§1 Turing Machines & their basic operations

...lead...two-way infinite tape

Def. A Turing Machine (TM) is a 7-tuple \( M = (Q, \Sigma, \Gamma, \delta, q_0, \delta, A) \) where

- \( Q \) is a finite set of control states,
- \( \Sigma \) is an alphabet called the input alphabet,
- \( \Gamma \) is an alphabet called the tape alphabet,
- \( q_0 \in Q \) is a specially designated initial state,
- \( \delta \in \Sigma \cup \Gamma \) is a special character called the blank symbol,
- \( A \subseteq Q \) is a set of designated accepting states,
- \( \delta \) is a relation from \( Q \times \Gamma \) to \( Q \times \Gamma \times \{L, R\} \), called the transition relation.

If \( \langle q, a \rangle, \langle q', b, R \rangle \rangle \in \delta \), we will write

\( \langle q, a \rangle \xrightarrow{a \leftarrow b, R} \langle q', b, R \rangle \) or \( q \xrightarrow{a} q' \).

This means that if the head is in state \( q \) and reads an "a", then it will replace the "a" by a "b", move one square to the right, and then change the control state of the head to \( q' \). The transition \( q \xrightarrow{a} q' \) means the same thing except that we move one square to the left.

\[ \cdots \text{lead...} \]
A configuration in a TM \( M \) is an ordered pair \( \langle q, \psi \rangle \) where \( q \) is the control state of the head, \( \psi = \text{non-blank portion of the tape to the left of the head} \), and \( \psi' = \text{the non-blank portion of the tape below the head and to the right of it} \). The underlined \( \psi \) means that the position of the head is above the first character in \( \psi \).

So a configuration \( \langle q, \psi \psi' \rangle \) is just an instantaneous description of the tape of the TM.

Configuration is \( \langle q, \text{dubc acbue} \rangle \)

The .... \( \psi \) and \( \psi' \) means that these portion of the tapes are all blanks. Sometime we include some of these blanks (from the blank portions) to show what the head will see if it moves to the right or to the left.

**Ex.1**

Let \( M \) be the TM that is defined as follows.

\( Q = \{A, B\} \)
\( T = \{0, 1\} \)
\( \Sigma = \{0, 1, \#\} \)
\( q_0 = A \)
\( A = \{B\} \)

and \( \Delta \) consists of the transitions

\[ \langle A, 0 \rangle \rightarrow \langle A, 1, R \rangle, \quad \langle A, 1 \rangle \rightarrow \langle A, 0, R \rangle, \quad \langle A, \# \rangle \rightarrow \langle B, \#, L \rangle \]

We can represent \( M \) by a transition graph as shown to the right.
Let us show what happens if we start $M_1$ with the string $0100$ as input.

Initial tape:

<table>
<thead>
<tr>
<th>State</th>
<th>Tape Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0100</td>
</tr>
<tr>
<td>A</td>
<td>100</td>
</tr>
<tr>
<td>A</td>
<td>1000</td>
</tr>
<tr>
<td>A</td>
<td>1011</td>
</tr>
</tbody>
</table>

Initial configuration: $\langle A, 0100 \rangle$

Final tape:

<table>
<thead>
<tr>
<th>State</th>
<th>Tape Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1011</td>
</tr>
<tr>
<td>B</td>
<td>100</td>
</tr>
</tbody>
</table>

Final configuration: $\langle B, 1011 \rangle$

At this point, no more transitions can be executed and we say that the TM halts.

Definition 1:
A halting configuration in a TM is a configuration from which no transition can be executed. A TM is said to halt if it reaches a halting configuration. An initial configuration is one in which the control state is the initial state.

Definition 2:
A computation by a TM is a sequence of transition that takes $M$ from an initial configuration to a halting configuration. We denote it by $\langle q_0, \omega \rangle \overset{*}{\rightarrow} \langle q_f, \eta \rangle$ or $\langle q_0, \omega \rangle \overset{*}{\rightarrow} \langle q_f, \eta \rangle$. $\langle A, 011 \rangle \overset{*}{\rightarrow} \langle A, 111 \rangle \overset{*}{\rightarrow} \langle A, 101 \rangle \overset{*}{\rightarrow} \langle A, 100 \rangle \overset{*}{\rightarrow} \langle B, 100 \rangle$ is a computation by the TM $M_1$ from Ex.1 and we write $\langle A, 011 \rangle \overset{*}{\rightarrow} \langle B, 100 \rangle$. 
A TM will not always halt on a given input. For example, the TM $M_2$ below with input alphabet $\Sigma_2$, will never halt on any input.

![TM Diagram]

With input $\rho=11$, this TM will move as follows.

$$\langle A, 11 \rangle \rightarrow \langle A, 11 \rangle \rightarrow \langle A, 11 \hat{\nu} \rangle \rightarrow \langle B, 11 \hat{\nu} \rangle$$

$$\rightarrow \langle B, 11\hat{\nu} \hat{\nu} \hat{\nu} \rangle \rightarrow \langle B, 11\hat{\nu} \hat{\nu} \hat{\nu} \hat{\nu} \hat{\nu} \hat{\nu} \hat{\nu} \hat{\nu} \rangle \rightarrow \cdots$$

**Def.** A TM $M$ is said to be a **Deterministic TM** if from each configuration (that is reachable from the initial state) at most one transition is executable.

Both of the examples $M$ & $M_2$ are deterministic TMs. In fact most of the TMs we give will be deterministic ones - because they are a lot easier to understand. We have not said anything yet about the accepting states of a TM - but we will do so in the next section. Also, whenever we give a TM as a transition graph, we have to make sure that we specify the input alphabet.

§2. Turing Machines as language recognizers

**Def.** Let $M$ be a TM with input alphabet $\Sigma$. The language recognized by $M$ is defined by

$$l(M) = \{ w \in \Sigma^* : \langle q_0, w \rangle \vdash \langle q_f, \emptyset \emptyset \rangle \text{ is a halted computation with } q_f \in AL(M) \}$$
If $M$ halts in an accepting state with $w \in \Sigma^*$ as input, we say that $M$ accepts the string $w$. So $L(M) =$ set of all strings in $\Sigma^*$ that are accepted by $M$.

Note: For a given string $w$, $M$ may not halt with $w$ as input, or $M$ may halt in a non-accepting state with $w$ as input. In both of these cases, we say that $M$ is not accepted (or rejected) by the TM $M$.

Ex. 1. Let $\Sigma = \{0, 1\}$. Find a TM $M$, which recognizes the language $L_1 = 10^*$. 

![Diagram of TM M]

Let us look at how $M$, behaves with the inputs (a) 100, (b) 101, (c) 011, (d) $\lambda$.

(a) $<A, 100> \rightarrow <C, 100> \rightarrow <C, 101> \rightarrow <C, 101> \rightarrow <C, 100u> \text{ halts}$ accepted

(b) $<A, 101> \rightarrow <C, 101> \rightarrow <B, 101u> \text{ halts}$ rejected

(c) $<A, 011> \rightarrow <B, 011> \text{ halts}$ rejected (d) $<A, \lambda> \rightarrow \text{ halts}$ rejected

Notice that $M$, did not have to process the whole string in (c) before it rejected 011. Notice also that $\lambda$ is represented by the completely blank tape.
There are other TMs which recognize the language $L_1 = 10^*$ and usually we try to have only one accepting state with no transitions exiting that state. Here is another TM, $M'$, which recognizes $10^*$.

Ex. 2 Let $T = \{a, b\}$. Find a TM $M_2$ which recognizes the language $\{a^k b^k : k \geq 0 \}$.

Let us look at how $M_2$ behaves with the inputs

(a) $ab$  
(b) $aab$  
(c) ?

(a) $\langle A, ab \rangle \vdash \langle B, x b \rangle$
$\vdash \langle C, xy \rangle$
$\vdash \langle A, xy \rangle$
$\vdash \langle D, xyu \rangle$
$\vdash \langle E, xyu \rangle$  
halts, accepted

(b) $\langle A, aab \rangle \vdash \langle B, x ab \rangle$
$\vdash \langle B, xab \rangle$
$\vdash \langle C, xay \rangle$
$\vdash \langle C, xay \rangle$
$\vdash \langle A, xay \rangle$
$\vdash \langle B, xxx \rangle$
$\vdash \langle B, xxyu \rangle$  
halts, rejected

(c) $\langle A, u \rangle \vdash \langle D, uu \rangle$
$\vdash \langle E, uu \rangle$  
halts, accepted
Extra H.W. Problems: Show how the TM $M_2$ behaves with the inputs
(a) $abb$ (b) $aba$ (c) $aabb$ (d) $ba$.

Ex. 3
Let $T = \{a, b, c\}$. Find a TM $M_3$ which recognizes the language
$L_3 = \{a^k b^k c^k : k \geq 1\}$

Let us see how $M$ behaves with the inputs
(a) $abc$ (b) $aabc$ (c) $\lambda$

(a) $\langle A, abc \rangle$
- $\langle B, xbc \rangle$
- $\langle C, xyc \rangle$
- $\langle D, xyz \rangle$
- $\langle A, xyz \rangle$
- $\langle E, xyz \rangle$
- $\langle F, xyz \rangle$
- $\langle G, xyz \rangle$

(b) $\langle A, aabc \rangle$
- $\langle B, xabc \rangle$
- $\langle C, xayc \rangle$
- $\langle D, xayy \rangle$
- $\langle A, xayy \rangle$
- $\langle E, xayy \rangle$
- $\langle F, xayy \rangle$
- $\langle B, xayy \rangle$

(c) $\langle A, \lambda \rangle$
halts

Def. A language $L \subseteq T^*$ is said to be Turing semi-decidable if we can find a TM $M$ with input alphabet $T$ such that $L(M) = L$.
Def. A language \( L \subseteq T^* \) is said to be Turing-decidable if we can find a TM \( M \) with input alphabet \( T \) such that \( M \) halts in an accepting state for each \( w \in L \), and \( M \) halts in a non-accepting state for each \( w \notin T^* \).

Note: There is a difference between the concepts of Turing-decidable and Turing semi-decidable. To be Turing-decidable, we have to find a TM \( M \) which always halts on each input from \( T \) — and if \( w \in L \), we will have to halt in an accepting state, but if \( w \notin L \) we will have to halt in a non-accepting state.

To be Turing semi-decidable, the TM \( M \) we find does not always have to halt. It only has to halt in an accepting state if \( w \in L \). But if \( w \notin L \), then \( M \) may fail to halt. This difference makes all Turing-decidable languages Turing semi-decidable, but the converse is not true.

Extra H.W. Problems: Show how the TM \( M_3 \) behaves on the following inputs:

(a) \( aabbcc \)  (b) \( aabbc \)  (c) \( abca \)
(d) \( abbcc \)  (e) \( abcc \)  (f) \( bac \)

Ex. 4. The languages \( L_1, L_2, \) and \( L_3 \) from Ex. 1–3 are all Turing-decidable languages.
§3 Turing Machines as computational devices.

Def. Let $T$ be an alphabet. A partial function $f: T^* \rightarrow T^*$ is a function $f: \mathbb{D} \rightarrow T^*$ where $\mathbb{D}$ is a subset of $T^*$. If $\mathbb{D} = T^*$, then we say that $f$ is a total function.

Def. Let $f: T^* \rightarrow T^*$ be a partial function. We say that $f$ is Turing-computable if we can find a TM $M$ with input alphabet $T$ such that we have $\text{Dom}(f) \iff <q_0, \omega> \vdash \langle q_f, q_f(\omega) \rangle$ is a halted computation with $q_f \in \mathbb{A}(M)$. Here the head is over the first character of $f(\omega)$ and $q_f$ is consider the "rough work".

Representations of numbers. To keep matters simple, we will restrict ourselves to partial functions from $\mathbb{N}^k$ to $\mathbb{N}$. Now there are many ways of representing a number as a string.

1. Basic ten representation: Alphabet $T = \{0, 1, 2, \ldots, 9\}$
   $a_n a_{n-1} \ldots a_0$ represents $a_n 10^n + a_{n-1} 10^{n-1} + \ldots + a_0 10^0$
   So $(247)_{10} = 2(10)^2 + 4(10)^1 + 7(10)^0$

2. Binary (Base 2) representation: Alphabet $T = \{0, 1\}$
   $a_n a_{n-1} \ldots a_1 a_0$ represents $a_n 2^n + a_{n-1} 2^{n-1} + \ldots + a_1 2^1 + a_0 2^0$
   So $(1101)_2 = 1(2)^3 + 1(2)^2 + 0(2)^1 + 1(2)^0 = (13)_{10}$

3. Monadic Representation: Alphabet $T = \{1\}$
   $111 \ldots 1$ (n times) repr. $n$. So $(4)_{10} = 1111$ & $(6)_{10} = 111111$. 
Ex. 1 Find a TM $M_1$ with input alphabet $T = \{1, \#\}$ which computes the total function $f: \mathbb{N}^2 \to \mathbb{N}$, $f(k, m) = k+m$ in Monadic notation.

Here the "#" is used like a comma to separate the two inputs. Let us see how $M_1$ behaves when trying to compute $f(1, 2) = 1+2$. The input will be $1\#11$.

\[
\langle A, 1\#11 \rangle \rightarrow \langle A, 1\#11 \rangle \rightarrow \langle B, 1111 \rangle \rightarrow \langle B, 1111 \rangle \\
\rightarrow \langle B, 1111 \rangle \rightarrow \langle C, 1111 \rangle \rightarrow \langle D, 1111 \rangle \\
\rightarrow \langle D, 111 \rangle \rightarrow \langle D, 111 \rangle \rightarrow \langle D, 111 \rangle \rightarrow \langle E, 111 \rangle.
\]

Let's see what happens if we try to compute $f(0,0) = 0+0$. The input will be $\#$

\[
\langle A, \# \rangle \rightarrow \langle B, 1\# \rangle \rightarrow \langle C, 1\# \rangle \rightarrow \langle D, 1\# \rangle \rightarrow \langle E, 1\# \rangle.
\]

So our answer is $1$ which in monadic notation means $0$. Hence $f(0,0) = 0+0 = 0$.

Extra H.W. Problems: Show how the TM $M_1$ computes
(a) $1+1$  (b) $0+2$  (c) $2+0$  (d) $2+1$.

Ex. 2 Find a TM $M_2$ with input alphabet $T = \{1, \#\}$ which computes the total function $f: \mathbb{N} \to \mathbb{N}$, $f(n) = 2n$ in monadic notation.
The idea behind the construction of \( M_2 \) is below.

1. Replace each "1" in the input by an \( x \). Then
2. Find the right most \( x \) & replace it by a "1". Then
3. Go to the beginning of the blank region on the right and create a "1" there.
4. Repeat steps 2 & 3 until there are no more \( x \)'s.
5. Finally move the head over the left most 1.

Let us see how \( M_2 \) computes \( f(2) = 2(2) \). Input = 11
\[
\langle A, 11 \rangle \rightarrow \langle A, x1 \rangle \rightarrow \langle A, xx1 \rangle \rightarrow \langle B, xx \rangle \rightarrow \langle C, x1 \rangle \rightarrow \langle B, x1 \rangle \rightarrow \langle C, 11 \rangle \rightarrow \langle B, 11 \rangle \rightarrow \langle C, 111 \rangle \rightarrow \langle B, 111 \rangle \rightarrow \langle C, 1111 \rangle \rightarrow \langle B, 1111 \rangle \rightarrow \langle D, 11111 \rangle.
\]
So \( f(2) = 4 \).

Let us also see how \( M_2 \) computes \( f(0) = 2(0) \). Input = \( \lambda \)
\[
\langle A, \lambda \rangle \rightarrow \langle B, \lambda \rangle \rightarrow \langle D, \lambda \rangle.
\]
So \( f(0) = 0 \).

Extra H.W. Problems: Show how \( M_2 \) computes
(a) \( f(1) \) (b) \( f(3) \)

Def. Let \( R \) be a binary relation on \( \mathbb{N} \). We say that \( R \) is **Turing semi-decidable** if we can find a TM \( M \) such that for the input \( \langle m,n \rangle \), \( M \) halts in an accepting state if \( \langle m,n \rangle \in R \); and \( M \) halts in a non-accepting state or \( M \) fails to halt if \( \langle m,n \rangle \notin R \). (Note: \( \langle m,n \rangle \in R \) is the same as saying \( mRn \))
Def. We say that $R$ is Turing-decidable if we can find a TM $M$ such that for the input $\langle m, n \rangle$,
$M$ halts in an accepting state if $\langle m, n \rangle \in R$; and
$M$ halts in a non-accepting state if $\langle m, n \rangle \notin R$.

Ex. 3
Show that the relation $R$ defined by $mRn$ if $m > n$, is Turing decidable using monadic notation.

Here, again in $M_3$, as in $M_1$ — we use "#" to separate the input. The TM $M_3$ shows that
$R$ is Turing-decidable. Let us see how $M$ behaves when $\langle 1, 2 \rangle$ is the input. In monadic
notation, this input is $1\#11$.

$\langle A, 1\#11 \rangle \rightarrow \langle B, x\#11 \rangle \rightarrow \langle C, x\#11 \rangle \rightarrow \langle D, x\#x \rangle$
$\rightarrow \langle E, x\#x \rangle \rightarrow \langle A, x\#x \rangle$ halts in non-accepting
state. Hence $1 \neq 2$.

Let's see what happens when $\langle 2, 0 \rangle$ is the input.
$\rightarrow \langle A, 1\#0 \rangle \rightarrow \langle B, x\#1\#0 \rangle \rightarrow \langle B, x\#1\#0 \rangle \rightarrow \langle C, x\#1\#0 \rangle$
$\rightarrow \langle F, x\#1\#0 \rangle$ halts in an accepting state. \therefore $2 > 0$.

Extra H.W. Problems. Show how $M_3$ behaves with the inputs:
(a) $\langle 2, 1 \rangle$ (b) $\langle 1, 1 \rangle$ (c) $\langle 1, 0 \rangle$ (d) $\langle 0, 2 \rangle$ (e) $\langle 3, 2 \rangle$
§4. Universal TMs, Halting Problem & Busy-beaver function

Even though, TMs are extremely slow & cumbersome, it can be shown that for any task for which there is an algorithm, a TM can be constructed to do the same task. TMs can be constructed to compute all of the familiar functions such as

(a) \( f_1(m, n) = m \cdot n \)  
(b) \( f_2(n) = 2^n \)  
(c) \( f_3(n) = n! \)  
(d) \( f_4(m, n) = m^n \)  
(e) \( f_5(n) = \lfloor \sqrt{n} \rfloor \)  
(g) \( f_6(n) = \lceil n \rceil \)

Here \( \lfloor x \rfloor \) = largest integer \( \leq x \) (floor function) and \( \lceil x \rceil \) = smallest integer \( \geq x \) (ceiling function).

Universal Turing Machines: There are even Turing machines, \( M_u \), such that if we are given an arb. TM, \( M \), and an arbitrary input, \( w \), for \( M \), we can simulate the action of \( M \) on \( w \) and obtain the correct output by using \( M_u \). Such Turing Machines, \( M_u \), are called Universal Turing Machines (UTMs).

The trick is to code everything in \( M \) & \( w \) as strings from the input alphabet of \( M_u \) and then show the configurations that we obtain once \( M \) starts operating on \( w \).

\[ M_u : \quad \ldots \# \quad \text{c}(M) \quad \# \quad \text{c}(w) \quad \# \quad \text{c}(\text{init config. of } M) \quad w \ldots \]

\[ \quad \text{code of } M, \quad \text{code of } w \]

\[ \ldots \# \quad \text{c}(M) \quad \# \quad \text{c}(w) \quad \# \quad \text{c}(\text{final config. of } M) \quad w \ldots \]

The TM, \( M_u \), will know what \( M \) will do at each step with the input \( w \) — because it can run back and check in \( \text{c}(M) \) & \( \text{c}(w) \) whenever it needs to.
The Halting Problem is the following question. Is there a TM, H, such that for any arb. TM, M, and any arb. input, w, for M, if we use c(M)#q0, as input, H will halt in an accepting state, if M halts on w; & H will halt in a non-accepting state, if M doesn't halt on w. [Here c(M) & c(w) are codings of M & w into the alphabet of H and "#" is used to separate inputs.]

The answer to the Halting Problem is NO. Even though the proof is important, it is not simple enough to present in class. So we will refer the reader to any of the standard textbooks. One might think that a UTM, Mu, can serve as H - but this is not so. Mu will halt in an accepting state if M halts on w but Mu will not halt if M doesn't halt on w since Mu just simulates the action of M on w.

Theorem 1: Let R be the binary relation on N which is defined as follows.

\(<c(M), c(w)> \in R \text{ iff } M \text{ halts with } w \text{ as input. Then } R \text{ is not a Turing-decidable relation. Here } c(M) \& c(w) \text{ are the codings of } M \& w \text{ as positive integers.}\n
The proof Theorem 1 just boils down to the fact that the answer to the Halting problem is NO. Indeed, if R was Turing-decidable, then we would have been able to find a TM H with exactly the properties in the Halting Problem.
So we have found a binary relation $R$ on $N$ which is not Turing-decidable. A universal TM will readily show that $R$ is Turing semi-decidable, but $R^c$ is not even Turing semi-decidable. It is natural to ask if there is a function $f : N \to N$ which is not Turing-computable — and indeed, there is.

**Def.** Let $T_n$ be the set of all TMs with $n$ states and with tape alphabet $\{\#, \$\}$. Since there are only a finite number of transitions between the $n$ states, the number of different TMs in $T$ will be finite.

**Def.** Let $H_n$ be the set of all TMs with $n$ states and with tape alphabet $\{\#, \$\}$ which halts with the blank tape as input. We define the Busy-beaver function $\beta : N \to N$ as follows.

$\beta(n) =$ maximum number of 1's that a TM in $H_n$ produces when it halts, after it is started on the blank tape.

**Theorem 2:** The function $\beta : N \to N$ is not Turing-computable.

In other words, there is no TM, $M_b$, such that for each $n \in N$, $(q_0, n) \xrightarrow{\star} (q_f, \# \beta(n))$ is a halted computation in $M_b$.

END OF CH. 5.