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A Practical and Comparative Study of Call Graph Construction Algorithms

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ABSTRACT: *A number of Call Graph construction algorithms have been designed for construction of Call Graphs for object-oriented languages. Each of the Call Graph contraction algorithms were proposed to keep in mind the improvements over previous Call Graphs in terms of precision, cost and accuracy. In object oriented languages the Call Graphs are generally contracted to represent the calling relationship between the program's methods. The Call Graph forms the bases for deducing the information about the classes and the methods that are actually invoked, this information can be used to find call sites were virtual function calls can be replaced by direct calls and inline-expansions can be put into work where ever possible. In this paper we present an empirical comparison of various well known Call Graph construction algorithms. Here we used Scoot bytecode reader as front-end to implement various Call Graph construction algorisms. In the processes Scoot bytecode reader is used to read the bytecode of a specific java program then the reachable methods are found for each invoked method. For storing information about the classes, methods, fields and statements we created our own set of data structures.*

Finally we tested and evaluated the developed algorithms with a variety of java benchmark programs to gather the information for the comparison of various Call Graph algorithms which is the goal of this work. We have included most of the Call Graph algorithms of popularity in this work. The main aim of the work is to consider all the dimensions of the Call Graph construction algorithms like cost, precision, memory and time requirements for its construction. The previous works has either not included all the algorithms of fame or have left some of their construction constraints untouched. This work will bring an effective empirical comparison to the front and will help to reveal that which Call Graph construction algorithm is best and when. The results in the work are mainly considered valid for java and other statically typed object-oriented languages.

I. INTRODUCTION

The Call Graphs are the basic data structures to analyze the calling relationships between program methods [1]. A Call Graph is generally a set of directed edges that connects the call sites to their corresponding target methods. A Call Graph is a very powerful tool that can be used in a number ways like it can help in planning testing strategies, reducing the program size by eliminating the methods that are not invoked, helps programmers to understand the nature of larger programs and dubbing etc. depending up on the static or dynamic behavior of the program the Call Graphs can be static or dynamic. The dynamic Call Graphs are constructed in one run of a program by recording all the target methods. On the other hand a static Call Graph represents every possible of a program. Since in a Call Graph a single call site can have multiple target methods because the method that is invoked by a specific call site can mainly be determined during run time based on in which context the call is made. This is clearly evident in object-oriented languages where the feature like inheritance and polymorphism makes the method calls to be very highly dependent on the execution context. For getting a set of target methods we can observe a number of executions of a program and a note of all method invocations of a call site can be made or we can make a note of such invocations in a single run of a program. The dynamic construction of Call Graph tends to under-estimate the number of method invocations by a call site and in contrast the static generation of a Call Graph tends to over-estimate it. Theoretically the dynamic Call Graphs are not safe and the static Call Graphs are expensive to construct.

II. MOTIVATION AND OBJECTIVES OF THE WORK

In programming world, the Object-Oriented paradigm has gained a wide popularity. Some its excited features such dynamic binding, polymorphism and garbage collection are have really made wonders in facilitating the programming, but at the same time these features may put adverse effects on program performance. In Object-Oriented languages the method call are used very frequently without any concern to whether compiler optimization techniques exist or not, and there is a possibility of presence of polymorphic

method calls. Therefore developers must consider the preciseness of code. Program analysis helps developers to get these problems and movies towards programming languages optimization.

Whole program analysis also called as Interprocedural Analysis is the analysis of the program source code. It is one of the method to enable an optimizing compiler to more precisely model the effects of noninied calls, thus enabling it to make less pessimistic assumptions about program behavior and reduce the performance impact of noninlined call sites [3]. Interprocedural Analysis produces the summary of the effect if each called method at each call site and the summary of effect of each caller at each procedure entry [2]. The Interprocedural Analysis not only produces the summary of effects of individual methods but also influence of interactions between methods. In general, for Whole Program Analysis Call Graph is one of the important prerequisite. A Call Graph acts an information transporter between methods, it can be helpful in eliminating virtual method calls, deducing the classes and methods which are never called in program, aliases, strangers and singletons as well. Call Graphs also applicable to Software Engineering tools like Eclipse to resolve program source code references or as an input to some point-to analysis applications for further analyzing. Call Graphs are also used for better understanding of program control flow that in turn increases the human comprehension of the program [4]. Call Graphs can also be used for program testing by determining the order of procedures and method calls. To conclude we can say that the main application of Call Graph construction is to eliminate the dead code by identifying the classes that are never loaded or whose objects are not created methods that are not called or the branches that are never used in any program run. It also helps in elimination of polymorphism, detection of aliases and strangers and detection of singletons etc.

In this work we will implement the most well known and recent Call Graph construction algorithms like CHA, RTA, CTA, and XTA by using Soot byte code reader for java. We are using soot as a standalone tool to implement and test the said algorithms with various Java Benchmark Programs and not as a plug-in to Eclipse.

The main tasks need to be accomplished as the primary objective of this work:

- To implement different Call Graph construction algorithms.
- Using some combination of small and large Java benchmark programs as input to the Call Graph Construction algorithms.
- Generate Call Graph for Java benchmark programs.
- Evaluating general results for different Call Graph construction algorithms.
- Comparing the Call Graphs generated by different algorithms in terms of preciseness, cost of construction, time required and other related parameters.

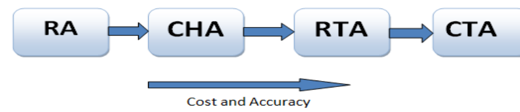
III. INTRODUCTION TO SOOT FRAMEWORK

Soot has been developed by the Sable research group of McGill University, who are mainly engaged with developing the tools for better understanding and faster execution of Java programs [5]. One of the best advantages of Soot is that it provides four levels of *Intermediate Representation* (IR) for analysis. All the IR levels have different levels of abstractions to offer different benefits at analysis. These for IR levels are *Jimple, Shimple, Baf and Grimp.* Soot can be used as a *Plug-in* to Eclipse or it can be used as a standalone tool as well. Different levels of IR have different uses like Baf is Bytecode representation and is somewhat similar to Java bytecode, similarly the jimple is stackless 3-address code useful for most of the analysis tasks. We have used jimple for our experimental setup. Jimple is prime Intermediate representations of Soot. Jimple is basically a typed 3-address statement based representation. Jimple can be created directly in Soot or it can be created by on Java source code or Java bytecode/java class files. To translate the bytecode into jimple new local variables need to be introduced for the implicitly stack locations and using subroutine elimination to remove jsr instructions. Linearization and naming of expression is of core considerations during the translation because the statements can refer only 3 local variables or constants. This represents the more convenient representation for optimization. In jimple an analysis has to handle only 15 statements in Jimple representation compared to more than 200 possible instructions in Java bytecode. Jimple is a hybrid between Java sourece code and Java bytecode. Jimple is the best foundation for most of the analysis works that do not require explicit control flow and Static Single Assignment (SSA) form of Shimple. In Soot Jimple Intermediate Representation can be found in the Packages like Soot.Jimple, Soot.Jimple.toolkit.* particularly in Soot.Jimple.toolkits.scalar and Soot.Jimple.toolkits.annotations.*.

IV. THE BASICS OF VARIOUS CALL GRAPH ALGORITHMS

A Call Graph forms the foundation for various analysis works. A call graph in general represents the calling relationship among the methods. A Call Graph is a finite rooted directed graph G (V, E) where V is a set of nodes and each node representing a method and E is a set of edges and each directed edge e (v, u) represents a method call from method v to method u. consider the example1 code and its corresponding Call Graph in fig 1. It clear from the above figure that each caller method can have set of possible callees in the Call Graph and if

there are no invocations in the method body then this set could have a size 0. Call Graph construction algorithms differ in complexity, cost, and accuracy. The more complex Call Graph algorithms give more accurate and precise Call Graphs.



The following sub-section gives the brief overview and formal definition of various Call Graph Construction algorithms which are in consideration of work of Call Graph comparison.

1. Reachabilty Analysis (RA)

Reachability Analysis is one the simples Call Graph construction algorithms, in fact it was the first algorithm for Call Graph construction. It gives associated with giving a Name-based resolution i.e. it considers only the method names and has nothing to do with method signatures. This algorithm suffers from the problem of generating largest set of reachable methods in comparison to its counterpart algorithms. The only aim of the RA is to compute a set *Reachables* of all the reachable methods. For formal definition of the algorithm we are using the nations somewhat similar to the notation in some previous works for the ease of understanding and retaining the tradition of notations. Lets us use s.n() notation for a call site that happens to occur in method boy M.m(), and the notation Edges for a set of calling relationships among methods.

The RA algorithms can be expressed as:

1. Start analysis and consider the *main* method and other entry points as *Reachables.*
2. For all M.m( ) in Reachables and for each call site s.n( ) such that s.n( ) is an expression of type S inside the method body M.m( )

If any C declares n() such that name (S.n( )= name (C.n( ))
Reachables = C.n( )
Edges = (M.m( ), C.n( ))

3. Repeat steps 2 until it reaches the stage were no changes can be made to *Reachables.*

Reachability Analysis finds all the reachable methods in a program and then adds them to the set of reachable methods. The RA does not take into account the method's parameters and return types, only the methods names are used to find the set of reachable methods. In spite of the fact that RA is less precise and very conservative algorithm it is still used in some applications like removing unreachable methods in link-time. Consider the Example code of Example 1, for this code on applying RA the set *Reachable* will be as:

Reachable = { Z.main ( ), X.foo ( ) , Y.foo ( ), Z.foo ( )}

The RA is based on fixed-point approach i.e. it keeps of adding the reachable method to the set *Reachable*s until there are no previously added methods in *Reachables* set to be processed and more changes take place in *Reachables.*

2. Class Hierarchy analysis (CHA)

CHA is an extended version of RA; it takes Class Hierarchy information into account and gives more precise results than simple RA algorithm. Since CHA implementation requires Class hierarchy information hence class hierarchy of whole programe must be available before running the CHA algorithm. Like RA the result of the CHA is also a set of Reachable method, since CHA is more precise than RA so the set of Reachables in CHA is smaller than that generated by RA and for each call site in the program, this set of reachable methods decrease. Notations that we require to describe the CHA in addition to that of RA are: type (b) as static type of B, subtypes(type (b)) as the set of sub-types(subclasses) of type(b) including B itself .Like

RA CHA also follows the fixed-point approach and can be described as follows:

1. Start analysis
2. For each method M.m( ) in the set *Reachables* and for each call site S.n() where S.n ( ) is an expression of type B inside method body M.m( );

For each class C belongs to subyptes(types(b))
If any class C decleares n ( ) such that Signature (B.n ( )=signature (C.n( ))

a. *Reachables*= C. ( );

b. *Edges*= (M.m (), C.n());
3. Repeat the step 2 until it reaches to the point where no more changes occur to the set *Reachables.*

The example 2 will shows an example code fragment and the corresponding set Reachables:
Example 2:

```
Class X {
foo(…){………}
foo_circle(……..){…..}
}

Class Y extends A{

 foo(…) {…………..}
foo_tringle(……){……….}

}
Class Z {
Z z= new Z();
foo(….) {………}
}
Class XYZ{
Void main(……….){
X x=new X( );
x.foo();
}}
```

Reachables = {XYZ.main( ),X.foo(),Y.foo()}

Here the set *Reachables* clearly smaller than the one we see in case of RA.

3. Rapid Type Analysis (RTA)

This algorithm was an improvement over the CHA. It takes the class-instantiation information into account for computation of Reachable methods a compared to that of only method names in simple RA and method names and method signatures in CHA. In addition to that of Class Hierarchy Information the RTA also considers the whole program's class-instantiation details as well. To limit the set of Reachable methods another set instantiated classes are used. For RTA algorithm we will use the notation IC for the set of cases that were instantiated in the program. The RTA too based on the fixed-point approach.

The RTA can be defined as follows:
1. Start analysis
2. For each method M.m() is set of *Reachables* and for each constructor Call site new C( ) inside method body M.m( )

If M.m() is in *Reachables*
C is in *IC//IC is for* instantiated classes
3. For each methods M.m ( ) in *Reachabels* and for each call site S.n( ) inside method body M.M ( )
For each class C belongs subtypes (type(b))
If any C declares n( )such that signature (B.())= signature (C. n()) and C belongs to IC

a. add C.n ( ) to *Reachables;*
b. *add (M.m ( ), C.n ()) to Edges;*
4. *Repeat the step 2 and 3 until it reaches to a fixed-point stage.*

For the code of example 2 after applying the RTA the Reachables and IC set will be as:

Reachables= { XYZ.main( ), X.foo()},
IC= {X, Z};

4. Class Type Analysis (CTA):

Since the preciseness call graph generated by any algorithm depends upon the number of sets it compute. Basically the results generated by any Call Graph construction algorithm is approximated by the

number of sets it generate for the program that is why each part of the program like classes methods and other entities of the program are associated with a set. The more number of sets an algorithm use the more precise call graph will it generate. As we has seen in above section that RA and CHA does not use any sets to compute their results, RTA uses one *set instantiated classes* to restrict the number of reachable methods and compute more precise call graphs. However the additional overhead that an algorithm must incorporate in order to compute these sets can be neglected.

CTA algorithm connects each class X with a set called Contain (X) to impose a restriction on set of possible call targets. This set is supposed to contain the object types that can be found inside the class X. basically it contains the Class X itself, all its supertypes, types that are carried by method calls such as return types and types which are created inside. For the formal definition of CTA the notations required are *Contains(X)* a set that keeps track of the contained classes of class X, *Supertypes(X)* as set of all subtypes (superclasses) of X. *F* as the static type of field of *f,* subtypes(*F)* as the set of all subtypes(subclasses) of *F, ParamererTypes(X.m( ))* for the set of static types of parameters of method X.m *( ) and ReturnType (St.n())* as the set of static return type of method St.n *( ).*

Formally the CTA can be written as:

1. Start analysis

2. For each method X.m() in Reachables
M belongs to Contains (X)
Supertypes(X) belongs to Contains (X)
for each constructor call site *new* B( ) inside method body X.m();
B belongs to *Contain(X)*
For each X.m( ) inside Class X targeting St.n();
Subtypes (ReturnType (St.n())) belongs to C*ontain* (X)
For each externally called method X.m() in Class X;
Subtypes (ParamaterType(X.m( ))) belongs to *Contain* (X)
For each field *f* that declared in Class X
Subtypes (F) belongs to *Contain* (X)

3. for each method X.m( ) in *Reachables* and for each call site S.n( ) inside method body X.m( );
for each Class C belongs to subtypes (types (b))
if any C declares n( ) such that signature(B.n())= signature (C.n())and
C belongs to *Contain (X)*
Add C.n ( ) to *Reachables;*
Add (X.m ( ), C.n( ) to *Edges;*

4. Repeat the step 2 and 3 until it reaches a point where no more changes can occur to the set *Reachables.*

It can be observed from the above formal definition that CTA is basically a bi-phased procedure. The first phase is called the Data flow phase and the second phase is called the Class Graph construction phase. In Data flow phase a set *Contains (X)* is constructed for each class X. this set includes the Class X, all its subtypes and all classes allocated within Class X. in second phase, CTA constructs the Call Graph as per the Data flow phase that puts a sort of restriction on the set of reachable methods and generation of more accurate Call Graph.

5. Separate Type Analysis XTA:

XTA is a new comer and one of most focused Call Graph construction algorithms. As mentioned above the preciseness of call graph generated by any call graph algorithm depends upon the number of sets it uses for construction of the call graph. There is a cost penalty for maintaining more sets by a Call Graph construction algorithm, but at the same time the preciseness of the Call graph generated is high. XTA is based on somewhat similar concept. XTA uses a separate set for each method M.m and for field X. this gives it the freedom of putting more restriction of the reachable methods. XTA has following constrains:

a. The *main* method is always Reachable.
b. For any method C.m() add C to M.m();
c. For any reachable method, for all the constructors of the new "C( )" that happens to occur inside the method body M.m ( ) add C to set of reachable methods.
d. For all reachable methods, for all fields X that can are read, add set of fields to set of methods.
e. For a reachable method, for its all fields X that are written, add ∩ of set of reachable methods and all subtypes (Type(X)) to the set of fields.

Since XTA uses distinct sets for all reachable methods and fields we can define the XTA in formal terms as follows:

1. Start analysis while considering main method and all entry points in the set of *Reachables.*
2. M.m () is in *Reachables;*
3. For all class static methods St, class (St) is in S(M.m())

New N is a constructor call site in the method M.m()

N ∈ S(M.m) and N.New( ) ∈ *Reachables AND (M.m(), N.New)* ∈ *Edges;*

e.n() is a filed access | call site in M.am( )

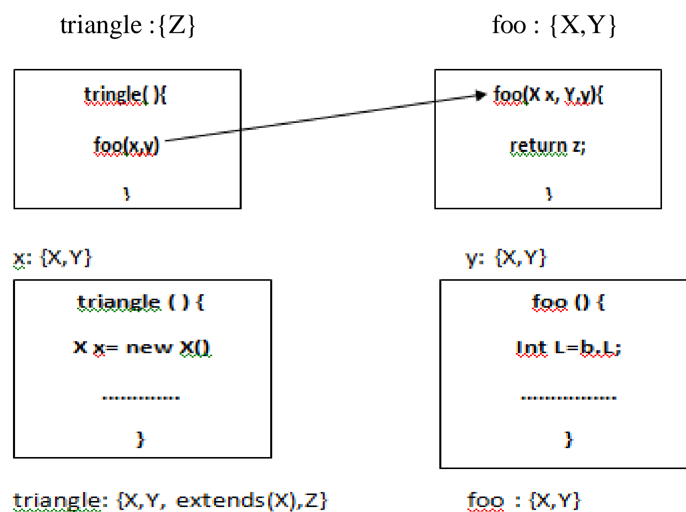
4. for each N ∈ subtypes (type(e)) AND *N* ∈ S(M.M()) : N.n()∈ *Reachables* AND subtypes (param(N.n()) ∩S(M.m()) is a ⊆S(N.n() AND

Subtype(result(N.n()) ∩ S(N.n()) ⊆ S(M.m()) AND (M.m(),N.n())∈ *Edges.*

When applying XTA to the sample code of Example 2 the following sets are expected to be used:

For each method the following sets will be there:

Similarly for each field:



V. IMPLEMENTATION OF ALGORITHMS AND IMPLEMENTATION ISSUES

We are using soot (Jimple) frame work for our purpose in order to be in line with other related works. In Soot when a Call Graph is available it can be accessed through the environment Class “Scene” by using method getCallGraph. The Call Graph call and other related constructs are can be found in the pakage Soot.Jimple.toolkits.callgraph. In Soot, a Call Graph as a collection of edges representing all method invocations. The method invocations include explicit method invocations, implicit invocations of static initializers, implicit calls of thread.run(), implicit call of finalizers, implicit calls by AccessControllers and many more. In Soot each edge in a Call Graph has four elements: source method, source statement, target method and the kind of edge (e.g. static invocation, virtual invocation, and interface invocation). To quarry the Call Graph in more detailed way Soot provides two constructs namely ReachableMethods and TransitiveTargets. To keep tract of which methods are reachable form the entry point the ReachableMethods object is used. *Contains(method)* checks whether any specific method is reachable, and the *listener()* method returns the iterator over the reachable method, where as the TransitiveTargets is very important for iterating over all methods possibly called from a certain method or any other method it calls.

We adopted the worklist approach as used in previous works for implementation of various Call Graph construction algorithms to make implementation simpler and more understandable. As mentioned in above algorithms the entry points are considered be reachable at the start of analysis. So the worklist also starts with nodes for all entry points like main, start, run etc. as each node for a method is added to the Call Graph, the edges from the call site in the node is also added. For every target node of an edge that is not already in call graph, it is added to the call graph and to the worklist as well. For CTA algorithm we started with initializing worklist with *main( )* method and a set of methods which are almost called in every program such as java.lang.Object.client() and java.lang.System.initilizeSystemClass(). Once the worklist is initialized we proceed with removing the first method in worklist and supposed it as a source node of the Call Graph. Then all of its statements are searched for each call site that is found, it corresponding methods are obtained. Then the edges are added from every source node to all reachable methods and they are added to worklist as well for

further processing. These steps are repeated for all the worklist members until there is not any previously added member and the worklist is empty. For implementation of other algorithms we used the results of previous algorithms as input to them with and added some additional features to them we got some significant performance improvements. For example while implementing RTA we used the resultant Call Graph as generated using CHA as input to it, as we know that all the classes are visited during CTA construction, by using additional feature like *instantiated classes* we get RTA. Every time a new feature is added a new set is used for that feature like the one we used for *instantiated classes.* The similar sort strategy of adding various new features as per the requirement of the algorithm is used for the other algorithms as well.
An important thing to note is what work list consists of.

While comparing call graphs both qualitative and quantities measures need to be consider. If call graphs are produced using the same tool the quantities comparison can be done easily and is a straight forward process, however qualitative differences are hard to get. For instance we can easily get the total number of edges of the number of reachable methods the graph form program starting point, but due to the large nature of programs getting the qualitative measures is really a hard job. There may be programs which contain the call sites that are never executed, like we have unused portion in the library, or there may be a function that if executed would a large module of program, but no actual execution reaches to the function in a call graph a single spurious edge to a function leads the entire the unused module to be included in the method is modeled as a lake, and each call edge as a connecting river [6].

VI. EXPERIMENTAL SETUP AND NATURE OF BANCHMARKS

Following table1 gives the brief description about the benchmarks used. All the experiments were run on Intel(R) Atom (TM) CPU 270 1.60GHz processor, 2 GB memory PC with Linux and Sun JVM 1.4.1.07 and off course running Soot and Eclipse frameworks, even though we have used only Soot for implementation and analysis purposes.

We have used the experiments on eight SPEC javm98 suite[7] as is done in most of the previous related works in addition we used some new benchmarks to make our results more authentic and applicable to the program size of any kind.

The bytecode reader used in the implementation process is the Soot, and the Intermediate Representation used is Jimple the prime intermediate representation of Soot. Soot is a Java optimization framework for analyzing and transformation of Java bytecode. Soot can be used as standalone tool to optimize or inspect class files, as well as framework to develop optimizations or transformations on Java bytecode [7]. To evaluate the implementations using Soot we used twelve benchmarks cited in table 1 along with their descriptions. To access the performance of Soot we can measure the Elapsed time and memory requirements of the benchmark programs and later can be used as performance metrics. Since the best way of comparing call graphs generated during interprocedural static analysis is to compare them with dynamic call graphs. The dynamic call graphs are constructed by recording the call sites that are executed and all the target functions that are called from each of them[6] more precisely static call graphs approximates the dynamic call graphs, and is defined by the abstract equivalent [5].we have tried a little to include the dynamic version of XTA in our work so that static and dynamic nature of call graphs can be compared, however the main the main metrics that are used in this work are the number of nodes were each node represents a reachable method, Number of Edges where each edge represents a calling relationship between methods, time elapsed that is the time taken from the initiation and the completion of Call Graph construction, Used memory, this is done by using Java garbage collection, we tried to free that memory occupied by various objects that are no longer in use, and measure the consumed memory for each Call Graph construction algorithm.

VII. EXPERIMENTAL COMPARISONS AND OUTCOMES.

Using Soot we tested the Call Graph algorithms with the benchmarks listed in table 1 multiple times, and then we compare the average resultant Call Graphs computed using CHA, RTA, CTA and XTA as per the set metrics defined in section VI.

a) *Number of Call Graph Nodes*

Different studies have revealed different results when comparing different Call Graph algorithms. The results we were able to produce are briefly shown in the Table 2. The Table 2 vital statistics that we were able to collect during various runs of the benchmarks on different Call Graph algorithms as presented in the table 2. From table 2 we can simply infer the following facts:

1. On comparing the RTA with CHA the average number of reachable methods that are reduced by RTA is approximately 4.065%, provided that minimum numbers of reduced reachable methods are 0.959% and the maximum are 12.584%.

2. On comparing the CTA with CHA the average number of reachable methods that are reduced by CTA is 6.551%, provided that the minimum numbers of reachable methods reduced are 2.001% and the maximum numbers of reachable methods reduced are 13.971%.
3. On comparing the XTA with CHA the average number of reachable methods reduced by XTA are approximately 20.526%, provided the minimum number of reachable methods reduced are13.429% and maximum number of reachable methods reduced are 30.294%.

b) ***Number of Edges in Call Graph***

On comparing the number of edges in Call Graphs computed using different algorithms are shown in Table 3.The Major summary for the number of edges generated using different algorithm are as:

1. In contrast to the CHA the RTA reduces the number of edges approximately at the average of 4.087%, provide the minimum numbers of edges reduced are about0.289% and the maximum number of edges reduced are about 15.953%.
2. In contrast the CHA the number of edges reduced by the CTA are approximately 16.876%, provided that the minimum number of reduced edges by CTA are 2.716% and the maximum number of edges reduced are about 25.968%.
3. XTA when compared with the CHA comes with more precise results, it reduces the number of edges approximately with an average of 22.730%, when the minimum number of edges reduced is about4.663% and the maximum number of edges reduced is about 64.44%.

c) ***Time Elapsed***

Time consumed by an algorithm depends on the how fast the *worklist* can be constructed and depends on Soot framework and the nature of benchmark and the Call Graph algorithm used. The time requirement for each algorithm with corresponding benchmark that we are able to estimate is shown in Table 5.When comparing the time requirements for each algorithm in Soot we were able to collect following statistics:

1. The time requirements for RTA are little more than that of CHA, when computed RTA needs approximately 1.297 more time than CHA, this may because of additional overhead of construction of extra sets for Call Graph construction.
2. On comparing the CTA with CHA, we can observe that CTA is slower than the CHA, and more precisely we can say that CTA 3.629 times faster than CHA.
3. When comparing the XTA with the CHA there is a significant time variation, we was able to found that XTA is on average 12.453 slower than that of CHA. This is because of its more struggles towards preciseness and extra overhead of maintaining more sets for construction of Call Graph.

d) ***Memory Utilized by Call Graph algorithms***

Soot uses a very different memory management scheme than other bytecode readers. Depends on memory requirements for various data structures and for how longs they need to be kept in the memory for further use the memory requirements of benchmarks can be made. In Soot garbage collectors can remove certain data structures for example class hierarchy information in Soot is kept in memory after Soot configuration. Table 6 shows some of the facts about memory requirements of various Call Graph construction algorithms in Soot.

VIII. CONCLUSION

In this work we have seen how various Call Graph algorithms differ from each other in various respects. We have analyzed that how Soot behaves with these algorithms. We can say that Soot is a Java optimization framework which is analyzed with a lot of functions [9].the Table 7 shows the overall results obtained from various Call Graph algorithms. According to the Table 7 we can see that compared to CHA the RTA has better results in terms of reduction of number of edges. That average percentage number of Nodes (reachable methods) reduced by RTA compared to CHA is 4.065%. similarly when CTA is put in front of CHA and the number of reduced Nodes(reachable methods) is 6.551% and in compared to CHA XTA shows significant results and reduces the number of Nodes (reachable methods) with average percentage of 20.526%. there are cases with many benchmarks when the performance of RTA is not good as per the expectations for example for Jack program the percentage of reduced reachable nods in just 0.959% and in Javac it is only about 1.376% but in the same time RTA has more significant performance like in programs JFreeChart and mpegaudio it reduces the number of reachable methods with a percentage of 12.584% and 8.824%. CTA as per the Table 7 goes far behind in reducing the number of reachable methods both in individual benchmark and on average as well for example in JFreeChart benchmark it can reduce the number of Nodes up to 13.971%. XTA goes an extra mile in reduction process it can recdce the number of Nodes in Call Graph up to 20.526% on average, and individually we can see for Javac program it reduced the Nodes up to 30.294 on average. The Table 7 shows the time penalty for each of the algorithms as we move towards the higher preciseness we can see

the time requirements of algorithms also increase. RTA is 1.297 times slower than CHA and CTA is around 3.6929% slower than CHA and comparatively the CHA is 12.453 faster than XTA.

The number of edges that is present in the Call Graph computed by each algorithm brought some interesting results to the front. When we see the number of edges reduced by RTA as compared to CHA, the RTA reduces the number of edges with percentage about 4.087% similarly CTA reduces the number of edges a percentage of about 16.876% and XTA comes again with good results and the number of reduction percentage is about 22.526% as compared to that of CHA. However the for this improvement the memory penalty is there. The algorithm that reduces more number of nodes and the edges elapses more time and consumes huge amount of memory. The details of which are present in the Table 7.

IX. FUTURE WORKS

It is better to compare the static Call Graphs to their dynamic counter parts. This work can be extended to some more Call Graph algorithms like VTA, and K-CFA [119]. Furthermore we can compare the framework used for implementation with other available alternatives to get even more accurate and precise results. We have the option of using Soot and ASM for construction of Call graphs and then better comparisons. In addition testing and comparing Call Graphs on different frame works will make results more general so that they can be applied on any optimization framework. Some new dimensions in terms of metrics like line number, number of variable, number of successors can be added for each Call Graph node and these metrics can be added to get a new Call Graph whose every node correspond to a different kinds of metrics.

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XI. LIST OF TABLES AND GRAPHS

Table 1: Benchmark Descriptions

S.No.	Benchmark	Description
1.	compress	A high-performance application to compress or uncompress large files; based on the Lempel-Zev method Web reference: www. Specbench.org.Javaclient/serverbenchmarks
2.	jess	A Java Expert shall systembased on NASA's CLIP system. Web reference: www.Specbench.org.Javaclient/serverbenchmarks
3.	db	Perform database functions on a memory-resident database Web reference: www.Specbench.org.Javaclient/serverbenchmarks
4.	javac	JDK 1.0.2 JAVA compiler Web reference: www.Specbench.org.Javaclient/serverbenchmarks
5.	mpegaudio	MPEG-audio file compression application. Web reference: www.Specbench.org.Javaclient/serverbenchmarks
6.	mtrt	Dual-threaded version of raytrace. Web reference: www.Specbench.org.Javaclient/serverbenchmarks
7.	jack	A java presser generator with Lexical analyzers (now JavaCC). Web reference: www.Specbench.org.Javaclient/serverbenchmarks
8.	ANTLR	A language tool that provides a framework for construction of recognizers, interpreters, compilers, and translators.
9.	BLOAT	It is a Java bytecode optimizer and analysis tool.
10.	EMMA	It is an open-source toolkit for measuring and reporting Java code.
11.	JFreeChart	It is an open-source java chart library, supporting a wide range of chart types.

Table 2: number of Reachable Methods (Nodes) in CHA, RTA, CTA and XTA Call Graphs.

Benchmark	CHA	RTA	CTA	XTA	RTA/CHA	CTA/CHA	XTA/CHA
compress	365	350	339	303	4.110	7.123	13.429
jess	1122	1104	1020	943	1.604	9.091	15.954
db	411	396	379	350	3.650	7.786	14.842
javac	1599	1577	1567	1198	1.376	2.001	25.078
mpegaudio	680	620	611	474	8.824	10.147	30.294
mtrt	601	586	581	464	2.496	3.328	22.795
jack	730	723	702	576	0.959	3.836	21.096
ANTLR	780	762	751	561	2.308	3.718	28.077
BOLT	2890	2755	2714	2312	4.671	6.090	20.000
EMMA	1409	1379	1339	1187	2.129	4.968	15.756
JFreeChart	2090	1827	1798	1704	12.584	13.971	18.469
AVERAGE					4.065	6.551	20.526

Chart 1: Comparison of Number of nodes in different Call Graphs.

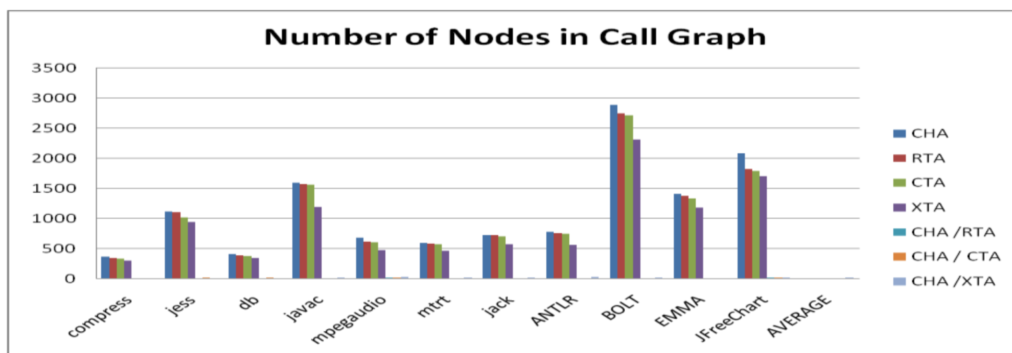

Table 3: Number of edges in Call Graphs generated by CHA, RTA, CTA and XTA.

benchmark	CHA	RTA	CTA	XTA	RTA/CHA	CTA/CHA	CHA /XTA
compress	1191	1001	978	897	15.953	17.884	24.685
jess	3913	3844	3674	3333	1.763	6.108	14.822
db	1498	1377	1109	1012	8.077	25.968	32.443
javac	8063	8003	7844	7687	0.744	2.716	4.663
mpegaudio	2150	1991	1897	1680	7.395	11.767	21.860
mtrt	2089	1989	1670	1599	4.787	20.057	23.456
jack	2899	2844	2609	2430	1.897	10.003	16.178
ANTLR	2996	2922	2567	2345	2.470	14.319	21.729
BOLT	21430	21368	19002	17998	0.289	11.330	16.015
EMMA	4778	4728	4601	4313	1.046	3.704	9.732
JFreeChart	16877	16786	6451	6001	0.539	61.776	64.443
AVERAGE					4.087	16.876	22.730

Chart 2: Comparison of Number of Edges in different Call Graphs.

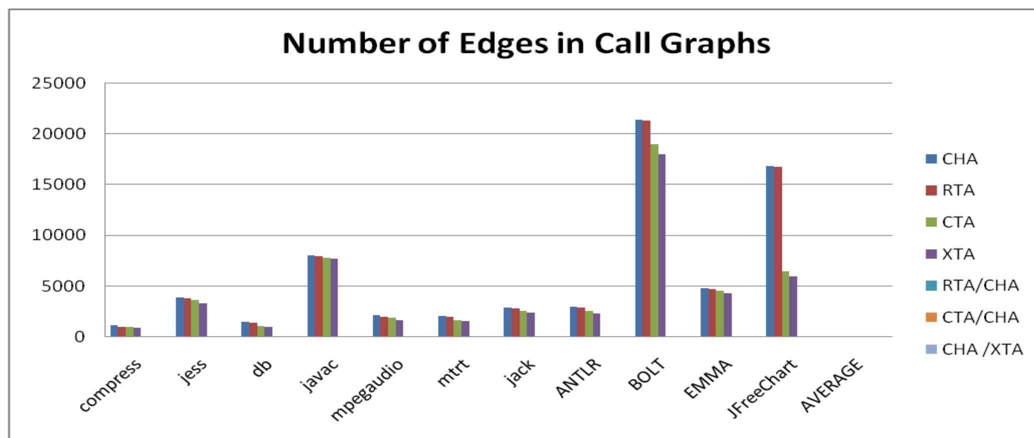

Table 4: Total number of Nodes and Edges in each Call Graph.

Benchmark	CHA		RTA		CTA		XTA	
	Number of Methods	Number of Edges	Number of Methods	Number of Edges	Number of Methods	Number of Edges	Number of Methods	Number of Edges
Compress	365	1191	350	1001	339	978	303	897
jess	1122	3913	350	3844	1020	3674	943	3333
db	411	1498	396	`1377	397	1109	350	1012
javac	1599	8063	1577	8003	1567	7844	1198	7687
mpegaudio	680	2150	620	1991	611	1897	474	1680
mtrt	601	2089	586	1989	581	1670	464	1599
jack	730	2899	723	2844	702	2609	576	2430
ANTLR	780	2996	762	2922	751	2567	561	2345
BOLT	2890	21430	2755	21368	2714	19002	2312	17998
EMMA	1409	4778	1379	4728	1339	4601	1187	4313
JFreeChat	2090	16877	1827	16786	1798	14879	1704	6001

Table 5: Comparison of time elapsed by CHA, RTA, CTA, and XTA.

benchmark	CHA	RTA	CTA	XTA	RTA Vs CHA	CTA Vs CHA	XTA Vs CHA
compress	0.051	0.067	0.475	0.985	1.314	7.090	19.314
jess	0.122	0.14	0.259	0.847	1.148	1.850	6.943
db	0.062	0.08	0.349	2.02	1.290	4.363	32.581
javac	0.172	0.352	0.562	1.948	2.047	1.597	11.326
mpegaudio	0.081	0.097	0.317	1.302	1.198	3.268	16.074
mtrt	0.61	0.86	1.969	2.663	1.410	2.290	4.366
jack	0.091	0.121	0.624	0.955	1.330	5.157	10.495
ANTLR	0.094	0.112	0.413	1.065	1.191	3.688	11.330
BOLT	0.857	0.967	2.567	5.013	1.128	2.655	5.849
EMMA	0.192	0.211	0.832	2.528	1.099	3.943	13.167
JFreeChart	0.657	0.732	2.947	3.641	1.114	4.026	5.542
AVERAGE					1.297	3.629	12.453

Chart 3: comparison of Time Elapsed by various algorithms for construction of call Graph

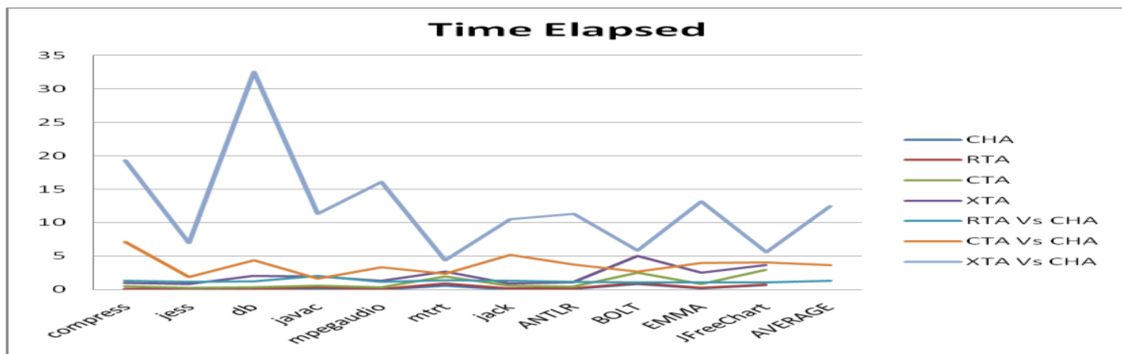

Table 6: Memory used in(MB) by various Call Graph algorithms.

benchmark	CHA	RTA	CTA	XTA
compress	48	50	53	184
Jess	69	70	71	266
Db	53	54	58	192
Javac	69	70	73	296
mpegaudio	57	60	60	202
Mtrt	55	59	59	195
Jack	59	63	63	299
ANTLR	60	65	65	204
BOLT	88	91	91	452
EMMA	78	83	83	420
JFreeChart	165	172	178	552
AVERAGE	72.81818	76.09091	77.63636	296.5455

Chart 4: The amount of memory used in MB's by various Call Graph algorithms.

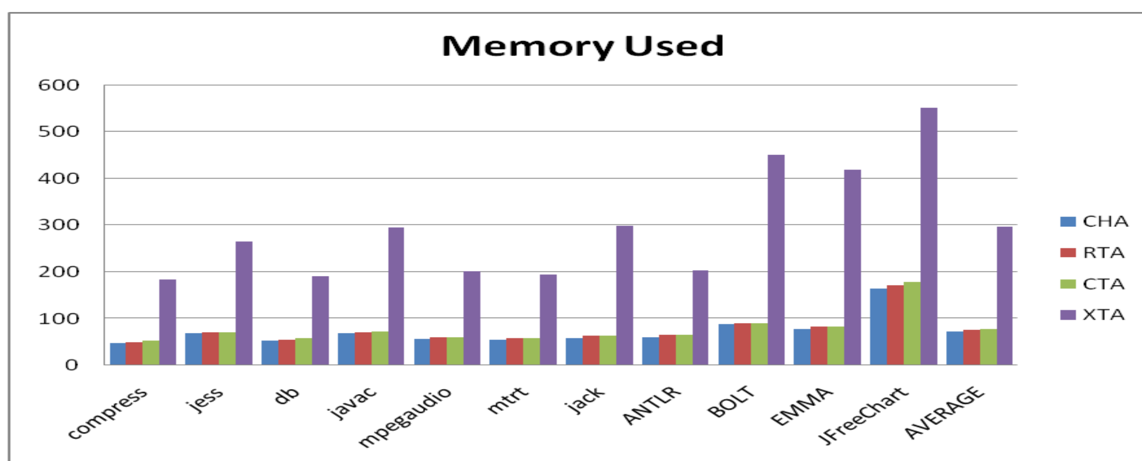

Table 7: overall comparison of various algorithms

benchmark	RTA/CHA %age of Nodes reduced	RTA/CHA %age of Edges reduced	CHA/RTA average Time Elapsed	CTA/CHA %age of Nodes reduced	CTA/CHA %age of Edges reduced	CHA/CTA average Time Elapsed	XTA/CHA %age of Nodes reduced	XTA/CHA %age of Edges reduced	CHA/XTA average Time Elapsed
compress	4.110	15.953	1.314	7.123	17.884	7.090	13.429	24.685	19.314
jess	1.604	1.763	1.148	9.091	6.108	1.850	15.954	14.822	6.943
db	3.650	8.077	1.290	7.786	25.968	4.363	14.842	32.443	32.581
javac	1.376	0.744	2.047	2.001	2.716	1.597	25.078	4.663	11.326
mpegaudio	8.824	7.395	1.198	10.147	11.767	3.268	30.294	21.860	16.074
mtrt	2.496	4.787	1.410	3.328	20.057	2.290	22.795	23.456	4.366
jack	0.959	1.897	1.330	3.836	10.003	5.157	21.096	16.178	10.495
ANTLR	2.308	2.470	1.191	3.718	14.319	3.688	28.077	21.729	11.330
BOLT	4.671	0.289	1.128	6.090	11.330	2.655	20.000	16.015	5.849
EMMA	2.129	1.046	1.099	4.968	3.704	3.943	15.756	9.732	13.167
JFreeChart	12.584	0.539	1.114	13.971	61.776	4.026	18.469	64.443	5.542
AVERAGE	4.065	4.087	1.297	6.551	16.876	3.629	20.526	22.730	12.453

Chart 5: the overall comparison chart.