Integer Range Analysis in LLVM

Maglione Sandro
10532096

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Abstract

The purpose of the range analysis is to reduce any waste of memory by allocating the minimum number of bits to each variable while maintaining the correctness of the code. This compile-time optimization allows the programmer to focus more on the problem at hand and less on the optimal type to assign to each variable (int, short, long).

In this report, I introduce a LLVM pass that performs a integer range analysis. The pass implements a static analysis of the source code to infer the minimum and maximum values assignable to any variable in the code. We are then able to compute the range of values assignable to each variable and minimize the number of bits allocated for each of them.

The tools is composed of two LLVM passes: a Constant Range Analysis and a Branch Range Analysis. The first pass analyizes the original IR instructions obtained from a source code without branches i.e. where all ranges are constants. The second pass requires the IR to be optimized using some intermediate LLVM passes (e.g. mem2reg, constprop), and then it computes the range of all the variables from a source code with branches and loops.

The passes have been tested on some example IRs obtained from source files written in the C language. In this report I am going to present some of the results achieved by the tool, some of its assumptions and limitations, and how the tool can be expanded and optimized in future versions.

1 Introduction

One of the main goals of a compiler is to optimize the code written by the programmer in order to be able to improve the performance of the software and exploit at best the hardware resources. This procedure allows the programmer to focus all her effort and time on the overall structure of the code and less on minor optimizations of each function and memory management. The compiler can extract major information from a static analysis of the code. This analysis allows the compiler to remove any unused code and to optimize the memory utilization by extracting all sort of information only by analyzing the code a static-time. This procedure can drastically improve the developer experience as well as the overall performance of the final application.

1.1 What is a Range Analysis

One of the possible optimization that the compiler can perform is a range analysis. The goal of a range analysis is to optimize the allocation of memory for all variables in the code. In order to achieve that, the compiler scans the original code to infer the minimum and maximum values that each variable can assume during runtime. If the compiler detects an overall range (defined as the distance between the minimum and maximum value) which is bounded, then the compiler can **optimize the memory allocated to a specific variable by reducing the number of bits assigned to it**.

One simple but significant example is the index variable used in a for loop. This variable is used to specify the number of iterations performed by the loop. Because of that, its value is often limited between two well defined numbers. The range analysis can detect the minimum and maximum value of the variable and optimize the number of bits allocated to it. If we think about the frequency of such for-loop constructs in an average source code, we can understand how such a simple procedure can greatly improve the performance of the code.

Code 1 Example of a for loop in which the range of the index variable can be detected and optimized by the range analysis. The range of the i variable goes from a minimum value of 0, to a maximum of 20. Therefore, we can assign only 6 bit to the variable.

```
1 #include <stdio.h>
2
```

```
3 int main()
4 {
5     for (int i = 0; i < 20; i++) {
6         printf ("Code to optimize");
7     }
8 }
```

1.2 LLVM

The tool here presented has been developed as a pass inside LLVM. LLVM is an open-source compiler infrastructure project. LLVM allows the developer to implement both a front end for any programming language, as well as a back end for any instruction set architecture. LLVM works by converting the intermediate representation (IR) generated by a compiler into a new optimized IR. The new IR can then be converted and linked into machine-dependent assembly language code for any specific target platform.

LLVM provides an API used to inspect and analyze the IR in order to further optimize the intermediate representation. The code which performs this optimization is called a pass. Each pass is written in C++. LLVM contains a predefined set of passes that can be used to perform some preliminary code optimizations. Furthermore, new passes can be implemented. Different passes can be run one after the other to generate the final IR to convert in assembly code. The constant range analysis pass works directly on the original IR generated by LLVM. The branch range analysis pass, instead, is designed to be run after some preliminary optimization passes provided by LLVM, such as mem2reg and constprop.

1.3 IR and SSA form

As discussed in the previous section, IR stands for Intermediate Representation and is an intermediate code representation used by LLVM to perform optimizations and analysis of the original source code. The IR generated by LLVM is a *.ll* file that contains a human-readable assembly-like code which can be inspected and optimized by implementing a LLVM pass.

The main characteristic of the IR generated by LLVM is that it is in **SSA form**. SSA stands for Static Single Assignment and it is a particular representation of the original source code in which each variable is assigned exactly once, and every variable is defined before it is used. This property enables

any sort of code analysis and optimization because it introduces a series of assumptions in the analyzed code which can be exploited by the compiler a static-time to infer more information from the original code.

Code 2 Here we can see an example of an IR generated by LLVM. Each IR is composed by a series of instructions grouped in different basic blocks. As we can see, each variable is assigned exactly once in the whole code, and every variable is defined before it is used.

```
1 define dso_local i32 @main() #0 {
2 entry:
3   %retval = alloca i32, align 4
4   %a = alloca i32, align 4
5   %b = alloca i32, align 4
6   %c = alloca i32, align 4
7   %d = alloca i32, align 4
8   store i32 0, i32* %retval, align 4
9   store i32 0, i32* %a, align 4
10  store i32 10, i32* %b, align 4
11  %0 = load i32, i32* %a, align 4
12  %add = add nsw i32 %0, 3
13  store i32 %add, i32* %c, align 4
14  %1 = load i32, i32* %b, align 4
15  %add1 = add nsw i32 %1, 10
16  store i32 %add1, i32* %d, align 4
17  ret i32 0
18 }
```

1.4 mem2reg

The branch range analysis is based on some preliminary LLVM passes which perform some intermediate optimization exploited by the tool's pass to improve the analysis. The most important of these preliminary passes is called mem2reg.

The main result of the mem2reg pass is to convert the original IR in a 'pruned' SSA form. The pass achieve this result by promoting memory references to be register references. Therefore, *load*, *alloca*, and *store* instructions are removed and *phi* instructions are introduced. A *phi* instruction is used to inform the compiler of the possible values assumed by a variable. In fact, it is possible that a variable is assigned or modified in different basic blocks of the code. The *phi* instruction contains a list of all the possible values assumed

by a variable at the entry of a basic block. This information allows the tool to infer the range of the variable based on the list of values that it can assume.

The other LLVM passes which are used by the tool are *constprop*, *dce*, *simplifycfg*, and *gvn*.

Code 3 Example of a IR generated using the preliminary passes mentioned above. As we can see, alloca, store, and load instructions have been removed and phi instructions have been introduced at the entry of the basic blocks.

```
1 define dso_local i32 @fun() #0 {
2 entry:
3   br label %for.cond
4
5 for.cond:
6     ; preds = %for.body, %entry
7   %a.0 = phi i32 [ 1, %entry ], [ %add, %for.body ]
8   %j.0 = phi i32 [ 10, %entry ], [ %inc, %for.body ]
9   %cmp = icmp slt i32 %j.0, 30
10   br i1 %cmp, label %for.body, label %for.end
11
12 for.body:
13    ; preds = %for.cond
14  %add = add nsw i32 %a.0, 10
15  %inc = add nsw i32 %j.0, 1
16   br label %for.cond
17
18 for.end:
19    ; preds = %for.cond
20  ret i32 %a.0
21 }
```

2 Related Works

The value range analysis is a critical technique utilized by major compilers to achieve better performance and code optimization. Over the years, many solutions have been proposed to implement an efficient value range analysis for different purposes.

Substantial results have been achieved by Raphael Ernani Rodrigues, Victor Hugo Sperle Campos, and Fernando Magno Quintao Pereira [9]. They developed an open-source LLVM pass that aims to detect and remove integer overflow using the value range propagation technique. The pass was able, on average, to eliminated 24.93% of the integer overflow checks.
Douglas do Couto Teixeira and Fernando Magno Quintao Pereira proposed a non-iterative range analysis algorithm on a production compiler [5]. They convert the original source code in e-SSA form (Extended Static Single Assignment) and they build a constraints graph which is then analyzed and resolved to compute the value ranges. Their tool was able to increased the number of 1-bit variables by 1.04x, 8-bit variables by 52.3x and 16-bit variables by 26.6x. It was also able to decreased the number of 32-bit variables by 1.33x.
Mark Stephenson Jonathan Babb and Saman Amarasinghe developed a bitwidth analysis algorithm [3]. Their algorithm works on the SSA form and performs a forward and backward propagation of the value ranges to extract more information and improve the performance. Their work is specific for the optimization of the performance of silicon compilers, and their reported major improvements when their tool was integrated in the DeepC Silicon Compiler [7].
Yang Ding and Weng Fai Wong propose a static analysis method for bitwidths in general applications [17]. They present some interesting general methodologies to handle value ranges representations, array handling, and loop handling.

3 Environment Setup

In order to use the tool you must clone and build the LLVM environment in your local machine. The LLVM project provides many resources online on how to install the infrastructure. In this report, I am going to highlight the main step required to setup the environment, from the actual build of LLVM to the installation of the tool.

3.1 Prerequisites

The prerequisites to install LLVM successfully are listed on the official LLVM guide. The main softwares required are:

- CMake
- GCC
- Python
- zlib
- GNU make

3.2 Setting up the LLVM environment

The first required step is the installation of LLVM. You must clone the open-source LLVM repository, hosted on Github, on your local machine. In order to do that, just navigate to your choosen directory and run the *git clone* command below:

git clone https://github.com/llvm/llvm-project.git

This command will create a *llvm-project* folder inside your directory. The folder contains all the files required to build and start using LLVM.
Navigate to the newly created folder and create a new *build* folder.

cd llvm-project
mkdir build
cd build

The next step is launching the *cmake* command to setup the build process. Many options are available. The following command is the default recommended on the Clang getting started guide:

cmake -DLLVM_ENABLE_PROJECTS=clang -G "Unix Makefiles" ../llvm

Finally, launch the *make* command to build the environemnt and install LLVM on your local machine. This builds both LLVM and Clang for debug mode. Note that generally this step may require some time to be completed.

make -j4

For more details, visit the Getting Started Guide available on the offical Clang-LLVM website.

3.3 Importing the passes

Once the build process of the LLVM environment is completed, we are ready to import and build the tool. The code for the tool's passes is available on Github.

The first step is to access the *Transforms* directory inside the llvm-project folder. Open the llvm-project folder and naviagate to the *llvm-project/llvm/lib/Transforms* folder. This folder contains all the transform passes available inside your LLVM installation. We are going to import both the constant range analysis pass and the branch range analysis pass as two different passes inside LLVM.

- Create two directories: **ConstantRange** and **BranchRange**.
- Update the *CMakeLists.txt* file inside */llvm-project/llvm/lib/Transforms* by adding the newly created directories: *add_subdirectory(ConstantRange) add_subdirectory(BranchRange)*
- Open *ConstantRange* directory
- Copy and paste the **ConstantRange.cpp** file inside the directory
- Create a new *CMakeLists.txt* file inside the directory
- Add the following code to the *CMakeLists.txt* file to allow LLVM to recognize the new pass:

```
1 add_llvm_loadable_module( LLVMConstantRange
2   ConstantRange.cpp
3
4   PLUGIN_TOOL
5   opt
6   )
```

- Navigate back to the *Transforms* folder and open *BranchRange* directory
- Copy and paste the **BranchRange.cpp** file inside the directory
- Create a new *CMakeLists.txt* file inside the directory
- Add the following code to the *CMakeLists.txt* file to allow LLVM to recognize the new pass:

```
1 add_llvm_loadable_module( LLVMBranchRange
2   BranchRange.cpp
3
4   PLUGIN_TOOL
5   opt
6   )
```

- Navigate back to the *llvm-project/build* folder
- Launch again the build command: **make -j4**

3.4 Running the code

After all the previous steps are completed, the passes are installed and built inside the LLVM environment and can be used to perform the range analysis.

The two command to use for the passes are **-const-range** for the constant range analysis and **-branch-range** for the branch range analysis.

- Import your source code in C language in a folder of your choice (in this guide I assume the name of the file is *example.c*)
- Navigate to the *llvm-project/build/bin* folder

- Run the command

  ./clang -S -emit-llvm [...path to your C code]/example.c

  for the constant range analysis, which generates directly the IR in *.ll* file, and

  ./clang -c -O0 -emit-llvm [...path to your C code]/example.c -o example.bc -Xclang -disable-O0-optnone

  for the branch range analysis, which generates a *bytecode* file

- For the branch range analysis pass, we need to compute an intermediate IR code using some LLVM preliminary passes. Run the following command to build the *.ll* version of the previously generate *bytecode* file:

  ./llvm-dis example.bc -o=example.ll

- Run the following command to apply the preliminary passes to the IR file:

  ./opt -mem2reg -constprop -dce -simplifycfg -gvn -S example.ll -o example-super.ll.

  This command generates another *example-super.ll* file which contains the IR code used by the branch range analysis pass

- Finally, run the command to launch the tool:

  ./opt -load ../lib/LLVMConstantRange.so -const-range <example.ll >/dev/null -debug

  to perform the constant range analysis on the IR file, or

  ./opt -load ../lib/LLVMBranchRange.so -branch-range <example-super.ll >/dev/null -debug

  to perform the branch range analysis on the optimized IR file

4 Methodology

4.1 Constant analysis

The constant range analysis performed by the tool aims to resolve all the values assumed by each variable in the source code. This pass assumes that no branch is present in the source code, and therefore all the variables can be resolved to a constant.

The rationale of the tools is that, in order to have a correct source code, each variable depends by one or more previously defined variable plus one or more constants. When this property is verified, it is possible to inspect a previous instruction to infer the value assumed by a variable in the current instruction.

The algorithm of the constant range analysis therefore scans each instruction one by one in the original IR computed by LLVM to resolve at each step the real value assumed by each variable as the code progress. At the end of the inspection, the tool will have discovered all the variables present in the source code and all their ranges, which, as state before, will be constant.

4.2 Branches and Phi nodes

The first major difference we can notice compared to the constant range analysis is the format of the IR code. As previously explained, the optimizations passes applied to the original IR allows the tool to extract more information from the code. Specifically, the mem2reg pass removes all unnecessary *alloca*, *load*, and *store* instructions from the original IR.

The major aid that the mem2reg pass offers to the analysis is the introduction of *phi* instructions. These instructions allows the tool to understand the possible values assumed by the variables that the *phi* instruction defines. These variables, in fact, assume different values when the current basic block is reached from a previous basic block above it, or from a subsequent basic block below it.

That is the principal difference with respect to the constant range analysis pass: with the introduction of branches, a single code scan is not enough anymore to extract all the information available on ranges. This can be noticed from this example in the branch range analysis section below, where the *phi* instructions introduce a dependency on a basic block with is located

after the current one. This happens because from the *for.body* basic block the code loops back to the *for.cond* basic block with the unconditional *br* instruction at line 16.

Another new instruction introduced is the *cmp* instruction. This instruction performs a value comparison between two variables or one variable and a constant. The result is then utilized by the next conditional *br* instruction to branch to one basic block or another basic block when the condition is verified and not verified respectively.

4.3 Loop ranges

The first source of information about the ranges assumed by the variables in the code is related to the loop condition. We can intuitively notice from the source code in C that, no matter the computations inside the loop body, the value of the variable j must be between 10 and 30 at the end of the function. In fact, the variable j is not involved in any computation, and its role is to determine the number of iterations of the loop. This construct is heavily used in all programming languages and source codes, and it can be greatly exploited by the range analysis to infer the ranges of the variables.

Code 4 Source code example for the Branch Range Analysis algorithm.

```
1 int fun()
2 {
3     int j = 10;
4     int a = 1;
5
6     for (; j < 30; ++j)
7     {
8         a = a + 10;
9     }
10
11    return a;
12 }
```

Furthermore, once we know that the loop tripcount is from 10 to 30, we can infer that the number of iterations performed of the loop body is 20. This additional information allows the tool to extract even more information on the value range of the variable *a*. Variable *a* is initially initialized to 1. After that, its value is updated inside the loop body of 10 at each iteration. Since we know that the number of iterations is equal to 20, we can infer the range of *a* from a minimum value of 1 to a maximum value of *1 + (20 x 10)*, which

is equal to 201.

At the end of the computation, the tool is able to assign a well-defined range to both variable j, by exploiting the information on the loop condition. and variable a, by exploiting the information about its initial value and the tripcount of the loop previously computed.

5 Constant Range Analysis

In this section I am going to introduce a simple example that aims to showcase the tool's constant range analysis algorithm. As already explained, the constant range analysis operates on the original IR of LLVM to extract the constant value of each variable in the source code. The assumption in the constant range analysis pass is that no branch is present in the code. Therefore, all the variables resolve to a constant range.

5.1 Example code

The following example illustrates all the major features provided by the tool for the constant range analysis. Here below is the source code written in C language and its translation in the default IR computed by LLVM.

Code 5 Example code for the Constant Range Analysis algorithm.

```
1 int main() {
2   int a = 9;
3   int b = a - 6;
4   int c = 3 + b;
5   int d = c + c;
6   return 0;
7 }
```

Code 6 Example code for the Constant Range Analysis converted in the default IR of LLVM.

```
1 define dso_local i32 @main() #0 {
2 entry:
3   %retval = alloca i32, align 4
4   %a = alloca i32, align 4
5   %b = alloca i32, align 4
6   %c = alloca i32, align 4
7   %d = alloca i32, align 4
8   store i32 0, i32* %retval, align 4
9   store i32 9, i32* %a, align 4
10  %0 = load i32, i32* %a, align 4
11  %sub = sub nsw i32 %0, 6
12  store i32 %sub, i32* %b, align 4
13  %1 = load i32, i32* %b, align 4
14  %add = add nsw i32 3, %1
15  store i32 %add, i32* %c, align 4
```

```
16   %2 = load i32, i32* %c, align 4
17   %3 = load i32, i32* %c, align 4
18   %add1 = add nsw i32 %2, %3
19   store i32 %add1, i32* %d, align 4
20   ret i32 0
21 }
```

The source code is composed of four variables: *a*, *b*, *c*, *d*. Each variable depends on another previous variable and/or a constant. From the example, we can clearly infer the constant value assumed by each of the variable inside the source code.

The tool computes the constant value of *a* as 9 from the *store* instruction at line 9. After that, a *sub* instruction is found. The tool resolves the value of *%0* in the operation to *%a*. Since we already computed the constant value of *%a* as 9, the tool performs the subtraction and assigns *9 - 6 = 3* to *%sub*. The following store instruction tells the tool that the value just computed is assigned to *%b*.
The same happens for the *add* instruction at line 14: the value of *%add* is computed as the sum of the constant value of *%b* and 3, and then the following store assigns the computed value of 6 to *%c*.
Finally, the last *add* instruction computes the sum between two other variables. The tool resolves the value of *%2* and *%3* to *%c*. The last store then assigns the sum *6 + 6 = 12* to *%d*.

At the end of the analysis, the tool reports the constant value of all the variables found in the code. The output of the constant range analysis on this example code is represented here below.

Code 7 Result of the Constant Range Analysis on the example code.

```
1 --- VALUE RANGES ---
2  retval(0, 0)
3  a(9, 9)
4  sub(3, 3)
5  b(3, 3)
6  add(6, 6)
7  c(6, 6)
8  add1(12, 12)
9  d(12, 12)
```

As we can see, the tool was able to infer correctly the constant value of all the variables in the code.

6 Branch Range Analysis

In this section I am going to present one example that illustrates all the major features of the branch range analysis algorithm. In order to perform the branch range analysis, we need to compute an optimized version of the default IR computed by LLVM. All the steps to produce the optimized IR are presented in the *Installation* section.

6.1 Example code

In the branch range analysis we introduce loops and branches. This makes the analysis more complex but also more interesting and useful in practice. Generally, every source code has multiple branches and loops. The tool is designed to extract as many information as possible at compile-time to improve the memory allocation of the variables in the source code. In the following example, I am going to explain all the major steps performed by the tool to extract all the ranges possible from the source code. Here below is reported the source code of the example and the optimized IR computed by LLVM.

Code 8 Source code example for the Branch Range Analysis algorithm.

```
1 int fun()
2 {
3     int j = 10;
4     int a = 1;
5
6     for (; j < 30; ++j)
7     {
8         a = a + 10;
9     }
10
11    return a;
12 }
```

Code 9 Oprimized IR generated by LLVM from the example source code.

```
1 define dso_local i32 @fun() #0 {
2 entry:
3   br label %for.cond
4
5 for.cond:
6     ; preds = %for.body, %entry
```

```
 7   %a.0 = phi i32 [ 1, %entry ], [ %add, %for.body ]
 8   %j.0 = phi i32 [ 10, %entry ], [ %inc, %for.body ]
 9   %cmp = icmp slt i32 %j.0, 30
10   br i1 %cmp, label %for.body, label %for.end
11
12 for.body:
13       ; preds = %for.cond
14   %add = add nsw i32 %a.0, 10
15   %inc = add nsw i32 %j.0, 1
16   br label %for.cond
17
18 for.end:
19       ; preds = %for.cond
20   ret i32 %a.0
21 }
```

6.2 Optimized IR

As states before, in order to improve the performance of the branch range analysis, we utilize some LLVM passes to optimize the original IR. These passes change the structure of the original IR to perform some preliminary optimizations that aim to simplify and make the computation of the variables' ranges faster and more reliable. Firstly, as we can see, *alloca*, *load*, and *store* instructions have been removed.

We notice the introduction of two *phi* instructions at line 7 and line 8. These instructions allows the tool to understand the possible values assumed by the variable *%a.0* and *%j.0*. These two variables, in fact, assume different values when the *for.cond* basic block is reached from the *entry* basic block above it, or from the *for.body* basic block below it.

This can be noticed from this example, where the *phi* instructions introduce a dependency on a basic block with is located after the current one. This happens because from the *for.body* basic block the code loops back to the *for.cond* basic block with the unconditional *br* instruction at line 16.

Another new instruction introduced is the *cmp* instruction at line 9. This instruction performs a *slt* (Signed Lower Than) comparison between the value of *%j.0* and a constant value of 30. This result is then utilized by the conditional *br* instruction at line 10 to branch to *for.body* or *for.end* when the condition is verified and not verified respectively.

6.3 Algorithm

In the methodology section I explained the rationale behind the algorithm and what information the tool can extract from the example source code. In this section, I am going to highlight the steps performed by the algorithm to actually compute the information on the ranges.

The pass contains a vector called *workList*. This *workList* contains all the basic blocks that are still to visit by the algorithm. The algorithm iterates over the elements inside the list until the list becomes empty. Initially, the only basic block inside the list is the *entry* block, which is present in every IR produced by LLVM.

For every basic block in the list, the algorithm inspects all the instructions contained in the basic block. For each possible instruction. the pass makes some computations to extract as many information as possible based on the current knowledge of the variable ranges. The first instruction encountered is the *br* instruction of the *entry* block at line 3. The algorithm recognizes the *for.cond* basic block in the branch instruction. Since the *for.cond* has never been visited before, the algorithm adds it to the *workList* vector and marks it as visited.

All the instruction of the *entry* block have been inspected. The next basic block inside the *workList* is *for.cond*. The algorithm proceeds to inspect all the instructions inside this basic block.

- The first *phi* instruction assigns 1 or *%add* to the value of variable *%a.0*. The range of *%add* is currently completely unknown. The pass assumes a possible range which spans from -infinite to +infinite in such case. Nonetheless, the *phi* instruction informs the analysis that the value of *%add* originates from the *for.body* basic block. Therefore, the algorithm inspects the *for.body* basic block and finds that the value of *%add* is dependent on the value of *%a.0*. Specifically, *%add* is updated with and *add* instruction. From this inspection, the algorithm infers that the minimum value assumed by *%a.0* at line 7 must be the value coming from the *entry* basic block. Therefore, after the first *phi* instruction, the range of *%a.0* is from a minimum of 1 to a maximum of +infinite.
- The analysis of the second *phi* instruction at line 8 is the same explained above for variable *%a.0*. This time, the value of *%j.0* is dependent on *%inc*, which is updated with an *add* instruction in basic block *for.body*. Therefore, at the end of this inspection, the range of *%j.0* is from 10

to +infinite.

- The next instruction is the *cmp* at line 9. The algorithm inspects the condition imposed by the instruction to infer the range of variable *%j.0* when the condition is verified and when the condition is not verified. The comparison is *slt*, therefore the condition is *%j.0* less than the constant value of 30. In the taken case, the possible range of *%j.0* is from -infinite to a maximum value of 29, while in the not taken case, the range spans from a minimum value of 30 to a maximum of +infinite. This information will be exploited by the following conditional *br* instruction.

- The last instruction of the *for.cond* basic block is a conditional *br* instruction. The algorithm utilizes both the previous ranges computed on the *cmp* instruction as well as the current range assigned to variable *%j.0* to compute the range that this variable can assume in case of branch taken to basic block *for.body* and in case of branch not taken to basic block *for.end*. Specifically, the algorithm already computed the minimum value of *%j.0* to be 10 and it also knows that, in case of branch taken, the maximum value possible for *%j.0* must be 29. Therefore, inside the *for.body* basic block, the range of *%j.0* is from a minimum value of 10 to a maximum value of 29. For the branch not taken case instead, the range of *%j.0* in the basic block *for.end* is from 10 to +infinite, since no other additional information can be inferred. Finally, both *for.body* and *for.end* are inserted inside the *workList*.

The next basic block in the list is *for.body*. This basic block contains two *add* instructions and one *br* instruction. The current ranges assumed by variable *%a.0* and variable *%j.0* are respectively from 1 to +infinite and from 10 to 29. Based on this information, the algorithm is able to compute the range of *%inc* from 11 to 30. Since the values of *%inc* are changed from the default of -infinite to +infinite, we know that we have some new information to propagate to the next basic block. Therefore, even if the *for.cond* basic block is marked as already visited, the algorithm adds it to the *workList*.

The next basic block in the list is *for.end*. Since the only instruction contained in the block body is *ret*, the algorithm cannot extract any additional information from it and just moves to the next basic block.

The algorithm now visits the *for.cond* basic block for the second time. From the inspection of the *for.body* block previously computed, we have a series of new information that can be exploited to improve the analysis. We now

know that the tripcount of the loop from *for.cond* to *for.body* and back to *for.cond* is based on the value of *%j.0*. We also computed that the possible range assumed by *%j.0* in the loop is from 10 to 29. Therefore, we compute the tripcount to be 20. Armed with this new information, we can completely infer the range of variable *%a.0*. In fact, since the varaible *%a.0* is updated by 10 at each iteration of the loop body, we can assign it a range that spans from a minimum value of 1 to a maximum value of *1 + (10 * 20)*, which is equal to 201. The range of *%j.0* was already known to be from 10 to 30 inside the *for.cond* basic block. Furthermore, we can now limit the range of *%j.0* inside the *for.end* basic block to a maximum value of 30 since we know that the range of *%j.0* cannot be greater than 30. Therefore, the new range of *%j.0* inside *for.end* becomes a constant of 30.

Completed this analysis, the algorithm terminates because, once the ranges becomes fixed and are not updated anymore, no basic block is added to the *workList*.

7 Experimental Results

The previous example aims to illustrate all the possible information that the tool can extract from a simple source code. Here below we can see the output of the algorithm on the example proposed.

Code 10 Output result of the branch range analysis algorithm on the example source code explained above.

```
1 --- VALUE-RANGES ---
2 BB: entry
3
4 BB: for.cond
5     a.0(1, 201) = 201 {9bit}
6     j.0(10, 30) = 21 {6bit}
7
8 BB: for.body
9     j.0(10, 29) = 20 {6bit}
10    add(-Inf, +Inf) = MAX
11    inc(11, 30) = 20 {6bit}
12
13 BB: for.end
14    j.0(30, 30) = 1 {2bit}
```

Based on this analysis, we can allocate 9 bits to the variable *a* and 6 bit to the variable *j*. This causes a reduction of 23 bit, from the standard 32 bit of an int variable, for variable *a* and of 26 bit for variable *j*.

Overall, this analysis yields a memory improvement of **71.8%** for the allocation of variable *a*, and of **81.3%** for the allocation of variable *j*. This causes an overall improvement of **76.6%** for the memory allocation of the whole function.

7.1 Bitwidth optimization

In this section I am going to present the results obtained by the tool on a series of benchmark source codes. The benchmarks used to test the performance of the tool are part of the **bitwise benchmarks** set. The benchmark set is composed by different source files written in the C language. These files implement some general algorithms used in different areas of engineering, computer science, and security. The benchmark are designed to test the performance of the analysis on a series of code patterns. Specifically, the source codes benchmark selected are *adpcm*, *bilint*, *bubblesort*, *convolve*,

edge_detect, *histogram*, *jacobi*, *levdurb*, *medain*, *motiontest*, and *newlife* [1].

All the test have been computed on a Linux Virtual Machine. The version of the operating system is *Ubuntu 16.04.6 LTS*, with kernel *Linux ubuntu 4.4.0-177-generic - x86_64 GNU/Linux*. The CPU is *Quad core Common KVM (MCP) cache: 16384 KB, clock speeds: max: 2799 MHz 1: 2799 MHz 2: 2799 MHz 3: 2799 MHz 4: 2799 MHz*. The default C Compiler of the machine is *GNU C Compiler version 5.4.0.20160609 (Ubuntu 5.4.0-6ubuntu1-16.04.12)*.

In order to measure the overall improved performance of the analysis, we run the tool and report the amount of bits saved by extracting information on the ranges of the variables. Specifically, the analysis presents the number of bits to allocate for each variable. We compare this optimization with the standard case without any range analysis inspection. We then report the overall amount of bits saved by the tool in percentage over the whole function. The same procedure has been run on all the source codes.

Another set of test has been done on some example test files. This set of tests aims to present the potential of the tool over loop-based source codes. Since the majority of information is extracted from loop condition and loop body, the tool performs particularly well on source codes based on loop cycles. The example files are designed to present the optimal-case analysis of the tool, and may not reflect a real case performance.

7.1.1 Performance

As previously stated, most of the information of the variables' range is extracted from the analysis of loops. On the other hand, the analysis is unable to infer any significant range information when the variable is user-defined (scanf) or is passed as an argument to the function.

Benchmark	Lines	Performance (%)	Saved bits
adpcm	196	14.72	245
bilint	114	0.00	0
bubblesort	69	34.76	356
convolve	81	35.49	727
edge_detect	182	37.63	289
histogram	110	33.75	594
jacobi	68	40.55	571
levdurb	50	8.06	111
median	99	38.12	427
motiontest	44	26.08	217
newlife	121	30.71	747

The graph reports an overview of the results obtained on the benchmark source codes. The chart reports the percentage of saved bits computed by the tool. As we can notice, the results vary based on the source file. Specifically, source files containing many loops and basic blocks achieve a higher performance. The tool did not perform particularly well on one basic block codes (*bilint*) and code with less branches and loops.

Over the whole analysis, the tool was able to achieve an average percentage of saved bits of **27.26%** with a standard deviation of **12.97%**. The maximal percentage of bits saved in one function is **40.55%** on the *jacobi* source code, while the lowest percentage of bits saved reported is **0.00%** on the *bilint* source code.

7.1.2 Loops-based source code

The most important results obtained by the tool are on loop-based source codes. In fact, the major strength of the tool is resolving and extracting ranges information from loop indexes and variables in the body of loops. Because of that, the analysis on the example test files reports an average optimization of **40.625%** on while-based source codes, with a standard deviation of **36.185%**. Similar result have been obtained on for-based source codes, with a average optimization of **40.312%**, with a standard deviation of **36.571%**. These results express the effectiveness of the tool in extracting loop-based range information. The similarity of the results on while and for loops is explained by the fact that generally for and while are both translated in similar ways in the IR representation by the mem2reg optimization pass.

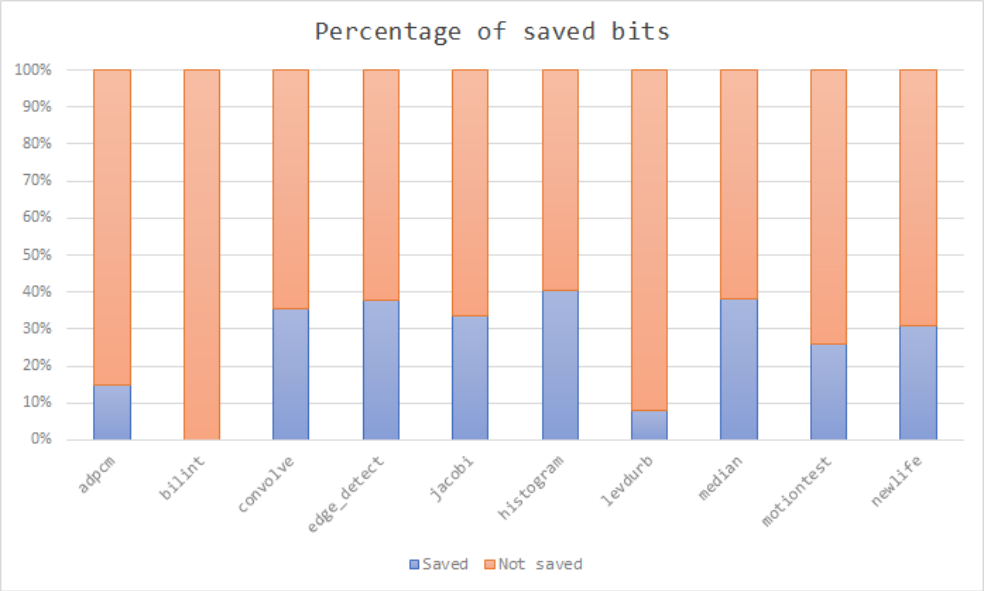

Figure 1: The graph above shows the percentage of bits saved by the tool after the optimization. The percentages are computed as the ratio between the sum of the number of bits allocated without range analysis and the number of bits allocated after the range analysis optimization of the tool. The performance have been collected on the source files of the bitwise benchmark set.

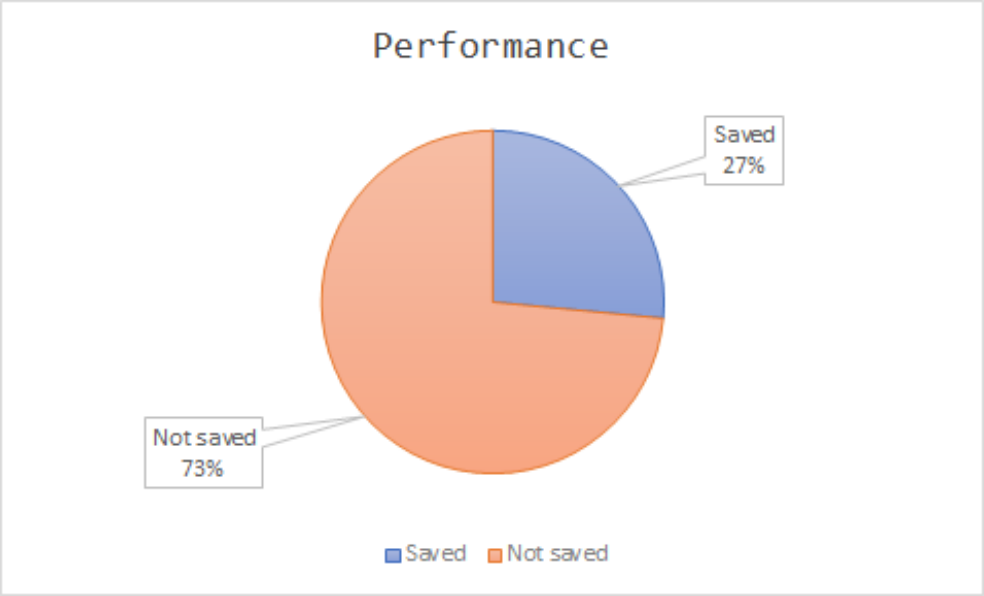

Figure 2: Overall, the tool range analysis was able to improve the bit memory allocation of 27.00%. This percentage as been computed as the ratio of the sum of the performance on all the benchmarks over the sum of the overall performance without optimization.

8 Future work

In this section I am going to highlight some of the current limitations of the tool and some proposes for future improvements.

8.1 Limitations

The tool supports all the most common instruction inside the IR form of LLVM. Nonetheless, the inspection of some instructions is still missing.

The range analysis can infer a great amount of information when the variables are initialized and updated internally inside the function body. The algorithm supports **scanf** instructions. However, the range analysis performs rather poorly over user-defined variables. This happen because the range of a user-define variable generally cannot be limited to a predefined minimum and maximum value, since we can never know at compile-time what value the user is going to insert. This lack of range for user-defined variables often causes a reduction of the performance of the range analysis. The same applies for argument variables of a function.

The major limitation of the tool is the lack of support for floating point variables. The introduction of floating point ranges complicates a lot the analysis. Many researches and proposes has been advanced for the range analysis of floating point variables, and other solutions are available online.

8.2 Possible improvements

Here I propose some improvements that can be implemented inside the tool for future versions:

- Adding support for floating point range analysis
- Adding support for more IR instructions that may introduce an improvement in performance. Generally speaking, not all instruction may be useful to extract information on ranges. Nonetheless, some advancement can be made by implementing a more thorough analysis of all the IR instruction of LLVM.
- Adding support for function parameters. Currently the tool does not support argument variables in input to the inspected function. It may be possible to improve the performance in case the argument variable analysis yields a more restrictive range.
- Adding support for pointer instructions. A pointer instruction introduces back *load* and *store* instructions in the branch range analysis IR code. Since pointers are broadly used in the C language, this improvement may greatly expand the scope of the tool.

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