All That Matrix
Final Project Report

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COMS W4115
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Contents

1. Introduction .............................................................................................................. 4
   1.1 Motivation ........................................................................................................... 4
   1.2 Overview ............................................................................................................ 4

2. Language Tutorial .................................................................................................. 4
   2.1 First Example .................................................................................................... 4
   2.2 Matrix Example ................................................................................................. 5
   2.3 Compile and Run Your Program ...................................................................... 5

   3.1 Introduction ....................................................................................................... 5
   3.2 Lexical Elements ............................................................................................... 5
      3.2.1 Comments .................................................................................................. 5
      3.2.2 Identifiers ................................................................................................. 6
      3.2.3 Keywords .................................................................................................. 6
      3.2.4 Punctuations .............................................................................................. 6
      3.2.5 Constants .................................................................................................. 6
   3.3 Data Types ......................................................................................................... 7
      3.3.1 Int ................................................................................................................ 7
      3.3.2 Boolean ....................................................................................................... 7
      3.3.3 String .......................................................................................................... 7
      3.3.4 Matrix ......................................................................................................... 7
   3.4 Expressions and Operators .............................................................................. 7
      3.4.1 Expressions ............................................................................................... 7
      3.4.2 Binary Operators ....................................................................................... 7
      3.4.3 Logical Operators ...................................................................................... 8
      3.4.4 Built-in Features ....................................................................................... 8
   3.5 Statements .......................................................................................................... 9
   3.6 Declarations ...................................................................................................... 9
      3.6.1 Program Definition ..................................................................................... 9
      3.6.2 Function Declarations ............................................................................... 9
   3.7 Scope .................................................................................................................. 9
   3.8 References ....................................................................................................... 9

4. Project Plan ............................................................................................................. 10
   4.1 Process .............................................................................................................. 10
1. Introduction

All That Matrix (ATM) is a programming language targeted at matrix manipulations with emphasize on clear syntax and lightweight compiler.

1.1 Motivation

Applications of matrix are very common across scientific fields. In statistics, matrices are used for probability calculations. In computer graphics, matrices are used to project and transform images. And you won’t get through a lecture of linear algebra without encountering matrices.

ATM provides intuitive matrix related operators with the goal of avoiding as many built-in functions as possible and making it easy to write custom functions in the language itself. Thus, built-in types, operators, and keywords are kept to a minimal set.

1.2 Overview

The syntax of ATM is very similar to C and Java, so novice should have a minimal learning curve. ATM code is translated into a set of native bytecode, which then gets executed against a built-in stack to produce the output.

2. Language Tutorial

An ATM program is a single file consisting of functions, defined and written above the mandatory main function, which is where the program always kicks off.

2.1 First Example

This is greatest common divisor written in ATM. This example shows general purpose features in ATM including function declaration, while loop and conditionals.

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

main()
{
    print(gcd(3,15));
}
```
2.2 Matrix Example
This example illustrates the declaration, initiation and accessing of matrix data types.

```c
main()
{
    int i;
    int j;
    matrix[3][3] m;
    m = [1,2,3|4,5,6|7,8,9];
    for (i = 1 ; i < 4 ; i = i + 1) {
        for (j = 1 ; j < 4 ; j = j + 1) {
            print(m[i][j]);
        }
    }
}
```

2.3 Compile and Run Your Program
Write your code in a .atm file and compile it by running these two commands.

```
$ make
$ ./atm -c <[path to your .atm file]
```

This will compile and run your code. You can see the AST of your program by using the “-a” parameter and you can examine the list of bytecode generated by using the “-b” parameter.


3.1 Introduction
All That Matrix is a programming language targeted at matrix manipulations with emphasize on the clear syntax and a lightweight compiler. All That Matrix provides intuitive matrix related operators with the goal of avoiding as many built-ins as possible and making it easy to write custom functions in the language itself. This language reference manual is inspired by the C reference manual [1].

3.2 Lexical Elements
3.2.1 Comments
Comments are delineated with an opening /* and closing */. The compiler will ignore comments. Nesting of comments is not supported.

```c
/* This is a comment */
```
3.2.2 Identifiers
Identifiers are sequences of characters that must start with a lower case letter and can be
followed by any number of upper-case letter, lower-case letters, digits, and underscores, used for
naming variables and functions. Identifiers are case sensitive.

    Identifier -> [a-z][a-zA-Z_0-9]*

3.2.3 Keywords
Keywords are reserved for use as part of the programming language and therefore, cannot be
used for any other purposes.

    int      matrix      main      return
    if       else        for       while
    export   print

3.2.4 Punctuations
Parentheses are used to indicate function calls, signify conditionals, and group formal arguments
to functions.

Curly Braces are used to indicate a block of statements.

Semicolons are used to signal the end of a statement and also to separate statements and
expressions in for loops.

3.2.5 Constants
There are a total of four constants in ATM: integer literal, string literal, boolean, and matrix.

3.2.5.1 Integer Literals
An integer constant is a sequence of digits.

    Integer Constant -> [0-9]+

3.2.5.2 String Literals
String literal constants are delineated by double quotation marks and can contain any character.

    String Literal Constant -> "[a-zA-Z _'-:!' ]*"

3.2.5.4 Boolean
Boolean constants, used in conditional logic, are represented by integer literals: 1 for true and 0
for false.

    Boolean -> 0 | 1
3.2.5.4 Matrix
Matrix constant are enclosed in square brackets with vertical bars separating the rows and commas separating the columns. Matrix constants are filled by integer literals.

\[
\begin{bmatrix}
1, 2, 3 & 4, 5, 6
\end{bmatrix}
\]
is a 2 by 3 matrix

3.3 Data Types
3.3.1 Int
Integers are used to represent boolean and to build compound type matrix. It must be declared before use.

```c
int my_integer;
my_integer = 8;
```

3.3.2 Boolean
Booleans are represented by integers: 1 for true and 0 for false. Booleans are only intended to be used in conditionals, so they are not declared.

3.3.3 String
Strings are surrounded by double quotation marks and are only designed to be used in two places. The first one is in print statement such as

```c
print("test string");
```
The second one is in specifying the export file name as in

```c
export(out_val, "my_output.txt");
```

3.3.4 Matrix
The one supported compound data types is matrix, which is declared with the keyword matrix and the number of rows and columns specified in brackets as in

```c
matrix[3][4] my_matrix;
```

3.4 Expressions and Operators
3.4.1 Expressions
An expression consists of at least one operand and zero or more operators. Operands are one of the typed objects such as matrix and can be an identifier, a constant, or a function call that returns a value.

3.4.2 Binary Operators
Binary operators for int and matrix data types follow the standard arithmetic and matrix operation rules. These operators are valid between two objects of the same type for integers. However, for matrices, the types between the two expressions can differ for certain operators.
For example, multiplication between an integer and a matrix is equivalent to scaling the matrix by the integer, whereas multiplication between two matrices follows the standard matrix multiplication rules.

In other words, the behavior of the operators depends on the type of the operands provided. For example, when adding two integers: 5 + 10, the result is 15. When adding two row matrices \([a_1, b_1| c_1, d_1] + [a_2, b_2| c_2, d_2]\), the result is the matrix \([a_1+a_2, b_1+b_2| c_1+c_2, d_1+d_2]\).

\[
\text{expression} + \text{expression} \\
\text{expression} - \text{expression} \\
\text{expression} \times \text{expression}
\]

One additional operator for integers is division. Note that the result is rounded to integers according to the rules in OCaml.

\[
\text{expression} / \text{expression}
\]

### 3.4.3 Logical Operators

These logical operators between two integers or matrices evaluate to boolean and are to be used in control flow. The data type on the left and right sides of the operator must be the same. In the case of matrices, their dimension must be the same as well.

\[
\text{expression} == \text{expression} \\
\text{expression} != \text{expression}
\]

These are additional logical operators for expressions of integers only.

\[
\text{expression} < \text{expression} \\
\text{expression} <= \text{expression} \\
\text{expression} > \text{expression} \\
\text{expression} >= \text{expression}
\]

### 3.4.4 Built-in Features

All That Matrix also provides a limited set of built-in functions and features to retrieve and save information.

print() is a built-in function that print the item at the top of the stack. The output format for a matrix is spaces separating the columns and new lines separating the rows.

export(identifier, string filename) is a built-in function that writes the output to an external file specified.

col_count(matrix m) is a built-in function that returns the number of columns the input matrix has.

row_count(matrix m) is a built-in function that returns the number of rows the input matrix has.
3.5 Statements
All statements must end with a semi-colon. All statements either declare a variable, use, or modify an existing variable. If-then-else statements, for and while loops are supported. The syntax rules for them are the same as the C language. All of the following are examples of statements.

```
return 0;            /* return statement */
If (a!=b)            /* control flow */
foo(2);              /* function call */
[2.4][2,4]*[1,0][8,2] /* expression */
while (i > 0)        /* while loop */
for (i = 1 ; i < n ; i = i + 1) /* foo loop*/
```

3.6 Declarations
3.6.1 Program Definition
A program in All That Matrix consists of list of global variables and a list of functions. User-defined functions should be above the main function. The program always looks for the function main to start off.

3.6.2 Function Declarations
A function declaration must start with the name of the function, followed by a list of zero or more parameters separated by commas and enclosed in parenthesis. Functions in All That Matrix must be declared and implemented simultaneously. The result can be returned in a return statement. Nested functions are not supported.

```
function_name (type arg1, type arg2,..)
{
    function body
}
```

3.7 Scope
A declared object is only visible in the scope enclosed by the nearest curly bracket pair. Declarations made within functions are visible only within those functions. A declaration is not visible to declarations that came before it. An identifier declared outside of any curly bracket pairs is a global variable, and thus, is accessible from anywhere of the program.

3.8. References
4. Project Plan

4.1 Process
Because this project was not a team project, I was responsible for all components. Hence, the approach I took may be somewhat different. I did not follow the approach where I did not move on to work on the parser until the scanner is completely done. I started with a very basic framework provided by Micro C and added new pieces to all components of the language iteratively.

There was no extensive and detailed period of project planning due to mostly timing constraint. I did not have all details of the language flushed out and I did not start coding until I’ve reviewed all lectures on Micro C and did some reading on O’Caml. By that time, it was already past mid of June, so I had only one month to turn over the project.

As I began writing the compiler, I realized that several rules I laid out initially was unclear and inconsistent and I had to go back and change it to make it work for the new specification.

However, development and Testing went well for me. I adopted the test-driven development approach where a new test was written before the code was in place to keep the development cycles short and focused. Core features are dealt with first before the built-in functions were included. Unit testing was the main focus until near the end of the development cycle, where integration testing kicked in.

4.2 Programming Style Guide
While this project did not run into the issue where different team members are vastly inconsistent in their coding style, I still try to adhere to the general style guide outlined in this section so that code across all components of the project are consistent and readable, which are the two main goals.

Spaces are used instead of tabs for indentation and grouping of blocks of similar structured code along with parenthesis. A single space should be placed on either side of assignment (=), operators (+,-,...), and comparisons (> , <,...).

One blank line is used to separate different sections of the code, block comments and the code that follows it.

No line should be longer than 100 characters. It is recommended to put the condition and body of if statements on separate lines and use indentation and parenthesis. Exceptions can be made if the condition and the body are both really short. Compound statements (multiple statements on the same line separated by semicolons) are generally discouraged.

Comments are kept to a minimum. They should be descriptive, and not simply repeat what the code does.
## 4.3 Project Timeline

<table>
<thead>
<tr>
<th>Start - End Date</th>
<th>Deliverables</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 06/11/2014</td>
<td>Proposal</td>
</tr>
<tr>
<td>- 07/02/2014</td>
<td>Language reference manual</td>
</tr>
<tr>
<td>- 07/31/2014</td>
<td>A very basic framework complete</td>
</tr>
<tr>
<td>08/01 – 08/20/2014</td>
<td>Short iterative development cycles for all components of the language</td>
</tr>
<tr>
<td>- 08/20/2014</td>
<td>Compile final report</td>
</tr>
<tr>
<td>- 08/22/2014</td>
<td>Project due</td>
</tr>
</tbody>
</table>

## 4.4 Project Log

<table>
<thead>
<tr>
<th>Date</th>
<th>Focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/07/2014</td>
<td>Start thinking about the focus of the language</td>
</tr>
<tr>
<td>06/10/2014</td>
<td>Complete the project proposal</td>
</tr>
<tr>
<td>06/27/2014</td>
<td>Start defining the language rules</td>
</tr>
<tr>
<td>07/01/2014</td>
<td>Complete the language reference manual</td>
</tr>
<tr>
<td>07/19/2014</td>
<td>Complete all lectures on Micro C</td>
</tr>
<tr>
<td>07/23/2014</td>
<td>Read more about O’Camllex and O’Camlyacc</td>
</tr>
<tr>
<td>07/27/2014</td>
<td>Get a very basic framework ready for development</td>
</tr>
<tr>
<td>08/02/2014</td>
<td>Add core set of token rules to scanner and appropriate placeholders in parser, ast, bytecode, compiler, and executor</td>
</tr>
<tr>
<td>08/03/2014</td>
<td>Add customized matrix data type</td>
</tr>
<tr>
<td>08/09/2014</td>
<td>Work on local and global variables</td>
</tr>
<tr>
<td>08/10/2014</td>
<td>Work on function declaration and function calling</td>
</tr>
<tr>
<td>08/16/2014</td>
<td>Implement operators for matrix</td>
</tr>
<tr>
<td>08/17/2014</td>
<td>Add in built-in functions</td>
</tr>
<tr>
<td>08/18/2014</td>
<td>Start integration testing</td>
</tr>
<tr>
<td>08/20/2014</td>
<td>Start compiling the final report</td>
</tr>
<tr>
<td>08/22/2014</td>
<td>Complete the final report</td>
</tr>
</tbody>
</table>

*Note: each entry such as “work on …” and “implement” involve adding the appropriate pieces to the parser, ast, compiler, and executor to pass testing.*

## 4.5 Development Environment

**Programming language:** O’Caml

Scanner: O’Camllex

Parser: O’Camlyacc

Test: automatic bash script for regression testing

Build: Makefile
5. Architectural Design

5.1 Overview
ATM is made up of a scanner, parser, AST, compiler and code executor.

5.2 Front-end
The scanner follows the basic convention of accepting the source file, converting it into a stream of tokens, eliminating useless tokens such as whitespace, comments, etc. The scanner raises an exception upon encountering of an illegal token.

The parser then accepts the token stream from the scanner and parses it based on the rules laid out in the language reference manual and constructs an abstract syntax tree. More useless tokens are eliminated in this process and an exception occurs when the input stream does not satisfy the predefined syntax.

5.3 Back-end
Instead of using translating the AST into Java code or some other language, I’ve decided to translate it into native bytecode which then gets executed off a stack I implemented to produce the final output. The stack is studied and taught in various computer science courses, but I’ve always only had its concept understood. Therefore, I decided to take this chance to implement it and get a first-hand experience on all the details behind it.

6. Testing Plan

6.1 Goal
There are two goals for testing. One is to decide what feature to implement next in the test-driven development. The other is to ensure that the new code does not introduce new bugs as in regression testing. These tests are not compressive, but they were created systematically, at least
one test case for each portion of the language reference manual, in order to find any inconsistencies in the way data is treated.

6.2 Methods

A test suite was kept and maintained throughout the development phase of the project. Before a new feature was implemented, for example, global variables, at least one test case was written for it immediately. Hence, the development cycle was test-driven where the end of one development iteration is signaled by the passing of this new test case along with all other tests in the test suite for regression.

The test cases were kept small because they were designed to reduce debugging effort so that when a test fails, I will know which part, sometimes down to the exact byte code implementation, was causing the problem. Once added, no test case was ever deleted from the test suite.

Toward the end of the development cycle, longer and more compressive test cases were added to test the integration of the different components.

A test case consists of two files, (1) a .atm file which contains a program written in ATM, and (2) a .out file which contains the expected output. All test cases were contained within the /test directory. Automation in the form of a bash script was used for running all test cases in the test suite, comparing the actual output with the expected output, and logging the result in a text file.

6.3 Test Suite

<table>
<thead>
<tr>
<th>file</th>
<th>focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>test-arith-int.atm</td>
<td>Add between integers</td>
</tr>
<tr>
<td>test-arith-int2.atm</td>
<td>Arithmetic between integers</td>
</tr>
<tr>
<td>test-arith-metric.atm</td>
<td>Add between matrices</td>
</tr>
<tr>
<td>test-arith-metric2.atm</td>
<td>Arithmetic between matrices</td>
</tr>
<tr>
<td>test-arith-metric3.atm</td>
<td>Arithmetic between integers and matrices</td>
</tr>
<tr>
<td>test-built-in-func.atm</td>
<td>built-in function col_count and row_count</td>
</tr>
<tr>
<td>test-built-in-func-export.atm</td>
<td>built-in function export with int</td>
</tr>
<tr>
<td>test-built-in-func-export2.atm</td>
<td>built-in function export with matrix</td>
</tr>
<tr>
<td>test-comment.atm</td>
<td>comment properly ignored</td>
</tr>
<tr>
<td>test-det.atm</td>
<td>built-in functions, variables, functions, if statement, operators</td>
</tr>
<tr>
<td>test-fib.atm</td>
<td>recursion, if statement, variables and function declarations</td>
</tr>
<tr>
<td>test-for1.atm</td>
<td>for loop with int</td>
</tr>
<tr>
<td>test-for2.atm</td>
<td>nested for loops with matrix</td>
</tr>
<tr>
<td>test-func1.atm</td>
<td>function declaration and call involving integers</td>
</tr>
<tr>
<td>test-func2.atm</td>
<td>function declaration and call involving matrices</td>
</tr>
<tr>
<td>test-func3.atm</td>
<td>function formal and actual arguments of type int</td>
</tr>
<tr>
<td>test-func4.atm</td>
<td>function formal and actual arguments of type matrix</td>
</tr>
<tr>
<td>test-gcd.atm</td>
<td>function declaration and call, while loop, if else statement</td>
</tr>
<tr>
<td>test-global1.atm</td>
<td>declaration and initialization of global variables of type int</td>
</tr>
<tr>
<td>test-global2.atm</td>
<td>declaration and initialization of global variables of type matrix</td>
</tr>
<tr>
<td>test-id.atm</td>
<td>identifiers</td>
</tr>
<tr>
<td>Name</td>
<td>Description</td>
</tr>
<tr>
<td>-------------------------</td>
<td>-------------------------------------------------------</td>
</tr>
<tr>
<td>test-if1.atm</td>
<td>if statement – evaluates to true</td>
</tr>
<tr>
<td>test-if2.atm</td>
<td>if statement – evaluates to false</td>
</tr>
<tr>
<td>test-if3.atm</td>
<td>if else statement - evaluates to false</td>
</tr>
<tr>
<td>test-if4.atm</td>
<td>if else statement - evaluates to true</td>
</tr>
<tr>
<td>test-ops-int.atm</td>
<td>logical operators for type int</td>
</tr>
<tr>
<td>test-ops-metric.atm</td>
<td>logical operators for type matrix</td>
</tr>
<tr>
<td>test-print-string.atm</td>
<td>print of type string</td>
</tr>
<tr>
<td>test-var-int.atm</td>
<td>declaration and initialization of local variables of type int</td>
</tr>
<tr>
<td>test-var-metric.atm</td>
<td>declaration and initialization of local variables of type matrix</td>
</tr>
<tr>
<td>test-while.atm</td>
<td>while loop</td>
</tr>
</tbody>
</table>

### 6.4 Representative Test Case 1
This is one of the earliest test cases written for testing the initialization and declaration of local variable of local variables.

```plaintext
main()
{
    matrix[3][2] b;
    matrix[3][3] a:
    a = [1,2,3|4,5,6|7,8,9];
    b = [8,2,1|1,0,5];
    print(b);
    print(a);
}
```

This is the translated bytecode.

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 global variables</td>
<td>18 Lit 2</td>
</tr>
<tr>
<td>0 Jsr 2</td>
<td>19 Lit 1</td>
</tr>
<tr>
<td>1 Hlt</td>
<td>20 Lit 1</td>
</tr>
<tr>
<td>2 Ent 21</td>
<td>21 Lit 0</td>
</tr>
<tr>
<td>3 Lit 1</td>
<td>22 Lit 5</td>
</tr>
<tr>
<td>4 Lit 2</td>
<td>23 Lit 3</td>
</tr>
<tr>
<td>5 Lit 3</td>
<td>24 Lit 2</td>
</tr>
<tr>
<td>6 Lit 4</td>
<td>25 Max</td>
</tr>
<tr>
<td>7 Lit 5</td>
<td>26 Sfp 9</td>
</tr>
<tr>
<td>8 Lit 6</td>
<td>27 Drp</td>
</tr>
<tr>
<td>9 Lit 7</td>
<td>28 Lfp 9</td>
</tr>
<tr>
<td>10 Lit 8</td>
<td>29 Jsr -1</td>
</tr>
<tr>
<td>11 Lit 9</td>
<td>30 Drp</td>
</tr>
<tr>
<td>12 Lit 3</td>
<td>31 Lfp 21</td>
</tr>
<tr>
<td>13 Lit 3</td>
<td>32 Jsr -1</td>
</tr>
<tr>
<td>14 Max</td>
<td>33 Drp</td>
</tr>
<tr>
<td>15 Sfp 21</td>
<td>34 Lit 0</td>
</tr>
<tr>
<td>16 Drp</td>
<td>35 Rts 0</td>
</tr>
<tr>
<td>17 Lit 8</td>
<td></td>
</tr>
</tbody>
</table>
6.5 Representative Test Case 2
This is a test case targeted at testing the correct functionality of nested for loops.

```c
main()
{
    int i;
    int j;
    matrix[3][3] m;
    m = [1,2,3|4,5,6|7,8,9];
    for (i = 1 ; i < 4 ; i = i + 1) {
        for (j = 1 ; j < 4 ; j = j + 1) {
            print(m[i][j]);
        }
    }
}
```

The bytecode produced for this is the following.

| 0 global variables                      | 18 Lit 2  |
| 0 Jsr 2                                 | 19 Lit 1  |
| 1 Hlt                                   | 20 Lit 1  |
| 2 Ent 21                                | 21 Lit 0  |
| 3 Lit 1                                 | 22 Lit 5  |
| 4 Lit 2                                 | 23 Lit 3  |
| 5 Lit 3                                 | 24 Lit 2  |
| 6 Lit 4                                 | 25 Max    |
| 7 Lit 5                                 | 26 Sfp 9  |
| 8 Lit 6                                 | 27 Drp    |
| 9 Lit 7                                 | 28 Lfp 9  |
| 10 Lit 8                                | 29 Jsr -1 |
| 11 Lit 9                                | 30 Drp    |
| 12 Lit 3                                | 31 Lfp 21 |
| 13 Lit 3                                | 32 Jsr -1 |
| 14 Max                                  | 33 Drp    |
| 15 Sfp 21                               | 34 Lit 0  |
| 16 Drp                                  | 35 Rts 0  |

6.6 Representative Test Case 3
This is a more comprehensive test intended for integration testing.

```c
is_square_matrix(input)
{
    return col_count(input) == row_count(input);
}
```
det2(input)
{
    return ((input[1][1])*(input[2][2])-(input[1][2])*(input[2][1]));
}
det3(input)
{
    int a;
    int b;
    int c;
    a = det2([input[2][2],input[2][3]|input[3][2],input[3][3]]);
    b = det2([input[2][1],input[2][3]|input[3][1],input[3][3]]);
    c = det2([input[2][1],input[2][2]|input[3][1],input[3][2]]);
    return (input[1][1])*a-(input[1][2])*b+(input[1][3])*c;
}
det(input)
{
    int ret_val;
    ret_val = 0;
    if (is_square_matrix(input)) {
        if (col_count(input)==2) {
            ret_val = det2(input);
        }
        if (col_count(input)==3) {
            ret_val = det3(input);
        }
    }
    return ret_val;
}
print_det(input)
{
    if (is_square_matrix(input)) {
        print("is a square matrix");
        print("determinant is");
        print(det(input));
    } else {
        print("is not a square matrix");
    }
}
main()
{
matrix[2][2] test_matrix1;
matrix[3][3] test_matrix2;
matrix[2][3] test_matrix3;
test_matrix1 = [2,8|1,7];
test_matrix2 = [12,5,1|7,4,0|1,2,3];
test_matrix3 = [12,5,1|7,4,0];
print("test_matrix1 results:");
print_det(test_matrix1);
print("test_matrix2 results:");
print_det(test_matrix2);
print("test_matrix3 results:");
print_det(test_matrix3);
}

The following is the bytecode produced for this.

```
0 global variables                116 Lit 2
 0 Jsr 2                          117 Acc
 1 Hlt                            118 Lfp -2
 2 Ent 28                         119 Lit 2
 3 Lit 2                          120 Lit 3
 4 Lit 8                          121 Acc
 5 Lit 1                          122 Lfp -2
 6 Lit 7                          123 Lit 3
 7 Lit 2                          124 Lit 3
 8 Lit 2                          125 Acc
 9 Max                             126 Lit 2
10 Sfp 7                          127 Lit 2
11 Drp                            128 Max
12 Lit 12                         129 Jsr 199
13 Lit 5                          130 Sfp 1
14 Lit 1                          131 Drp
15 Lit 7                          132 Lfp -2
16 Lit 4                          133 Lit 1
17 Lit 0                          134 Lit 2
18 Lit 1                          135 Acc
19 Lit 2                          136 Lfp -2
20 Lit 3                          137 Lit 3
21 Lit 3                          138 Lit 2
22 Lit 3                          139 Acc
23 Max                             140 Lfp -2
24 Sfp 19                         141 Lit 1
25 Drp                            142 Lit 3
26 Lit 12                         143 Acc
27 Lit 5                          144 Lfp -2
28 Lit 1                          145 Lit 3
```
<p>| 29 Lit 7 | 146 Lit 3 |
| 30 Lit 4 | 147 Acc |
| 31 Lit 0 | 148 Lit 2 |
| 32 Lit 3 | 149 Lit 2 |
| 33 Lit 2 | 150 Max |
| 34 Max  | 151 Jsr 199 |
| 35 Sfp 28| 152 Sfp 2 |
| 36 Drp  | 153 Drp |
| 37 Stg test_matrix1 results: | 154 Lfp -2 |
| 38 Jsr -1 | 155 Lit 1 |
| 39 Drp  | 156 Lit 2 |
| 40 Lfp 7 | 157 Acc |
| 41 Jsr 57 | 158 Lfp -2 |
| 42 Drp  | 159 Lit 2 |
| 43 Stg test_matrix2 results: | 160 Lit 2 |
| 44 Jsr -1 | 161 Acc |
| 45 Drp  | 162 Lfp -2 |
| 46 Lfp 19 | 163 Lit 1 |
| 47 Jsr 57 | 164 Lit 3 |
| 48 Drp  | 165 Acc |
| 49 Stg test_matrix3 results: | 166 Lfp -2 |
| 50 Jsr -1 | 167 Lit 2 |
| 51 Drp  | 168 Lit 3 |
| 52 Lfp 28 | 169 Acc |
| 53 Jsr 57 | 170 Lit 2 |
| 54 Drp  | 171 Lit 2 |
| 55 Lit 0 | 172 Max |
| 56 Rts 0 | 173 Jsr 199 |
| 57 Ent 0 | 174 Sfp 3 |
| 58 Lfp -2 | 175 Drp |
| 59 Jsr 222 | 176 Lfp -2 |
| 60 Beq 12 | 177 Lit 1 |
| 61 Stg is a square matrix | 178 Lit 1 |
| 62 Jsr -1 | 179 Acc |
| 63 Drp  | 180 Lfp 1 |
| 64 Stg determinant is | 181 Mul |
| 65 Jsr -1 | 182 Lfp -2 |
| 66 Drp  | 183 Lit 2 |
| 67 Lfp -2 | 184 Lit 1 |
| 68 Jsr 77 | 185 Acc |
| 69 Jsr -1 | 186 Lfp 2 |
| 70 Drp  | 187 Mul |
| 71 Bra 4 | 188 Sub |
| 72 Stg is not a square matrix | 189 Lfp -2 |
| 73 Jsr -1 | 190 Lit 3 |
| 74 Drp  | 191 Lit 1 |</p>
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7. Lessons Learned

In this project, the one thing that I found most useful was the test suite. With many of the
projects that I’ve done in the past, testing had never been woven into the development cycle as
tightly as this project did. In the past, testing was done ad hoc with mostly random print
statements and debugger at the most. However, the test-driven development I adopted this time
put testing in the center of the project, and it helped discover all kinds of bugs.

Also, thinking in O’Caml was a very different experience for me, I spent a lot of time in the
beginning to learn in detail how all the components work together from scanning of the input to
translating it into AST and eventually, running the bytecode.

It was overwhelming initially, and I did not know how and where to start and the shortness of
summer semester certainly did not help. I find myself procrastinating. I did not start the actual
development until I’ve gone through all of the lectures on Micro C, which was past the middle of
June. I was getting panicked as the deadline is fast approaching and had to cut certain features I
had set out to do in the initial plan.

My advice is to start the project early, specifically, try to find ways to motivate your to work on
the project. For people in a team, peer pressure can often work wonders. Set goals for each of the
member the next time you meet. Allocate dedicated hours per week to work on the project as you
would for lectures. I find that test-driven development worked very well for me because it made
the development cycle shorter, made me focus on one thing at a time, and pushed me forward to
the next iteration.

8. Appendix
8.1 scanner.mll

```ocaml
{ open Parser }

rule token = parse
    | [' ' '
' 'r' 'n']  { token lexbuf } 
    | '/\n'   { comment lexbuf } 
    | '|'    { BAR} 
    | '('    { LPAREN } 
    | ')'    { RPAREN } 
    | '{'    { LBRACE } 
    | '}'    { RBRACE } 
    | ';'    { SEMI } 
    | ','    { COMMA } 
    | '+'    { PLUS } 
    | '-'    { MINUS } 
    | '*='   { TIMES } 
    | '/'    { DIVIDE } 
    | '='    { ASSIGN } 
    | '=='   { EQ } ```
8.2 parser.mly

```ml
%{ open Ast %}

%token SEMI LPAREN RPAREN LBRACE RBRACE LBRACKET RBRACKET COMMA BAR
%token PLUS MINUS TIMES DIVIDE ASSIGN
%token EQ NEQ LT LEQ GT GEQ
%token RETURN IF ELSE FOR WHILE
%token <int> LITERAL
%token <string> ID
%token <string> STRING
%token <string> DATA_TYPE
%token EOF

%nonassoc NOELSE
%nonassoc ELSE
%right ASSIGN
%left EQ NEQ
%left LT GT LEQ GEQ
%left PLUS MINUS
%left TIMES DIVIDE
```
%start program
%type <Ast.program> program

%%

program:
  /* nothing */ { [], [] }
  | program vdecl { ($2 :: fst $1), snd $1 }
  | program fdecl { fst $1, ($2 :: snd $1) }

fdecl:
  ID LPAREN formals_opt RPAREN LBRACE vdecl_list stmt_list RBRACE
  { { fname = $1;
    formals = $3;
    locals = List.rev $6;
    body = List.rev $7 } }

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

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

vdecl_list:
  /* nothing */ { [] }
  | vdecl_list vdecl { $2 :: $1 }

vdecl:
  DATA_TYPE ID SEMI
  { {data_type = $1; id = $2; rows = 0; cols = 0} }
  | DATA_TYPE LBRACKET LITERAL RBRACKET LBRACKET LITERAL RBRACKET ID SEMI
  { {data_type = $1; id = $8; rows = $3; cols = $6} }

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

stmt:
  expr SEMI { Expr($1) }
  | RETURN expr SEMI { Return($2) }
  | LBRACE stmt_list RBRACE { Block(List.rev $2) }
  | IF LPAREN expr RPAREN stmt %prec NOELSE { If($3, $5, Block([])) }
IF LPAREN expr RPAREN stmt ELSE stmt { If($3, $5, $7) }
FOR LPAREN expr_opt SEMI expr_opt SEMI expr_opt RPAREN stmt
{ For($3, $5, $7, $9) }
WHILE LPAREN expr RPAREN stmt { While($3, $5) }

expr_opt:
/* nothing */ { Noexpr }
expr { $1 }

expr:
LITERAL { Literal($1) }
ID { Id($1) }
STRING { String($1) }
expr LBRACKET expr RBRACKET LBRACKET expr RBRACKET { Access($1, $3, $6) }
LBRACKET matrix RBRACKET { Matrix($2) }
expr PLUS expr { Binop($1, Add, $3) }
expr MINUS expr { Binop($1, Sub, $3) }
expr TIMES expr { Binop($1, Mult, $3) }
expr DIVIDE expr { Binop($1, Div, $3) }
expr EQ expr { Binop($1, Equal, $3) }
expr NEQ expr { Binop($1, Neq, $3) }
expr LT expr { Binop($1, Less, $3) }
expr LEQ expr { Binop($1, Leq, $3) }
expr GT expr { Binop($1, Greater, $3) }
expr GEQ expr { Binop($1, Geq, $3) }
ID ASSIGN expr { Assign($1, $3) }
ID LPAREN actuals_opt RPAREN { Call($1, $3) }
LPAREN expr RPAREN { $2 }

row:
{ [] }
expr { [$1] }
row COMMA expr { $3 :: $1 }

matrix:
row { [List.rev $1] }
matrix BAR row { $1 @ [List.rev $3] }

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

actuals_list:
expr { [$1] }
actuals_list COMMA expr { $3 :: $1 }
8.3 ast.ml

type op = Add | Sub | Mul | Div | Equal | Neq | Less | Leq | Greater | Geq

type expr =
  | Literal of int
  | String of string
  | Id of string
  | Access of expr * expr * expr
  | Matrix of expr list list
  | Binop of expr * op * expr
  | Assign of string * expr
  | Call of string * expr list
  | Noexpr

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

type var_decl = {
  data_type : string;
  id : string;
  rows: int;
  cols: int
}

type func_decl = {
  fname : string;
  formals : string list;
  locals : var_decl list;
  body : stmt list;
}

type program = var_decl list * func_decl list

let rec string_of_expr = function
  | Literal(l) -> string_of_int l
  | String(s) -> s
  | Id(s) -> s
  | Access(m, r, c) -> string_of_expr m ^ " " ^ string_of_expr r ^ " " ^ string_of_expr c
  | Matrix(m) -> String.concat " " (List.map string_of_expr (List.concat m))
  | Binop(e1, o, e2) -> string_of_expr e1 ^ " " ^ (match o with
    | Add -> " + "
    | Sub -> " - "
    | Mul -> " * "
    | Div -> " / "
    | Equal -> " == "
    | Neq -> " <> "
    | Less -> " < "
    | Leq -> " <= "
    | Greater -> " > "
    | Geq -> " >= "
  ) ^ string_of_expr e2
  | Noexpr -> " "

let rec string_of_stmt = function
   Block(stmts) -> "{\n" ^ String.concat "}\n"
| Expr(expr) -> string_of_expr expr ^ ";\n"
| Return(e) -> "return " ^ string_of_expr expr ^ ";\n"
| If(e, s, Block([])) -> "if (" ^ string_of_expr e ^ ")\n" ^ string_of_stmt s
| If(e, s1, s2) -> "if (" ^ string_of_expr e ^ ")\n" ^ string_of_stmt s1 ^ "else\n" ^ string_of_stmt s2
| For(e1, e2, e3, s) -> "for (" ^ string_of_expr e1 ^ " ; " ^ string_of_expr e2 ^ " ; " ^ string_of_expr e3 ^ ")\n" ^ string_of_stmt s
| While(e, s) -> "while (" ^ string_of_expr e ^ ")\n" ^ string_of_stmt s

let string_of_vdecl var =
   var.data_type ^ " " ^ var.id ^ ";\n"

let string_of_fdecl fdecl =
   fdecl.fname ^ "(" ^ String.concat fdecl.formals ^ ")\n{" ^ String.concat "}\n" ^ String.concat "\n" ^ String.concat "\n" ^ String.concat "\n" ^ String.concat "\n"

let string_of_program (vars, funcs) =
   String.concat "\n" ^ String.concat "\n" ^ String.concat "\n" ^ String.concat "\n" ^ String.concat "\n"

8.4 bytecode.ml

type bstmt =
   Lit of int  (* Push a literal *)
| Stg of string  (* Push a string *)
| Max  (* Indicate matrix data type *)
| Acc  (* Access matrix *)
| 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 (* Push FP, 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 *)
Hlt (* Terminate *)

type prog = {
  num Globals : int; (* Number of global variables *)
  size Globals : int; (* Size of global variables *)
  text : bstmt array; (* Code for all the functions *)
}

let string_of_stmt = function
  Lit(i) -> "Lit " ^ string_of_int i
  Stg(s) -> "Stg " ^ s
  Max -> "Max"
  Acc -> "Acc"
  Drp -> "Drp"
  Bin(Ast.Add) -> "Add"
  Bin(Ast.Sub) -> "Sub"
  Bin(Ast.Mult) -> "Mul"
  Bin(Ast.Div) -> "Div"
  Bin(Ast.Equal) -> "Eqn"
  Bin(Ast.Neq) -> "Neq"
  Bin(Ast.Less) -> "Lt"
  Bin(Ast.Leq) -> "Leq"
  Bin(Ast.Greater) -> "Gt"
  Bin(Ast.Geq) -> "Geq"
  Lod(i) -> "Lod " ^ string_of_int i
  Str(i) -> "Str " ^ string_of_int i
  Lfp(i) -> "Lfp " ^ string_of_int i
  Sfp(i) -> "Sfp " ^ string_of_int i
  Jsr(i) -> "Jsr " ^ string_of_int i
  Ent(i) -> "Ent " ^ string_of_int i
  Rts(i) -> "Rts " ^ string_of_int i
  Bne(i) -> "Bne " ^ string_of_int i
  Beq(i) -> "Beq " ^ string_of_int i
  Bra(i) -> "Bra " ^ string_of_int i
  Hlt -> "Hlt"

let string_of_prog p =
  string_of_int p.num Globals ^ " global variables\n" ^
  let funca = Array.mapi (fun i s -> string_of_int i ^ " " ^ string_of_stmt s) p.text
  in String.concat "\n" (Array.to_list funca)
8.5 compile.ml

```ml
open Ast
open Bytecode

module StringMap = Map.Make(String)

(* Symbol table: Information about all the names in scope *)

type env = {
  function_index : int StringMap.t; (* Index for each function *)
  global_index   : int StringMap.t; (* Address for global variables *)
  local_index    : int StringMap.t; (* FP offset for locals *)
  arg_index      : int StringMap.t; (* FP offset for args *)
}

(* val enum : int -> 'a list -> (int * 'a) list *)

let rec enum stride n = function
  | [] -> []
  | hd::tl -> (n, hd) :: enum stride (n+stride) tl

let rec enum_vars n = function
  | [] -> []
  | hd::tl -> (n+1, hd.data_type="matrix" then (n+3+(hd.rows*hd.cols)), hd.id) else (n+1) tl

(*helper function for calculating the size of allocated variables*)

let size_vars = function vars -> List.fold_left (fun s l ->
  if l.data_type="matrix" then
    (3+(if l.rows > 0 then l.rows else 1)*(if l.cols > 0 then l.cols else 1))
  else
    1)
    0 vars

(* val 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., a reference to an unknown
```
let translate (globals, functions) =

(* Allocate "addresses" for each global variable *)

let global_indexes = string_map_pairs StringMap.empty (enum_vars 0 globals) in

(* Assign indexes to function names; built-in "print" is special *)
let built_in_functions =
    StringMap.add "export" (-4) (StringMap.add "col_count" (-3) (StringMap.add "row_count" (-2) (StringMap.add "print" (-1) StringMap.empty))) in

let function_indexes = string_map_pairs built_in_functions (enum 1 1 (List.map (fun f -> f.fname) functions)) in

(* Translate a function in AST form into a list of bytecode statements *)

let translate env fdecl =

(* Bookkeeping: FP offsets for locals and arguments *)

let num_formals = List.length fdecl.formals
and size_locals = size_vars fdecl.locals
and local_offsets = enum_vars 0 fdecl.locals
and formal_offsets = enum (-1) (-2) fdecl.formals in

let env = { env with
    local_index = string_map_pairs StringMap.empty local_offsets;
    arg_index = string_map_pairs StringMap.empty formal_offsets} in

let rec expr = function
    Literal i -> [Lit i]
| Id s -> (try [Lfp (StringMap.find s env.local_index)]
            with Not_found -> try [Lfp (StringMap.find s env.arg_index)]
            with Not_found -> try [Lod (StringMap.find s env.global_index)]
            with Not_found -> raise (Failure ("undeclared variable " ^ s))]
| Access(m, r, c) -> expr m @ expr c @ expr r @ [Acc]
| Matrix(m) -> List.concat (List.map expr (List.concat m)) @
              [Lit (List.length (List.nth m 0))] @ [Lit (List.length m)] @ [Max]
| Binop (e1, op, e2) -> expr e1 @ expr e2 @ [Bin op]
| Assign (s, e) -> expr e @ (}
try [Sfp (StringMap.find s env.local_index)]
with Not_found -> try [Sfp (StringMap.find s env.arg_index)]
with Not_found -> try [Str (StringMap.find s env.global_index)]
with Not_found -> raise (Failure ("undeclared variable " ^ s))
| Call (fname, actuals) -> (try (List.concat (List.map expr (List.rev actuals))) @
[Jsr (StringMap.find fname env.function_index) ]
with Not_found -> raise (Failure ("undefined function " ^ fname))
| Noexpr -> []

in let rec stmt = function
  Block sl -> List.concat (List.map stmt sl)
| Expr e -> expr e @ [Drp]
| Return e -> expr e @ [Rts num_formals]
| If (p, t, f) -> let t' = stmt t and f' = stmt f in
  expr p @ [Beq(2 + List.length t')] @
  t' @ [Bra(1 + List.length f')] @ f'
| For (e1, e2, e3, b) -> stmt (Block([Expr(e1);
  While(e2, Block([b; Expr(e3)]))]))
| While (e, b) -> let b' = stmt b and e' = expr e in
  [Bra (1+ List.length b')] @ b' @ e' @
  [Bne ((List.length b' + List.length e'))]

in [Ent size_locals] @ (* Entry: allocate space for locals *)
stmt (Block fdecl.body) @ (* Body *)
[Lit 0; Rts num_formals] (* Default = return 0 *)

in let env = { function_index = function_indexes;
  global_index = global_indexes;
  local_index = StringMap.empty;
  arg_index = StringMap.empty } in

(* Code executed to start the program: Jsr main; halt *)

let entry_function = try
  [Jsr (StringMap.find "main" function_indexes); Hlt]
with Not_found -> raise (Failure("no "main" function")) in

(* Compile the functions *)

let func_bodies = entry_function :: List.map (translate env) functions 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 globals;
 size Globals = size vars globals;
(* 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))
}

8.6 execute.ml

open Ast
open Bytecode

(* Stack layout just after "Ent":

    <-- SP
 Local n
 ...
 Local 0
 Saved FP  <-- FP
 Saved PC
 Arg 0
 ...
 Arg n *)

let execute_prog prog =
 let stack = Array.make 1024 "0"
 and globals = Array.make prog.size_globals "0" in

let rec exec fp sp pc = match prog.text.(pc) with
    Lit i  -> stack.(sp) <- string_of_int i ; exec fp (sp+1) (pc+1)
 | Stg s  -> stack.(sp) <- s ; exec fp (sp+1) (pc+1)
 | Max   -> stack.(sp) <- "Max" ; exec fp (sp+1) (pc+1)
 | Acc -> if stack.(sp-3) = "Max" then
        let rows = (int_of_string stack.(sp-4)) and
            cols = (int_of_string stack.(sp-5)) and
            r = (int_of_string stack.(sp-1)) and
            c = (int_of_string stack.(sp-2)) in ( stack.(sp-5-(rows*cols)) <- stack.(sp-6-(rows*cols)+((r-1)*cols)+c); exec fp (sp-4-(rows*cols)) (pc+1))
 | Drp  -> exec fp (sp-1) (pc+1)
 | Bin op -> if stack.(sp-1) = "Max" || stack.(sp-2) = "Max" then ((
    match op with
        ...
```
Add | Sub | Equal | Neq -> ( 
    let rows = (int_of_string stack.(sp-2)) and 
    cols = (int_of_string stack.(sp-3)) in ( 
    for i = 4 to (3+rows*cols) do 
        let op1 = (int_of_string stack.(sp-3-i-rows*cols)) and 
            op2 = (int_of_string stack.(sp-i)) in 
        stack.(sp-i) <- (let boolean i = if i then "1" else "0" in 
            match op with 
            | Add -> string_of_int (op1 + op2) 
            | Sub -> string_of_int (op1 - op2) 
            | Equal -> boolean (op1 = op2) 
            | Neq -> boolean (op1 != op2) 
        done)) 
    | Mult -> ( 
        if stack.(sp-1) <> "Max" then ( 
            let rows = (int_of_string stack.(sp-3)) and 
                cols = (int_of_string stack.(sp-4)) and 
                    const = (int_of_string stack.(sp-1)) in ( 
                stack.(sp-1) <- "Max";
                stack.(sp-2) <- string_of_int rows;
                stack.(sp-3) <- string_of_int cols;
                for i = 5 to (4+rows*cols) do 
                    stack.(sp-i+1) <- string_of_int (const*(int_of_string stack.(sp-i)))
            done)
            else ( 
            let rows2 = (int_of_string stack.(sp-5)) and 
                cols2 = (int_of_string stack.(sp-6)) in ( 
                if cols2 != rows then (raise (Failure("Operators for * do not satisfy matrix multiplication criteria"))) 
                else ( 
                let ops1 = ref [] and ops2 = ref [] and 
                    res = ref [] and sum = ref 0 in ( 
                let count = ref 0 and 
                    m = (Array.sub stack (sp-rows*cols-6*rows2*cols2) (rows2*cols2)) in 
                for i = 0 to (Array.length m - 1) do 
                    count := (!count + 1);
                    ops1 := (!ops1 @ [Array.get m i]);
                    if !count = cols2 then ( 
```
count := 0;
let len = List.length !ops1 in
for j = cols2 downto 1 do
ops1 := (!ops1 @ [List.nth !ops1 (len - j)])
done)
done;
let count = ref 0 and
m = (Array.sub stack (sp - rows*cols - 3) (rows*cols)) in (for r = 1 to rows2 do
for c = 1 to cols do
for i = 0 to (Array.length m - 1) do
count := (!count + 1);
if !count = c then (ops2 := (!ops2 @ [Array.get m i]));
if !count = cols then (count := 0)
done
done;
count := 0;
stack.(sp-2) <- string_of_int rows2;
for i = 0 to (List.length !ops1 - 1) do
count := (!count + 1);
sum := (!sum + ((int_of_string (List.nth !ops1 i))*(int_of_string (List.nth !ops2 i))));
if !count = cols2 then (res := (!res @ ![sum]); count := 0; sum := 0)
done;
for i = 0 to (List.length !res - 1) do
stack.(sp-3-(rows2*cols)+i) <- (string_of_int (List.nth !res i))
done)
))))
)
(match op with
| Add | Sub | Mult -> ()
| Equal -> let rows = (int_of_string stack.(sp-2)) and
cols = (int_of_string stack.(sp-3)) in
stack.(sp-1) <- (let cmp = (Array.fold_left (fun s e -> s + (int_of_string e)) 0 (Array.sub stack (sp-3-rows*cols) (rows*cols))) in
if cmp = (rows*cols) then "1" else "0")
| Neq -> let rows = (int_of_string stack.(sp-2)) and
cols = (int_of_string stack.(sp-3)) in
stack.(sp-1) <- (let cmp = (Array.fold_left (fun s e -> s + (int_of_string e)) 0 (Array.sub stack (sp-3-rows*cols) (rows*cols))) in
if cmp > 0 then "1" else "0"))
exec fp sp (pc+1))
else (
    let op1 = (int_of_string stack.(sp-2)) and
    op2 = (int_of_string stack.(sp-1)) in
    stack.(sp-2) <- (let boolean i = if i then "1" else "0" in
        match op with
        | Add  -> string_of_int (op1 + op2)
        | Sub  -> string_of_int (op1 - op2)
        | Mult -> string_of_int (op1 * op2)
        | Div  -> string_of_int (op1 / op2)
        | Equal -> boolean (op1 = op2)
        | Neq  -> boolean (op1 != op2)
        | Less -> boolean (op1 <  op2)
        | Leq  -> boolean (op1 <= op2)
        | Greater -> boolean (op1 >  op2)
        | Geq  -> boolean (op1 >= op2));
    exec fp (sp-1) (pc+1)))
| Lod i -> if globals.(i-1) = "Max" then
    let rows = (int_of_string globals.(i-2)) and
    cols = (int_of_string globals.(i-3)) in
    for j = 1 to (3+rows*cols) do
        stack.(sp+(3+rows*cols)-j) <- globals.(i-j)
    done;
    exec fp (sp+(rows*cols+3)) (pc+1))
else (stack.(sp) <- globals.(i-1);
    exec fp (sp+1) (pc+1))
| Str i -> if stack.(sp-1) = "Max" then
    let rows = (int_of_string stack.(sp-2)) and
    cols = (int_of_string stack.(sp-3)) in
    for j = 1 to (3+rows*cols) do
        globals.(i-j) <- stack.(sp-j)
    done
else (globals.(i-1) <- stack.(sp-1));
    exec fp sp (pc+1))
| Lfp i -> if i < 0 then let rec f1 = (fun x offset ->
    if offset = (-2) then x
    else if stack.(fp+x) = "Max" then
        f1 (x-3-(int_of_string stack.(fp+x-1))*(int_of_string stack.(fp+x-2))) (offset+1)
    else f1 (x-1) (offset+1)) in
    if stack.(fp+(f1 (-2) i)) = "Max" then
        let rows = (int_of_string stack.(fp+(f1 (-2) i)-1)) and
        cols = (int_of_string stack.(fp+(f1 (-2) i)-2)) in
        for j = 1 to (rows*cols+3) do
            stack.(sp+(rows*cols+3)-j) <- stack.(fp+(f1 (-2) i)-j+1)
        done;
exec fp (sp+rows*cols+3) (pc+1))
else (stack.(sp) <- stack.(fp+i);
exec fp (sp+1) (pc+1)))
else if stack.(fp+i-1) = "Max" then (let rows = (int_of_string stack.(fp+i-2)) and
cols = (int_of_string stack.(fp+i-3)) in (for j = 1 to (rows*cols+3) do
stack.(sp+(rows*cols+3)-j) <- stack.(fp+i-j)
done);
exec fp (sp+(if stack.(fp+i-1) = "Max" then (rows*cols+3) else 1)) (pc+1))
else (stack.(sp) <- stack.(fp+i);
exec fp (sp+1) (pc+1))
| Sfp i -> if stack.(sp-1) = "Max" then (let rows = (int_of_string stack.(sp-2)) and
cols = (int_of_string stack.(sp-3)) in (for i = rows downto 1 do
Array.iter (fun e -> Printf.printf "%s " e)
(Array.sub stack (sp-3-i*cols) cols);
Printf.printf "\n"
done))
else (stack.(fp+i) <- stack.(sp-1));
exec fp sp (pc+1)
| Jsrd -> if stack.(sp-1) = "Max" then (let rows = (int_of_string stack.(sp-2)) and
cols = (int_of_string stack.(sp-3)) in (for i = rows downto 1 do
Array.iter (fun e -> Printf.printf "%s " e)
(Array.sub stack (sp-3-i*cols) cols);
Printf.printf "\n"
done))
else (print_endline stack.(sp-1));
exec fp sp (pc+1)
| Jsrd-1 -> if stack.(sp-1) = "Max" then
let rows = (int_of_string stack.(sp-2)) and
cols = (int_of_string stack.(sp-3)) in (for i = rows downto 1 do
Array.iter (fun e -> Printf.printf "%s " e)
(Array.sub stack (sp-3-i*cols) cols);
Printf.printf "\n"
done))
else (print_endline stack.(sp-1));
exec fp sp (pc+1)
| Jsrd-2 -> if stack.(sp-1) = "Max" then
let rows = (int_of_string stack.(sp-2)) and
cols = (int_of_string stack.(sp-3)) in (stack.(sp-3-(cols*rows)) <- string_of_int rows;
exec fp (sp-2-(cols*rows)) (pc+1))
| Jsrd-3 -> if stack.(sp-1) = "Max" then
let rows = (int_of_string stack.(sp-2)) and
cols = (int_of_string stack.(sp-3)) in (stack.(sp-3-(cols*rows)) <- string_of_int cols;
exec fp (sp-2-(cols*rows)) (pc+1))
| Jsrd-4 -> let oc = open_out stack.(sp-1) in (if stack.(sp-2) = "Max" then
let rows = (int_of_string stack.(sp-3)) and
cols = (int_of_string stack.(sp-4)) in (
for i = rows downto 1 do
    Array.iter (fun e -> Printf.fprintf oc "%s " e) (Array.sub stack (sp-4-i*cols) cols);
    Printf.fprintf oc "\n"
    done
else
    Printf.fprintf oc "%s" stack.(sp-2));
exec fp sp (pc+1)
| Jsr i -> stack.(sp) <- string_of_int (pc + 1);
exec fp (sp+1) i
| Ent i -> stack.(sp) <- string_of_int fp;
exec sp (sp+i+1) (pc+1)
| Rts i -> let j = (if i > 0 then (let rec f1 = (fun x offset ->
    if offset = 0 then x
    else if stack.(fp+x) = "Max" then
        f1 (x-3-(int_of_string stack.(fp+x-1))*(
            int_of_string stack.(fp+x-2))) (offset+1)
    else f1 (x-1) (offset+1)) in (f1 (-2) (-i))
    else i) in (let new_fp = int_of_string stack.(fp) and
    new_pc = int_of_string stack.(fp-1) in
    if stack.(sp-1) = "Max" then (let rows = (int_of_string stack.(sp-2)) and
    cols = (int_of_string stack.(sp-3)) in
    for x = 1 to (rows*cols+3) do
    stack.(fp-j-x) <- stack.(sp-x)
    done)
    else stack.(fp-j-1) <- stack.(sp-1);
exec new_fp (fp-j) new_pc)
| Beq i -> exec fp (sp-1) (pc + if (int_of_string stack.(sp-1)) = 0 then i else 1)
| Bne i -> exec fp (sp-1) (pc + if (int_of_string stack.(sp-1)) != 0 then i else 1)
| Bra i -> exec fp sp (pc+i)
| Hlt -> ()
in exec 0 0 0

8.7 atm.ml

type action = Ast | Bytecode | Compile

let _ =
let action =
if Array.length Sys.argv > 1 then
    List.assoc Sys.argv.(1) ["-a", Ast];
    ("-b", Bytecode);
    ("-c", Compile)]
else Compile in
let lexbuf = Lexing.from_channel stdin in
let program = Parser.program Scanner.token lexbuf in match action with
  Ast -> let listing = Ast.string_of_program program in print_string listing
| Bytecode -> let listing = Bytecode.string_of_prog (Compile.translate program) in
  print_endline listing
| Compile -> Execute.execute_prog (Compile.translate program)