Announcements
Be sure to take advantage of the following resources:

- Homework Solution Sessions - Saturday and Sunday 2:30p-3:30p in GHC 4101
- We will be releasing our grading rubrics to make the learning objectives/takeaways of homework problems explicit.

Too Many Definitions

- Informally, a Turing machine is a machine with a finite set of states, a tape (memory) that is infinite in one direction that can process inputs over some alphabet. At each step, the machine makes the following decisions (based on the state it is in and the symbol it’s tape-head is currently reading): move to some state, write some symbol at the current cell currently under the tape head, and move the tape head to the left or to the right.

- Formally, we define a Turing machine to be a 7-tuple $(Q, q_0, q_{accept}, q_{reject}, \Sigma, \Gamma, \delta)$, where $Q$ is the set of states, $q_0$ is the start state, $q_{accept}$ and $q_{reject}$ are the final states, $\Sigma$ is the input alphabet, $\Gamma \supseteq \Sigma \cup \{\_|\}$ is the tape alphabet, and $\delta : Q' \times \Gamma \rightarrow Q \times \Gamma \times \{L, R\}$, where $Q' = Q \setminus \{q_{accept}, q_{reject}\}$ is the transition function.

- A Turing machine is called a decider if for all inputs $x \in \Sigma^*$, it halts and either accepts or rejects $x$.

- A language $L \subseteq \Sigma^*$ is called decidable if there exists a decider Turing machine $M$ such that $L = L(M)$.

- Let $L$ and $K$ be languages, where $K$ is decidable. We say that solving $L$ reduces to solving $K$ (or simply, $L$ reduces to $K$, denoted $L \leq K$), if we can decide $L$ by using a decider for $K$ as a subroutine (helper function).
Closure Ceremony

Suppose that $L_1$ and $L_2$ are decidable languages. Show that the languages $L_1 \cdot L_2$ and $L_1^*$ are decidable as well.\(^1\)

Let $M_1$ and $M_2$ be two Turing machines that decide $L_1$ and $L_2$ respectively. Similarly, we construct $M_3$ and $M_4$ as following:

```python
def M3(x):
    for each of the $|x| + 1$ ways to divide $x$ as $yz$:
        simulate $M_1$ on $y$
        if $M_1$ accepts:
            simulate $M_2$ on $z$
            if $M_2$ accepts, accept
        reject

def M4(x):
    if length of $x$ is 0:
        accept
    for each sorted list of indices $[0, a_1, a_2, ..., |x|]$:
        // the indices a subset of $\{0, 1, 2, ..., |x|\}$
        // each list starts with 0 and ends with $|x|$
        string_is_good = true
        for each ordered pair of adjacent indices $(p, q)$:
            simulate $M_1$ on $x[p:q]$
            // $x[p:q]$ is the section of $x$ from the $p$th to the $q-1$ th character
            if $M_1$ accepts:
                pass // i.e. keep executing
            else:
                string_is_good = false
                break
        if string_is_good:
            accept
        reject
```

We can show that $M_3$ and $M_4$ decide $L_1 \cdot L_2$ and $L_1^*$, respectively.

Note that we’ve implicitly appealed to the Church-Turing thesis, since we’ve written pseudocode to show the existence of two Turing machines.

Freeze All Automata Functions

Prove that the following languages are decidable by reducing it to $\text{EMPTY}_{\text{DFA}}$.

(a) $\text{NO} - \text{ODD} - \text{ONES} = \{ \langle D \rangle : D$ does not accept any string containing an odd number of 1’s $\}$

\(^1\)Exercise: show that $L_1 \cup L_2$ and $L_1 \cap L_2$ are also decidable.
Let \( L \) be the language of all strings with an odd number of 1’s. We leave it as a short exercise to show \( L \) is regular by drawing a DFA.

We then construct a decider for \( \text{NO} - \text{ODD} - \text{ONES} \) as follows. Let \( M \) be a decider for \( \text{EMPTY}_{\text{DFA}} \). Construct a DFA \( D' \) such that \( L(D') = L(D) \cap L \). Run \( M \) on \( \langle D' \rangle \) and return the answer.

Proof of correctness:
Suppose that \( \langle D \rangle \in \text{NO} - \text{ODD} - \text{ONES} \). Then \( L(D) \cap L = \emptyset \), so then \( M(\langle D' \rangle) \) will accept as desired.

Conversely, if \( \langle D \rangle \notin \text{NO} - \text{ODD} - \text{ONES} \) then \( L(D) \cap L \neq \emptyset \) so then \( M(\langle D' \rangle) \) will reject as desired.

(b) \( \text{INF}_{\text{DFA}} = \{ \langle D \rangle : D \text{ is a DFA with } L(D) \text{ infinite} \} \).

Hint: Consider a DFA with \( k \) states that accepts some string with more than \( k \) characters.

We first prove the following lemma: If a DFA with \( k \) states accepts some string with greater than \( k \) characters, then it will accept infinitely many strings.

Proof:
Let \( D \) be a DFA with \( k \) states accepting the string \( w = w_1w_2...w_n \), where \( n > k \). By PHP, we must have \( w_1...w_i \) and \( w_1...w_j \) \( (i < j) \) end on the same state \( q \in Q \). It follows that \( w_1...w_i(w_{i+1}...w_j)^m \) ends on \( q \) for \( m \in \mathbb{N} \). So, all the strings of the form \( w_1...w_i(w_{i+1}...w_j)^m w_{j+1}...w_n \) for \( m \in \mathbb{N} \) are accepted. This completes the proof of the lemma.

We now move onto the main claim. We construct a decider for \( \text{INF}_{\text{DFA}} \) as follows:

(a) Given \( D \) where \( D \) is a DFA, let \( k \) be how many states it has.

(b) Construct a DFA \( D' \) such that \( L(D') = \{ w : |w| > k \} \). (Again, we leave the proof that this is regular as a simple exercise).

(c) Construct a DFA \( D'' \) such that \( L(D'') = L(D') \cap L(D) \).

(d) Run the decider for \( \text{EMPTY}_{\text{DFA}} \) on \( D'' \).

(e) If the decider accepts, reject. Else accept.

Proof of correctness:
Suppose \( L(D) \) is infinite. Since there are only finitely many strings of length \( \leq k \), \( D \) accepts some string of length greater than \( k \). So we must have \( L(D'') \) be nonempty, and therefore we accept, as desired.

Suppose \( L(D) \) is finite. Then by the contrapositive of our lemma it accepts no strings of length greater than \( k \). It follows that \( L(D'') = \emptyset \), so we reject, as desired.

**Not Just Your Regular Old TM**

Suppose we change the definition of a TM so that the transition function has the form

\[
\delta : Q \times \Gamma \to Q \times \Gamma \times \{ R, S \}
\]

where the meaning of \( S \) is “stay”. That is, at each step, the tape head can move one cell to the right or stay in the same position. Suppose \( M \) is a TM of this new kind, and suppose also that \( M \) is a decider. Show that \( L(M) \) is a regular language.
We construct a DFA that accepts exactly the language $L(M)$. The DFA will be specified by the 5-tuple $(Q, \Sigma, \delta, q_0, F)$ whose components will be specified below.

First, let $M'$ be $M$ with all pointless states removed. Clearly $M'$ is equivalent to $M$ on all inputs, since we removed states that no input ever reached, so it suffices to prove the language of $M'$ is regular. The reason for $M'$ will become clear when we define the transition function. We drop the prime and refer to $M'$ as $M$ from here.

$Q$ is equivalent to the set of states of $M$, and $\Sigma$ is equivalent to the input alphabet of $M$.

$\delta$ is the transition function that will be defined as follows for $(q, a) \in Q \times \Sigma$. If $q \in \{q_{\text{acc}}, q_{\text{rej}}\}$, then define $\delta(q, a) = q$.

Else, we case on whether the transition moves the head to the right or stays. If $\delta(q, a) = (q_x, b, R)$, then define $\delta(q, a) = q_x$. If $\delta(q, a) = (q_x, b, S)$, define $q_1 = q_x$ and $b_1 = b$ and begin the following inductive process. Assume that $(q_n, b_n)$ is defined for some $n \geq 1$. If $q_n \in \{q_{\text{acc}}, q_{\text{rej}}\}$, then terminate and let $\delta(q, a) = q_n$. Else, consider $\delta(q_n, b_n) = (q', b, D)$ where $D \in \{R, S\}$. If $D = R$, then terminate and let $\delta(q, a) = q'$. Else ($D = S$) define $q_{n+1} = q'$ and $b_{n+1} = b$, proceed inductively. If this process does not terminate, then there is an infinite loop when the head reads $a$ at state $q$ (no state in $M$ is pointless, so we can do this with some input) which contradicts the assumption that $M$ is a decider. Therefore, we have a well-defined transition function $\delta : Q \times \Sigma \rightarrow Q$.

$q_0$ is equivalent to the initial state of $M$. Since we are using $\Sigma$ instead of $\Gamma$ as our DFA alphabet, we will not have as many transitions in the DFA as we had in $M$. Say that a state $q$ is good if running $M$ on the blank input, starting at $q$, ends at $q_{\text{acc}}$. Let $F$ be the set of good states in $M$. Note that $q_{\text{acc}} \in F$.

We claim that the above DFA accepts exactly the language $L(M)$. If $x \in L(M)$, then there is a finite sequence of states $q_0, q_1, \ldots, q_n = q_{\text{acc}}$ corresponding to the behavior of $M$ on $x$. By construction, our DFA will follow the “collapsed” version of the above sequence. By this we mean to take every maximal contiguous subsequence of states $q_i, q_{i+1}, \ldots, q_j$ such that the head does not move from $q_i$ to $q_j$, and replace this subsequence with a single $q_i$. Our transition function ensures that the DFA will transition from $q_i$ to $q_{i+1}$ (unless $j = n$ in which we transition to $q_{\text{acc}}$. Or the character read at $q_i$ is blank, in which case all subsequent characters are blank, we don’t transition in the DFA, but $q_i$ is good.). Analogous proof will show that if $x \notin L(M)$, then $x$ will terminate at $q_{\text{rej}}$ or a state that is not good, and therefore not be accepted by the DFA. This shows that $M$ and the DFA are equivalent, so $L(M)$ regular.

(Extra) Only $19.99!$ Call now!

Dr. Hyper Turing Machines Inc LLC is selling a whole host of new Turing machines, each for $19.99:

- Bi-infinite TMs - with a tape that stretches infinitely in both directions!
- Infinitely-scalable TMs - choose however many tapes heads you like!
- Quad-core TMs - now with 4 tapes (each with its own tape head)

Normal TMs usually go for $9.99 these days. Your friend (who’s not very Turing-savvy) is in the market for a new Turing machine and just texted you asking you for purchasing advice. Your instincts tell
you that maybe most of this is marketing hype. But some of those improvements do sound pretty compelling... Your friend doesn't use their TM for all that much - mostly just browsing the web and checking email. What should you recommend them to do?

If your friend isn't concerned about performance, they should just buy a normal TM. All of the above are equivalent to normal TMs.

- We can easily simulate a bi-infinite tape TM with a singly-infinite one. The idea is to index the cells on a bi-infinite tape with the integers and the cells of the singly-infinite tape with the naturals, and then perform the usual bijection. Given input $x$, we first space out $x$ by inserting one space between each pair of adjacent characters. After this, we can simulate a move of the tape-head by moving two cells in the same direction (if it is on an odd-numbered cell), and by moving two cells in the opposite direction (if it is on an even-numbered cell). The only exception to this scheme is when we are on the first cell. If we move left from the first cell in the bi-infinite TM, we just move one cell to the right in the singly-infinite TM. How do we know that we are on the first cell? We 'mark' the symbol on the first cell at the very beginning, and keep it marked. We achieve this by adding a symbol $a'$ for every symbol $a$ in the alphabet.

- If $M$ is a $k$-tape-head TM, then we describe a TM $S$ that simulates $M$. We add to our tape alphabet the ability to 'dot' symbols (i.e. for each symbol $a$, add the symbol $a'$), demarcating where $M$'s tape heads are. To simulate a single move of $M$, $S$ first makes a pass to determine what symbols are underneath $M$'s tape heads. $S$ then makes a second pass and performs the appropriate transitions for each virtual tape head.

- We can simulate a 4-tape Turing machine $M$ with a normal 1-tape Turing machine $S$. We keep the contents of the 4 tapes on a single tape, with a # as a separator. We expand the tape alphabet to allow ourselves to dot a symbol (this keeps track of where the virtual tape heads are).

$$\#w_1\# \cdots \#w_4\#$$

To simulate a single move, $S$ scans from the 1st # to the 5th # in order to figure out what symbols lay underneath the tape heads. $S$ then performs a second pass to update the tapes according to the way $M$'s transition function dictates. An edge case that we need to handle: if $S$ ever moves one of the virtual heads onto a #, this signifies that $M$ has moved one of its heads onto previously unread tape. In this case, $S$ copies everything over 10 spots and writes blanks on the new space generated (this is kind of like requesting memory via malloc).

The fact that Turing machines can be changed in so many ways and remain equivalent in power provides evidence that the Turing machine is a quite robust model of computation. This robustness may help justify Turing machines as a reasonable abstraction of computation.

(Bonus) Tick Tock Clock

Write a Turing Machine that does the following: given an input string $s \in \{0,1\}^*$, the Turing machine should finish with a binary representation of $|s|$ on the tape (and nothing else). The TM should run in time at most $c_1 |s| \log |s| + c_2$ steps, where $c_1, c_2$ are some constants.
The overarching idea is to drag a counter (of size $\log |s|$) with you and keep incrementing it as you scan the input.
We can mark the region of the tape dedicated to the counter with a beginning dot on the leftmost cell of the counter region, and an end dot on the next cell in the input.
To initialize, we can check if the first cell is a blank or not. If it is, then we write a 0 and halt. Otherwise, we write a 1 with a begin dot and shift write, and add an end dot.

Then, we execute the following repeating procedure:

Look at current cell: if it’s blank, remove the dot and halt.
Otherwise, go left until hitting the begin dot. We then increment the number in our counter region.
After finishing incrementing, we then move right: if we’re on a cell with a dot, we restart our repeating procedure. Otherwise, we shift our entire counter region one cell to the right, and write a blank in the leftmost cell of the counter region before the shift. Then we move right until we hit the cell with the end dot, and we restart our procedure.

This writes the binary number since we’re rewriting it into the space right before the next new cell of the input.

We execute the repeating procedure for each cell in the input, of which there are $|s|$. The binary representation of $|s|$ is $\log(|s|)$ in length. For each iteration of the procedure, we make at most 2 passes over the counter region: one for incrementing, and possibly one more for shifting.

Thus, we can upper bound the steps in each iteration of the procedure by $c_1 \log(|s|)$ and since we have $|s|$ iterations, we can upper bound that by $c_1 |s| \log(|s|)$. We can upper bound the constant number of initializations steps we perform by some $c_2$, so we can bound the total number of steps by $c_1 |s| \log(|s|) + c_2$. 