GPL
Final Report

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1 Introduction

GPL (Graph Programming Language) is designed for graph related programming. It has intuitive ways of declaring graphs as well as the built-in data types for graph and its components such as edges and nodes. Its syntax is similar to C-like main stream imperative languages. It also supports user defined functions. With GPL, the user can easily built graphs and graph-related algorithms to solve real life problems. GPL is compied into C, which can then be compiled into machine code using gcc or clang.

1.1 Motivation

While graph is an important part in Computer Science and Mathematics, there are not many programming languages with built-in support for graph, not mentioning an intuitive way of describing the data structure of a graph. We decided to build GPL to discover the possibilities.

1.2 Key Features

Intuitive Graph Declaration
One can declare an undirected or directed graph by using a combination of dashes and greater-than symbol. One can express the weight of an edge by including a number, or a string or even an expression in the parenthesis. One can also refer to the weight by dot operator. This will be explained in detail in the next section.

User Defined Function
The user can defined their own functions. This expands the expressiveness of GPL, and make it more flexible. With the support of user defined function, GPL can easily express simple algorithms such as GCD in recursive or iterative fashion; more complicated algorithm such as Kruskal's minimum spanning tree algorithm can also be expressed.

Complete Control Structures
GPL has most of the popular structures appeared in main stream programming languages such as for and while loops, if and if else statements. More details will be revealed in the next section.

2 Language Tutorial

2.1 Basic Structure of A GPL Program

Unlike many popular programming languages, GPL is not object-oriented, therefore, it does not support class, or struct. A basic program consist of a main function. As simple as it sounds, this all it needs. For example, the simplest GPL program and a hello-word example are provided below.

```
// the simplest GPL program
void main() {
}
// hello word
void main() {
  print("Hello World!");
}
```

2.2 Built-in Data Types and Variable Assignment

GPL supports a set of primitive types, integer (int), character (char) and string (string). Notice that in GPL, string is also a primitive type. The following code illustrates the how to assign values for built-in data types.

```
int main() {
  int i = 41;
  char c = '4';
  string s = "43";
  // you can also declare first and assign later
  char k;
  k = 'k';
  return 0;
}
```

2.3 Control Structures

The following code illustrates the usage of for loop, while loop, and if statements. In short, the syntax is similar to C's.

```
void main() {
  int soln = 42;
  if (soln == 42) { // the { } can be omitted here
    print("That is the answer.\n");
```

```
   }
   int num = 0;
   for (int i = 0; i < 10; i+=1)
      num += 1; // ++ or -- is not support; +=, -=, /=, *=, %= are
   while (num > 0)
      num -= 1; // can also use num += -1;
   if (num == 0 && soln == 42) // or operator is ||
      print("Running correctly.\n");
}
```

2.4 Writing and Calling a Function

The first part of the function is return type, if none, use "void". However, as the entry point of any GPL program, main() has to be void. The second part is function body, surrounded by curly brackets. Below is an example of a recursive GCD algorithm that illustrates the usage of function.

```
int gcd(int a, int b) {
   if (b == 0)
      return a;
   else
      return gcd(b, a % b);
}

void main() {
   print(gcd(20, 40));
}
```

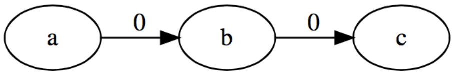
2.5 Advanced Date Types

For all primitive types, GPL has a corresponding array type. Different from the main stream programming style, to declare an array, the size of the array is explicitly written in "[ ]" on the left side. The following example illustrate that.

```
void main() {
   int[3] a; // initialized to 0
   a[2] = 2;
   print(a[2]); // should print 2
}
```

2.6 Defining a Graph

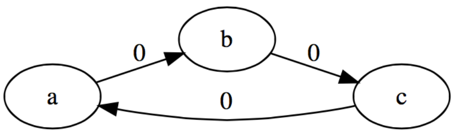
The following three ways of defining the simple graph shown below are equivalent. They all result in the same representation as the following figure.




```
void main() {
   graph g1 = [
      a -> b -> c;
   ];
   graph g2 = [
      a -> b;
      b -> c;
   ];
   graph g3 = [
      b -> c;
      a -> b;
   ];
}
```

2.6.1 Defining a Graph with Redundancy

The syntax is the exactly the same. The purpose of the illustration is to show that GPL will sort out the graph even though some lines in the definition could be redundant. The bottom line is that there should be no conflict in the definitions of a graph. In this illustration, we define a loop. GPL will ignore the redundant part in definitions.



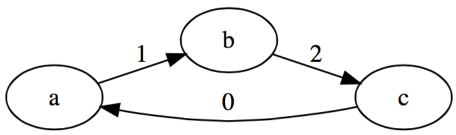

```
void main() {
   graph g1 = [
      a -> b -> c -> a;
      a -> b; // ignored
      c -> a; // ignored
      b -> c; // ignored
```

```
  ];
}
```

2.6.2 Defining a Graph with Edge Weights

This is probably the most creative and intuitive way of defining a graph with edge weights. Weights are flexible in terms of the form, it can be of as simple as an int type, or an expression that results in an value of type int. Notice that defining a weight for an edge is optional in graph. The default weight is zero. The following illustrates how to define a graph equivalent to the figure shown below.

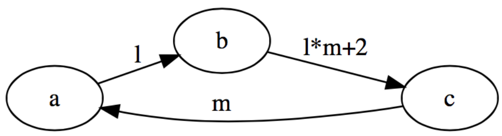
```
void main() {
  graph g1 = [
    a -(1)> b -(2)> c -> a;
  ];
}
```



As mentioned previously, expressions that are evaluated as integer values can also be used as edge weights. The following example demonstrates it.

```
void main() {
  int l = 2;
  int m = 2%a;
  graph g1 = [
    a -(l)> b -(l*m+2)> c -(m)> a;
  ];
}
```

Below is the image representation of the graph defined above.



3 Language Manual

3.1 Introduction

Graph is a very powerful data structure that can be used to model a variety of systems in many fields. Graph is such a fundamental model that people have developed libraries dedicated to graphs in almost all general-purpose high-level programming languages. However, implementing graph-related algorithms in languages like Java or C++, even with the benefit of using third-party graph libraries, entails manual manipulation of nodes and edges. This could prove to be error-prone (with pointer manipulations in C++), tedious (verbose especially in Java), and daunting (to people new to the programming world).

The Graph Programming Language (GPL) is a domain-specific language that attempts to remedy these problems. GPL strives to hide most logic behind graph handling under the hood, so that programmers are able to focus more on using graphs, instead of implementing them.

The primary goal of GPL is to allow programmers to create, use, and manipulate graphs in a natural, flexible and intuitive way. All graph-based algorithms should be easier to implement in GPL, e.g. shortest path, spanning tree, strong connectivity. Because all trees are graphs, GPL is automatically suitable for applications involving tree structures, such as priority queues (min/max heaps), binary search trees, or any kind of hierarchical data representation.

3.2 Lexical Conventions

3.2.1 Comments

Two slashes "//" introduce one-line comment, which is terminated by the newline character. For multiline comment, /* is used to start commenting and */ is used to terminate commenting. Nested commenting is not supported by the language.

3.2.2 Identifiers

An identifier consists of a sequence of letters, digits, and the underscore character; the first character of an identifier cannot be a digit. Upper and lower case letters are considered different.

3.2.3 Keywords

The following identifiers are reserved by the language to have specific meanings and may not be used otherwise:

boolean	break	char
continue	edge	else
for	graph	if
int	node	return
string	while	

3.2.4 Object Type

In GPL, graph, edge, node, and string are object types. "Object" implies that they are not primitive data types, and they can have member functions and fields which can be invoked or accessed through the dot operator. Graph, node, edge, and string are the only four object types in GPL; GPL does not support user-defined objects, but does support user-defined functions.

3.2.5 Literals

3.2.5.1 Integer literals Integer literals are decimal (base 10). An integer literal is just a sequence of digits.

3.2.5.2 Character literals A character literal is one or two characters enclosed by single quotes. Two characters enclosed by single quotes are for escape characters. The first character must be back-slash, and the second one can be back-slash, single quote, 'n', 'r', 't'; they represent backslash, single-quote, line-feed, carriage-return, and tab, respectively. The only valid representation of the single-quote character is a back-slash followed by a single-quote, enclosed in two single quotes.

3.2.5.3 Boolean literals There are exactly two boolean literals: **true** and **false**.

3.2.5.4 String literals A string literal is a sequence of characters enclosed by double quotes. Backslash, double-quote, line-feed, carriage-return, and tab characters need to be escaped by a preceding back-slash, similar to character literals.

3.2.5.5 Graph literals A graph literal is a list of weighted directed edges enclosed by square brackets. All weights must be integers. Only directed edges are supported by GPL.

3.3 Expressions

3.3.1 Primary Expressions

3.3.1.1 identifier An identifier is a unique (in its own scope) name used to identify an entity in the program. It can be the name of a function, parameter, or variable. A reserved keyword cannot be used as an identifier.

For array identifier, the following member functions can be used:

len()	this member function returns the size of the array
sort()	this member function can only be used for int, char, or edge arrays and it sorts the element

3.3.1.2 literal Literals include strings, characters, numbers (integer), and graphs.

3.3.1.3 string String is an object type of the language. String is immutable.

String has the following two member functions:

len()	this member function returns the length of the string
substr(a, len)	this member function returns the substring starting at index **a**, and includes **len** characters.
empty()	this member function returns true if the string is empty
at(i)	this member function returns the character at the specified index
append(s)	this member function appends s to the called string

3.3.1.4 node Node is an object type of the language. It represents a node in a graph.

Node has member function:

getID()	returns the unique integer ID of the specified node

3.3.1.5 edge

Edge is an object type of the language. It connects two nodes.

Edge has member functions:

getWeight()	returns the weight of the edge.
getSrc()	returns the source node of this edge.
getDst()	returns the destination node of this edge.

3.3.1.6 graph

Graph is an object type of the language. It represents a directed graph which consists of nodes and directed edges with integer weights.

The nodes in a graph can be accessed like fields. For example, if graph g has node v, then the node is represented by the expression "g.v".

Graph has member functions:

getNode(int id)	returns the node with specified id
getEdge(node src, node dst)	returns the specified edge. If the specified edge does not exist, a run-time exception is raised.
getAllEdges()	returns the list of edges in the graph as an array
getAllNodes()	returns the list of nodes in the graph as an array
getWeight(node src, node dst)	returns the weight of the edge that goes from src to dst node
getEdgeCount()	returns the number of edges in the graph
getNodeCount()	returns the number of nodes in the graph
getInNeighbours(node n)	returns an array of nodes that have edge to the specified node
getOutNeighbours(node n)	returns an array of nodes that this node has edges to

3.3.1.7 (expression)

The parenthesized expression is the same as expression. Including an expression in a pair of parentheses does not imply any precedence of the expression.

3.3.1.8 primary-expression [expression]

The primary-expression in this part can only be array. The expression can only be integers within the range of the array. primary-expression [expression] means to access the expression-th element in the array.

3.3.1.9 primary-expression (expression)

This expression means a functional call, where primary-expression is an identifier that is a name of a function. The expression in the pair of brackets is parameter(s) to in the call. It can be single parameter. If there are more than one parameters, they should be separated by a comma.

3.3.1.10 primary-lvalue . member-function-of-object-type An lvalue expression followed by a dot followed by the name of a member function of object-type is a primary expression.

3.3.2 Graph Definition Operators

3.3.2.1 identifier − > identifier The − > binary operator connects two nodes with zero-weighted directed edge. The direction goes from first node identifier to second node identifier.

3.3.2.2 identifier :− > identifier, identifier, ... The :− > operator connects first node identifier with all the other node identifier that follow with zero-weighted directed edge.

3.3.2.3 identifier −(expression)> identifier The −(identifier)> operator connects two nodes with weighted directed edge. The direction goes from first node identifier to second node identifier. The weight of the edge equals the expression in the middle. The expression must be of int type.

3.3.2.4 identifier : −(expression)> identifier, identifier, ... The : −(expression)> operator connects first node identifier with all the other node identifier what follow with weighted directed edge. The weight of the edge equals the expression in parentheses. The expression must be of int type.

3.3.3 Unary Operators

Unary operators are grouped from right to left.

3.3.3.1 − expression The − unary operator can be applied to an expression of type int or char, and results in the negative of the expression.

3.3.3.2 ! expression The ! unary operator can only be applied to an expression of boolean type, and results in the opposite of the truth value of the expression

3.3.4 Multiplicative Operators

3.3.4.1 expression * expression The binary operator * indicates multiplication between expression and expression. The expression pair can be in the following combinations. 1) int int 2) char char 3) int char 4) char int. In case 3, and 4, all the parameters will be treated as int.

3.3.4.2 expression / expression The binary operator / indicates division between expression and expression. The expression pair can be in the following combinations. 1) int int 2) char char 3) int char 4) char int. In case 3, and 4, all the parameters will be treated as int.

3.3.4.3 expression % expression The binary % operator outputs the remainder from the division of the first expression by the second. The expression pair can be in the following combinations. 1) int int 2) char char 3) int char 4) char int. In case 3, and 4, all the parameters will be treated as int.

3.3.5 Additive operators

3.3.5.1 expression + expression The binary + operator outputs the addition of the first expression and the second expression. The expression pair can be in the following combinations. 1) int int 2) char char 3) int char 4) char int. In case 3, and 4, all the parameters will be treated as int.

3.3.5.2 expression - expression The binary - operator outputs the result of the first expression minus that of the second expression. The expression pair can be in the following combinations. 1) int int 2) char char 3) int char 4) char int. In case 3, and 4, all the parameters will be treated as int.

3.3.6 Relational operators

3.3.6.1 expression < expression

3.3.6.2 expression > expression

3.3.6.3 expression <= expression

3.3.6.4 expression >= expression

3.3.6.5 expression == expression

3.3.6.6 expression ! = expression The relational operators $<$ (less than), $>$ (greater than), $<=$ (less than or equal to), $>=$ (greater than or equal to), $==$ (equal to), $! =$ (not equal to) all yield boolean **true** or **false**. The two expressions being compared must be of the same type, and they can be int, float, char or string. Characters are compared by ASCII values; strings are compared lexicographically.

3.3.7 Assignment operators

3.3.7.1 variable = expression The binary = operator indicates that the result of the expression on the right side is stored in the variable on the left. If there is already data stored in the variable, the data will be replaced. The variable can be any legal type defined in the language.

3.3.7.2 variable += expression The binary += operator indicates that the value of the variable on the right side will be incremented by the quantity of the result of the expression on the left side. This operator requires the two expressions to be in the same numerical type, i.e. either both in int, or both in char.

3.3.7.3 variable -= expression The binary -= operator indicates that the value of the variable on the right side will be decremented by the quantity of the result of the expression on the left side. This operator requires the two expressions to be in the same numerical type, i.e. either both in int, or both in int.

3.3.8 Logical operators

3.3.8.1 boolean-expression && boolean-expression

3.3.8.2 boolean-expression || boolean-expression The logical operators && (and) and || (or) can be applied to two boolean expressions, and results in the logical AND or OR of the truth values of the two boolean expressions.

3.3.9 Function calls

Function calls are made by function identifier followed by the list of arguments separated by commas enclosed by parentheses. Function overloading, functions with the same name but different set of argument types, is supported.

3.4 Declarations

3.4.1 Type specifiers

The type-specifiers are

```
type-specifier:
      int
      char
      string
      graph
      node
      edge
      type-specifier [ ]
```

3.4.2 Variable Declarators

```
declarator:
   type-specifier identifier
   type-specifier identifier = expr
```

3.4.3 Graph Expression

```
graph-expr
   [ graph-body ]

graph-body
   edge-declaration-list

edge-declaration-list:
      edge-declaration;
      edge-declaration; edge-declaration-list

edge-stmt:
      node-declarator
      node-declarator -> edge-stmt
      node-declarator - ( expr ) > edge-stmt

edge-declaration:
      edge-stmt
      node-declarator : - ( expr ) > node-declarator-list
```

```
     node-declarator : -> node-declarator-list

node-declarator-list:
     node-declarator
     node-declarator node-declarator-list

node-declarator:
     identifier
```

3.4.4 Function declarations

```
function-decl:
   retval formals_opt ) { stmt_list }


procdecl: /*procedure (aka. void function) declarator*/
     void identifier ( formals_opt ) { stmt_list }

retval:
        vartype identifier (

formals_opt:
   /* nothing */
     formal_list

formal_list:
        vardecl
     formal_list , vardecl
```

3.5 Statements

3.5.1 Expression statement

Expression statement is an expression followed by semicolon.

3.5.2 Compound statement

The compound statement is a list of statements surrounded by parentheses.

3.5.3 Conditional statement

There are two types of conditional statements:

- Type 1: if (expression) statement
- Type 2: if (expression) statement else statement

In type 1, if expression is evaluated to be true, the statement will be executed. In type 2, if expression is evaluated to be true, the first statement will be executed, otherwise the second statement will be executed.

3.5.4 While statement

The while statement can be described as: while (expression) statement

As long as the expression is evaluated to be true, the statement will be executed repeatedly. The expression is evaluated before the execution of statement.

3.5.5 For statement

The for statement can be expressed as:

for (expression-1; expression-2; expression-3) statement

expression-1 defines the initialization of the loop. expression-2 is the test that will be evaluated for truth in each loop. expression-3 defines what to do after each loop has been executed.

3.5.6 Return statement

Return statement can be described as: return (expression)

The expression can be either a simple expression, which will be evaluated to a value and then be returned to the calling function. Alternatively, the expression can be consisted of one or more function calls, then the return statement will be executed after all function calls have been returned.

3.5.7 Null statement

A null statement consists a single semicolon. It is useful in a for loop where one or more of the three expressions is not defined (or unneeded to define).

3.6 Scoping

There are three rules of scoping. The first rule states that the global variables and functions can be referred from anywhere in the code even before it is declared. The second rule states that the variables declared in a function can be referred only after the declaration. The third rule states that the variables declared in a function bind closer than the variables declared outside the function. For example, there is a variable named a in a function, even though, outside the function, there may be a variable a, because of the stronger binding of the variable declared in the function, if one refers a in the function, he or she refers to the one declared in the function.

4 Project Plan

4.1 Planning

Our group routinely meet on Friday and Saturday, and holidays like Thanksgiving. Initially, the idea was that each of us should work on our own part individually, but as the project progressed, we realized that it is more efficient to work together in CLIC lab. We also meet with Olivia on Thursday. Since we only have three team members, scheduling a time to work together is relatively easy. Because that new problems came as we the development went further, we gave up making clear plans for each week. Instead, every time we meet, we solve a major issue encountered in that week.

4.2 Specification

We treated the LRM as a rough guideline of our language. At the beginning, we build the language in the format specified exactly in the reference manual, but later, we realized that the reference manual itself had many details unspecified, therefore we made the decision during the development, and came back to update the reference manual. Other problem with the early specification is that some features are too hard to implement. For example, initially, the syntax we specified in the manual on defining graph always end up in shift reduce error, and it turned with the old syntax, it cannot distinguish a block of graph content and a block of regular code. In cases like that, we modified the specification.

4.3 Development

We worked together in CLIC lab, using git as version control. Not only OCaml code, but also testing scripts, reports, and reference manual are hosted in GitHub. Other than the meeting with Olivia, we do not have dedicating meetings. One reason is that we only have three team members, no such meeting is necessary. The other reason is that we work together, and we have fully awareness of everyone's progress.

4.4 Testing

The full automatic testing suite was written right after we finished the scanner. We have dedicated individual writing test cases for each part of the language so that the rest of the team can focus on developing. We have a large number of test cases, each case only focus on one aspect of the language. Each test case uses with the language as deviously as possible. We test both the cases where the language should fail (raising exceptions), and should not. Each test case is a pair of files. One GPL source code, one output file. The automatic test suite will compare the actual output of the source code to the expected output and decides whether it is a pass or fail.

4.5 Programming Style Guide

The coding style is the same as the ones presented in class. We did not enforce a specific style since we are both new to OCaml. The bottom line is that each of us can understand the code. During the process, no one has written any code that other cannot understand.

4.6 Project Timeline

Add a table briefly describe what we did on each day, after the project is done.

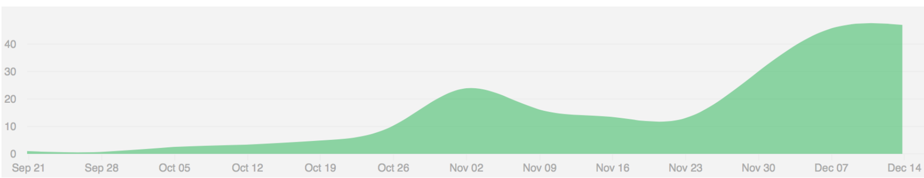


Figure 1: Git Statistics from Sep 21, 2014 to Dec 17, 2014

Oct 10, 2014
Start writing LRM, scanner

Nov 04, 2014
Building parser, ast, testing scripts

Nov 08, 2014
Continue on parser and ast

Nov 14, 2014
Continue on parser and ast

Nov 15, 2014
AST done

Nov 21, 2014
Start writing SAST, code generation, test cases

Nov 28, 2014
Keep working on SAST, code generation, and test cases; start writing demo

Nov 30, 2014
Working on SAST, code generation, test cases, and demo

Dec 06, 2014
Updated testing scripts, building language libraries, SAST, test cases, demo

Dec 09, 2014
Working on SAST, code generation, test cases, demo, and final report

Dec 11, 2014
Same as above

Dec 14, 2014
SAST passed all test cases, building code generation, test cases, demo, and final report

Dec 15, 2014
All demos worked correctly, code generation stablized, improving SAST, final report

Dec 17, 2014
Final presentation

4.7 Roles and Responsibility

Ephraim Park

The assigned role was system architect. I have worked on the scanner, parser, ast, sast, and LRM. I am the major contributor of scanner, and sast.

Peiqian Li

The assigned focus was verification and validation. I wrote the test suite, and I have worked on the scanner, parser, ast, sast, LRM, and code generation.

Qingxiang Jia

The assigned role was project manager and language guru. I have worked on the parser and ast, writing test cases, demo code, LRM and final report.

4.7.1 Development Environment

All of the team members work on OS X with OCaml compiler installed. The most popular editors are vim and Sublime Text. We did not use any IDE. Git is used as version control, GitHub is the host. For complicated demo, we used Python as proof of concept and then translated it into GPL.

4.7.2 Project Log

Attach the git log after the project is done.

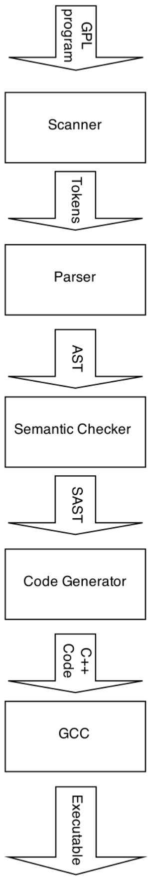
5 Architectural Design

The architectural design of GPL is demonstrated in the following block diagram:

Scanning and parsing were implemented by all three team members together; semantic check was done by Ephraim Park; code generation was done by Peiqian Li.

5.1 Scanning

We used **ocamllex** to tokenize the input source program into parsable units, to be further processed by the parser. The scanner discards comments, tabs, newlines, and space characters. Escaped characters or sequence of escaped



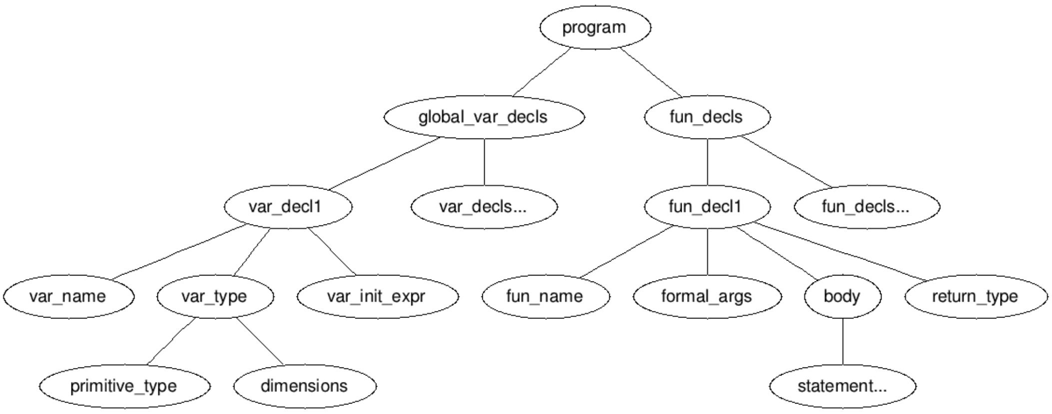
characters in the source program are unescaped by the scanner before being handed to the parser.

5.2 Parsing and Abstract Syntax Tree

We used **ocamlyacc** to parse the scanned tokens to an abstract syntax tree, as illustrated below. The parser rejects syntactically incorrect input programs.

5.3 Semantic check and SAST

In this stage, the parsed AST is checked for various semantic errors, including reference to undefined variables or functions, type mismatch in expressions or function parameter passing, variable redefinition within the same scope. We used a hash map to maintain variable and function references. We support function overloading by mapping a function name to a list of functions with different formal arguments.



5.4 Code generation

The code generator takes a semantically checked abstract syntax tree, and generates the target program in C++. Since C++ does not natively support multi-dimensional array, we makes use of multiple levels **vector**. All primitive types, i.e. int, char, and bool, are passed by values, whereas array, string, graph, node and edge are passed by reference.

6 Test Plan

6.1 GPL Demo Code

6.1.1 GCD

Below is the recursive version of GCD written in GPL.

```
int gcd(int a, int b) {
   if (b == 0)
      return a;
   else
      return gcd(b, a % b);
}

int main() {
   print(gcd(20, 40));
   return 0;
}
```

The next is the target language program (in C++) of the code above. The code is not formatted.

```
#include <vector>
#include "libprint.h"
#include "libstring.h"
#include "libgraph.h"
using namespace std;
;
void _main();
int _gcd(int _a, int _b);
void _main() {
;
{
(_print(_gcd(20, 40 ) ));
}

}
int _gcd(int _a, int _b) {
;
;
{
if ((_b == 0))
return _a;
else return _gcd(_b, (_a % _b) );
}

}
int main() { _main(); return 0;}
```

The following is the iterative version of GCD written in GPL.

```
int gcd(int a, int b) {
   while (a != b) {
      if (a > b)
         a = a - b;
      else
         b = b - a;
   }
   return a;
}

int main() {
   print(gcd(20, 40));
   return 0;
}
```

The next is the target language program (in C++) of the code above.

```
#include <vector>
#include "libprint.h"
#include "libstring.h"
#include "libgraph.h"
using namespace std;
;
void _main();
int _gcd(int _a, int _b);
void _main() {
;
{
(_print(_gcd(20, 40 ) ));
}

}
int _gcd(int _a, int _b) {
;
;
{
while ((_a != _b)) {
if ((_a > _b))
((_a = (_a - _b)));
else ((_b = (_b - _a)));
}

return _a;
}

}
int main() { _main(); return 0;}
```

6.2 Test Suite

The following is the automated test suite script.

```
#!/bin/bash

GPL="src/gpl"

# Set time limit for all operations
ulimit -t 30
```

```
successcount=0
errorcount=0

Check() {
    basename=`echo $1 | sed 's/.*\\///
                             s/.gpl//'`

    [ -f "test/$basename.err" ] && expectation=1 || expectation=0

    echo "###### Testing $basename"

    eval "$GPL <$* >/dev/null 2>&1" && actual=0 || actual=1

    if [[ ($expectation -eq 0) && ($actual -eq 0) ]] ; then
   eval "./a.out >output.txt"
   eval "diff -B --strip-trailing-cr output.txt test/$basename.out
       >/dev/null" && actual=0 || actual=1
    fi

    if [ $expectation -eq $actual ] ; then
      echo "###### SUCCESS" 1>&2
   successcount=$((successcount+1))
    else
      echo "###### FAILED" 1>&2
      errorcount=$((errorcount+1))
    fi
}

if [ $# -eq 0 ]; then
   test_files="test/*.gpl"

   for test in $test_files
   do
      Check $test
   done

   if [ $errorcount -eq 0 ]; then
       echo "All tests passed!"
   else
       echo "$successcount passed; $errorcount failed."
   fi
```

```
  exit $errorcount

else
  Check "test/$1.gpl"
fi
```

6.3 Test Cases Explained

Qingxiang wrote most of the test cases, however, both Ephraim and Peiqian contributed for each part they are responsible for.

File Name	Purpose
arith.gpl	Test the arithmetic operations and print statement for integers.
assn0.gpl	Test integer declaration, assignment, and arithmetic operations on variables.
assn1.gpl	Test initialization on declaration for type int, char, and string.
assn2.gpl	More tests for the previous conditions.
assn3.gpl	Negative test case for char being misassigned to int type.
array1.gpl	Test integer array declaration, assignment, and access.
array2.gpl	Test string array declaration, assignment, and access.
array3.gpl	Test calling on string and integer array length.
array4.gpl	Test string and integer array access and reassignment.
array5.gpl	Test len() function of multi-dimensional arrays for int, char, and string.
array6.gpl	Test variable assignment for multi-dimensional arrays of type int, char, and string.
array7.gpl	Test the usage of expressions for array capacity.
bool.gpl	Test boolean calculus and print for boolean values.
bool1.gpl	Test boolean assignment and print for boolean variable.
bool2.gpl	Test print on boolean variable when there are many brackets.
bool3.gpl	Test boolean calculus on complex boolean operations.
bool4.gpl	Additional test on complex boolean operations.
func.gpl	Negative test case for parameter mismatch.
glb_init1.gpl	Test variable global initialization.
glb_init2.gpl	Negative test case for variable global initialization.

File Name	Purpose
graph0.gpl	Test graph declaration and weight assignment for undirected edges.
graph1.gpl	Test graph declaration and weight assignment for directed edges.
graph2.gpl	Test declaration of undirected edge by two declaration of directed edges. The last redundant assignment should override values in both direction.
graph3.gpl	Test mixed declaration of undirected edge and directed edge.
graph4.gpl	Test redundant edge declaration.
graph5.gpl	Test weight update when redundant edge is declared.
if0.gpl	Test if-else statement.
newline.gpl	Test newline symbol assignment to char type.
plus.gpl	Test addition operation.
print.gpl	Test print of integer, char, and string.
rand_chars.gpl	Test if the parser can reject gibberish.
return0.gpl	Negative test case for function return.
return1.gpl	Test function return with complicated control structures.
return2.gpl	Negative test case for function return with complicated control structures.
return3.gpl	Test returning array of type int, char, and string.
scope1.gpl	Test scope in function calls.
scope2.gpl	It should reject variable declaration in loop invariant.
scope3.gpl	Test scope in for loop.
scope4.gpl	Test scope between for loop and function call.
scope5.gpl	Test scope in nested loops.
scope6.gpl	Test scope of function call in a loop.
scope7.gpl	Test scope of a loop, and function call which also has a loop.
scope8.gpl	Negative test case for scoping.
sort0.gpl	Test built-in function sort() on primitive array.
sort1.gpl	Test built-in function sort() on edge array.
sort2.gpl	More test on sort().
strlen.gpl	Test calling on len() of a string.
var_name0.gpl	Test if the parser can allow weird but legal variable name.
var_name1.gpl	A more devious version of the above test.

File Name	Purpose
var_name2.gpl	Test string assignment and print.
var_name3.gpl	Test variable assignment on integer and corresponding print statement.
var_name4.gpl	Test variable assignment on character and corresponding print statement.
var_name5.gpl	Test if the semantic check can reject illegal character assignment.

7 Lessons Learned

7.1 Ephraim Park

Really think through the language before start coding. Whenever making a design decision think about how that decision will be represented in target code. Try to learn OCaml in the beginning of the semester! Lastly, try to meet every week and work together. We met once a week for about 5 hours, and were able to finish the project in time without much stress.

7.2 Peiqian Li

Learn how to debug OCaml programs early. OCaml runtime system has an option for triggering the backtrace when an uncaught exception aborts the program, and another one for turning on debugging support for **ocamlyacc**-generated parsers. The latter is especially helpful when figuring out what's wrong with the grammar, because the automaton prints a trace of its actions when the p option is turned on. Run "export OCAMLRUNPARAM=p" in shell to turn this option on.

7.3 Qingxiang Jia

We need comprehensive test cases. Apart from thinking absolutely devious, the test cases should include *every* aspect of the language. The only thing that is always true is that the test cases do not cover every corner of the language. One time we though we had covered all major parts of the language, but during demo writing, we realized that the implementation of if-else statement buggy. This bug was hard to find because it was in the language level. Test thoroughly before writing complex demo.

8 Appendix

8.1 scanner.mll

```
{
  open Parser
  open Scanf

  let unescaped s =
      Scanf.sscanf s "%C%!" (fun x -> x)
}

rule token = parse
  [' ' '\t' '\r' '\n'] { token lexbuf }
| "/*"                  { comment lexbuf }
| "//"                  { singlelinecom lexbuf}
| '('                   { LPAR }
| ')'                   { RPAR }
| '['                   { LBKT }
| ']'                   { RBKT }
| '{'                   { LCUR }
| '}'                   { RCUR }
| ';'                   { SEMICOL }
| ':'                   { COL }
| ','                   { COMMA }
| '.'                   { DOT }
| '+'                   { PLUS }
| '-'                   { MINUS }
| '*'                   { MUL }
| '/'                   { DIV }
| '%'                   { MOD }
| "**"                  { POW }
| "+="                  { INC }
| "-="                  { DEC }
| "*="                  { SMUL }
| "/="                  { SDIV }
| "%="                  { SMOD }
| '='                   { ASN }
| "=="                  { EQ }
| "!="                  { NEQ }
| '<'                   { LT }
| "<="                  { LEQ }
| ">"                   { GT }
```

```
| ">="                { GEQ }
| "&&"                { AND }
| "||"                { OR }
| '!'                 { NOT }
| "--"                { EDGEU }
| "->"                { EDGED }
| "--:"               { ADJU }
| "->:"               { ADJD }
| "in"                { IN }
| "continue"          { CONT }
| "break"             { BREAK }
| "if"                { IF }
| "else"              { ELSE }
| "for"               { FOR }
| "while"             { WHILE }
| "return"            { RET }
| "null"              { NULL }
| "int"               { INT }
| "char"              { CHAR }
| "string"            { STR }
| "graph"             { GRAPH }
| "node"              { NODE }
| "edge"              { EDGE }
| "void"              { VOID }
| "bool"              { BOOL }
| "true"              { BOOLEAN_LIT(true) }
| "false"             { BOOLEAN_LIT(false) }
| ('\'' ([' '-'&' '('-'[' ']'-'~'] as c) '\'')
                      { CHAR_LIT(c) }
| ("'\\\\'" | "'\\''" | "'\\n'" | "'\\r'" | "'\\t'") as s
                      { CHAR_LIT(unescaped s) }
| ('0' | ['1'-'9']+['0'-'9']*) as lit
                      { NUM_LIT(int_of_string lit) }
| '"' (([' '-'!' '#'-'[' ']'-'~'] | '\\' ['\\' '"' 'n' 'r' 't'])*
   as s) '"'
                      { STR_LIT(s) }
| ['a'-'z' 'A'-'Z' '_']['a'-'z' 'A'-'Z' '0'-'9' '_']* as lit
                      { ID("_" ^ lit) }
| eof                 { EOF }
| _ as c              { raise (Failure("illegal character " ^
   Char.escaped c)) }

and comment = parse
```

```
  "*/" { token lexbuf }
| _    { comment lexbuf }

and singlelinecom = parse
  "\n" { token lexbuf }
| eof  { EOF }
| _    { singlelinecom lexbuf}
```

8.2 parser.mly

```
%{ open Ast %}

%token LPAR RPAR LBKT RBKT LCUR RCUR SEMICOL COMMA DOT COL
%token PLUS MINUS MUL DIV MOD POW INC DEC SMUL SDIV SMOD
%token ASN AND IS OR NOT
%token EQ NEQ LT LEQ GT GEQ
%token EDGEU EDGED ADJU ADJD
%token FUNC IN CONT BREAK IF ELSE FOR WHILE RET VOID
%token INT CHAR STR BOOL GRAPH NODE EDGE
%token <int> NUM_LIT
%token <string> ID
%token <bool> BOOLEAN_LIT
%token <string> STR_LIT
%token <char> CHAR_LIT
%token NULL
%token EOF

%left COMMA
%left EDGEU EDGED EDGEW EDGEWD
%right ASN INC DEC SMUL SDIV SMOD
%left OR
%left AND
%left IS NOT
%left IN
%left EQ NEQ LT LEQ GT GEQ
%left PLUS MINUS
%left MUL DIV MOD
%right POW
%left DOT
%left LBKT RBKT
%left LPAR RPAR
%nonassoc ELSE
```

```
%start program
%type <Ast.program> program
%type <Ast.var_type> vartype
%type <Ast.var_decl> vardecl
%type <Ast.func_decl> fdecl
%type <Ast.func_decl> procdecl
%type <Ast.expr> expr
%type <Ast.stmt> stmt
%type <Ast.node> node_declarator
%%

program:
   /* nothing */ { {gdecls=[]; fdecls=[] } }
 | program vardeclstmt { {gdecls=$2::$1.gdecls; fdecls=$1.fdecls} }
 | program fdecl { {gdecls= $1.gdecls; fdecls=$2::$1.fdecls} }
 | program procdecl { {gdecls= $1.gdecls; fdecls=$2::$1.fdecls} }

fdecl:
   retval formals_opt RPAR LCUR stmt_list RCUR
     {
      if (String.compare (snd $1) "main") == 0 then
        raise Main_not_void
      else
        { fname = snd $1;
           formals = $2;
           body = Block(List.rev $5);
           ret = fst $1
           } }

procdecl: /*procedure (aka. void function) declarator*/
    VOID ID LPAR formals_opt RPAR LCUR stmt_list RCUR {
      { fname = $2;
         formals = $4;
         body = Block(List.rev $7);
         ret = {ptype = (if (String.compare $2 "main") == 0 then
             Int else Void); dimension = []}
      }
    }

retval:
    vartype ID LPAR { $1, $2 }
```

```
formals_opt:
    /* nothing */ { [] }
  | formal_list { List.rev $1 }

formal_list:
    vardecl                  { [$1] }
  | formal_list COMMA vardecl { $3 :: $1 }

vardeclstmt:
    vardecl SEMICOL { $1 }

vardecl:
    vartype ID    {
                      {
                      vname = $2;
                      vtype = $1;
                      vinit = Noexpr;
                      }
                  }
    | vartype ID ASN expr
                  {
                      {
                          vname = $2;
                          vtype = $1;
                          vinit = $4;
                      }
                  }

vartype:
    INT         {
                    {
                        ptype = Int;
                        dimension = []
                    }
                }
    |CHAR       {
                    {
                        ptype = Char;
                        dimension = []
                    }
                }
    |STR        {
                    {
```

```
                ptype = Str;
                dimension = []
            }
        }
    |GRAPH     {
            {
                ptype = Graph;
                dimension = []
            }
        }
    |NODE      {
            {
                ptype = Node;
                dimension = []
            }
        }
    |EDGE      {
            {
                ptype = Edge;
                dimension = []
            }
        }
    |BOOL      {
            {
                ptype = Bool;
                dimension = []
            }
        }
    |vartype LBKT expr_opt RBKT {

                            {
                                ptype = $1.ptype;
                                dimension = (if $3 == Noexpr then
                                    NumLit(0) else $3) ::
                                    $1.dimension;
                            }
                        }

stmt_list:
    /* nothing */ { [] }
  | stmt_list stmt { $2 :: $1 }

stmt:
```

```
    expr SEMICOL { Expr( $1 ) }
  | RET expr SEMICOL { Return($2) }
  | RET SEMICOL { Return(Noexpr) }
  | LCUR stmt_list RCUR { Block(List.rev $2) }
  | IF LPAR expr RPAR stmt { If($3, $5, Block([])) }
  | IF LPAR expr RPAR stmt ELSE stmt { If($3, $5, $7) }
  | FOR LPAR expr_opt SEMICOL expr_opt SEMICOL expr_opt RPAR stmt
     { For($3, $5, $7, $9) }
  | WHILE LPAR expr RPAR stmt { While($3, $5) }
  | vardeclstmt { Localvar($1) }

expr_opt:
                { Noexpr }
  | expr        { $1 }

expr:
    BOOLEAN_LIT    { BoolLit($1) }
  | CHAR_LIT       { CharLit($1) }
  | NUM_LIT        { NumLit($1) }
  | STR_LIT        { StrLit($1) }
  | NULL           { Null }
  | MINUS NUM_LIT  { NumLit(-$2) }
  | PLUS NUM_LIT   { NumLit($2) }
  | MINUS lvalue   { Negof($2) }
  | PLUS lvalue    { $2 }
  | NOT expr       { Notof($2) }
  | expr IN expr   { Binop($1, In, $3) }
  | expr PLUS  expr { Binop($1, Add, $3) }
  | expr MINUS expr { Binop($1, Sub, $3) }
  | expr MUL expr  { Binop($1, Mul, $3) }
  | expr DIV expr  { Binop($1, Div, $3) }
  | expr MOD expr  { Binop($1, Mod, $3) }
  | expr POW expr  { Binop($1, Pow, $3) }
  | expr EQ   expr { Binop($1, Eq, $3) }
  | expr NEQ  expr { Binop($1, Neq, $3) }
  | expr LT   expr { Binop($1, Less, $3) }
  | expr LEQ  expr { Binop($1, Leq, $3) }
  | expr GT   expr { Binop($1, Greater, $3) }
  | expr GEQ  expr { Binop($1, Geq, $3) }
  | expr OR   expr { Binop($1, Or, $3) }
  | expr AND  expr { Binop($1, And, $3) }
  | expr INC expr  { Assign($1, Sadd, $3) }
  | expr DEC expr  { Assign($1, Ssub, $3) }
```

```
  | expr SMUL expr { Assign($1, Smul, $3) }
  | expr SDIV expr { Assign($1, Sdiv, $3) }
  | expr SMOD expr { Assign($1, Smod, $3) }
  | expr ASN expr  { Assign($1, Asn, $3) }
  | f_call { Call(fst $1, snd $1) }
  | expr DOT ID { MultiId($1, Dot, $3) }
  | expr DOT f_call { Call(fst $3, $1::(snd $3)) }
  | lvalue         { $1 }
  | gexpr          { GraphLit($1) }

f_call:
    ID LPAR actuals_opt RPAR { $1, $3 }

gexpr:
    LBKT graph_body RBKT { $2 }

graph_body:
    edge_declaration_list { $1 }

edge_declaration_list:
    edge_declaration SEMICOL { $1 }
  | edge_declaration SEMICOL edge_declaration_list { $1 @ $3 }

edge_stmt:
    node_declarator { $1, [] }
  | node_declarator EDGEU edge_stmt { $1, {src = $1; dest = fst $3;
     weight =
     NumLit(0)} :: {src = fst $3; dest = $1; weight = NumLit(0)}
         ::snd $3 }
  | node_declarator EDGED edge_stmt { $1, {src = $1; dest = fst $3;
     weight =
     NumLit(0)} :: snd $3 }
  | node_declarator MINUS LPAR expr RPAR MINUS edge_stmt { $1, {src
     = $1; dest = fst $7; weight = $4} :: {src = fst $7; dest =
     $1; weight = $4} :: snd $7}
  | node_declarator MINUS LPAR expr RPAR GT edge_stmt { $1, {src =
     $1; dest = fst $7; weight = $4} :: snd $7}

edge_declaration:
    edge_stmt { snd $1 }
  | node_declarator COL MINUS LPAR expr RPAR MINUS
     node_declarator_list { let rec construct_dedges nodes =
```

```
                                                                match
                                                                   nodes
                                                                   with
                                                                  []
                                                                     ->
                                                                     []
                                                                |
                                                                   node
                                                                   ::
                                                                   nodes
                                                                      ->
                                                                      {
                                                                      src
                                                                      =
                                                                      $1;
                                                                      dest
                                                                      =
                                                                      node;
                                                                      weight
                                                                      =
                                                                      $5
                                                                      }
                                                                      ::
                                                                          {
                                                                             src
                                                                             =
                                                                             noc
                                                                             des
                                                                             =
                                                                             $1
                                                                             wei
                                                                             =
                                                                             $5
                                                                             }
                                                                             ::
                                                                          (const
                                                                             noc
                                                              in
                                                                 construct_dedges
                                                                 $8
                                                                 }
| node_declarator COL MINUS LPAR expr RPAR GT
   node_declarator_list { let construct_edge_triplet node = {
```

```
      src = $1; dest = node; weight = $5 }
                                                                  in
                                                                     List.map
                                                                     construct_edge_tri
                                                                     $8
                                                                     }
  | node_declarator COL EDGEU node_declarator_list { let rec
      construct_dedges nodes = match nodes with
                                                        [] -> []
                                                      | node :: nodes
                                                         ->
                                                            { src =
                                                               $1;
                                                               dest
                                                               =
                                                               node;
                                                               weight
                                                               =
                                                               NumLit(0)
                                                               } ::
                                                               { src
                                                               =
                                                               node;
                                                               dest
                                                               = $1;
                                                               weight
                                                               =
                                                               NumLit(0)
                                                               } ::
                                                               (construct_dedges
                                                               nodes)
                                                    in construct_dedges
                                                       $4 }
  | node_declarator COL EDGED node_declarator_list { let
      construct_edge_triplet node = { src = $1; dest = node; weight
      = NumLit(0) }
                                                     in List.map
                                                        construct_edge_triplet
                                                        $4 }

node_declarator_list:
    node_declarator { [$1] }
    | node_declarator node_declarator_list { $1 :: $2}
```

```
node_declarator:
    ID  { $1 }

lvalue:
        var  {$1}
        | LPAR expr RPAR {$2}

var:
        ID     { Id($1) }
        | arr  { Array( fst $1, snd $1) }

arr:
    ID LBKT expr RBKT { $1, [$3] }
    | arr LBKT expr RBKT { fst $1, $3 :: snd $1 }

actuals_opt:
    /* nothing */ { [] }
  | actuals_list { List.rev $1 }

actuals_list:
    expr                   { [$1] }
  | actuals_list COMMA expr { $3 :: $1 }
```

8.3 ast.ml

```
type binop = In | Add | Sub | Mul | Div | Mod | Pow | Eq | Neq |
    Less | Leq | Greater | Geq
        | Or | And
type asnop = Sadd | Ssub | Smul | Sdiv | Smod | Asn
type resolve = Dot

type ptypes = Int | Char | Str | Graph | Node | Edge | Bool | Void
    | Err

type expr =
    BoolLit of bool
  | CharLit of char
  | NumLit of int
  | StrLit of string
  | Negof of expr
  | Notof of expr
```

```
  | Id of string
  | MultiId of expr * resolve * string
  | Array of string * expr list
  | Binop of expr * binop * expr
  | Assign of expr * asnop * expr
  | Call of string * expr list
  | GraphLit of edge list
  | Null
  | Noexpr

and var_type = {
  ptype: ptypes;
  dimension: expr list;
}

and var_decl = {
  vname: string;
  vtype: var_type;
  vinit: expr;
}

and node = string

and edge = {
    src: node;
    dest: node;
    weight: expr;
}

type stmt =
    Block of stmt list
  | Expr of expr
  | Return of expr
  | If of expr * stmt * stmt
  | For of expr * expr * expr * stmt
  | While of expr * stmt
  | Localvar of var_decl

type func_decl = {
  fname : string;
  formals : var_decl list;
  body : stmt;
  ret : var_type
```

```
}

type program = {
  gdecls : var_decl list;
  fdecls : func_decl list
}

exception Main_not_void


(* for printing the AST out *)

let string_of_binop = function
  In -> "in"
| Add -> "+"
| Sub -> "-"
| Mul -> "*"
| Div -> "/"
| Mod -> "%"
| Pow -> "^"
| Eq -> "=="
| Neq -> "!="
| Less -> "<"
| Leq -> "<="
| Greater -> ">"
| Geq -> ">="
| Or -> "||"
| And -> "&&"

let string_of_asnop = function
  Sadd -> "+="
| Ssub -> "-="
| Smul -> "*="
| Sdiv -> "/="
| Smod -> "%="
| Asn -> "="

let rec string_of_expr = function
    BoolLit(lit) -> "BoolLit( " ^ string_of_bool lit ^ " )"
  | CharLit(lit) -> "CharLit( " ^ Char.escaped lit ^ " )"
  | NumLit(lit) -> "NumLit( " ^ string_of_int lit ^ " )"
  | StrLit(lit) -> "StrLit( " ^ lit ^ " )"
  | Negof(exp) -> "Negof( " ^ string_of_expr exp ^ " )"
```

```
  | Notof(exp) -> "Notof( " ^ string_of_expr exp ^ " )"
  | Id(id) -> "Id( " ^ id ^ " )"
  | Array(id, indices) -> "Array( " ^ id ^ ", indices: [" ^
     String.concat "][" (List.map string_of_expr indices) ^ "] )"
  | Binop(exp1, binop, exp2) -> "Binop( " ^ string_of_expr exp1 ^ "
     " ^ string_of_binop binop ^ " " ^ string_of_expr exp2 ^ " )"
  | Assign(exp1, asnop, exp2) -> "Assign( " ^ string_of_expr exp1 ^
     " " ^ string_of_asnop asnop ^ " " ^ string_of_expr exp2 ^ " )"
  | Call(fid, param) -> "Call( " ^ fid ^ ", " ^ String.concat "; "
     (List.map string_of_expr param) ^ " )"
  | GraphLit(edges) -> "GraphLit {\n" ^ String.concat "\n"
     (List.map string_of_edge edges) ^ "\n}"
  | MultiId(obj, dot, field) -> "MultiId( " ^ string_of_expr obj ^
     "." ^ field
  | Null -> "Null"
  | Noexpr -> "Noexpr"

and string_of_edge edge =
  edge.src ^ " -> " ^ edge.dest ^ " weight = " ^ string_of_expr
     edge.weight

let string_of_ptypes = function
    Int -> "int"
  | Char -> "char"
  | Str -> "str"
  | Graph -> "graph"
  | Node -> "node"
  | Edge -> "edge"
  | Bool -> "bool"
  | Void -> "void"
  | _ -> "unknown_type"

let string_of_var_type vartype = "ptype: " ^ string_of_ptypes
    vartype.ptype ^ "; dimension_length: " ^ string_of_int
    (List.length vartype.dimension)

let string_of_var_decl vardecl = "Var( name: " ^ vardecl.vname ^
    "; " ^ string_of_var_type vardecl.vtype ^ "; " ^ string_of_expr
    vardecl.vinit ^ " )"

let rec string_of_stmt = function
    Block(stmt_list) -> (String.concat "\n" (List.map
       string_of_stmt stmt_list)) ^ "\n"
```

```
  | Expr(expr) -> "Expr( " ^ (string_of_expr expr) ^ " )"
  | Return(expr) -> "Return( " ^ (string_of_expr expr) ^ ")"
  | If(expr, stmt1, stmt2) -> "if (" ^ (string_of_expr expr) ^
     ")\n" ^ (string_of_stmt stmt1) ^ (string_of_stmt stmt2) ^ ")"
  | For(init, test, after, stmt) -> "for (" ^ string_of_expr init ^
     ", " ^ string_of_expr test ^ ", " ^ string_of_expr after ^ ")
     {\n" ^ string_of_stmt stmt ^ "\n}"
  | While(test, stmt) -> "while( " ^ (string_of_expr test) ^ " )
     {\n" ^ (string_of_stmt stmt) ^ "\n}"
  | Localvar(var) -> "LocalVar( " ^ (string_of_var_decl var) ^ " )"

let string_of_func_decl funcdecl = "Function( type: (" ^
    string_of_var_type funcdecl.ret ^ ") name: \"" ^ funcdecl.fname
    ^ "\" formals: "
  ^ (String.concat ", " (List.map string_of_var_decl
     funcdecl.formals))
  ^ ") {\n" ^ string_of_stmt funcdecl.body ^ "\n}"

let string_of_program prog = "Program_START\n" ^ (String.concat
    "\n" (List.map string_of_var_decl prog.gdecls)) ^ "\n\n" ^
   (String.concat "\n\n" (List.map string_of_func_decl
      prog.fdecls)) ^ "\nProgram_END\n"
```

8.4 sast.ml

```
open Ast

module StringMap = Map.Make(String)

exception MultiId_err
exception Dup_var_id
exception Return_type_err
exception Init_type_err
exception Func_param_err
exception Func_duplicate
exception No_var
exception Arr_err
exception No_func
exception Type_err
exception Var_type
exception Err_s_check_stmt_list
exception Err_s_check_stmt_if
```

```
exception Err_s_check_stmt_for
exception Err_s_check_stmt_while
exception Main_not_found
exception Current_not_found
exception Edge_not_int_type
exception Msg_error of string

type t_expr = { exp: expr; typ: s_var_type }

and s_var_type = {
    s_ptype: ptypes;
    s_dimension: t_expr list;
}

and s_var_decl = {
    s_vname: string;
    s_vtype: s_var_type;
    s_vinit: t_expr;
}

and s_node = string

and s_edge = {
    s_src: s_node;
    s_dest: s_node;
    s_weight: t_expr;
}

and s_stmt =
      S_Block of s_stmt list
    | S_Expr of t_expr
    | S_Return of t_expr
    | S_If of t_expr * s_stmt * s_stmt
    | S_For of t_expr * t_expr * t_expr * s_stmt
    | S_While of t_expr * s_stmt
    | S_Localvar of s_var_decl

and s_func_decl = {
    s_fname : string;
    s_formals : s_var_decl list;
    s_body : s_stmt;
    s_ret : s_var_type
}
```

```
and s_program = {
    s_gdecls : s_var_decl list;
    s_fdecls : s_func_decl list;
}
```

```
let rec string_of_s_stmt = function
    S_Block(stmt_list) -> (String.concat "\n" (List.map
        string_of_s_stmt stmt_list)) ^ "\n"
  | S_Expr(expr) -> "Expr( " ^ (string_of_s_expr expr) ^ " )"
  | S_Return(expr) -> "Return( " ^ (string_of_s_expr expr) ^ " )"
  | S_Localvar(var) -> "LocalVar( " ^ (string_of_s_var_decl var) ^
      " )"
  | S_If(expr, stmt1, stmt2) -> "if (" ^ (string_of_s_expr expr) ^
      ")\n" ^ (string_of_s_stmt stmt1) ^ (string_of_s_stmt stmt2) ^
      " )"
  | S_For(init, test, after, stmt) -> "for (" ^ string_of_s_expr
      init ^ ", " ^ string_of_s_expr test ^ ", " ^ string_of_s_expr
      after ^ ") {\n" ^ string_of_s_stmt stmt ^ "\n}"
  | S_While(test, stmt) -> "while( " ^ (string_of_s_expr test) ^ "
      ) {\n" ^ (string_of_s_stmt stmt) ^ "\n}"

and string_of_s_expr expr = "T_Expr( " ^ (string_of_expr expr.exp)
    ^ " type : "
^ (string_of_s_var_type expr.typ) ^ " )\n"

and string_of_s_var_type vartype = "ptype: " ^ string_of_ptypes
    vartype.s_ptype
^ "; dimension_length: " ^ string_of_int (List.length
    vartype.s_dimension)

and string_of_s_var_decl vardecl = "S_Var( name: " ^
    vardecl.s_vname ^ "; " ^
string_of_s_var_type vardecl.s_vtype ^ "; " ^ string_of_s_expr
    vardecl.s_vinit ^ " )"

and string_of_s_func_decl funcdecl = "Function ( type: (" ^
    string_of_s_var_type
funcdecl.s_ret ^ ") name: \"" ^ funcdecl.s_fname ^ "\" formals: " ^
```

```
(String.concat ", " (List.map string_of_s_var_decl
    funcdecl.s_formals)) ^ ")
{\n" ^ string_of_s_stmt funcdecl.s_body ^ "\n}"

let string_of_program prog = "Sast_Program_Start\n" ^
    (String.concat "\n" (List.map
string_of_s_var_decl prog.s_gdecls)) ^ "\n\n" ^
    (String.concat "\n\n" (List.map string_of_s_func_decl
        prog.s_fdecls)) ^
    "\nProgram_END\n"
```

```
let rec type_of_var id v_context =
           if StringMap.mem id v_context then
               fst (StringMap.find id v_context)
           else
               raise No_var

let type_of_obj_field obj field = {
  s_ptype = Node;
  s_dimension = []
}

let rec type_of_expr f_context v_context exp = match exp with
     BoolLit(lit) -> { s_ptype = Bool; s_dimension = [] }
   | CharLit(lit) -> { s_ptype = Char; s_dimension = [] }
   | NumLit(lit) -> { s_ptype = Int; s_dimension = [] }
   | StrLit(lit) -> { s_ptype = Str; s_dimension = [] }
   | Binop(exp1, binop, exp2) ->
          (match binop with
           In -> { s_ptype = Bool; s_dimension = [] }
          | Add | Sub | Mul | Div | Pow->
                 let type1 = type_of_expr f_context v_context exp1
                     and
                      type2 = type_of_expr f_context v_context exp2
                          in
                      if (type1.s_ptype == Int || type1.s_ptype ==
                          Char) &&
                         (type2.s_ptype == Int || type2.s_ptype ==
                             Char) &&
```

```
                (List.length type1.s_dimension == 0) &&
                (List.length type2.s_dimension == 0) then
                       if type1.s_ptype == type2.s_ptype
                          then
                           type1
                       else
                           { s_ptype = Int; s_dimension =
                               [] }
             else
                 raise Type_err

| Mod -> let type1 = type_of_expr f_context v_context
   exp1 and
             type2 = type_of_expr f_context v_context exp2
                 in
             if (type1.s_ptype == Int || type1.s_ptype ==
                 Char) &&
                (type2.s_ptype == Int || type2.s_ptype ==
                   Char) &&
                (List.length type1.s_dimension == 0) &&
                (List.length type2.s_dimension == 0) then
                    if type1.s_ptype == type2.s_ptype then
                        type1
                    else
                        { s_ptype = Int; s_dimension = [] }
             else
                 raise Type_err
| Eq | Neq -> let type1 = type_of_expr f_context
   v_context exp1 and
                   type2 = type_of_expr f_context
                       v_context exp2 in
                   if type1.s_ptype == type2.s_ptype &&
                     (List.length type1.s_dimension) ==
                     (List.length type2.s_dimension) then
                     { s_ptype = Bool; s_dimension = [] }
                   else
                     raise Type_err

| Less | Leq | Greater | Geq -> let type1 = type_of_expr
   f_context v_context exp1 and
             type2 = type_of_expr f_context v_context exp2
                 in
```

```
                    if (type1.s_ptype == Int || type1.s_ptype ==
                        Char || type1.s_ptype == Str) &&
                       (type2.s_ptype == Int || type2.s_ptype ==
                          Char || type2.s_ptype == Str) &&
                       (List.length type1.s_dimension == 0) &&
                       (List.length type2.s_dimension == 0) then
                          if type1.s_ptype == type2.s_ptype then
                              { s_ptype = Bool; s_dimension = []
                                 }
                          else
                             if type1.s_ptype == Str ||
                                 type2.s_ptype ==
                                 Str
                             then
                                  raise Type_err
                             else
                                 { s_ptype = Bool; s_dimension =
                                    [] }
                    else
                        raise Type_err

             | Or | And -> let type1 = type_of_expr f_context
                 v_context exp1 and
                    type2 = type_of_expr f_context v_context exp2
                        in
                    if (type1.s_ptype == Bool) &&
                       (type2.s_ptype == Bool) &&
                       (List.length type1.s_dimension == 0) &&
                       (List.length type2.s_dimension == 0) then
                          { s_ptype = Bool; s_dimension = [] }
                    else
                        raise Type_err )
| Assign(exp1, asnop, exp2) -> (match asnop with
     Asn -> let type1 = type_of_expr f_context v_context exp1 and
                type2 = type_of_expr f_context v_context exp2 in
                if type1.s_ptype == type2.s_ptype &&
                List.length type1.s_dimension ==
                    List.length type2.s_dimension then
                    type1
                else raise Type_err
   | Sadd | Ssub | Smul | Sdiv ->
          let type1 = type_of_expr f_context v_context exp1 and
              type2 = type_of_expr f_context v_context exp2 in
```

```
            if (type1.s_ptype == Int || type1.s_ptype == Char)
                &&
               (type2.s_ptype == Int || type2.s_ptype == Char)
                  &&
               (List.length type1.s_dimension == 0) &&
               (List.length type2.s_dimension == 0) then
                 type1
            else
                 raise Type_err
  | Smod ->
         let type1 = type_of_expr f_context v_context exp1 and
             type2 = type_of_expr f_context v_context exp2 in
            if (type1.s_ptype == Int || type1.s_ptype == Char)
                &&
               (type2.s_ptype == Int || type2.s_ptype == Char)
                  &&
               (List.length type1.s_dimension == 0) &&
               (List.length type2.s_dimension == 0) then
                 type1
            else
                 raise Type_err )

| Call(fid, param) ->
      type_of_func_ret fid param f_context v_context
| GraphLit(edges) ->
      ignore (List.map (fun x -> type_of_expr f_context
         v_context x.weight) edges);
      { s_ptype = Graph; s_dimension = [] }
| Null -> { s_ptype = Void; s_dimension = [] } (* is this
   correct ? *)
| Noexpr -> { s_ptype = Void; s_dimension = [] } (* is this
   correct ? *)
| Notof(exp) ->
      let type1 = type_of_expr f_context v_context exp in
      if type1.s_ptype == Bool then type1
      else raise Type_err (* Error if exp is not Bool *)
| Id(id) -> type_of_var id v_context
| MultiId(obj, dot, field) ->
      type_of_obj_field obj field (*Check this... *)
| Array(id, indices) ->
      type_of_array id indices f_context v_context (* Error if
         indices and dimension not matched *)
| Negof(exp) ->
```

```
      let exp_type = (type_of_expr f_context v_context exp) in
        if (exp_type.s_ptype == Int || exp_type.s_ptype == Char)
           then exp_type
        else raise Type_err

and type_of_array id indices f_context v_context =
    (if StringMap.mem id v_context then
        let a_type = fst (StringMap.find id v_context) in
        if List.length a_type.s_dimension >= List.length indices
           then
           let s_indices = List.map (fun x -> type_of_expr
              f_context v_context x) indices in
           if List.length
           (List.filter (fun a -> (a.s_ptype == Int || a.s_ptype ==
              Char)) s_indices) ==
              List.length s_indices then
                 let rec cut_dimension num d_list = match d_list
                    with
                    hd::tl -> if (num > 0) then cut_dimension
                       (num-1) tl
                                   else d_list
                    | [] -> []
                 in
                 { s_ptype = a_type.s_ptype;
                 s_dimension = cut_dimension (List.length
                    s_indices) a_type.s_dimension}
           else
              raise Arr_err
        else
           raise Arr_err
    else
        raise Arr_err)

and type_of_func_ret fid param f_context v_context=
    if (String.compare fid "_len" == 0) && ((List.length param) ==
        1) && (List.length (type_of_expr f_context v_context
        (List.hd param)).s_dimension) != 0 then
      {s_ptype = Int; s_dimension = []}
    else
    if StringMap.mem fid f_context then
        let s_param = List.map (fun x -> type_of_expr f_context
           v_context x) param in
        let rec param_check t_l1 t_l2 = (match t_l1, t_l2 with
```

```
                        [], [] -> true
                      | hd::tl, [] -> false
                      | [], hd::tl -> false
                      | h1::t1, h2::t2 ->
                            if h1.s_ptype == h2.s_ptype &&
                            List.length h1.s_dimension ==
                               List.length h2.s_dimension then
                               param_check t1 t2
                            else
                               false) in
        snd (List.find (fun a -> param_check (fst a) s_param)
           (StringMap.find fid f_context))
     else
        raise No_func


let rec s_check_expr f_context v_context in_exp = match in_exp with
      Binop(exp1, binop, exp2) ->
           {exp = Binop((s_check_expr f_context v_context
              exp1).exp, binop, (s_check_expr f_context v_context
              exp2).exp); typ = type_of_expr f_context v_context
              in_exp }
    | Assign(exp1, asnop, exp2) ->
           {exp = Assign((s_check_expr f_context v_context
              exp1).exp, asnop, (s_check_expr f_context v_context
              exp2).exp); typ = type_of_expr f_context v_context
              in_exp }
    | Call(fid, param) ->
          if (String.compare fid "_len" == 0) && List.length param
             == 1 && List.length (s_check_expr f_context v_context
             (List.hd param)).typ.s_dimension != 0 then
             {exp = MultiId(List.hd param, Dot, "size()"); typ =
                {s_ptype = Int; s_dimension = []}}
          else
             {exp = Call(fid, List.map (fun a -> (s_check_expr
                f_context v_context a).exp) param); typ =
                (type_of_expr f_context v_context in_exp)}
    | Notof(exp) ->
          {exp = Notof((s_check_expr f_context v_context
             exp).exp); typ = type_of_expr f_context v_context
             in_exp}
    | MultiId(obj, dot, field) ->
```

```
        if (type_of_expr f_context v_context obj).s_ptype ==
            Graph
        then
            {exp = MultiId((s_check_expr f_context v_context
                obj).exp, dot, "getNode(\"" ^ field ^ "\")");
                typ = {s_ptype = Node; s_dimension = []}}
        else
            if (type_of_expr f_context v_context obj).s_ptype ==
                Str &&
            String.compare field "size()" == 0
            then
                {exp = MultiId((s_check_expr f_context v_context
                    obj).exp, dot, field); typ = {s_ptype = Int;
                    s_dimension = []}}
            else
                raise MultiId_err
| Array(id, indices) ->
        {exp = Array(id, List.map (fun a -> (s_check_expr
            f_context v_context a).exp) indices); typ =
            type_of_expr f_context v_context in_exp}
| Negof(exp) ->
        {exp = Notof((s_check_expr f_context v_context
            exp).exp); typ = type_of_expr f_context v_context
            in_exp}
| GraphLit(edges) ->
        let t_edges = List.map (fun x -> (s_check_expr f_context
            v_context x.weight).typ) edges in
        if (List.length (List.filter (fun a -> a.s_ptype != Int
            || List.length a.s_dimension != 0) t_edges)) != 0
            then
            raise Edge_not_int_type
        else
            {exp = in_exp; typ = { s_ptype = Graph; s_dimension
                = [] }}
| _ -> {exp = in_exp; typ = (type_of_expr f_context v_context
    in_exp)}

let s_check_var_type f_context v_context vtype =
    let dimention_type_list = (List.map (fun expr -> type_of_expr
        f_context v_context expr) vtype.dimension) in
      if List.length (List.filter (fun a -> (a.s_ptype == Int))
          dimention_type_list) == List.length dimention_type_list
      then
```

```
        {s_ptype = vtype.ptype;
        s_dimension = List.map (fun expr -> s_check_expr
           f_context v_context expr) vtype.dimension }
     else (* Error dimension not int*)
        raise Var_type

let s_stmt_context_v f_context v_context level stmt = match stmt
   with
   Localvar(vdecl) ->
     let lhs = (s_check_var_type f_context v_context vdecl.vtype)
        and rhs = (type_of_expr f_context v_context vdecl.vinit)
        in
      if vdecl.vinit == Noexpr || (List.length lhs.s_dimension ==
         List.length rhs.s_dimension && lhs.s_ptype ==
         rhs.s_ptype) then
         if StringMap.mem vdecl.vname v_context then
            let p_level = snd (StringMap.find vdecl.vname
               v_context) in
            if p_level == level then
               raise Dup_var_id
            else
               StringMap.add vdecl.vname ((s_check_var_type
                  f_context v_context vdecl.vtype), level)
                  v_context
         else
            StringMap.add vdecl.vname ((s_check_var_type
               f_context v_context vdecl.vtype), level)
               v_context
      else
         raise Init_type_err
  | _ -> v_context

let s_check_var_decl f_context v_context vdecl =
   let lhs = (s_check_var_type f_context v_context vdecl.vtype)
      and rhs =
      (type_of_expr f_context v_context vdecl.vinit) in
   if vdecl.vinit == Noexpr || (List.length lhs.s_dimension ==
      List.length rhs.s_dimension && lhs.s_ptype == rhs.s_ptype)
      then
     { s_vname = vdecl.vname; s_vtype = (s_check_var_type
        f_context v_context vdecl.vtype);
     s_vinit = (s_check_expr f_context v_context vdecl.vinit) }
   else
```

```
        raise Init_type_err

let rec s_check_stmt_list context_list stmt_list = match
    context_list, stmt_list with
     [], [] -> []
   | context_hd::context_tl, stmt_hd::stmt_tl ->
          (s_check_stmt (fst context_hd) (snd context_hd) stmt_hd)
        :: (s_check_stmt_list context_tl stmt_tl)
   | _, _ -> raise Err_s_check_stmt_list

and s_check_stmt f_context v_context level stmt =
  match stmt with
     If(expr, stmt1, stmt2) ->
      let exp_type = type_of_expr f_context v_context expr in
      if (exp_type.s_ptype == Bool && exp_type.s_dimension == [])
      then
          S_If(s_check_expr f_context v_context expr,
          s_check_stmt f_context v_context level stmt1,
          s_check_stmt f_context v_context level stmt2)
      else
          raise Err_s_check_stmt_if; (* Error need boolean
              expression in if *)
   | For(expr1, expr2, expr3, stmt) ->
          let expr2_t = type_of_expr f_context v_context expr2 in
       if expr2_t.s_ptype == Bool && List.length
           expr2_t.s_dimension == 0
       then
           S_For(s_check_expr f_context v_context expr1,
           s_check_expr f_context v_context expr2,
           s_check_expr f_context v_context expr3,
           s_check_stmt f_context v_context level stmt)
       else
           raise Err_s_check_stmt_for; (* Error need boolean
               expression in for *)
   | While(expr, stmt) ->
          let expr_t = type_of_expr f_context v_context expr in
       if expr_t.s_ptype == Bool && expr_t.s_dimension == []
       then
           S_While(s_check_expr f_context v_context expr,
           s_check_stmt f_context v_context level stmt)
       else
           raise Err_s_check_stmt_while; (* Error need boolean
               expression in while *)
```

```
  | Expr(expr) ->
        S_Expr(s_check_expr f_context v_context expr)
  | Return(expr) ->
        let t_exp = s_check_expr f_context v_context expr in
        if StringMap.mem "0current" f_context then
          let cur = StringMap.find "0current" f_context in
          if t_exp.typ.s_ptype == (snd (List.hd cur)).s_ptype &&
               List.length t_exp.typ.s_dimension == List.length
                   (snd (List.hd cur)).s_dimension then
                   S_Return(s_check_expr f_context v_context expr)
          else
              raise Return_type_err

        else
            raise Current_not_found
  | Localvar(vdecl) ->
        S_Localvar(s_check_var_decl f_context v_context vdecl)
  | Block(stmt_list) ->
        let first(f,_,_) = f and second(_,s,_) = s and third
            (_,_,t) = t in
        S_Block(
         List.rev ( first
            (
            List.fold_left

        (fun x y ->
         (((s_check_stmt
            (second x)
            (third x)
             (level+1)
         y) ::
         (first x)),
          (second x),
         (s_stmt_context_v (second x) (third x) (level+1) y)))

        ([], f_context, v_context)
         stmt_list)

     ))

let s_check_func_decl f_context v_context fdecl =
    let s_formals_t = List.map (fun var_decl -> s_check_var_decl
       f_context v_context
```

```
    var_decl) fdecl.formals in
    let s_ret_t = s_check_var_type f_context v_context fdecl.ret in
    {s_fname = fdecl.fname;
     s_formals = s_formals_t;
     s_ret = s_ret_t;
     s_body = s_check_stmt (StringMap.add "0current" [(List.map
         (fun a ->
         a.s_vtype) s_formals_t,s_ret_t)] f_context)
             (List.fold_left (fun a l ->
             if StringMap.mem l.s_vname a && snd (StringMap.find
                 l.s_vname a) == 1 then
                 raise Dup_var_id
             else
                 StringMap.add l.s_vname (l.s_vtype, 1) a) v_context
                     s_formals_t) 1 fdecl.body
    }

let rec s_check_func_decls f_context v_context func_decl_list =
    match func_decl_list with
     [] -> []
   | hd::tl ->
      (s_check_func_decl f_context v_context hd) ::
          (s_check_func_decls f_context v_context tl)

let s_var_decl_to_var_map map s_vdecl =
    if StringMap.mem s_vdecl.s_vname map then
        raise Dup_var_id
    else
        StringMap.add s_vdecl.s_vname (s_vdecl.s_vtype, 0) map

let is_s_var_type_equal t1 t2 =
    if t1.s_ptype == t2.s_ptype && List.length t1.s_dimension ==
        List.length t2.s_dimension
    then
        true
    else
        false

let rec is_s_var_type_list_equal l1 l2 = match l1, l2 with
    [], [] -> true
   | [], hd::tl -> false
   | hd::tl, [] -> false
   | h1::t1, h2::t2 ->
```

```
            if is_s_var_type_equal h1 h2 then
                is_s_var_type_list_equal t1 t2
            else
                false

(* for overloading functions *)
let func_decl_check_func_map s_var_type_list_list s_var_type_list =
    let check = List.map (fun l1 -> is_s_var_type_list_equal (fst
        l1) s_var_type_list)
    s_var_type_list_list in
    if List.length (List.filter (fun a -> a) check) != 0 then
        true
    else
        false

let func_decl_to_func_map map fdecl v_context =
    let f_s_var_type_list = List.map (fun a -> a.s_vtype) (List.map
        (fun a -> s_check_var_decl StringMap.empty v_context a)
        fdecl.formals) in
    if StringMap.mem fdecl.fname map
    then
        if func_decl_check_func_map (StringMap.find fdecl.fname
            map) f_s_var_type_list
        then
            raise Func_duplicate
        else
            StringMap.add fdecl.fname ((f_s_var_type_list,
                s_check_var_type StringMap.empty v_context
                fdecl.ret)::StringMap.find fdecl.fname map) map
    else
        StringMap.add fdecl.fname [(f_s_var_type_list,
            s_check_var_type StringMap.empty v_context fdecl.ret)]
            map

let s_check_program prog =
  let temp_s_gdecls = List.map (fun var_decl -> s_check_var_decl
      StringMap.empty StringMap.empty var_decl) prog.gdecls
  and std_func = (let map = StringMap.empty in
  let map = StringMap.add "_print" [([{s_ptype = Int; s_dimension =
      []}], {s_ptype = Void; s_dimension = []});
                                  ([{s_ptype = Char; s_dimension =
                                      []}], {s_ptype = Void;
                                      s_dimension = []});
```

```
                              ([{s_ptype = Str; s_dimension =
                                 []}], {s_ptype = Void;
                                 s_dimension = []});
                              ([{s_ptype = Bool; s_dimension =
                                 []}], {s_ptype = Void;
                                 s_dimension = []});
                              ([{s_ptype = Node; s_dimension =
                                 []}], {s_ptype = Void;
                                 s_dimension = []})] map in
let map = StringMap.add "_len" [([{s_ptype = Str; s_dimension =
    []}], {s_ptype = Int; s_dimension = []})] map in
let map = StringMap.add "_sort" [([{s_ptype = Int; s_dimension =
    [{exp = NumLit(0); typ = {s_ptype = Int; s_dimension =
    []}}]}], {s_ptype = Void; s_dimension = []});
                             ([{s_ptype = Char; s_dimension =
                                [{exp = NumLit(0); typ =
                                {s_ptype = Int; s_dimension =
                                []}}]}], {s_ptype = Void;
                                s_dimension = []});
                             ([{s_ptype = Str; s_dimension =
                                [{exp = NumLit(0); typ =
                                {s_ptype = Int; s_dimension =
                                []}}]}], {s_ptype = Void;
                                s_dimension = []});
                             ([{s_ptype = Edge; s_dimension =
                                [{exp = NumLit(0); typ =
                                {s_ptype = Int; s_dimension =
                                []}}]}], {s_ptype = Void;
                                s_dimension = []})] map in
let map = StringMap.add "_empty" [([{s_ptype = Str; s_dimension =
    []}], {s_ptype = Bool; s_dimension = []})] map in
let map = StringMap.add "_at" [([{s_ptype = Str; s_dimension =
    []}; {s_ptype = Int; s_dimension = []}], {s_ptype = Char;
    s_dimension = []})] map in
let map = StringMap.add "_append" [([{s_ptype = Str; s_dimension
    = []}; {s_ptype = Str; s_dimension = []}], {s_ptype = Void;
    s_dimension = []}); ([{s_ptype = Str; s_dimension = []};
    {s_ptype = Char; s_dimension = []}], {s_ptype = Void;
    s_dimension = []})] map in
let map = StringMap.add "_getNode" [([{s_ptype = Graph;
    s_dimension = []}; {s_ptype = Str; s_dimension = []}],
    {s_ptype = Node; s_dimension = []});
```

```
                                ([{s_ptype = Graph; s_dimension =
                                    []}; {s_ptype = Int;
                                    s_dimension = []}], {s_ptype =
                                    Node; s_dimension = []})] map
                                    in
let map = StringMap.add "_getEdge" [([{s_ptype = Graph;
    s_dimension = []}; {s_ptype = Str; s_dimension = []};
    {s_ptype = Str; s_dimension = []}], {s_ptype = Edge;
    s_dimension = []});
                                ([{s_ptype = Graph; s_dimension =
                                    []}; {s_ptype = Node;
                                    s_dimension = []}; {s_ptype =
                                    Node; s_dimension = []}],
                                    {s_ptype = Edge; s_dimension =
                                    []})] map in
let map = StringMap.add "_getAllEdges" [([{s_ptype = Graph;
    s_dimension = []}], {s_ptype = Edge; s_dimension = [{exp =
    NumLit(0); typ = {s_ptype = Int; s_dimension = []}}]})] map in
let map = StringMap.add "_getAllNodes" [([{s_ptype = Graph;
    s_dimension = []}], {s_ptype = Node; s_dimension = [{exp =
    NumLit(0); typ = {s_ptype = Int; s_dimension = []}}]})] map in
let map = StringMap.add "_getWeight" [([{s_ptype = Edge;
    s_dimension = []}],{s_ptype = Int; s_dimension = []});
                                  ([{s_ptype = Graph; s_dimension
                                      = []}; {s_ptype = Node;
                                      s_dimension = []}; {s_ptype
                                      = Node; s_dimension =
                                      []}],{s_ptype = Int;
                                      s_dimension = []})] map in
let map = StringMap.add "_getNodeCount" [([{s_ptype = Graph;
    s_dimension = []}], {s_ptype = Int; s_dimension = []})] map in
let map = StringMap.add "_getEdgeCount" [([{s_ptype = Graph;
    s_dimension = []}], {s_ptype = Int; s_dimension = []})] map in
let map = StringMap.add "_getID" [([{s_ptype = Node; s_dimension
    = []}], {s_ptype = Int; s_dimension = []})] map in
let map = StringMap.add "_getSrc" [([{s_ptype = Edge; s_dimension
    = []}], {s_ptype = Node; s_dimension = []})] map in
let map = StringMap.add "_getDst" [([{s_ptype = Edge; s_dimension
    = []}], {s_ptype = Node; s_dimension = []})] map in
let map = StringMap.add "_getInNeighbours" [([{s_ptype = Graph;
    s_dimension = []}; {s_ptype = Node; s_dimension =
    []}],{s_ptype = Node; s_dimension = [{exp = NumLit(0); typ =
    {s_ptype=Int; s_dimension =[]}}]})] map in
```

```
  let map = StringMap.add "_getOutNeighbours" [([{s_ptype = Graph;
      s_dimension = []}; {s_ptype = Node; s_dimension =
      []}],{s_ptype = Node; s_dimension = [{exp = NumLit(0); typ =
      {s_ptype=Int; s_dimension =[]}}]})] map in
  StringMap.add "_substr" [([{s_ptype = Str; s_dimension = []};
      {s_ptype = Int; s_dimension = []}; {s_ptype = Int;
      s_dimension = []}], {s_ptype = Str; s_dimension = []})] map)
  in
{
  s_gdecls = temp_s_gdecls;
  s_fdecls =
    let v_context = List.fold_left s_var_decl_to_var_map
       StringMap.empty temp_s_gdecls in
    let f_context = List.fold_left (fun x y ->
       func_decl_to_func_map x y v_context) std_func prog.fdecls in
    if StringMap.mem "_main" f_context then s_check_func_decls
       f_context v_context prog.fdecls
    else raise Main_not_found
}
```

8.5 cgen.ml

```
open Printf
open Ast
open Sast

let string_of_binop = function
  In -> "in"
| Add -> "+"
| Sub -> "-"
| Mul -> "*"
| Div -> "/"
| Mod -> "%"
| Pow -> "^"
| Eq -> "=="
| Neq -> "!="
| Less -> "<"
| Leq -> "<="
| Greater -> ">"
| Geq -> ">="
| Or -> "||"
| And -> "&&"
```

```
let string_of_asnop = function
  Sadd -> "+="
| Ssub -> "-="
| Smul -> "*="
| Sdiv -> "/="
| Smod -> "%="
| Asn -> "="

let rec string_of_expr = function
    BoolLit(lit) -> string_of_bool lit
  | CharLit(lit) -> "'" ^ Char.escaped lit ^ "'"
  | NumLit(lit) -> string_of_int lit
  | StrLit(lit) -> "\"" ^ lit ^ "\""
  | Negof(exp) -> "(-" ^ string_of_expr exp ^ ")"
  | Notof(exp) -> "(!" ^ string_of_expr exp ^ ")"
  | Id(id) -> id
  | Array(id, indices) -> "(" ^ id ^ "[" ^ String.concat "]["
      (List.map string_of_expr indices) ^ "] )"
  | Binop(exp1, binop, exp2) -> "(" ^ string_of_expr exp1 ^ " " ^
      string_of_binop binop ^ " " ^ string_of_expr exp2 ^ ")"
  | Assign(exp1, asnop, exp2) -> "(" ^ string_of_expr exp1 ^ " " ^
      string_of_asnop asnop ^ " " ^ string_of_expr exp2 ^ ")"
  | Call(fid, param) -> (string_of_call fid param)
  | GraphLit(edges) -> "newGraph(" ^ string_of_int (List.length
      edges) ^ ", " ^ String.concat ", " (List.map string_of_edge
      edges) ^ ")"
  | MultiId(obj, dot, field) -> if (String.compare field "size()"
      == 0) then ("(int)(" ^ string_of_expr obj ^ "." ^ field ^
      ")") else ("(" ^ string_of_expr obj ^ "." ^ field ^ ")")
  | Null -> "NULL"
  | Noexpr -> ""

and string_of_call fid param = fid ^ "(" ^ String.concat ", "
    (List.map string_of_expr param) ^ " )"

and string_of_edge edge =
  "new edge_decl(\"" ^ edge.src ^ "\", \"" ^ edge.dest ^ "\", " ^
      string_of_expr edge.weight ^ ")"


let string_of_ptypes = function
    Int -> "int"
```

```
  | Char -> "char"
  | Str -> "string"
  | Graph -> "graph"
  | Node -> "node"
  | Edge -> "edge"
  | Bool -> "bool"
  | Void -> "void"
  | _ -> "unknown_type"

let rec string_of_var_type s_ptype dimensions =
  if dimensions == 0 then
    string_of_ptypes s_ptype
  else
    "vector < " ^ (string_of_var_type s_ptype (dimensions-1)) ^ " >"

let rec list_of_array_init list_dim acc_for_loop acc_resize_exp =
  match list_dim with
    [] -> []
  | hd :: tl -> let loop_var = "i" ^ string_of_int (List.length
      list_dim) in
      (acc_for_loop ^ acc_resize_exp ^ ".resize(" ^ (string_of_expr
          hd.exp) ^ ");\n") ::
      list_of_array_init
        tl
        (acc_for_loop ^ "for(int " ^ loop_var ^ " = 0; " ^ loop_var
            ^ " < " ^ (string_of_expr hd.exp) ^ "; " ^ loop_var ^
            "++)\n")
        (acc_resize_exp ^ "[" ^ loop_var ^ "]")

let string_of_array_init list_dim id=
  String.concat "\n" (list_of_array_init list_dim "" id)

let string_of_global_var_decl vardecl =
  let str_decl = (string_of_var_type vardecl.s_vtype.s_ptype
      (List.length vardecl.s_vtype.s_dimension)) ^ " " ^
      vardecl.s_vname in
    if vardecl.s_vinit.exp == Noexpr then
      ((str_decl ^ ";\n"), (string_of_array_init (List.rev
          vardecl.s_vtype.s_dimension) vardecl.s_vname))
    else
      (str_decl ^ " = " ^ string_of_expr vardecl.s_vinit.exp ^ ";",
          "")
```

```
let string_of_var_decl vardecl =
  let str_decl = (string_of_var_type vardecl.s_vtype.s_ptype
      (List.length vardecl.s_vtype.s_dimension)) ^ " " ^
      vardecl.s_vname in
    if vardecl.s_vinit.exp == Noexpr then
      str_decl ^ ";\n" ^ (string_of_array_init (List.rev
          vardecl.s_vtype.s_dimension) vardecl.s_vname)
    else
      str_decl ^ " = " ^ string_of_expr vardecl.s_vinit.exp ^ ";"

let string_of_param_var_decl vardecl =
  if (List.length vardecl.s_vtype.s_dimension) > 0 ||
      (vardecl.s_vtype.s_ptype == Graph || vardecl.s_vtype.s_ptype
      == Node || vardecl.s_vtype.s_ptype == Edge ||
      vardecl.s_vtype.s_ptype == Str) then
    "const " ^ (string_of_var_type vardecl.s_vtype.s_ptype
        (List.length vardecl.s_vtype.s_dimension)) ^ " &_" ^
        vardecl.s_vname
  else
    (string_of_var_type vardecl.s_vtype.s_ptype (List.length
        vardecl.s_vtype.s_dimension)) ^ " " ^ vardecl.s_vname

let rec string_of_stmt = function
    S_Block(stmt_list) -> "{\n" ^ (String.concat "\n" (List.map
        string_of_stmt stmt_list)) ^ "\n}\n"
  | S_Expr(expr) -> "(" ^ (string_of_expr expr.exp) ^ ");"
  | S_Return(expr) -> "return " ^ (string_of_expr expr.exp) ^ ";"
  | S_If(expr, stmt1, stmt2) -> "if (" ^ (string_of_expr expr.exp)
      ^ ")\n" ^ (string_of_stmt stmt1) ^ "\nelse " ^
      (string_of_stmt stmt2)
  | S_For(init, test, after, stmt) -> "for (" ^ string_of_expr
      init.exp ^ "; " ^ string_of_expr test.exp ^ "; " ^
      string_of_expr after.exp ^ ") " ^ string_of_stmt stmt
  | S_While(test, stmt) -> "while (" ^ (string_of_expr test.exp) ^
      ") " ^ (string_of_stmt stmt)
  | S_Localvar(var) -> string_of_var_decl var

let string_of_func_decl_only funcdecl = string_of_var_type
    funcdecl.s_ret.s_ptype (List.length funcdecl.s_ret.s_dimension)
    ^ " " ^ funcdecl.s_fname ^ "("
  ^ (String.concat ", " (List.map string_of_param_var_decl
      funcdecl.s_formals)) ^ ");"
```

```
let string_of_func_decl_with_body global_arr_init funcdecl =
  let cast_away_const vardecl =
    if (List.length vardecl.s_vtype.s_dimension) > 0 ||
        (vardecl.s_vtype.s_ptype == Graph ||
        vardecl.s_vtype.s_ptype == Node || vardecl.s_vtype.s_ptype
        == Edge || vardecl.s_vtype.s_ptype == Str) then
      let nonconst_ref_type = (string_of_var_type
          vardecl.s_vtype.s_ptype (List.length
          vardecl.s_vtype.s_dimension)) in
        nonconst_ref_type ^ " &" ^ vardecl.s_vname ^ " = (" ^
            nonconst_ref_type ^ " &)_" ^ vardecl.s_vname
    else
      ""
  in
  string_of_var_type funcdecl.s_ret.s_ptype (List.length
      funcdecl.s_ret.s_dimension) ^ " " ^ funcdecl.s_fname ^ "("
  ^ (String.concat ", " (List.map string_of_param_var_decl
      funcdecl.s_formals))
  ^ ") {\n" ^ (String.concat ";\n" (List.map cast_away_const
  funcdecl.s_formals)) ^ ";\n" ^ (if (String.compare
      funcdecl.s_fname "_main") == 0 then global_arr_init else "")
      ^ string_of_stmt funcdecl.s_body ^ "\n}"

let string_of_program prog =
  let global_var_tuple_list = (List.map string_of_global_var_decl
      prog.s_gdecls) in
  "#include <vector>\n#include \"libprint.h\"\n#include
      \"libstring.h\"\n#include \"libgraph.h\"\nusing namespace
      std;\n"
  ^ (String.concat ";\n" (List.map fst global_var_tuple_list)) ^
      ";\n"
   ^ (String.concat "\n" (List.map string_of_func_decl_only
       prog.s_fdecls)) ^ "\n"
  ^ (String.concat "\n" (List.map (fun fdecls ->
      string_of_func_decl_with_body (String.concat "\n" (List.map
      snd global_var_tuple_list)) fdecls) prog.s_fdecls)) ^ "\n"
  ^ "int main() { _main(); return 0;}"

let write_c_program filename program =
  let file = open_out filename in
    fprintf file "%s" (string_of_program program);
    close_out file
```

8.6 gpl.ml

```
(*
  GPL Complier
*)
type action = Ast | Sast | Cgen | Verbose

let _ =
  let action = if Array.length Sys.argv > 1 then
    List.assoc Sys.argv.(1) [ ("-a", Ast); ("-s", Sast); ("-c",
        Cgen); ]
  else Cgen in

  let lexbuf = Lexing.from_channel stdin in
  let program = Parser.program Scanner.token lexbuf in
  match action with
    Ast -> print_string (Ast.string_of_program program)
  | Sast -> print_string (Sast.string_of_program
      (Sast.s_check_program program))
  | Cgen -> Cgen.write_c_program "intermediate.cc"
      (Sast.s_check_program program);
            ignore (Sys.command "g++ -w intermediate.cc -Isrc")
  | _ -> print_string "Unrecognized option"
```

8.7 libgraph.h

```
#ifndef __LIBGRAPH_H_
#define __LIBGRAPH_H_

#include <map>
#include <string>
#include <iostream>
#include <cstdlib>
#include <algorithm>
#include <cstdarg>
#include <set>

using namespace std;

void raiseError(const string &msg) {
   cerr << msg << endl;
```

```
    exit(1);
}

class graph;
struct node;

class edge {
public:
    string src, dst; //symbols of source and destination node
    int weight;
    const graph *g; //ptr to graph to which this node belongs

    edge() {}

    edge(const edge &o) : src(o.src), dst(o.dst), weight(o.weight),
        g(o.g) {}

    edge(const string &src, const string &dst, int weight, const
        graph *g) : src(src), dst(dst), weight(weight), g(g) {}

    int getWeight() const {
        return weight;
    }

    bool operator<(const edge &o) const {
        return weight < o.weight;
    }

};

struct edge_decl {
    string src, dst;
    int weight;
    edge_decl(const string &src, const string &dst, int weight) :
        src(src), dst(dst), weight(weight) {}
};

struct node {
    string symbol;
    const graph *g; //ptr to graph to which this node belongs

    node() {}
```

```
  node(const string &symbol, const graph *g) : symbol(symbol),
     g(g) {}

  bool operator==(const node &o) const {
    return symbol == o.symbol && g == o.g;
  }
};

class graph {
  int nextNodeIndex;
  map<string, int> nodeIndex;
  map< pair<string, string>, int > weight;
  vector<string> nodes;
public:
  graph() : nextNodeIndex(0) {}

  node getNode(const string &symbol) const {
    if(nodeIndex.find(symbol) == nodeIndex.end()) {
      raiseError("Node " + symbol + " does not exist.");
    }
    return node(symbol, this);
  }

  node getNode(int id) const {
    return node(nodes[id], this);
  }

  int getNodeIndex(const string &symbol) const {
    map<string, int>::const_iterator it = nodeIndex.find(symbol);
    if(it == nodeIndex.end()) {
      raiseError("Node " + symbol + " does not exist.");
    }
    return it->second;
  }

  int getNodeCount() const {
    return int(nodes.size());
  }

  int getEdgeCount() const {
    return int(weight.size());
  }
```

```
vector<node> getInNeighbours(const string &symbol) const {
   vector<node> ret;
   for(map<pair<string, string>, int>::const_iterator it =
       weight.begin(); it != weight.end(); it++) {
      if((it->first).second == symbol)
         ret.push_back(node((it->first).first, this));
   }
   return ret;
}

vector<node> getOutNeighbours(const string &symbol) const {
   vector<node> ret;
   for(map<pair<string, string>, int>::const_iterator it =
       weight.begin(); it != weight.end(); it++) {
      if((it->first).first == symbol)
         ret.push_back(node((it->first).second, this));
   }
   return ret;
}

edge getEdge(const string &a, const string &b) const {
   map<pair<string, string>, int>::const_iterator it =
       weight.find(make_pair(a, b));
   if(it == weight.end()) raiseError("Edge <" + a + ", " + b +
       "> does not exist.");
   return edge((it->first).first, (it->first).second,
       it->second, this);
}

vector<edge> getAllEdges() const {
   vector<edge> edges;
   for(map<pair<string, string>, int>::const_iterator it =
       weight.begin(); it != weight.end(); it++) {
      edges.push_back(edge((it->first).first,
         (it->first).second, it->second, this));
   }
   return edges;
}

void addEdge(const string &src, const string &dst, int w = 0) {
   if(nodeIndex.find(src) == nodeIndex.end()) {
      nodeIndex[src] = nextNodeIndex++;
      nodes.push_back(src);
```

```
    }
    if(nodeIndex.find(dst) == nodeIndex.end()) {
      nodeIndex[dst] = nextNodeIndex++;
      nodes.push_back(dst);
    }
    weight[make_pair(src, dst)] = w;
  }

  void deleteEdge(const string &src, const string &dst) {
    weight.erase(make_pair(src, dst));
  }

};

graph newGraph(int numEdges, ...) {
  va_list edges;
  va_start(edges, numEdges);
  graph g;
  for(int i=0; i<numEdges; ++i) {
    edge_decl *e = va_arg(edges, edge_decl*);
    g.addEdge(e->src, e->dst, e->weight);
    delete e;
  }
  va_end(edges);
  return g;
}

vector<node> _getInNeighbours(const graph &g, const node &n) {
  return g.getInNeighbours(n.symbol);
}

vector<node> _getOutNeighbours(const graph &g, const node &n) {
  return g.getOutNeighbours(n.symbol);
}

int _getID(const node &n) {
  return (n.g)->getNodeIndex(n.symbol);
}

node _getNode(const graph &g, string symbol) {
  return g.getNode(symbol);
}
```

```
node _getNode(const graph &g, int id) {
   return g.getNode(id);
}

edge _getEdge(const graph &g, const string &src, const string
    &dst) {
   return g.getEdge(src, dst);
}

edge _getEdge(const graph &g, const node &src, const node &dst) {
   return g.getEdge(src.symbol, dst.symbol);
}

int _getWeight(const edge &e) {
   return e.getWeight();
}

int _getWeight(const graph &g, const node &src, const node &dst) {
   return g.getEdge(src.symbol, dst.symbol).getWeight();
}

void _addEdge(graph &g, const string &src, const string &dst, int
    weight = 0) {
   g.addEdge(src, dst, weight);
}

vector<edge> _getAllEdges(const graph &g) {
   return g.getAllEdges();
}

int _getNodeCount(const graph &g) {
   return g.getNodeCount();
}

int _getEdgeCount(const graph &g) {
   return g.getEdgeCount();
}

node _getSrc(const edge &e) {
   return node(e.src, e.g);
}

node _getDst(const edge &e) {
```

```
    return node(e.dst, e.g);
}

void _sort(vector<int> &v) {
    sort(v.begin(), v.end());
}

void _sort(vector<char> &v) {
    sort(v.begin(), v.end());
}

void _sort(vector<string> &v) {
    sort(v.begin(), v.end());
}

void _sort(vector<edge> &v) {
    sort(v.begin(), v.end());
}

#endif
```

8.8 libprint.h

```
#ifndef __LIBPRINT_H_
#define __LIBPRINT_H_

#include <iostream>
#include <string>
#include "libgraph.h"

using namespace std;

void _print(int n) {
    cout << n << endl;
}

void _print(double n) {
    cout << n << endl;
}

void _print(string n) {
    cout << n << endl;
```

```
}

void _print(char c) {
   cout << c << endl;
}

void _print(const char *s) {
   cout << string(s) << endl;
}

void _print(bool v) {
   cout << (v ? "true" : "false") << endl;
}

void _print(const node &n) {
   cout << n.symbol.substr(1) << endl;
}

#endif
```

8.9 libstring.h

```
int _len(const string &s) {
   return s.size();
}

bool _empty(const string &s) {
   return s.empty();
}

char _at(const string &s, int i) {
   return s.at(i);
}

void _append(string &a, const string &b) {
   a += b;
}

void _append(string &s, char c) {
   s += c;
}
```

```
string _substr(const string &s, int pos, int len) {
   return s.substr(pos, len);
}
```

8.10 Demo: Kosaraju.gpl

```
bool[100] visited;
int[100] stack;
int n;
int top;
graph g;

void dfs(int n) {
   visited[n] = true;
   node[] v = g.getOutNeighbours(g.getNode(n));
   int i;
   for(i = 0; i<v.len(); i+=1) {
      int id = v[i].getID();
      if(!visited[id]) {
         dfs(id);
      }
   }
   stack[top] = n;
   top += 1;
}

void rev_dfs(int n) {
   visited[n] = true;
   node this = g.getNode(n);
   print(this);
   node[] v = g.getInNeighbours(this);
   int i;
   for(i = 0; i<v.len(); i+=1) {
      int id = v[i].getID();
      if(!visited[id]) {
         rev_dfs(id);
      }
   }
}

void main() {
   g = [
```

```
      a -> b;
      b :-> c d e;
      c -> f;
      d :-> e g;
      e :-> b f g;
      f :-> c h;
      g -> h -> g;
      g -> j -> k -> l -> j -> i -> g;
   ];
   n = g.getNodeCount();

   int i;
   for(i = 0; i<n; i+=1)
      if(!visited[i])
         dfs(i);

   for(i = 0; i<n; i+=1) visited[i] = false;

   for(i = n-1; i>=0; i-=1)
      if(!visited[stack[i]]) {
         print("=== Strongly connected component ===");
         rev_dfs(stack[i]);
         print("=== End ===\n");
      }
}
```

8.11 Demo: all_path.gpl

```
void print_path(graph g, node cur, node dest, node[] path) {
    node[path.len() + 1] cur_path;
    int i;
    int j;
    for (i=0; i<path.len(); i+=1) {
        cur_path[i] = path[i];
    }
    cur_path[path.len()] = cur;

    if (cur == dest) {
       int i;
       print("Start");
       for (i=0; i<cur_path.len(); i+=1) {
           print(cur_path[i]);
```

```
        }
        print("End\n");
        return;
    }
    node[g.getOutNeighbours(cur).len()] adj =
        g.getOutNeighbours(cur);
    int flag;
    for (i=0; i<adj.len(); i+=1) {
        flag = 0;
        for (j=0; j<path.len(); j+=1) {
            if (adj[i] == path[j]) {
                flag = 1;
            }
        }
        if (flag == 0) {
            print_path(g, adj[i], dest, cur_path);
        }
    }
}

void main() {
    graph g = [a :-> b c;
               b :-> c d;
               c :-> e;
               d :-> j i;
               e :-> h f;
               f :-> b;
               g :-> j;
               h :-> i;
               i :-> g;
               j :-> f;];
    node[0] empty;
    print_path(g, g.a, g.g, empty);
}
```

8.12 Demo: dijkstra.gpl

```
void main() {
    graph g = [a -(2)> b;
               a -(3)> c;
               b -(7)> c;
               b -(1)> d;
```

```
          c -(6)> e;
          d -(7)> j;
          d -(6)> i;
          e -(2)> h;
          e -(8)> f;
          f -(9)> b;
          g -(4)> j;
          h -(3)> i;
          i -(9)> g;
          j -(13)> f;];

// from a to f
int[g.getNodeCount()] s_path;
node[g.getNodeCount()] trail;
int[g.getNodeCount()] visited;
int i;
int j;
int min;
for (i=0; i<g.getNodeCount(); i+=1) {
    s_path[i] = -1;
    visited[i] = 0;
    trail[i] = g.getNode(i);
}
s_path[g.a.getID()] = 0;
node[g.getOutNeighbours(g.a).len()] adj_nodes =
    g.getOutNeighbours(g.a);
for (i=0; i<adj_nodes.len(); i+=1) {
    s_path[adj_nodes[i].getID()] = g.getWeight(g.a,
        adj_nodes[i]);
    trail[adj_nodes[i].getID()] = g.a;
}
int d;

for (i=0; i<g.getNodeCount(); i+=1) {
    min = -1;
    for (j=0; j<g.getNodeCount(); j+=1) {
        if ((min == -1 || (s_path[j] != -1 && min > s_path[j]))
            && visited[j] == 0) {
            min = s_path[j];
            d = i;
        }
    }
    visited[d] = 1;
```

```
        node d_n = g.getNode(d);
        node[g.getOutNeighbours(d_n).len()] d_adj =
            g.getOutNeighbours(d_n);
        for (j=0; j<d_adj.len(); j+=1) {
            if (s_path[d_adj[j].getID()] == -1 ||
                s_path[d_adj[j].getID()] > s_path[d] +
                g.getWeight(d_n, d_adj[j])) {
                s_path[d_adj[j].getID()] = s_path[d] +
                    g.getWeight(d_n, d_adj[j]);
                trail[d_adj[j].getID()] = d_n;
            }
        }
    }

    print(s_path[g.g.getID()]);
    d = g.g.getID();
    node[g.getNodeCount()] path;
    int p = 0;
    path[p] = g.g;
    p += 1;
    while(!(trail[d] == g.a)) {
        path[p] = trail[d];
        p += 1;
        d = trail[d].getID();
    }
    path[p] = g.a;
    p += 1;
    for (i=p-1; i>=0; i-=1) {
        print(path[i]);
    }
}
```

8.13 Demo: edge_merge_sort.gpl

```
edge[] edge_merge_sort(edge[] lst)
{
   if (lst.len() <= 1)
      return lst;
   int size_left = lst.len() / 2;
   int size_right = lst.len() - size_left;
   edge[size_left] left;
   edge[size_right] right;
```

```
    int i;
    for (i = 0; i < size_left; i+=1)
        left[i] = lst[i];
    for (i = size_left; i < lst.len(); i+=1)
        right[i-size_left] = lst[i];
    return edge_merge(edge_merge_sort(left), edge_merge_sort(right));
}

edge[] edge_merge(edge[] left, edge[] right)
{
    int i = 0;
    int j = 0;
    int k = 0;
    edge[left.len() + right.len()] res;
    while (i < left.len() && j < right.len())
        if (left[i].getWeight() >= right[j].getWeight())
        {
            res[k] = right[j];
            k += 1;
            j += 1;
        } else
        {
            res[k] = left[i];
            k += 1;
            i += 1;
        }
    if (i == left.len())
        for (; k < res.len(); k+=1)
        {
            res[k] = right[j];
            j += 1;
        }
    if (j == right.len())
        for (; k < res.len(); k+=1)
        {
            res[k] = left[i];
            i += 1;
        }
    return res;
}

void main()
{
```

```
   graph g;
   g =
   [
      a -(2)> b -(3)> d -(5)> e;
      b -(7)> e;
      a -(1)> c -(4)> d;
   ];
   edge[] sorted_edges = edge_merge_sort(g.getAllEdges());
   int i;
   for (i = 0; i < sorted_edges.len(); i+=1)
      print(sorted_edges[i].getWeight());
}
```

8.14 Demo: int_merge_sort.gpl

```
int[] int_merge_sort(int[] lst)
{
   if (lst.len() <= 1)
      return lst;
   int size_left = lst.len() / 2;
   int size_right = lst.len() - size_left;
   int[size_left] left;
   int[size_right] right;
   int i;
   for (i = 0; i < size_left; i+=1)
      left[i] = lst[i];
   for (i = size_left; i < lst.len(); i+=1)
      right[i-size_left] = lst[i];
   return int_merge(int_merge_sort(left), int_merge_sort(right));
}

int[] int_merge(int[] left, int[] right)
{
   int i = 0;
   int j = 0;
   int k = 0;
   int[left.len() + right.len()] res;
   while (i < left.len() && j < right.len())
      if (left[i] >= right[j])
      {
         res[k] = right[j];
         k += 1;
```

```
            j += 1;
        } else
        {
            res[k] = left[i];
            k += 1;
            i += 1;
        }
    if (i == left.len())
        for (; k < res.len(); k+=1)
        {
            res[k] = right[j];
            j += 1;
        }
    if (j == right.len())
        for (; k < res.len(); k+=1)
        {
            res[k] = left[i];
            i += 1;
        }
    return res;
}

void main()
{
    int[10] a;
    a[0] = 2;
    a[1] = 5;
    a[2] = 3;
    a[3] = 2;
    a[4] = 2;
    a[5] = 4;
    a[6] = 9;
    a[7] = 7;
    a[8] = 1;
    a[9] = 2;
    int[10] res;
    res = int_merge_sort(a);
    int i;
    for (i = 0; i < res.len(); i+=1)
        print(res[i]);
}
```

8.15 Demo: gcd_i.gpl

```
int gcd(int a, int b) {
   while (a != b) {
      if (a > b)
         a = a - b;
      else
         b = b - a;
   }
   return a;
}

void main() {
   print(gcd(20, 40));
}
```

8.16 Demo: gcd_r.gpl

```
int gcd(int a, int b)
{
   if (b == 0)
      return a;
   else
      return gcd(b, a % b);
}

void main()
{
   print(gcd(20, 40));
}
```

8.17 Demo: edge_merge_sort.gpl

```
edge[] edge_merge_sort(edge[] lst)
{
   if (lst.len() <= 1)
      return lst;
   int size_left = lst.len() / 2;
   int size_right = lst.len() - size_left;
   edge[size_left] left;
```

```
  edge[size_right] right;
  int i;
  for (i = 0; i < size_left; i+=1)
    left[i] = lst[i];
  for (i = size_left; i < lst.len(); i+=1)
    right[i-size_left] = lst[i];
  return edge_merge(edge_merge_sort(left), edge_merge_sort(right));
}

edge[] edge_merge(edge[] left, edge[] right)
{
  int i = 0;
  int j = 0;
  int k = 0;
  edge[left.len() + right.len()] res;
  while (i < left.len() && j < right.len())
    if (left[i].getWeight() >= right[j].getWeight())
    {
      res[k] = right[j];
      k += 1;
      j += 1;
    } else
    {
      res[k] = left[i];
      k += 1;
      i += 1;
    }
  if (i == left.len())
    for (; k < res.len(); k+=1)
    {
      res[k] = right[j];
      j += 1;
    }
  if (j == right.len())
    for (; k < res.len(); k+=1)
    {
      res[k] = left[i];
      i += 1;
    }
  return res;
}

void make_set(int[] rank, int[] paren)
```

```
{
   int i;
   for (i = 0; i < rank.len(); i+=1)
      paren[i] = i;
}

void link(int x, int y, int[] rank, int[] paren)
{
   if (rank[x] > rank[y])
      paren[y] = x;
   else
   {
      paren[x] = y;
      if (rank[x] == rank[y])
         rank[y] = rank[y] + 1;
   }
}

int find_set(int x, int[] rank, int[] paren)
{
   if (x != paren[x])
   {
      paren[x] = find_set(paren[x], rank, paren);
      return paren[x];
   }
   return x;
}

void union(int x, int y, int[] rank, int[] paren)
{
   link(find_set(x, rank, paren), find_set(y, rank, paren), rank,
       paren);
}

edge[] run_kruskal(graph g)
{
   edge[] sorted_edges = edge_merge_sort(g.getAllEdges());
   edge[g.getNodeCount()-1] spanning;
   int[g.getNodeCount()] rank;
   int[g.getNodeCount()] paren;
   make_set(rank, paren);
   int i;
   int accu = -1;
```

```
    int k;
    for (i = 0; i < sorted_edges.len(); i+=1)
    {
        if (find_set(sorted_edges[i].getSrc().getID(), rank, paren)
            != find_set(sorted_edges[i].getDst().getID(), rank,
            paren))
        {
            union(sorted_edges[i].getSrc().getID(),
                sorted_edges[i].getDst().getID(), rank, paren);
            accu += 1;
            spanning[accu] = sorted_edges[i];
        }
    }
    return spanning;
}


void main()
{
    graph g =
    [
        A -(12)> D -(16)> F -(42)> H -(3)> G -(11)> E -(12)> C -(17)>
            B -(5)> A;
        A -(15)> C -(1)> D -(19)> B;
        D -(5)> E -(10)> F -(7)> G;
        D -(7)> H;
    ];
    edge[] spanning = run_kruskal(g);
    int i;
    for (i = 0; i < spanning.len(); i+=1) {
        print(spanning[i].getSrc());
        print(spanning[i].getDst());
        print(spanning[i].getWeight());
        print("");
    }
}
```

8.18 Demo: kruskal.gpl

```
edge[] edge_merge_sort(edge[] lst)
{
    if (lst.len() <= 1)
```

```
    return lst;
  int size_left = lst.len() / 2;
  int size_right = lst.len() - size_left;
  edge[size_left] left;
  edge[size_right] right;
  int i;
  for (i = 0; i < size_left; i+=1)
    left[i] = lst[i];
  for (i = size_left; i < lst.len(); i+=1)
    right[i-size_left] = lst[i];
  return edge_merge(edge_merge_sort(left), edge_merge_sort(right));
}

edge[] edge_merge(edge[] left, edge[] right)
{
  int i = 0;
  int j = 0;
  int k = 0;
  edge[left.len() + right.len()] res;
  while (i < left.len() && j < right.len())
    if (left[i].getWeight() >= right[j].getWeight())
    {
      res[k] = right[j];
      k += 1;
      j += 1;
    } else
    {
      res[k] = left[i];
      k += 1;
      i += 1;
    }
  if (i == left.len())
    for (; k < res.len(); k+=1)
    {
      res[k] = right[j];
      j += 1;
    }
  if (j == right.len())
    for (; k < res.len(); k+=1)
    {
      res[k] = left[i];
      i += 1;
    }
```

```
  return res;
}

void make_set(int[] rank, int[] paren)
{
  int i;
  for (i = 0; i < rank.len(); i+=1)
    paren[i] = i;
}

void link(int x, int y, int[] rank, int[] paren)
{
  if (rank[x] > rank[y])
    paren[y] = x;
  else
  {
    paren[x] = y;
    if (rank[x] == rank[y])
      rank[y] = rank[y] + 1;
  }
}

int find_set(int x, int[] rank, int[] paren)
{
  if (x != paren[x])
  {
    paren[x] = find_set(paren[x], rank, paren);
    return paren[x];
  }
  return x;
}

void union(int x, int y, int[] rank, int[] paren)
{
  link(find_set(x, rank, paren), find_set(y, rank, paren), rank,
     paren);
}

edge[] run_kruskal(graph g)
{
  edge[] sorted_edges = edge_merge_sort(g.getAllEdges());
  edge[g.getNodeCount()-1] spanning;
  int[g.getNodeCount()] rank;
```

```
  int[g.getNodeCount()] paren;
  make_set(rank, paren);
  int i;
  int accu = -1;
  int k;
  for (i = 0; i < sorted_edges.len(); i+=1)
  {
    if (find_set(sorted_edges[i].getSrc().getID(), rank, paren)
        != find_set(sorted_edges[i].getDst().getID(), rank,
        paren))
    {
      union(sorted_edges[i].getSrc().getID(),
          sorted_edges[i].getDst().getID(), rank, paren);
      accu += 1;
      spanning[accu] = sorted_edges[i];
    }
  }
  return spanning;
}


void main()
{
  graph g =
  [
    A -(12)> D -(16)> F -(42)> H -(3)> G -(11)> E -(12)> C -(17)>
        B -(5)> A;
    A -(15)> C -(1)> D -(19)> B;
    D -(5)> E -(10)> F -(7)> G;
    D -(7)> H;
  ];
  edge[] spanning = run_kruskal(g);
  int i;
  for (i = 0; i < spanning.len(); i+=1) {
    print(spanning[i].getSrc());
    print(spanning[i].getDst());
    print(spanning[i].getWeight());
    print("");
  }
}
```

8.19 Demo: slides.gpl

```
int time = 1130;

void main()
{
   string[3] student;
   string prof = "edwards";
   int[3][2][1] prof_brain;
   student[0] = "ephraim";
   student[1] = "peiqian";
   student[2] = "qingxiang";
   while (time < 1201)
   {
      do_slides(student[0], student[1], student[2], prof_brain);
      time += 300;
   }
   print("presentation done");
   graph result_graph = [
      prof -(2*time/4)> really -> likes -(5)> it;
      prof -(2)> really -(20)> hates -(-3)> it;
   ];
   edge[] edges = result_graph.getAllEdges();
   for (time = 0; time < 5; time+=1)
      print(edges[time].getDst().);
}

void do_slides(string s1, string s2, string s3, int[][][] audience)
{
   int i;
   int j;
   int k;
   for (i = 0; i < audience.len(); i+=1)
      for(j = 0; j < audience[0].len(); j+=1)
         for(k = 0; k < audience[0][0].len(); k+=1)
            audience[i][j][k] = 42;
}
```