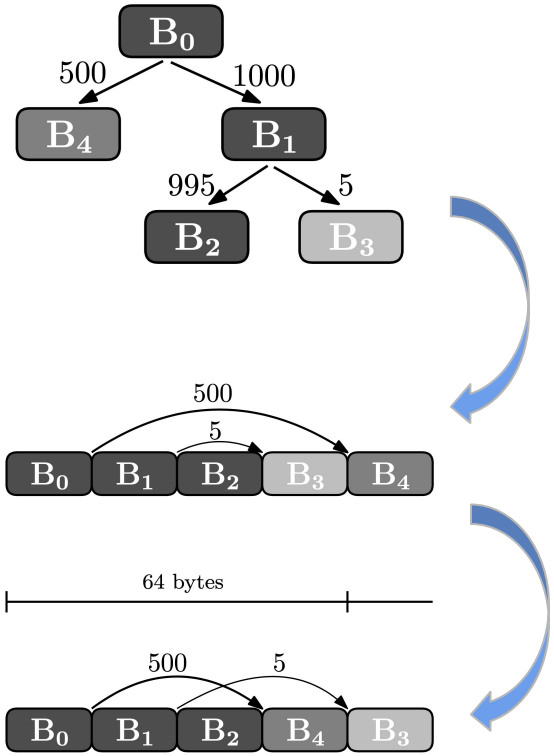
Introduction

Current techniques for basic block reordering:

- increasing the average number of instructions executed per cache line
- reducing the number of mispredicted branches
- minimizing cache line conflicts

This paper:

Design and implement an algorithm ***reordering*** basic blocks layouts in memory that ***directly*** optimizes the performance of an application.



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Approach

(1) Learn a ***proxy metric*** that describes the relationship between the performance of a binary and the ordering of its basic blocks.
   (a) ***identifying a set of features*** representing how basic block ordering can influence performance,
   (b) ***collecting training data*** by running extensive experiments and measuring the performance, and
   (c) ***using machine learning*** to select the best combination of the features for a score that best predicts CPU performance.

(2) Suggest an ***efficient algorithm*** that, given a control flow graph for a procedure, builds an improved ordering of the basic blocks optimizing the learned metric.

Related Work

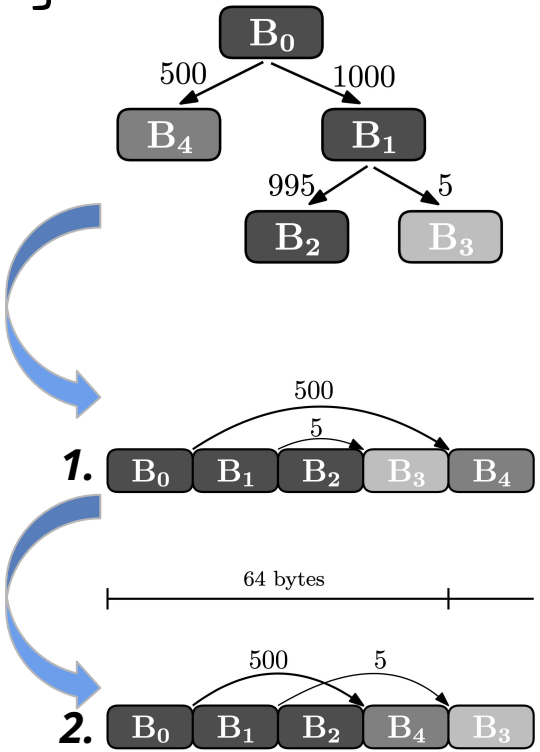
Pettis and Hansen[2]:

- Basis for the majority of modern code reordering techniques.
- An approach greedily merges chains of functions and is designed to primarily reduce ITLB misses.

Most of the existing works focus on *field reordering* and *structure splitting* based on the field hotness and data affinities.

Optimization Model - Basic Block Reordering

- Position blocks so that the **hottest** successor of a block will most likely be a **fall-through** branch, that is, located right next to the predecessor in memory layout. (**B0-B1-B2**)
- Reduces the number of **taken branches** and the working set **size of the I-cache**, while relieving pressure from the branch predictor unit. (**Order 1. to 2.**)



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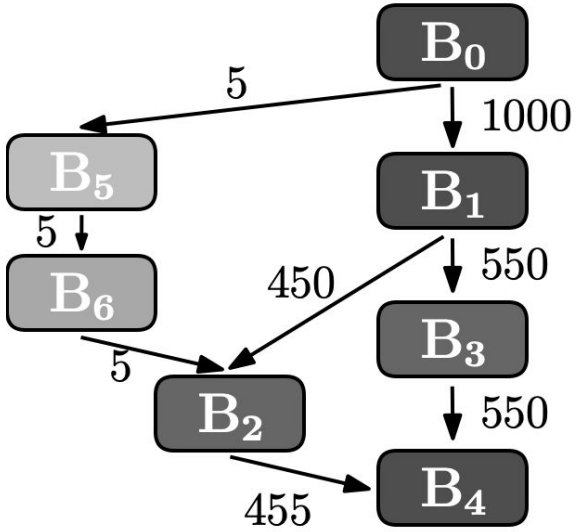
Optimization Model - Data Collection

- Extract a weighted directed **control flow graph** for every function in the profiled binary.
- **Vertices** (basic blocks) and **Edges** (branches) of the graph are extracted via the BOLT infrastructure, which is based on LLVM.
- **Weights** between the basic blocks correspond to the total number of times the jumps appear in collected Last Branch Records (LBR), a list of the last 16 taken branches, in Intel X86 processor.



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Optimization Model - TSP

Reordering Problem Formulation: **TRAVELING SALESMAN PROBLEM** (TSP)

Definition: Given a directed control flow graph comprising of basic blocks and frequencies of jumps between the blocks, find an ordering of the blocks such that the number of fall-through jumps is maximized.

TSP score: $$\text{TSP} = \sum_{(s,t)} w(s,t) \times \begin{cases} 1 & \text{if } \text{len}(s,t) = 0, \\ 0 & \text{if } \text{len}(s,t) > 0, \end{cases}$$

Where ***w(s,t)*** is the frequency and **len(*s, t*)** is the jump length from branch s to t.

*jump length: the distance (in bytes) between the end of the source block to the beginning of the target block

Optimization Model - More Characteristics

The performance might also depend on other characteristics of a branch, which are **NOT** included in TSP.

- The length of a jump impacts the performance of instruction caches.
- The direction of a branch plays a role for branch
- The branches can be classified into *unconditional* (if the out-degree is one) and *conditional* (if the out-degree is two)

We need a new score to include these characteristics!

ExtTSP

As for scoring the ordering, we also need to consider some characteristics of branch

$$\text{ExtTSP} = \sum_{(s,t)} w(s,t) \times K_{s,t} \times h_{s,t}\big(\text{len}(s,t)\big)$$

1. $w(s,t)$: the frequency of branch s ➡ t
2. $0 \le K_{s,t} \le 1$: the weight coefficient modeling the relative importance of the branch optimization
   a. Six categories
      i. Conditional and Unconditional of fall-through, forward, and backward
3. $h_{s,t}$: a function accounts for the importance of branch length
   a. 1 for zero-length jumps
   b. 0 for jumps exceeding a prescribed length
   c. Monotonically decreased between these two values

$$(1 - (\frac{\text{len}(jump)}{M})^{\alpha})$$

Learning Parameters

The parameters for ExtTSP cannot be decided manually

- Run experiments on:
  - Clang and HipHop Virtual Machine (HHVM)
- Each experiment consists of:
  - Constructing A distinct ordering of BB
  - Running a binaring
  - Measuring performance metrics vis the Linux perf tool
- This paper evaluated 50 distinct block orderings and conducted 250 exp. (5 different algorithms).
- Trying to find the parameters that have the highest correlation with the performance.

Learning Parameters

$$\text{ExtTSP} = \sum_{(s,t)} w(s,t) \times \begin{cases} 1 & \text{if } \text{len}(s,t) = 0, \\ 0.1 \cdot \left(1 - \frac{\text{len}(s,t)}{1024}\right) & \text{if } 0 < \text{len}(s,t) \leq 1024 \\ & \text{and } s < t, \\ 0.1 \cdot \left(1 - \frac{\text{len}(s,t)}{640}\right) & \text{if } 0 < \text{len}(s,t) \leq 640 \\ & \text{and } t < s, \\ 0 & \text{otherwise.} \end{cases}$$

- After combining similar weights(diff< **0.05**) and excluding small values(value < **0.05**)
- Here is the final unified model

Heuristic for Basic Block Reordering in Memory

Greedy Heuristic

Algorithm 1: Basic Block Reordering

Input : control flow graph $G = (V, E, w)$,
the entry point $v^* \in V$

Output: ordering of basic blocks $(v^* = B_1, B_2, \ldots, B_{|V|})$

Function `ReorderBasicBlocks`

- **for** $v \in V$ **do** `/* initial chain creation */`
  - $Chains \leftarrow Chains \cup (v)$;
- **while** $|Chains| > 1$ **do** `/* chain merging */`
  - **for** $c_i, c_j \in Chains$ **do**
    - $gain[c_i, c_j] \leftarrow$ `ComputeMergeGain`(c_i, c_j);
  - `/* find best pair of chains */`
  - $src, dst \leftarrow \arg\max_{i,j} gain[c_i, c_j]$;
  - `/* merge the pair and update chains */`
  - $Chains \leftarrow Chains \cup$ `Merge`$(src, dst) \setminus \{src, dst\}$;
- **return** *ordering given by the remaining chain;*

Step 1: Initialize Chains

Function `ComputeMergeGain`(src, dst)

- `/* try all ways to split chain` src `*/`
- **for** $i = 1$ **to** blocks(src) **do**
  - `/* break the chain at index` i `*/`
  - $s_1 \leftarrow src[1 : i]$;
  - $s_2 \leftarrow src[i + 1 : \text{blocks}(src)]$;
  - `/* try all valid ways to concatenate */`
  - $score_i \leftarrow \max \begin{cases} \text{ExtTSP}(s_1, s_2, dst) \text{ if } v^* \notin dst \\ \text{ExtTSP}(s_1, dst, s_2) \text{ if } v^* \notin dst \\ \text{ExtTSP}(s_2, s_1, dst) \text{ if } v^* \notin s_1, dst \\ \text{ExtTSP}(s_2, dst, s_1) \text{ if } v^* \notin s_1, dst \\ \text{ExtTSP}(dst, s_1, s_2) \text{ if } v^* \notin src \\ \text{ExtTSP}(dst, s_2, s_1) \text{ if } v^* \notin src \end{cases}$
- `/* the gain of merging chains` src `and` dst `*/`
- **return** $\max_i score_i - \text{ExtTSP}(src) - \text{ExtTSP}(dst)$;

Heuristic for Basic Block Reordering in Memory

Step 2: Iterate through all pairs of Chains

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Function `ReorderBasicBlocks`

```
for v ∈ V do                                   /* initial chain creation */
    Chains ← Chains ∪ (v);
while |Chains| > 1 do                          /* chain merging */
    for c_i, c_j ∈ Chains do
        gain[c_i, c_j] ← ComputeMergeGain(c_i, c_j);
    /* find best pair of chains                                          */
    src, dst ← arg max_{i,j} gain[c_i, c_j];
    /* merge the pair and update chains                                 */
    Chains ← Chains ∪ Merge(src, dst) \ {src, dst};
return ordering given by the remaining chain;
```

Function `ComputeMergeGain` (src, dst)

```
/* try all ways to split chain src                                      */
for i = 1 to blocks(src) do
    /* break the chain at index i                                       */
    s_1 ← src[1 : i];
    s_2 ← src[i + 1 : blocks(src)];
    /* try all valid ways to concatenate                                */
    score_i ← max { ExtTSP(s_1, s_2, dst)      if v* ∉ dst
                  { ExtTSP(s_1, dst, s_2)      if v* ∉ dst
                  { ExtTSP(s_2, s_1, dst)      if v* ∉ s_1, dst
                  { ExtTSP(s_2, dst, s_1)      if v* ∉ s_1, dst
                  { ExtTSP(dst, s_1, s_2)      if v* ∉ src
                  { ExtTSP(dst, s_2, s_1)      if v* ∉ src
/* the gain of merging chains src and dst                               */
return max_i score_i − ExtTSP(src) − ExtTSP(dst);
```

Heuristic for Basic Block Reordering in Memory

Step 3: Compute Merge Gain

Greedy Heuristic

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Input : control flow graph $G = (V, E, w)$,
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- `/* the gain of merging chains` src `and` dst `*/`
- **return** $\max_i score_i - \text{ExtTSP}(src) - \text{ExtTSP}(dst)$;

Heuristic for Basic Block Reordering in Memory

Step 4: Merge the pair of Chains with highest ExtTSP Gain

Greedy Heuristic

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the entry point $v^* \in V$
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Function `ReorderBasicBlocks`

```
for v ∈ V do                                   /* initial chain creation */
    Chains ← Chains ∪ (v);
while |Chains| > 1 do                          /* chain merging */
    for c_i, c_j ∈ Chains do
        gain[c_i, c_j] ← ComputeMergeGain(c_i, c_j);
    /* find best pair of chains                                          */
    src, dst ← arg max_{i,j} gain[c_i, c_j];
    /* merge the pair and update chains                                 */
    Chains ← Chains ∪ Merge(src, dst) \ {src, dst};
return ordering given by the remaining chain;
```

Function `ComputeMergeGain` (src, dst)

```
/* try all ways to split chain src                                      */
for i = 1 to blocks(src) do
    /* break the chain at index i                                       */
    s_1 ← src[1 : i];
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    /* try all valid ways to concatenate                                */
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                  { ExtTSP(s_1, dst, s_2)    if v* ∉ dst
                  { ExtTSP(s_2, s_1, dst)    if v* ∉ s_1, dst
                  { ExtTSP(s_2, dst, s_1)    if v* ∉ s_1, dst
                  { ExtTSP(dst, s_1, s_2)    if v* ∉ src
                  { ExtTSP(dst, s_2, s_1)    if v* ∉ src
/* the gain of merging chains src and dst                               */
return max_i score_i − ExtTSP(src) − ExtTSP(dst);
```
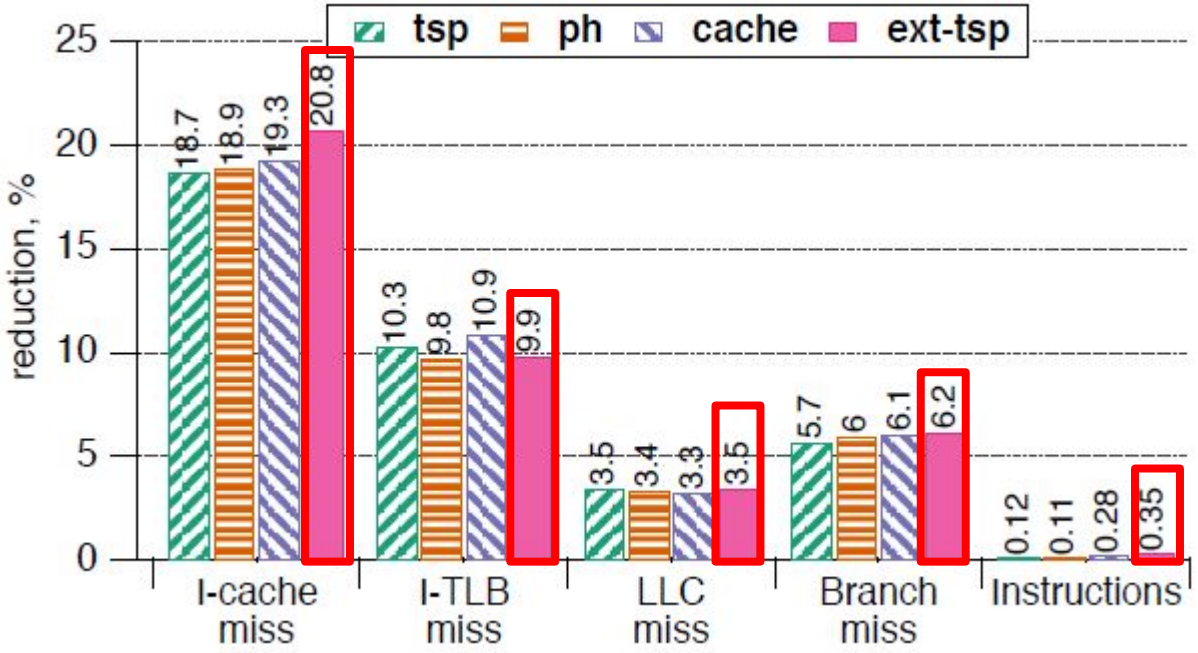
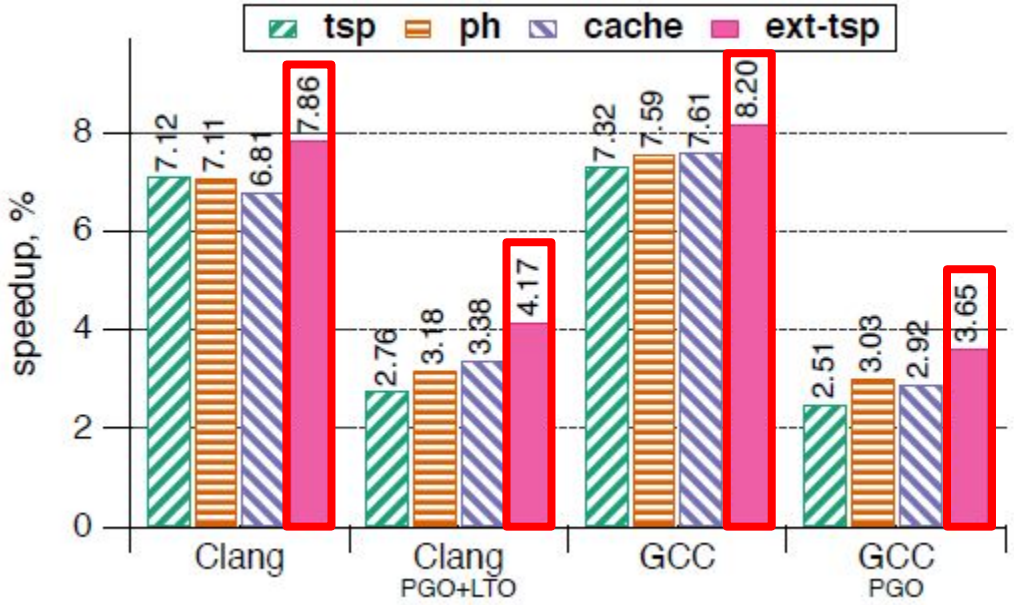

Evaluation

perf on HipHop Virtual Machine(HHVM) - reduction rate of misses



Evaluation

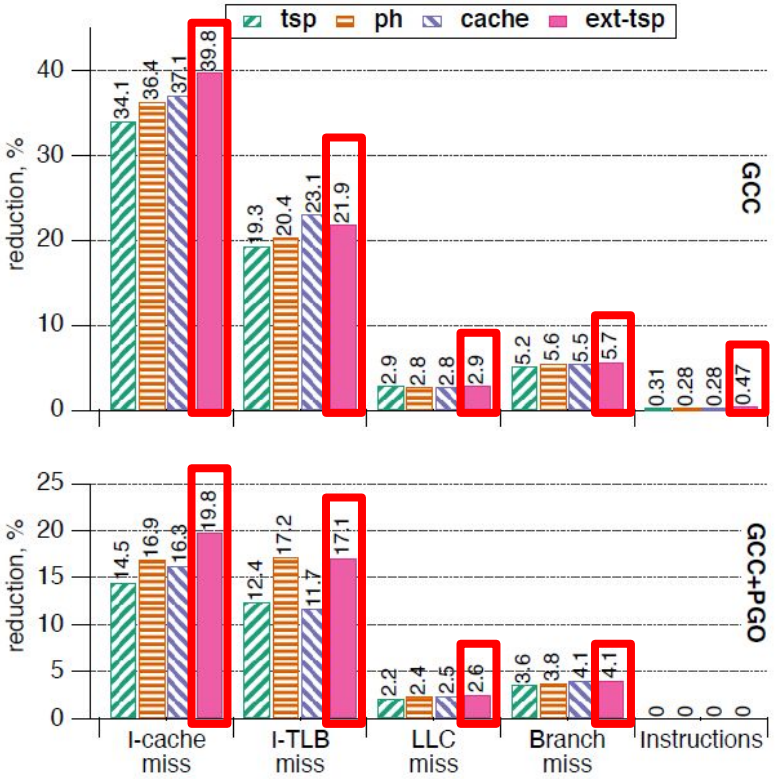
Performance Improvement - Clang and GCC



Evaluation

Perf - reduction of misses

(with/without PGO)



Limitations & Potential Future Directions

- **Limitations**

  1. Many *complementary optimizations are not investigated* in detail.

  2. The measurable gains from the heuristics algorithm is only produced *within the scope* of each individual function.

- **Potential Future Directions**

  1. *Integrate complementary optimizations* into the algorithm, such as checking unrolling loops and/or duplicating blocks to avoid extra jumps.

  2. After doing further research, the refinement of the heuristics algorithm can probably take advantage of the *cross-procedure reordering*[3].

References

[1] A. Newell and S. Pupyrev. “Improved Basic Block Reordering.” IEEE Transactions on Computers, vol. 69, no. 12, 2020, pp. 1784–1794.

[2] K. Pettis and R. C. Hansen, “Profile guided code positioning,” in SIGPLAN Notices, vol. 25, no. 6. ACM, 1990, pp. 16–27.

[3] J. Torrellas, C. Xia, and R. L. Daigle, “Optimizing the instruction cache performance of the operating system,” IEEE Transactions on Computers, vol. 47, no. 12, pp. 1363–1381, 1998.

Q&A

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