# Final Report

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***Abstract*—MemSan's initial goal was to become a user-supplied data flow analyzer targeting memory-sensitize functions like strcpy that could lead to buffer overflow vulnerabilities. This paper will explain the steps that succeeded and those that didn't, the architecture, the problems encountered and some ideas on how the process could have been improved.**

## 1. Introduction

The project was split up into 5 parts: metrics extraction, UML class diagrams construction, Control Flow Graph extraction, dominator analysis and, finally, program slicing. Four of the five steps were done and can work on some more trivial examples that do not require a complex compilation process with multiple dependencies and modern C++ constructs like multiple namespaces. One problem that will be discussed is the fact that some of the last steps are dependant on each other and a problem on the CFG might impact the development speed drastically.

## 2. Testing

The project can be compiled with the provided Makefile and outputs the LOG6302 binary. There is also a "analysis" Makefile target that can be triggered to run the python script that will output the different .dot files and one target especially for the first lab that can be triggered with the "-tp1" switch on the Analyzer.py script .csv for the metrics for with the "tp1" target in the Makefile.

## 3. Metrics extraction

### 3.1. Introduction

The first part was metrics extraction like the number of if statements and method and class name. The relevant piece of code is in the src/metrics.py file and the parseClass function.

### 3.2. Methodology

First, it is needed to reconstruct a simplified AST that will be processed later. We produce our own AST representation because our tool is aimed at specific goals and would be obstructed by the number of attributes the original clang AST. We are then decoupled from clang and can more easily implement new parsers and use the same code for the same analysis. For example, our AST output for the same code fits in 20 lines of XML instead of 81 lines of a the custom clang AST output format with also has longer lines. As you can also see, we have full control of our format to ease our post processing. At that step, our custom AST was simple, without any metadata needed for other analyses and consisted only of basic blocs like while statetements, for statements, if's and variables.

**3.2.1. Custom AST implementation.** Using clang's RecursiveASTVisitor, some methods were overriden to redefine the behaviour the visitor on specific elements that I wanted to analyze. I then redefined 5 different traverses and 2 visits. The redefined traverses are the following: TraverseWhileStmt, TraverseIfStmt, TraverseCXXMethodDecl, TraverseCXXRecordDecl, TraverseFunctionDecl. We chose to override traverses for those because they can encapsulate other elements I am interested in and it is then important to visit its children. For example, a class will have methods definitions inside of it and I needed information on the latter to complete our analysis. Because the other 2 elements, VarDecl and BreakStmt, are simpler elements that can't encapsulate others that I want to analyze, visits sufficed to create opening and closing XML tags for our custom AST. The XML format was chosen for its wide use and tree-like structure that fits ASTs well. Elements were subsequently added in the other parts of the project.

**3.2.2. Metrics analysis.** The code metrics extraction is written in Python3 and entirely decoupled from clang. The metric extraction was then a simple walk of the resulting XML tree that counted each instance of code we wanted to measure. The result is exactly what was provided in the project's description which means a CSV file with the following format: ID, FILENAME, CLASSNAME, METHODNAME, #IF, #WHILE, #BREAK, #VARS. It starts and finishes with a 'dump' tag that encapsulates each files that were processed.

### 3.3. Results

The example used for the testing was the one provided, i.e. tests/LOG6302_TP1_example.cpp. It consists only of one method definition (function metrics were not calculated and therefore the main function is not analyzed) Bar in the Foo class. Metrics can be found in the src/metrics.txt file. For the provided example, we then have the following line for output :

0, LOG6302_TP1_example.cpp ,Foo,bar,1,0,0,0

This is the correct output because we have the correct filename, a unique ID, the correct class name, method name, and there is only one if instance, which was correctly calculated.

**3.3.1. Running the project.** To test these results, it is possible to re-run the LOG6302 on any method and run the Makefile with the tp1 target (make tp1).

### 3.4. Difficulties

**3.4.1. LLVM version.** Apart from getting the right version of llvm for the project, no real difficulty was encountered at this stage of the project. I tried the other llvm versions but couldn't make the seed project work with it. I think it would be best to update the seed project to the latest stable llvm version because that caused me some issues where the official documentation that is more easily searchable with Google than its offline counterpart. Because the seed project was a couple versions late, some methods that would have been helpful in some cases and were explained in the online documentation was not in the 3.3 version. For example, many ways are used to get the line number in clang and some have been created in the last few versions which made those methods appear in the documentation but couldn't be used in the project.

**3.4.2. Backwards compatibility.** For the final project, I think it wasn't clear that the final project needed to incorporate all the parts and be able to output every step to be evaluated as I thought that I was already submitted and reviewed so I worked on the previous version of my code base and deleted some functions and changed the way some things worked. This broke retro-compatibility but wsa fixed for the first lab but wasn't for the second as you will see.

## 4. UML class diagrams

### 4.1. Introduction

The second part of the project was to build UML class diagrams from C++ source code. This part took more time than the first lab but didn't prove itself a real problem like the CFG extraction was. I lacked time to properly add this part of the project to the final project and is then located in its own folder in MemSan/tp2 with its own build process. It is possible to test these functionalities in the tp2/ directory with the same process as the main project. The interesting code is in the several nodes created and the parseClass method of the Analyzer class.

### 4.2. Methodology

For the UML class diagrams, I didn't need the number of local variables, break statements, if statements and while statements. I ended up initially deleting that part of the code and broke backwards compatibility like so. The code to generate the UML class diagrams is then in another folder by itself as a snapshot of the release of the second lab. Only one visit was added, the FieldDecl one. This one provides a visit for the class attributes. The type also needed to be extracted in our AST. Luckily, the getType() method was defined with the getAsString() method to convert from internal clang types to strings. This was used for CXXRecordDecl which are classes and FieldDecl. For methods, getResultType() was called to resolve the return value type. This one proved tricky as it will be explained in the difficulties section later. For the XML part, the following tags were added: parentClass that stores the name of the base class in case the class MemSan is analyzing inherits from another one, methodReturnType that stores the return value type of that method. Also, since the attributes were new in this part of the project, I needed tags to identify them. We added the attribute tag to encapsulate all the attributes information As I couldn't get a real project meeting the course requirements to compile using my tool, the test called LOG6302_TP1_example.cpp was heavily modified to test the new use cases. The new file is named LOG6302_TP2_example.cpp and is located in the tests folder. I now use a base class named BaseClass that has one public and one private attribute and a method that returns a void*. One class inherits from this base class and is called ChildClass. The third and final class doesn't use inheritance but has an attribute that is of the type BaseClass. This example can then demonstrate most of the use cases.

### 4.3. Results

Apart from the fact that all methods and attributes are private because no logic to verify that the method is public or private has been implemented. From the official documentation, the isPublic() method should be accessible to verify this quite easily but the 3.3 version doesn't seem to have such methods on the same types of objects which complicated that implementation. The results for the LOG6302_TP2_example.cpp file that can be found in the root folder of the tp2 subfolder are in appendix 2.

### 4.4. Difficulties

**4.4.1. Real project compilation.** Some significant amount of time before the deadline of that part of the project was on trying to compile a big code base with more than 100K LOC. Various projects were tested to try to make it work like the code base of Firefox, chromium, chromium-os, kvm and sqlite. Sqlite was the most promising but, as it is C and not C++, it couldn't be used for the UML class diagram part of the project since C doesn't have the concepts of classes, inheritance and so on. Global namespaces were also a challenge and was fixed much later on with the use of only libcxx from llvm and not its GNU equivalent. This was only known a few days before the final deadline and then couldn't be used properly because other small bugs appeared during the parsing. After researching the final issues I had with the compilation of a major project, I found only one reference of this issue in the LLVM mailing list and was not resolved to this date. I then decided to focus on other parts of the project instead.

# 5. CFG Extraction

## 5.1. Introduction

This is the part where I had the most problems with. Because the next steps needed a perfect CFG. I needed to make sure my Control Flow Graph was good before I could be able to write more code or, because I implemented some parts of the code even when I still had a broken Control Flow Graph, be able to debug it correctly with the results making more sense. The interesting parts of the code are in the parse* functions in Analyzer as well as the recursiveDump and parseNode methods and the buildCFG and dump_cfg methods.

## 5.2. Methodology

Clang's ASTRecursiveVisitor was still used for the part that builds our own AST. Some parts were added like: VisitBreakStmt, VisitContinueStmt, VisitUnaryOperator, TraverseForStmt, TraverseReturnStmt. Python classes for the analysis part of the project were once again added to ease the analysis.

**5.2.1. Modifications introduced.** Introduced in the second part of the project, Nodes were still used to interpret the output of the C++ part of the project. Although the core concept was the same (using nodes), a lot of refactoring had to take place to be able to walk the AST recursively as it eased the construction of the control flow graph. First, every node class was stripped down to only its name and then I added a node type to facilitate the implementation as I didn't need to check if the object was an instance of any node that could be possible. Every node was then added a children attribute that is a list of all its children. An edge will then be added between a parent node and a child node in the dumping process.

**5.2.2. Initial approach.** The walk of the AST is split into two catefories: one is responsible for the dispatch to the right parse function according to the XML tag that it reads so we don't have to repeat the dispatch code in every parse function of every node type. The second one are the parser functions which every node type has one of. Every node type has its own steps required like the WhileNode which needs a whileEnd and whileBegin as well as a testing condition to break out of the loop. Similar logic has been implement for the ForNode as well as the ifNode. The others are simpler and only need to be linked to its immediate predecessor as it is the case for the unaryOperator, ContinueStmt and BreakStmt. The ReturnStmt is a special case has it need to linked to the exit node. The exit node is a singleton node that is the first to be created to be able to link to it without errors when GraphViz parses the output of our tool.

**5.2.3. Problems with the first approach.** At first, the CFG produced was the one included in appendix 2. Some bugs were still present as you can see from the figure. Firstly, the unaryOperator is in the wrong order as the returnStmt is currently a traverse and the unaryOperator is treated like its child but it is the returnStmt that is linked to the exit node. Secondly, some edges are missing and I couldn't find the bug in the logic in time. Thridly, some edges are duplicated as we can see in one of the return nodes. This is caused by the fact that the return node has multiple parents and causes the node to be visited multiple times and then the logic that is responsible for linking the return node to the exit nodes is executed multiple times.

**5.2.4. Issues explanation.** Those issues can be explained with a few different reasons. First, the control structures like loops and conditional branches should have been completely structured as an independent block acting as any other node in the Control Flow Graph. I tried and was convinced that those should be linked in a more complicated fashion than it should have been. For example, the while node implementation has a condition node added to make the last statement of the inside of the loop

**5.2.5. Revised approach.** This previous methodology had problems and was tougher to debug and longer to implement because it needed to copy the changes made for the nodes on all nodes implementation which was a cause for some minor bugs. The final implementation was stripped down from all the possible code statements having a node class each, like ForNode for example, to one node implementation called BaseNode. This sped up the debugging but reduced overall code quality. At first, this was done to make a better visitor but, as method overriding is not possible as far as I can tell in Python3, this wasn't as useful as it wold have been in Java or C++ for example.

## 5.3. Results

The final results were a lot more convincing when the code was not as trivial as the initial tests were. For example, the file results/final_cfg.png shows the resulting CFG for the wc.c program. It was not included in this paper as it is much too big for the template. The only major bug that is still showing but doesn't affect the dominators analysis as much as other bugs that were more apparent in the structure is the fact that I didn't find a way to reliably see if the binaryOperators were used in the condition of a conditional statement or were inside the following statements. For example, a if statement is followed by a condition but the code inside the if statement can use binary operators like "¡" and I did not want to match those as it was not a proper solution to the problem and that problem was not a real issue for the dominators analysis as only a few nodes were swapped. When the more complicated nodes such as loops and conditional statements were self-contained, I did not have problems with nonsensical edges that were added when those structures were embedded one inside the other.

### 5.4. Difficulties

As the architecture is completely custom and really little amount of the course's notes are on the construction of the Control Flow Graph and how to handle some Control Flow statements like while and if can easily be translated to a structure that will fit a CFG correctly, some mistakes were made even in the conception phase of my Control Flow Graph because I took the Dragon's book approach for while statements, if statements and others but, conceptually, I had some issues with how it was represented when embedded in other constructs like whiles and ifs. For example, at first, it was close to working when the code was trivial but, even wc.c with ifs embedded in a while, my approach didn't work at all.

## 6. Dominator Analysis

### 6.1. Introduction

The next part that needed to be implemented was the analysis of the dominators in the program to be able to do control flow analysis. As this part of the project could have been as challenging as the previous one. A reference implementation was provided which helped a lot. The important code for this part are the java_*dom_tree and nca methods.

### 6.2. Methodology and Results

**6.2.1. Dominators.** The reference implementation was studied and reimplemented with my node structure in Python. For the dominators tree, the results that you can see in results/dom.png seem to be correct. The dominators are in one single tree and follow the logic of the definition of the dominators.

**6.2.2. Post-dominators.** I used the approach of reversing the parents and the children of all the nodes and running the dominators algorithm again to output the post-dominators but encountered a problem with my WhileEnd node which did not have a post-dominator tree parent at the end of the algorithm and I still have not figured out why at the moment of the final release. As the next analysis are based on this result results will be affected and much harder to debug and verify their validity. The results for this analysis is provided in results/pdom.png.

### 6.3. Difficulties

Because the dominators analysis and control dependency and so forth all relied on a correct CFG output, those bugs slowed me down dramatically and, frankly made me stressed and underwhelmed with the results. The problems with the post-dominator analysis and why it doesn't seem to affect the dominator analysis are still unknown. The hypothesis is that some incorrect children nodes are added for the while nodes and are not a problem for the dominator analysis but when switched with the parents for the post-dominators, it renders the end result wrong. The code that is responsible of adding those incorrect nodes was not found in time and therefore, the problem could not be fixed.

## 7. Program Slicing

### 7.1. Introduction

The final part of the project was to slice the wordcount program. A slice is defined as a subset of the code that is data and control independent from the rest.

### 7.2. Methodology and Results

**7.2.1. Control Dependency Graph.** After the post-dominator analysis, I tried to extract the Control Dependency Graph with the post-dominators tree. I reimplemented the algorithm from the course slides the best I could. The final result is not really impressive but seems to show that the logic is partly right as the condition node that is working seems to have the correct nodes linked to it. The other nodes are not working but seemed to be processed while debugging. The hypothesis is that a logic bug was introduced while implementing the verification of the post-dominance of one node compared to another that has an edge between the two. I tried swapping the logic but then caused an infinite loop.

**7.2.2. Data Dependency Graph.** For the data dependency graph, the clang logic was implemented in the sense that binary operators that were assignments were analyzed to extract the left hand side to get the defined variable and the right hand side for the used variable. The left hand side was not hard to implement as it is easy to get the LHS from a clang Expr but the right hand side was more difficult because it could consist of multiple variables or expressions like it is the case in the "nc = nc + 1" line in wordcount. I looked for various ways to extract the right hand side variables but ended up writing the whole right hand side in the XML that would have been processed by the Python part later. Due to a lack of time and results in the previous parts, the python processing and analysis of the valid references was not implemented.

**7.2.3. Linking everything together and output a slice.** As the previous two graphs were either wrong or not finished, the final slicing was not implemented.

## 8. Final Results

As I couldn't figure a way to make a real code base to compile. Real results could not be extracted and analyzed.

## 9. General Difficulties

### 9.1. Real Project Compilation

I think this project required a major amount of time that was difficult to manage on a end of bachelors schedule. Before the Control Flow Graph, everything went smooth and required a decent amount of time. Also, as I really wanted to make a real project work, I spent some significant time on the problem while searching for the causes of those problems in a normal compiling context but the solutions didn't apply in my case as the code was supposed to compile without modification to the code but only the way it was loaded with the right dependencies and the correct flags. The solutions that were tried was to use the libcxx provided by llvm but I still had other includes that weren't compatible with my clang version which made me thought that the problem of dependencies couldn't be solved simply with the llvm libraries. I tried using older versions of libraries as my clang version was not up to date but this approach failed. Some projects, like chromium-os, copies a lot of its dependencies in the project to make changes to them and fix some problems without the need to wait for a patch of a third party. Those libraries were tested but I still had the same problems. Lastly, pre-processing of the code was tried but didn't solve all the problems as well and even created some. Pre-processing consisted of a small script that deleted the includes and namespace to solve those problems because undefined functions only caused warnings but deleting namespaces proved to be difficult to fix in big code bases that used them heavily like you would expect from a major modern C++ project.

### 9.2. Time

As many single point of failures could be encountered, the project stalled many times until debugging was done and code was corrected. This made me decide to double down on having complete features and some features missing instead of a big set of unfinished and incorrect features. Because the final steps of the project weren't finished and totally working, I prioritized the code to the quizzes which didn't help my understanding of the final steps and proved a bad choice.

### 9.3. Control Flow structures

As explained before, the problems I had with the Control Flow Graph took me a long time to fix properly and required some major changes in the project structure which impacted the final code quality, subsequent analyses based on the Control Flow Graph and made me loose some important amounts of time which were essential to the success of the project.

### 9.4. Implementation bugs

Some bugs were caused by Python more advanced features that I tried to leverage to make better and more compact code. One of the example is the comparison overloading with __eq__ methods on the BaseNode and Edge classes. This was useful to easily compare nodes and edges like they were standard types of the language but were hidden in other files while the big majority of the project's logic was in the Analyzer class. Since I had lots of problems with the Control Flow Graphs loops and conditional statements, it took me a while to find bugs that were related to those operations as they succeeded most of the time but failed in some edge cases like comparison with the FunctionNode which was a standalone node for functions that was a relic of the old project architecture. These also took time to debug and solve, which impacted the end result as well.

### 9.5. Debugging

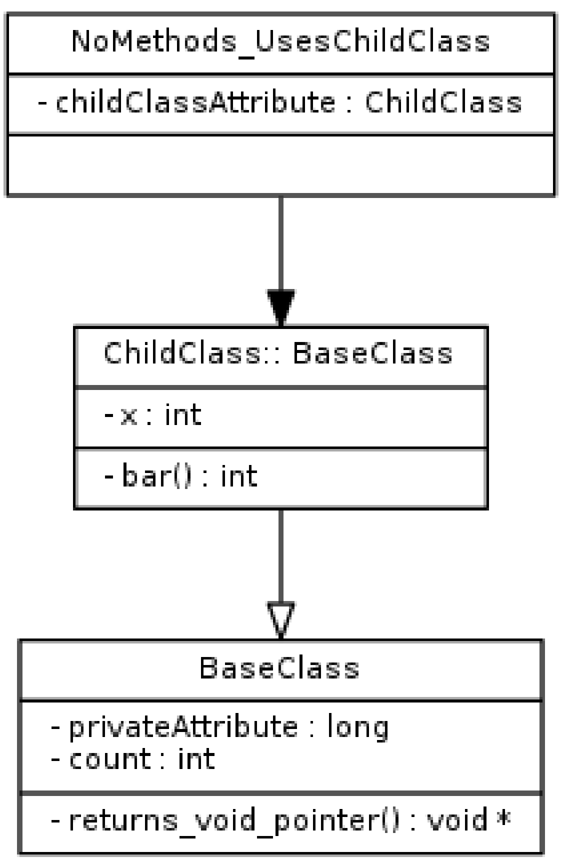
As the AST dumping logic was separated from the analyses, I had to go back and forth in two different parts of the project with distinct concepts related to each other. The XML output changed a few times and different bugs were introduced while making changes and were not as easy to see because the XML output was wrong but I thought that the analysis part was wrong. The output file was then more hidden and tougher to see its problems when debugging in PyCharm.

## 10. Conclusion

I first thought the problems I had with the Control Flow Graph were trivial but needed a complete restructuration of my approach and even of the whole project's structure to ease the implementation, changes and debugging. I am not satisfied with the end result has it fails to reach the ultimate goal of program slicing and even data dependency. I think I should have spent more time before the fourth lab to fix my Control Flow Graph and ask questions and reach out for help before I was in trouble. I also think this a major single point of failure for the project and should be reviewed thoroughly to make sure students will be able to make progress in the following weeks. I also think an initial backup project should be provided to be guaranteed to work if the student chooses to use clang as it is the default seed project for the course.

# 11. Appendix

## 11.1. UML class diagram




## 11.2. First release of the CFG