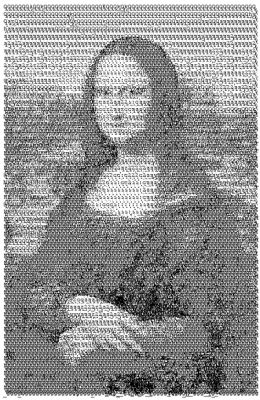
EZ-ASCII:

A Language for ASCII-Art Manipulation



Dmitriy Gromov (dg2720)

Joe Lee (jyl2157)

Yilei Wang (yw2493)

Xin Ye (xy2190)

Feifei Zhong (fz2185)

December 19th, 2012

Table of Contents

[1 Introduction 4](#_Toc343617567)

[1.1 Motivation 4](#_Toc343617568)

[1.2 Background 4](#_Toc343617569)

[2 Language Tutorial 5](#_Toc343617570)

[2.1 Getting Started 5](#_Toc343617571)

[2.1.1 Compiler Requirements 5](#_Toc343617572)

[2.1.2 How to Compile and Run Program 5](#_Toc343617573)

[2.1.3 A First EZ-ASCII Program 6](#_Toc343617574)

[2.2 Variables and Arithmetic Expressions 6](#_Toc343617575)

[2.2.1 Types 6](#_Toc343617576)

[2.2.2 Operators 7](#_Toc343617577)

[2.2.3 Selection 7](#_Toc343617578)

[2.3 Branch Statement 7](#_Toc343617579)

[2.4 Loop Statement 8](#_Toc343617580)

[2.5 Functions 8](#_Toc343617581)

[2.6 Built-in Canvas Functions 8](#_Toc343617582)

[2.7 Examples 9](#_Toc343617583)

[2.7.1 A Simple ACSII Art file 9](#_Toc343617584)

[2.7.2 Draw New ACSII Art 10](#_Toc343617585)

[2.7.3 More Examples 11](#_Toc343617586)

[3 Language Reference Manual 14](#_Toc343617587)

[3.1 Program Definition 14](#_Toc343617588)

[3.2 Lexical Conventions 14](#_Toc343617589)

[3.2.1 Tokens 14](#_Toc343617590)

[3.2.2 Comments 14](#_Toc343617591)

[3.2.3 Identifiers 14](#_Toc343617592)

[3.2.4 Keywords 14](#_Toc343617593)

[3.2.5 Constants 15](#_Toc343617594)

[3.2.6 Granularity and Intensity 16](#_Toc343617599)

[3.3 Meaning of Identifiers 16](#_Toc343617600)

[3.3.1 Types 16](#_Toc343617601)

[3.4 Expressions 17](#_Toc343617602)

[3.4.1 Unary Minus Operator 17](#_Toc343617603)

[3.4.2 Multiplicative Operators 17](#_Toc343617604)

[3.4.3 Additive Operators 18](#_Toc343617605)

[3.4.4 Relational Operators 18](#_Toc343617606)

[3.4.5 Logical Negation Operator 18](#_Toc343617607)

[3.4.6 Equality Operators 18](#_Toc343617608)

[3.4.7 Logical AND Operator 19](#_Toc343617609)

[3.4.8 Logical OR Operator 19](#_Toc343617610)

[3.4.9 Comma Operator 19](#_Toc343617611)

[3.4.10 Selection Operator 19](#_Toc343617612)

[3.4.11 Mask Operator 20](#_Toc343617613)

[3.4.12 Arrow Operator 20](#_Toc343617614)

[3.4.13 Canvas Attribute Accessor (read-only) 21](#_Toc343617615)

[3.4.14 Function Calls 21](#_Toc343617616)

[3.4.15 Include 21](#_Toc343617617)

[3.5 Declarations 21](#_Toc343617618)

[3.5.1 Function Declarations 21](#_Toc343617619)

[3.5.2 Variable Declarations 22](#_Toc343617620)

[3.6 Statements 22](#_Toc343617621)

[3.6.1 Assignment/Output Statements 23](#_Toc343617622)

[3.6.2 Conditional Statement 23](#_Toc343617623)

[3.6.3 For Statement 23](#_Toc343617624)

[3.6.4 Return Statement 24](#_Toc343617625)

[3.7 Scope and Linkage 24](#_Toc343617626)

[3.7.1 Lexical Scope 24](#_Toc343617627)

[3.8 System Functions 25](#_Toc343617628)

[3.8.1 Blank 25](#_Toc343617629)

[3.8.2 Load 25](#_Toc343617630)

[3.8.3 Shift 26](#_Toc343617631)

[4 Project Plan 27](#_Toc343617632)

[4.1 Project Process 27](#_Toc343617633)

[4.1.1 Proposal phase 27](#_Toc343617634)

[4.1.2 LRM phase 27](#_Toc343617635)

[4.1.3 Code Design and Implementation 27](#_Toc343617636)

[4.2 Programming Style Guide 27](#_Toc343617637)

[4.3 Project Timeline 28](#_Toc343617638)

[4.4 Member Roles and Responsibilities 29](#_Toc343617639)

[4.4 Development Tools and Environment 29](#_Toc343617640)

[4.5 Project Log 30](#_Toc343617641)

[5 Architectural Design 31](#_Toc343617642)

[5.1 Compiling and Executing 31](#_Toc343617643)

[6 Test Plan 33](#_Toc343617644)

[6.1 Representative Source Program and Target Program 33](#_Toc343617645)

[6.1.1 Example 1 33](#_Toc343617646)

[6.1.2 Example 2 33](#_Toc343617648)

[6.2 Test Cases and Test Suits 35](#_Toc343617649)

[6.3 Test Automation 36](#_Toc343617650)

[6.4 Test Responsibility 36](#_Toc343617651)

[7 Lessons Learned 37](#_Toc343617652)

[7.1 Dmitriy Gromov 37](#_Toc343617653)

[7.2 Feifei Zhong 37](#_Toc343617654)

[7.3 Yilei Wang 37](#_Toc343617655)

[7.4 Xin Ye 38](#_Toc343617656)

[7.5 Joe Lee 38](#_Toc343617657)

[7.6 Advice For Future Teams 38](#_Toc343617658)

[8 Appendix 39](#_Toc343617659)

[8.1 preprocess.ml 39](#_Toc343617660)

[8.2 scanner.mll 40](#_Toc343617661)

[8.3 parser.mly 42](#_Toc343617662)

[8.4 ast.ml 45](#_Toc343617663)

[8.5 ssanalyzer.ml 49](#_Toc343617664)

[8.6 sast.ml 60](#_Toc343617665)

[8.7 hashtypes.ml 61](#_Toc343617666)

[8.8 interpret.ml 61](#_Toc343617667)

[8.9 compiler.ml 67](#_Toc343617668)

[8.10 bytecode.ml 75](#_Toc343617669)

[8.11 execute.ml 76](#_Toc343617670)

[8.12 canvas.ml 88](#_Toc343617671)

[8.13 ezac.ml 95](#_Toc343617672)

[8.14 reuse.ml 97](#_Toc343617673)

[8.15 Makefile 97](#_Toc343617674)

[8.16 runtests.sh 99](#_Toc343617675)

# 1 Introduction

## 1.1 Motivation

Many times when using text files or command-line interfaces, a user may have the need to display an image using ASCII characters, whether for aesthetic (decoration) or functional (diagram) purposes. Generating small, simple geometric shapes, let alone more complicated diagrams, is a tedious process for the user. For example, let us consider a simple use case where the user would like to display a square with some elements around it in a defined drawing space. If the square ever needs to be moved or resized, the user must not only re-draw the square, but also maintain or update the elements that are affected by the move. This is a non-trivial manual process and is not sustainable for larger, more complicated diagrams. Similarly, translating an image file (.bmp, .jpg, .png…) into a corresponding 2D array of ASCII characters is non-trivial.

We propose to solve this problem by implementing a programming language (EZ-ASCII) for the purpose of creating and manipulating ASCII Art, a form of drawing pictures using only the characters defined by the ASCII character set. The goals of EZ-ASCII are to 1) abstract away from the user the task of mapping/converting characters to intensities (and vice versa), 2) allow easy manipulation of the image (selection, replacement, movement, masking) with the use of a “canvas” built-in type, and 3) provide flexible features with simple syntax which allows developers to easily build on top of the built-in library functions.

## 1.2 Background

While drawing ASCII art, one generally only has the option of varying color intensity. Color intensity in this case is defined by how much of the space allotted for a character is actually used by the character. For example, ‘@’ would describe an intense color, while ‘,’ would describe a non-intense color. The language will provide some default mapping of characters and intensities, so that the user can work with intensities instead of spending time determining which ASCII characters to use. However, if a user feels the need to use a specific character, they will have the option of overwriting the default mapping for the color intensity. Since many characters have similar intensities, we will not provide a mapping of all characters to intensities by default. If desired, the user will be able to increase the granularity of intensities as needed.

For image manipulation, the user will have the complete freedom to change any character in that image or change all characters of a given intensity to a different one. This way, an image's color can be "inverted" or simply darkened to conform to the user's tastes. Furthermore, the user will have the ability to apply simple transformations to a range of characters (e.g. shift several cells up and to the left). One of the main uses for this programing language will naturally be to convert images from other formats into an ASCII format. Moreover, given the various abilities available to the programmer, he/she should quickly be able to set up functionality to draw various shapes and constructs and manually create images.

# 2 Language Tutorial

The EZ-ASCII language was primarily designed to provide simple mechanisms for creating and manipulating ASCII Art images, but may also stand as a simple general-purpose programming language. The following tutorial will give a quick tour of setting up a development environment for EZ-ASCII and creating a simple program.

## 2.1 Getting Started

### 2.1.1 Compiler Requirements

EZ-ASCII requires the following to be installed:

1. OCaml (4.00.0) - <http://caml.inria.fr/ocaml/>
2. Python (2.7.3) - <http://www.python.org/>
3. PIL (Python Imaging Library) - <http://www.pythonware.com/products/pil/>
4. For Windows, a Windows installer is available from the PIL homepage.
5. For Mac OS, download *Imaging-1.1.7.tar.gz* file from PIL website, and extract it. Use the following commands to build and install:

$cd Imaging-1.1.7

$python setup.py build

$sudo python setup.py install

1. For Linux users, use the following command to install PIL on Linux:

$sudo apt-get install python-imaging

### 2.1.2 How to Compile and Run a Program

1. Extract the EZ-ASCII compiler source files into a directory.
2. Run make to build the executable **ezac**.
3. The **ezac** executable takes a .eza source file as input, and allows some command-line parameters. A usage example is ezac [options] <source-file>. The following options are supported:

|  |  |
| --- | --- |
| Flag | Description |
| -a | generates the abstract syntax tree (AST) for the input program and outputs it in string format |
| -s | runs static semantic analysis on the source program and outputs any errors found |
| -i | runs the interpreter on the source program |
| -b | compiles the source file into bytecode and outputs the bytecode in string format |
| -c | compiles the source file into bytecode and executes it |
| -cd | performs the same operation as with the –c flag, but runs in debug mode (outputs debug statements) |

Note that for development purposes, any output (e.g. –a, -s, -b, -cd) is currently set to stdout, giving the developer flexibility in piping it to any output stream. If a developer were to run the compiler with the –c option in an actual release of the compiler, it should output the bytecode to a file, which would in turn be passed as input to a separate bytecode-interpreter executable. This is trivial to implement, and for efficiency purposes we have kept everything in a single executable with stdout as the default output stream.

### 2.1.3 A First EZ-ASCII Program

A simple “Hello, world!” program could look like the following:

d <- “Hello, world!”; // store string in variable d

d -> out; // output d to stdout

In this simple two-line example, we first store (by use of the <- assignment operator) the “Hello, world!” string in a variable d. Note that there is no explicit variable declaration; the assignment statement implicitly handles the creation of the variable d with the correct type (string). The output operator (->) here uses the keyword out which signifies to output to standard out. We will see later that the output operator may output to a file, and in addition, a second boolean render parameter may be specified in the case of outputting canvases.

Note the C-style line-comments (//), and each line delimited with a semicolon.

## 2.2 Variables and Arithmetic Expressions

### 2.2.1 Types

EZ-ASCII has four variable types: boolean, integer, string, and canvas. A boolean type may be either true or false. Integers are in the allowed range that OCaml supports (31 bits on 32-bit processors, 63 bits on 64-bit processors). Strings are sequences of characters, and are represented by surrounding double quotes. A canvas is represented internally as record with a data field which holds the 2D array of integer intensities, and a granularity field which stores the granularity level of the canvas image.

As noted above, there is no explicit type declaration, so even after a variable is assigned a type, any subsequent assignment may alter its type.

i <- ~(3 > 2); // variable i assigned boolean false

i <- 2; // variable i now assigned integer 2

i <- “hello”; // variable i now assigned string “hello”

i <- load(“lena.jpg”, 10); // Use built-in function load which

// loads an image file with granularity

// value and stores it as a canvas

### 2.2.2 Operators

EZ-ASCII supports a variety of operators. Some example expressions are as follow (see the reference manual section for a complete listing of operators):

i <- -(1 + 1); // i assigned -2

i <- 2 \* 2; // i assigned 4

i <- 5 / 2; // i assigned 2

i <- 7 % 3; // i assigned 1

i <- 1 \* 3 + 2; // i assigned 5

i <- 5 – 1; // i assigned 4

i <- “hello “ + “world!”; // i assigned “hello world!”

img3 <- img1[2:8, 1:4] + img2[,]; // img3 assigned additive layering

img4 <- img1[,] – img3; // img4 assigned difference layering

i <- ~(1 > 2); // i assigned true

i <- (1>2 || 2>1); // i assigned true

i <- (1>2 && 2>1); // i assigned false

### 2.2.3 Selection

The selection operator can be applied to a canvas type variable. It returns an equal size canvas with the selected points value, and the rest of points are blank. A complete list of examples is as follows:

img1[1,1] //select a single point value at coordinate (1,1) of img

img1[1, 1:4] //select a horizon slice in row 1 from column 1 to 4

img1[1:4, 1] //select a vertical slice in column 1 from row 1 to 4

img1[1:4, 2:5] //select a range of row from 1 to 4 and a range of column from 2 to 5

img1[,] //select a copy of canvas img1

## 2.3 Branch Statement

The following is an example of an if-else conditional statement (note that the else-block is optional):

if (2 < 3) {

e <- 3;

e -> out;

z <- "hello world!";

z -> out;

}

else {

f <- 8;

f -> out;

}

The output is:

3

hello world!

## 2.4 Loop Statement

The following is an example of a for loop in EZ-ASCII:

for i <- 0 | i < 5 | i <- i + 1 {

i -> out;

}

The output is:

0

1

2

3

4

## 2.5 Functions

The following is an example of recursive function in EZ-ASCII:

Fun factorial(x) {

if(x <= 1) {

return 1;

}

else

return factorial(x - 1) \* x;

}

a <- factorial(6);

a -> out;

The output is:

720

## 2.6 Built-in Canvas Functions

There are three built-in functions of EZ-ASCII relating to canvas operations - load, blank, and shift. The following is a list of examples using these functions.

canvas <- load(“lena.jpg”, 10); // load image “lena.jpg” and

// normalize it with a granularity

// of 10

canvas <- blank(10, 10, 8); // output an empty canvas with size 10 \*

// 10 and a granularity of 8

img <- shift(img2, SHIFT\_UP, 6); //shift img2 up with 6 spaces

## 2.7 Examples

### 2.7.1 A Simple ACSII Art file

canvas <- load(“bot.jpg”, 10);

sel1 <- canvas[10:20, 30:40]; // All points in that range

//(10:20, 30:40) padded by -1

sel2 <- canvas[<3]; // All points with intensity less

// than 3 padded by -1

canvas -> out, true;

sel2 -> out, true;

@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@@@@@@k@@@@@@@@@@@@@@@@@@@@\*\*\*@@@@@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@@@@@@k\*@@@@@@@@@@@@@@@@@@@kk@@@@@@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@@@@@@\*k@@@\*\*kZZZZZZkk\*\*@@@k\*@@@@@@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@@@@@@@k\*\*kkZZZZZZZZZZZZk\*k\*@@@@@@@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@@@@@@@kZZZZZZZZZZZZZZZZZZZ\*@@@@@@@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@@@@@@\*ZZZZZZZZZZZZZZZZZZZZk\*@@@@@@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@@@@@kZZZZZZZZZZZZZZZZZZZZkZZ\*@@@@@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@@@@kZZZZ\*@\*ZZZZZZZZZZZk@\*ZZZZk@@@@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@@@\*ZZZZZ\*@\*ZZZZZZZZZZZk@@kZZZZ\*@@@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@@\*kZZZZZk\*kZZZZZZZZZZZk\*\*kZZZZZ@@@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@@kZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ\*@@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@\*ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ@@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@\*ZZkZZZZZZZZZZZZZZZZZZZZZZZZZZZZ\*@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@kZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZk@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@kZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZk@@@@@@@@@@@@@@

@@@@@@@@@@@\*\*@@@\*ZZZkZZZZZZZZZZZZZZZZZZZZZZZZZZZZk@@\*\*kk\*@@@@@@@

@@@@@@@@@\*kZZZk@@\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*@\*kZZZk\*@@@@@@

@@@@@@@@@ZZZZZZ\*@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZkk@kZZZZZk\*@@@@@

@@@@@@@@\*ZZZkZZk@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ@kZZZZZZ\*@@@@@

@@@@@@@@kZZZZZZk@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZk@ZZZZZZZ\*@@@@@

@@@@@@@@\*ZZZZZZk@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ@ZZZkZZZ\*@@@@@

@@@@@@@@kZZZZZZk@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZk@kZZZZZZ\*@@@@@

@@@@@@@@kZZZZZZk@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ@ZZZZZZZ\*@@@@@

@@@@@@@@kZZZZZZk@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ@ZZZZZZZ\*@@@@@

@@@@@@@@kZZZZZZk@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ@ZZZZZZZ\*@@@@@

@@@@@@@@kZZZZZZk@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ@ZZZZZZZ\*@@@@@

@@@@@@@@kZZZZZZk@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ@ZZZZZZZ\*@@@@@

@@@@@@@@kZZZZZZk@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ@ZZZZZZZ\*@@@@@

@@@@@@@@kZZZZZZk@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ@ZZZZZZZ\*@@@@@

@@@@@@@@kZZZZZZk@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ@ZZZZZZZ\*@@@@@

@@@@@@@@kZZZZZZk@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ@ZZZZZZZ\*@@@@@

@@@@@@@@kZZZZZZk@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ@ZZZZZZZ\*@@@@@

@@@@@@@@kZZZZZZk@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ@ZZZZZZZ\*@@@@@

@@@@@@@@kZZZZZZk@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ@ZZZZZZZ\*@@@@@

@@@@@@@@kZZZZZZk@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ@ZZZZZZZ\*@@@@@

@@@@@@@@kZZZZZZk@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ@ZZZZZZZ\*@@@@@

@@@@@@@@kZZZZZZk@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ@ZZZZZZZ\*@@@@@

@@@@@@@@kZZZZZZk@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ@ZZZZZZZ\*@@@@@

@@@@@@@@kZZZZZZk@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ@ZZZZZZZ\*@@@@@

@@@@@@@@kkZZZZZZ@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZk@kZZZZZZ\*@@@@@

@@@@@@@@\*ZZZZZZk@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZk@kZZZZZk\*@@@@@

@@@@@@@@@kZZZtk@@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZk@\*kZZZk\*@@@@@@

@@@@@@@@@\*kkZk\*@@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZk@@\*kkk\*@@@@@@@

@@@@@@@@@@@@@@@@@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@ZZZZZZZZZZZZZkZZZZZZZZZZZZZZZZZZk@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@kZZZZZZZZZZZtZZZZZZZkZZZZZZZZZZZk@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@kkZZZZZZZZZZZkZZZZZZZZZZZZZZkZZk\*@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@@\*\*\*\*\*ZZZZZZZ\*\*\*\*\*\*\*kZZZZZZZ\*\*\*\*@@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@@@@@@@ZZZZZZZ@@@@@@@\*kZZZZZk@@@@@@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@@@@@@@ZZZZZZZ@@@@@@@\*ZZZZZZk@@@@@@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@@@@@@@kZZZZZZ@@@@@@@\*ZZZZZZk@@@@@@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@@@@@@@ZZZZZZZ@@@@@@@\*ZZZZZZk@@@@@@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@@@@@@@ZZZZZZZ@@@@@@@@ZZZZZZk@@@@@@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@@@@@@@ZZkZZZZ@@@@@@@@ZZZZZZZ@@@@@@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@@@@@@@ZZZZZZZ@@@@@@@@ZZZZZZk@@@@@@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@@@@@@@ZZZZZZZ@@@@@@@@ZZZZZZk@@@@@@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@@@@@@@kZZZZZk@@@@@@@@ZZZZZZk@@@@@@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@@@@@@@\*ZZZZZk@@@@@@@@kZZZZZ\*@@@@@@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@@@@@@@@kZZZk@@@@@@@@@\*kZZkk@@@@@@@@@@@@@@@@@@@@

@@@@@@@@@@@@@@@@@@@@@@@@@\*\*k@@@@@@@@@@@\*\*k\*@@@@@@@@@@@@@@@@@@@@@

ZZZZZZ

ZZZZZZZZZZZZ

ZZZZZZZZZZZZZZZZZZZ

ZZZZZZZZZZZZZZZZZZZZ

ZZZZZZZZZZZZZZZZZZZZ ZZ

ZZZZ ZZZZZZZZZZZ ZZZZ

ZZZZZ ZZZZZZZZZZZ ZZZZ

ZZZZZ ZZZZZZZZZZZ ZZZZZ

ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ

ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ

ZZ ZZZZZZZZZZZZZZZZZZZZZZZZZZZZ

ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ

ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ

ZZZ ZZZZZZZZZZZZZZZZZZZZZZZZZZZZ

ZZZ ZZZ

ZZZZZZ ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ ZZZZZ

ZZZ ZZ ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ ZZZZZZ

ZZZZZZ ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ ZZZZZZZ

ZZZZZZ ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ ZZZ ZZZ

ZZZZZZ ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ ZZZZZZ

ZZZZZZ ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ ZZZZZZZ

ZZZZZZ ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ ZZZZZZZ

ZZZZZZ ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ ZZZZZZZ

ZZZZZZ ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ ZZZZZZZ

ZZZZZZ ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ ZZZZZZZ

ZZZZZZ ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ ZZZZZZZ

ZZZZZZ ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ ZZZZZZZ

ZZZZZZ ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ ZZZZZZZ

ZZZZZZ ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ ZZZZZZZ

ZZZZZZ ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ ZZZZZZZ

ZZZZZZ ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ ZZZZZZZ

ZZZZZZ ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ ZZZZZZZ

ZZZZZZ ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ ZZZZZZZ

ZZZZZZ ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ ZZZZZZZ

ZZZZZZ ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ ZZZZZZZ

ZZZZZZ ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ ZZZZZZZ

ZZZZZZ ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ ZZZZZZZ

ZZZZZZ ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ ZZZZZZ

ZZZZZZ ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ ZZZZZ

ZZZt ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ ZZZ

Z ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ

ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ

ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ

ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ

ZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZZ

ZZZZZZZZZZZZZ ZZZZZZZZZZZZZZZZZZ

ZZZZZZZZZZZtZZZZZZZ ZZZZZZZZZZZ

ZZZZZZZZZZZ ZZZZZZZZZZZZZZ ZZ

ZZZZZZZ ZZZZZZZ

ZZZZZZZ ZZZZZ

ZZZZZZZ ZZZZZZ

ZZZZZZ ZZZZZZ

ZZZZZZZ ZZZZZZ

ZZZZZZZ ZZZZZZ

ZZ ZZZZ ZZZZZZZ

ZZZZZZZ ZZZZZZ

ZZZZZZZ ZZZZZZ

ZZZZZ ZZZZZZ

ZZZZZ ZZZZZ

ZZZ ZZ

### 2.7.2 Draw New ACSII Art

canv <- blank(10,10,10);

for i <- 0 | i < 9 | i <- i + 1

{

canv[i,i] <- 9;

}

canv -> out, true;

@.........

.@........

..@.......

...@......

....@.....

.....@....

......@...

.......@..

........@.

..........

### 2.7.3 More Examples

// Filter Extremes

// This is sort of like contrast raising.

include "../demo/demo\_lib.eza";

intensity <- 60;

c <- load\_image("../image/lena.jpeg", 60);

c -> out, true;

c[<15] <- 0;

c[>40] <- c$g - 1;

nothing <- "";

nothing -> out;

c -> out, true;

CLCttLLCJYYfc{{[]]r][rrvunnxnxnxznxnxxnjxnnxnnnzznznnnuuxnnvvc[cjtLLLLtLtttLLCtQkba[}cnuucvuuucvurrJ

CLLtLLttJYYfc{{][[]]]rcvunxnnnnxznxxxnnnnxnnunnnnnnnnnuvxnnuur[rxtCttttLtLLtLLtOkbh]]cvvvcvcuvvvvcct

LLCLLttCUUJfu1{}}[}]]rcvvunnunnnunxxnxnxxnnunnnnxunnuunnnxnnvv][ujLLLLLLLtLttttfabdZ}rvcvvcvvvunun[>

LCLtLtLUUUCjc11}][}[[rrvuunnnnnnnnxnnxnnunnnnnnnxnnnnnunnuunncr[rztCCCCCCLtLfftfUhdbr]vrcvvcvuunx}+<

LLCCLtCJJCCfn}{[]][]}rvcuunnnnxnnnxnxnunnnxznnuxxxnuunnnununvxr[}nfLJCJCCLCCttttfobdO]ccvuvvxunz{<>>

tLLLCCJUCLCfc1}{[}}}]]cvvuvnnnnununnnnnnuvnuuuuunnnnnvuunuvnunr]]vjCCJCCCLtttttfjChdkn]cvvuvunz1l<<>

LCLCCJUJCCJjc11{[}}][]rvvunxununxnnnxxnxucuunuunnxnxvunnuunnnrc][uzLCCLCCLLCtCttfjQbpa}ccvcunn{<<>>>

CLCCJUJULCCfc)1}[[[}[rcvvvnunucnuununnxuuvvvnvvvnnnnnnuunuunucc]rvztLCLCCLCLLtLttjjhpdJ}rcvux{++l>>i

JJJUYJJCCCJjc|{[}][}}rrcuuvuuvuvnunuxnnnunurcvvvnnnnuuuununuvucrrvxttCCCLLLLCttttjzObph]r]cz1+<+i><<

JCCUCttLJCJtc(1}[r]}[rccucununuuunnznuzuujxzYYUncvvvnnnnunuuucc][cxfftLLtLttLLfffjjzhddQ}rv(<<<!l!>>

CCJULjzCCCJfv(1}]}[]]rcvvnnnvnnxnunnnuftxfXJ0Z0X00xrvvnuuuuuccrr[rxfjftLLttLtffzzjjzXbppjr)<<<>>i><<

CCXCjuzLJUJfv|({}}}[[cccvnuuuxxncnuzutjjtxLtYOOOO00occvxvvuccrr[}vjzjffttffzfjfjjjzzzhpqb[<<>>i!\_><+

CUJLv{xLJJJtv)|1[}{[[]vcvcuvuuxuffnvczujnffLZUOJXZ00QOcrvcvcccr]]czfjjftfLzjjtjjzjjjztbpp<+\_i>l>>i++

JYLj{}jJUCJfc||)1{}[[[]rcuvvvucUruccuuuxzzCLZCXXQQO0QQo]rvccvrr[}rzftffjftjzjfzjjjjjjjopt\_+>!!i>!<>!

XUfr?}zJUJCjr?){[[{{}]r[cvcvvvnrrcvuuxxfczzfCU0OXoQoQa0oj}}rrr}r{rzLttjznjtjjjzfjjfffLLn<+><!i>>>>l-

YCz(|[xJCJCfr?({}{}}[[[vrccvvuzv[rccvnvzjuftUYZX0QOQoO0Okbr}[[}]}rjLLfjucnffftzjjfjffLx<+\_>i<<!><l+>

Ltr|(]fCJJCfr?({{{{}[]rcvuvcvx][rurvcxcxxzzffXQZXoQXZbkbbdp|{[}{1rztLLjv1]zfjjjjjjfttf+>\_i<!+i<<i|<j

tv(1)]zJUCJfc|(1{}[{}]rrrvcvur]rcuv]rnnxzujLCYXX0Lobhahhbkda|){11rzLfLjnl!cffjjfzjzjL>++!>><!><l)?zj

n1)(1}zCJJJjr?1{{[{{[[]ccvcu]}vrcccrunzjxtfjtYZJJaoahahahbbpj|)({rzLtLfx|<{ntjzjjfjf)\_<>i><i>>il?nfz

})11(}xCJJCjr|({[}}}[]rvcvcur[rcvrcvnxzzzfzjfXnOaaaQQQhoQahkptl|)rzLLtfn?\_lvjffjjfLt<+<i><+!<!IInfzL

))11(}zCJUCfr|(1}}{[[]rccvn][cr]rvrnvxxjnuuxxzoQ0oooOaahhhhhkdQI|]zLLftn(>+1ntfzjftl\_+ii!<!<>i!vzfLJ

){){)[ztCJCjr|({1[}{[]ccrrj[}rrrrvnjjfnfjnzv0ZaOOOYQahhhakhhkbd)I}xLLtfn(<+>]nfzztn<<<!>!>>i><[tzfCJ

){{{)[jCJJCjr||){}]{][]crjc[][[]rrvxnxzfxzvZQQO0Yoa0ohQhkOahhkdqi1xfLtCn(<<-inkhZf<>ii>!iii>>|tzjLCt

)(1{(}zLJJCfrl|1{{1}][]]}b]}rrrrvnnzjvxr]jXaZYOOOQQoQQoQhkahhkkdr(xtLLtn(<+-Qk0kpk+<ii|ii>IiijfzCCCL

1()1){xLUJCfrl?){{{}}[}r}Q[{rr]]rnrrzxn]JZXUQYZX000oQXooaoohaakbp?nCCLtnl\_\_kZkdbdm++>!>i<>i<ntzCCCCL

11[1[}nLUJJj]?l{{}}}[[rr[Y}}r]rcuuuxvu[CXCXLZY00ZZOXQoQaaoaaQohhkQutLCfci}dJbkhhkq++!<<>+!<?LjLCCCCC

{{}}{[xLJUUfr|({}][}}]crntr}{rrr]vuvx}JCjZXJXQY0ZYXQX0oQoaCaooaaakkfttz{h0Zkhaohdp+>>>>>!>\_jffCCLLLL

}}{{[[jtJUUtc|()}}{[}[r[0jr{r}cucurvctfjjLYXJU0ZCZXO0X00aUOQQQaaQQhttjQkookhaoakdd<><!<+>+}LjCLLLCLL

}1{}}rzJUUYLc|)1}[}{[[}{dtv]]]rvxruvjjjrLCLYC0Ot0XZO0O0CZOZ00QZQ0OQXCaOZkaoaohakdd<>>>>i!lfftCLLLLLL

}}1{}]xJUXYLr||{{]{{}[}1hLcr}]]vux]tzfcftJLUZCJZXUXUOQZOX0O0OYOXOXZaOoahaooaaaQhdd+>i><>>ctfCCCCtLLt

{}[{{}jCYYYtc?|{{}[{}}[)hjzj[}]rr]zjj[fffjUZtZXtYZYUUXXXOZQXZXJZUYQOohaQooohhCZapI\_<!+iilLjtCCCCLLCC

{{{{1[zCUYYLr|({}}}{[}})Qjxzv1}r{jntrftztfjxUYJUUXJYJLYYXOYYXXCJaZokQ0QQQoohYLZJaii>><>lxffCCCCCCLCL

{{{11]zCYYYLc?){{{{}}{}|0Cfzc}r[zxfujjffzLztLJXLJYZtJJYUJUXYUL0U0aa0QQoooaahCZtXh\_>i+>i{LjLCCLLLLCLL

{{{{{rjCYYYLu?){{{{}{}1)O0Utu[1zjzcffxxxjxJLfJLnfjCCJLUCJtLtYZOaoZZQ0oaaaakjUYrQ+\_i!l>!fftCCtLtLLLCL

{{}{}]zCUYYLv(|{}{{{{{{|h0Cnfcuvx[jjzcxjnCcfn]}zC]]tLvjt)LjQCaoQQQQooahaahht|{Xd\_>><i>}tjCCLLCLLLtLL

}}}}[cjCXXXCv||{{}1{{}1(bOJuCcvu]xnzvnnnxttv]|ijLx}((l!>\_lYYao0o00QaoaahhJ1))fb<+>!>>>ffLCCCLLCLLLtt

}}{1[rzJYYYCu((1{}[{}{}|k0Zuxc]]vnxvxxuzjuuv[cI|rl(l?>\_~tzOho0QaQQQoakh[)(){Col+>>>>+{LjCJCCLCLCtLLt

]]{{}rfCYYYCu(|{{}{{{{}(doOnxj{cnxnvxvjzvx}l|li[r!)|>+-YrOOZQ0Z0OQQoQnn{)}fY0+>>i<>I>xfCJCCCCLCLLtLt

]]}{}cjCUYULv||1}1}}1}})nhhtjjrjn}nnufxtr|?i>++c>I?>+[Xco0XOZ0O00QoZ{]zLUUUQ<+ii><><)fzJJJJCCLCLtLLt

[[[[}]jJYYYCn?|}}{{1}[]}(koXC{vj[ucxjzv|illi!\_|!!!In>ZvoQXZXXU0OOQIrv]nLYXQ!\_<i>>>!>njtJJUJCCCLLLLLt

[rr{}]zCUXYLu||1{[{{{}[[{doUYunrnnnuc[](l!+r~i{lil\_-uxo0OXZXJXO0XO)|{j}tYoi>+>!!<>>lznJUJCCJCCCCCLLL

]][{{}zJUUXCn||){{}1{[]][|aO]vuvnvccr)|(}!>{>+>({{l[c0OOXXXXXZO0oQz(]lztC><+ii!i<i<|nxUUCJJCCCCCLLLL

][[{{{zCXUXLn?|{{}}}}[]rr)baxucvrjn1)(!i?)ii{+<<+l)UXX0YJXXXUoooooY}>}xfv<+>!i!i+<icuLJJUCJJCCCLLCLL

[[[{{1nLUYYJn|?11}}{{rrrr1bb}crrunui!l+i)|+\_r1\_-<rZzZ0OJCZJYOQaoaaO{+i?C)<<i!Il<><|jzttJUJCCJJCLLLtL

{[[{{1xCUYYCz(|1{[{}}}jcr}hXrr{x]ll1)+l!>??!l+\_-jJCxC0YUJjJOQQoahhaci+|C|>i!!l>>!<vxLLtttCCCCJCCCLLt

[[}{1{nCUYYCz|({[}{}}rvccc]ocruxu(>\_(<<\_!ll|([~tjUXjUQJJfCU0Qohahkhzl-IY{>ll!l>>>!znJJttfftfLCCLLLLf

}[}}11nCYYYJx?(1{}[[}[rccvcZrxnxIi[>+>(!<>i|-xCuCZ0tZYLtCYXZQoaakkkL)<<u{iiI!!>i+{jjJCCJLtLfffjftLtL

}[}{[1xCUYXCu(|1}{][[]rvvvvjcvv]i-1+l]i<\_>!]+c}CUUZXYtUJJXXXQQQaakkX{+\_|jI?!li>><xntJCCCUUCtffjjjjtf

}}{}{1xCYXYJn(|1}}{}[]rvcal\_xur<)\_]lii+<<++<!{ZXCJQOl}uzUZXXOQQQahaCI<\_>Ci>!?l><?zuCCCCLCCCLLtffjzzz

[]{[{1nCYYXCx|(1{]{[}[rcufi+Lr1l<lu-l<+-\_l!-j0YatOUjLLu|luUYXQOQQY])(<+!JI|l>><i[xzCCLCLCCCCtLLtfjzx

{{}{1)nLXXYCz|11{[{[}{rxCfYj(!In|{)>>+]<i+-JXUoXO[}?|(<]nczJY0Q0jv!lI?\_?X)!Ii>lixuLLtLLtLLttLLtLfffz

{{{1((nLYXXCz|?(1[}{1vbjfL(|\_c]{I|1)!\_\_r++I}U0oQ)l>><I?<1xntUah]!>li!>+IO)!!>!iijxCLtLCLtCttCtttjfzz

{}{1|?nCXXXLn|({{{}{(CZftf?\_)><|1i<<j+<<i?jaZ0ou|i{1+Io}]cnzXbL>+[Ui<<+lY(li!><]zfCLttLttttttjfjjzxn

}}{)|?nLXZZCu)(][[}]!lZdv>\_)Il?)(i<\_l><++!uYQoCcxr}rlaatcrvjXd}j)rU>>++iUI1iii<njCLtLttttttffjjxxnzL

[}]1)luCXXXJz(1}]]+!CLt<\_{[(+<l{{v<+!><\_\_zOOajczfjurvfLYfuuzZpYxxL}i!>><L1l>+!vzxLLtftLfLttfzjxxxJZO

}[}1(lvLYZOUx()}][xjJ?}iirz]ilc[zf+<<><-rrX0C{njffffzjtttnnnYqYfnu}{I\_>ituI+>\_{xfCtLfttfttfjzznCZ000

}))|?luLXXZUx))}r]r]?|<<I[>|\_l>jIr>>>i><[X0o)rnfCUUJJUJUzjnuYpOCLnv]l+I>Lz|>><uxCLLtttffjffzzxYQQ000

1}(|llvCYXZJz(1{[jLt|(i>|(u\_++}]x+|+<><frOh<}vujtJXYXJXCfjnuCbQYfxncl<><CLi<!<jnCLLLttttfjzzxUQQQ00Q

|(||IivLXXXUx1)}]u}{)Ilrc?<<<>><\_1]<<i<ch0+irvxftCXZYYUCffznLpoCCjxni<!ijtil+|zfCtLfftftjjznCQQQQQQo

l||?I!ctUYXYx?)1[rncr??i?uli<+<i<()r\_-jvQZ+I[vzzttJXXUUCjjnnthkJtjucli!+rn\_l>vxXLttftjfjfjnnQQQQQohh

|?|lI>vLYYXJx?|{xc+[[li[Ll>l+\_>|+[ru-\_cok-I![unxztCYUUJLxxnuzodUfznr+il\_1u|!\_zxJCLLttffjzznJQQ0Qahha

||Ili>vLUXXCx||]cxir(>)}}{-<<~1{L(f<~urh+<(?}vnxzttLCLCjnvvczXqLLzn1\_>l+|L]+lzjLLLtLtfjjzxxOQ0Qahhhh

(|(I!+vLUXXUz|)j[r|I|!{<{zx>l\_lC]}><zncY\_<)l{unnzjtLCCLz]xzunZwjfxv>>!?!<Lz\_rfCtLftLtfffjuJoQQahaahh

)|?ll<vtUYXUz}|{]{I{)-[irX[>!+>ix\_+-UXUi\_+1|}vnnzjttLLCfcx!rvChtfnu<<li<+Yj+zjCtLfttjfjjznOQQoaahhhh

|?|?llnLYXXYx((}r|lIln||nr(~>L+-(>!}fUi\_<>}|[cunxtfttLLfxuxurLYtzn1!<!l++Jf>fjCLfttjttjjxj0Qohhhhkhh

??|?l1zCJYXUj)({[n>I|!|(}(r1ljl)|cY}uC>!li{(]vuxxzjjLCLLtfzZYQYtzu><<I|><fjlffLLttfffjfjxLQQahhhhhhh

lll?l1zCUYZUx)|{j[!nl>?l))jv)?++XUY)o-<>|i?[rvunjjzztttttfLaZoJjx}><!(ll+czrftLtttfjjfzjnUQQhhhhhhhk

IllIl)zCUXZXj(ln[(?{!l!(I1lcj~[]jQ(U+?><l>>[{uunjzzxjjjjzLJboQJzx+<<I||!+]rxfLttfjffjjjxnYoahhhhhkkk

lill!(zJYXZYj(|1}l<[I>!r}lcrc)rQk1c+<I<il!>{1rnunxfjrvnnnuvxxr{j)<i>()|i+lvtjLLttfftjfjzvXakhkhhkkkk

>illI)jCYXXUz|](jli>liln{r(r)xxpC(t<>><!l|i(|]vunzjjnv]runujLnzj<><!!?)ii>jLfLLttffffjjzn0hkkkkkkkkk

i>!ll{xCYYZUxu?r[Ij\_<llL<r{i[juh]X>ii>!>I?i)l[rcvnxjfncnnfJJCjfl<l<!<?)Ii>CLtCLLLtffjjjnuQbkkkkkkkhh

>i!il{xCXXZYz|?nriz>(i(rc1)j{UrjLl!!?!i!l?iIl)[rcnxzjxnncnzvfzx++>>l<l(!l<CCtLLLLttfjjznvabkkkbkhhah

<i>>]1ntYXZYj||{|>I>)l]f]cvv)z[J|>i!li!>l!>!l))]ruxxzxzxzjfLfj<>>iI>+l{I|iUttLLLLCtffjzuchdbbbbhhhkk

>>i>[{ntYXXUz)?rI[!\_{ll}]r{?c}}C>i>iiii<i><I?lI1[vnzxjttLJUCfzi>il?><l|lIiXjfLLLttftjxzuchbbkkkkkhhh

<i<>(}xtYYXYj(|{l?>+)I1[lxr]vur!!Iil!ii!!!!!Il>>)]uxjjtUJJUJLili>I><i|?(<lXjCLtttfttjjxnnddkkkbkaaaa

<>>!?[nCYYXYj(l)<[lI!i>xl)rtuCxl>>>l>!>ii<!il!li>Il)cnjtJJtjz+!i!!!>l|?{i!YjnjjfffftjzxcJdbkkkkhaZu>

>><<l(uLYUXUx}L(+{!l!<+vliuclLlUI+<l<I<i+><l!iI({cxfzjjCCJUXOr>>i!!i!())llJc[rcvnxfjzxnrQdhhhhhOx>+>

lI>\_!IrfUUYJz](t+(IlI!lun<]L}r{?n>i|>l<<liill!l)cnunxzjfjjtXQahUl!i>))(??ljunvrr]]rcunurokhhha0C!<!(

xr|il>)fUUYaz?1l\_<(-i|1ixlz){nrr|v>?<(<<!>>!l!>)uvuuzxzzzjCZQooahZ\_\_|{|II>Lzxnnvr}}1{}](Qhahhat<>l||

zzv)?>)jJUYUjcQ+++(~llI-)r{|u{nvC>?l<{>>>l>i!!<)rcucxjjzjtJO00Qoahh<i{??l!tjfzzxnuc}(crlQhkkox<l|(1|

vjfn1>)jYYYJzo)>>>!?I||u+!?l(uxf-tt><)>!!l>il{>(cxrzxjzzjCJYOO0oakkk>(Il!?tffzjzxnuv]uv}abkhX>I)({}1

[nffu>)fYYXUj}?+>IIi>?><<clIr|zuzvi><{l>>liil]>?nrnxzjjztCCUYZOQohhbd><l?rjfjfjjzxxuvnutkkbanl{11r})

+}fJz!(fYXXYjr!+<[li<l?\_I{})|{{jX<nv\_(li>li>?c!|rnnxzzjjttLUYZO0oahkd0<ilLzfffjjzzznvxzZdbkQ|(){c[{[

-ijUtlljYXXYfh<<l>i<>I(<>Il(rl|vJ?n0+)|>>|>i{ri?rnxxxzjftLCJYXZOoahkdd+>-tzjjjjzxzzvvjXabbhJ|{}rr){[

-izYLiIjXXZYfn+\_!+<>]iI+>-!l]1(jU>))\_(1l>l<i}cl}unxzzxzjfftCUYZO0ohkbdb+~fztfjzznxuvxoakbbQ])1]c11}{

-\_uYC!>fXXZUfr>l>++-[i\_>i+>I}lIzLjYX-li>>i>|ru|)vxxxxzzjjjLCCYYO0Qhhkbp~~zCfjjjzxxvvOdkkbkJ{){r[1}]{

--vYC?>fXXXYt[I<>i!|{!>|>+I}>vvzlxz\_ii+i<<I}nul)nnzjzzzzzffLCUXZ0Qahbkd]-zjfjzjjxnuvQbabbox[{}c[1[}{

~-]UJ)!jXYXUjn+>+i<>1lIi>+\_r\_ljx|-+[run!!>lrun![nxxzjxnzjfftLUUXOQoahbdh+jjfjzxzxuuvakadkUc[}[[1{[{(

<\_[CJ{ljYXZXj]<+++?<I?\_+<<+><|v]c}+-l>l(>>)vuu>[nzzjzzxzzjjLCCJYOQokhkkbljtfjzjjxnnnXaodhjr]{[({[{{1

<\_|CCrlzXXXYzx(++{>+I>!i1i(!}|]r!]|-!I><<I}vu](uxjzzxxxzxjjtLCJYZQQhhkkb[jnxjjjjxxzzxCadon]{{1|r{(}{

\_-|LCrlxUXXYff!\_>!+>Ii?!>+><v{>{<ln<+!<\_>?rvul)nnzjjzjxzjjfttCJUX0Qahkbk0[)}cnjzzzjtzfhbXr{1{|}[11{)

\_-iYXn!nUYXXtr{+!<>iI!|>\_+>c[r?l<|li><+<l1crr!cnxjjzfjxxzzjftLCUY00ahkkbd|}l|1{[rnLLxJdhf{|)?)[})}{?

<+>JOj!nJYYXLc|<\_+!+il?l+!<!]xt}{+!>>\_<i1]cc\_1xxzzzjjjjxzzjjttLJUX0ohhkbd|111(li>i}QJQbZ1!(|1]1(1[{l

l(|tOLInUXXXjx>i><<<II?l<>i1>?z{l>>++\_+|[vciluznjzjjffjzzzzjjLLLUYZQohkkbt{]{}|I++rhthknl!|l]1((}}?l

))[LZJInJXXZxvi<<>>>><(><+!!<!l}v>+++<!)rc>icnnxzjzzjzzjzzjzjttCJUO0ahhkkk)]]}{)l>{o00jiiIl1{I|1r}|l

I}rtZC|nUXZXfc+<>I>i<I1l|+|li>|ri><+-+|{)-(]unnxzjzjjfjjjzzzzfLLCUXOQohkkb|}}{})|1ch0]l!?l)}|?)]}1??

<|{xXU1nJXZXL1>>ll>1>||?}>l>1I}C><l<>>>>(]cuunnxnzxjjjjfjjjjzjfLCJXZ0oahkb{){][{}][J}(?|l1r(?l]c}|II

>>)uYUcuCZXXC?>l<l![<!!i?-1|!vlnr<<+i?)}ccvuxunxxnjzjzjjzfjjfjfLtJUO0Qohkb0){[]]r]c}1{{||[()I1c]}?i!

i>lvoonuJXOZ}l<i<!l>+!>>lu<u-l>|l><il{rcrvuunnnxxzzzzjzfffffffffCJYXZOoahhh({][cvcr][r{(})??)rnc|!!i

>i!nooYvCXXXcii!<l(Il]!l\_x+u<lI|Iv-l)}]ccvuunnxzzzjxzjjjjfttffttCJCXZOQahhh?([}cvvrcuc1{1((?rn](!>!?

CLCttLLCJYYfc{{[]]r][rrvunnxnxnxznxnxxnjxnnxnnnzznznnnuuxnnvvc[cjtLLLLtLtttLLCt@@@@[}cnuucvuuucvurrJ

CLLtLLttJYYfc{{][[]]]rcvunxnnnnxznxxxnnnnxnnunnnnnnnnnuvxnnuur[rxtCttttLtLLtLLt@@@@]]cvvvcvcuvvvvcct

LLCLLttCUUJfu1{}}[}]]rcvvunnunnnunxxnxnxxnnunnnnxunnuunnnxnnvv][ujLLLLLLLtLttttf@@@@}rvcvvcvvvunun[.

LCLtLtLUUUCjc11}][}[[rrvuunnnnnnnnxnnxnnunnnnnnnxnnnnnunnuunncr[rztCCCCCCLtLfftfU@@@r]vrcvvcvuunx}..

LLCCLtCJJCCfn}{[]][]}rvcuunnnnxnnnxnxnunnnxznnuxxxnuunnnununvxr[}nfLJCJCCLCCttttf@@@@]ccvuvvxunz{...

tLLLCCJUCLCfc1}{[}}}]]cvvuvnnnnununnnnnnuvnuuuuunnnnnvuunuvnunr]]vjCCJCCCLtttttfjC@@@n]cvvuvunz1l...

LCLCCJUJCCJjc11{[}}][]rvvunxununxnnnxxnxucuunuunnxnxvunnuunnnrc][uzLCCLCCLLCtCttfj@@@@}ccvcunn{.....

CLCCJUJULCCfc)1}[[[}[rcvvvnunucnuununnxuuvvvnvvvnnnnnnuunuunucc]rvztLCLCCLCLLtLttjj@@@J}rcvux{......

JJJUYJJCCCJjc|{[}][}}rrcuuvuuvuvnunuxnnnunurcvvvnnnnuuuununuvucrrvxttCCCLLLLCttttjz@@@@]r]cz1.......

JCCUCttLJCJtc(1}[r]}[rccucununuuunnznuzuujxzYYUncvvvnnnnunuuucc][cxfftLLtLttLLfffjjz@@@@}rv(........

CCJULjzCCCJfv(1}]}[]]rcvvnnnvnnxnunnnuftxf@J@@@@@@xrvvnuuuuuccrr[rxfjftLLttLtffzzjjz@@@@jr).........

CC@CjuzLJUJfv|({}}}[[cccvnuuuxxncnuzutjjtxLtY@@@@@@@ccvxvvuccrr[}vjzjffttffzfjfjjjzzz@@@@[..........

CUJLv{xLJJJtv)|1[}{[[]vcvcuvuuxuffnvczujnffL@U@J@@@@@@crvcvcccr]]czfjjftfLzjjtjjzjjjzt@@@...........

JYLj{}jJUCJfc||)1{}[[[]rcuvvvucUruccuuuxzzCL@C@@@@@@@@@]rvccvrr[}rzftffjftjzjfzjjjjjjj@@t...........

@Ufr?}zJUJCjr?){[[{{}]r[cvcvvvnrrcvuuxxfczzfCU@@@@@@@@@@j}}rrr}r{rzLttjznjtjjjzfjjfffLLn..........l.

YCz(|[xJCJCfr?({}{}}[[[vrccvvuzv[rccvnvzjuftUY@@@@@@@@@@@@r}[[}]}rjLLfjucnffftzjjfjffLx..........l..

Ltr|(]fCJJCfr?({{{{}[]rcvuvcvx][rurvcxcxxzzff@@@@@@@@@@@@@@|{[}{1rztLLjv1]zfjjjjjjfttf...........|.j

tv(1)]zJUCJfc|(1{}[{}]rrrvcvur]rcuv]rnnxzujLCY@@@L@@@@@@@@@@|){11rzLfLjnl.cffjjfzjzjL..........l)?zj

n1)(1}zCJJJjr?1{{[{{[[]ccvcu]}vrcccrunzjxtfjtY@JJ@@@@@@@@@@@j|)({rzLtLfx|.{ntjzjjfjf)..........l?nfz

})11(}xCJJCjr|({[}}}[]rvcvcur[rcvrcvnxzzzfzjf@n@@@@@@@@@@@@@@tl|)rzLLtfn?..vjffjjfLt..........IInfzL

))11(}zCJUCfr|(1}}{[[]rccvn][cr]rvrnvxxjnuuxxz@@@@@@@@@@@@@@@@@I|]zLLftn(..1ntfzjftl...........vzfLJ

){){)[ztCJCjr|({1[}{[]ccrrj[}rrrrvnjjfnfjnzv@@@@@@Y@@@@@@@@@@@@)I}xLLtfn(...]nfzztn...........[tzfCJ

){{{)[jCJJCjr||){}]{][]crjc[][[]rrvxnxzfxzv@@@@@Y@@@@@@@@@@@@@@@.1xfLtCn(....n@@@f...........|tzjLCt

)(1{(}zLJJCfrl|1{{1}][]]}@]}rrrrvnnzjvxr]j@@@Y@@@@@@@@@@@@@@@@@@r(xtLLtn(...@@@@@@....|...I..jfzCCCL

1()1){xLUJCfrl?){{{}}[}r}@[{rr]]rnrrzxn]J@@U@Y@@@@@@@@@@@@@@@@@@@?nCCLtnl..@@@@@@@..........ntzCCCCL

11[1[}nLUJJj]?l{{}}}[[rr[Y}}r]rcuuuxvu[C@C@L@Y@@@@@@@@@@@@@@@@@@@@utLCfc.}@J@@@@@@.........?LjLCCCCC

{{}}{[xLJUUfr|({}][}}]crntr}{rrr]vuvx}JCj@@J@@Y@@Y@@@@@@@@C@@@@@@@@fttz{@@@@@@@@@@.........jffCCLLLL

}}{{[[jtJUUtc|()}}{[}[r[@jr{r}cucurvctfjjLY@JU@@C@@@@@@@@U@@@@@@@@@ttj@@@@@@@@@@@@........}LjCLLLCLL

}1{}}rzJUUYLc|)1}[}{[[}{@tv]]]rvxruvjjjrLCLYC@@t@@@@@@@C@@@@@@@@@@@@C@@@@@@@@@@@@@.......lfftCLLLLLL

}}1{}]xJU@YLr||{{]{{}[}1@Lcr}]]vux]tzfcftJLU@CJ@@U@U@@@@@@@@@Y@@@@@@@@@@@@@@@@@@@@.......ctfCCCCtLLt

{}[{{}jCYYYtc?|{{}[{}}[)@jzj[}]rr]zjj[fffjU@t@@tY@YUU@@@@@@@@@J@UY@@@@@@@@@@@C@@@I......lLjtCCCCLLCC

{{{{1[zCUYYLr|({}}}{[}})@jxzv1}r{jntrftztfjxUYJUU@JYJLYY@@YY@@CJ@@@@@@@@@@@@YL@J@......lxffCCCCCCLCL

{{{11]zCYYYLc?){{{{}}{}|@Cfzc}r[zxfujjffzLztLJ@LJY@tJJYUJU@YUL@U@@@@@@@@@@@@C@t@@......{LjLCCLLLLCLL

{{{{{rjCYYYLu?){{{{}{}1)@@Utu[1zjzcffxxxjxJLfJLnfjCCJLUCJtLtY@@@@@@@@@@@@@@jUYr@....l..fftCCtLtLLLCL

{{}{}]zCUYYLv(|{}{{{{{{|@@Cnfcuvx[jjzcxjnCcfn]}zC]]tLvjt)Lj@C@@@@@@@@@@@@@@t|{@@......}tjCCLLCLLLtLL

}}}}[cjC@@@Cv||{{}1{{}1(@@JuCcvu]xnzvnnnxttv]|.jLx}((....lYY@@@@@@@@@@@@@J1))f@.......ffLCCCLLCLLLtt

}}{1[rzJYYYCu((1{}[{}{}|@@@uxc]]vnxvxxuzjuuv[cI|rl(.?...tz@@@@@@@@@@@@@[)(){C@.......{LjCJCCLCLCtLLt

]]{{}rfCYYYCu(|{{}{{{{}(@@@nxj{cnxnvxvjzvx}.|..[r.)|...Yr@@@@@@@@@@@@nn{)}fY@......I.xfCJCCCCLCLLtLt

]]}{}cjCUYULv||1}1}}1}})n@@tjjrjn}nnufxtr|?....c.I?..[@c@@@@@@@@@@@@{]zLUUU@........)fzJJJJCCLCLtLLt

[[[[}]jJYYYCn?|}}{{1}[]}(@@@C{vj[ucxjzv|.l....|...In.@v@@@@@@U@@@@Irv]nLY@@.........njtJJUJCCCLLLLLt

[rr{}]zCU@YLu||1{[{{{}[[{@@UYunrnnnuc[](...r..{.....ux@@@@@@J@@@@@)|{j}tY@.........lznJUJCCJCCCCCLLL

]][{{}zJUU@Cn||){{}1{[]][|@@]vuvnvccr)|(}..{...({{l[c@@@@@@@@@@@@@z(].ztC..........|nxUUCJJCCCCCLLLL

][[{{{zC@U@Ln?|{{}}}}[]rr)@@xucvrjn1)(..?)..{.....)U@@@YJ@@@U@@@@@Y}.}xfv..........cuLJJUCJJCCCLLCLL

[[[{{1nLUYYJn|?11}}{{rrrr1@@}crrunu.....)|..r1...r@z@@@JC@JY@@@@@@@{..?C)....I....|jzttJUJCCJJCLLLtL

{[[{{1xCUYYCz(|1{[{}}}jcr}@@rr{x].l1)....??.....jJCxC@YUJjJ@@@@@@@@c..|C|.........vxLLtttCCCCJCCCLLt

[[}{1{nCUYYCz|({[}{}}rvccc]@cruxu(..(.....l|([.tjU@jU@JJfCU@@@@@@@@zl.IY{.........znJJttfftfLCCLLLLf

}[}}11nCYYYJx?(1{}[[}[rccvc@rxnxI.[...(....|.xCuC@@t@YLtCY@@@@@@@@@L)..u{..I.....{jjJCCJLtLfffjftLtL

}[}{[1xCUY@Cu(|1}{][[]rvvvvjcvv]..1..].....].c}CUU@@YtUJJ@@@@@@@@@@@{..|jI?......xntJCCCUUCtffjjjjtf

}}{}{1xCY@YJn(|1}}{}[]rvc@l.xur.).]..........{@@CJ@@l}uzU@@@@@@@@@@CI...C...?...?zuCCCCLCCCLLtffjzzz

[]{[{1nCYY@Cx|(1{]{[}[rcuf..Lr1..lu.........j@Y@t@UjLLu|.uUY@@@@@Y])(...JI|l....[xzCCLCLCCCCtLLtfjzx

{{}{1)nL@@YCz|11{[{[}{rxCfYj(.In|{)...]....J@U@@@[}?|(.]nczJY@@@jv.lI?.?@).I....xuLLtLLtLLttLLtLfffz

{{{1((nLY@@Cz|?(1[}{1v@jfL(|.c]{I|1)...r..I}U@@@)l...I?.1xntU@@]..l....I@)......jxCLtLCLtCttCtttjfzz

{}{1|?nC@@@Ln|({{{}{(C@ftf?.)..|1...j....?j@@@@u|.{1.I@}]cnz@@L..[U.....Y(l....]zfCLttLttttttjfjjzxn

}}{)|?nL@@@Cu)(][[}].l@@v..)Il?)(...l.....uY@@Ccxr}rl@@tcrvj@@}j)rU.....UI1....njCLtLttttttffjjxxnzL

[}]1)luC@@@Jz(1}]]..CLt..{[(..l{{v.......z@@@jczfjurvfLYfuuz@@YxxL}.....L1l...vzxLLtftLfLttfzjxxxJ@@

}[}1(lvLY@@Ux()}][xjJ?}..rz].lc[zf......rr@@C{njffffzjtttnnnY@Yfnu}{I...tuI...{xfCtLfttfttfjzznC@@@@

}))|?.uL@@@Ux))}r]r]?|..I[.|...jIr......[@@@)rnfCUUJJUJUzjnuY@@CLnv]..I.Lz|...uxCLLtttffjffzzxY@@@@@

1}(|l.vCY@@Jz(1{[jLt|(..|(u...}]x.|....fr@@.}vujtJ@Y@J@CfjnuC@@Yfxncl...CL....jnCLLLttttfjzzxU@@@@@@

|(||I.vL@@@Ux1)}]u}{)I.rc?.......1]....c@@..rvxftC@@YYUCffznL@@CCjxn....jt...|zfCtLfftftjjznC@@@@@@@

l||?I.ctUY@Yx?)1[rncr??.?u.......()r..jv@@.I[vzzttJ@@UUCjjnnt@@Jtjuc....rn...vx@Lttftjfjfjnn@@@@@@@@

|?|lI.vLYY@Jx?|{xc.[[..[Ll.....|.[ru..c@@.I.[unxztCYUUJLxxnuz@@Ufznr..l.1u|..zxJCLLttffjzznJ@@@@@@@@

||Il..vLU@@Cx||]cx.r(.)}}{....1{L(f..ur@..(?}vnxzttLCLCjnvvcz@@LLzn1..l.|L]..zjLLLtLtfjjzxx@@@@@@@@@

(|(I..vLU@@Uz|)j[r|I|.{.{zx....C]}..zncY..)l{unnzjtLCCLz]xzun@@jfxv...?..Lz.rfCtLftLtfffjuJ@@@@@@@@@

)|?l..vtUY@Uz}|{]{I{).[.r@[.....x...U@U...1|}vnnzjttLLCfcx.rvC@tfnu......Yj.zjCtLfttjfjjzn@@@@@@@@@@

|?|?llnLY@@Yx((}r|.I.n||nr(..L..(..}fU....}|[cunxtfttLLfxuxurLYtzn1...l..Jf.fjCLfttjttjjxj@@@@@@@@@@

??|?l1zCJY@Uj)({[n.I|.|(}(r1lj.)|cY}uC....{(]vuxxzjjLCLLtfz@Y@Ytzu...I|..fjlffLLttfffjfjxL@@@@@@@@@@

lll?.1zCUY@Ux)|{j[.n..?l))jv)?..@UY)@...|.?[rvunjjzztttttfL@@@Jjx}...(l..czrftLtttfjjfzjnU@@@@@@@@@@

I.lIl)zCU@@@j(ln[(?{...(I1.cj.[]j@(U.?..l..[{uunjzzxjjjjzLJ@@@Jzx...I||..]rxfLttfjffjjjxnY@@@@@@@@@@

...l.(zJY@@Yj(|1}..[I..r}lcrc)r@@1c..I.....{1rnunxfjrvnnnuvxxr{j)...()|...vtjLLttfftjfjzv@@@@@@@@@@@

....I)jCY@@Uz|](j......n{r(r)xx@C(t......|.(|]vunzjjnv]runujLnzj.....?)...jLfLLttffffjjzn@@@@@@@@@@@

....l{xCYY@Uxu?r[Ij..l.L.r{.[ju@]@......I?.)l[rcvnxjfncnnfJJCjf......?)I..CLtCLLLtffjjjnu@@@@@@@@@@@

....l{xC@@@Yz|?nr.z.(.(rc1)j{UrjL...?...l?.I.)[rcnxzjxnncnzvfzx......l(...CCtLLLLttfjjznv@@@@@@@@@@@

....]1ntY@@Yj||{|.I.).]f]cvv)z[J|............))]ruxxzxzxzjfLfj....I..l{I|.UttLLLLCtffjzuc@@@@@@@@@@@

....[{ntY@@Uz)?rI[..{..}]r{?c}}C...........I?lI1[vnzxjttLJUCfz....?..l|lI.@jfLLLttftjxzuc@@@@@@@@@@@

....(}xtYY@Yj(|{.?..)I1[.xr]vur..I..........I...)]uxjjtUJJUJL.l..I...|?(..@jCLtttfttjjxnn@@@@@@@@@@@

....?[nCYY@Yj(l).[.I...x.)rtuCx....l..........l..I.)cnjtJJtjz........|?{..YjnjjfffftjzxcJ@@@@@@@@@u.

....l(uLYU@Ux}L(.{.l...vl.uclLlUI..l.I........I({cxfzjjCCJU@@r.......()).lJc[rcvnxfjzxnr@@@@@@@@x...

.I...IrfUUYJz](t.(I.I..un.]L}r{?n..|...........)cnunxzjfjjt@@@@U....))(??.junvrr]]rcunur@@@@@@@C...(

xr|...)fUUY@z?1...(..|1.xlz){nrr|v.?.(.........)uvuuzxzzzjC@@@@@@@..|{|II.Lzxnnvr}}1{}](@@@@@@t..l||

zzv)?.)jJUYUjc@...(.l.I.)r{|u{nvC.?l.{...l.....)rcucxjjzjtJ@@@@@@@@..{??l.tjfzzxnuc}(crl@@@@@x.l|(1|

vjfn1.)jYYYJz@)....?I||u..?.(uxf.tt..)...l...{.(cxrzxjzzjCJY@@@@@@@@.(Il.?tffzjzxnuv]uv}@@@@@.I)({}1

[nffu.)fYY@Uj}?..II..?...c.Ir|zuzv...{.......].?nrnxzjjztCCUY@@@@@@@@..l?rjfjfjjzxxuvnut@@@@n.{11r})

.}fJz.(fY@@Yjr...[...l?.I{})|{{j@.nv.(......?c.|rnnxzzjjttLUY@@@@@@@@@...Lzfffjjzzznvxz@@@@@|(){c[{[

..jUt..jY@@Yf@.......I(..I.(r.|vJ?n@.)|..|..{r.?rnxxxzjftLCJY@@@@@@@@@...tzjjjjzxzzvvj@@@@@J|{}rr){[

..zYL.Ij@@@Yfn......].I....l]1(jU.)).(1..l..}cl}unxzzxzjfftCUY@@@@@@@@@..fztfjzznxuvx@@@@@@])1]c11}{

..uYC..f@@@Ufr......[......I}.IzLjY@.......|ru|)vxxxxzzjjjLCCYY@@@@@@@@..zCfjjjzxxvv@@@@@@J{){r[1}]{

..vYC?.f@@@Yt[I....|{..|..I}.vvz.xz.......I}nu.)nnzjzzzzzffLCU@@@@@@@@@].zjfjzjjxnuv@@@@@@x[{}c[1[}{

..]UJ).j@Y@Ujn......1.I....r.ljx|..[run...lrun.[nxxzjxnzjfftLUU@@@@@@@@@.jjfjzxzxuuv@@@@@Uc[}[[1{[{(

..[CJ{ljY@@@j]....?.I?.......|v]c}.....(..)vuu.[nzzjzzxzzjjLCCJY@@@@@@@@.jtfjzjjxnnn@@@@@jr]{[({[{{1

..|CCrlz@@@Yzx(..{..I...1.(.}|]r.]|..I...I}vu](uxjzzxxxzxjjtLCJY@@@@@@@@[jnxjjjjxxzzxC@@@n]{{1|r{(}{

..|LCr.xU@@Yff......I.?.....v{.{..n......?rvu.)nnzjjzjxzjjfttCJU@@@@@@@@@[)}cnjzzzjtzf@@@r{1{|}[11{)

...Y@n.nUY@@tr{.....I.|....c[r?l.|......l1crr.cnxjjzfjxxzzjftLCUY@@@@@@@@|}l|1{[rnLLxJ@@f{|)?)[})}{?

...J@j.nJYY@Lc|.......?.....]xt}{.......1]cc.1xxzzzjjjjxzzjjttLJU@@@@@@@@|111(....}@J@@@1.(|1]1(1[{.

l(|t@LInU@@@jx......II?l...1.?z{.......|[vc..uznjzjjffjzzzzjjLLLUY@@@@@@@t{]{}|I..r@t@@n..|l]1((}}?.

))[L@JInJ@@@xv........(........}v......)rc..cnnxzjzzjzzjzzjzjttCJU@@@@@@@@)]]}{)..{@@@j..Il1{I|1r}|.

I}rt@C|nU@@@fc...I...I1.|.|...|r......|{).(]unnxzjzjjfjjjzzzzfLLCU@@@@@@@@|}}{})|1c@@]l.?l)}|?)]}1??

.|{x@U1nJ@@@L1.....1.||?}.l.1I}C........(]cuunnxnzxjjjjfjjjjzjfLCJ@@@@@@@@{){][{}][J}(?|l1r(?l]c}|II

..)uYUcuC@@@C?...l.[....?.1|.v.nr....?)}ccvuxunxxnjzjzjjzfjjfjfLtJU@@@@@@@@){[]]r]c}1{{||[()I1c]}?..

...v@@nuJ@@@}...........lu.u...|l....{rcrvuunnnxxzzzzjzfffffffffCJY@@@@@@@@({][cvcr][r{(})??)rnc|...

...n@@YvC@@@c....l(Il]...x.u..I|Iv..)}]ccvuunnxzzzjxzjjjjfttffttCJC@@@@@@@@?([}cvvrcuc1{1((?rn](...?

# 3 Language Reference Manual

## 3.1 Program Definition

The structure of an EZ-ASCII program source file consists of expression statements and functions.  A main()function may be optionally specified to denote the main entry point of the program.

*< global statements >  
< function declarations >  
fun main() {  
 <main program code>  
}*

## 3.2 Lexical Conventions

### 3.2.1 Tokens

There are six types of tokens:  identifiers, keywords, constants, string literals, operators, and other separators.  Blanks, horizontal, and vertical tabs, newlines, formfeeds, and comments as described below (collectively, “white space”) are ignored except as they separate tokens.  Some white space is required to separate otherwise adjacent identifiers, keywords, and constants.

### 3.2.2 Comments

When a // symbol is encountered, the // symbol and the rest of the line is considered a comment and is ignored by the compiler.

// This is a comment line  
img[x1, y1] <- 1; // This is another comment

### 3.2.3 Identifiers

An identifier is a sequence of letters and digits.  The first character must be a letter; the underscore \_ counts as a letter.  Upper and lower case letters are different.

### 3.2.4 Keywords

The following identifiers are reserved for use as keywords, and may not be used otherwise:

Table 3.1 Keywords

|  |  |  |
| --- | --- | --- |
| blank | load | SHIFT\_LEFT |
| else | main | SHIFT\_RIGHT |
| false | map | SHIFT\_UP |
| Fun | out | true |
| for | return |  |
| if | shift |  |
| include | SHIFT\_DOWN |  |

### 3.2.5 Constants

There are four types of constants in EZ-ASCII and they are listed as follows:

* Boolean Constants: A boolean constant is either true or false (case-sensitive).
* Integer Constants: An integer constant consists of a sequence of digits.

i <- 213

There are 4 labeled integer constants to define shifting directions

SHIFT\_UP, SHIFT\_LEFT, SHIFT\_DOWN, SHIFT\_RIGHT

Their values are 0, 1, 2, 3 respectively.

* String Constants**:** A string constant consists of a sequence of characters enclosed in double quotes “”. The following characters may be used with escape sequences:

Table 3.2 Characters For Escape Sequence

|  |  |
| --- | --- |
| **Character** | **Escape Sequence** |
| newline | \n |
| horizontal tab | \t |
| single quote | \’ |
| double quote | \” |
| backslash | \\ |

Mapping Constants: An intensity mapping consists of a table mapping

intensities to characters. A custom mapping can be defined using the

keyword **map**:

map <- {I0:”C0”, I1:”C1”,...,IN:”CN”}

where each I is an intensity, and the corresponding C is the character mapped to that intensity. Any reference to the intensity mapping will refer to the most recent assignment of *MAP* or the default if none has been assigned.

The default mapping is a map of all printable ASCII characters ordered in ascending order based on how many pixels each character takes up in each character space.

### 3.2.6 Granularity and Intensity

A mapping must have at least two values and the granularity must be at least 2. The minimum intensity will be the least intense item in the map and the maximum will be the most intense. For intensities between 1 and *n - 1* where *n* is the size of the mapping the distance between each intensity is as close to even as possible. The formula for this is defined as follows:

diff = (n - 2) / ((g - 2) + 1)

where *n* is again the size of the map, and *g* is the granularity.

## 3.3 Meaning of Identifiers

Identifiers may refer to objects (locations in storage) or functions. A function and an object may not be referred to using the same identifier – the following is a syntax error:

foo <- 3

fun foo() {

*<function-body>*

}

### 3.3.1 Types

There are four types:

* Boolean: A boolean stores one bit of information and may have the value true or false.
* Integer: Integers can store 32-bits of data and are signed.
* String: Strings are sequences of characters, and are bounded only by available memory.
* Canvas: A canvas is the primary storage type in EZ-ASCII. All of the image modification happens on this type. Internally, it is represented as a two-dimensional array of integers referred to as intensities. This canvas can be loaded from an existing image file or it can be created manually. Additionally, a canvas has the following readable attributes: width and height in number of characters, and granularity.

There are two methods of creating a canvas in EZ-ASCII. The first is to load an existing image using the load built-in function, and the second is to use the blank built-in function (see built-in functions). In the case of loading an external image file, a custom intensity mapping may be specified to specify the granularity of the image, or the default will be used. Various operations may be performed on canvases, including selection, movement, and masking.

## 3.4 Expressions

### 3.4.1 Unary Minus Operator

The operand of the unary *-* operator must have arithmetic type, and the result is the negative of its operand.

i <- -(1 + 4) // i assigned -5

### 3.4.2 Multiplicative Operators

The multiplicative operators \*, /, and % group left-to-right and require their operands to be of the same primitive types.

If the operands are of integer type, then the result of the \* operator is the product of the operands. The result of the / operator is the quotient of the operands and the result of the % is the remainder after integer division on the operands. The / operator results in an integer (fractions truncated).

If the operands are of any other type, a syntax error will occur.

i <- 2 \* 3 // i assigned 6

i <- 3 / 2 // i assigned 1

i <- 2 / 3 // i assigned 0

i <- 3 % 6 // i assigned 0

i <- 5 % 3 // i assigned 2

### 3.4.3 Additive Operators

The additive operators + and – group left-to-right and require their operands to be of the same primitive types. The grammar is as follows:

If the operands are of integer type, then the result of the + operator is the sum of the operands, and the - operator is the difference of the operands.

If the operands are of string type, then the result of the + operator is the concatenation of the operands, and the – operator will result in a syntax error.

If the operands are of type canvas, then the result of the + operator is a new canvas where each intensity is the result of adding the two corresponding intensities from the operand canvases, truncated to the maximum mapped intensity. The result of the – operator is a new canvas where each intensity is the result of the difference between the two corresponding intensities from the operand canvases, truncated to the minimum intensity of 0.

If the operands are of boolean type, a syntax error will occur.

i <- 1 + 2 \* 3 + 4 // i assigned 11

j <- 5 – 3 // j assigned 2

k <- “hello “ + “world!” // k assigned “hello world!”

k <- “hello “ – “world!” // syntax error

img3 <- img1[3:8, 2:4] + img2[,] // img3 assigned additive layering

img4 <- img1[,] – img3 // img4 assigned difference layering

m <- k + img4 // syntax error

n <- true + img4 // syntax error

### 3.4.4 Relational Operators

The relational operators group left to right, i.e. a < b < c is parsed as (a < b) < c. The operators < (less), > (greater), <= (less than or equal), and >= (greater than or equal) all yield a boolean true or false. The two variables on either side of a relational operator must be of the same type.

### 3.4.5 Logical Negation Operator

The operand of the ~ operator must have boolean type, and the result is true if the value of its operand compares equal to false, and false otherwise.

b <- ~(3 > 2) // b assigned false

### 3.4.6 Equality Operators

The = (equal to) and ~= (not equal to) operators are analogous to the relational operators except for their lower precedence. For example, a<b = c<d is parsed as (a<b) = (c<d) and evaluates to true if a<b and c<d have the same truth-value.

### 3.4.7 Logical AND Operator

The && operator groups left-to-right, returning true if both its operands compare unequal to false, and false otherwise. Both operands must be of boolean type, except in the case of boolean expressions used in a selection operator, in which case both operands must be of a boolean expression type that satisfies the selection operator (see selection operator).

### 3.4.8 Logical OR Operator

The || operator groups left-to-right, returning true if either of its operands compares unequal to false, and false otherwise. Both operands must be of boolean type, except in the case of boolean expressions used in a selection operator, in which case both operands must be of a boolean expression type that satisfies the selection operator (see selection operator).

### 3.4.9 Comma Operator

A pair of expressions separated by a comma “,” is evaluated left to right.

### 3.4.10 Selection Operator

The selection operator [] denotes a selection on the canvas that it is applied to. When the selection operator is used on a canvas, the return value is a canvas of equal size, which contains only the points of interest (rest are blank). There are multiple types of selections possible depending on different integer parameters for the selection operator, as follows:

 Selection of a single point

*identifier[x, y]* – x and y are integer types which denote the x and y coordinates of a single point.

 Selection of rectangles/slices

*identifier[x1:x2, y1:y2]* – x1:x2 denotes a range of rows (inclusive), and y1:y2 denotes a range of columns (inclusive).

*identifier[x, y1:y2]* – A horizontal slice in row x from columns y1 to y2 (inclusive).

*identifier[x1:x2, y]* – A vertical slice in column y from rows x1 to x2 (inclusive).

*identifier[,]* – Returns a new copy of the canvas (all rows and columns).

 Selection by boolean expression

*identifier[boolean expression]* – selects elements with intensity that satisfy the boolean expression. Boolean expressions for the selection operator must be of the format *[condition][intensity]*, where *[condition]* may be either a relational or equality operator (<, >, <=, >=, ~=, =), and *[intensity]* is an integer value. Boolean expressions may be chained by a logical AND operator (&&) or logical OR operator (||).

### 3.4.11 Mask Operator

The & operator groups left-to-right, operating on canvas types. It returns a new canvas where at any given position, the intensity is 0 if the corresponding intensity in the second operand is 0, and the intensity is the corresponding intensity in the first operand if the corresponding intensity in the second operand is greater than 0. In other words, it returns the first canvas operand, but where the corresponding areas in the second canvas are 0, the corresponding areas in the first canvas are “masked” out. Any operand type other than a canvas type is a syntax error.

img3 <- img1 & img2 // img3 is img1 with img2 applied as a mask

i <- 2 & 3 // syntax error

### 3.4.12 Arrow Operator

There are two arrow operators <- (left) and -> (right), which are used for assignment and output, respectively.

 Assignment

The <- left arrow operator assigns the value of the expression to its right to the variable to its left. If the variable is undefined, it is created. If the variable is already in memory, its contents are overwritten with the new value.

*identifier* <- *expression*

Examples:

canvas <- load(“pic.jpg”, 10); // the variable canvas holds image data

canvas <- 2; // the variable canvas holds an integer

for i <- 2 | i < 10 | i <- i + 1 {

...

}

Output

The -> right arrow operator outputs the value of the variable to its left to either a file specified by a filepath string to its right, or to standard output, specified by the keyword out. The left-hand-side variable must have been assigned previously, otherwise a compiler error will result.

d <- “output string”;

d -> out; // outputs “output string” to standard out

If the left operand is a canvas, an intensity map may be optionally supplied to dynamically change the intensity mapping.

canvas -> out, render; // outputs image canvas to standard out

canvas(map) -> “test2.txt”, render; // outputs image canvas to file

// with new mapping

render must be a boolean value that specifies whether or not the intensities should be converted to their corresponding characters before being printed. If render is false and it is printed to a file, the file is post pended with the extension .i. If render is true, then the file will map will be applied and the actual image will be printed.

### 3.4.13 Canvas Attribute Accessor (read-only)

The $ operator may be appended to a canvas identifier along with one of [w, h, g] for width, height, and granularity, respectively, to read the attribute of interest from an existing canvas object as follows:

canvas <- load(“test.jpg”, map)

canvas$w -> [width-integer]

canvas$h -> [height-integer]

canvas$g -> [granularity-integer]

### 3.4.14 Function Calls

A function call moves program execution to the target function. The syntax of a function call is:

*function-name* ( *identifier-listopt* )

where *identifier-list* is defined as:

*identifier*

*identifier-list , identifier*

A function must be declared before the function call.

### 3.4.15 Include

The include keyword allows you to add functionality from another EZ-ASCII code file to the one you are currently working on and has the following syntax:

include [filepath];

filepath must be the location of another EZ-ASCII file. At compilation time the code included in the desired file will be copied into the file being compiled. Note that identically named global variables or function names in both files will cause compilation errors.

## 3.5 Declarations

### 3.5.1 Function Declarations

A function is declared as:

*Fun function-name* ( *identifier-listopt* ) { *<function-body>* }

where *identifier-list* is defined as:

*identifier*

*identifier-list , identifier*

Functions act as blocks of code that can be called when desired. Functions can be optionally passed a list of input parameters which are passed by value, and the parameters will be copies of the inputs for the function body. Functions can also optionally return some value at the end of their execution. A function may also call itself recursively in its body.

fun foo(img) {

img[>3] <- 5;

img[4:8, 3:6] <- 6;

return img;

}

// recursive factorial

fun factorial(x) {

if(x = 1) return 1;

else return x \* factorial(x – 1);

}

### 3.5.2 Variable Declarations

Variable declarations are declared as:

Variable-name <- *expression*

Type declarations are not required - variable types are inferred from the declaration. A variable may be set to a different value with a different type even if previously declared, e.g. the following will not result in an error:

i <- 3; // i holds 3

i <- load(“test.jpg”, map); // i now holds a canvas

## 3.6 Statements

Except as described, statements in EZ-ASCII are executed in sequence. Statements are executed for their effect and do not have return values. They fall into several groups.

*Statement:*

*assignment-statement*

*output-statement*

*conditional-statement*

*for-statement*

*selection-statement*

*return-statement*

*include-statement*

### 3.6.1 Assignment/Output Statements

Most statements in EZ-ASCII are assignment/output statements. The former is any assignment operation, and the latter is any output operation.

img(map) -> "test2.txt";

img[x1, y1] <- 1;

img2 <- shift(img, SHIFT\_UP, 5);

### 3.6.2 Conditional Statement

Conditional statements allow for one of several flows of control. An if statement may be used with or without an else clause. The grammar is as follows:

if ( *expression* ) *statement*

if ( expression ) *statement* else *statement*

The expression in the if statement must be of boolean type, and if it evaluates to true, the first sub-statement is executed. In the second form, the second sub-statement is executed if the expression evaluates to false.

if(1 > 0) “true case” -> out; // “true case” is output to standard out

if(true) {

*...*

}

if(3 > 4) “three is greater than four” -> out;

else “the world is sane” -> out;

The else ambiguity is resolved by connecting an else with the last encountered else-less if at the same block nesting level.

if(2 ~= 2)

if(3 > 2)

else “this else binds to the second if” -> out;

### 3.6.3 For Statement

The for statement specifies looping.

for *expression­­opt* | *expressionopt* | *expressionopt* *statement*

In the for statement, the first expression is evaluated once, and thus specifies initialization for the loop. There is no restriction on its type. The second expression must be a boolean expression; it is evaluated before each iteration, and if it becomes false, the for is terminated. The third expression is evaluated after each iteration, and thus specifies a re-initialization for the loop. There is no restriction on its type. Any of the three expressions may be dropped. A missing second expression makes the implied test equivalent to testing a true constant.

for i <- 2 | i < 10 | i <- i + 1

{

img[i, i] <- 3;

}

### 3.6.4 Return Statement

return *expressionopt* ;

A function returns to its caller by the return statement. When return is followed by an expression, the value is returned to the caller of the function. A function without a return statement returns the integer 0 by default.

fun a(x) {

return x + 1;

}

// boo has no explicit return value

fun boo() {

*<body>*

}

## 3.7 Scope and Linkage

### 3.7.1 Lexical Scope

Variable Scope

Variables declared outside of functions have global scope and are accessible from anywhere in the program. Within a function, scoping rules proceed in the following manner. First, when execution enters a function, all of the function parameters are allocated as local variables for the duration of the function. Second, if a variable does not match a formal parameter, it is checked with the list of globally allocated variables, and may be modified/read. Finally, if a variable does not match any function parameter or global, it is allocated as a new local variable for the duration of the function call. This implies that new globals cannot be created from within functions, though they can be modified.

i <- 1;

fun foo(p) {

p -> out; // p is a local with value passed in as a parameter

i -> out; // i refers to the global i, outputs 1

a <- 4; // a is a new local

return a;

}

i <- foo(i); // global i is overridden with the return value of foo

i -> out; // outputs 4

Function Scope

Functions have global scope. A function may not be referred to unless it has been previously declared.

Fun foo() {

*<body>*

}

runfunc <- a();

runfunc <- b(); // error – b undefined

## 3.8 System Functions

### 3.8.1 Blank

blank ( [width], [height], [granularity] )

Blank takes three integer input parameters (width and height in number of characters, and a granularity level), and outputs an empty canvas with attributes set accordingly. An empty canvas in EZ-ASCII is one such that all of the intensities are 0.

### 3.8.2 Load

load ( [filepath], [granularity] )

load takes a string filepath to an existing image file and an integer granularity level as inputs. . If the file name contains the extension .i, it is assumed to be an EZ-ASCII intensity file. In this case, it will load the image directly without any processing. This case will throw an error if the intensities found in file are not compatible with the granularity specified. Otherwise, it uses the Python Imaging Library to convert the image into an EZ-ASCII intensity file. PIL is used to convert the image into 8-bit gray scale and shrink it down to at most 100 by 100 pixels. The 8-bit gray scale values are then normalized according to the granularity and those values written to a file in EZ-ASCII intensity format. This new file is then read in into a canvas which is returned. The side effect of creating a new file is useful because it takes up at most 20K and can be used to quickly reload the canvas on bigger images.

### 3.8.3 Shift

shift( [canvas], [shift\_dir], [dist] )

shift takes a valid canvas identifier canvas, a integer value shift\_dir representing which direction to shift in and a distance to shift, dist. For simplicity, shift\_dir will accept only 4 possible values: SHIFT\_UP, SHIFT\_DOWN, SHIFT\_LEFT, SHIFT\_RIGHT. These values are described in section 2.5.2. The purpose of shift is to take all of the characters in on a canvas and shift them in the shift\_dir direction, dist spaces.

The direction itself is implied by the names of the variables (e.g. SHIFT\_LEFT means left). Dist must be greater than 0 and less than the width of the canvas if shifting left or right or less than the height if shifting up or down. The result of this function will be to return a representation of the canvas with everything shifted.

Please note, if the movement causes a character to go beyond the border of the canvas it will disappear. Shifting one column past the right edge will cause the right most edge to disappear and the second to right most column will take its place. Furthermore in this case, the left most column will be padded with intensities of -1. The analogous situation is true for all other shifting directions.

# 4 Project Plan

## 4.1 Project Process

### 4.1.1 Proposal phase

During the early phase of the project, the team met on every Monday after class for two hours to brainstorm ideas for implementing a new language. This continued until the proposal was drafted.

### 4.1.2 LRM phase

Once receiving positive feedback from TA on Oct. 3rd, the team started working on the actual details of our language, specifying syntax/symantics and grammar rules. The syntax of the language was built primarily around making canvas manipulations simple and intuitive for the end-user. We also began working on the basic structure of the scanner and parser to investigate any potential ambiguities of our language. During this time we also set up a Git repository to track our source code.

### 4.1.3 Code Design and Implementation

We initially concentrated our efforts in getting most of our language implemented in the scanner, parser, and ast before moving forward. Once we had most of the language parsing working correctly, we started working on a basic interpreter that supported our entire language except for the canvas functionality in order to demonstrate a proof of concept. During this time, we created a top-level file along with a Makefile to trivialize the build process, and also started creating a suite of unit tests. Once we felt confident that the interpreter was working well, we started working on the compiler, bytecode, and bytecode-executor. When the compiler was mostly finished, we added a static semantic analysis module which interfaced between the parser and the compiler to check for compile-time errors.

## 4.2 Programming Style Guide

We adhered to the following general and OCaml coding conventions:

* 1. Descriptive comments occur immediately before the block of code they are related to.
  2. Scoping is indicated by single tab of 4 spaces (every let block should be properly indented, and nested let blocks should be additionally indented accordingly).
  3. Global variables are used sparingly, if at all (functional style).
  4. Similar code should be separated into separate modules for modularity and scalability purposes. Similarly, place any generic code in separate modules as a re-use library.
  5. Each module should have a block commented header describing the module’s purpose.
  6. Significant functions should be accompanied by a detailed comment as to the function’s purpose, inputs, outputs, and any other information which would be helpful for other developers.
  7. Side effects should be used sparingly, and only when the benefit of the side effect outweighs the alternative. In the case that the use of the side effect may confuse other developers, a descriptive comment should be added.
  8. Since OCaml is a functional language, prefer functional programming style over iterative-style programming, when possible.
  9. Variables and functions should have intuitive names when possible for maximal clarity, e.g. a variable that stores accumulated data within a recursive function should have something like “acc” or “accum” somewhere in its name. The names “i, j, k” are typically reserved for loop counters.
  10. Unless it is absolutely obvious, when accessing functions and types from other modules, prepend the module name – e.g. when pattern matching against a type from the Ast module, the pattern should be Ast.\* (where \* is the Ast type of interest).
  11. When pattern matching, always have a catch all case of some form so that the end-user does not see an OCaml matching error. This ensures that in the case that a developer extends the pattern but forgets to add the new patterns to the match list, the catch-all case code is executed.
  12. Define descriptive custom exceptions to help other developers during debugging.
  13. Wrap any debug code with an appropriate debug flag – remove it once a unit test provides coverage.

## 4.3 Project Timeline

**Table 4.1 Project Timeline**

|  |  |
| --- | --- |
| **Date** | **Milestone** |
| 09-26-2012 | Language proposal submitted. |
| 10-25-2012 | Basic scanner, parser, interpreter started to test LRM. |
| 10-31-2012 | The language reference manual complete. |
| 11-08-2012 | Basic AST implemented |
| 11-26-2012 | Test harness added. Interpreter/Ast/Scanner/Parser completed for language (no canvas functionality yet). Start work on Compiler/Bytecode/Execute, and canvas functionality. |
| 12-12-2012 | Compiler/Bytecode/Execute complete. Added simple Preprocessor. Canvas load functionality implemented via python script utilizing PIL library. Static semantic analysis module started. Final report work started. |
| 12-15-2012 | Canvas functionality and static semantic analysis module completed. |
| 12-17-2012 | Project Final Report completed. |

## 4.4 Member Roles and Responsibilities

**Table 4.2 Member Roles**

|  |  |  |
| --- | --- | --- |
| **Team Member** | **Code Responsibility** | **Documentation Responsibilities** |
| Dmitriy (leader) | AST, Parser, Canvas functionality, Preprocessor, Compiler, Bytecode execution, unit testing | Project Proposal, LRM, Final Report (sections 1-8) |
| Feifei | Scanner, Parser | Project Proposal, LRM, Final Report(sections 2, 6, 7) |
| Yilei | AST, Scanner, Parser | Project Proposal, LRM, Final Report (sections 1, 3, 4, 5, 7) |
| Xin | AST, Scanner, Parser | Project Proposal, LRM, Final Report (sections 4, 7) |
| Joe | AST, Scanner, Parser, Static Semantic Analysis, Compiler, Bytecode execution, unit testing | Project Proposal, LRM, Final Report (sections 1-8) |

## 4.4 Development Tools and Environment

The EZ-ASCII compiler source files were written primarily in OCaml (v4.00.0), with the exception of a python script used to load image files with PIL (Python Image Library). We used make to build our executable, and a bash script to run our unit tests and output the test run summaries. Team members used various text editors of choice, from Vim (with omlet.vim OCaml plugin) to Sublime 2 and Notepad++.

We used Git version control to manage our project source, and took advantage of free Github hosting.

## 4.5 Project Log

**Table 4.3 Project Log**

|  |  |
| --- | --- |
| **Date** | **Work Done** |
| 09/10/2012 | Team formed, first meeting, brainstormed ideas for project language. |
| 09/17/2012 | Second meeting, solidifying idea of ASCII-art manipulation language |
| 09/24/2012 | Third meeting, project proposal drafted, Git version control setup |
| 09/28/2012 | Project proposal submitted. |
| 10/08/2012 | Fourth meeting, discuss language implementation details. |
| 10/15/2012 | Fifth meeting, finalize language details. |
| 10/22/2012 | Sixth meeting, divide up portions of LRM. |
| 10/25/2012 | Basic scanner, parser, and interpreter started. |
| 10/29/2012 | Seventh meeting, final version of LRM submitted. |
| 11/2/2012 | Roadmapped work ahead, divided up portions of scanner, parser, and AST. Start image manipulation implementation investigation. |
| 11/8/2012 | Basic AST completed. |
| 11/9/2012 | Began integrating AST and parser. Image manipulation implementation investigation continues. |
| 11/26/2012 | Scanner, Parser, Ast, Interpreter, and top-level Ezac modules working except for Canvas functionality. Test harness added for running unit tests. |
| 12/04/2012 | Started adding image supporting features and Preprocessor. |
| 12/12/2012 | Compiler, Bytecode, Execute modules finished. Canvas load function implemented with Python script calling into PIL library functions. Final report started. |
| 12/15/2012 | Semantic analysis module added, rest of canvas functions finished. |
| 12/16/2012 | New development stopped on compiler apart from final bug fixes and unit testing. final report and presentation slides finished |
| 12/17/2012 | Final report and presentation slides completed. |

# 5 Architectural Design

This section presents the compiling and executing process of EZ-ASCII program.

## 5.1 Compiling and Executing

EZ-ASCII compiler takes EZ-ASCII source code files (\*.eza) as input. The first step is a preprocessing step where the compiler recursively finds all include statements and prepends all dependent modules’ source code into one accumulated source program. The accumulated source program is then given to the scanner, which outputs a stream of tokens if successful. The parser then runs on the tokens and constructs them into an abstract syntax tree (AST) according to production rules. The static semantic analyzer then takes in the AST and runs through the entire program, stepping through function calls, in order to find compile-time errors such as type errors, undefined variable/function errors, invalid canvas selection operators, etc. If any errors occur, the errors are output and compilation stops. Otherwise, the compiler performs a second pass through the Ast program to generate the bytecode. Finally, if compilation is successful, the execute module takes the bytecode program and executes it using a stack. The stack-type is of integer, which can be literal values or addresses. If an address is encountered with a local/global load/store bytecode, a lookup/update is performed on a hashtable, which stores all non-integer types (booleans, strings, canvases). The compilation and execution process is illustrated in Figure 5.1.

The following is a list of our source modules and contributors:

|  |  |
| --- | --- |
| Makefile | Joe, Dmitriy |
| runtests.sh, unit testing | Joe, Dmitriy |
| scanner.mll | Joe, Dmitriy, Xin, Feifei, Yilei |
| parser.mly | Joe, Dmitriy, Xin, Feifei |
| ast.ml | Joe, Dmitriy, Yilei, Xin |
| interpreter.ml | Joe |
| compiler.ml | Joe, Dmitriy |
| execute.ml | Joe, Dmitriy |
| bytecode.ml | Joe, Dmitriy |
| ezac.ml (top-level) | Joe, Dmitriy |
| canvas.ml | Dmitriy |
| load\_img.py | Dmitriy |
| preprocess.ml | Dmitriy |
| sast.ml | Joe |
| hashtypes.ml | Joe, Dmitriy |
| reuse.ml | Joe |

Figure 5.1

# 6 Test Plan

It is important to have robust testing when writing a complex program like a compiler. During initial development, we tested basic operations manually. Once more features were added to the interpreter, we created a test harness shell script to begin automating our test cases and comparing actual outputs with the expected outputs. When we designed our test cases, we wrote one test for each feature specified in the Language Reference Manual (LRM); meanwhile, we built sequences of tests that start with the simplest version, and gradually evolve into more complex versions.

## 6.1 Representative Source Program and Target Program

### 6.1.1 Example 1

// Loops through various granularities and shows the result.

min\_gran <- 2;

max\_gran <- 65;

for i <- min\_gran | i < max\_gran | i <- i + 1

{

c <- load ("../image/joconde.jpg", i);

c -> out , true;

### }

-- Byte code down -> right

Lit 2

Str 0

Drp 1

Lit 65

Str 1

Drp 1

Lod 0

Str 2

Drp 1

Bra 16

Lct 0

Lod 2

Jsr -3

Str 3

Drp 1

Lct 1

Lod 3

Jsr -1

Drp 1

Drp 1

Lod 2

Lit 1

Bin +

Str 2

Drp 1

Lod 2

Lod 1

Bin <

Bne -18

Hlt

### 6.1.2 Example 2

// Demo Library

Fun load\_image(path, gran)

{

c <- load(path, gran);

return c;

}

Fun invert(c)

{

z <- blank(c$h, c$w, c$g);

for i <- 0 | i < c$g | i <- i+1

{

d <- c[=i];

d[=i] <- c$g-i-1;

z <- z & d;

}

return z;

}

-----

// Inverts Apple Image

include "../demo/demo\_lib.eza";

a <- load\_image("../image/apple.jpeg", 10);

i <- invert(a);

a -> out, true;

i -> out, true;

-- Bytecode Down -> Right

Lit 10

Lct 0

Jsr 20

Str 0

Drp 1

Lod 0

Jsr 29

Str 1

Drp 1

Lct 1

Lod 0

Jsr -1

Drp 1

Drp 1

Lct 2

Lod 1

Jsr -1

Drp 1

Drp 1

Hlt

Ent 0

Lfp -2

Lfp -3

Jsr -3

Sfp 3

Lfp 3

Rts 2

Lit 0

Rts 2

Ent 0

Lfp -2

Catr $H

Lfp -2

Catr $W

Lfp -2

Catr $G

Jsr -4

Sfp 2

Lit 0

Str 1

Drp 1

Bra 28

Lod 1

Lit 0

Lit 8

Lfp -2

Jsr -6

Sfp 3

Lod 1

Lit 0

Lit 8

Lfp -2

Catr $G

Lod 1

Bin -

Lit 1

Bin -

Lfp 3

Jsr -7

Lfp 2

Lfp 3

Bin MASK

Sfp 2

Drp 1

Lod 1

Lit 1

Bin +

Str 1

Drp 1

Lod 1

Lfp -2

Catr $G

Bin <

Bne -31

Lfp 2

Rts 1

Lit 0

Rts 1

## 6.2 Test Cases and Test Suits

To maintain confidence that new code does not break old code, we maintained a suite of unit tests. As we implemented each feature of our language, a basic unit test was added to ensure correct functionality. Intermediate and more difficult unit tests were also added for each feature to cover possible corner cases as more of the compiler was developed. Our test cases can be divided into two categories: functional tests and semantic tests. Functional tests are used to ensure the features of our compiler perform correctly. All functionality tests need to pass. The semantic analysis ensures that all the illegal semantic errors be caught, thus all semantic analysis tests need to fail. A complete list of test cases is as follows:

**Table 6.1 Test Cases**

|  |  |  |  |
| --- | --- | --- | --- |
| assign | include | select2 | typecheck5 |
| blank | include2 | selectall | typecheck6 |
| canvas | loadcanvas | selectbinop1 | typecheck7 |
| canvasattr | mainfunction1 | selecthslice | typecheck8 |
| canvasset | mainfunction2 | selecthsliceall | typecheck9 |
| for1 | mainfunction3 | selectpoint1 |  |
| for2 | mainfunction4 | selectrect1 |  |
| fun1 | mask | selectvslice |  |
| fun2 | minus1 | selectvsliceall |  |
| fun3 | minus2 | shift |  |
| fun4 | minus3 | string |  |
| fun5 | outToFile | string2 |  |
| fun6 | recursion1 | string3 |  |
| if1 | recursion2 | typecheck1 |  |
| if2 | recursion3 | typecheck10 |  |
| if3 | relops | typecheck11 |  |
| if4 | scope1 | typecheck12 |  |
| ifelse1 | scope2 | typecheck2 |  |
| ifelse2 | scope3 | typecheck3 |  |
| ifelse3 | select | typecheck4 |  |

## 6.3 Test Automation

A set of unit tests was written, each a .eza source file. Each unit test also has a corresponding .gs (gold standard) file which has the correct expected output of the program (or an error message for semantic tests). A shell script, runtests.sh, was written which when run, performs the following for each unit test: 1) Compile the test source file with the built executable and execute the bytecode (-c option), 2) pipe the output to a .out file, 3) compare the .out file with the corresponding .gs file, 4) if the contents are different, then output the difference to a .diff file using the diff utility, and finally 5) output the summary of the test run. It is important to note that each time a test is run, it is compiled and executed.

## 6.4 Test Responsibility

During initial development, each team member was responsible for informally testing his code by examining standard output. Once significant work was done on the interpreter, Joe added the runtests.sh script and began populating the unit test suite. As development proceeded, Joe and Dmitriy maintained the unit tests and added more as development proceeded.

# 7 Lessons Learned

## 7.1 Dmitriy Gromov

This project was a learning experience that was both very informative and eye opening. I had never been exposed to a functional language programming language before and so the very first lesson learned was how to more effectively read documentation of written languages. This was dually important, as OCaml does not have a huge user base and there are fewer examples of OCaml code as opposed to C or Java code.

Having been selected as the lead on this project, I also learned about some of the difficulties in managing a group. When work assignments weren’t specified properly or there was confusion about what needed to be done, work was delayed or done incorrectly. Dealing with these issues taught me about the different kind of problems that can occur when managing groups of people and how to deal with them in an effective way. Towards the end of working on this project, it became easier to tell what could practically be done in parallel, who should be assigned what work, and when a democratic approach to decision making was not an appropriate thing to do.

Finally, aside from learning OCaml and a lot about compilers in general, I became much more familiar with Git. I had worked in industry for two years where we used source control but I never did anything past checking in and reverting my code. Over the course of this project we went through several broken branches and spent about a week fixing the repository. I became very familiar with what Git was capable of and gained a better understanding of how to use it. I was very grateful for this because it helped me with similar issues in other classes and I am sure it will help me in the future.

## 7.2 Feifei Zhong

It’s my first time to do a complex a project like a complier. There are several things I learned from this project. Firstly, GitHub, a version control system, is the important tool I learned for doing a team project. Secondly, it’s much harder than I thought to start writing the simple interpreter. The reason is that it took me almost one and half days to figure out the error in AST while I’m implementing the for loop. In addition, regression test suite we used is another important tool that I learned. I also learned some ways to wrap C/C++ code in Ocaml when I’m trying to figure out the canvas part of our project; however, my code didn’t work, and we gave up using the Cimg library. Finally, effective teamwork is very important. It’s better for team members to know each other well.

## 7.3 Yilei Wang

I first would like to thank my teammates. I really learned of a great deal from them, both knowledge and commitment to hard work.

Version control System is the first lesson I learned in this project. It’s so helpful in keeping track of progress when multiple people work on the same project. The most important thing learned is of course building a language from ground up. Starting with trivial constructs, I learned how to add to the output little by little and detect error in the process of building AST, scanner and parser.

## 7.4 Xin Ye

This is the first time I have participated in the compiler project. Through the course of it, there are many lessons I learned. First, since in this project, I mainly focused on the AST, scanner and parser, I realized a good design in them can save a lot of efforts in the coding process. What I said about a good design simply means the simpler the better. In order to reach this goal, it’s better to finish scanner, parser, and define the AST before finalizing the LRM, and then continuously modify them to make them simpler while integrating with other parts. Second, while coding and integrating codes with other team members, I came across and understood better about the issues that Prof. Edwards talked about in class, i.e. scoping. This is a really good learning process for me. Also Github is a very useful and powerful tool in order to make coding done neatly while working as a team. Finally, planning ahead, compromising and communicating with each other as much as possible are very important factors when working with other team members. Also it is important to help each other and look into the problems together if someone is not able to accomplish job on time. In summary, this project introduces me to the area of programming language design, which I have never had experience before and teaches me a lot.

## 7.5 Joe Lee

Overall, I enjoyed the work on this compiler project. I have had some industry experience in software engineering, so I was able to focus purely on implementation and not have to worry about learning version control, or good software engineering practices (one-click builds, unit testing). I enjoyed learning Git, which I had not used before. I did not enjoy learning OCaml at first, but looking back, I fully agree that it is a powerful language (particularly the pattern matching features), and am glad I had the opportunity to learn it. I am really glad that we started the initial compiler work (scanner, parser, interpreter) relatively early, as it paid off to have more of our language defined, so that we could focus on implementing the bytecode generation. If I had to pinpoint the most valuable lesson learned, I would say that I learned that the project work itself, though it was a lot, was not really the most difficult part; rather, it is the teamwork aspect. No one on the team knew each other, so it was difficult for everyone to work well together – it may have proved useful at the beginning of the semester to set expectations of each team member.

## 7.6 Advice For Future Teams

An obvious piece of advice would be to work together as early as possible. None of the members on our team knew each other, so the team had to spend some time adjusting to each team member’s working styles, and getting everyone up to speed on Git version control. We are glad that we started our scanner and parser modules while working on the LRM; this gave us the advantage of mostly dealing with implementation after the LRM deadline. Another word of advice would be to spend time at the beginning of the semester setting expectations for each team member.

# 8 Appendix

## 8.1 preprocess.ml

(\* FILENAME : preprocess.ml

\* AUTHOR(S): Dmitriy Gromov (dg2720)

\* PURPOSE :

\*)

open Str

let read\_file fname =

let ic = open\_in fname in

let n = in\_channel\_length ic in

let s = String.create n in

really\_input ic s 0 n;

close\_in ic;

(s) ;;

let run fname =

let prog\_text = read\_file fname in

let white\_sp = "[\r\n\t ]" in

let inc\_regex = Str.regexp (

"include" (\* include \*)

^ white\_sp ^ "+" (\* atleast 1 space btwn include and filename \*)

^ "\"\\(.+\\)\"" (\* "sometext" - Only the part between the quotes goes in \*)

^ white\_sp ^ "\*" ^ ";" ^ white\_sp ^ "\*";

) in (\* Possible space between end of string and semi-colon \*)

(\* let comm\_regex = Str.regexp (

"//.\*" (\* Two slashes followed by anything until new line. \*)

) in

let remove\_comments text =

let q = Str.global\_replace comm\_regex "" text in

(q)

in \*)

let rec replace\_include text =

let find\_include text =

try

ignore (Str.search\_forward inc\_regex text 0);

true

with Not\_found ->

false

in

if find\_include text then

let q = Str.global\_substitute inc\_regex (

fun m ->

let inc\_name = Str.matched\_group 1 m in

read\_file inc\_name

) text

in

replace\_include ( q )

else

text

(\* in replace\_include (remove\_comments prog\_text) \*)

in replace\_include prog\_text

## 8.2 scanner.mll

(\* FILENAME : scanner.mll

\* AUTHOR(S): Joe Lee (jyl2157), Dmitriy Gromov (dg2720),

\* Yilei Wang (yw2493), Peter Ye (xy2190), Feifei Zhong (fz2185)

\* PURPOSE : Scanner definition for EZ-ASCII.

\*)

{

open Parser

exception Eof

}

let letter = ['a'-'z' 'A'-'Z']

let digit = ['0'-'9']

let dblquote = '"'

(\* printable ASCII chars, excluding double quote and forward slash \*)

let printable = ['!' '#'-'.' '0'-'~']

(\* escape sequences: newline, horiz tab, single/double quote, back/forw slash \*)

let esc\_char = "\\n" | "\\t" | "\\\"" | "\\\'" | "\\" | "/"

let comment = "//" \_\* ['\r' '\n']

(\* allowable characters for strings \*)

let strchar = printable | ' ' | '\t' | esc\_char

rule token = parse

[' ' '\t'] { token lexbuf }

| ['\n' '\r'] { token lexbuf }

| "//" { comment lexbuf }

| "," { COMMA }

| ";" { SEMICOLON }

(\* arithmetic operators \*)

| "+" { PLUS }

| "-" { MINUS }

| "\*" { TIMES }

| "/" { DIVIDE }

| "%" { MOD }

(\* relational operators \*)

| "&&" { AND }

| "||" { OR }

(\* boolean operators/keywords \*)

| "<" { LT }

| ">" { GT }

| "=" { EQ }

| "<=" { LEQ }

| ">=" { GEQ }

| "~=" { NEQ }

| "~" { NEGATE }

| "true" { BOOLLITERAL(true) }

| "false" { BOOLLITERAL(false) }

(\* canvas operators/keywords/constants \*)

| "&" { MASK }

| "[" { LBRACKET }

| "]" { RBRACKET }

| ":" { COLON }

| "out" { STDOUT }

| "SHIFT\_UP" { INTLITERAL(0) }

| "SHIFT\_LEFT" { INTLITERAL(1) }

| "SHIFT\_DOWN" { INTLITERAL(2) }

| "SHIFT\_RIGHT" { INTLITERAL(3) }

| "$w" { ATTR\_W }

| "$h" { ATTR\_H }

| "$g" { ATTR\_G }

(\* statement operators/keywords \*)

| "if" { IF }

| "else" { ELSE }

| "for" { FOR }

| "|" { FOR\_SEP }

| "Fun" { FXN }

| "include" { INCLUDE }

| "return" { RETURN }

(\* remove leading/trailing newlines

\* for braces \*)

| "{" { LBRACE }

| "}" { RBRACE }

| "(" { LPAREN }

| ")" { RPAREN }

| "<-" { ASSIGN }

| "->" { OUTPUT }

(\* built-in functions \*)

| "main" { MAIN }

| "blank" { BLANK }

| "load" { LOAD }

| "map" { MAP }

| "shift" { SHIFT }

| letter (letter | digit | '\_')\* as id { ID(id) }

| digit+ as lit { INTLITERAL(int\_of\_string lit) }

| dblquote strchar\* dblquote as str { STR(String.sub str 1 ((String.length str) - 2)) }

| eof { EOF } (\* raise Eof } \*)

and comment = parse

(\* end of line marks end of comment \*)

['\n' '\r'] { token lexbuf }

(\* ignore everything else \*)

| \_ { comment lexbuf }

## 8.3 parser.mly

/\* FILENAME : parser.mly

\* AUTHOR(S): Joe Lee (jyl2157), Dmitriy Gromov (dg2720),

\* Yilei Wang (yw2493), Peter Ye (xy2190), Feifei Zhong (fz2185)

\* PURPOSE : Parser definition for EZ-ASCII.

\*/

%{ open Ast %}

%token <int> INTLITERAL

%token <bool> BOOLLITERAL

%token <string> ID

%token <string> CMP

%token <string> STR

%token TRUE, FALSE

%token AND, OR, COMMA, SEMICOLON, COLON, LBRACKET, RBRACKET, LPAREN, RPAREN, EOF

%token LT, GT, EQ, LEQ, GEQ, NEQ, NEGATE

%token ATTR, MASK, IF, ELSE, FOR, FOR\_SEP, INCLUDE, RETURN, LBRACE, RBRACE, FXN

%token PLUS, MINUS, TIMES, DIVIDE, MOD

%token ASSIGN, OUTPUT, ATTR\_W, ATTR\_H, ATTR\_G, STDOUT

%token MAIN, BLANK, LOAD, INCLUDE, MAP, SHIFT

%token CANVAS

%nonassoc NOELSE

%nonassoc ELSE

%left MASK, PLUS, MINUS /\* lowest precedence \*/

%left TIMES, DIVIDE, MOD

%left EQ, NEQ

%left LT, GT, GEQ, LEQ

%left AND, OR

%left LPAREN, RPAREN

%right ASSIGN

%nonassoc UMINUS /\* highest precedence \*/

%start program /\* the entry point \*/

%type <Ast.program> program

%%

program:

/\* nothing \*/ { [], [] }

| program stmt { List.rev($2 :: List.rev (fst $1)), snd $1 }

| program funcdecl { (fst $1), List.rev ($2 :: List.rev (snd $1)) }

funcdecl:

FXN ID LPAREN param\_list RPAREN LBRACE stmt\_list RBRACE

{ { fname = $2; params = List.rev $4; body = List.rev $7 } }

| FXN MAIN LPAREN RPAREN LBRACE stmt\_list RBRACE

{ { fname = "main"; params = []; body = List.rev $6 } }

param\_list:

/\* nothing \*/ { [] }

| ID { [$1] }

| param\_list COMMA ID { $3 :: $1 }

stmt\_list:

/\* nothing \*/ { [] }

| stmt\_list stmt { $2 :: $1 }

stmt:

ID ASSIGN expr SEMICOLON { Assign($1, $3) }

| ID OUTPUT STDOUT SEMICOLON { OutputC(Id($1), BoolLiteral(false)) }

| ID OUTPUT STDOUT COMMA expr SEMICOLON { OutputC(Id($1), $5)}

| ID OUTPUT expr SEMICOLON { OutputF(Id($1), $3, BoolLiteral(false)) }

| ID OUTPUT expr COMMA expr SEMICOLON { OutputF(Id($1), $3, $5) }

| IF LPAREN expr RPAREN cond\_body %prec NOELSE { If($3, $5) }

| IF LPAREN expr RPAREN cond\_body ELSE cond\_body { If\_else($3, $5, $7) }

| FOR stmt\_in\_for FOR\_SEP expr FOR\_SEP stmt\_in\_for LBRACE

stmt\_list RBRACE { For($2, $4, $6, List.rev $8) }

| RETURN expr SEMICOLON { Return($2) }

| INCLUDE STR SEMICOLON { Include($2) }

| ID LBRACKET select\_expr RBRACKET ASSIGN expr SEMICOLON {CanSet(Id($1), $3, $6)}

stmt\_in\_for:

ID ASSIGN expr { Assign($1, $3) }

select\_bool\_expr:

LT expr { Select\_Binop (Lt, $2) }

| GT expr { Select\_Binop (Gt, $2) }

| EQ expr { Select\_Binop (Eq, $2) }

| LEQ expr { Select\_Binop (Leq, $2) }

| GEQ expr { Select\_Binop (Geq, $2) }

| NEQ expr { Select\_Binop (Neq, $2) }

/\* | bool\_expr AND bool\_expr { $1, $3 }

| bool\_expr OR bool\_expr { $1, $3 } \*/

select\_expr:

expr COMMA expr { Select\_Point($1, $3) }

| expr COLON expr COMMA expr COLON expr { Select\_Rect($1, $3, $5, $7) }

| expr COMMA expr COLON expr { Select\_VSlice($1, $3, $5) }

| expr COLON expr COMMA expr { Select\_HSlice($1, $3, $5) }

| expr COMMA { Select\_VSliceAll($1) }

| COMMA expr { Select\_HSliceAll($2) }

| COMMA { Select\_All }

| select\_bool\_expr { Select\_Bool($1) }

cond\_body:

/\* If no braces are supplied in a

\* conditional body, we expect one statement;

\* Otherwise, we expect a statement list.

\*/

stmt { [$1] }

| LBRACE stmt\_list RBRACE { List.rev $2 }

expr\_list:

/\* nothing \*/ { [] }

| expr { [$1] }

| expr\_list COMMA expr { $3 :: $1 }

expr:

INTLITERAL { IntLiteral($1) }

| MINUS INTLITERAL %prec UMINUS { IntLiteral(- $2) }

| BOOLLITERAL { BoolLiteral($1) }

| STR { StrLiteral($1) }

| ID { Id($1) }

| expr PLUS expr { Binop($1, Plus, $3) }

| expr MINUS expr { Binop($1, Minus, $3) }

| expr TIMES expr { Binop($1, Times, $3) }

| expr DIVIDE expr { Binop($1, Divide, $3) }

| expr MOD expr { Binop($1, Mod, $3) }

| expr EQ expr { Binop($1, Eq, $3) }

| expr NEQ expr { Binop($1, Neq, $3) }

| expr LT expr { Binop($1, Lt, $3) }

| expr GT expr { Binop($1, Gt, $3) }

| expr LEQ expr { Binop($1, Leq, $3) }

| expr GEQ expr { Binop($1, Geq, $3) }

| expr OR expr { Binop($1, Or, $3) }

| expr AND expr { Binop($1, And, $3) }

| expr MASK expr { Binop($1, Mask, $3) }

| ID LPAREN expr\_list RPAREN { Call($1, List.rev $3) }

| LPAREN expr RPAREN { $2 }

| ID LBRACKET select\_expr RBRACKET { Select(Id($1), $3) }

| ID ATTR\_W { GetAttr (Id($1), W)}

| ID ATTR\_H { GetAttr (Id($1), H)}

| ID ATTR\_G { GetAttr (Id($1), G)}

| LOAD LPAREN expr COMMA expr RPAREN { Load($3, $5) }

| BLANK LPAREN expr COMMA expr COMMA expr RPAREN { Blank ($3, $5, $7 ) }

| SHIFT LPAREN ID COMMA expr COMMA expr RPAREN { Shift (Id($3), $5, $7 ) }

## 8.4 ast.ml

(\* FILENAME : ast.ml

\* AUTHOR(S): Joe Lee (jyl2157), Dmitriy Gromov (dg2720),

\* Yilei Wang (yw2493), Peter Ye (xy2190)

\* PURPOSE : Define abstract syntax tree for EZ-ASCII.

\*)

type op = Plus | Minus | Times | Divide | Mod

| And | Or

| Lt | Gt | Eq | Leq | Geq | Neq

| Mask

let op\_id op =

match op with

| Eq -> 0

| Neq -> 1

| Lt -> 2

| Leq -> 3

| Gt -> 4

| Geq -> 5

let string\_of\_op op =

match op with

Plus -> "+"

| Minus -> "-"

| Times -> "\*"

| Divide -> "/"

| Mod -> "%"

| And -> "&&"

| Or -> "||"

| Eq -> "="

| Neq -> "~="

| Lt -> "<"

| Leq -> "<="

| Gt -> ">"

| Geq -> ">="

| Mask -> "MASK"

type attr = W | H | G

type seltype = POINT | RECT | VSLICE

| HSLICE | VSLICE\_ALL | HSLICE\_ALL | ALL

type expr =

IntLiteral of int (\* 42 \*)

| StrLiteral of string (\* "this is a string" \*)

| BoolLiteral of bool (\* true \*)

| Id of string (\* foo \*)

| Binop of expr \* op \* expr (\* a + b \*)

| Call of string \* expr list (\* foo(1, 25) \*)

| Load of expr \* expr (\* load("filename", 10) \*)

| Blank of expr \* expr \* expr (\* blank(x, y, g) \*)

| Shift of expr \* expr \* expr

| Select\_Point of expr \* expr (\* [1,2] \*)

| Select\_Rect of expr \* expr \* expr \* expr (\* [1:2, 3:4] \*)

| Select\_VSlice of expr \* expr \* expr (\* [1, 3:4] \*)

| Select\_HSlice of expr \* expr \* expr (\* [1:2, 3] \*)

| Select\_VSliceAll of expr (\* [3, ] \*)

| Select\_HSliceAll of expr (\* [, 3] \*)

| Select\_All (\* [,] \*)

| Select of expr \* expr (\* canv[...] \*)

| Select\_Binop of op \* expr (\* canv[<5] \*)

| Select\_Bool of expr (\* <5 \*)

| GetAttr of expr \* attr (\* canv$w \*)

type stmt = (\* Statements \*)

Assign of string \* expr (\* foo <- 42 \*)

| OutputC of expr \* expr (\* canvas -> out \*)

| OutputF of expr \* expr \* expr (\* canvas -> "C:\test.png" \*)

| If of expr \* stmt list (\* if (foo = 42) {} \*)

| If\_else of expr \* stmt list \* stmt list (\* if (foo = 42) {} else {} \*)

| For of stmt \* expr \* stmt \* stmt list (\* for i <- 0 | i < 10 | i <- i + 1 { ... } \*)

| Return of expr (\* return 42; \*)

| Include of string (\* include super\_awesome.eza \*)

| CanSet of expr \* expr \* expr (\* can[..] <- 1 \*)

type func\_decl = {

fname : string; (\* Name of the function \*)

params : string list; (\* Formal argument names \*)

body : stmt list;

}

type program = stmt list \* func\_decl list (\* global vars, fxn declarations \*)

let string\_of\_attr = function

W -> "$W"

| H -> "$H"

| G -> "$G"

let rec string\_of\_expr = function

IntLiteral(l) -> string\_of\_int l

| StrLiteral(l) -> "\"" ^ l ^ "\""

| BoolLiteral(l) -> if l == true then "true" else "false"

| Id(s) -> s

| Binop(e1, o, e2) ->

string\_of\_expr e1 ^ " " ^ (string\_of\_op o) ^ " " ^ string\_of\_expr e2

| Call(f, el) -> f ^ "(" ^ String.concat ", " (List.map string\_of\_expr el) ^ ")"

| Load(e1, gran) -> "Load(" ^ string\_of\_expr e1 ^ ", " ^ string\_of\_expr gran ^ ")"

| Blank(e1, e2, e3) -> "Blank(" ^ string\_of\_expr e1 ^ ", " ^ string\_of\_expr e2 ^ ", " ^ string\_of\_expr e3 ^ ")"

| Shift(e1, dir, e3) -> "Shift(" ^ string\_of\_expr e1 ^ ", " ^ string\_of\_expr dir ^ ", " ^ string\_of\_expr e3 ^ ")"

| Select\_Point (x, y) -> "[" ^ string\_of\_expr x ^ ", " ^ string\_of\_expr y ^ "] -- point select"

| Select\_Rect (x1, x2, y1, y2) -> "[" ^ string\_of\_expr x1 ^ ":" ^ string\_of\_expr x2 ^ ", "

^ string\_of\_expr y1 ^ ":" ^ string\_of\_expr y2 ^ "] -- rect select"

| Select\_VSlice (x1, y1, y2) -> "[" ^ string\_of\_expr x1 ^ ", "

^ string\_of\_expr y1 ^ ":" ^ string\_of\_expr y2 ^ "] -- vslice"

| Select\_HSlice (x1, x2, y1) -> "[" ^ string\_of\_expr x1 ^ ":" ^ string\_of\_expr x2

^ ", " ^ string\_of\_expr y1 ^ "] -hslice"

| Select\_VSliceAll x1 -> "[" ^ string\_of\_expr x1 ^ ",] - vslice\_all"

| Select\_HSliceAll y1 -> "[," ^ string\_of\_expr y1 ^ "] - hslice all"

| Select\_All -> "[,] - select all"

| Select\_Binop(o, e2) ->

(

match o with

| And -> "&&"

| Or -> "||"

| Eq -> "="

| Neq -> "~="

| Lt -> "<"

| Leq -> "<="

| Gt -> ">"

| Geq -> ">="

| \_ -> "error"

)

^ " " ^ string\_of\_expr e2

| Select\_Bool(e1) -> "[" ^ string\_of\_expr e1 ^ "] "

| Select (canv, selection) -> string\_of\_expr canv ^ string\_of\_expr selection

| GetAttr(canv, attr) -> string\_of\_expr canv ^ " -> " ^ string\_of\_attr attr

let rec string\_of\_stmt = function

| Return(expr) -> "return " ^ string\_of\_expr expr ^ ";"

| If(e, sl1) -> "if (" ^ string\_of\_expr e ^ ")

{\n" ^ String.concat "\n" (List.map string\_of\_stmt sl1) ^ "\n}"

| If\_else(e, sl1, sl2) ->

"if (" ^ string\_of\_expr e

^ "){\n" ^ String.concat "\n" (List.map string\_of\_stmt sl1)

^ "\n}\nelse{\n"

^ String.concat "\n" (List.map string\_of\_stmt sl2) ^ "\n}"

| For(s1, e2, s3, sl4) ->

"for (" ^ string\_of\_stmt s1 ^ " | " ^ string\_of\_expr e2 ^ " | " ^ string\_of\_stmt s3 ^ ")\n

{\n" ^ String.concat "\n" (List.map string\_of\_stmt sl4) ^ "\n}"

| OutputC(e, render\_expr) ->

string\_of\_expr e ^ ", " ^ string\_of\_expr render\_expr ^ " -> out"

| OutputF(e, fname, render\_expr) ->

string\_of\_expr e ^ ", " ^ string\_of\_expr render\_expr ^ " -> " ^ string\_of\_expr fname

| Assign(v, e) ->

v ^ " <- " ^ string\_of\_expr e

| CanSet(can, sel, exp) -> string\_of\_expr can ^ string\_of\_expr sel ^ " <- " ^ string\_of\_expr exp

| Include(str) ->

"include " ^ str

let string\_of\_fdecl fdecl =

fdecl.fname ^ "(" ^ String.concat ", " fdecl.params ^ ")\n{\n"

^ String.concat "\n" (List.map string\_of\_stmt fdecl.body)

^ "\n}\n"

let string\_of\_program (vars, funcs) =

String.concat "\n" (List.map string\_of\_stmt vars) ^ "\n\n" ^

String.concat "\n" (List.map string\_of\_fdecl funcs)

## 8.5 ssanalyzer.ml

(\* FILENAME : ssanalyzer.ml

\* AUTHOR(s): Joe Lee (jyl2157)

\* PURPOSE : Checks for type errors, undefined var/fxn errors, converts ast to sast.

\*)

open Ast

open Sast

type t =

Void

| Int

| Bool

| Char

| String

| RelOp

| Canvas

let string\_of\_t = function

Void -> "Void"

| Int -> "Int"

| Bool -> "Bool"

| Char -> "Char"

| String -> "String"

| RelOp -> "&&, ||, =, ~=, <, <=. >, >="

| Canvas -> "Canvas"

module StringMap = Map.Make(String)

type fxn\_env = {

mutable local\_env : (Sast.expr\_detail \* t) StringMap.t;

mutable ret\_type : (Sast.expr\_detail \* t);

fxn\_name : string;

fxn\_params : string list;

fxn\_body : Ast.stmt list;

}

(\* Translation environment \*)

type env = {

mutable global\_env : (Sast.expr\_detail \* t) StringMap.t;

mutable fxn\_envs : fxn\_env StringMap.t;

}

exception TypeException of Ast.expr \* Ast.expr \* t \* t

exception BinopException of Ast.op \* Ast.expr \* t

exception UndefinedVarException of Ast.expr

exception UndefinedFxnException of string \* Ast.expr

(\* takes Ast program and runs static semantic analysis (type errors, etc..) \*)

let semantic\_checker (stmt\_lst, func\_decls) =

(\* Check an expr \*)

let rec expr env scope = function

Ast.IntLiteral(i) ->

Sast.IntLiteral(i), Int

| Ast.StrLiteral(s) ->

Sast.StrLiteral(s), String

| Ast.BoolLiteral(b) ->

Sast.BoolLiteral(b), Bool

| Ast.Id(s) ->

if scope <> "\*global\*"

then

(try

let search\_local = (StringMap.find s (StringMap.find scope env.fxn\_envs).local\_env) in

search\_local

with Not\_found ->

(try

let search\_global = StringMap.find s env.global\_env in

search\_global

with Not\_found ->

raise (UndefinedVarException(Ast.Id(s)))))

else

(try

let search\_global = StringMap.find s env.global\_env in

search\_global

with Not\_found ->

raise (UndefinedVarException (Ast.Id(s))))

| Ast.Binop(e1, op, e2) ->

let (v1, t1) = expr env scope e1

and (v2, t2) = expr env scope e2 in

(match op with

Ast.Plus ->

(match (t1, t2) with

(Int, Int) ->

Sast.Binop(e1, op, e2), Int

| (String, String) ->

Sast.Binop(e1, op, e2), String

| (\_, \_) ->

raise(TypeException(e2, Ast.Binop(e1, op, e2), t1, t2))

)

| Ast.Minus | Ast.Times | Ast.Divide | Ast.Mod ->

(match (t1, t2) with

(Int, Int) ->

Sast.Binop(e1, op, e2), Int

| (\_, \_) ->

raise(TypeException(e2, Ast.Binop(e1, op, e2), Int, t2))

)

| Ast.Eq | Ast.Neq | Ast.Lt | Ast.Gt | Ast.Leq | Ast.Geq ->

(match (t1, t2) with

(Int, Int) ->

Sast.Binop(e1, op, e2), Bool

| (\_, \_) ->

raise(TypeException(e2, Ast.Binop(e1, op, e2), Int, t2))

)

| Ast.Or | Ast.And ->

(match (t1, t2) with

(Bool, Bool) ->

Sast.Binop(e1, op, e2), Bool

| (\_, \_) ->

raise(TypeException(e2, Ast.Binop(e1, op, e2), Bool, t2))

)

| Ast.Mask ->

Sast.Binop(e1, op, e2), Canvas (\* need to do \*)

);

| Ast.Call(fname, actuals) ->

(\* no need to execute recursive calls \*)

if (scope <> "\*global\*") && (fname = scope)

then

(try

let fxn\_env\_lookup = (StringMap.find fname env.fxn\_envs) in

fxn\_env\_lookup.ret\_type

with Not\_found ->

raise (UndefinedFxnException (fname, Ast.Call(fname, actuals))))

else

(try

(\* first evaluate the actuals \*)

let res = (List.map (expr env scope) (List.rev actuals)) in

let fxn\_env\_lookup = (StringMap.find fname env.fxn\_envs) in

let bindings = List.combine (fxn\_env\_lookup.fxn\_params) res in

let rec init\_loc\_env accum\_env = function

[] -> accum\_env

| (param\_name, (sast\_elem, typ)) :: tail ->

init\_loc\_env (StringMap.add param\_name (sast\_elem, typ) accum\_env) tail

in

(\* Side effect: Initialize a local environment with the new parameter values \*)

fxn\_env\_lookup.local\_env <- init\_loc\_env StringMap.empty bindings;

(\* execute the function\_body, which will eventually

\* update the return type \*)

let \_ = List.map (stmt env fxn\_env\_lookup.fxn\_name) fxn\_env\_lookup.fxn\_body

in

(\* finally, return the possibly updated return type

\* (it is already initialized to (IntLiteral(0), Int)) \*)

fxn\_env\_lookup.ret\_type

with Not\_found ->

raise (UndefinedFxnException (fname, Ast.Call(fname, actuals))))

| Ast.Load(filepath\_expr, gran\_expr) ->

let (v1, t1) = (expr env scope) filepath\_expr

and (v2, t2) = (expr env scope) gran\_expr in

if not (t1 = String)

then

raise(TypeException(filepath\_expr, Ast.Load(filepath\_expr, gran\_expr), String, t1))

else

if not (t2 = Int)

then

raise(TypeException(gran\_expr, Ast.Load(filepath\_expr, gran\_expr), Int, t2))

else

Sast.Load(filepath\_expr, gran\_expr), Canvas

| Ast.Blank(height, width, granularity) ->

let (v1, t1) = (expr env scope) height

and (v2, t2) = (expr env scope) width

and (v3, t3) = (expr env scope) granularity

in

(match (t1, t2, t3) with

(Int, Int, Int) ->

Sast.Canvas, Canvas

| (\_, Int, Int) ->

raise(TypeException(height, Ast.Blank(height, width, granularity), Int, t1))

| (Int, \_, Int) ->

raise(TypeException(width, Ast.Blank(height, width, granularity), Int, t2))

| (Int, Int, \_) ->

raise(TypeException(granularity, Ast.Blank(height, width, granularity), Int, t3))

| (\_, \_, \_) ->

raise(TypeException(height, Ast.Blank(height, width, granularity), Int, t1))

)

| Ast.Select\_Point (x, y) ->

let (v1, t1) = (expr env scope) x

and (v2, t2) = (expr env scope) y

in

(match (t1, t2) with

(Int, Int) ->

Sast.Canvas, Canvas

| (Int, \_) ->

raise(TypeException(y, Ast.Select\_Point(x, y), Int, t2))

| (\_, \_) ->

raise(TypeException(x, Ast.Select\_Point(x, y), Int, t1))

)

| Ast.Select\_Rect (x1, x2, y1, y2) ->

let (v1, t1) = (expr env scope) x1

and (v2, t2) = (expr env scope) x2

and (v3, t3) = (expr env scope) y1

and (v4, t4) = (expr env scope) y2

in

(match (t1, t2, t3, t4) with

(Int, Int, Int, Int) ->

Sast.Canvas, Canvas

| (Int, Int, Int, \_) ->

raise(TypeException(y2, Ast.Select\_Rect(x1, x2, y1, y2), Int, t4))

| (Int, Int, \_, Int) ->

raise(TypeException(y1, Ast.Select\_Rect(x1, x2, y1, y2), Int, t3))

| (Int, \_, Int, Int) ->

raise(TypeException(x2, Ast.Select\_Rect(x1, x2, y1, y2), Int, t2))

| (\_, \_, \_, \_) ->

raise(TypeException(x1, Ast.Select\_Rect(x1, x2, y1, y2), Int, t1))

)

| Ast.Select\_VSlice (x1, y1, y2) ->

let (v1, t1) = (expr env scope) x1

and (v2, t2) = (expr env scope) y1

and (v3, t3) = (expr env scope) y2

in

(match (t1, t2, t3) with

(Int, Int, Int) ->

Sast.Canvas, Canvas

| (Int, Int, \_) ->

raise(TypeException(y2, Ast.Select\_VSlice(x1, y1, y2), Int, t3))

| (Int, \_, Int) ->

raise(TypeException(y1, Ast.Select\_VSlice(x1, y1, y2), Int, t2))

| (\_, \_, \_) ->

raise(TypeException(x1, Ast.Select\_VSlice(x1, y1, y2), Int, t1))

)

| Ast.Select\_HSlice (x1, x2, y1) ->

let (v1, t1) = (expr env scope) x1

and (v2, t2) = (expr env scope) x2

and (v3, t3) = (expr env scope) y1

in

(match (t1, t2, t3) with

(Int, Int, Int) ->

Sast.Canvas, Canvas

| (Int, Int, \_) ->

raise(TypeException(y1, Ast.Select\_HSlice(x1, x2, y1), Int, t3))

| (Int, \_, Int) ->

raise(TypeException(x2, Ast.Select\_HSlice(x1, x2, y1), Int, t2))

| (\_, \_, \_) ->

raise(TypeException(x1, Ast.Select\_HSlice(x1, x2, y1), Int, t1))

)

| Ast.Select\_VSliceAll x ->

let (v1, t1) = (expr env scope) x

in

(match t1 with

Int ->

Sast.Canvas, Canvas

| \_ ->

raise(TypeException(x, Ast.Select\_VSliceAll(x), Int, t1))

)

| Ast.Select\_HSliceAll y ->

let (v1, t1) = (expr env scope) y

in

(match t1 with

Int ->

Sast.Canvas, Canvas

| \_ ->

raise(TypeException(y, Ast.Select\_HSliceAll(y), Int, t1))

)

| Ast.Select\_All ->

Sast.Canvas, Canvas

| Ast.Select (canv, selection) ->

let (v1, t1) = (expr env scope) canv

and (v2, t2) = (expr env scope) selection

in

(match (t1, t2) with

(Canvas, Canvas) ->

Sast.Canvas, Canvas

| (Canvas, \_) ->

raise(TypeException(selection, Ast.Select(canv, selection), Canvas, t2))

| (\_, \_) ->

raise(TypeException(canv, Ast.Select(canv, selection), Canvas, t1))

)

| Ast.Select\_Binop(op, e) ->

let (v1, t1) = (expr env scope) e

in

(match (op, t1) with

(\* op must be a relational operator \*)

(Ast.Eq, Int | Ast.Neq, Int | Ast.Lt, Int | Ast.Gt, Int

| Ast.Leq, Int | Ast.Geq, Int) ->

Sast.Canvas, Canvas

(\*

| (Ast.And, Bool | Ast.Or, Bool) ->

Sast.Canvas, Canvas

\*)

| (Ast.Eq, \_ | Ast.Neq, \_ | Ast.Lt, \_ | Ast.Gt, \_ | Ast.Leq, \_ | Ast.Geq, \_) ->

raise(TypeException(e, Ast.Select\_Binop(op, e), Int, t1))

(\*

| (Ast.And, \_ | Ast.Or, \_) ->

raise(TypeException(e, Ast.Select\_Binop(op, e), Bool, t1))

\*)

| (\_, \_) ->

raise(BinopException(op, Ast.Select\_Binop(op, e), RelOp))

)

| Ast.Select\_Bool(e) ->

(\* e here is select\_bool\_expr which ultimately has type Canvas \*)

let (v1, t1) = (expr env scope) e

in

(match t1 with

Canvas ->

Sast.Canvas, Canvas

| \_ ->

raise(TypeException(e, Ast.Select\_Bool(e), Canvas, t1))

)

| Ast.Shift(canv, dir, count) ->

let (v1, t1) = (expr env scope) canv

and (v2, t2) = (expr env scope) dir

and (v3, t3) = (expr env scope) count

in

(match (t1, t2, t3) with

(Canvas, Int, Int) ->

Sast.Canvas, Canvas

| (Canvas, Int, \_) ->

raise(TypeException(count, Ast.Shift(canv, dir, count), Int, t3))

| (Canvas, \_, Int) ->

raise(TypeException(dir, Ast.Shift(canv, dir, count), Int, t2))

| (\_, \_, \_) ->

raise(TypeException(canv, Ast.Shift(canv, dir, count), Canvas, t1))

)

| Ast.GetAttr(canv, attr) ->

let (v1, t1) = (expr env scope) canv in

(match t1 with

Canvas ->

(match attr with

Ast.W | Ast.H | Ast.G ->

Sast.Canvas, Canvas )

| \_ ->

raise(TypeException(canv, Ast.GetAttr(canv, attr), Canvas, t1))

)

(\* execute statement \*)

and stmt env scope = function

Ast.Assign(var, e) ->

let ev = (expr env scope e) in

if scope <> "\*global\*"

then

(\*

\* if we are in a function, variable lookup proceeds as:

\* 1) Check if the variable is a formal (parameter)

\* 2) Check if the variable is declared globally

\* 3) Finally if both 1 and 2 don't hold, create a new local

\*)

(

let f\_env = (StringMap.find scope env.fxn\_envs)

in

if (StringMap.mem var f\_env.local\_env)

then

f\_env.local\_env <- (StringMap.add var ev f\_env.local\_env)

else

if (StringMap.mem var env.global\_env)

then

env.global\_env <- (StringMap.add var ev env.global\_env)

else

f\_env.local\_env <- StringMap.add var ev f\_env.local\_env

)

else

env.global\_env <- (StringMap.add var ev env.global\_env)

| Ast.OutputC(var, var\_rend) ->

let (var\_val, var\_typ) = expr env scope var

and (var\_rend\_val, var\_rend\_typ) = expr env scope var\_rend

in

(match (var\_typ, var\_rend\_typ) with

(Canvas, Bool) ->

();

| (\_, Bool ) ->

( match var\_rend with

Ast.BoolLiteral(b) -> if b

then raise(TypeException(var\_rend, var\_rend, Bool, var\_rend\_typ))

else ()

| \_ -> raise(TypeException(var\_rend, var\_rend, Bool, var\_rend\_typ)) ) ;

| (\_, \_) ->

raise(TypeException(var\_rend, var\_rend, Bool, var\_rend\_typ))

);

| Ast.OutputF(var, var\_fname, var\_rend) ->

let (var\_val, var\_typ) = expr env scope var

and (var\_rend\_val, var\_rend\_typ) = expr env scope var\_rend

(\* and (var\_fname\_val, var\_fname\_typ) = expr env scope var\_fname \*)

in

(match (var\_typ, var\_rend\_typ) with

(Canvas, Bool) ->

();

| (\_, Bool ) ->

( match var\_rend with

Ast.BoolLiteral(b) -> if b

then raise(TypeException(var\_rend, var\_rend, Bool, var\_rend\_typ))

else ()

| \_ -> raise(TypeException(var\_rend, var\_rend, Bool, var\_rend\_typ)) ) ;

| (\_, \_) ->

raise(TypeException(var\_rend, var\_rend, Bool, var\_rend\_typ))

);

| Ast.If(cond, stmt\_lst) ->

let (cond\_val, cond\_typ) = expr env scope cond in

(match cond\_typ with

Bool ->

();

| \_ ->

raise(TypeException(cond, cond, Bool, cond\_typ))

);

(\* regardless of the condition, check the statements \*)

List.iter (stmt env scope) stmt\_lst;

();

| Ast.If\_else(cond, stmt\_lst1, stmt\_lst2) ->

let (cond\_val, cond\_typ) = expr env scope cond in

(match cond\_typ with

Bool -> ();

| \_ -> raise(TypeException(cond, cond, Bool, cond\_typ))

);

(\* regardless of the condition, check both blocks \*)

List.iter (stmt env scope) stmt\_lst1;

List.iter (stmt env scope) stmt\_lst2;

();

| Ast.For(s1, e1, s2, stmt\_lst) ->

(stmt env scope s1);

let (e1\_val, e1\_typ) = (expr env scope e1)

in

(match e1\_typ with

Bool -> ();

| \_ -> raise(TypeException(e1, e1, Bool, e1\_typ))

);

(\* we only need to check the statement body once \*)

List.iter (stmt env scope) stmt\_lst;

stmt env scope s2;

();

| Ast.Return(e) ->

let (v, typ) = expr env scope e

and fxn\_env\_lookup = StringMap.find scope env.fxn\_envs

in

fxn\_env\_lookup.ret\_type <- (v, typ);

| Ast.Include(str) ->

(); (\* no type checking needed since we know it's already a string \*)

| Ast.CanSet (canv, select\_expr, set\_expr) ->

let (v1, t1) = (expr env scope) canv

and (v2, t2) = (expr env scope) select\_expr

and (v3, t3) = (expr env scope) set\_expr

in

(match (t1, t2, t3) with

(Canvas, Canvas, Int) ->

();

| (Canvas, Canvas, \_) ->

raise(TypeException(set\_expr, set\_expr, Int, t3))

| (Canvas, \_, Int) ->

raise(TypeException(select\_expr, select\_expr, Canvas, t2))

| (\_, \_, \_) ->

raise(TypeException(canv, canv, Canvas, t1))

)

(\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

\* start main code here

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*)

in let env = {

global\_env = StringMap.empty;

fxn\_envs = StringMap.empty;

} in

let rec add\_fxn accum\_env = function

[] -> accum\_env

| fxn\_decl :: rest ->

let f\_env =

{

local\_env = StringMap.empty;

ret\_type = (Sast.IntLiteral(0), Int); (\* return 0 by default \*)

fxn\_name = fxn\_decl.fname;

fxn\_params = fxn\_decl.params;

fxn\_body = fxn\_decl.body;

}

in

env.fxn\_envs <- StringMap.add fxn\_decl.fname f\_env env.fxn\_envs;

add\_fxn env rest

in

(\* add func\_decls to env.fxn\_envs \*)

let env = add\_fxn env func\_decls

in

(\* execute the global statements \*)

List.iter (stmt env "\*global\*") stmt\_lst;

(\* return the ast program unchanged for now - need to return sast.program

\* later \*)

(stmt\_lst, func\_decls)

## 8.6 sast.ml

(\* FILENAME : sast.ml

\* AUTHOR(s): Joe Lee (jyl2157)

\* PURPOSE : Defines sast.

\*)

type expr\_detail =

IntLiteral of int

| StrLiteral of string

| BoolLiteral of bool

| Canvas (\* of Ast.expr \* Ast.expr \* Ast.expr \*)

| Binop of Ast.expr \* Ast.op \* Ast.expr

| Load of Ast.expr \* Ast.expr

## 8.7 hashtypes.ml

(\* FILENAME : hashtypes.ml

\* AUTHOR(s): Joe Lee (jyl2157)

\* PURPOSE : Define custom types for hash map values to support EZ-ASCII's

\* types.

\*)

open Canvas

type ct =

(\* Note: The compiler will not add any int types to the hash map

\* but the bytecode executor might during binop operations \*)

Int of int

| String of string

| Bool of bool

| Canvas of Canvas.canvas

let string\_of\_ct render = function

Int(i) -> string\_of\_int i

| String(s) -> ( Scanf.unescaped s )

| Bool(b) -> string\_of\_bool b

| Canvas(c) -> (Canvas.string\_of\_canvas c Canvas.default\_map render)

## 8.8 interpret.ml

(\* FILENAME : interpret.ml

\* AUTHOR(S): Joe Lee (jyl2157), Dmitriy Gromov (dg2720)

\* PURPOSE : Interpreter for EZ-ASCII.

\*)

open Parser

open Scanner

open Ast

module NameMap =

Map.Make(struct

type t = string

let compare x y = Pervasives.compare x y

end)

exception ReturnException of string \* string NameMap.t NameMap.t

(\* given a NameMap, print its bindings

\*)

let env\_to\_str m =

let bindings = NameMap.bindings m in

let rec print\_map\_helper s = function

[] -> s

| hd :: tl -> print\_map\_helper ((fst hd) ^ " = " ^ (string\_of\_int (snd hd)) ^ "\n" ^ s) tl

in print\_map\_helper "" bindings

(\* helper function \*)

let bool\_of\_int i =

if i > 0 then true

else false

(\* ============================================================

\* Interpreter main method. Its called in ezac with -i switch.

\*

\*

\* ============================================================ \*)

let run lexbuf =

let (stmt\_lst, fxns\_lst) =

try

(Parser.program Scanner.token lexbuf)

with Parsing.Parse\_error ->

let curr = lexbuf.Lexing.lex\_curr\_p in

let line = curr.Lexing.pos\_lnum in

let cnum = curr.Lexing.pos\_cnum - curr.Lexing.pos\_bol in

let tok = Lexing.lexeme lexbuf in

print\_endline (">>> Parse error at line " ^ (string\_of\_int line) ^ ", character " ^ (string\_of\_int cnum) ^ ": '" ^ tok ^ "'");

exit 0;

in

(\* =====================================================

\* eval function

\*

\* Takes Ast.expr type and evaluates it, returning a

\* string value and updated environment pair.

\* ===================================================== \*)

let rec eval env scope = function

Ast.IntLiteral(e1) -> string\_of\_int e1, env

| Ast.StrLiteral(e1) -> e1, env

| Ast.BoolLiteral(e1) ->

if e1 then

"1", env

else

"0", env

| Ast.Id(var) ->

let local\_decls = (NameMap.find scope env)

in

(\* Look for the variable in the function's local scope \*)

if NameMap.mem var local\_decls

then (NameMap.find var local\_decls), env

(\* If variable not found in local scope, look in global scope \*)

else

let global\_decls = (NameMap.find "\*global\*" env)

in

if NameMap.mem var global\_decls

then (NameMap.find var global\_decls), env

(\* Otherwise, error. \*)

else raise (Failure (">>> Undefined identifier: " ^ var))

| Ast.Binop(e1, op, e2) ->

let v1, env = eval env scope e1 in

let v2, env = eval env scope e2 in

let boolean i = if i then 1 else 0 in

string\_of\_int (

match op with

Plus -> (int\_of\_string v1) + (int\_of\_string v2)

| Minus -> (int\_of\_string v1) - (int\_of\_string v2)

| Times -> (int\_of\_string v1) \* (int\_of\_string v2)

| Divide -> (int\_of\_string v1) / (int\_of\_string v2)

| Mod -> (int\_of\_string v1) mod (int\_of\_string v2)

| Eq -> boolean((int\_of\_string v1) == (int\_of\_string v2))

| Neq -> boolean((int\_of\_string v1) != (int\_of\_string v2))

| Lt -> boolean((int\_of\_string v1) < (int\_of\_string v2))

| Gt -> boolean((int\_of\_string v1) > (int\_of\_string v2))

| Leq -> boolean((int\_of\_string v1) <= (int\_of\_string v2))

| Geq -> boolean((int\_of\_string v1) >= (int\_of\_string v2))

| Or -> boolean((bool\_of\_int (int\_of\_string v1)) || (bool\_of\_int (int\_of\_string v2)))

| And -> boolean((bool\_of\_int (int\_of\_string v1)) && (bool\_of\_int (int\_of\_string v2)))

| Mask -> 1 (\* NEED TO DO \*)

), env

| Ast.Call(fxn\_name, param\_exprs) ->

(\* Find the target function from the list of function declarations.

\* Target function is as defined in the Ast:

\* {

\* fname : string;

\* params : string list;

\* body : stmt list;

\* }

\*

\* Note: Need to add error handling for when user tries to call

\* an undefined function. \*)

let target\_fxn = List.find (fun s -> s.fname = fxn\_name) fxns\_lst

in

let fxn\_env = NameMap.find fxn\_name env

in

(\* For every parameter in the function environment,

\* initialize it to the VALUE of the parameter expression

\* that the user passed in.

\* (e.g. if the function declaration is foo(a, b, c),

\* and the user calls with foo(1+2, 3+4, 5+6),

\* evaluate each parameter expression and update the

\* function environment accordingly.

\*

\* Note: error handling needs to be added for the case where

\* the user supplies the incorrect number of arguments. \*)

let rec setparams fxn\_env' = function

[] -> fxn\_env'

| hd :: tail ->

(\* make sure we evaluate the parameter

\* expressions in their CURRENT environments \*)

let (param\_expr\_val, \_) = eval env scope (snd hd)

in

setparams (NameMap.add (fst hd) param\_expr\_val fxn\_env') tail

in let fxn\_env =

setparams fxn\_env (List.combine target\_fxn.params param\_exprs)

in

(\* Update the global env with the fxn\_env

\* before executing the function body. \*)

let update\_env = (NameMap.add target\_fxn.fname fxn\_env env)

in

try

let (update\_env', fxn\_name) = List.fold\_left (exec)

(update\_env, target\_fxn.fname)

target\_fxn.body

(\* by default, return 0 if no return statement given \*)

in "", update\_env'

with ReturnException(ret\_val, eval\_env) -> ret\_val, eval\_env

and

(\* =====================================================

\* exec function

\*

\* Takes Ast.stmt type and executes it, returning an

\* updated environment.

\* ===================================================== \*)

exec (env, scope) = function

Assign(var, e) ->

(\* update the environment for the expression first \*)

let e\_val, e\_env = eval env scope e in

(\* print\_endline (">>> " ^ var ^ " assigned " ^ e\_val); \*)

let update\_global = function

(var, var\_val) ->

let updated\_submap = (NameMap.add var var\_val (NameMap.find "\*global\*" e\_env))

in (NameMap.add "\*global\*" updated\_submap e\_env)

in

if scope = "\*global\*"

then

(\* If global scope, then just update the global env \*)

(update\_global (var, e\_val)), scope

else

let local\_decls = (NameMap.find scope e\_env)

in

(\* Look for variable in local scope \*)

if NameMap.mem var local\_decls

then

(\* If variable found in local scope, assign to local version;

\* otherwise, assign it in global scope. \*)

let updated\_env = (NameMap.add var e\_val local\_decls)

in (NameMap.add scope updated\_env e\_env), scope

else (update\_global (var, e\_val)), scope

| OutputC(var) ->

let e\_val, e\_env = eval env scope var

in

(\* print\_endline(e\_val); \*)

(\* Printf.printf( "%s\n", e\_val); \*)

(\* Printf.printf "%s\n" (Scanf.unescaped e\_val); \*)

e\_env, scope;

| OutputF(var, f) ->

(\* No-op, NEED TO DO) \*)

env, scope;

| If(cond, stmt\_lst) ->

let c1, c\_env = eval env scope cond in

if (bool\_of\_int (int\_of\_string c1)) then

List.fold\_left (exec) (c\_env, scope) stmt\_lst

else env, scope

| If\_else(cond, stmt\_lst1, stmt\_lst2) ->

let c1, c\_env = eval env scope cond in

if (bool\_of\_int (int\_of\_string c1)) then

List.fold\_left (exec) (c\_env, scope) stmt\_lst1

else

List.fold\_left (exec) (c\_env, scope) stmt\_lst2

| For(s1, e1, s2, stmt\_lst) ->

let (env, scope) = (exec (env, scope)) s1 in

let rec loop (env, scope) =

let v, env = eval env scope e1 in

if (bool\_of\_int (int\_of\_string v)) then

let (body\_env, body\_scope) = List.fold\_left (exec) (env, scope) stmt\_lst in

loop (exec (body\_env, body\_scope) s2)

else env, scope

in loop (env, scope)

| Return(exp) ->

let exp\_val, exp\_env = eval env scope exp in

raise (ReturnException(exp\_val, exp\_env))

in

let rec parse\_stmts env scope = function

[] -> env

| hd :: tail ->

(\* execute statements and return updated environments \*)

let (updated\_env, scope) = exec (env, scope) hd

in

(parse\_stmts updated\_env scope) tail

in

try

let init\_env =

(\* The initial global NameMap env consists of one key-value

\* pair, \*global\* : NameMap.empty. Then for every

\* function declaration, add a key-value pair where

\* the key is the function name, and the value is

\* a NameMap initialized with the function parameters

\* as keys, and empty strings for values. \*)

(List.fold\_left

(fun new\_env fxn\_decl ->

let fxn\_env = (List.fold\_left

(fun tmp\_env param\_id -> NameMap.add param\_id "" tmp\_env)

NameMap.empty

fxn\_decl.params)

in NameMap.add fxn\_decl.fname fxn\_env new\_env)

(NameMap.add "\*global\*" NameMap.empty NameMap.empty)

fxns\_lst)

in (parse\_stmts init\_env "\*global\*") stmt\_lst

with

| Failure(s) ->

print\_endline s;

exit 0;

## 8.9 compiler.ml

(\* FILENAME : compiler.ml

\* AUTHOR(S): Joe Lee (jyl2157), Dmitriy Gromov (dg2720)

\* PURPOSE : Translate abstract syntax tree to bytecode.

\*)

open Ast

open Bytecode

(\*open Ezatypes\*)

open Hashtypes

open Canvas

(\* global hash table

\* keys are absolute integer addresses

\* values are of type Hashtypes.ct \*)

let glob\_ht = Hashtbl.create 2048

(\* initialize hash counter to keep track of next available key \*)

let hash\_counter = ref 0;

module StringMap = Map.Make(String)

(\* Translation environment \*)

type env = {

function\_idx : int StringMap.t; (\* Index for each function \*)

mutable global\_idx : int StringMap.t; (\* "Address" for global vars \*)

mutable local\_idx : int StringMap.t; (\* FP offset for args, locals \*)

num\_formals : int; (\* Number of parameters \*)

}

(\* enum : int -> 'a list -> (int \* 'a) list \*)

let rec enum stride n = function

[] -> []

| hd::tl -> (n, hd) :: enum stride (n+stride) tl

(\* string\_map\_pairs : StringMap 'a -> (int \* 'a) list -> StringMap 'a \*)

let string\_map\_pairs map pairs =

List.fold\_left (fun m (i, n) -> StringMap.add n i m) map pairs

(\* Translate a program in AST form into a bytecode program.

\* Throw an exception if something is wrong, (e.g. reference

\* to an unknown var or function.

\*)

let translate (stmt\_lst, func\_decls) =

let built\_in\_functions =

let rec bif\_helper map counter = function

[] -> map

| hd :: tl ->

(bif\_helper (StringMap.add hd (counter) map) (counter-1)) tl

(\* add built-in functions here \*)

(\* reserve -1 for printing \*)

(\* reserve -2 for printing to file \*)

in (bif\_helper StringMap.empty (-3)) ["load"; "blank"; "shift"]

in

let function\_indexes = string\_map\_pairs built\_in\_functions

(\* start built-in functions at 2, reserve 1 for

\* top-level statements pseudofunction \*)

(enum 1 2 (List.map (fun f -> f.fname) func\_decls)) in

(\* Translate an expr \*)

let rec expr env = function

Ast.IntLiteral(i) -> [Lit i]

| Ast.StrLiteral(s) ->

Hashtbl.add glob\_ht !hash\_counter (Hashtypes.String s);

let ret\_val = [Lct !hash\_counter] in

hash\_counter := !hash\_counter+1; (\* incr value of hash\_counter ref \*)

ret\_val

| Ast.BoolLiteral(b) ->

Hashtbl.add glob\_ht !hash\_counter (Hashtypes.Bool b);

let ret\_val = [Lct !hash\_counter] in

hash\_counter := !hash\_counter+1; (\* incr hash\_counter in-place \*)

ret\_val

| Ast.Id(s) ->

(try

let search\_local = (StringMap.find s env.local\_idx) in

[Lfp search\_local]

with Not\_found ->

(try

let search\_global = StringMap.find s env.global\_idx in

[Lod search\_global]

with Not\_found ->

raise (Failure ("Undeclared variable " ^ s))))

| Ast.Binop(e1, op, e2) ->

let ev1 = (expr env) e1

and ev2 = (expr env) e2 in

ev1 @ ev2 @ [Bin op]

| Ast.Call(fname, actuals) ->

(try

(\* first evaluate the actuals \*)

let res = (List.map (expr env) (List.rev actuals))

in

(List.concat res) @ [Jsr (StringMap.find fname env.function\_idx)]

with Not\_found ->

raise (Failure ("Undefined function: " ^ fname)))

| Ast.Load(filepath\_expr, gran\_expr) ->

let ev1\_val = (expr env) filepath\_expr

and ev2\_val = (expr env) gran\_expr in

ev1\_val @ ev2\_val @ [Jsr (-3)]

| Ast.Blank(height, width, granularity) ->

let ev1\_val = (expr env) height

and ev2\_val = (expr env) width

and ev3\_val = (expr env) granularity in

ev1\_val @ ev2\_val @ ev3\_val @ [Jsr (-4)]

| Ast.Select\_Point (x, y) ->

let ev1\_val = (expr env) x

and ev2\_val = (expr env) y in

ev1\_val @ ev2\_val @ [Lit (Canvas.select\_type (Canvas.POINT))]

| Ast.Select\_Rect (x1, x2, y1, y2) ->

let ev1\_val = (expr env) x1

and ev2\_val = (expr env) x2

and ev3\_val = (expr env) y1

and ev4\_val = (expr env) y2 in

ev1\_val @ ev2\_val @ ev3\_val @ ev4\_val @ [Lit (Canvas.select\_type (Canvas.RECT))]

| Ast.Select\_VSlice (x1, y1, y2) ->

let ev1\_val = (expr env) x1

and ev2\_val = (expr env) y1

and ev3\_val = (expr env) y2 in

ev1\_val @ ev2\_val @ ev3\_val @ [Lit (Canvas.select\_type (Canvas.VSLICE))]

| Ast.Select\_HSlice (x1, x2, y1) ->

let ev1\_val = (expr env) x1

and ev2\_val = (expr env) x2

and ev3\_val = (expr env) y1 in

ev1\_val @ ev2\_val @ ev3\_val @ [Lit (Canvas.select\_type (Canvas.HSLICE))]

| Ast.Select\_VSliceAll x ->

let ev1\_val = (expr env) x in

ev1\_val @ [Lit (Canvas.select\_type (Canvas.VSLICE\_ALL))]

| Ast.Select\_HSliceAll y ->

let ev1\_val = (expr env) y in

ev1\_val @ [Lit (Canvas.select\_type (Canvas.HSLICE\_ALL))]

| Ast.Select\_All ->

[Lit (Canvas.select\_type (Canvas.ALL))]

| Ast.Select (canv, selection) ->

let ev1\_val = (expr env) canv

in

(expr env) selection @ ev1\_val @ [Jsr (-6)]

| Ast.Select\_Bool(e) ->

let expr\_val = (expr env) e in

expr\_val @ [Lit (Canvas.select\_type (Canvas.BOOL))]

| Ast.Select\_Binop (op, e) ->

let expr\_val = (expr env) e

and op\_id = Ast.op\_id op in

expr\_val @ [Lit op\_id]

| Ast.Shift(canv, dir, count) ->

let canv\_val = (expr env) canv

and dir\_val = (expr env) dir

and count\_val = (expr env) count in

count\_val @ dir\_val @ canv\_val @ [Jsr (-5)]

| Ast.GetAttr(canv, attr) ->

let canv\_val = (expr env) canv

in

canv\_val @ [CAtr attr]

(\* \*)

and stmt env scope = function

(\* need to update assign later \*)

Ast.Assign(var, e) ->

let ev = (expr env e) in

ev @

if scope = "\*local\*"

then

(\*

\* if we are in a function, variable lookup proceeds as:

\* 1) Check if the variable is a formal (parameter)

\* 2) Check if the variable is declared globally

\* 3) Finally if both 1 and 2 don't hold, create a new local

\*)

if (StringMap.mem var env.local\_idx)

then

let exis\_local\_idx = StringMap.find var env.local\_idx in

(\* side effect: update env.local\_idx \*)

env.local\_idx <- (StringMap.add var exis\_local\_idx env.local\_idx);

[Sfp exis\_local\_idx]

else

if (StringMap.mem var env.global\_idx)

then

let exis\_global\_idx = StringMap.find var env.global\_idx in

(\* side effect: update env.global\_idx \*)

env.global\_idx <- (StringMap.add var exis\_global\_idx env.global\_idx);

[Str exis\_global\_idx]

else

(\* note the +1 for the next available local idx \*)

let new\_local\_idx = (List.length (StringMap.bindings env.local\_idx)) + 1

in

(\* side effect: modify env.local\_idx \*)

env.local\_idx <- (StringMap.add var new\_local\_idx env.local\_idx);

[Sfp new\_local\_idx]

else

[Str

(if (StringMap.mem var env.global\_idx)

then

let exis\_global\_idx = StringMap.find var env.global\_idx in

env.global\_idx <- (StringMap.add var exis\_global\_idx env.global\_idx);

exis\_global\_idx

else

let new\_global\_idx = (List.length (StringMap.bindings env.global\_idx))

in

(\* side effect: modify env.global\_idx \*)

env.global\_idx <- (StringMap.add var new\_global\_idx env.global\_idx);

new\_global\_idx)]

| Ast.OutputC(var, rend) ->

let var\_val = (expr env var) in

let rend\_val = (expr env rend) in

rend\_val @ var\_val @ [Jsr (-1)]

| Ast.OutputF(var, fn, rend) ->

let var\_val = (expr env var) in

let fn\_val = (expr env fn) in

let rend\_val = (expr env rend) in

rend\_val @ fn\_val @ var\_val @ [Jsr (-2)]

| Ast.If(cond, stmt\_lst) ->

let t\_stmts = (List.concat (List.map (stmt env scope) stmt\_lst))

in

(expr env cond) @

[Beq (1 + List.length t\_stmts)] @

t\_stmts

| Ast.If\_else(cond, stmt\_lst1, stmt\_lst2) ->

let t\_stmts = (List.concat (List.map (stmt env scope) stmt\_lst1))

and f\_stmts = (List.concat (List.map (stmt env scope) stmt\_lst2))

in

(expr env cond) @

[Beq (2 + List.length t\_stmts)] @

t\_stmts @

[Bra (1 + List.length f\_stmts)] @

f\_stmts

| Ast.For(s1, e1, s2, stmt\_lst) ->

(\* note: order of executing statements and evaluating expressions here

\* matters since the environment can be updated on each

\* execution/evaluation

\*)

let s1' = (stmt env scope s1)

and e1' = (expr env e1)

and for\_body\_stmts = (List.concat (List.map (stmt env scope) stmt\_lst)) @ (stmt env scope s2)

in

let

for\_body\_length = (List.length for\_body\_stmts) in

s1' @

[Bra (1 + for\_body\_length)] @

for\_body\_stmts @

e1' @

[Bne (-(for\_body\_length + List.length e1'))]

| Ast.Return(e) ->

(expr env e) @ [Rts env.num\_formals]

| Ast.CanSet(can, select\_exp, inten)->

let int\_exp = (expr env inten)

and sel\_exp = (expr env select\_exp)

and can\_exp = (expr env can) in

sel\_exp @ int\_exp @ can\_exp @ [Jsr (-7)]

| Ast.Include(str) ->

[]

(\*

\* Translates a function

\*)

in let translate env fdecl =

(\* Bookkeeping: FP offsets for locals and args \*)

let num\_formals = List.length fdecl.params

(\* we don't currently have locals...\*)

and num\_locals = 0 (\* List.length \*)

and formal\_offsets = (enum (-1) (-2) fdecl.params)

in

let formal\_offsets' = (List.map (fun (i, s) -> (i, s)) formal\_offsets)

in

let env = { env with local\_idx = string\_map\_pairs StringMap.empty formal\_offsets';

num\_formals = num\_formals }

in

[Ent num\_locals] @ (\* Entry: allocate space for locals \*)

(List.concat (List.map (stmt env "\*local\*") fdecl.body)) @ (\* Body \*)

[Lit 0; Rts num\_formals] (\* Default - return 0 \*)

in let env = {

function\_idx = function\_indexes;

global\_idx = StringMap.empty; (\* global\_indexes; \*)

local\_idx = StringMap.empty;

num\_formals = 0

} in

(\* Compile the global statement list \*)

let glob\_stmts = (List.concat (List.map (stmt env "\*global\*") stmt\_lst)) in

let main\_func\_call =

try

[Jsr (StringMap.find "main" function\_indexes)]

with Not\_found -> []

in

(\* Compile the functions, and prepend compiled global statements and Hlt \*)

let func\_bodies = (glob\_stmts @ main\_func\_call) :: [Hlt] :: List.map (translate env) func\_decls in

(\* Calculate function entry points by adding their lengths \*)

let (fun\_offset\_list, \_) = List.fold\_left

(fun (l, i) f -> (i :: l, (i + List.length f)))

([], 0)

func\_bodies in

let func\_offset = Array.of\_list (List.rev fun\_offset\_list)

in

{

num\_globals = List.length (StringMap.bindings env.global\_idx);

(\* Concatenate the compiled functions and replace the

\* function indexes in Jsr statements with PC values \*)

text = Array.of\_list

(List.map (function Jsr i when i > 0 ->

Jsr func\_offset.(i)

| \_ as s -> s)

(List.concat func\_bodies));

glob\_hash = glob\_ht;

glob\_hash\_counter = hash\_counter;

}

## 8.10 bytecode.ml

(\* FILENAME : bytecode.ml

\* AUTHOR(S): Joe Lee (jyl2157), Dmitriy Gromov (dg2720)

\* PURPOSE : Specify assembly operators, type definition of prog

\* which is returned by Compiler.translate, and a string

\* representation (string\_of\_prog).

\*)

open Ast

open Hashtypes

type bstmt =

Lit of int (\* Push a literal \*)

| Drp (\* Discard a value \*)

| Bin of Ast.op (\* Perform arithmetic on top of stack \*)

| Lod of int (\* Fetch global variable \*)

| Str of int (\* Store global variable \*)

| Lfp of int (\* Load frame pointer relative \*)

| Sfp of int (\* Store frame pointer relative \*)

| Jsr of int (\* Call function by absolute address \*)

| Ent of int (\* PushFP, FP->SP, SP+=i \*)

| Rts of int (\* Restore FP, SP, consume formals, push result \*)

| Beq of int (\* Branch relative if top-of-stack is zero \*)

| Bne of int (\* Branch relative if top-of-stack is non-zero \*)

| Bra of int (\* Branch relative \*)

| Lct of int (\* Load complex type by absolute address \*)

| CAtr of Ast.attr (\* Get Canvas Attribute\*)

| Hlt (\* Terminate \*)

\*)

type prog = {

num\_globals : int; (\* Number of global variables \*)

text : bstmt array; (\* Code for all the functions \*)

(\* global hash table initially populated by compiler \*)

glob\_hash : (int, Hashtypes.ct) Hashtbl.t;

glob\_hash\_counter : int ref;

}

let string\_of\_prog prog =

let rec string\_of\_prog\_helper s = function

[] -> s

| hd :: tail ->

let s =

match hd with

Lit(i) -> s ^ "Lit " ^ string\_of\_int i ^ "\n"

| Drp -> s ^ "Drp\n"

| Bin(op) -> s ^ "Bin\n"

| Lod(i) -> s ^ "Lod " ^ string\_of\_int i ^ "\n"

| Str(i) -> s ^ "Str " ^ string\_of\_int i ^ "\n"

| Lfp(i) -> s ^ "Lfp " ^ string\_of\_int i ^ "\n"

| Sfp(i) -> s ^ "Sfp " ^ string\_of\_int i ^ "\n"

| Jsr(i) -> s ^ "Jsr " ^ string\_of\_int i ^ "\n"

| Ent(i) -> s ^ "Ent " ^ string\_of\_int i ^ "\n"

| Rts(i) -> s ^ "Rts " ^ string\_of\_int i ^ "\n"

| Beq(i) -> s ^ "Beq " ^ string\_of\_int i ^ "\n"

| Bne(i) -> s ^ "Bne " ^ string\_of\_int i ^ "\n"

| Bra(i) -> s ^ "Bra " ^ string\_of\_int i ^ "\n"

| Lct(i) -> s ^ "Lct " ^ string\_of\_int i ^ "\n"

| CAtr(a) -> s ^ "Catr " ^ Ast.string\_of\_attr a ^ "\n"

| Hlt -> s ^ "Hlt\n"

in string\_of\_prog\_helper s tail

in string\_of\_prog\_helper "" (Array.to\_list prog.text)

## 8.11 execute.ml

(\* FILENAME : execute.ml

\* AUTHOR(S): Joe Lee (jyl2157), Dmitriy Gromov (dg2720)

\* PURPOSE : Execute bytecode returned from Compile.translate

\*)

open Ast

open Bytecode

open Hashtypes

open Canvas

(\* stack type can be either Int (value) or Address (pointer) \*)

type stack\_t =

IntValue of int

| Address of int

let execute\_prog prog debug\_flag =

(\* wrapper functions around extracting types from the stack \*)

let pop\_int = function

IntValue(i) -> i

| Address(i) -> raise (Failure ("Expected an int but popped an address."))

and pop\_address\_val = function

IntValue(i) -> raise (Failure ("Expected an address but popped an int."))

| Address(i) -> (Hashtbl.find prog.glob\_hash i)

in

let stack = Array.make 1024 (IntValue 0)

and globals = Array.make prog.num\_globals (IntValue 0)

in

let get\_pnts sel\_type soff canv =

(\* This match should be on some sort of enum \*)

let h = (Canvas.height canv -1)

and w = (Canvas.width canv -1) in

( match sel\_type with

1 ->

let x = pop\_int stack.(soff - 1)

and y = pop\_int stack.(soff) in

Canvas.select\_point x y

| 2 ->

let x1 = pop\_int stack.(soff - 3)

and x2 = pop\_int stack.(soff - 2)

and y1 = pop\_int stack.(soff - 1)

and y2 = pop\_int stack.(soff) in

Canvas.select\_rect x1 x2 y1 y2

| 3 ->

let x = pop\_int stack.(soff - 2)

and y1 = pop\_int stack.(soff - 1)

and y2 = pop\_int stack.(soff) in

Canvas.select\_hslice x y1 y2

| 4 ->

let x1 = pop\_int stack.(soff - 2)

and x2 = pop\_int stack.(soff - 1)

and y = pop\_int stack.(soff) in

Canvas.select\_vslice x1 x2 y

| 5 ->

let x = pop\_int stack.(soff) in

Canvas.select\_hslice\_all x w

| 6 ->

let y = pop\_int stack.(soff) in

Canvas.select\_vslice\_all y h

| 7 ->

Canvas.select\_all h w

| 8 ->

let op\_id = pop\_int stack.(soff)

and limit = pop\_int stack.(soff - 1) in

(match op\_id with

0 ->

let eq x y =

Canvas.get x y canv == limit in

Canvas.fetch\_match 0 h w eq [];

| 1 ->

let neq x y =

Canvas.get x y canv != limit in

Canvas.fetch\_match 0 h w neq [];

| 2 ->

let less x y =

Canvas.get x y canv < limit in

Canvas.fetch\_match 0 h w less [];

| 3 ->

let leq x y =

Canvas.get x y canv <= limit in

Canvas.fetch\_match 0 h w leq [];

| 4 ->

let gt x y =

Canvas.get x y canv > limit in

Canvas.fetch\_match 0 h w gt [];

| 5 ->

let gte x y =

Canvas.get x y canv >= limit in

Canvas.fetch\_match 0 h w gte [];

| \_ -> raise (Failure("Invalid Select: SS should catch this")))

| \_ ->

raise (Failure("Invalid Select: SS should catch this")) )

and debug s =

if debug\_flag then print\_string s

in

debug ("DEBUG: num\_globals is " ^ string\_of\_int prog.num\_globals ^ "\n");

try

let rec exec fp sp pc =

debug ("DEBUG: fp=" ^ (string\_of\_int fp) ^ ", sp=" ^ (string\_of\_int sp) ^ ", pc=" ^ (string\_of\_int pc) ^ ": ");

match prog.text.(pc) with

Lit i ->

stack.(sp) <- IntValue i;

debug ("Lit " ^ string\_of\_int i ^ "\n");

exec fp (sp+1) (pc+1)

| Lct i ->

stack.(sp) <- Address i;

debug ("Lct " ^ string\_of\_int i ^ "\n");

exec fp (sp+1) (pc+1)

| Drp ->

debug ("Drp " ^ "\n");

exec fp (sp-1) (pc+1)

| Bin op ->

let op1 =

(match stack.(sp-2) with

IntValue(i) -> Hashtypes.Int(i)

| Address(i) -> (Hashtbl.find prog.glob\_hash i) (\* add error handling \*)

)

and op2 =

(match stack.(sp-1) with

IntValue(i) -> Hashtypes.Int(i)

| Address(i) -> (Hashtbl.find prog.glob\_hash i) (\* add error handling \*)

)

in

(stack.(sp-2) <-

(let boolean b = if b then 1 else 0

and bool\_of\_int i = if i > 0 then true else false

in

(match (op1, op2) with

(Hashtypes.Int(i), Hashtypes.Int(j)) ->

(match op with

Plus ->

debug("Bin +: i=" ^ string\_of\_int i ^ " j=" ^ string\_of\_int j ^ "\n");

IntValue (i + j)

| Minus ->

debug("Bin -: i=" ^ string\_of\_int i ^ " j=" ^ string\_of\_int j ^ "\n");

IntValue (i - j)

| Times ->

debug("Bin \*: i=" ^ string\_of\_int i ^ " j=" ^ string\_of\_int j ^ "\n");

IntValue (i \* j)

| Divide ->

debug("Bin /: i=" ^ string\_of\_int i ^ " j=" ^ string\_of\_int j ^ "\n");

IntValue (i / j)

| Mod ->

debug("Bin mod: i=" ^ string\_of\_int i ^ " j=" ^ string\_of\_int j ^ "\n");

IntValue (i mod j)

| Eq ->

debug("Bin eq: i=" ^ string\_of\_int i ^ " j=" ^ string\_of\_int j ^ "\n");

IntValue (boolean (i = j))

| Neq ->

debug("Bin neq: i=" ^ string\_of\_int i ^ " j=" ^ string\_of\_int j ^ "\n");

IntValue (boolean (i != j))

| Lt ->

debug("Bin <: i=" ^ string\_of\_int i ^ " j=" ^ string\_of\_int j ^ "\n");

IntValue (boolean (i < j))

| Gt ->

debug("Bin >: i=" ^ string\_of\_int i ^ " j=" ^ string\_of\_int j ^ "\n");

IntValue (boolean (i > j))

| Leq ->

debug("Bin <=: i=" ^ string\_of\_int i ^ " j=" ^ string\_of\_int j ^ "\n");

IntValue (boolean (i <= j))

| Geq ->

debug("Bin >=: i=" ^ string\_of\_int i ^ " j=" ^ string\_of\_int j ^ "\n");

IntValue (boolean (i >= j))

| Or ->

debug("Bin ||: i=" ^ string\_of\_int i ^ " j=" ^ string\_of\_int j ^ "\n");

IntValue (boolean ((bool\_of\_int i) || (bool\_of\_int j)))

| And ->

debug("Bin &&: i=" ^ string\_of\_int i ^ " j=" ^ string\_of\_int j ^ "\n");

IntValue (boolean ((bool\_of\_int i) && (bool\_of\_int j)))

| Mask ->

raise( Failure("Mask is not valid for bools. SS should catch this"))

)

| (Hashtypes.Bool(b1), Hashtypes.Bool(b2)) ->

(match op with

Eq ->

debug("Bin eq: b1=" ^ string\_of\_bool b1 ^ " b2=" ^ string\_of\_bool b2 ^ "\n");

Hashtbl.add prog.glob\_hash !(prog.glob\_hash\_counter) (Hashtypes.Bool (b1 = b2));

let ret\_val = Address !(prog.glob\_hash\_counter) in

prog.glob\_hash\_counter := !(prog.glob\_hash\_counter)+1;

ret\_val

| Neq ->

debug("Bin neq: b1=" ^ string\_of\_bool b1 ^ " b2=" ^ string\_of\_bool b2 ^ "\n");

Hashtbl.add prog.glob\_hash !(prog.glob\_hash\_counter) (Hashtypes.Bool (b1 != b2));

let ret\_val = Address !(prog.glob\_hash\_counter) in

prog.glob\_hash\_counter := !(prog.glob\_hash\_counter)+1;

ret\_val

| Or ->

debug("Bin ||: b1=" ^ string\_of\_bool b1 ^ " b2=" ^ string\_of\_bool b2 ^ "\n");

Hashtbl.add prog.glob\_hash !(prog.glob\_hash\_counter) (Hashtypes.Bool (b1 || b2));

let ret\_val = Address !(prog.glob\_hash\_counter) in

prog.glob\_hash\_counter := !(prog.glob\_hash\_counter)+1;

ret\_val

| And ->

debug("Bin &&: b1=" ^ string\_of\_bool b1 ^ " b2=" ^ string\_of\_bool b2 ^ "\n");

Hashtbl.add prog.glob\_hash !(prog.glob\_hash\_counter) (Hashtypes.Bool (b1 && b2));

let ret\_val = Address !(prog.glob\_hash\_counter) in

prog.glob\_hash\_counter := !(prog.glob\_hash\_counter)+1;

ret\_val

| \_ ->

raise (Failure ("Binop not supported for boolean types."))

)

| (Hashtypes.String(s1), Hashtypes.String(s2)) ->

(match op with

Plus ->

(\* + operator for string operands is a

\* concatenation \*)

debug("Bin +: string1=" ^ s1 ^ " string2=" ^ s2 ^ "\n");

Hashtbl.add prog.glob\_hash !(prog.glob\_hash\_counter) (Hashtypes.String (s1 ^ s2));

let ret\_val = Address !(prog.glob\_hash\_counter) in

prog.glob\_hash\_counter := !(prog.glob\_hash\_counter) + 1;

ret\_val

| \_ ->

raise (Failure ("Binop not supported for string types."))

)

| (Hashtypes.Canvas(c1), Hashtypes.Canvas(c2)) ->

( match op with

Mask ->

debug("Canvas 1\n: " ^(Hashtypes.string\_of\_ct true (Hashtypes.Canvas(c1)) ) ^ "\n");

debug("Canvas 1\n: " ^(Hashtypes.string\_of\_ct true (Hashtypes.Canvas(c2)) ) ^ "\n");

Hashtbl.add prog.glob\_hash !(prog.glob\_hash\_counter) (Hashtypes.Canvas (Canvas.mask c1 c2));

let ret\_val = Address !(prog.glob\_hash\_counter) in

prog.glob\_hash\_counter := !(prog.glob\_hash\_counter)+1;

ret\_val

| \_ ->

raise (Failure ("Binop not supported for canvas types."))

)

| (\_, \_) ->

(\* This shouldn't happened if the SS gets to it first \*)

raise (Failure ("Binop not supported on those operand types."))

)));

exec fp (sp-1) (pc+1)

| Lod i ->

stack.(sp) <- globals.(i);

debug ("Lod " ^ string\_of\_int i ^ " Global=" ^

(match globals.(i) with

IntValue(j) -> "Int value " ^ string\_of\_int j

| Address(j) -> "Pointer to address " ^ string\_of\_int j

) ^ "\n");

exec fp (sp+1) (pc+1)

| Str i ->

(\*

(match (stack.(sp-1), globals.(i)) with

Address(j), Address(k) ->

if j != k then

(\* if assigning a different pointer to a hash pair, no

\* longer need the old hash pair, so remove it \*)

(); (\*Hashtbl.remove prog.glob\_hash k; \*)

globals.(i) <- stack.(sp-1)

| \_ ->

globals.(i) <- stack.(sp-1));

\*)

globals.(i) <- stack.(sp-1);

debug ("Str " ^ string\_of\_int i ^ "\n");

exec fp sp (pc+1)

| Lfp i ->

(\*

(match (stack.(fp+i), stack.(sp)) with

Address(j), Address(k) ->

if j != k then

(\* if over-writing a local, remove hash for

\* the local being overwritten \*)

(\* if assigning a different pointer to a hash pair, no

\* longer need the old hash pair, so remove it \*)

Hashtbl.remove prog.glob\_hash k;

stack.(sp) <- stack.(fp+i)

| \_ ->

stack.(sp) <- stack.(fp+i));

\*)

stack.(sp) <- stack.(fp + i);

debug ("Lfp " ^ string\_of\_int i ^ "\n");

exec fp (sp+1) (pc+1)

| Sfp i ->

stack.(fp+i) <- stack.(sp-1);

debug ("Sfp " ^ string\_of\_int i ^ "\n");

exec fp (sp+1) (pc+1)

(\* here Jsr -1, refers to OutputC functionality \*)

| CAtr atr ->

debug ("CAtr ");

let canv\_id = stack.(sp-1) in

let canv = (match pop\_address\_val canv\_id with

Hashtypes.Canvas(c) -> c

| \_ -> raise (Failure ("Catr needs to be given a canvas"))) in

let result =

(

match atr with

Ast.W -> Canvas.width canv

| Ast.H -> Canvas.height canv

| Ast.G -> Canvas.granularity canv

) in

stack.(sp-1) <- IntValue result;

exec fp sp (pc+1)

| Jsr(-1) ->

debug ("Jsr -1" ^ "\n");

let lookup =

(match stack.(sp-1) with

IntValue(i) -> Hashtypes.Int(i)

| Address(i) ->

try (Hashtbl.find prog.glob\_hash i)

with Not\_found ->

(\* add error handling \*)

raise(Failure("Jsr -1: No value found at address " ^ string\_of\_int i))

) in

let render =

(match stack.(sp-2) with

IntValue(i) -> raise (Failure ("Jsr -1: Render should be a boolean."))

| Address(i) ->

match (Hashtbl.find prog.glob\_hash i) with

Hashtypes.Bool(b) -> b

| \_ -> raise(Failure ("Jsr -1: Render should be a boolean."))

) in

print\_endline (Hashtypes.string\_of\_ct render lookup);

exec fp sp (pc+1)

| Jsr(-2) ->

debug ("Jsr -2");

let lookup =

(match stack.(sp-1) with

IntValue(i) -> Hashtypes.Int(i)

| Address(i) -> (Hashtbl.find prog.glob\_hash i) (\* add error handling \*)

) in

let render =

(match stack.(sp-3) with

IntValue(i) -> raise (Failure ("Render should be a boolean"))

| Address(i) -> match (Hashtbl.find prog.glob\_hash i)

with

Hashtypes.Bool(b) -> b (\* add error handling \*)

| \_ -> raise (Failure("Jsr -2 expected a boolean render but got a different type."))

) in

let filename =

( match (pop\_address\_val stack.(sp-2)) with

Hashtypes.String(s) ->

(match lookup with

Hashtypes.Canvas(c) -> Canvas.make\_name s render

| \_ -> s )

| \_ ->

raise (Failure("Jsr -2 expected a string filepath but got a different type."))

) in

let oc = open\_out filename in

output\_string oc ( (Hashtypes.string\_of\_ct render lookup) ^ "\n" );

exec fp sp (pc+1)

| Jsr(-3) ->

(\* CANVAS LOADING \*)

debug ("Jsr -2" ^ "\n");

let gran\_val = pop\_int(stack.(sp-1))

and path =

match (pop\_address\_val stack.(sp-2)) with

Hashtypes.String(s) -> s

| \_ ->

raise (Failure("Jsr -2 expected a string filepath but got a different type."))

in

let granularity = string\_of\_int gran\_val

in

let filename\_parts = Str.split (Str.regexp "/") path in

let filename =

match Str.string\_match (Str.regexp ".+.i") (List.hd (List.rev filename\_parts)) 0 with

false ->

debug ("Trying to open: " ^ "../tmp/" ^ List.hd (List.rev filename\_parts) ^ ".i" ^ "\n");

let comm = "python util/load\_img.py " ^ path ^ " " ^ granularity in

let \_ = Sys.command (comm)

in ();

"../tmp/" ^ List.hd (List.rev filename\_parts) ^ ".i"

| true ->

debug ("Trying to open raw: " ^ path ^ "\n");

path

in

Hashtbl.add prog.glob\_hash !(prog.glob\_hash\_counter)

(Hashtypes.Canvas (Canvas.load\_canvas filename gran\_val));

let ret\_val = Address !(prog.glob\_hash\_counter) in

prog.glob\_hash\_counter := !(prog.glob\_hash\_counter)+1;

stack.(sp-1) <- ret\_val;

exec fp sp (pc+1)

| Jsr(-4) ->

(\* BLANK \*)

debug ("Jsr -4" ^ "\n");

let h\_val = (pop\_int stack.(sp-3))

and w\_val = (pop\_int stack.(sp-2))

and g\_val = (pop\_int stack.(sp-1))

in

Hashtbl.add prog.glob\_hash !(prog.glob\_hash\_counter)

(Hashtypes.Canvas (Canvas.blank h\_val w\_val g\_val 0));

let ret\_val = Address !(prog.glob\_hash\_counter) in

prog.glob\_hash\_counter := !(prog.glob\_hash\_counter)+1;

stack.(sp-1) <- ret\_val;

exec fp sp (pc+1)

| Jsr (-5) ->

(\* SHIFT \*)

debug ("Jsr -5" ^ "\n");

let existing = match (pop\_address\_val stack.(sp-1)) with

Hashtypes.Canvas(c) -> c

| \_ -> raise(Failure("Jsr -6: Expected canvas type."))

and dir = pop\_int stack.(sp-2)

and dist = pop\_int stack.(sp-3)

in

let shifted = (Canvas.shift existing dir dist) in

Hashtbl.add prog.glob\_hash !(prog.glob\_hash\_counter)

(Hashtypes.Canvas (shifted));

let ret\_val = Address !(prog.glob\_hash\_counter) in

prog.glob\_hash\_counter := !(prog.glob\_hash\_counter)+1;

stack.(sp-1) <- ret\_val;

exec fp sp (pc+1)

| Jsr (-6) ->

(\* SELECT \*)

debug ("Jsr -6: - Select Piece of Canvas" ^ "\n");

let existing = match (pop\_address\_val stack.(sp-1)) with

Hashtypes.Canvas(c) -> c

| \_ -> raise(Failure("Jsr -6: Expected canvas type.")) in

let sel\_type = (pop\_int stack.(sp-2)) in

let stack\_offset = sp-3 in

let pnts = get\_pnts

sel\_type stack\_offset existing in

let selected = (Canvas.select\_rect\_from\_list pnts existing) in

Hashtbl.add prog.glob\_hash !(prog.glob\_hash\_counter) (Hashtypes.Canvas(selected));

let ret\_val = Address !(prog.glob\_hash\_counter) in

prog.glob\_hash\_counter := !(prog.glob\_hash\_counter)+1;

stack.(sp-1) <- ret\_val;

exec fp sp (pc+1)

| Jsr (-7) ->

(\* SET POINT \*)

debug ("Jsr -7: - Set point" ^ "\n");

let existing = match (pop\_address\_val stack.(sp-1)) with

Hashtypes.Canvas(c) -> c

| \_ -> raise(Failure("Jsr -6: Expected canvas type."))

and set\_val = (pop\_int stack.(sp-2))

and sel\_type = (pop\_int stack.(sp-3))

and stack\_offset = sp-4 in

let pnts = get\_pnts sel\_type stack\_offset existing in

Canvas.set\_from\_list existing set\_val pnts;

(\*

Don't actually need to set the canvas back to what it was because it's being modified directly.

let modified\_can = (Canvas.set\_from\_list existing set\_val pnts) in

Hashtbl.add prog.glob\_hash !(prog.glob\_hash\_counter) (Hashtypes.Canvas(modified\_can));

\*)

exec fp sp (pc + 1)

| Jsr i ->

stack.(sp) <- IntValue (pc + 1);

debug ("Jsr " ^ string\_of\_int i ^ "\n");

exec fp (sp+1) i

| Ent i ->

stack.(sp) <- IntValue (fp);

debug ("Ent " ^ string\_of\_int i ^ "\n");

exec sp (sp+i+1) (pc+1)

| Rts i ->

let new\_fp = pop\_int stack.(fp)

and new\_pc = pop\_int stack.(fp-1)

in

stack.(fp-i-1) <- stack.(sp-1);

debug ("Rts " ^ string\_of\_int i ^ "\n");

exec new\_fp (fp-i) new\_pc

| Beq i ->

debug ("Beq " ^ string\_of\_int i ^ "\n");

exec fp (sp-1)

(pc +

if (match stack.(sp-1) with

IntValue(k) -> (k = 0)

| Address(k) -> match (Hashtbl.find prog.glob\_hash k) with

Hashtypes.Bool(b) -> not b

| \_ -> raise(Failure("Beq operation: Address lookup resulted in a non-boolean type.")))

then i

else 1)

| Bne i ->

debug ("Bne " ^ string\_of\_int i ^ "\n");

exec fp (sp-1)

(pc +

if (match stack.(sp-1) with

IntValue(k) -> (k != 0)

| Address(k) -> match (Hashtbl.find prog.glob\_hash k) with

Hashtypes.Bool(b) -> not b

| \_ -> raise(Failure("Bne operation: Address lookup resulted in a non-boolean type.")))

then i

else 1)

| Bra i ->

debug ("Bra " ^ string\_of\_int i ^ "\n");

exec fp sp (pc+i)

| Hlt -> ()

in exec 0 0 0

with e -> (\* catch all exceptions \*)

Printf.eprintf "Runtime error: %s\n" (Printexc.to\_string e);

## 8.12 canvas.ml

(\* AUTHOR(S): Dmitriy Gromov (dg2720), Joe Lee (jyl2157)

\* PURPOSE : Canvas functions (loading, preprocessing, blank,

\* string\_of\_canvas, etc...).

\*)

module IntMap =

Map.Make(

struct type t = int

let compare = compare end

)

let make\_map vals =

let rec add\_val the\_map = function

v :: vs -> (add\_val (IntMap.add (IntMap.cardinal the\_map) v the\_map) vs)

| [] -> the\_map

in add\_val IntMap.empty vals

(\* Default mapping taken from http://incredibleart.org/links/ascii/new\_faq.html \*)

let default\_map =

make\_map (['.';'`';'^';':';'"';';';'~';

'-';'\_';'+';'<';'>';'i';'!'

;'l';'I';'l';'?';'|';

'(';')';'1';'{';'}';'[';']';

'r';'c';'v';'u';'n';'x';'z';'j'

;'f';'t';'L';'C';'J';'U';'Y';'X'

;'Z';'O';'0';'Q';'o';'a';'h';'k'

;'b';'d';'p';'q';'w';'m';'\*';'W';

'M';'B';'8';'&';'%';'$';'#';'@'])

(\* If 0 or Max Granularity Then min or max, otherwise even dist \*)

let get\_char\_for\_intensity intensity granularity map =

let max\_int = (granularity - 1) in

let card = (IntMap.cardinal map) in

let idx =

match intensity == 0 with

true -> 0

| false -> match intensity == max\_int with

true -> ((card-1))

| false -> let divisor = ( card - 2 ) / (granularity - 2) in

let x = (card - 2 ) / divisor in

x \* intensity

in

Char.escaped (IntMap.find idx map);

type canvas =

{

data: int array array;

gran: int;

};;

type stypes =

POINT

| RECT

| VSLICE

| HSLICE

| VSLICE\_ALL

| HSLICE\_ALL

| ALL

| BOOL

let select\_type = function

POINT -> 1

| RECT -> 2

| VSLICE -> 3

| HSLICE -> 4

| VSLICE\_ALL -> 5

| HSLICE\_ALL -> 6

| ALL -> 7

| BOOL -> 8

type dir =

UP

| LEFT

| DOWN

| RIGHT

let get\_dir = function

0 -> (UP)

| 1 -> (LEFT)

| 2 -> (DOWN)

| 3 -> (RIGHT)

| \_ -> raise(Failure ("Not a valid Direction"))

(\* Blank Function \*)

let blank height width granularity default=

{

data = Array.make\_matrix height width default;

gran = granularity

}

(\* Make File Name \*)

let make\_name name render =

if render then

name

else

String.concat "" [name; ".i"]

(\* Print Row \*)

let string\_of\_row row render the\_map gran =

match render with

false -> String.concat " " (Array.to\_list (Array.map string\_of\_int row ))

| true -> String.concat "" (Array.to\_list (Array.map (fun x -> match x with

(-1) -> " "

| \_ -> (get\_char\_for\_intensity

x gran the\_map)) row))

let string\_of\_canvas can map render =

String.concat "\n" (Array.to\_list(Array.map (fun r -> string\_of\_row r render map can.gran ) can.data))

(\* CANVAS ATTRIBUTES \*)

let height can =

Array.length can.data

let width can =

Array.length can.data.(0)

let granularity can =

can.gran

(\* END CANVAS ATTRIBUTES \*)

let create\_blank\_from\_existing existing default =

blank (height existing) (width existing) (granularity existing) default

(\* SELECT \*)

let get x y can =

if x < (height can) && x >= 0

&& y < (width can) && y >= 0

then

can.data.(x).(y)

else

raise (Failure("(" ^ string\_of\_int x ^ ", " ^ string\_of\_int y ^ ") is out of bounds of canvas"))

(\* MASK \*)

let set x y intensity can =

if x < (height can) && x >= 0

&& y < (width can) && y >= 0

then

can.data.(x).(y) <- intensity

let accept\_all x y =

true

let rec fetch\_row x1 y1 y2 acc cond=

match y1 <= y2 with

true ->

if (cond x1 y1) then

(x1, y1) :: fetch\_row x1 (y1+1) y2 acc cond

else fetch\_row x1 (y1+1) y2 acc cond

| false -> []

let rec fetch\_box x1 x2 y1 y2 acc =

match x1 <= x2 with

true -> (fetch\_row x1 y1 y2 acc accept\_all) @ fetch\_box (x1+1) x2 y1 y2 acc

| false -> []

let rec fetch\_match x h w cond acc =

match x <= h with

true -> (fetch\_row x 0 w acc cond) @ fetch\_match (x+1) h w cond acc

| false -> []

let string\_of\_point = function

(x, y) -> string\_of\_int x ^ " " ^ string\_of\_int y ;;

let rec print\_l = function

x :: xs -> print\_endline (string\_of\_point x);

print\_l xs

| [] -> ""

let rec set\_point can intensity = function

x :: xs -> (match (x) with

(i,j) ->

(match intensity >= 0 with

true -> set i j intensity can

| false -> ());

set\_point can intensity xs;

)

| [] -> ()

;;

(\* let set\_points\_int points can intensity =

let l = (fetch\_match can []) in

set\_point can intensity l

\*)

let set\_rect\_can l old\_can new\_can=

let rec set\_point = function

x :: xs -> (match x with

(i,j) ->

let selected = get i j old\_can in

match selected >= 0 with

true -> set i j selected new\_can

| false -> ()

);

set\_point xs;

| [] -> ()

in

set\_point (l);

(new\_can)

let set\_from\_list can intensity pnts =

set\_point can intensity pnts

let select\_rect\_from\_list l can =

let blank\_slate = create\_blank\_from\_existing can (-1) in

set\_rect\_can l can blank\_slate

(\*

The following functions simply return points representing various boxes

They are labels for the various select operations.

\*)

let select\_rect x1 x2 y1 y2 =

fetch\_box x1 x2 y1 y2 []

let select\_point x y =

fetch\_box x x y y []

let select\_hslice x y1 y2 =

fetch\_box x x y1 y2 []

let select\_vslice x1 x2 y =

fetch\_box x1 x2 y y []

let select\_hslice\_all x w=

fetch\_box x x 0 (w) []

let select\_vslice\_all y h =

fetch\_box 0 (h) y y []

let select\_all h w=

fetch\_box 0 (h) 0 (w) []

(\* END SELECT \*)

let mask can1 can2 =

let blank\_slate = create\_blank\_from\_existing can1 (-1) in

let pl = select\_all ((height can2)-1) ((width can2)-1) in

let cp\_can1 = set\_rect\_can pl can1 blank\_slate in

(set\_rect\_can pl can2 cp\_can1 )

let shift can dir steps =

let shifted = create\_blank\_from\_existing can (-1) in

let rec set\_point = function

x :: xs -> (match (x) with

(i,j) ->

( let intensity = get i j can

and new\_point =

(match ( get\_dir (dir) ) with

UP ->

(i - steps, j)

| DOWN ->

(i + steps, j)

| LEFT ->

(i, j - steps)

| RIGHT ->

(i, j + steps)

) in

(

match new\_point with

(a, b) -> set a b intensity shifted

)

)

);

set\_point xs;

| [] -> ()

in

let l =

(match ( get\_dir (dir) ) with

UP ->

(fetch\_box steps (((height can)-1)) 0 ((width can)-1) [])

| DOWN ->

(fetch\_box 0 (((height can)-1) - steps) 0 ((width can)-1) [])

| LEFT ->

(fetch\_box 0 ((height can)-1) steps ((width can)-1) [])

| RIGHT ->

(fetch\_box 0 (((height can)-1)) 0 (((width can)-1) - steps) [])

) in

set\_point (l);

shifted

(\* Loads an image from filepath fname, and returns

\* canvas type int array array \*)

let load\_canvas fname granularity =

let ic = open\_in fname in

let n = in\_channel\_length ic in

let s = String.create n in

really\_input ic s 0 n;

close\_in ic;

let lines = Str.split (Str.regexp("\n")) s in

let can = {

data = (Array.make\_matrix (List.length lines) (String.length (List.hd lines))) 0;

gran = granularity;

}

in

let x = ref 0 in

List.iter (

fun line ->

let row = Str.split (Str.regexp(" ")) line in

can.data.(!x) <- (Array.of\_list (List.map int\_of\_string row));

x := !x+1

) lines;

(can);;

## 8.13 ezac.ml

(\* FILENAME : ezac.ml

\* AUTHOR(S): Joe Lee (jyl2157), Dmitriy Gromov (dg2720)

\* PURPOSE : Top-level file providing command-line interface to

\* bytecode executor, compiler, interpreter.

\*)

open Ast

open Parser

open Scanner

open Bytecode

open Ssanalyzer

open Compiler

open Execute

open Preprocess

type action = Ast | StaticSemanticChecker | Interpret | Bytecode | Compile

let \_ =

let (action, debug\_flag, filepath) =

let param\_count = Array.length Sys.argv in

if param\_count > 2 then

let option = (List.assoc Sys.argv.(1)

[ ("-a", (Ast, false));

("-s", (StaticSemanticChecker, false));

("-i", (Interpret, false));

("-b", (Bytecode, false));

("-c", (Compile, false));

("-cd", (Compile, true))

])

in (fst option), (snd option), Sys.argv.(2)

else

if param\_count = 2 then

(Compile, false, Sys.argv.(1))

else raise (Failure ("Invalid number of arguments."))

in

let preprocessed = Preprocess.run (filepath) in

let lexbuf = Lexing.from\_string preprocessed in

let program = try

(Parser.program Scanner.token lexbuf)

with Parsing.Parse\_error ->

let curr = lexbuf.Lexing.lex\_curr\_p in

(\* let line = curr.Lexing.pos\_lnum in \*)

let cnum = curr.Lexing.pos\_cnum - curr.Lexing.pos\_bol in

let tok = Lexing.lexeme lexbuf in

print\_endline (">>> Parse error at character " ^ (string\_of\_int cnum) ^ ": '" ^ tok ^ "'");

exit 0;

in

let run\_ssanalyzer program =

(try

let ret = Ssanalyzer.semantic\_checker program

in ret

with

TypeException(astexpr1, astexpr2, expected\_typ, actual\_typ) ->

print\_endline("Type error at subexpression " ^ (Ast.string\_of\_expr astexpr1) ^ " in expression " ^ (Ast.string\_of\_expr astexpr2) ^ ". Expected type " ^ (Ssanalyzer.string\_of\_t expected\_typ) ^ " but got type " ^ (Ssanalyzer.string\_of\_t actual\_typ ^ "."));

exit(0)

| BinopException(astop, astexpr, expected\_op) ->

print\_endline("Binop error in expression " ^ (Ast.string\_of\_expr astexpr) ^ ". Expected binop " ^ (Ssanalyzer.string\_of\_t expected\_op) ^ " but got binop " ^ (Ast.string\_of\_op astop));

exit(0)

| UndefinedVarException(astexpr) ->

print\_endline("Undefined variable " ^ (Ast.string\_of\_expr astexpr));

exit(0)

| UndefinedFxnException(fxn\_name, astexpr2) ->

print\_endline("Undefined function " ^ fxn\_name ^ " in expression " ^ (Ast.string\_of\_expr astexpr2));

exit(0)

| Failure(s) ->

print\_endline(s);

exit(0)

)

in

match action with

Ast -> let listing = Ast.string\_of\_program program in print\_string listing

| StaticSemanticChecker ->

let \_ = run\_ssanalyzer program in

print\_endline("Static semantic checker finished with no errors.")

| Interpret ->

print\_string "Interpret: nada at the moment" (\* ignore (Interpret.run program) \*)

| Bytecode ->

let listing = Bytecode.string\_of\_prog (Compiler.translate program)

in print\_endline listing

| Compile ->

let checked\_prog = run\_ssanalyzer program

in

let program = Compiler.translate checked\_prog

in Execute.execute\_prog program debug\_flag

## 8.14 reuse.ml

(\* FILENAME : reuse.ml

\* AUTHOR(S): Joe Lee (jyl2157)

\* PURPOSE : Functions for re-use.

\*)

(\* given a string, splits it into a list of chars \*)

let explode s =

let rec exp i l =

if i < 0 then l else exp (i - 1) (s.[i] :: l) in

exp (String.length s - 1) [];

(\* given a list of chars, joins them and returns a string \*)

let implode lst =

let res = String.create (List.length lst) in

let rec imp i = function

| [] -> res

| c :: lst -> res.[i] <- c; imp (i + 1) lst in

imp 0 lst;

(\* debug function to inspect environment \*)

let env\_to\_str m =

let bindings = StringMap.bindings m in

let rec print\_map\_helper s = function

[] -> s

| hd :: tl -> print\_map\_helper ((fst hd) ^ " = " ^ (string\_of\_int (snd hd)) ^ "\n" ^ s) tl

in print\_map\_helper "" bindings;

## 8.15 Makefile

# FILENAME : Makefile

# AUTHOR(S): Joe Lee (jyl2157), Dmitriy Gromov (dg2720)

# PURPOSE : Makefile for EZ-ASCII project.

OBJS = ast.cmo scanner.cmo parser.cmo sast.cmo ssanalyzer.cmo preprocess.cmo bytecode.cmo canvas.cmo compiler.cmo hashtypes.cmo execute.cmo ezac.cmo

ezac : $(OBJS)

ocamlc -o ezac str.cma $(OBJS)

scanner.ml : scanner.mll

ocamllex scanner.mll

parser.ml parser.mli : parser.mly

ocamlyacc parser.mly

%.cmo : %.ml

ocamlc -c $<

%.cmi : %.mli

ocamlc -c $<

.PHONY : clean

clean :

rm -rf \*.cmo \*.cmi ezac parser.mli parser.ml scanner.ml

# generated by ocamldep \*.ml \*.mli

ast.cmo :

ast.cmx :

bytecode.cmo : hashtypes.cmo ast.cmo

bytecode.cmx : hashtypes.cmx ast.cmx

canvas.cmo :

canvas.cmx :

compiler.cmo : canvas.cmo hashtypes.cmo bytecode.cmo ast.cmo

compiler.cmx : canvas.cmx hashtypes.cmx bytecode.cmx ast.cmx

execute.cmo : hashtypes.cmo bytecode.cmo ast.cmo

execute.cmx : hashtypes.cmx bytecode.cmx ast.cmx

ezac.cmo : ssanalyzer.cmo scanner.cmo preprocess.cmo parser.cmi execute.cmo compiler.cmo bytecode.cmo ast.cmo

ezac.cmx : ssanalyzer.cmx scanner.cmx preprocess.cmx parser.cmx execute.cmx compiler.cmx bytecode.cmx ast.cmx

hashtypes.cmo : canvas.cmo

hashtypes.cmx : canvas.cmx

interpret.cmo : scanner.cmo parser.cmi ast.cmo

interpret.cmx : scanner.cmx parser.cmx ast.cmx

parser.cmo : ast.cmo parser.cmi

parser.cmx : ast.cmx parser.cmi

preprocess.cmo :

preprocess.cmx :

sast.cmo :

sast.cmx :

scanner.cmo : parser.cmi

scanner.cmx : parser.cmx

ssanalyzer.cmo :

ssanalyzer.cmx :

parser.cmi : ast.cmo

## 8.16 runtests.sh

#!/bin/bash

# FILENAME : runtests.sh

# AUTHOR(S): Joe Lee (jyl2157)

# PURPOSE : Shell script to run tests on executable.

# Each test in the tests dir is run on the executable

# with its standard out piped to a .out file. The .out

# file is compared with a corresponding .gs (gold standard)

# file for each test. If the test fails (output differs),

# a .diff file is created for developer use.

APP=$(dirname $0)/ezac

globallog=test\_ezac.log

testdir=tests

rm -f $globallog

error=0

Check() {

basename=$(basename $1)

basename=${basename%.\*}

ezafile=$testdir/${basename}.eza

reffile=$testdir/${basename}.gs

outfile=$testdir/${basename}.out

difffile=$testdir/${basename}.diff

echo -n "Running $basename..."

$APP $ezafile > $outfile 2>&1 || {

echo "Failed: ezac terminated."

error=1;

return 1

}

diff -b $reffile $outfile > $difffile 2>&1 || {

echo "Failed: output mismatch."

error=1;

return 1

}

rm $outfile $difffile

echo "OK."

}

for file in $testdir/test\*.eza

do

Check $file 2>> $globallog

done

exit $error