University of Glasgow | School of Computing Science

Honours Individual Project Dissertation

Turing Machine Language

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Abstract

Acknowledgements

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Signature: Pete Gautam Date: 27 September 2022

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1 Introduction

2 Background

In this chapter, we review the concept of Turing Machines and constructing a parser for a programming language.

2.1 Turing Machines

In this section, we review the definition of Turing Machines and executing a TM on a valid tape.

A *Turing Machine* (TM) is a collection (Q, Σ, δ, q_0), where:

- Q is a set of states, including the accept state q_Y and reject state q_N;
- Σ is the set of letters, which does not include the `blank` symbol;
- $\delta\colon Q \setminus \{q_Y, q_N\} \times \Sigma^+ \to Q \times \Sigma^+ \times \{\texttt{left}, \texttt{right}\}$, where $\Sigma^+ = \Sigma \cup \{\texttt{blank}\}$, is the transition function; and
- $q_0 \in Q$ is the starting state.

This definition is taken from Dawson (2007). We can represent a TM as a directed graph, with vertices as states and edges as transitions. For example, the following is a TM:

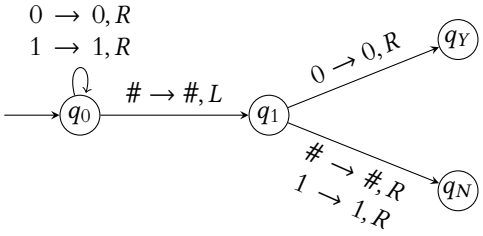


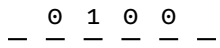
Figure 2.1: *A Turing Machine that accepts binary numbers divisible by 2.*

In this case, the alphabet $\Sigma = \{0, 1\}$. The blank symbol is denoted by #. The initial state is denoted by q_0; the accept state q_Y and the reject state q_N. Every edge corresponds to an evaluation of the transition function δ, e.g. $\delta(q_0, a) = (q_1, \texttt{blank}, \texttt{right})$.

Let Σ be an alphabet. A *tape* T *on* Σ is a function $T\colon \mathbb{Z} \to \Sigma^+$. In particular, the tape has infinite entries in both directions. Moreover, T is a *valid tape* if only finitely many symbols on T are not `blank`, and all the values that can be non-`blank` are non-`blank`. That is, there exist integers a, b such that for all $x \in \mathbb{Z}$, $T(x)$ is not `blank` if and only $x \geq a$ and $x \leq b$. We will represent a tape using a figure. For instance, let $\Sigma = \{0, 1\}$, and let T be the tape on Σ given below:

$$T(x) = \begin{cases} 0 & x \in \{0, 2, 3\} \\ 1 & x \in \{1\} \\ \texttt{blank} & \text{otherwise.} \end{cases}$$

Then, the following figure represents the tape T:



We will assume that the first non-blank value is at index 0.

A TM can be executed on a tape. Let M be a TM with alphabet Σ, and let T be a (valid) tape on Σ. We execute M on T inductively, as follows:

- At any point during execution, we maintain 3 objects- a tape on Σ, a state in M and an index in the tape (called the *tapehead index*).
- At the start, the tape is T; the tapehead index is 0; and the state is the initial state q_0.
- At some point during the execution, assume that we have the tape S, tapehead index j, with *tapehead value* $T(j) = t$, and a non-terminating state q (i.e. not q_Y or q_N). Denote $\delta(q, t) = (q', t', \texttt{dir})$. Then, the next state is q', and the next tape S' and the next tapehead index j' are given by:

$$S'(x) = \begin{cases} t' & x = i \\ S(x) & \text{otherwise,} \end{cases} \qquad j' = \begin{cases} j+1 & \texttt{dir} = \texttt{right} \\ j-1 & \texttt{dir} = \texttt{left}. \end{cases}$$

  If the state q' is not a terminating state, then the execution continues with these 3 objects. Otherwise, execution is terminated with terminating state q'.

2.2 Parser

TODO

3 Requirements

I used MoScoWs to specify the requirements for the project. In particular, the requirements were partitioned into one of the 4 sections: must have, should have, could have and will not have. Since the project has multiple parts, each part had its own MoScoW section.

3.1 Developing TML

Must Have A specification document for the TML must be created. The specification should include the following:

- a formal and an informal definition for the language;
- how to execute a program on a valid tape; and
- a proof of equivalence between TMs and TML programs (which involves constructing a TM for a TML program, and vice versa).

Should Have The specification should include examples. In particular, there should be examples of valid and invalid programs, and those that illustrate the proofs (e.g. how to convert a TM into a TML program) so that it is easier to follow.

Could Have The specification could connect TML program with the Church-Turing Thesis. In particular, a proof of equivalence could be explored between TML program and λ-calculus.

3.2 Developing the parser for TML

Must Have The parser must be able to:

- parse a string representation of a TM program to a program context;
- validate a program context; and
- execute a program context on a valid tape.

Should Have The parser should be able to convert a program context to a TM. Compared to the 3 must-have requirements, this requirement was considered to be of the lowest priority, and so was considered a should-have.

Could Have The parser should be able to execute a TM on a tape. This might help in the website to illustrate execution on the converted TM.

Will Not Have The parser will not be able to convert a TM into a TML program.

3.3 The website

Must Have The website must:

- have a code editor for TML;
- be able to convert a valid program to a TM and present it as a FSM;
- be able to execute a program on a valid tape, one step at a time.

Should Have The code editor should support syntax highlighting. Assuming that the initial FSM representation rendered by the website places the states in a random manner, without considering which states are linked and should be placed closer, the user should be able to drag them around.

Could Have The editor could support error detection. The user could be able to configure the website, e.g. change the editor theme, the editor font size and the speed of tape execution. The website could convert a program to its definition as a TM. The website could support automatic placement of states (within the FSM) in an aesthetic manner instead of having the user drag it.

Will Not Have The editor will not be able to automatically fix errors. The website will not be able to execute a TM on a tape (without a program). The website will not able to convert a TM into a TML program.

4 Turing Machine Language

In this chapter, we define the Turing Machine Language (TML) as an alternative to Turing Machines (TM). We will define the syntax of a TML program and how it can be executed on a tape in a similar manner to TMs. We will then prove that there is an equivalence between TML programs and TMs in terms of their execution on a tape.

4.1 Turing Machine Language Program

In this section, we will define the syntax of the Turing Machine Language with an example. We next analyse the syntax and define execution of a valid TML program on a tape in a similar manner to the execution of a TM.

Consider the following TML program.

```
1  alphabet = {"0", "1"}
2  module isEven {
3     while 0, 1 {
4        move right
5     } if blank {
6        move left
7        if 0 {
8           changeto blank
9           accept
10       } if 1, blank {
11          changeto blank
12          reject
13       }
14    }
15 }
```

A program in TML will be used to execute on a tape, so the syntax used guides us in executing the program on a tape. We will see that later. For now, we consider the rules of the TML program:

- A valid TML *program* is composed of the *alphabet*, followed by one or more *modules*. In the example above, the alphabet of the program is $\{0, 1\}$, and the program has a single module called `isEven`.
- A module contains one or more *blocks* (a specific sequence of commands). There are two types of blocks- *basic blocks* and *switch blocks*.
- A basic block consists of *basic commands* (*changeto*, *move* or *flow* command). A basic block consists of at least one basic command, but it is not necessary for a basic block to be composed of all the basic commands. If multiple commands are present in a basic block, they must be in the following order- *changeto*, *move* and *flow* command. In the program above, there is are many basic blocks, e.g. at lines 4, 6, 8-9 and 11-12. We do not say that line 8 is a basic block by itself; we want the basic block to be as long as possible.

- A *switch block* consists of cases (*if* or *while* commands), each of which corresponds to one or more letters. A switch block must contain precisely one case for each of the letter in the alphabet, including the `blank` letter. The first block within a case block cannot be another switch block. In the program above, there is a switch block at lines 3-14 and a nested switch block at lines 7-13.
- The body of an *if* command can be composed of multiple blocks. These blocks can be both basic blocks and switch blocks. We can see this at lines 5-13; the *if* block has a basic block at line 6 and then a switch block.
- The body of a *while* command must be composed of a single basic block. The basic block cannot have a *flow* command. This is because when we execute a *while* block, the next block to run is the switch block it is in; we cannot accept, reject or go to another module.
- A switch block must be the final block present; it cannot be followed by a basic block.

The EBNF for the TML and examples of syntax errors are given in the appendix.

We will now consider how to execute a tape on a valid TML program. Let P be a TML program with alphabet Σ and let T be a tape on Σ. We execute P on T inductively, as follows:

- At any point during execution, we maintain 3 objects- a tape on Σ, a block of P and the tapehead index.
- At the start, the tape is T; the tapehead index is 0; and the block is the first block in the first module in P.
- At some point during the execution, assume that we have the tape S, tapehead index j, with tapehead value $T(j) = t$, and a block b. We define the next triple as follows:
  - if b is a switch block, we take the first block from the case corresponding to the tapehead value- because the program is valid, this is a basic block; we will now refer to this block as b.
  - if b has a *changeto* `val` command, the next tape T' is given by

$$T'(x) = \begin{cases} \texttt{val} & x = i \\ T(x) & \text{otherwise.} \end{cases}$$

    If the *changeto* command is missing, then the tapehead $T' = T$.
  - if b has a *move* `dir` command, the next tapehead index is given by:

$$i' = \begin{cases} i+1 & \texttt{dir} = \texttt{right} \\ i-1 & \texttt{dir} = \texttt{left}. \end{cases}$$

    If the *move* command is missing, then $i' = i - 1$.
  - we either terminate or determine the next block b' to execute (in decreasing precedence):
    - if the block is the body of a while case block, then the next block $b' = b$, i.e. we execute this switch block again (not necessarily the same case block);
    - if the block contains a terminating *flow* command, execution is terminated and we return the terminated state (`accept` or `reject`);
    - if the block contains a *goto* `mod` command, then b' is the first block of the module `mod`;
    - if the block is not the final block in the current module, then b' is next block in this module;
    - otherwise, execution is terminated and we return the state `reject`.

  If execution is not terminated, execution continues with the next triplet.

An example that illustrates the execution process is given in the appendix.

4.2 Complete TML Programs

When we defined execution of a valid TML program on a tape above, we said that a basic block need not have all 3 types of commands (*changeto*, *move* and a *flow* command), but in the execution above, we have established some 'default' ways in which a program gets executed. In particular,

- if the *changeto* command is missing, we do not change the value of the tape;
- if the *move* command is missing, we move left;
- if the *flow* command is missing, we can establish what to do using the rules described above- this is a bit more complicated than the two commands above.

Nonetheless, it is possible to include these 'default' commands to give a *complete* version of the program. This is what we will establish in this section.

Consider the following complete program.

```
alphabet = {"0", "1"}
module isOdd {
   // move to the end
   while 0 {
      changeto 0
      move right
   } while 1 {
      changeto 1
      move right
   } if blank {
      changeto blank
      move left
      goto isOddCheck
   }
}
module isOddCheck {
   // accept if and only if the value is 1
   if 0, blank {
      changeto 0
      move left
      reject
   } if 1 {
      changeto blank
      move left
      accept
   }
}
```

Now, we consider the rules that a complete TML program obeys:

- A basic block in a complete program has all the necessary commands- if the basic block is inside *while* case, it has a *changeto* command and a *move* command; otherwise, it also has a *flow* command.
- A module in a complete program is composed of a single switch block.

We will now construct a complete TML program for a valid TML program.

1. We first break each module into smaller modules so that every module has just one basic/switch block- we add a *goto* command to the next module if it appeared just below this block.

2. Then, we can convert each basic block to a switch block by just adding a single case that applies to each letter in the alphabet.
3. Finally, we add the default values to each basic block to get a complete TML program.

This way, we can associate every block in the valid program with a corresponding block in the complete program. The complete version is always a switch block and might have more commands than the original block, but it still has all the commands present in the original block.

An example that illustrates this process is given in the appendix.

Theorem 1. *Let P be a valid TM program. Then, P and its completion P^+ execute on every valid tape T in the same way.*

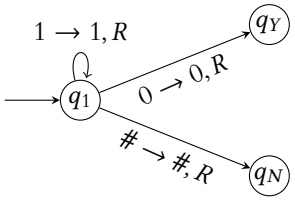
The proof of the theorem is given in the appendix.

Because of the equivalence between valid and complete programs, we will assume that every valid program is complete from now on.

4.3 Equivalence of TMs and TMLs

In this section, we will show that there is an equivalence between TMs and valid (complete) TML programs. We will first construct a valid TML program for a TM and then show that it has the same behaviour as the TM. Later, we will construct a TM for a complete TML program, and show the equivalence in this case as well.

We will first illustrate how to convert a TM to a (complete) TML program. So, consider the following TM: Consider the following TM:



Then, its corresponding TML program is the following:

```
alphabet = {"0", "1"}
module has0 {
   while 1 {
      changeto 1
      move right
   } if 0 {
      changeto 0
      move right
      accept
   } if blank {
      changeto blank
      move left
      reject
   }
}
```

In general, we convert each (non-terminating) state in the TM M to a TML module. The following is how we create the module:

- the module contains a single *switch* command;
- for each letter σ in the alphabet Σ^+, denote $\delta(q, \sigma) = (q', \sigma', \texttt{dir})$. We add a case in the *switch* command corresponding to letter σ (an *if* case if $q' \neq q$, otherwise a *while* case) with the following commands:
  - `changeto` σ'
  - `move` *dir*
  - in the case of an *if* block, if q' is `accept`, then the command `accept`; if q' is `reject`, then the command `reject`; otherwise, `goto` q'.

Moreover, we can construct the program P with:

- the alphabet Σ;
- modules corresponding to every state q in M;
- the module corresponding to the initial state q_0 placed at the top.

We say that P is *the corresponding program for M*.

Theorem 2. *Let M be a TM, and let P be the corresponding program for M. Then, M and P execute on every valid tape T in the same way.*

The proof of the theorem is given in the appendix.

Next, we construct a TM for a (complete) TML program. This process is essentially the inverse of the one we saw converting a complete TML program to a TM. In particular, for each module m in P, we construct the state q as follows- for each letter σ in Σ^+, we define $\delta(q, \sigma) = (q', \sigma', \texttt{dir})$, where:

- the value σ' is the letter given in the *changeto* command within m;
- the value `dir` is the direction given in the *move* command within m;
- if the *flow* command in m corresponding to σ is `accept`, then q' is the `accept` state; if it is `reject`, then q' is the `reject` state; if we are in a *while* block, then $q' = q$; otherwise, q' is the state corresponding to the module given in the *goto* command.

Then, the TM with all the states q, the same alphabet Σ, the transition function δ and initial state q_0 corresponding to the first module in P is the *corresponding TM for P*. An example illustrating this process is given in the appendix.

Theorem 3. *Let P be a complete TM program, and let M be the corresponding TM for P. Then, P and M execute on every valid tape T in the same way.*

The proof of the theorem is given in the appendix.

Hence, we have established that for any valid TML program, there is a TM, and vice versa.

5 Turing Machine Parser and Website

5.1 Parser

5.1.1 Design

5.1.2 Implementation

5.2 Website

5.2.1 Design

5.2.2 Implementation

6 Evaluation

In the project, there were 2 aspects to evaluate- the TML and the website. Both aspects were evaluated continually through unit tests during production and tested using a user evaluation.

After the website had been completed, a user evaluation was conducted on 18 second year computing students. TMs are taught to students that have few years of programming experience, and for this reason second years were chosen. Note that they had little familiarity, if any, with Turing Machines and were introduced to both TMs and TML during the evaluation session. The aim of the evaluation was for them to get acquainted with the two concepts, and then to:

- compare TMs and TML programs;
- understand whether writing a TML program would help in drawing a TM; and
- evaluate the website.

The evaluation session also served as a great opportunity to ask for any features to be added to the website and the language.

During the evaluation session, students were first introduced to TML programs. They were then expected to understand what language two mystery TML programs accept. This was done by checking whether the programs accepted some values, which should have helped them understand the way the program operates and decode the language it accepts. They were expected to use the website to help them follow the code and understand the steps in execution. Then, they were introduced to TMs, and expected to decode 2 TMs in a similar manner. Since the website can only execute TML programs, they were given TML programs for the TM. Note however that this did not defeat the purpose of testing TMs since:

- most students found it easier to follow execution in TMs (a diagram) than TML (a program); and
- the programs given were complete TML programs, which are quite close to TMs.

Finally, they were asked to write some programs in the TML. Like in the previous sections, they were free to use the website to write the programs and test its correctness. The first few programs were quite similar to the code they had seen before. The remaining programs were somewhat more difficult, and for this reason they were optional. Nonetheless, many students attempted them and wrote impressive programs! The evaluation took about 50 minutes to be completed. The students were asked to fill out a worksheet with their answers.

After they had completed the worksheet, they completed a survey to evaluate the language and the website. To avoid writing programs on paper, students were asked to copy their code from the final part of the worksheet to the survey. The results of the survey are discussed in detail in the next section. Both the worksheet and the survey are given in the appendix.

6.1 Evaluation Results

6.1.1 Parser and Language Evaluation

The parser was continually tested during production to ensure correctness. This was achieved using unit testing. They were used to test all aspects of the parser, and were extensive. In fact, the unit tests had more than 95% code coverage.

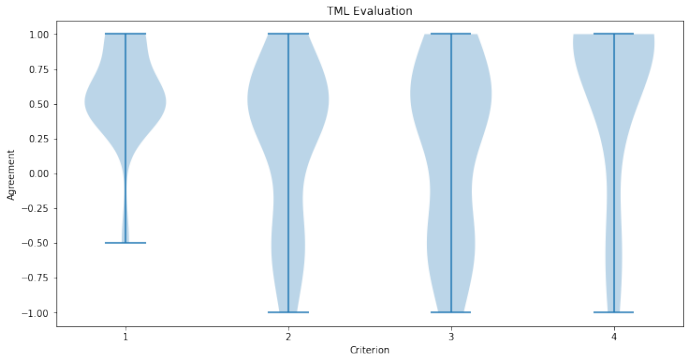


Figure 6.1: *A violin plot that summarises the results of the survey relating to the TML with respect to the 4 criteria. The agreement value refers to how much the user agrees to the statement:* -1 *is strongly disagree;* -0.5 *disagree;* 0.5 *agree and* 1 *strongly agree. The whiskers show the range of answers, e.g. nobody said they strongly disagreed with criterion 1. Moreover, the density is proportional to the number of participants answering the question with that value, e.g. most people answered criterion 1 with the value* 0.5 *(agree).*

During user evaluation, users were asked to evaluate the language in the following criteria:

1. TML is easy to understand
2. TML is easy to write programs in
3. I was able to fix errors in my code using the error messages provided
4. I was able to easily reason executing a program on a tape

They were asked to rate how much they agreed with each statement, and the result is summarised for each criterion in Figure 6.1.

It is clear that most students found the language easy to understand. However, a smaller number of students believed that the language is easy to write programs in- the solutions to the worksheet illustrate that most students were able to correctly execute a program on a tape, and see whether it accepts a value, but found it harder to write (correct) programs. This is quite expected given that they were only exposed to the language for about an hour.

Most students found it easy to reason executing a program on a tape- they were able to run the code on the website and follow the code quite easily. Many found the error messages quite useful and it helped them write correct programs, but few disagreed with this. Some of the error messages could have been given more details, for example a missing case in a switch block did not identify what letter in the case was missing. Moreover, there was a minor bug in the position of the switch block (where it ended one line later than the correct position). The feedback from students helped identify these issues, and they were fixed in due time.

The TML was then directly compared to TMs. In particular, students were asked to compare TMs and TML programs in the following criteria:

1. I am more confident in writing a program in TML than drawing a TM
2. I find it easier to reason what a TML program accepts than a TM

The students were asked to rate how much they agreed with each statement, and the result is summarised for the two criteria in Figure 6.2.

Overall, students seem to be more comfortable with TML than TM. They were more confident writing a TML than drawing a TM- this is expected since they were not asked to draw a TM. However, it is surprising that many found it easier to reason a TML program than a TM. This is because many claimed that it is easier to follow a diagram than code. Nonetheless, the students

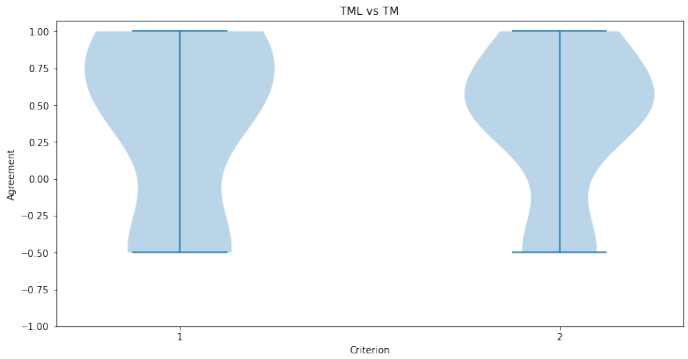


Figure 6.2: *A violin plot that summarises the results of the survey that compare TM and TML with respect to the 2 criteria.*

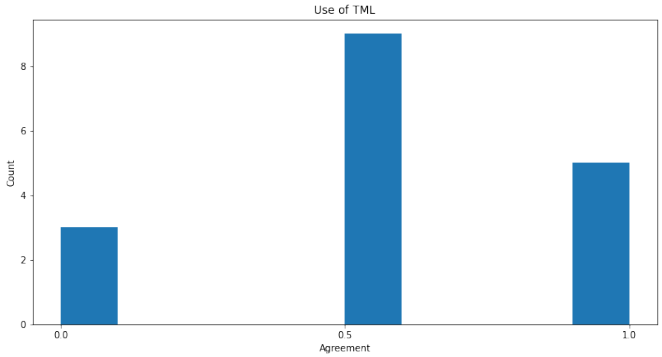


Figure 6.3: *A histogram that summarises whether the users would consider writing a TML program before drawing a TM. 0 means no; 0.5 means maybe; and 1 means yes.*

might have found it easier to reason a TML program since the worksheet focuses much more on TML than TM.

The students were then asked whether they would consider writing a TML program before drawing a TM. The response of this question is summarised in Figure 6.3.

When drawing a TM for some algorithm, it is quite helpful to plan the machine beforehand. TML provides an opportunity where it is possible to reason in detail how the algorithm is meant to execute on a tape without considering the states and transitions in a TM. Moreover, it is quite easy to naturally convert a TML to a TM. I believe this is the main selling point of the language. The results clearly show that many would consider drawing it. The hesitation might result from the little experience that they had gotten.

6.1.2 Website Evaluation

Like with the language, the website was also continually tested during production for correctness. This was achieved through unit testing. Unlike the testing for language, this was however less successful due to the limits in mocking frameworks and time constraints. Nonetheless, the tests covered all the major parts of the website and ensured that all the functionalities implemented were correct.

During the user evaluation, the students were expected to use the website to understand TMLs and TMs. For this reason, they were able to evaluate the website from their experience. In the

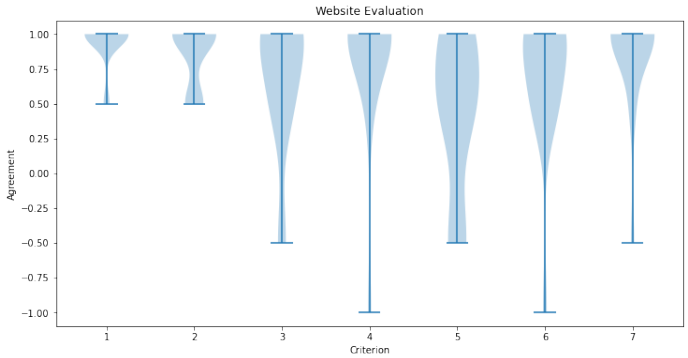


Figure 6.4: *A violin plot that summarises the results of the survey relating to the website with respect to the 7 criteria.*

survey, they were asked to evaluate the website in the following 7 criteria:

1. The website is easy to follow
2. The presentation of the website is intuitive
3. There were no visible bugs in the website
4. The website was fast
5. The website feels complete
6. The code execution was easy to follow
7. The code editor was easy to use

The results of the survey are summarised in Figure 6.4.

It is evident that most found the website easy to follow and intuitive to use. Initially, there were a few bugs present in the website, e.g. the TM did not change to the latest version when tape execution began. However, in later sessions, most students believed that the website had few bugs. Most also found the website to be fast and complete.

Some did not find code execution easy to follow- this was particularly the case with long programs where students had to scroll to find the currently executing block of code. Also, many found the code editor easy to use. There were some issues in using the code editor during the first session- the code cannot be edited while being executed, but there was no feedback to inform the user about this issue. In the later sessions, a warning pop-up was added to warn them of this issue and students were able to fix the issue easily.

6.2 Limitations to Evaluation

Due to the time constraints of the project, there were some limitations to the evaluation, in user evaluation. The biggest limitation was the length of the evaluation session. It was hard to find a balance between a productive session and a short session. For this reason, it was not possible to test the students' ability to draw TMs. Moreover, a significant portion of the question do not require the student to understand TMs or TML programs; they can just run the code on the website and get the answer. This was done to help the students grasp the language easily. When it came to describing the values that a program/TM accepted, it was clear that some had not understood the program. For instance, in a mystery program that accepts values that are 3 mod 4, some students claimed that the program accepts all odd numbers! Moreover, although students were asked to write some TM programs, this could not be tested completely. In fact, the core questions only involved making minor changes to the programs they were given; it was only the optional questions that truly tested their ability to write TM programs and reason about them.

7 Conclusion

7.1 Future Work

There are many additions that can be made to the product in future. Some of these were discovered during production, and some as part of user evaluation.

7.1.1 Language

Although the language is equivalent to TMs, it is still quite low-level. There are many common paradigms that can be added to the language. These include:

1. the ability to traverse to the end and start in one command, e.g. `move start` and `move end`;
2. an else clause (an if block for the remaining characters);
3. the ability for modules to be parametrised with respect to letters.

The first feature is a very common feature seen in plenty of programs. It was brought up plenty of times during the evaluation sessions and given as an example of a feature to add in the survey. The second point is also somewhat common and was suggested by a student. These two features should not be difficult to add to the language.

The final feature was also discovered during the survey. Students were quite frustrated when they realised that the programs they had written would not work since it would introduce a blank entry within the middle of the tape. This feature would certainly remedy this issue, but adding this feature might make TML much simpler than TMs- students are *expected* to write programs in a way that ensures that no spaces are added to the tape. Nonetheless, it is possible to write a module that shifts values to the left or the right, so if implemented, this can be added as an in-built module.

Another feature that could be added to the language is the ability to convert a TM into a 'good' TML program. Currently, the proof of equivalence only provides a way to convert TMs into complete TML programs. Moreover, the proof relies on a one-way conversion from valid TML programs to complete TML programs. Hence, it would be a good idea to consider converting a TM (or equivalent, a complete TML program) to a TML program that is nested, and not complete. One way to do so would be to achieve maximum nesting by replacing `goto` commands with the actual module, however this is not optimal. In particular, we would have a lot of duplicate code present. Instead, it might be a good idea to only replace modules that are only called once, and to keep modules that are called multiple times separate.

7.1.2 Website

There are many possible improvements to the website, which were discovered during production and user evaluation. These were some of the features that can be added:

- support for direct execution of a TM;
- a play button on the tape section to execute long programs on long tapes without pressing the step button hundreds of times;

- the ability to collapse the panels; and
- the ability to customise the number of tape entries to be shown.

All of these are great features that could be added to the website and would make it more usable and easier to keep track of code execution.

Another feature that can be added is to make the website more responsive. The FSM is currently being produced using the graphviz framework. The resulting image has hard-coded dimensions which makes it hard to make the website responsive. It is not completely possible to make the graph fixed; only the maximum size can be specified. Moreover, for complex FSMs with 20 nodes, the nodes are quite small so it is hard to follow code. To fix this, one of the following features could be added:

- the ability to zoom in and drag the FSM panel; or
- the ability to scroll the FSM panel.

A | TML EBNF

The following is the EBNF for the Turing Machine Language.

program = *alphabet module*$^{+}$
alphabet = `alphabet =` { *seq-val* }
module = `module` *id* { *block*$^{+}$ }
block = *basic-block* | *switch-block*
switch-block = *case-block*$^{+}$
case-block = *if-block* | *while-block*
if-block = `if` *seq-val* {*block*$^{+}$}
while-block = `while` *seq-val* { *core-com*$^{+}$ }
basic-block = (*core-com* | *flow-com*)$^{+}$
core-com = `move` *direction* | `changeto` *value*
flow-com = `goto` *id* | *terminate*
terminate = `reject` | `accept`
direction = `left` | `right`
seq-val = (*value*`,`)* *value*
value = `blank` | `a` | `b` | `c` | ... | `z` | `0` | `1` | ... | `9`
id = (`a` | `b` | `c` | ... | `z` | `A` | `B` | `C` | ... | `Z`)$^{+}$

B Incorrect TML Programs

Below is a selection of incorrect TML programs, along with an explanation as to why they are incorrect.

- **Invalid while block (flow command)**

```
alphabet = {a, b}
module main {
   while a, b {
      accept
   }
}
```

A while block cannot have a flow command. We know that the next block to be executed is the same block, so this doesn't make sense- are we meant to terminate or re-run the current block?

- **Invalid while block (multiple blocks)**

```
alphabet = {a, b}
module main {
   while blank {
      move left
      move right
   }
}
```

A while block must be composed of a single basic block. We know that a while block corresponds to a self-loop, so if we have 2 blocks, we would need another state to link to the current state. This doesn't make sense, so we can only have one block. The block must also be a simple block since we have already fixed what character the while block applies to.

- **Invalid switch block (first block not basic)**

```
alphabet = {a, b}
module main {
   if a, blank {
      if a {
         move right
      }
   }
}
```

The first block in a switch block must be a basic block. That is, we cannot have nested if blocks without an intermediate command. This does not make sense semantically- in the case above, we should just have a single if block for `a`.

- **Invalid module (flow command not final)**

```
1  alphabet = {a, b}
2  module main {
3     goto simple
4     move left
5  }
6  module simple {
7     reject
8  }
```

If we have a *flow*-command in a block, then it must be the final command. A *flow*-command moves to terminating execution or executing a module from the start, so any command below it cannot be executed. In this case, we are moving to a different block called `simple`, so we never move `left`.

- **Invalid module (switch block not final)**

```
1  alphabet = {a, b}
2  module a {
3     if a, b {
4        changeto blank
5        move right
6        move right
7        changeto b
8     } if blank {
9        move left
10       changeto a
11       reject
12    }
13    accept
14 }
```

If a module has a *switch* block, it must be the final block. In this case, that is not the case. It is possible that the program is meant to accept if we execute the *if*-block at line 3, but it is not possible to continue the *if*-block at line 8- this block already ends with a flow command. So, the execution would be unclear if this was allowed.

- **Invalid module (invalid name)**

```
1  alphabet = {a, b}
2  module accept {
3     move right
4  }
```

A module cannot be named `accept` or `reject`. It can be named any of the other keywords, but not `accept` or `reject`.

C | TML Examples

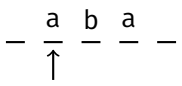
C.1 Executing a TML program on a Tape

Consider the following TML program:

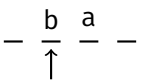
```
alphabet = {"a", "b"}
module palindrome {
   if blank {
      accept
   } if a {
      changeto blank
      move right
      while a, b {
         move right
      } if blank {
         move left
         if blank, a {
            changeto blank
            move left
            goto restart
         } if b {
            reject
         }
      }
   } if b {
      changeto blank
      move right
      while a, b {
         move right
      } if blank {
         move left
         if blank, b {
            changeto blank
            move left
            goto restart
         } if a {
            reject
         }
      }
   }
}
module restart {
   while a, b {
      move left
   } if blank {
      move right
      goto palindrome
```

```
43     }
44 }
```

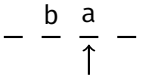
We will execute the program on the following tape.



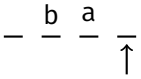
The arrow points at the tapehead value. We first execute the first block in the module `palindrome`. Since the tapehead value is `a`, we execute the basic block at lines 5-20. So, we change the tapehead value to `blank`, and the tapehead moves to the right by one step. Since this is an *if*-block, without a flow command, and there is a block following this one, the next block to be executed is the switch block at lines 8-19. Now, the current tape is the following.



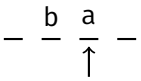
The current block is a switch block. The tapehead value is `b`, so we are at the *while* command at line 9. The basic block here only contains a *move* command. So, we leave the tape as is, and the tapehead moves to the right once. This is a *while* command, so the next block to execute is still this switch block. The current tape state is the following.



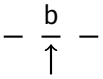
The current block is still a switch block. The tapehead value is `a`, so we execute the same *while* command at line 9. Moreover, the next block to execute is still the switch block. Now, the current tape state is the following.



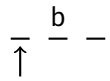
For the third time, we are executing the same switch block. Now, however, the tapehead value is `blank`, so we execute the first block of the *if* command at line 5, i.e. we move to the left. Since this is an *if* command and this is not the last block in the if command, the next block to execute is the switch block at lines 12-18.



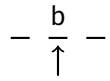
Now, the current block is a switch block. The tapehead value is `a`, so we take the basic block at lines 12-16. The value of the tapehead becomes `blank`, and moves to the left. The next block to execute is the switch block in `restart`.



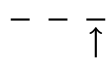
Since the current tapehead value is `b`, we execute the basic block at line 39. So, we move to the left, and the tape is left as is. Moreover, since this is a while block, the next block to execute is still the switch block.



Since the current tapehead state is `blank`, we execute the basic block at lines 40–43. So, we move to the left, and the tape is left as is. The next block to execute is the switch block at `palindrome`.



Since the current tapehead state is `b`, we execute the basic block at lines 21–22. So, we change the tapehead value to `blank`, move to the right. This is a while block, so the next block to be executed is still the switch block.



At this point, the tapehead index moves between the blank values as we move to the basic block at line 3. Then, the execution terminates and we accept the tape.

C.2 Completing a TML program

The steps to convert a TML program to complete it is the following:

1. We first break each module into smaller modules so that every module has just one basic/switch block- we add a *goto* command to the next module if it appeared just below this block.
2. Then, we can convert each basic block to a switch block by just adding a single case that applies to each letter in the alphabet.
3. Finally, we add the default values to each basic block to get a complete TML program.

We illustrate this with an example. Assume we first have the following program.

```
alphabet = {"a", "b"}
module simpleProgram {
   changeto b
   move left
   move right
   accept
}
```

After applying step 1 of completion, we get the following program.

```
alphabet = {"a", "b"}
module simple1 {
   changeto b
```

```
    move left
    goto simple2
}
module simple2 {
    move right
    accept
}
```

After applying step 2, we have the following program.

```
alphabet = {"a", "b"}
module simple1 {
    if a, b, blank {
        changeto b
        move left
        goto simple2
    }
}
module simple2 {
    if a, b, blank {
        move right
        accept
    }
}
```

Finally, after applying step 3, we get the following program:

```
alphabet = {"a", "b"}
module simple1 {
    if a {
        changeto b
        move left
        goto simple2
    } if b {
        changeto b
        move left
        goto simple2
    } if blank {
        changeto b
        move left
        goto simple2
    }
}
module simple2 {
    if a {
        changeto a
        move right
        accept
    } if b {
        changeto b
        move right
        accept
    } if blank {
        move right
```

```
        accept
    }
}
```

This program obeys the definition of a complete program.

C.3 Converting a TM to a complete TML program

Consider the following complete TM program:

```
alphabet = {"a", "b"}
module moveToEnd {
    while a {
        changeto a
        move right
    } while b {
        changeto b
        move right
    } if blank {
        changeto blank
        move left
        goto checkAFirst
    }
}
module checkAFirst {
    if a {
        changeto blank
        move left
        goto checkASecond
    } if b, blank {
        changeto blank
        move left
        reject
    }
}
module checkASecond {
    if a {
        changeto blank
        move left
        accept
    } if b, blank {
        changeto blank
        move left
        reject
    }
}
```

Then, its corresponding TM is the following:

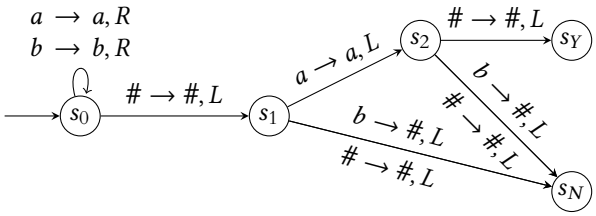


Figure C.1: *The TM corresponding to the program above. The state s_0 corresponds to the module* `moveToEnd`*; the state s_1 corresponds to the module* `checkAFirst`*; and the state s_2 corresponds to the module* `checkASecond`*.*

A Proofs of the Theorems

Theorem 1. *Let P be a valid TML program. Then, P and its completion P^+ execute on every valid tape T in the same way. That is,*

- *for every valid index n, if we have tape T_n, tapehead index i_n and module m_n with executing block b_n for the TM program P, and we have tape S_n, tapehead index j_n and module t_n, then $T_n = S_n$, $i_n = j_n$, and t_n is the corresponding complete module block of b_n;*
- *P terminates execution on T if and only if P^+ terminates execution on T, with the same final status (`accept` or `reject`).*

Proof. We prove this by induction on the execution step (of the tape).

- At the start, we have the same tape T for both P and P^+, with tapehead index 0. Moreover, the corresponding (completed) module of the first block in the first module of P is the first module of P. So, the result is true if $n = 0$.
- Now, assume that the result is true for some integer n, where the block b_n in the TML program P does not end with a terminating *flow* command. Let σ_n be the letter at index $i_n = j_n$ on the tape $S_n = T_n$.
  - If the *changeto* command is missing in b_n for σ_n, then the next tape $T_{n+1} = T_n$. In the complete module m_n, the case for σ_n will have the command `changeto` σ_n. So, the next tape is given by:
    $$S_{n+1}(x) = \begin{cases} S_n(x) & x \neq j_n \\ \sigma_n & \text{otherwise} \end{cases}.$$
    Therefore, we have $S_{n+1} = S_n$ as well. So, $T_{n+1} = S_{n+1}$. Otherwise, we have the same *changeto* command in the two blocks, in which case $T_{n+1} = S_{n+1}$ as well.
  - If the *move* command is missing in b_n for σ_n, then the next tapehead index $i_{n+1} = i_n - 1$. In the complete module m_n, the case for σ_n will have the command `move left`, so we also have $j_{n+1} = j_n - 1$. Applying the inductive hypothesis, we have $i_{n+1} = j_{n+1}$. Otherwise, we have the same *move* command, meaning that $i_{n+1} = j_{n+1}$ as well.
  - We now consider the next block b_{n+1}:
    - If the block b_n is a *switch* block with a *while* case for σ_n, then this is still true in the module m_n. So, the next block to be executed in P is b_n, and the next module to be executed in P^+ is m_n. In that case, the corresponding module of the block $b_{n+1} = b_n$ is still $m_{n+1} = m_n$.
    - Instead, if the block b_n has no *flow* command for σ_n, and is not the last block, then the next block to execute is the block just below b_n, referred as b_{n+1}. By the definition of P^+, we find that the case block in the module m_n has a *goto* command, going to the module m_{n+1} which corresponds to the block b_{n+1}.
    - Now, if the *flow* command is missing for σ_n and this is the last block, then execution is terminated with the status `reject` for the program P. In that case, the case for σ_n in the module m_n has the `reject` command present, so the same happens for P^+ as well.

    - Otherwise, both P and P^+ have the same flow command, meaning that there is either correspondence between the next module to be executed, or both the program terminate with the same status.

In that case, P and P^+ execute on T the same way by induction. □

Theorem 2. *Let M be a TM, and let P be the corresponding program for M. Then, M and P execute on every valid tape T in the same way. That is,*

- *for every valid index n, if we have tape T_n, tapehead index i_n and module m_n for the TM program P, and we have tape S_n, tapehead index j_n and state q_n for the TM M, then $T_n = S_n$, $i_n = j_n$ and m_n is the corresponding module for q_n;*
- *M terminates execution on T if and only if P terminates execution on T, with the same final status (`accept` or `reject`).*

Proof. We prove this by induction on the execution step.

- At the start, we have the same tape T for both M and P, with tapehead index 0. Moreover, the first module in P corresponds to the initial state q_0. So, the result is true if $n = 0$.
- Now, assume that the result is true for some integer n, where the TM state q_n is not `accept` or `reject`. In that case, $T_n = S_n$, $i_n = j_n$ and m_n is the corresponding module for q_n. Let σ_n be the letter at index $i_n = j_n$ on the tape $T_n = S_n$. Denote $q(q_n, \sigma_n) = (q_{n+1}, \sigma_{n+1}, \texttt{dir})$. In that case,

$$T_{n+1}(x) = \begin{cases} T_n(x) & x \neq i_n \\ \sigma_{n+1} & \text{otherwise,} \end{cases} \qquad i_{n+1} = \begin{cases} i_n - 1 & \texttt{dir} = \texttt{left} \\ i_n + 1 & \texttt{dir} = \texttt{right,} \end{cases}$$

  and the next state is q_{n+1}.
  - We know that the module m_n in TM program P corresponds to the state q_n, so it has a `changeto` σ_{n+1} command for the case σ_n. In the case, the next tape for P is:

$$S_{n+1}(x) = \begin{cases} S_n(x) & x \neq i_n \\ \sigma_{n+1} & \text{otherwise.} \end{cases}$$

    So, $T_{n+1} = S_{n+1}$.
  - Similarly, the case also contains a `move dir` command. This implies that the next tapehead index for P is:

$$j_{n+1} = \begin{cases} j_n - 1 & \texttt{dir} = \texttt{left} \\ j_n + 1 & \texttt{dir} = \texttt{right.} \end{cases}$$

    Hence, $i_{n+1} = j_{n+1}$.
  - Next, we consider the value of q_{n+1}:
    - If $q_{n+1} = q_n$, then the case block is a *while* block, and vice versa. So, the next module to be executed is m_n. In that case, m_{n+1} still corresponds to q_{n+1}.
    - Otherwise, we have an *if* block.
      - In particular, if q_{n+1} is the `accept` state, then the case for σ_n contains the *flow* command `accept`, and vice versa. In that case, execution terminates with the same final status of `accept`. The same is true for `reject`.
      - Otherwise, the module contains the command `goto` m_{n+1}, where m_{n+1} is the corresponding module for q_{n+1}.

In that case, P and M execute on T the same way by induction. □

Theorem 3. *Let P be a complete TM program, and let M be the corresponding TM for P. Then, P and M execute on every valid tape T in the same way. That is,*

- *for every valid index n, if we have tape T_n, tapehead index i_n and module m_n for TM program P, and we have tape S_n, tapehead index j_n and state q_n for the TM M, then $T_n = S_n$, $i_n = j_n$ and q_n is the corresponding state for m_n;*
- *P terminates execution on T if and only if M terminates execution on T, with the same final status (*`accept` *or* `reject`*).*

Proof. We prove this as well by induction on the execution step of the tape.

- At the start, we have the same tape T for both P and M, with tapehead index 0. Moreover, the initial state q_0 in M corresponds to the first module in P. So, the result is true if $n = 0$.
- Now, assume that the result is true for some integer n, which is not the terminating step in execution. In that case, $S_n = T_n$, $j_n = i_n$ and q_n is the corresponding state for m_n. Let σ_n be the letter at index $j_n = i_n$ on the tape $S_n = T_n$. We now consider the single switch block in m_n:
  - If the block in m_n corresponding to σ_n is a *while* block, then we know that its body is partially complete, and so is composed of the following commands:
    - `changeto` σ_{n+1}
    - `move dir`

    So, we have $\delta(q_n, \sigma_n) = (q_n, \sigma_{n+1}, \texttt{dir})$. Using the same argument as in Theorem 2, we find that $T_{n+1} = S_{n+1}$ and $i_{n+1} = j_{n+1}$. Also, $q_{n+1} = q_n$ is the corresponding state for $m_{n+1} = m_n$.
  - Otherwise, we have an *if* command. In this case, the case body is complete, and so composed of the following commands:
    - `changeto` σ_{n+1}
    - `move dir`
    - `accept`, `reject` or `goto` m_{n+1}.

    So, we have $\delta(q_n, \sigma_n) = (q_{n+1}, \sigma_{n+1}, \texttt{dir})$, where q_{n+1} is the corresponding state to the *flow* command present. Here too, we have $T_{n+1} = S_{n+1}$ and $i_{n+1} = j_{n+1}$ by construction.

  Now, we consider the flow command:
  - If we have an `accept` command in the body, then q_{n+1} is the accepting state, and vice versa. So, we terminate execution with the final status of `accept`. The same is true for `reject`.
  - Otherwise, the state q_{n+1} is the corresponding state to the module m_{n+1}.

  In all cases, there is a correspondence between the state for m_{n+1} and q_{n+1}.

So, the result follows from induction. □

D Evaluation Content

D.1 Worksheet

D.1.1 Introduction to Turing Machine Language

In this section, you are given some programs in Turing Machine Language (TML). They will be used to explain the syntax of the programming language and how they can be run on tapes.

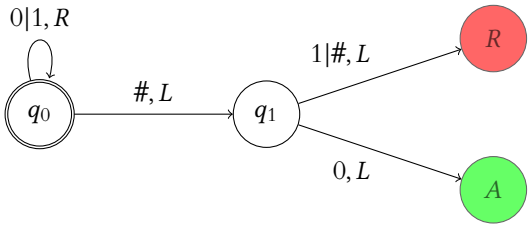
- `isDiv2`:

```
// checks whether a binary number is divisible by 2
alphabet = {0, 1}
module isDiv2 {
   // move to the end
   while 0, 1 {
      move right
   } if blank {
      move left
      // check last letter is 0
      if 0 {
         accept
      } if 1, blank {
         reject
      }
   }
}
```

- `isDiv2Rec`:

```
alphabet = {0, 1}
module isDiv2Rec {
   // recursive case: not at the end => move closer to the end
   if 0, 1 {
      move right
      goto isDiv2Rec
   }
   // base case: at the end => check final letter 0
   if blank {
      move left
      if 0 {
         accept
      } if 1, blank {
         reject
      }
   }
}
```

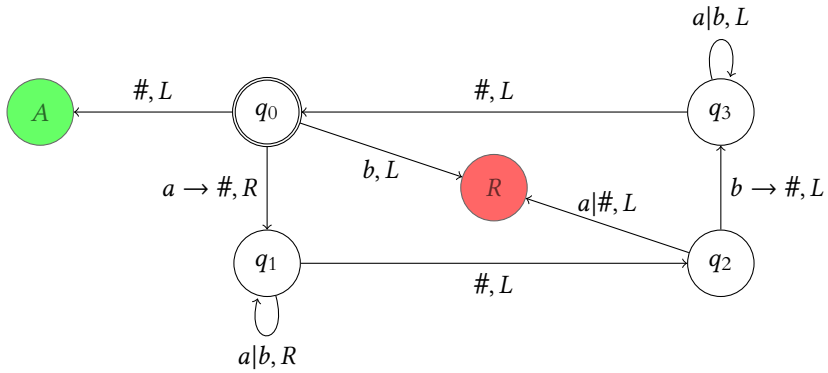
Both `isDiv2` and `isDiv2Rec` correspond to the following Turing Machine (TM):



- `aNbN`:

```
// accepts strings of the form a^nb^n for some n >= 0
// e.g. blank, ab, aabb, aaabbb, etc.
alphabet = {a, b}
module aNbN {
   // empty string => base case, accept
   if blank {
      accept
   }
   // cannot start with b
   if b {
      reject
   }
   // starts with a => remove the last b
   if a {
      changeto blank
      move right
      // move to the end
      while a, b {
         move right
      } if blank {
         move left
         // the last letter must be a b
         if a, blank {
            reject
         } if b {
            changeto blank
            move left
            // move back and restart
            while a, b {
               move left
            } if blank {
               move right
               goto aNbN
            }
         }
      }
   }
}
```

The program `aNbN` corresponds to the following TM:



D.1.2 Identifying TML Programs

In this section, you are presented with TML programs. You will be given some tape values to run the program in and decode what values the program accepts. You are encouraged to use the website to try and solve this.

1. Consider the following TML Program:

```
alphabet = {0, 1}
module mystery1 {
   while 0, 1 {
      move right
   } if blank {
      move left
      if blank, 0 {
         reject
      } if 1 {
         move left
         if blank, 1 {
            reject
         } if 0 {
            accept
         }
      }
   }
}
```

   (a) Does the program accept the values:
      i. 10 (NOTE: This is 2 in decimal)
      ii. 1
      iii. 100 (NOTE: This is 4 in decimal)
      iv. 101 (NOTE: This is 5 in decimal)
      v. 110 (NOTE: This is 6 in decimal)
   (b) Describe the values this program accepts.

2. Consider the following TML program:

```
alphabet = {a, b}
module mystery2 {
   if blank {
      accept
   } if b {
      reject
   } if a {
      changeto blank
      move right
      if b, blank {
         reject
      } if a {
         changeto blank
         move right
         while a, b {
            move right
         } if blank {
            move left
            if a, blank {
               reject
            } if b {
               changeto blank
               move left
               if a, blank {
                  reject
               } if b {
                  changeto blank
                  move left
                  while a, b {
                     move left
                  } if blank {
                     move right
                     goto mystery2
                  }
               }
            }
         }
      }
   }
}
```

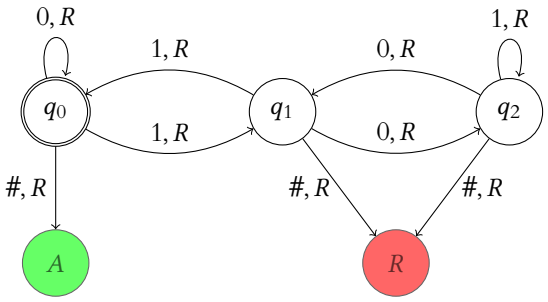
(a) Does the program accept the values:
   i. *ab*
   ii. *aabb*
   iii. *abba*
   iv. *bab*

(b) Describe the values this program accepts.

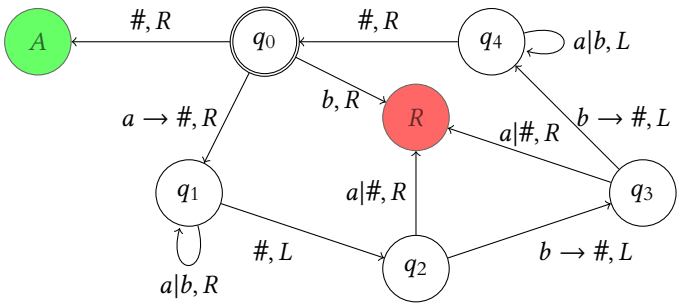
D.1.3 Identifying TMs

In this section, you are presented with TMs. You will be given some tape values to run the program in and decode what values the program accepts. Since the website can only execute TML programs, you are also given the TML program for the code, but it is not comprehensible like the previous programs; you will likely find it easier to understand the TM than the program (which you should do!).

1. Consider the following TM FSM:



   You are given a basic representation of this FSM as code in Teams. The file is called mystery3.
   (a) Does the TM accept the values:
      i. 11 (NOTE: This is 3 in decimal)
      ii. 10 (NOTE: This is 2 in decimal)
      iii. 1
      iv. 110 (NOTE: This is 6 in decimal)
      v. 1001 (NOTE: This is 9 in decimal)
   (b) Describe the values this program accepts.
2. Consider the following TM FSM:



   You are given a basic representation of this FSM as code in Teams. The file is called mystery4.
   (a) Does this TM accept the values:
      i. *ab*
      ii. *abb*
      iii. *aabbbb*
      iv. *bab*
      v. *abba*
   (b) Describe the values this program accepts.

D.1.4 Writing TML Programs

Following a similar syntax to the code given above, write the following programs. You are free to use the website to check the accuracy of the program while writing the programs. Please answer these questions in the survey.

1. divisibility by 4 in binary iteratively [HINT: Go to the end and check for 2 zeros. Allow 0 as well.]
2. divisibility by 4 in binary, recursively.

The remaining questions are optional.

3. strings of the form $a^n b^m c^{n+m}$
4. strings of the form $a^n b^n c^n$
5. HARD: check there are same number of a's and b's

D.2 Checklist

D.3 Survey

School of Computing Science
University of Glasgow

Ethics checklist form for 3rd/4th/5th year, and taught MSc projects

This form is only applicable for projects that use other people ('participants') for the collection of information, typically in getting comments about a system or a system design, getting information about how a system could be used, or evaluating a working system.

If no other people have been involved in the collection of information, then you do not need to complete this form.

If your evaluation does not comply with any one or more of the points below, please contact the Chair of the School of Computing Science Ethics Committee (matthew.chalmers@glasgow.ac.uk) for advice.

If your evaluation does comply with all the points below, please sign this form and submit it with your project.

---

1. Participants were not exposed to any risks greater than those encountered in their normal working life.

   Investigators have a responsibility to protect participants from physical and mental harm during the investigation. The risk of harm must be no greater than in ordinary life. Areas of potential risk that require ethical approval include, but are not limited to, investigations that occur outside usual laboratory areas, or that require participant mobility (e.g. walking, running, use of public transport), unusual or repetitive activity or movement, that use sensory deprivation (e.g. ear plugs or blindfolds), bright or flashing lights, loud or disorienting noises, smell, taste, vibration, or force feedback

2. The experimental materials were paper-based, or comprised software running on standard hardware.

   Participants should not be exposed to any risks associated with the use of non-standard equipment: anything other than pen-and-paper, standard PCs, laptops, iPads, mobile phones and common hand-held devices is considered non-standard.

3. All participants explicitly stated that they agreed to take part, and that their data could be used in the project.

   If the results of the evaluation are likely to be used beyond the term of the project (for example, the software is to be deployed, or the data is to be published), then signed consent is necessary. A separate consent form should be signed by each participant.

   Otherwise, verbal consent is sufficient, and should be explicitly requested in the introductory script.

4. No incentives were offered to the participants.

   The payment of participants must not be used to induce them to risk harm beyond that which they risk without payment in their normal lifestyle.

5. No information about the evaluation or materials was intentionally withheld from the participants.
   Withholding information or misleading participants is unacceptable if participants are likely to object or show unease when debriefed.

6. No participant was under the age of 16.
   Parental consent is required for participants under the age of 16.

7. No participant has an impairment that may limit their understanding or communication.
   Additional consent is required for participants with impairments.

8. Neither I nor my supervisor is in a position of authority or influence over any of the participants.
   A position of authority or influence over any participant must not be allowed to pressurise participants to take part in, or remain in, any experiment.

9. All participants were informed that they could withdraw at any time.
   All participants have the right to withdraw at any time during the investigation. They should be told this in the introductory script.

10. All participants have been informed of my contact details.
    All participants must be able to contact the investigator after the investigation. They should be given the details of both student and module co-ordinator or supervisor as part of the debriefing.

11. The evaluation was discussed with all the participants at the end of the session, and all participants had the opportunity to ask questions.
    The student must provide the participants with sufficient information in the debriefing to enable them to understand the nature of the investigation. In cases where remote participants may withdraw from the experiment early and it is not possible to debrief them, the fact that doing so will result in their not being debriefed should be mentioned in the introductory text.

12. All the data collected from the participants is stored in an anonymous form.
    All participant data (hard-copy and soft-copy) should be stored securely, and in anonymous form.

Project title Turing Machine Language

Student's Name Pete Gautam

Student Number 2481471G

Student's Signature Pete

Supervisor's Signature Daniela Dondlia

Date 8/2/2023

Pete Evaluation Survey

This is the follow-up survey to the worksheet. There are 2 parts to this- evaluating the programming language and the website.

* Required

1. How many years of programming experience do you have? *

- ◯ 0-1 Year
- ◯ 1-2 Years
- ◯ More than 3 Years

2. Were you familiar with Turing Machines before the workshop? *

- ◯ Familiar
- ◯ Somewhat familiar
- ◯ Not familiar

Final Questions

3. Iterative program that checks for divisibility by 4

4. Recursive program that checks for divisibility by 4

5. Strings of the form a^n b^m c^n+m

6. Strings of the form a^n b^n c^n

7. Check there are the same number of a's and b's

The Programming Language

8. Evaluate the Turing Machine Language (TML) under the following categories. Note that the focus here is on the **language**, and not the website. *

	Strongly Disagree	Disagree	Agree	Strongly Agree
TML is easy to understand	◯	◯	◯	◯
TML is easy to write programs in	◯	◯	◯	◯
I was able to fix errors in my code using the error messages provided	◯	◯	◯	◯
I was able to easily reason executing a program on a tape	◯	◯	◯	◯

9. Do you have any general comments about the language?

10. Are there any features that should be added to the language in your opinion, e.g. moving to the end of the tape in one line of code?

11. Compare programs in Turing Machine language (TML) with Turing Machines (TM) *

	Strongly Disagree	Disagree	Agree	Strongly agree
I am more confident in writing a program in TML than drawing a TM	◯	◯	◯	◯
I find it easier to reason what a TML program accepts than a TM	◯	◯	◯	◯

12. If you had to draw a TM, would you write a TML program for it first? *

- ◯ Yes
- ◯ No
- ◯ Maybe

Website Evaluation

13. Evaluate the website under the following categories: *

	Strongly disagree	Disagree	Agree	Strongly agree
The website is easy to follow	◯	◯	◯	◯
The presentation of the website is intuitive	◯	◯	◯	◯
There were no visible bugs in the website	◯	◯	◯	◯
The website was fast	◯	◯	◯	◯
The website feels complete	◯	◯	◯	◯
The code execution was easy to follow	◯	◯	◯	◯
The code editor was easy to use	◯	◯	◯	◯

14. The website presents tape execution using pop-ups. Do you think this is a good idea or should it be replaced by just a short paragraph within the tape section, or anything else? *

- ◯ Pop-ups are fine!
- ◯ A short paragraph is a better idea
- ◯ Other

15. Are there any features you would like to be added to the website?

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Microsoft Forms

Bibliography

Dawson, Jr, J. W. (2007), 'The essential turing: Seminal writings in computing, logic, philosophy, artificial ingelligence, and artificial life plus the secrets of enigma, by alan m. turing (author) and b. jack copeland (editor)'.