RIFS: Run-time Invariant Function Specialization

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Motivation

- **Workloads in both industry and academia are becoming increasingly complex**
  - Sophisticated control and data flows
- **Software complexity leads to unexpected inefficiencies**
  - Hard to detect and locate manually
  - Prevents achieving optimal performance
- **Compiler optimization techniques**
  - Improve the performance
  - Reduce the power consumption of applications
- **In this project, we focus on optimizing runtime value invariant function calls and we introduce RIFS.**

Motivating Example

```
int foo(int a, int b) {
   int c,d;
    a = 76;
   compute(a, c);
   ..
   compute(a, d);
}
int compute(int x, int y) {

  for(int i =0 ; i< y; i++){
      if(x % 2 != 1){
         x++;
         y= x+2*y;
         ….
      }
   } return x + y;}
```

Constant Propagation

✓

Motivating Example

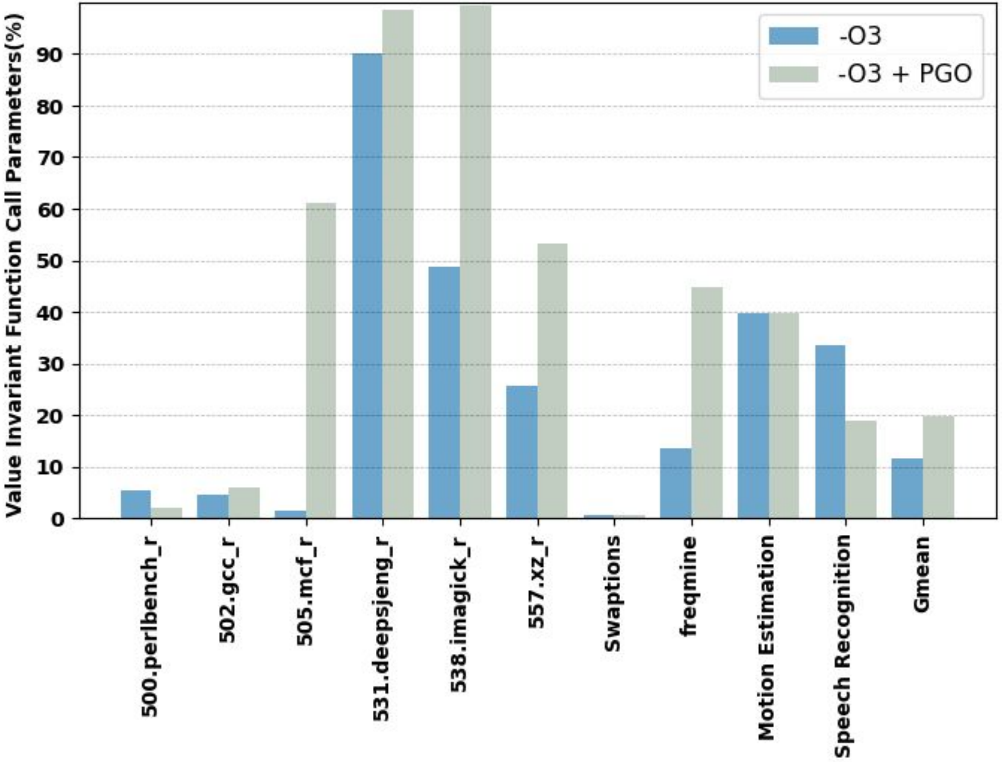
```
int foo(int a, int b) {
    int c,d;
    compute(a, c);      a = 76
    ..
    compute(a, d);
}
int compute(int x, int y) {
  for(int i =0 ; i< y; i++){
      if(x % 2 != 1){
          x++;
          y= x+2*y;
          ….
      }
  }
  return x + y;}
```

Are existing compilers able to optimize the redundant operations in compute function?

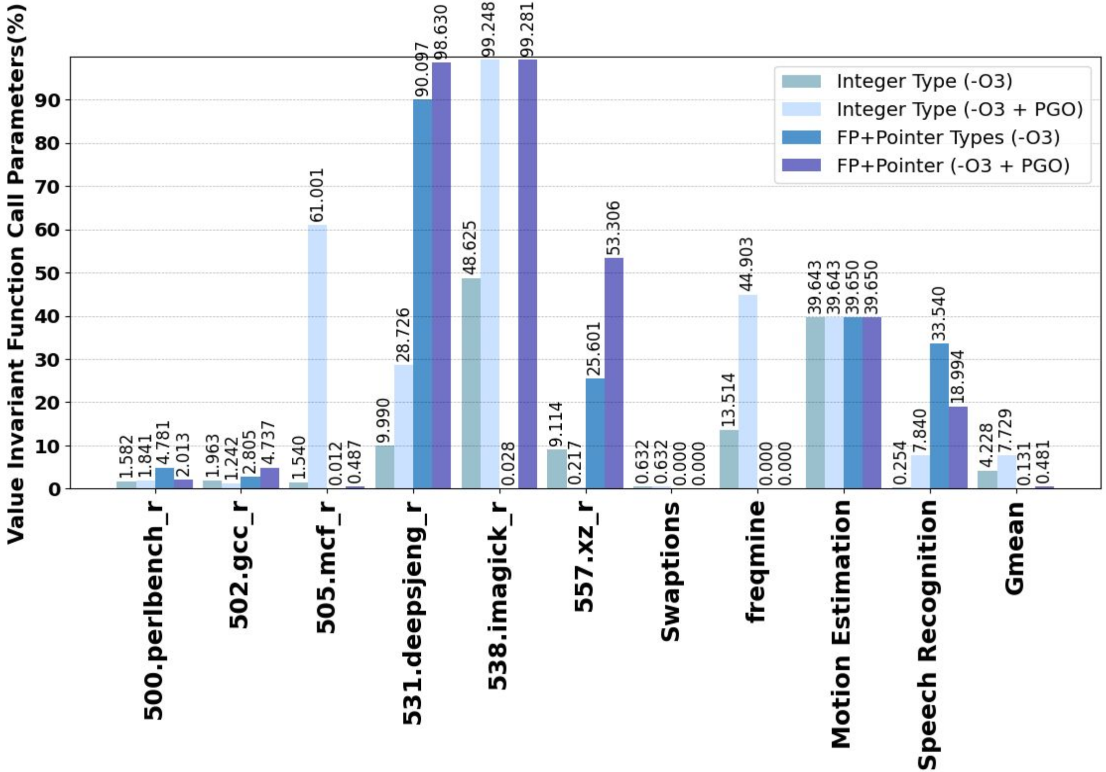
Existing Compiler Optimizations

- **PGO = Profile-Guided Optimization**
  - More information about application behavior → better optimization opportunities
    - **Profiled data**
      - Control Flow, execution counts, object types, values …
    - **Some example of optimizations:**
      - Block layout
      - Inlining heuristics
      - …
- **LTO = Link-time Optimization (BOLT, Propeller)**
  - Function and basic-block reordering to optimize instruction cache performance

Value Invariant Function call parameters



Data type of value invariant function call parameters



Value Invariant Function call parameters

Application	#Function	#Call Sites	#Dynamic Calls	#Dynamic Invariant Calls	#Fully Invariant Arguments	#Semi Invariant Arguments
500.perlbench_r	2373	3529	550202562	10128257	330	37
502.gcc_r	5973	23412	462328286	5741878	2371	126
505.mcf_r	36	106	89561282	54633640	10	3
531.deepsjeng_r	96	220	211391314	60723797	95	27
538.imagick_r	1950	1111	24028558	23847907	209	12
557.xz_r	307	256	13818099	29972	68	4
Swaptions	24	59	474601872	3000060	8	0
freqmine	42	117	116915331	52499017	6	1
Motion Estimation	11	38	29467837	11681808	5	0
Spectral Clustering	12	58	2017367	4	6	0
Kmeans Clustering	5	39	22530853	1	3	0
Speech Recognition	771	1211	21015711	1647539	252	12

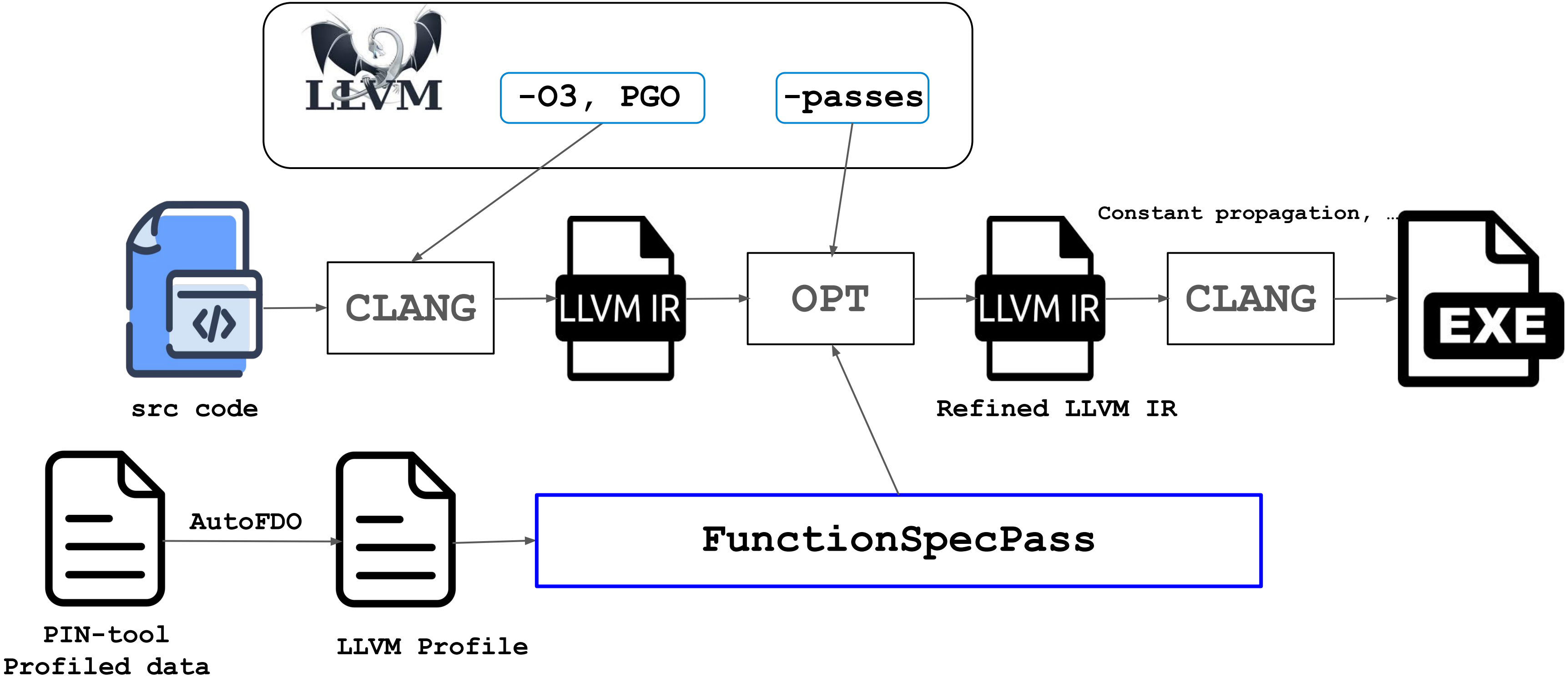
RIFS

- **We propose runtime invariant function specialization (RIFS):**
  - A technique to improve performance via value invariant function specialization
  - An application independent, generic technique that can be integrated into existing profile-guided optimization pipelines.
  - An Intel Pin-based value profiling tool to capture value invariant behavior of function call parameters
  - An LLVM function level pass utilizing profile data for automatic and safe code transformations

Profile Collection

- **Runtime profiling is required to track value-invariant variables**
- **A PIN-based value profiling tool**
  - Profiles function calls with integer, floating point, and pointer type arguments.
  - Utilizes GDB to capture the full signature of the functions including the number, type, and index of all arguments.
  - For each argument of each instrumented function, the tool caches the most frequently used N (N=8) values and their frequency of occurrence.
  - RIFS executes multiple Pin tool threads in parallel to reduce the total profiling time
  - A profile → The PC , name of the Caller, Callee, the execution frequency, the most frequent profiled values, and their occurrence ratio among all calls.

LLVM optimization pipeline



Profile-Guided Function Specialization LLVM Pass

```
Require: Profiling files (AutoFDOProfile, PinProfile)
procedure FuncSpecPass ( Function F )
    for all PC in PinProfile do                                    ▷ PC of Call
        ArgIndexVec[PC] ← argument index
        ArgValVec[PC] ← argument value
        ArgInfo←{ ArgIndexVec, ArgValVec }
    for all BB in F do
        for all I in BB do
            Found←SearchForIRInstr(I,AutoFDOProfile)
            if Found then
                Calls ← I
    for all C in Calls do
        Callee←getCalledFunction(C)
        if <isCandidateFunction(Callee)> then
            do_FuncSpecialization(C, ArgInfo)
procedure do_FuncSpecialization ( C, ArgInfo )
    FS←createSpecialization(Callee)
    for all Arg in FS do
        if <Arg is Value Invariant> then
            ArgsToUpdate ← Arg
    for all Elem in ArgsToUpdate do
        NewArg ← CreateNewArg(elem, ArgVal)
        for all dep in ArgsDepInstr[Elem] do
            NewArg ← setOperand(dep)
    SplitBlockAndInsertIfThenElse(Condition, C, ThenTerm, ElseTerm)
    Condition ← Arg value is EQUAL to the Profiled Value
    ThenTerm ← FastCallPath
    ElseTerm ← OrgCallPath
    if <Condition> then
        Jump to "FastCallPath"
        FastCall ← C.clone()
        FS ← setCalledFunction(FastCall)
    else
        Jump to "OrgCallPath"
```

(1) Determines all functions on the IR level that need to be specialized

(2) Replicates the body of all specialized functions

(3) Replaces the the function argument with a constant local variable in the replica

(4) Inserts a branch instruction to select between the original and replica function.

IR of Callsite before/after Function Specialization Pass

```
; Function Attrs: mustprogress uwtable
define dso_local noundef i32 @_Z21HJM_Swaption_BlockingPddddddiidS_PS_llii(ptr
nocapture noundef writeonly %0, double noundef %1, double noundef %2, double
noundef %3, double noundef %4, double noundef %5, i32 noundef %6, i32 noundef %7,
double noundef %8, ptr noundef %9, ptr noundef %10, i64 noundef %11, i64 noundef
%12, i32 noundef %13, i32 noundef %14) local_unnamed_addr #3 !dbg !1254 {
....

123:                                                  ; preds = %326, %93
 %124 = phi double [ 0.000000e+00, %93 ], [ %328, %326 ]
 %125 = phi double [ 0.000000e+00, %93 ], [ %327, %326 ]
 %126 = phi i64 [ 0, %93 ], [ %329, %326 ]
 %127 = call noundef i32 @_Z28HJM_SimPath_Forward_BlockingPPdiidS_S_S0_Pli(ptr
noundef %35, i32 noundef %6, i32 noundef %7, double noundef %8, ptr noundef %36,
ptr noundef %42, ptr noundef %10, ptr noundef nonnull %16, i32 noundef %13), !dbg
!1323
%128 = icmp eq i32 %127, 1, !dbg !1324
 br i1 %128, label %129, label %347, !dbg !1325

129:                                                  ; preds = %123
 br i1 %108, label %196, label %130, !dbg !1326
...
```

```
; Function Attrs: mustprogress uwtable
define dso_local noundef i32 @_Z28HJM_SimPath_Forward_BlockingPPdiidS_S_S0_Pli(ptr nocapture noundef
readonly %0, i32 noundef %1, i32 noundef %2, double noundef %3, ptr nocapture noundef readonly %4, ptr
nocapture noundef readonly %5, ptr nocapture noundef readonly %6, ptr noundef %7, i32 noundef %8)
local_unnamed_addr #3 !dbg !1090 {
123:                                                  ; preds = %330, %93
 %124 = phi double [ 0.000000e+00, %93 ], [ %332, %330 ]
 %125 = phi double [ 0.000000e+00, %93 ], [ %331, %330 ]
 %126 = phi i64 [ 0, %93 ], [ %333, %330 ]
 %127 = trunc i64 76 to i32
 %128 = icmp eq i32 %7, %127
 br i1 %128, label %FastCallPath-0, label %OrgCallPath-0
FastCallPath-0:                                       ; preds = %123
 %129 = call noundef i32 @_Z28HJM_SimPath_Forward_BlockingPPdiidS_S_S0_Pli.1(ptr noundef %35, i32
noundef %6, i32 noundef %7, double noundef %8, ptr noundef %36, ptr noundef %42, ptr noundef %10, ptr
noundef nonnull %16, i32 noundef %13), !dbg !1323
 br label %tail-0
OrgCallPath-0:                                        ; preds = %123
 %130 = call noundef i32 @_Z28HJM_SimPath_Forward_BlockingPPdiidS_S_S0_Pli(ptr noundef %35, i32
noundef %6, i32 noundef %7, double noundef %8, ptr noundef %36, ptr noundef %42, ptr noundef %10, ptr
noundef nonnull %16, i32 noundef %13), !dbg !1323
 br label %tail-0
tail-0:                                               ; preds = %OrgCallPath-0, %FastCallPath-0
 %131 = phi i32 [ %129, %FastCallPath-0 ], [ %130, %OrgCallPath-0 ], !dbg !1323
 %132 = icmp eq i32 %131, 1, !dbg !1324
 br i1 %132, label %133, label %351, !dbg !1325
133:                                                  ; preds = %tail-0
 br i1 %108, label %200, label %134, !dbg !1326
```

IR of Callee before Function Specialization Pass

CRSS

_Z28HJM_SimPath_Forward_BlockingPPdiidS_S_S0_Pli(swaptions)

```
; Function Attrs: mustprogress uwtable
define dso_local noundef i32 @_Z28HJM_SimPath_Forward_BlockingPPdiidS_S_S0_Pli(ptr
nocapture noundef readonly %0, i32 noundef %1, i32 noundef %2, double noundef %3, ptr
nocapture noundef readonly %4, ptr nocapture noundef readonly %5, ptr nocapture noundef
readonly %6, ptr noundef %7, i32 noundef %8) local_unnamed_addr #3 !dbg !1090 {
 %10 = sitofp i32 %1 to double, !dbg !1091
 %11 = fdiv double %3, %10, !dbg !1092
 %12 = tail call double @sqrt(double noundef %11) #28, !dbg !1093
 %13 = add nsw i32 %2, -1, !dbg !1094
 %14 = sext i32 %13 to i64, !dbg !1095
 %15 = mul nsw i32 %8, %1, !dbg !1096
 %16 = add nsw i32 %15, -1, !dbg !1097
 %17 = sext i32 %16 to i64, !dbg !1098
 %18 = tail call noundef ptr @_Z7dmatrixllll(i64 noundef 0, i64 noundef %14, i64 noundef
0, i64 noundef %17), !dbg !1099
 %19 = tail call noundef ptr @_Z7dmatrixllll(i64 noundef 0, i64 noundef %14, i64 noundef
0, i64 noundef %17), !dbg !1100
 %20 = icmp sgt i32 %8, 0, !dbg !1101
 %21 = icmp sgt i32 %1, 0
 %22 = and i1 %20, %21, !dbg !1103
 br i1 %22, label %23, label %167, !dbg !1103

23: …
```

```
All instructions that are dependent to the value of arg %2:
elem: i32 %2, Index: 2, val: 3
Instr:   %13 = add nsw i32 %2, -1, !dbg !32 op_index: 0
Instr:   %139 = icmp sgt i32 %2, 0 op_index: 0
Instr:   %146 = zext i32 %2 to i64 op_index: 0
Instr:   %168 = icmp sgt i32 %2, 0, !dbg !119 op_index: 0
Instr:   %171 = icmp sgt i32 %2, 0, !dbg !119 op_index: 0
Instr:   %177 = zext i32 %2 to i64, !dbg !119 op_index: 0
Instr:   %213 = zext i32 %2 to i64 op_index: 0
Instr:   %215 = icmp eq i32 %2, 1 op_index: 0
```

IR of Callee before Function Specialization Pass

CRSS

_Z28HJM_SimPath_Forward_BlockingPPdiidS_S_S0_Pli(swaptions)

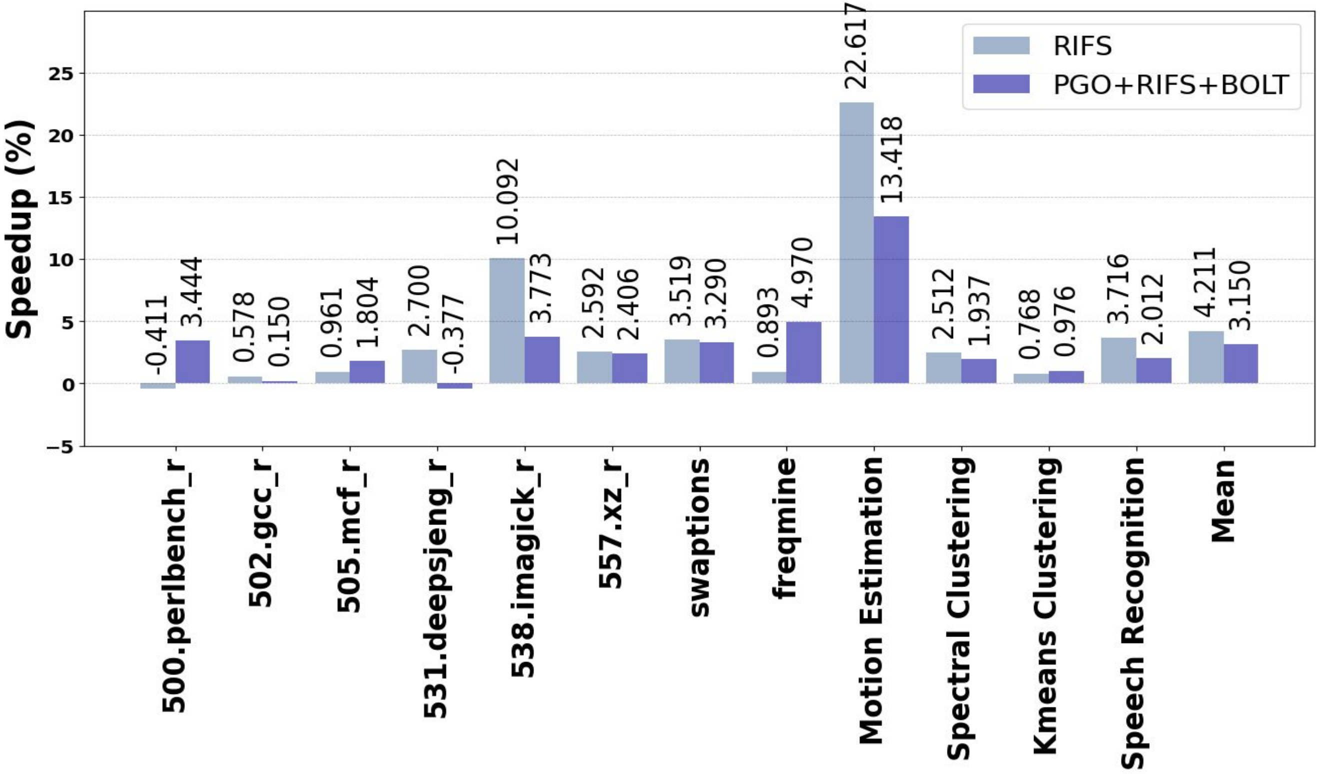
```
; Function Attrs: mustprogress uwtable
define dso_local noundef i32 @_Z28HJM_SimPath_Forward_BlockingPPdiidS_S_S0_Pli(ptr
nocapture noundef readonly %0, i32 noundef %1, i32 noundef %2, double noundef %3, ptr
nocapture noundef readonly %4, ptr nocapture noundef readonly %5, ptr nocapture noundef
readonly %6, ptr noundef %7, i32 noundef %8) local_unnamed_addr #3 !dbg !1090 {
 %10 = sitofp i32 %1 to double, !dbg !1091
 %11 = fdiv double %3, %10, !dbg !1092
 %12 = tail call double @sqrt(double noundef %11) #28, !dbg !1093
 %13 = add nsw i32 %2, -1, !dbg !1094
 %14 = sext i32 %13 to i64, !dbg !1095
 %15 = mul nsw i32 %8, %1, !dbg !1096
 %16 = add nsw i32 %15, -1, !dbg !1097
 %17 = sext i32 %16 to i64, !dbg !1098
 %18 = tail call noundef ptr @_Z7dmatrixllll(i64 noundef 0, i64 noundef %14, i64 noundef
0, i64 noundef %17), !dbg !1099
 %19 = tail call noundef ptr @_Z7dmatrixllll(i64 noundef 0, i64 noundef %14, i64 noundef
0, i64 noundef %17), !dbg !1100
 %20 = icmp sgt i32 %8, 0, !dbg !1101
 %21 = icmp sgt i32 %1, 0
 %22 = and i1 %20, %21, !dbg !1103
 br i1 %22, label %23, label %167, !dbg !1103

23: …
```

_Z28HJM_SimPath_Forward_BlockingPPdiidS_S_S0_Pli.1(swaptions)

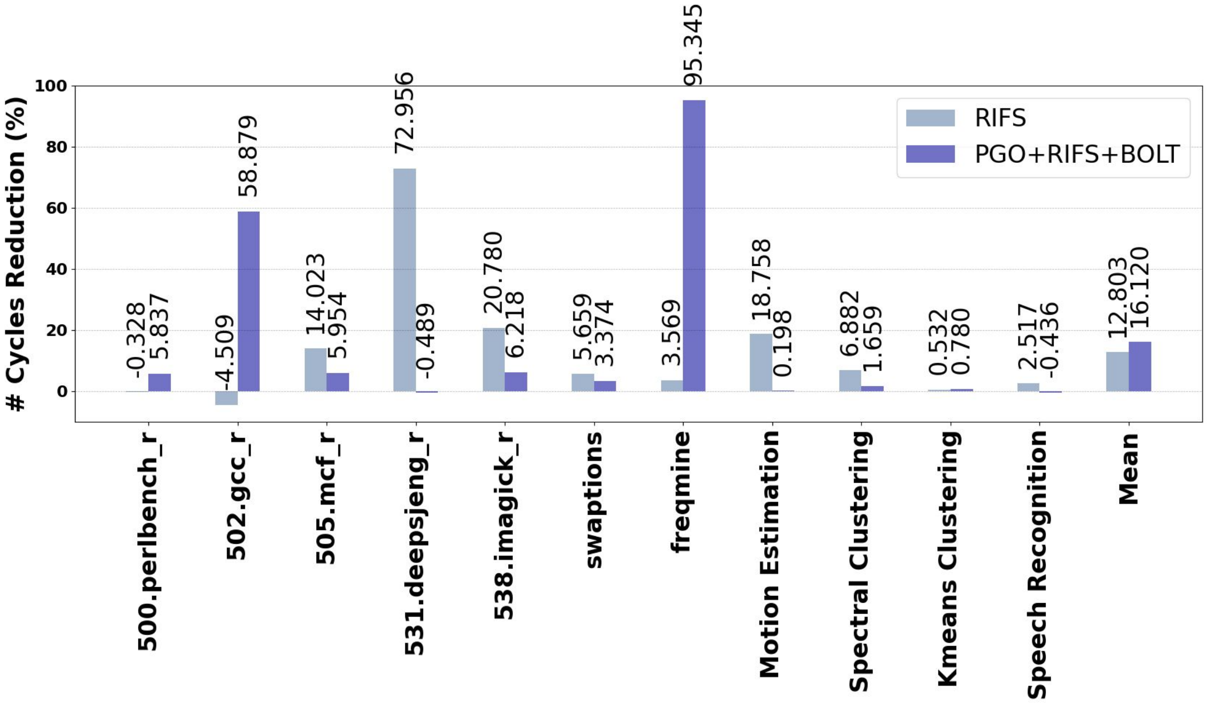
```
; Function Attrs: mustprogress uwtable
define dso_local noundef i32 @_Z28HJM_SimPath_Forward_BlockingPPdiidS_S_S0_Pli.1(ptr nocapture
noundef readonly %0, i32 noundef %1, i32 noundef %2, double noundef %3, ptr nocapture noundef
readonly %4, ptr nocapture noundef readonly %5, ptr nocapture noundef readonly %6, ptr noundef
%7, i32 noundef %8) local_unnamed_addr #3 !dbg !1946 {
 %arg2 = alloca i32, align 4, !dbg !1947
 store i32 76, ptr %arg2, align 4, !dbg !1947
 %argLoaded2 = load i32, ptr %arg2, align 4, !dbg !1947
 %10 = sitofp i32 %1 to double, !dbg !1947
 %11 = fdiv double %3, %10, !dbg !1948
 %12 = tail call double @sqrt(double noundef %11) #28, !dbg !1949
 %13 = add nsw i32 %argLoaded2, -1, !dbg !1950
 %14 = sext i32 %13 to i64, !dbg !1951
 %15 = mul nsw i32 %8, %1, !dbg !1952
 %16 = add nsw i32 %15, -1, !dbg !1953
 %17 = sext i32 %16 to i64, !dbg !1954
 %18 = tail call noundef ptr @_Z7dmatrixllll(i64 noundef 0, i64 noundef %14, i64 noundef 0, i64
noundef %17), !dbg !1955
 %19 = tail call noundef ptr @_Z7dmatrixllll(i64 noundef 0, i64 noundef %14, i64 noundef 0, i64
noundef %17), !dbg !1956
 %20 = icmp sgt i32 %8, 0, !dbg !1957
 %21 = icmp sgt i32 %1, 0
 %22 = and i1 %20, %21, !dbg !1959
 br i1 %22, label %23, label %167, !dbg !1959
23: …
```

Speedup(x)

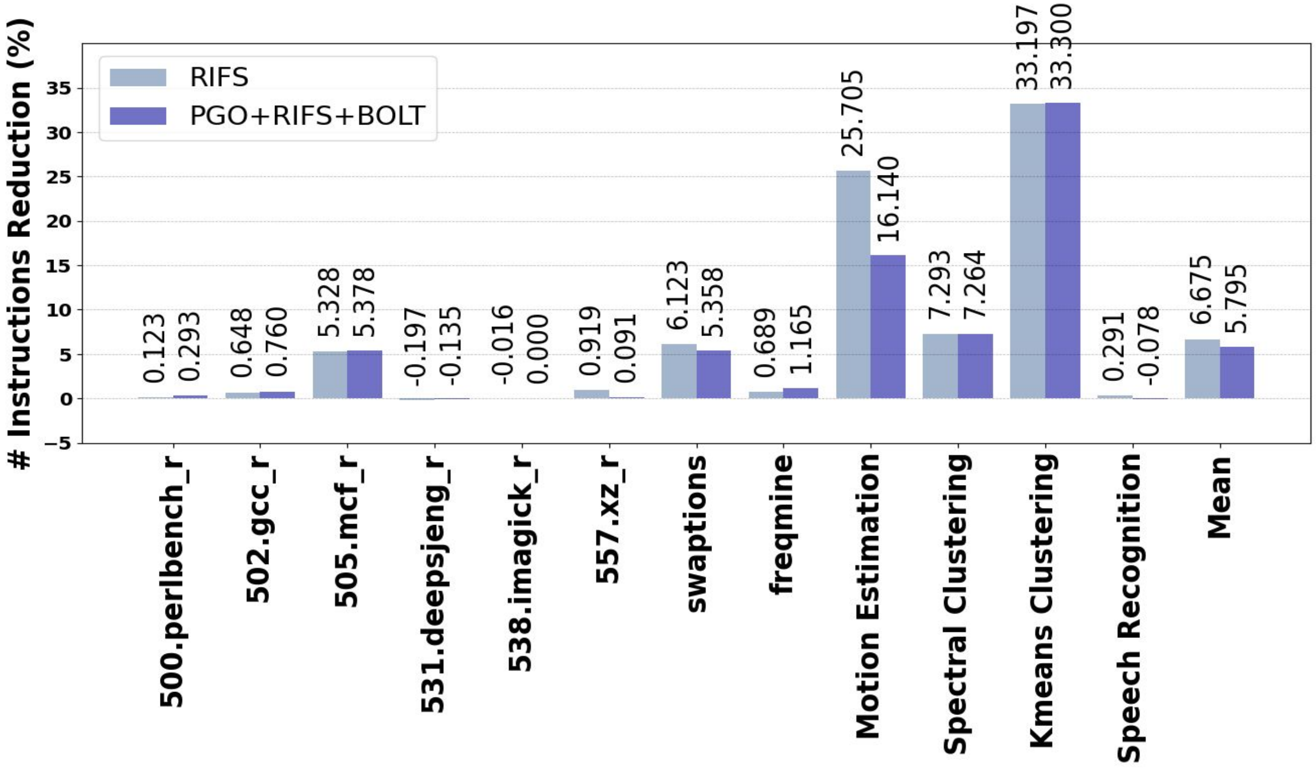


RIFS
PGO+RIFS+BOLT
Speedup (%)
25
20
15
10
5
0
−5
-0.411
3.444
0.578
0.150
0.961
1.804
2.700
-0.377
10.092
3.773
2.592
2.406
3.519
3.290
0.893
4.970
22.617
13.418
2.512
1.937
0.768
0.976
3.716
2.012
4.211
3.150
500.perlbench_r
502.gcc_r
505.mcf_r
531.deepsjeng_r
538.imagick_r
557.xz_r
swaptions
freqmine
Motion Estimation
Spectral Clustering
Kmeans Clustering
Speech Recognition
Mean

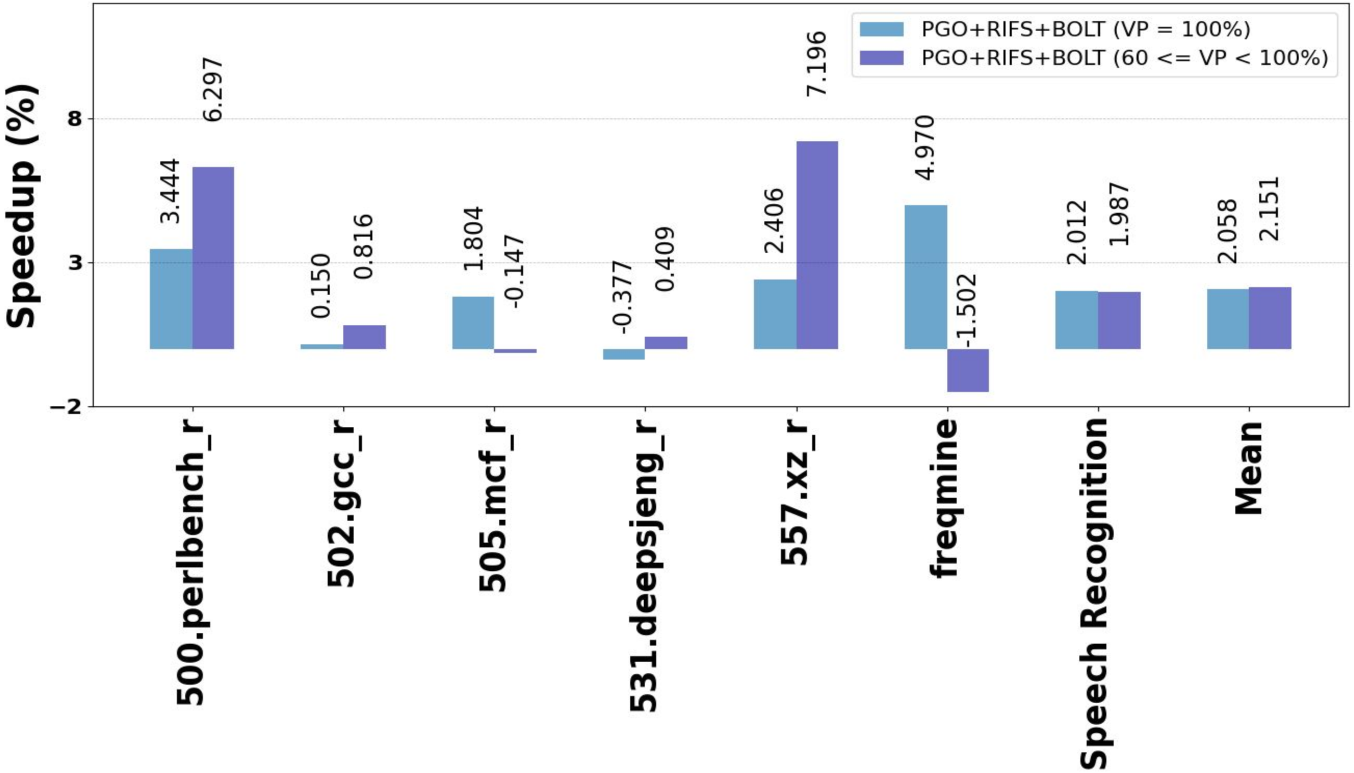
Cycles reduction (x) consumed by original and specialized functions



Instructions Reduction(x)



Speedup(x) for semi-invariant function call parameters



Conclusion

- RIFS leverages a binary instrumentation profiling tool to learn invariant function call arguments
- We have shown that profiling data can be used to optimize code by enabling constant-value propagation opportunities.
- We introduce a fully automatic and safe LLVM code transformation pass that can be easily integrated into existing compilation pipelines.
- In the context of 12 real-world applications, RIFS achieves a speedup of 4.21% and instructions reduction of 6.67% on average over the LLVM baseline (-O3).
- RIFS improves execution time by 3.15% over PGO+BOLT and reduces instructions by 5.79% on average.

Future Works

- ❖ Increase the coverage of performing Function specialization for RIFS by enabling call stack analysis
- ❖ We want to study more when specializing value-invariant function calls can be beneficial for performance and when it is not beneficial → cost-model

Thank You

Questions?

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Speedup (x) for different optimization candidates policies