

The University of York

Department of Computer Science

Submitted in part fulfilment for the degree of MEng.

Tracing and Debugging in GP2

Joshua Asch

Date TBC

Supervisor: Detlef Plump

Number of words = 8740, as counted by `wc -w`.
This includes the body of the report only.

Abstract

The University of York has developed a graph programming language, GP2 (Graph Programs 2), which has a small IDE. In this project, new features are designed, implemented, and evaluated which allow users to step through a GP2 program in the IDE.

Contents

1	Introduction	9
1.1	Motivation	9
1.2	Ethics	9
2	Literature Review	10
2.1	Programming by Graph Transformation	10
2.1.1	Graph Programming	10
2.1.2	The GP2 Language	10
2.2	Tracing and Debugging	18
2.2.1	Debugging in Imperative Languages	18
2.2.2	Tracing in Functional Languages	21
2.2.3	Debugging With Other Graph Programming Tools	22
2.2.4	Previous Work on Debugging in GP2	24
3	Requirements	25
3.1	Potential Users	25
3.2	Integration and Maintainability	25
3.3	User Scenarios	26
3.3.1	Experienced GP2 Programmer	26
3.3.2	New User Learning GP2	28
3.4	List of Requirements	30
4	Design	32
4.1	Design Considerations	32
4.1.1	Implementations of GP2	32
4.1.2	Backtracking in the GP2 Compiler	33
4.1.3	Non-determinism	34
4.1.4	Program Representation	36
4.2	Proposed Solutions	36
4.2.1	Modify Compiler to Run Partial Programs	36
4.2.2	Use Tracing to Step Through Execution History	38
4.3	Chosen Solution	39

Contents

5	Implementation	41
5.1	Trace File Format	41
6	Evaluation	46
6.1	Requirements Tracing	46
6.2	Performance	46
6.3	User Feedback	46
7	Conclusions	47
7.1	Future Work	47

List of Figures

2.1	A rule in GP2	11
2.2	GP2's type hierarchy for labels	12
2.3	A GP2 rule which uses labels	13
2.4	Attempting to apply a rule when the match violates the dangling condition	14
2.5	Definition of 2-colouring in GP2	17
2.6	Example execution of 2-colouring	18
3.1	Alternate version of the 2-colourable program	27
3.2	Simplest possible non-two-colourable graph	27
3.3	Simple program to learn the semantics of IF-THEN-ELSE . .	29

List of Tables

3.1	List of system requirements identified for the debugging tool	31
-----	---	----

1 Introduction

1.1 Motivation

Introduce the project, explain why the project needs doing

1.2 Ethics

Discuss the ethical considerations for the project, which there may not be any at all, if no humans are involved.

2 Literature Review

2.1 Programming by Graph Transformation

2.1.1 Graph Programming

Graph programming involves a series of transformations applied to a graph. The problem being solved must be redefined in terms of a start graph and an algorithm represented by graph transformations. The final graph at the end of the algorithm gives the solution to the problem.

Historically, programming by graph transformation required using a programming language such as C or Java, implementing data structures to represent graphs, and directly making modifications to the graph in the program. However, recently some attempts have been made to create tools for graph programming which abstract away the representation of the graphs, allowing the programmer to focus on the program itself.

Some of these tools include GROOVE [1], AGG [2], GrGen [3], and, most recently, GP2 [4]. All of these are domain-specific languages for graph programming which also provide a graphical interface to describe graphs and transformations.

These kinds of tools take a representation of a graph program, as defined in their graphical editor, and transform this into a runnable program. This can be implemented in a number of languages, including Java (in the case of AGG and GROOVE), C# .NET (GrGen), or C (GP2). This program can then be executed to find the output graph generated by the algorithm.

2.1.2 The GP2 Language

GP2 (Graph Programs 2) is a programming language developed at the University of York [4, 5], an updated implementation of the original language, GP [6]. It is designed for writing programs at a high level, to perform graph transformations without having to implement data structures to represent the graphs in more traditional lower level languages such as C.



Figure 2.1: A rule in GP2

Programming in GP2 consists of an input graph, known as the *host graph*, a set of *rules*, and a *program* which defines the order in which to apply the rules. Running a GP2 program on a host graph produces a new graph as a result, called the *output graph*.

Rules

Rules are the basic building blocks of a GP2 program and are defined by a left-hand-side (LHS), a right-hand-side (RHS), and optionally a conditional clause. A rule can be thought of as the definition of a transformation; a subgraph matching the LHS of the rule is transformed to resemble the RHS. An example of a GP2 rule is shown in Figure 2.1.

The conditional clause is used to specify additional constraints on the subgraph matching the LHS. Any match has to both match the LHS and conform to the constraints defined by the conditional clause.

In a compiled program, a rule is split into two phases. The *match* phase searches the current graph for a subgraph which matches the LHS of the rule. This must be an *injective match*, meaning that each item in the LHS must be matched with exactly one item in the host graph.

In this implementation of GP2, rule matches are chosen deterministically due to the impracticality of generating all non-deterministic possibilities, which is what GP1 did. If no match is found for the LHS, the rule is considered *failed*. If a match is found, the program moves on to the second phase, the *application*.

A rule specifies a number of *interface nodes*, nodes which are present in both the LHS and the RHS. These interface nodes can be seen in Figure 2.1; they are the nodes with small numeric identifiers below them. During the application phase, any nodes in the LHS which are *not* interface nodes will be deleted. Similarly, any non-interface nodes which appear in the



Figure 2.2: GP2's type hierarchy for labels

RHS will be created. At the end of the application phase, the subgraph will match the RHS of the rule definition. The new graph created by the application of this rule, an *intermediate graph*, is then used as the input to the next part of the program.

In the example in Figure 2.1, the program will search for a subgraph containing two nodes without an edge connecting them. If a match is found, it will be transformed to resemble the RHS by adding an edge between the nodes.

Labels

Nodes and edges in a graph defined in GP2 can also have *labels*. Labels can be used cosmetically, without affecting the execution of the program, or they can be included in rules to have the program read and modify labels.

GP2 has a type hierarchy for labels, shown in Figure 2.2. Labels can be of any of these five types. An *atom* consists of a single entity, either an *int* or a *string*. A *list* is a collection of zero or more *atoms* concatenated together; the concatenation is shown using a colon (:).

Host graphs and the LHS and RHS of rules must be *totally labelled*, meaning that every node and edge must have a label. If the programmer wishes to use a node or edge which appears to be unlabelled, they can use the empty list for that label.

Labels behave in two subtly different ways depending on where they are used. In a graph, a label has a specific value, similar to an integer or

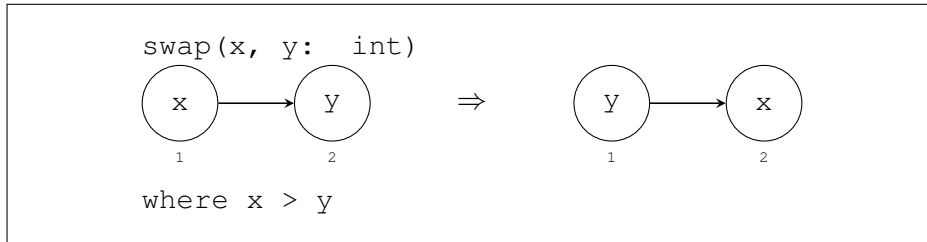


Figure 2.3: A GP2 rule which uses labels

string literal in a conventional programming language. When used in a rule, labels can either use literal values to match nodes with exact label values, or they can use expressions which can match a range of label values.

When matching a rule involving labels, GP2 finds a variable assignment which matches the expressions of the labels in the graph. The values in this assignment are identical when used in the RHS of the rule.

When using labels in a rule, the type of each label must be specified so that GP2 can find an assignment for each one. A rule which specifies a certain label type can match any label with that type or a more specific type in the type hierarchy. For example, a rule which contains a label of type `string` can match a node which has a `char` label. The `list` type will match any label.

The rule in Figure 2.3 will only match a pair of nodes where the labels are both integers, and the value of the source node's label is greater than the value of the target node's label. This rule demonstrates both that labels can be used as conditions in the program, and also that a rule can modify labels. It also shows that labels act like variables when used in a rule, since the values of `x` and `y` are re-used in the RHS.

The Dangling Condition

There is an additional condition which determines whether a rule can be matched, the *dangling condition*. This condition states that if a rule causes a node to be deleted, the rule must also delete all edges incident to that node. In other words, all non-interface nodes in a rule match must have no incoming or outgoing edges which are not also part of the match.

Figure 2.4 shows the result of attempting to apply a rule where the match violates the dangling condition. Since node 2 is not an interface node, it is deleted during the application of the `delete` rule. However,



Figure 2.4: Attempting to apply a rule when the match violates the dangling condition

the rule does not specify that the edge from 4 to 2 should be deleted. This leaves a *dangling edge* from node 4 with no target. The dangling condition is used to ensure that rule applications result in no dangling edges.

Programs

A GP2 program defines the order in which to apply rules using 8 simple control structures:

SEQUENCE Two subprograms separated by a semicolon “`P; Q`” are applied one after the other.

RULE SET Rules in curly braces “`{R1, R2, R3}`” define a set, where exactly one rule from the set is executed, chosen non-deterministically from all rules in the set which have a valid match. If there are no rules in the set which match, the program fails in the same way as if a single rule failed to match.

IF-THEN-ELSE In the statement “if `C` then `P` else `Q`”, a copy of the graph is taken, before executing the sub-program `C`. The result, i.e. success or failure, is then used to determine whether to run `P` or

Q. If *C* succeeded, *P* is executed on the copy of the original graph. If it failed, then *Q* is executed on the original graph. Note that by taking a copy first, any changes made by *C* are always reverted before executing either *P* or *Q*.

TRY-THEN-ELSE Similar to IF-THEN-ELSE, but *C* is only reverted if it fails. Thus any changes made by *C* are *not* reverted before executing *P*, but they *are* reverted before executing *Q*.

AS-LONG-AS-POSSIBLE A subprogram followed by an exclamation point "*P*!" is executed repeatedly until it fails. When *P* fails, the graph is reverted back to the last successful state, that is, the state it was in at the end of the last successfully applied rule from *P*.

The keyword `break` can also be used to exit from a loop before reaching the end. When using `break`, the graph is *not* reverted before continuing with the program.

PROCEDURE Similar to a *C* preprocessor macro, a procedure is simply a named subprogram where any reference to the procedure name can be replaced with the definition of the procedure. Procedures are not allowed to be recursive.

SKIP A no-op which always succeeds, and does not affect the graph. Invoked using the keyword "`skip`". This is the same as executing a rule with an empty LHS and an empty RHS, which always matches and does nothing to the graph.

FAIL A statement which always fails and does not affect the graph. This is the same as attempting to execute a rule for which there are no matches. Invoked using the keyword "`fail`". It can also be simulated using an empty `RULE SET {}`.

OR In the statement "*P or Q*", exactly one subprogram, either *P* or *Q* is chosen non-deterministically and executed. Unlike the `RULE SET` construction, if the chosen subprogram fails, the other is *not* applied instead, and the program fails.

For GP2, a subprogram is either a single rule, referenced by its name, or one of the above control structures. Therefore it is possible to nest control structures to create more complex programs.

In general, execution of a program continues until either all statements are executed, or until a statement results in an attempt to apply a rule

which has no matches in the graph. The exceptions to this are `As-Long-As-Possible` statements, and the conditional statements in `If-Then-Else` and `Try-Then-Else` structures. In these cases, a failure to match a rule does not halt execution of the program.

Figure 2.5 shows an example GP2 program, an adapted version of the program used as a case study in Bak’s thesis on GP2 [5, p.126]. It is a simple program which determines whether a graph is *2-colourable*, that is, its nodes can be coloured using two different colours without two nodes of the same colour being connected by an edge. This program requires that the graph is *connected*, meaning there is an undirected path between every pair of nodes.

This program consists of four rules and uses many of the constructs outlined previously, including `Try-Then-Else`, `If-Then-Else`, `Rule Sets`, `As-Long-As-Possible` and `Procedures`.

It also takes advantage of another feature of GP2, the ability to *colour* a node. The colour of a node is a property which can be set by a rule, or the host graph can contain coloured nodes. The colour is taken into account when searching for a rule match; for example, in this program, `joined_reds` will only match when both the nodes’ colours are red.

An example execution of the 2-colouring program is shown in Figure 2.6. Starting with an uncoloured graph, the algorithm picks a node and colours it red using the `init` rule. It then traverses the graph colouring nodes in alternating colours using the `colour_blue` and `colour_red` rules, by defining them as a `RULE SET` in a `PROCEDURE` and executing it `As-Long-As-Possible`. When no more uncoloured nodes are present in the graph, the `Colour` procedure will be unable to match any further rules, so it will end.

To check whether the produced colouring is valid, the entire `Main` procedure is wrapped in a `Try-Then-Else` statement. After executing `Colour`, the `Invalid` procedure runs. This procedure uses the two remaining rules, `joined_reds` and `joined_blues`, to see if any adjacent nodes are the same colour. If they are, one of these rules will match, triggering the conditional statement `fail` from the `If-Then-Else` statement. This in turn causes the outer `try` to fail, reverting all changes made to the graph and returning the uncoloured input graph.

However, if `Invalid` fails to match either of the rules, it must mean that no two same-coloured nodes are connected via an edge. This means that it is a valid colouring. The `fail` statement is not executed, meaning the `try` succeeds. The changes to the graph are kept, and the modified graph is returned as the result of the program.

2.1 Programming by Graph Transformation

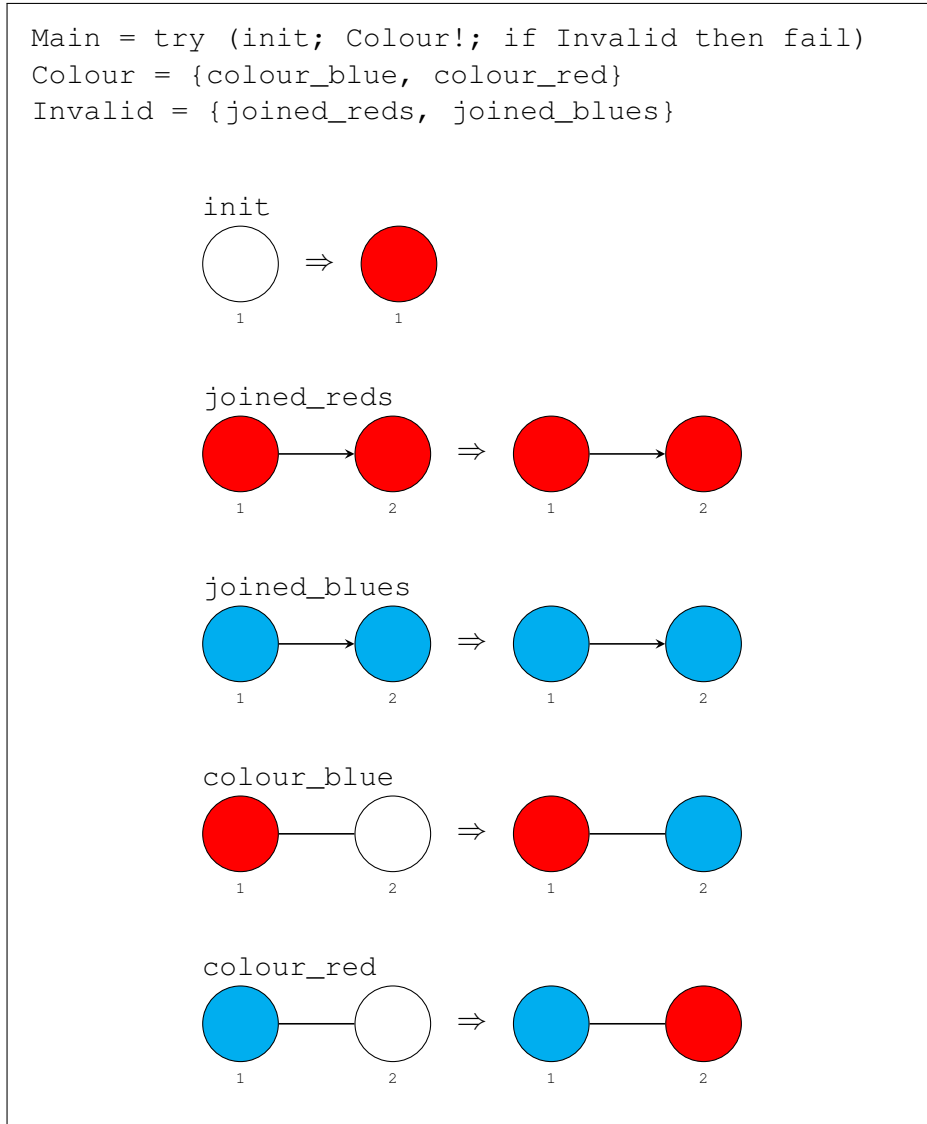


Figure 2.5: Definition of 2-colouring in GP2

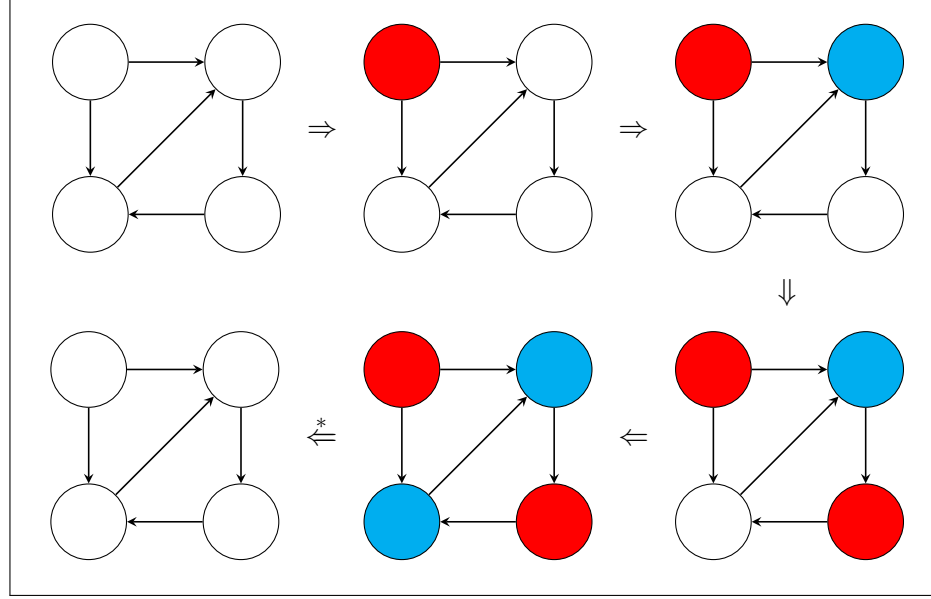


Figure 2.6: Example execution of 2-colouring

In the example execution in Figure 2.6, the host graph is not 2-colourable. When the rules in `Colour` can no longer be matched, `joined_blues` inside `Invalid` will match with the nodes in the bottom-left and top-right of the graph. Because this rule was successfully applied (even though it has no effect on the graph), the `IF-THEN-ELSE` causes the program to enter the fail state. This in turn means that the `TRY-THEN-ELSE` surrounding the program fails, and all the changes made to the input graph are reversed. The output graph is therefore identical to the input graph.

2.2 Tracing and Debugging

2.2.1 Debugging in Imperative Languages

When programming in a high level imperative language, such as C or Java, the programmer will more often than not have access to a *debugger*. In [7], Sammet says that a program in a high level language without debugger support may be "harder to debug than an assembly language which the programmer understands", since the programmer has to interpret the compiled code, rather than reading the source code they wrote.

Most language interpreters and Integrated Development Environments (IDEs) have a debugger built in [8], and standalone debuggers are also available for some languages. For C, this may be `gdb` [9], while for Java, it might be `jdb` [10].

A debugger is intended to allow the programmer to pause their program during execution, so that they can inspect the contents of variables and other memory locations. It also allows them to run their program step-by-step to see its execution flow; they may wish to check that a function is called at the expected point during execution, for instance.

Some debuggers also include more advanced features to make debugging easier and to give the programmer more insight into their program. Breakpoints are a common feature which allow the programmer to specify a line of source code and have the program execute normally until the breakpoint is reached, at which point execution will pause, or *break*.

Because GP2 has a rule-based structure, unlike imperative programming languages, it is not clear what a “line of code” represents in a GP2 program. The textual part of a GP2 program can indeed have lines, but since a single line in a GP2 program can be complex and use many rules, this is too high-level to consider a “line of code” as a debugger does. In an imperative language, a single line of code may only perform one or two actions, so inspecting each line individually shows the flow of the program. In GP2, running a line of the textual program could result in tens or hundreds of rules being applied if *As-Long-As-Possible* is used, for example. It may be inappropriate to focus on how debuggers are implemented for imperative languages when considering GP2.

IDEs

A debugger is often available from within the Integrated Development Environment (IDE) for a language. For example, the Visual Studio IDE for C, C++, and C# includes the Visual Studio Debugger [11]. One of the most prevalent Java IDEs, Eclipse, integrates with `jdb` [12].

When an IDE integrates with a debugger, it can provide additional functionality by allowing the programmer to interact with the source code and the debugger visually in the same environment. Visual Studio and Eclipse both allow breakpoints to be set directly on a line of source code in the editor, for instance. IDEs often allow the programmer to trace program execution through the source code, by highlighting each line of code as the programmer steps through in the debugger.

It may be useful to use some of these ideas for GP2. For instance, when

stepping through a GP2 program, it would be helpful to highlight the current statement or rule being executed, to give the user context.

Edit-and-Continue

Edit-and-continue is an even more advanced feature which requires specific compiler support, and is usually only available in IDEs, since they have access to both the compiler and the debugger. It allows the programmer to pause execution of the program, edit the source code, recompile the program, and continue execution from the previous paused state, without having to restart the program from the beginning. Edit-and-continue is useful for reducing the time taken to find and fix bugs, since fixes can be implemented and tested without having to stop and restart the program's execution.

It is unclear whether edit-and-continue would be a good addition to GP2. On one hand, it can speed up debugging because the programmer does not have to start the program again from the beginning. On the other hand, it is not clear how this feature could be implemented in GP2. It would not make sense for the user to be able to edit the input graph or an intermediate graph while execution is paused, because the result of the program would be incorrect. Editing the rules and program text would make more sense, but this could lead to problems, such as if the user pauses execution after matching a rule, and then edits that rule in a way that makes the match incorrect.

Reverse Debugging

`gdb` supports what is called *reverse debugging* [13]. This allows program execution to actually be reversed, running the program backwards to reach an earlier state. This can come in useful to look for non-deterministic bugs which do not always occur; the program can be run until the bug occurs, then executed in reverse to look for the cause.

This ability comes with a trade-off, however; running with reverse debugging enabled reduces the performance of the running program. It can only be used in specific cases and cannot be enabled all the time, since the program would run much slower and possibly exhibit time-related bugs. Reverse debugging is also only available for `gdb` running on Linux.

`gdb`'s implementation of reverse debugging involves recording the machine state after each instruction execution, including the values stored in memory and registers. To reverse an instruction, the state from the

previous instruction is simply restored, making it appear as if the reversed instruction was never executed. This implementation allows powerful interaction with the program; it can reverse a single instruction at a time, or it can be run backwards until a breakpoint is reached. In theory, although `gdb` does not support this, this system could allow a form of “checkpointing” where execution can be skipped directly back to an arbitrary point by simply restoring the state from that point.

Reverse debugging may be a useful feature for GP2, because it would allow a programmer to step backwards through the execution of a GP2 program to inspect the intermediate graph before and after a rule application, to see what changed. This method is more akin to tracing than traditional debugging, since the debugger is storing a history of everything that occurs during execution.

While the implementation of reverse debugging in `gdb` is limited to the Linux platform, this is because its implementation requires monitoring calls to the kernel and system APIs. This is irrelevant to GP2, because it would only need to trace rule matches and applications, both of which are implemented inside GP2 itself.

2.2.2 Tracing in Functional Languages

The syntax and execution of a GP2 program is very similar to that of a functional programming language. For example, a function in Haskell is similar to a rule or set of rules in GP2; the function defines left-hand-sides and right-hand-sides, and executing it with an argument looks for a LHS which matches the argument, and returns the RHS. This similarity to the matching and application of rules in GP2 suggests that it would be appropriate to consider it like a functional language when implementing debugging or tracing.

Because of the nature of functional languages, it is rare to see traditional debuggers like those used with imperative languages [14]. Lazy evaluation, where the value of a statement is only calculated when it is required, means that pausing execution on a line of code may not reveal the value of a statement on that line, because it will not be evaluated until later in the program.

To avoid this problem, functional programmers will often use tracing instead. This is where additional code is added to the program which simply outputs information about what the program is doing, either to the console or to a file on disk. The programmer then reads this information back once the program has finished, to see what steps the

program took and identify where it differed from the expected execution.

Tracing can be done in primitive ways, by manually adding `print` statements to the code, but there are also more sophisticated tools available. For Haskell, for instance, a handful of different tracing tools are available [15]. Two of them, Freja and Hat, are modified Haskell compilers which add automatic tracing functionality to the compiled program. When the program runs, trace information is stored in the program heap, which can then be accessed at the end of execution. The other tool, Hood, is a Haskell library which is used by importing it and adding `observe` annotations to the code, which preserve lazy evaluation and output information about the program as it runs. The programmer would then inspect the output from the annotations to trace through the program.

The benefit of compiler based tools like Freja and Hat is the programmer does not need to think about where to put tracing code, since all code is traced automatically in the compiled program. However, storing a full trace of an entire program takes up space either in memory or on disk; the advantage of a manual tool like Hood is the programmer can reduce the number of trace points to reduce the trace size.

Another disadvantage of Hat is that it has a very large impact on performance, running more than ten times slower than the original Haskell program [15]. Hat adds a lot of overhead at runtime, since the program has to do a lot of extra work to store the tracing data. On the other hand, Freja is also a tracing tool, yet Chitil, Runciman, and Koopman state that the overhead is "not noticeable". It is clear that the performance impact of these tools depends on their implementation.

2.2.3 Debugging With Other Graph Programming Tools

Each of the three other graph programming tools mentioned in Section 2.1.1 have their own debugging or tracing tools.

AGG

Of the three tools, AGG has the simplest debugging tools. It allows the user to select a rule in their graph grammar and then look through all the matches for that rule, by showing them on the current graph.

A unique feature of AGG is that it also allows the user to manually create a match; by selecting nodes and edges first in the LHS of the rule, and then in the graph, the user creates a mapping between the rule and

the current graph to create a match. The tool will alert the user if they attempt to select a mapping which is not a true match.

When a match has been chosen, either automatically or manually, the rule can then be applied by clicking a `Transformation Step` button in the editor. After a rule has been applied, an `Undo Step` button becomes available which reverts the changes made by the most recent rule application.

GROOVE

GROOVE also allows the user to inspect all possible rule matches for the current graph. In the list of rules shown in the editor, the possible matches for each are shown underneath each rule. These matches can be clicked to highlight them on the graph, and double-clicking applies the rule, updating the graph.

Similar to AGG, it is possible to undo a single rule application. However, GROOVE also keeps a history of all previous graph states. In the “State Space Explorer”, the tool shows a transition diagram containing all the previously visited graph states, with the transitions representing the rule applied to reach a given state. In this view, the user can select a previous state and jump back to it, allowing the user to undo multiple rule applications at once, or even undoing previous rule applications and re-applying other rules, in one step.

GrGen

GrGen’s debugger is different in that it is controlled using a command-line style interface, rather than using buttons in the editor UI. It provides a command to apply a single rule, similar to the other two tools.

However, when applying a rule, GrGen can show more detail. It can show the steps required to apply a rule: the match, the modification to the graph, and the result. It shows each of these stages individually, highlighting the relevant areas on the graph at each stage.

Another unique feature of GrGen’s debugger is that it allows the user to tell the program to run until the end of the current loop. GrGen supports a loop structure similar to GP2’s `AS-LONG-AS-POSSIBLE`, and the debugger’s `step out` command will continue to execute until the current loop ends, giving control back to the user.

Finally, GrGen also supports a feature similar to breakpoints. It allows the user to specify a condition, and when that condition is met, execution

will pause. One type of condition which can be specified is a certain modification to the graph, such as pausing execution when a specific node is deleted from the graph.

2.2.4 Previous Work on Debugging in GP2

There has been some previous work to add debugging facilities to GP2 [16]. This work was focused on modifying the compiler to support stepping through a program.

In that project, command line arguments were added to allow the user to specify how big a "step" should be, and how many steps to execute before stopping. This allows GP2 to approximate breakpoints by picking an appropriate step size and count in order to finish execution at the point the programmer is interested in.

However, there are some problems with this method. For one, once the specified number of steps have been executed, the program terminates completely and outputs the current graph. This means that if the programmer wishes to step through the program one rule at a time, for example, they must run the compiler multiple times and increase the number of steps by one each time, wasting time by re-executing earlier steps at each iteration.

Another problem is that, although the compiler was modified, the graphical editor remains unchanged, and so does not support the new partial execution feature. For the feature to be most useful, it would have to be integrated into the editor.

3 Requirements

Before designing and implementing a system, the requirements for the system need to be considered. These requirements should be based on expected real-world usage of the tool and keep the goals of the tool in mind.

3.1 Potential Users

In order to decide what the requirements for a debugging tool are, it is useful to consider the types of user who would potentially use such a tool. There are two main potential audiences for a GP2 debugging tool:

- Programmers who have written a GP2 program which they would like to debug. Either the program produces unexpected output, or it never terminates, so the programmer wishes to use the debugging tools to understand why their program is behaving incorrectly, and then fix the bug.
- New users of GP2 who are still learning the language. GP2 is an unconventional language and its concepts can be unfamiliar to inexperienced users. Allowing these users to step through a GP2 program would let them see how GP2 works and help them to understand the language faster.

However, it should be noted that the debugger is not a substitute for documentation or user manuals; the debugger should not be expected to explain the semantics of GP2, but rather act as a tool to show the process of running a GP2 program.

3.2 Integration and Maintainability

Consideration should also be given to how the new features are integrated into GP2. The experience of using existing GP2 features should be unaffected, and the codebase should stay maintainable for future developers of GP2. The high-level requirements this leads to are:

3 Requirements

- Backwards compatibility. Adding a debugging tool should not impact the existing features of GP2, the compiler, or the IDE. Programs written before the addition of debugging tools should still be runnable in the new IDE.
- Make debugging optional. The user should not be forced to use the debugging tools every time they run their program, and should be able to choose when to enable them.
- Minimise the performance impact. Running a program with debugging tools should affect performance as little as possible, and running with debugging disabled should have no performance impact compared to the previous version of GP2.
- Keep the codebase maintainable. When modifying existing code, or adding new code, follow conventions and make code readable. Make the intent of any changes clear to ensure future developers will understand what has been changed.

3.3 User Scenarios

To further identify specific low level requirements for the tool, two hypothetical user scenarios have been created to show potential situations a user could be in, and how the debugging tools can help the user complete their task in those situations.

3.3.1 Experienced GP2 Programmer

In the first scenario, the user is an experienced GP2 programmer who understands all the concepts and semantics of GP2. They have written a program similar to the one shown in Figure 2.5, to determine whether a graph is two-colourable.

However, their program is slightly different, and does not output the coloured graph when it is two-colourable; instead, the original, uncoloured graph is always returned, and an extra node is added to show the result. If the graph is two-colourable, a green node is added, otherwise a red node is added. The program they have written is shown in Figure 3.1, along with the two new rules, `add_red_node` and `add_green_node`. The other rules are omitted since they are identical to the rules in the original program.



Figure 3.1: Alternate version of the 2-colourable program

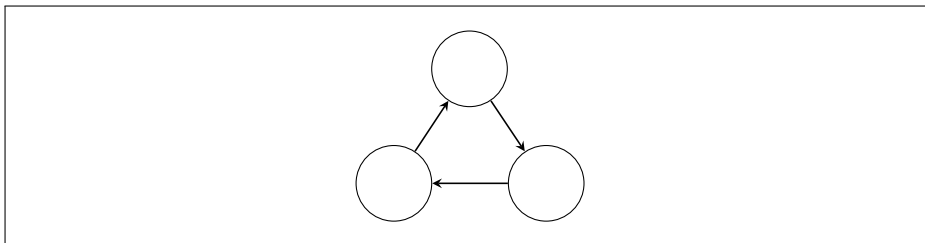


Figure 3.2: Simplest possible non-two-colourable graph

Unfortunately, when they test their program, for some inputs it gives the incorrect result; for certain non-two-colourable graphs, the program still adds a green node to indicate that it is two-colourable. Just by inspecting the program, the user cannot determine what the bug is with the program, so they decide to use the simplest possible non-two-colourable input graph, shown in Figure 3.2, and use the debugger to step through their program.

As they step through the program, the `init` rule colours the top node red, then `colour_blue` is applied, followed by `colour_red`. This results in the graph being coloured red, blue, red running clockwise. Clearly the rules for colouring nodes are defined correctly, so the bug must be in the error detection logic.

They continue stepping through the program and it reaches the `Invalid`

3 Requirements

procedure. They use the debugger to highlight a match for `Invalid` without applying it, and it turns out there are none, which should not be the case. They first look at the definitions for the `joined_reds` and `joined_blues` rules, and they are definitely correct. Finally they look at the definition of `Invalid` itself, and realise they have put `joined_blues` in the rule set twice, so `joined_reds` is never actually used.

The bug in this program was fairly subtle, since the general structure of the program is mostly correct; there are two rules in `Invalid` as expected, but the same rule was added twice. Without the debugger to step through the program, it may have taken much longer to spot this mistake, since stepping through allowed the user to see the coloured graph before it was reverted by the `if` statement.

The ability to view a match without applying it also helped in this case, since it allowed the user to see that none of the rules in `Invalid` matched, without automatically exiting the `if` condition when no rules matched.

3.3.2 New User Learning GP2

In the second scenario, the user is inexperienced with GP2 and is still trying to learn the language. They understand most of how the language works, but they are having trouble with understanding the semantics of IF-THEN-ELSE.

They have written a very simple GP2 program, shown in Figure 3.3, which consists of three rules and a single IF-THEN-TRY statement. When they run this program on the input graph shown, they incorrectly expect the output graph to match the RHS of the `bridge` rule, because they expect `insert` to be applied, followed by `bridge`.

In actuality, this program fails, because the changes made by `insert` are reverted before attempting to match `bridge`, meaning there is no possible match for `bridge`.

The result confuses the user, who then decides to use the debugger to step through the program to see what happened. The first thing they see is the program tries to match `insert` and succeeds, which they expected. However, then they advance to the next execution step and are surprised that no changes have been made to the graph. They then realise that they had mixed up the semantics of IF-THEN-ELSE and TRY-THEN-ELSE.

Ideally in this situation, the debugger would explicitly show that backtracking will occur once the `if` condition has been verified. It may



Figure 3.3: Simple program to learn the semantics of IF-THEN-ELSE

3 Requirements

also allow the user to step backwards and forwards over the program so they can make sure they understand what is happening.

By inspecting the execution of this simple program, the user has successfully used the debugger to aid their learning; even though the debugger does not explain the semantics directly, the user can understand how the program works.

3.4 List of Requirements

Table 3.1 shows a list of all requirements which have been identified for the GP2 debugging tool.

3.4 List of Requirements

ID	Description
1	The system must be able to trace execution of a GP2 program.
1.1	The system must be able to apply individual rules, one at a time, to step through a program.
1.2	It is desirable for the system to allow the user to step backwards through a program.
1.3	It is desirable for the system to execute an entire control sequence in one step.
2	The system must have a visual debugging component.
2.1	The system must highlight the rule being applied when stepping through a program.
2.2	The system must highlight the next rule match in the graph.
2.3	It is desirable for the system to highlight changes which were made as a result of the previously applied rule.
2.4	It is desirable for the system to highlight the current position in the textual portion of the program.
2.5	The system must show each intermediate graph in the IDE.
3	The system must allow debugging to be controlled from within the GP2 IDE.
3.1	The system must provide a way to advance execution by one step.
3.2	It is desirable for the system to provide a way to backtrack execution by one step.
3.3	The system must provide a way to find a match for the next rule, but not apply the rule. (See requirement 2.2)
3.4	The system must provide a way to apply a rule for which a match has been found but not yet applied. (See requirement 3.4)
3.5	The system must provide a way to run an entire program without debugging it.
4	The system must act in a predictable and consistent way during each execution of a program.
4.1	The system must produce identical results whether debugging is enabled or not.
4.2	The system must be able to load existing projects created before the system was modified.

Table 3.1: List of system requirements identified for the debugging tool

4 Design

Explain the design phase, what was considered, and what ultimately became the choice for what to do.

4.1 Design Considerations

4.1.1 Implementations of GP2

There are two implementations of GP2, an interpreter written in Haskell [5, ch. 5.3], and a compiler written in C [5, ch. 5.5]. The interpreter is intended to provide a reference for other implementations of GP2, and for the GP2 developers. The GP2 IDE uses the compiler, not the interpreter, to run the user's program.

The interpreter may be of some interest, since an interpreter runs "live", moving through the program executing each statement as it is reached. This behaviour could be exploited to implement a form of debugging, by pausing execution of the interpreter at various points and outputting the current state of the program.

To take advantage of the interpreter, the GP2 editor would have to be modified so that it runs the user's program using the interpreter rather than the compiler.

The other difference between the interpreter and the compiler is that the compiled program only produces one output for a given input to a program. The interpreter returns all unique output graphs, up to isomorphism. For debugging purposes, this may be of interest to the user, since it allows them to see all the possibilities of their program. To the developer of the debugger, this is a disadvantage, since the GP2 IDE does not currently support displaying all possible outputs.

Additionally, because the interpreter is only a reference implementation, the compiler is the implementation intended for most users. If the IDE were to be changed to run the interpreter for debugging programs, checks would have to be made to ensure that the interpreter produces identical outputs to a compiled version of the same program. This may involve adding a "single-result mode" to the interpreter, where only one

output graph is produced, instead of all possibilities. This would require substantial changes to the interpreter.

4.1.2 Backtracking in the GP2 Compiler

To support some operations, such as IF-THEN-ELSE, the GP2 compiler uses *backtracking*, where any changes to the graph are reversed [5, ch. 5.8]. If the condition in an IF-THEN-ELSE structure fails, any changes need to be reversed before applying the ELSE subprogram.

This feature of the compiler could be used as part of the debugging features, by using it to allow the user to step backwards through the program as it runs, similar to the reverse debugging mentioned in Section 2.2.1. It would allow the user to see the state of the graph before a certain rule was applied, for instance.

However, this backtracking is not available at all points in a program's execution; backtracking code is only added by the compiler if static analysis shows that it is necessary. For example, since the AS-LONG-AS-POSSIBLE construct cannot fail, the compiler does not add backtracking code for it. The compiler would have to be modified to add backtracking code to the entire program.

Communicating Backtracking to the User

When the user is debugging a program which causes backtracking to occur, the tool must indicate in some way that this has happened. For inexperienced users especially, if the graph reverts back to a previous state with no explanation, it could be extremely confusing.

There are multiple ways the debugging tool could communicate backtracking to the user:

- Show a message when backtracking occurs. This is the simplest option, which would involve showing a message somewhere in the IDE when the graph is reverted. This would explain to the user what has happened, although they may still not understand why the backtracking occurred, or what previous state was restored.
- Highlight the part of the user's program where the backtracking is rooted. For instance, if the program contains "if r1 then p1 else p2" (assuming r1 is a rule and p1 and p2 are procedures), "if r1" could be highlighted differently to indicate that it may produce backtracking. This would give the user more insight into

why the backtracking has occurred, although it may still not be clear which previous graph state has been restored.

- Show the previous state somewhere in the IDE. This method would provide the most context. It allows the user to see exactly what will happen when backtracking occurs. It could also be combined with the previous idea to give additional information. Combining both would allow the user to see the cause of the backtracking, and also what changes occurred.

4.1.3 Non-determinism

While the definition of GP2 includes non-determinism, such as when choosing a rule from a RULE SET, the implementation of the C compiler is mostly deterministic. When executing a RULE SET, the generated C program will always select the first rule in the set which matches, rather than non-deterministically selecting from all the rules which match. This is shown in Listing 4.1, which shows the code which the compiler generates for the statement “{r1, r2, r3}”. This code tries each rule in turn, and stops when it finds the first one which has a match.

Listing 4.1: Generated code for a RULE SET structure

```
do
{
    if(matchMain_r1(M_Main_r1))
    {
        applyMain_r1(M_Main_r1, false);
        success = true;
        break;
    }
    if(matchMain_r2(M_Main_r2))
    {
        applyMain_r2(M_Main_r2, false);
        success = true;
        break;
    }
    if(matchMain_r3(M_Main_r3))
    {
        applyMain_r3(M_Main_r3, false);
        success = true;
    }
}
```

```

    }
    else
    {
        ...
        // Failure handling omitted for brevity
    }
} while(false);

```

If a user is familiar with the GP2 specification, they may expect their program to run non-deterministically. They may also expect features in the debugger related to this non-determinism, such as showing all the possible matches for a rule, or showing all the matching rules in a RULE SET. However, because the code for a RULE SET does not attempt to match any other rules once a match is found, the debugger cannot show all matching rules. Enabling this would require modifying the compiler to find all matches before picking one, even if it still always picked the first match.

The exception to this is the OR statement. In the GP2 compiler, this statement does not always choose the same option, but instead uses the `rand()` function to randomly choose between the two possibilities. This seems to act counter to requirement 4 for the debugger, which states that the system must be predictable, because on each execution of the program, it is random whether the first option or second option will be chosen.

However, the debugger cannot take responsibility for how the user's program is structured. Listing 4.2 shows plain C code which is analogous to a GP2 OR statement, which randomly calls one of two functions based on a random number. A C programmer would not expect the debugger to always follow the same execution path when debugging this code, so it is reasonable to take the same approach with a GP2 debugger.

Listing 4.2: C code analagous to GP2's OR statement

```

int random = rand();
if ((random % 2) == 0) {
    someFunction();
}
else {
    someOtherFunction();
}

```

In a similar vein, the order of rules within a `RULE SET` can affect the execution of a program, since the first matching rule is always applied, as discussed previously. This means that if the user edits their program and re-orders the rules in a `RULE SET`, their program may give different results. Again, this issue is due to the structure of the program, which the debugger cannot take responsibility for.

4.1.4 Program Representation

When a user creates a graph using the visual editor in the IDE, the graph must be converted to a text based format in order to compile and run the GP2 program. Depending on the position of elements in the editor, isomorphic graphs may be converted to different textual representations, with the nodes and edges listed in a different order, for example.

This is relevant to the debugger because when running a program, the order of nodes and edges will affect which matches are selected when applying a rule. If the user runs their program and then rearranges the nodes in the editor, running the program again may give a different result graph. This would be surprising to a user, since they did not modify the structure of the graph, only its layout.

Without modifying the algorithm for converting a graph to the text based representation, it is not possible to avoid the problem. It may be useful to warn the user if the representation of their graph changes, so that they are aware it may give different results.

4.2 Proposed Solutions

Two different possible high-level designs are outlined below, along with the advantages and disadvantages of each.

4.2.1 Modify Compiler to Run Partial Programs

Following a similar method to the previous work on adding debugging to GP2 [16], the compiler would be modified so that it can run part of a program and stop, giving intermediate results. The IDE would interact with the compiler to control how much of the program to run, and to display the intermediate graphs to the user.

The IDE would have two modes for running a program. The first mode would act exactly as the current version of the IDE, running the entire

program and displaying the result. No changes would need to be made to the IDE for this mode.

The second mode would be for debugging the program, and would provide the user with controls to step through their program. Each time a step is taken, the compiler would be invoked on the most recent intermediate graph, solving the problem from the previous project of having to re-run the first steps. To enable this, the output must also include some reference to the point which has been reached in the program, in order to continue from the same point next time.

Advantages

- Similar work to this has already been done, so implementing this design would be an extension of that rather than a new solution created from scratch.
- Non-terminating or long-running programs do not have to be run in their entirety, saving the user time when debugging a program, since they do not have to wait for execution to finish.
- As shown in the previous project, it is possible to implement partial execution in the compiler without affecting compilation or runtime performance. It is likely that the tracing method would impact runtime performance in some way.

Disadvantages

- It would be difficult to allow the user to step backwards through the program with this method, because each invocation of the compiler would be separate, meaning the use of backtracking would be impossible, and if the output is simply a graph and the current position in the program, there is no way to discover what changes were made to the graph during the last invocation.
- Continuing from a partially executed state would be impossible if the user edits their program or the input graph before continuing. While this would be an error on the user's part, it could potentially be confusing if they edit the program to fix a bug and then click continue instead of restarting from the beginning.
- Adding various granularity options for partial execution would require adding many new command line arguments to the compiler.

Having a lot of command line arguments related to debugging may confuse users, and could also lead to potential bugs when using these arguments programmatically from the IDE.

4.2.2 Use Tracing to Step Through Execution History

Instead of pausing execution to show the current state of the program, this method would instead add tracing to the user's program, and the IDE would run the entire program before stepping through the history. This is similar to how tools such as Hat (discussed in Section 2.2.2) work.

The existing way of running a program in the IDE would remain unchanged, and would not enable tracing, to avoid any performance impact of having tracing turned on. A second button in the UI would run the program with tracing turned on, and then switch the IDE into a mode which allows the user to examine the execution history of their program.

Advantages

- It would be possible to add the ability to jump to any point in the program's execution, since all states would be stored. Using the other proposed method, jumping to a specific point would involve running the program and somehow detecting when the requested state is reached.
- Stepping through a program would be much faster than using partial execution because another process does not have to be executed at each step.
- Debugging would not be dependent on the compiler, once the programs has been compiled and run, so certain additional debugging features could be added to the IDE without requiring the compiler to be updated.

Disadvantages

- Debugging a non-terminating program may be impossible because the program may never output a trace, unless the compiler can be modified to produce programs which terminate upon receiving a signal, and save their trace before exiting.

- Storing a trace may use a lot of memory or disk space, depending on the implementation.
- It would not be possible to add the ability for a user to choose a rule to apply, or a match to apply a rule to, since execution has already finished when the user regains control.

4.3 Chosen Solution

The second solution, tracing a program and then allowing the user to step through the execution history, has been selected as the chosen design to implement debugging features in GP2.

This solution has advantages over the other design, such as the ability to more easily implement more program traversal methods, including backwards stepping and jumping to a specific point in time. Each step through the trace will also be much faster than the other design; the IDE does not have to wait for the program to run a step and return the results, because the program has already been run.

Another advantage of this design is that it can also help the problem of debugging a program which uses the `Or` statement. Since the trace can be used repeatedly once the program has finished running, the user can step through the program multiple times without having to re-run the program. This means that the branch chosen when stepping through the `Or` statement will remain constant until the user edits the program and has to run it again.

The solution also has trade-offs, such as a possible impact on runtime performance; extra work needs to be done to store the trace. Runtime performance, while one of the requirements outlined in Section 3.4, is less important than the user's ability to actually debug their program. For the same reason that IDEs such as Visual Studio disable compiler optimisation by default when debugging, an accurate debugger is more useful than a higher performance one.

A lot of memory and disk space is available on modern hardware; it is unlikely that a GP2 trace would exhaust the available resources on a relatively recent machine. In addition, the GP2 IDE is not currently distributed outside of the University of York, meaning that the target hardware is mostly the university hardware, which is designed to have a large amount of both RAM and hard disk space available.

Additionally, a trace format will need to be designed and implemented so that the program and the IDE can communicate. This will be a simple

4 *Design*

Domain-Specific Language (DSL) which represents the actions a GP2 program takes. Part of this format can be based on the existing DSL which defines the machine readable format of graphs and programs in GP2.

Finally, although the other proposed design would have trivially allowed non-terminating programs to be debugged, this design does not have a clear solution to this problem. It is more difficult to support non-terminating programs with tracing, since as first glance it appears the program has to finish running before it can output a trace. However, it is possible to get around this by, for example, periodically writing a partial trace to disk. Then, if the program is non-terminating and needs to be killed, the user will still be able to trace through the earlier part of the execution and be able to debug their program.

5 Implementation

5.1 Trace File Format

The running program and the IDE must communicate in some way in order for the debugging interface in the IDE to show the execution of the program. To do this, the program trace is stored in a file on disk, so that the program can write to it and the IDE can read from it.

The format used for these files is completely internal to the GP2 system and does not need to be edited or read directly by users. This means that the format can focus on requirements such as being easy to parse in the IDE's C++ code, rather than focusing on making it human readable.

Two formats were considered for trace files, one formatted as an XML document, and one formatted as a plain text document with a custom structure inside. An example trace file in each format is shown in Listing 5.1 and Listing 5.2. These examples both show a theoretical execution of the incorrect 2-colouring program from Figure 3.1.

Listing 5.1: XML based trace file example

```
<?xml version="1.0" encoding="UTF-8" ?>
<trace program="2_colouring.gp2"
  input_graph="triangle.host">
  <if backtracking="true">
    <condition>
      <rule name="init">
        <match>
          <node id="0" />
        </match>
        <apply>
          <remarked>
            <node id="0" old="0" new="1" />
          </remarked>
        </apply>
      </rule>
```

5 Implementation

```
<loop>
  <iteration>
    <prcoedure name="Colour">
      <ruleset rules="colour_red,colour_blue">
        <rule name="colour_blue">
          <match>
            <node id="0" />
            <node id="1" />
            <edge id="0" />
          </match>
          <apply>
            <remarked>
              <node id="1" old="0" new="2" />
            </remarked>
          </apply>
        </rule>
      </ruleset>
    </prcoedure>
  </iteration>

  <iteration>
    <prcoedure name="Colour">
      <ruleset rules="colour_red,colour_blue">
        <rule name="colour_red">
          <match>
            <node id="1" />
            <node id="2" />
            <edge id="1" />
          </match>
          <apply>
            <remarked>
              <node id="2" old="0" new="1" />
            </remarked>
          </apply>
        </rule>
      </ruleset>
    </prcoedure>
  </iteration>
</loop>
```

```

    <prcoedure name="Invalid">
      <ruleset rules="joined_blues,joined_blues">
        <rule name="joined_blues">
          </rule>
        </ruleset>
      </prcoedure>
    </condition>

    <else>
      <rule name="add_green_node">
        <match></match>
        <apply>
          <added>
            <node id="3" label="empty" mark="3"
              root="false" />
          </added>
        </apply>
      </rule>
    </else>
  </if>
</trace>

```

Listing 5.2: Plain text trace file example

```

PROG ; 2-colouring.gp2 ; triangle.host
IFFS ; 1
CNDS
RULE ; init ; n0
MARK ; n0 ; 0 ; 1
LOPS
ITRS
PRCS ; Colour
SETS ; colour_red,colour_blue
RULE ; colour_blue ; n0,n1,e0
MARK ; n1 ; 0 ; 2
SETE
PRCE
ITRE
ITRS
PRCS ; Colour

```

5 Implementation

```
SETS ; colour_red,colour_blue
RULE ; colour_red ; n1,n2,e1
MARK ; n2 ; 0 ; 1
SETE
PRCE
ITRE
LOPE
PRCS ; Invalid
SETS ; joined_blues,joined_blues
RULE ; joined_blues ; fail
SETE
PRCE
CNDE
ELSS
RULE ; add_green_node ; ()
NEWN ; 3 ; () ; 3 ; 0
ELSE
IFFE
```

In the XML format, each action in a program is represented by a tag. The attributes are used to provide details, such as the label of a node, or whether an IF-THEN-ELSE required backtracking.

In the plain text format, each action is represented by a line of text similar to a line in assembly; it begins with a four-letter code representing the operation, which is followed by the details for the operation, separated by semicolons.

The XML format was ultimately chosen because it has multiple advantages over the plain text format.

One advantage of the XML format is that the Qt framework, which the GP2 IDE uses, has a built in XML parser which would make implementation much easier. Using the plain text format would require a custom parser to implement. GP2 project files (.gpp files) also use XML, meaning it can be expected that other GP2 developers understand how to use the XML parser from the Qt framework, making the code easier to maintain.

In addition, the XML format is easier to understand by a user if they open the file directly. This is because each of the parameters are named, since XML tag attributes are name-value pairs. In the plain text format, the parameters are simply listed with no other information, making it harder to determine what each one means. The XML tag names are also more descriptive than the four letter codes from the plain text format.

Whilst readability is not an important factor to end users, it increases maintainability for other GP2 developers, because it is easier to understand how GP2 interprets the format. It also means that it is easier to manually read a trace file if necessary, such as if the IDE crashes while trying to read the file.

A disadvantage of this format is that, because every tag has to be closed for the XML to be valid, there may be situations where the trace file saved by the running program is invalid. For example, if the program contains a bug and fails to terminate, the user may have to kill the running program, which would cause the closing tags not to be written to the file. Additional code is required in the IDE to handle any cases where the end of the XML document is missing. This would not have occurred with the other format, because any number of lines form a valid file in that format.

6 Evaluation

6.1 Requirements Tracing

Go back and compare the implemented debugging tools to the requirements from chapter 3.

6.2 Performance

Test the performance of some GP2 algorithms with tracing turned on and off.

6.3 User Feedback

(If there's time) Get some users to use the new features and get feedback from them.

7 Conclusions

Summary of what has been achieved in the project.

7.1 Future Work

What's missing (e.g. what requirements weren't met) and what other improvements could be made by someone else?

Bibliography

- [1] A. H. Ghamarian, M. de Mol, A. Rensink, E. Zambon, and M. Zimakova, "Modelling and analysis using GROOVE," *International Journal on Software Tools for Technology Transfer*, vol. 14, no. 1, pp. 15–40, 2012.
- [2] C. Ermel, M. Rudolf, G. Taentzer *et al.*, "The AGG approach: Language and environment," in *Handbook of Graph Grammars and Computing by Graph Transformation*. World Scientific Publishing Co., Inc., 1999, pp. 551–603.
- [3] E. Jakumeit, S. Buchwald, and M. Kroll, "GrGen.NET - the expressive, convenient and fast graph rewrite system," *International Journal on Software Tools for Technology Transfer*, vol. 12, no. 3–4, pp. 263–271, 2010.
- [4] D. Plump, "The design of GP₂," in *Proc. International Workshop on Reduction Strategies in Rewriting and Programming (WRS 2011)*, ser. Electronic Proceedings in Theoretical Computer Science, vol. 82, 2012, pp. 1–16.
- [5] C. Bak, "GP 2: Efficient implementation of a graph programming language," Ph.D. dissertation, University of York, September 2015.
- [6] D. Plump, "The graph programming language GP," in *Algebraic Informatics: Third International Conference, CAI 2009, Thessaloniki, Greece, May 19–22, 2009, Proceedings*, ser. Lecture Notes in Computer Science, vol. 5725, 2009, pp. 99–122.
- [7] J. E. Sammet, *Programming Languages: History and Fundamentals*. Prentice-Hall, Inc., Englewood Cliffs, NJ, 1969, ch. 1, p. 18.
- [8] M. L. Scott, *Programming Language Pragmatics*, 3rd ed. Morgan Kaufmann, Burlington MA, 2009, ch. 15, p. 806.
- [9] Free Software Foundation. (2016, October) GDB: The GNU project debugger. [Online]. Available: <https://www.gnu.org/software/gdb/>

- [10] Oracle. jdb - the Java debugger. [Online]. Available: <http://docs.oracle.com/javase/7/docs/technotes/tools/windows/jdb.html>
- [11] Microsoft. Debugging in Visual Studio. [Online]. Available: <https://msdn.microsoft.com/en-us/library/sc65sadd.aspx>
- [12] Eclipse Foundation. Eclipse IDE for Java developers. [Online]. Available: <http://www.eclipse.org/downloads/packages/eclipse-ide-java-developers/neon1a>
- [13] Free Software Foundation. (2012, November) GDB and reverse debugging. [Online]. Available: <https://www.gnu.org/software/gdb/news/reversible.html>
- [14] P. Wadler, "Functional programming: Why no one uses functional languages," *ACM SIGPLAN Notices*, vol. 33, no. 8, pp. 23–27, 1998.
- [15] O. Chitil, C. Runciman, and P. Koopman, "Freja, Hat and Hood - a comparative evaluation of three systems for tracing and debugging lazy functional programs," in *Implementation of Functional Languages: 12th International Workshop, IFL 2000*, pp. 176–193.
- [16] H. Taylor, "Tracing & debugging GP2," Master's thesis, University of York, April 2016.