

CS 302.1 - Automata Theory

Lecture 10

Shantanav Chakraborty

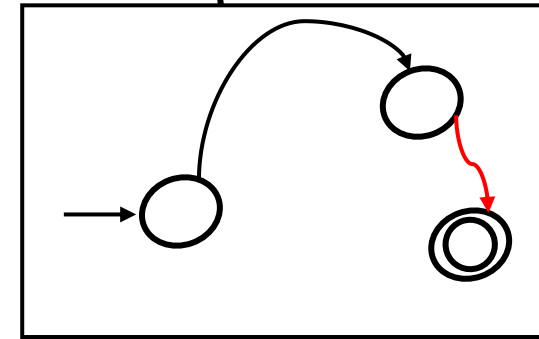
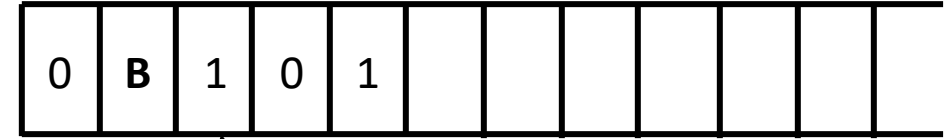
Center for Quantum Science and Technology (CQST)

Center for Security, Theory and Algorithms (CSTAR)

IIIT Hyderabad



A diagram showing a transition from a left oval to a right oval, labeled $a, b, L/R$.

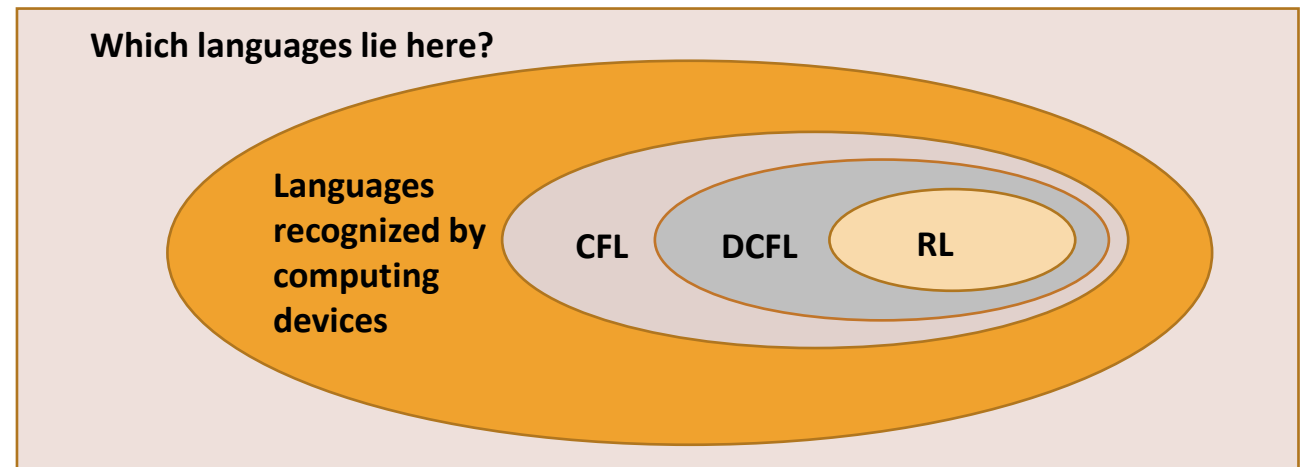


- TM **halts** and **accepts/rejects** on reaching the **accept** or **reject** states
- TM may never halt – it may loop forever.

Configuration of a TM: Combination of the current tape contents, the current state and the current head location. $X\ 0\ 0\ 1\ 1\ 1\ B\ B\ B\ B\ \dots$

$$X\ 0\ 0\ 1\ 1\ 1\ B\ B\ B\ B\ \dots$$
$$\uparrow q_1$$

- C_1 is the start configuration M on w .
- Each C_i yields C_{i+1} .
- C_k is an accepting configuration



Variants of Turing Machine models

A TM model \mathcal{M}_1 is equivalent to another model \mathcal{M}_2 :

- \mathcal{M}_2 can be simulated by \mathcal{M}_1 and vice versa.

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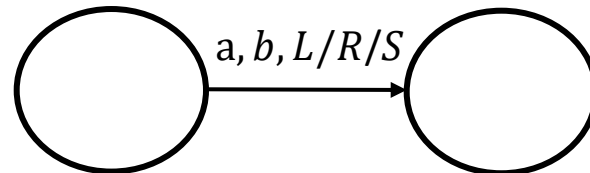
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Lazy Turing Machine: The head can either move left, move right or stay put (L, R, S)



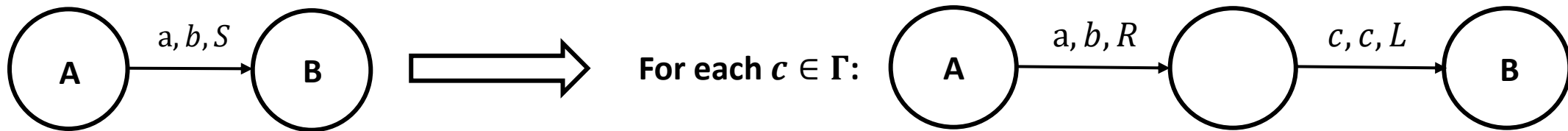
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Hence a *lazy Turing machine* model is **equivalent** to a standard Turing Machine model.

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k -read/write tapes instead of one: What does a k -tape TM, S look like? k -tape TM also has k heads, each associated with a tape.

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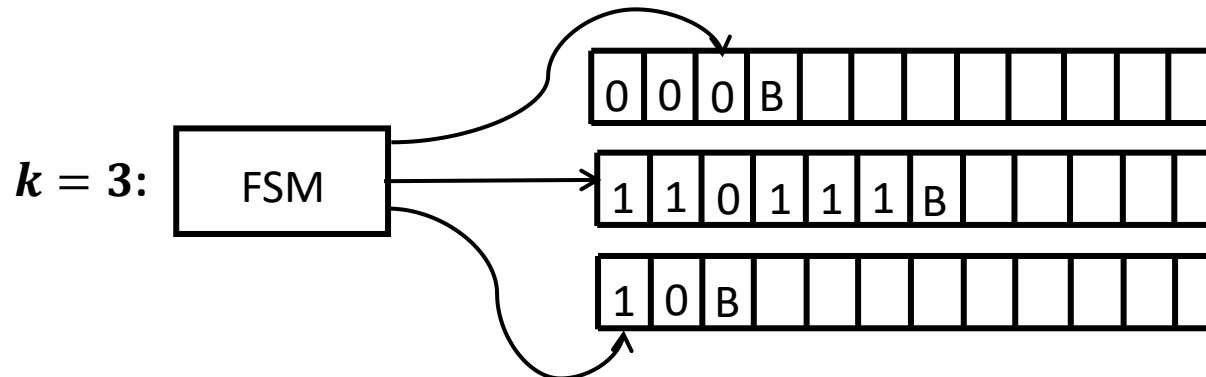
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k -read/write tapes instead of one: What does a k -tape TM look like? k -tape TM also has k heads, each associated with a tape. New transition function

$$\delta_S: Q \times \Gamma^k \rightarrow Q \times \Gamma^k \times \{L, R\}^k, \text{ i.e. } \delta_S(q_i, a_1, \dots, a_k) = (q_j, b_1, \dots, b_k, L, R, \dots, L)$$



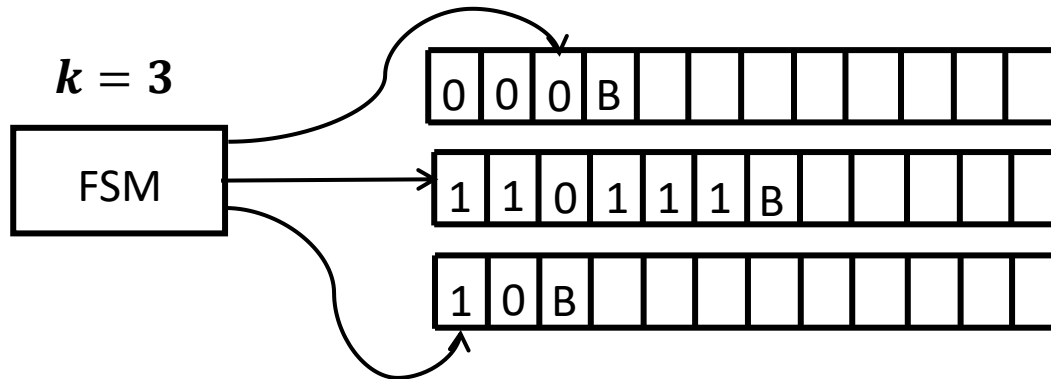
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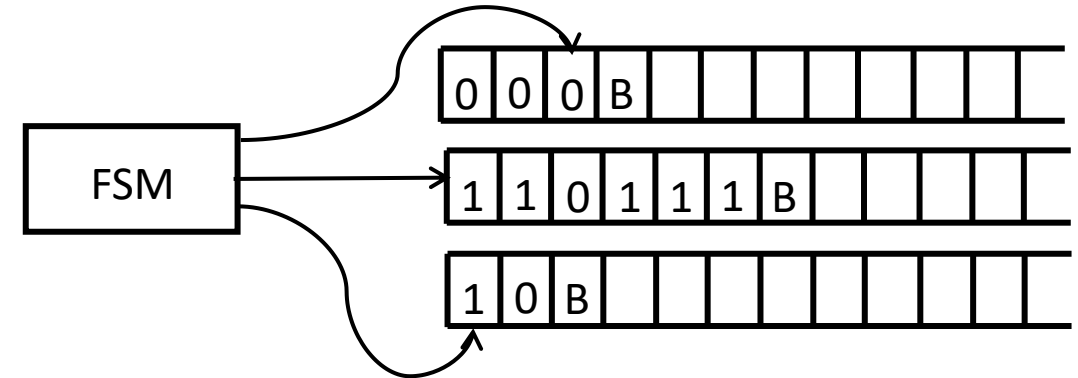


- To simulate S with M , we store the entire information of the k tapes in one single tape.
- M uses \$ to separate the contents of the k tapes.
- To keep track of the locations of the k heads, M marks the symbols where the heads would be, with a ' '.

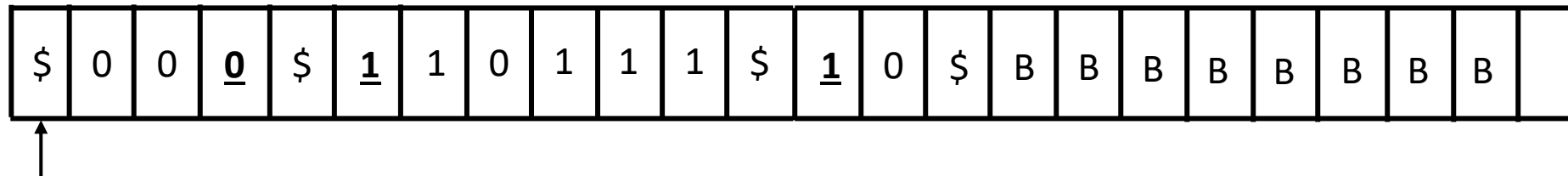
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- Single tape TM M **first scans the entire tape from leftmost \$ to rightmost \$** ($k + 1$ in all) to determine the symbols under the virtual heads. Then it makes a second pass to update the tape according to δ_S .
- If it so happens that M 's head needs to go to the right of any of the intermediate \$ $\Rightarrow S$ has moved the head on the corresponding tape to the unread blank symbols. Starting from this cell to the rightmost \$, **shift one cell to the right to make space to write a blank on the empty tape cell** and simulate as before.

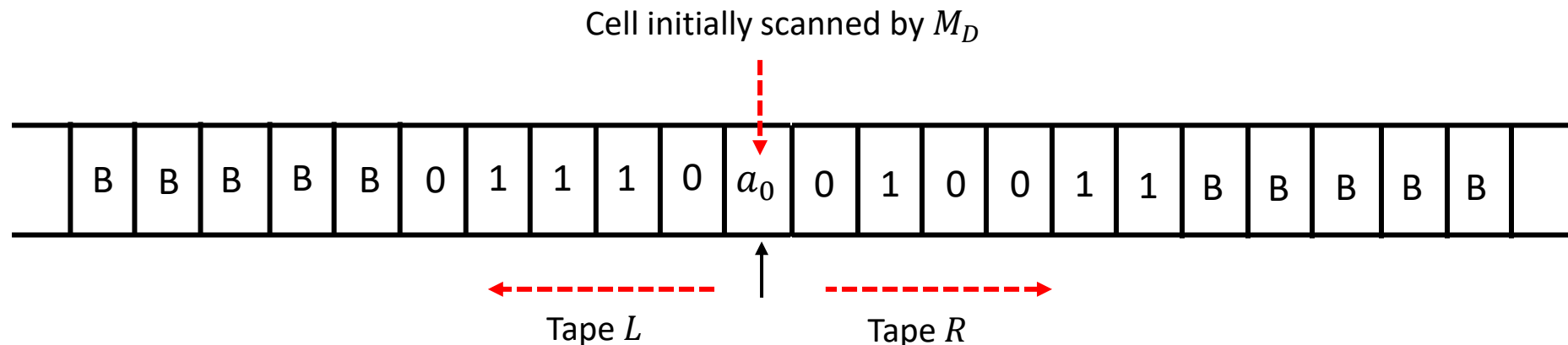
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Two-way infinite Tape: Let M_D be the TM equipped with this power.

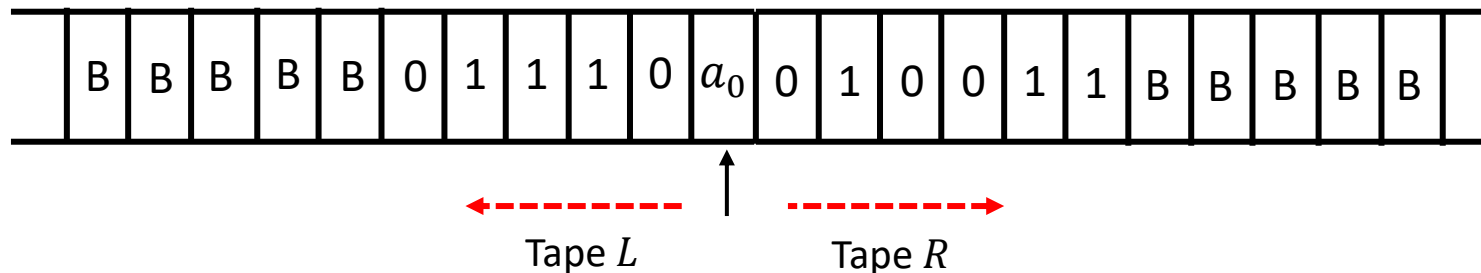


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- Cut the two tapes of M_D into Tape R and $(\text{Tape } L)^R$. We get a two-tape TM.
- Whenever M_D uses the tape to the right of the a_0 , Tape R is used.
- When M_D uses the tape to the left of a_0 , $(\text{Tape } L)^R$ is used.

M_D isn't any more powerful than a one way infinite tape TM.

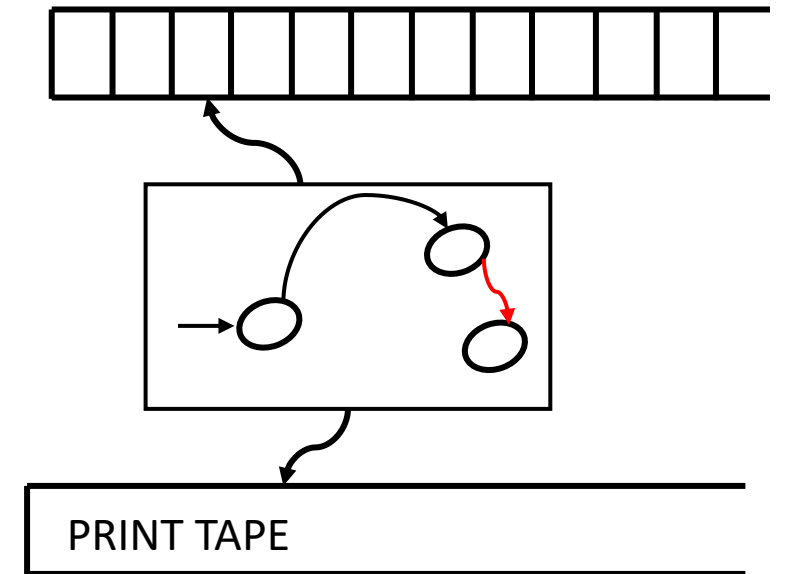
So a TM with a two-way infinite tape is equivalent to a TM with a one-way infinite tape.

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Enumerators: TM attached with a printer



Variants of Turing Machine models

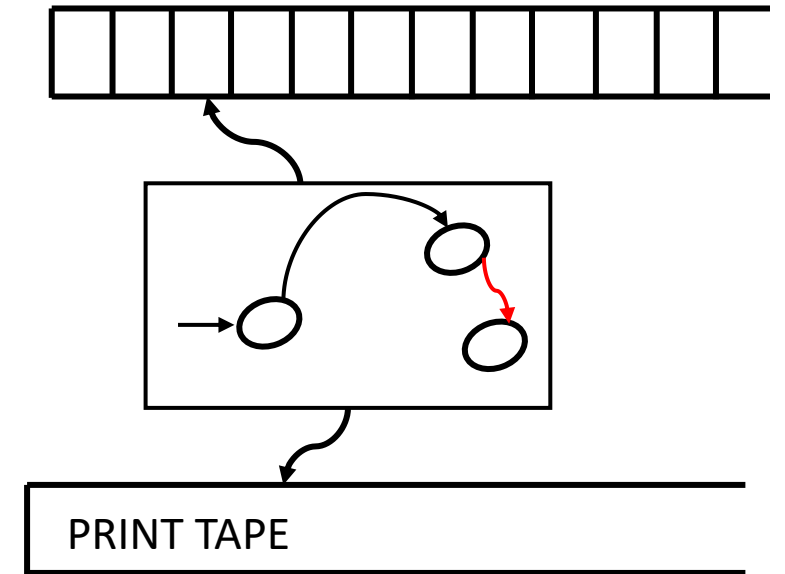
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Enumerators: TM attached with a printer

- The Enumerator E uses the print tape to output strings
- The input tape is initially blank
- The language of E is the set of strings that it prints out
- If E does not halt, it may print infinitely many strings in some order

$$\mathcal{L}(E) = \{w \in \Sigma^* \mid w \text{ is printed by } E\}$$



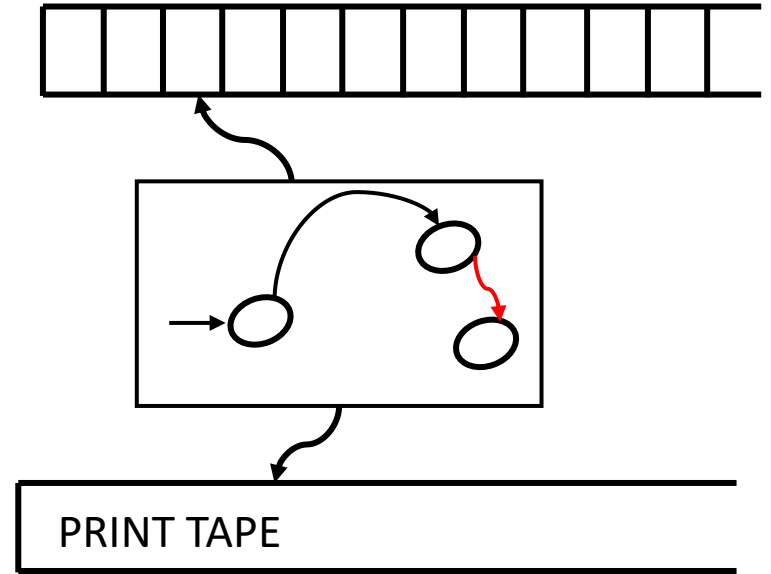
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Enumerators: TM attached with a printer

If $L(M)$ is the language recognized by a Turing Machine M then there exists an enumerator E that enumerates it.



Variants of Turing Machine models

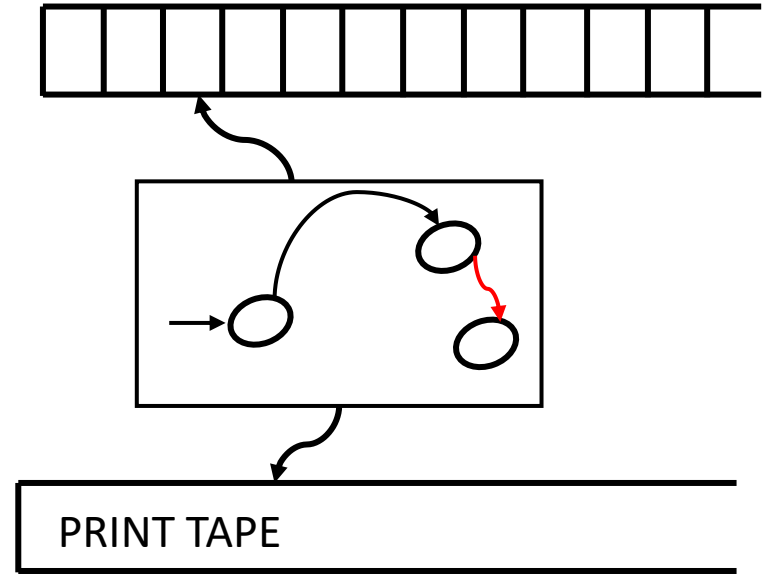
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The set of all finite length (binary) strings is **countably infinite**.



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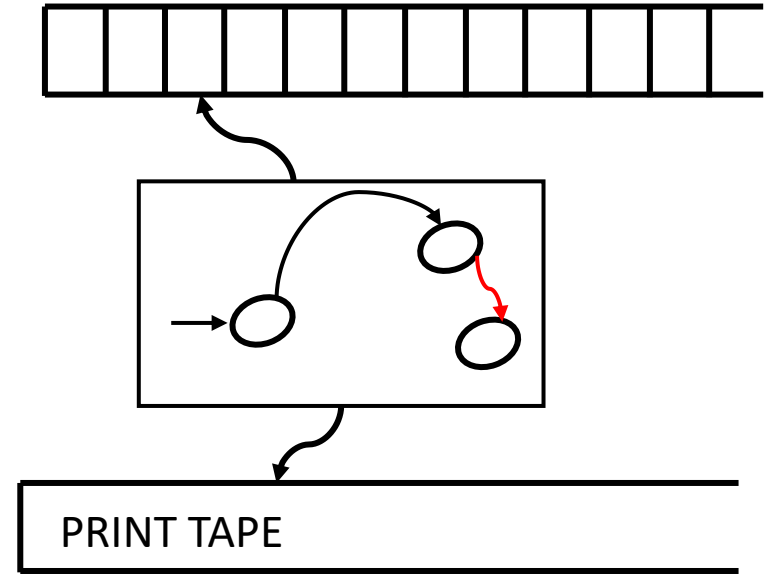
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If $L(M)$ is the language recognized by a Turing Machine M then there exists an enumerator E that enumerates it.

The set of all finite length (binary) strings is **countably infinite**.

- Lexicographically generate all binary strings one after the other. There exists a one-one correspondence with \mathbb{N} .
- We can lexicographically generate all (binary) strings and number them:

$$s_1 = 0, s_2 = 1, s_3 = 00, \dots$$



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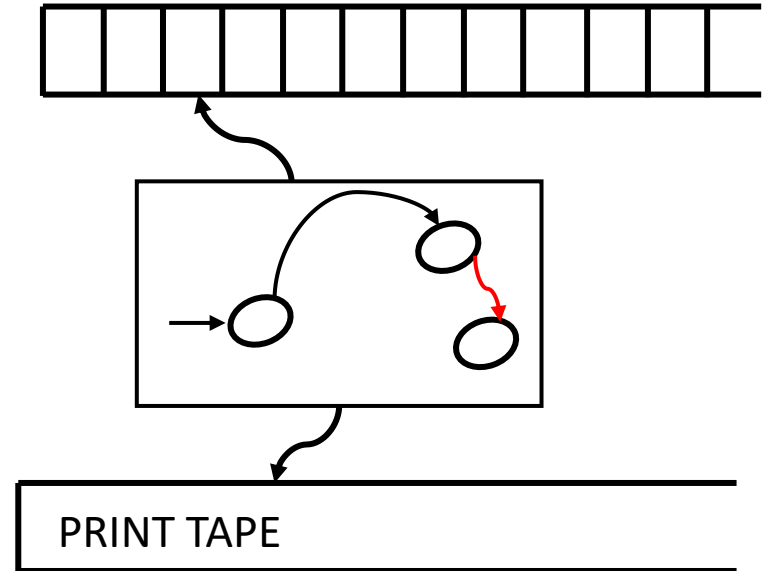
Proof:

For $i = 1, 2, \dots$

For $j = 1, 2, \dots, i$

Run M with string s_j for i steps.

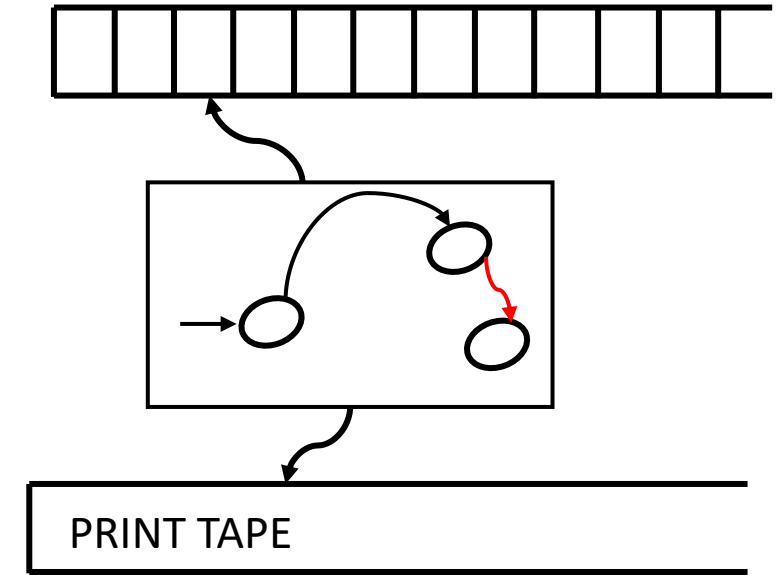
If any string is accepted, then PRINT it.



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Enumerators: TM attached with a printer

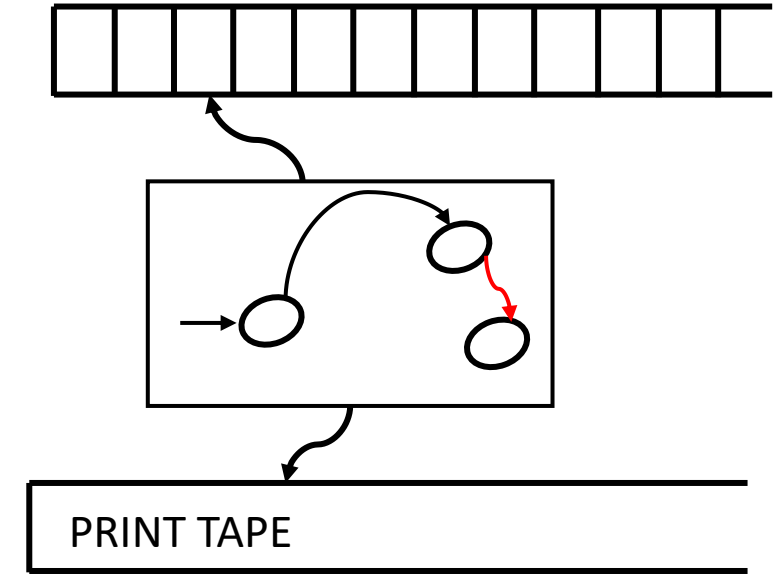
If there exists an Enumerator E , then there exists a Turing Machine M such that $L(M) = L(E)$.

Proof: ???

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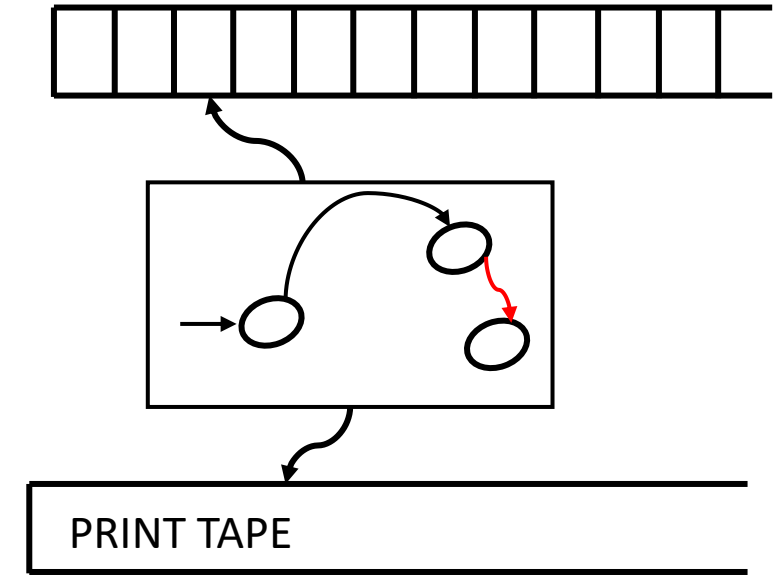
M = On input w :

1. Run E . Every time E prints some string, compare it with w .
2. If they match, ACCEPT.

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E and M are equivalent

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Non-deterministic Turing Machines (NTM): In a deterministic Turing machine, from a given configuration, exactly one configuration is available to it at any stage. For an NTM however,

- At any point in the computation, several possible configurations are available.

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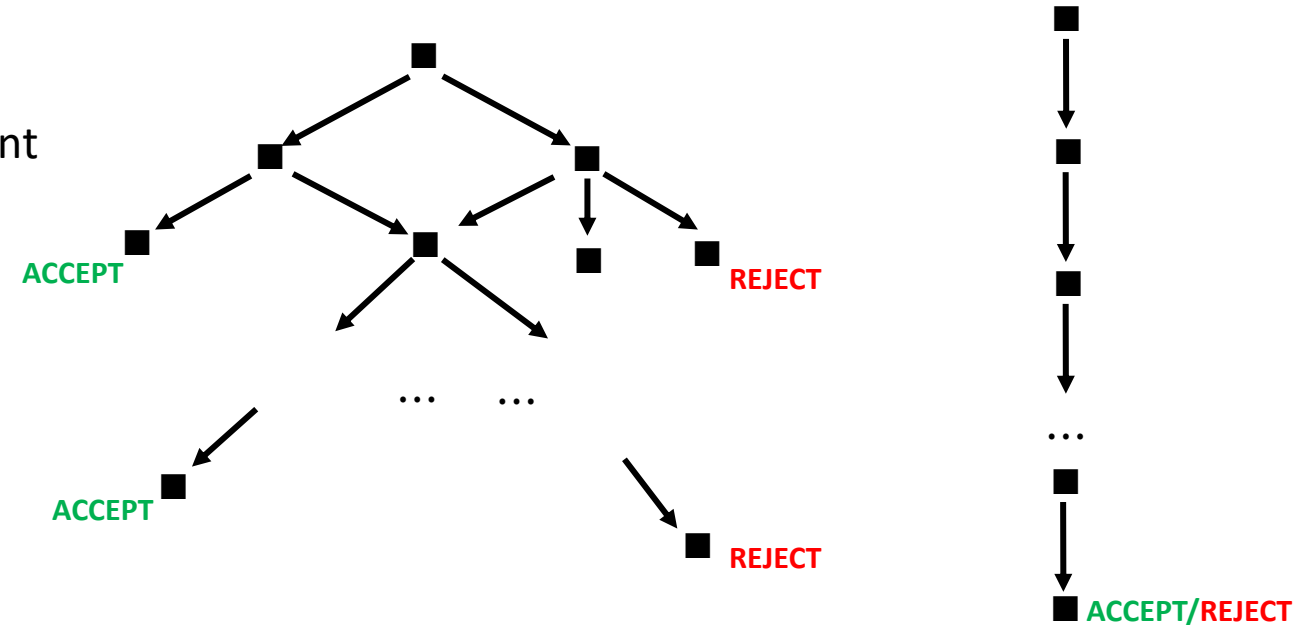
Non-deterministic Turing Machines (NTM): In a deterministic Turing machine, from a given configuration, exactly one configuration is available to it at any stage. For an NTM however,

- At any point in the computation, several possible configurations are available.
- Its transition function is $\delta_N: Q \times \Gamma \rightarrow \mathcal{P}(Q \times \Gamma \times \{L, R\})$, i.e. $\delta(q_i, a) \rightarrow \{(q_j, b, R), (q_k, c, L) \dots\}$

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- The computation corresponds to a configuration tree: From the starting configuration, the computation has several branches, each of which leads to a different configuration.
- If any branch of the computation, leads to an accepting configuration, the NTM accepts. Immediately, DTM is a special case of NTM

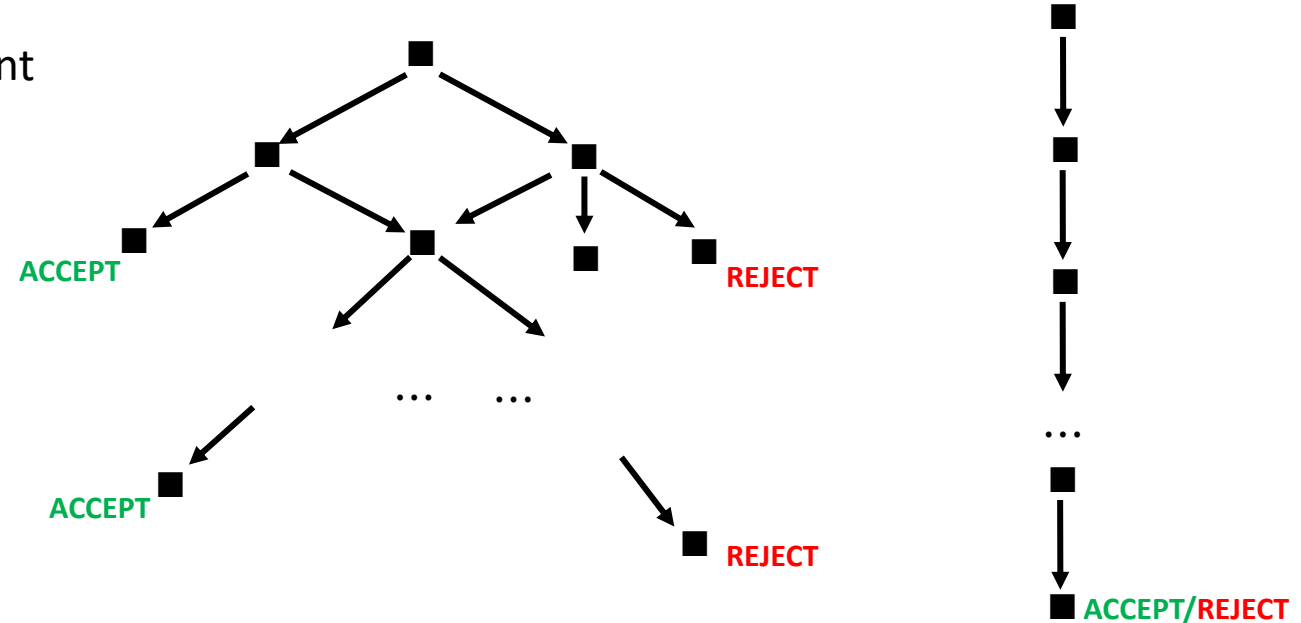
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Non-deterministic Turing Machines (NTM):

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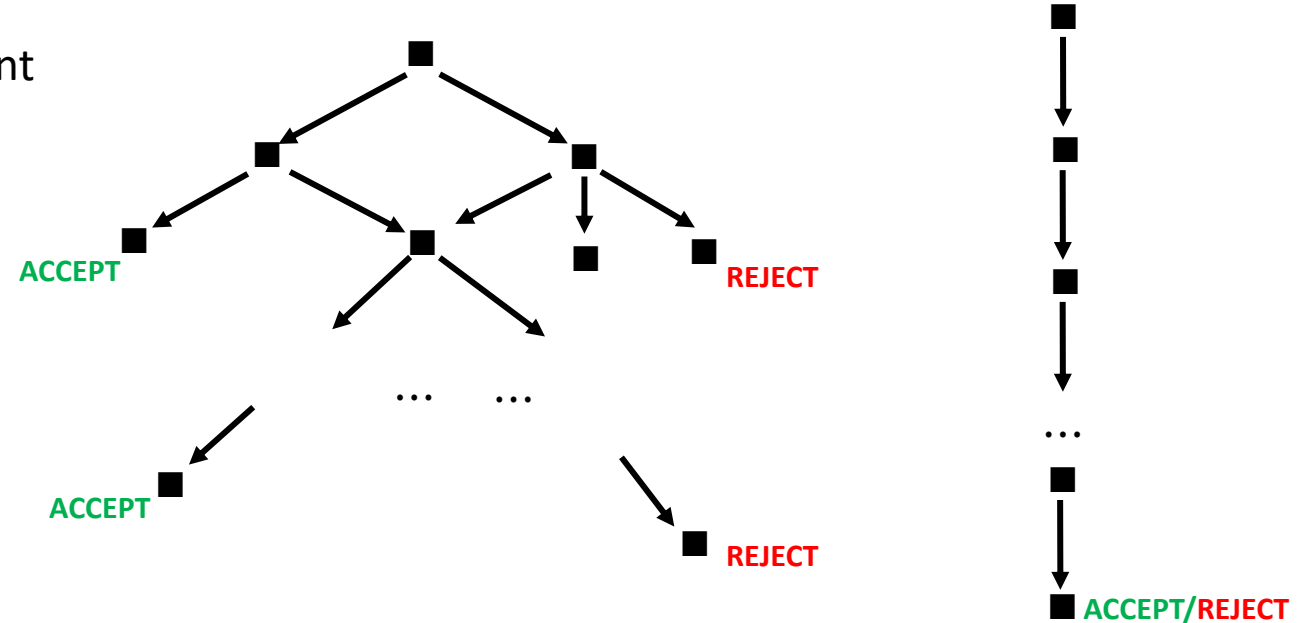
Are NTMs more powerful than DTMs? No. Any NTM can be simulated by a DTM. How?

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Any NTM can be simulated by a DTM



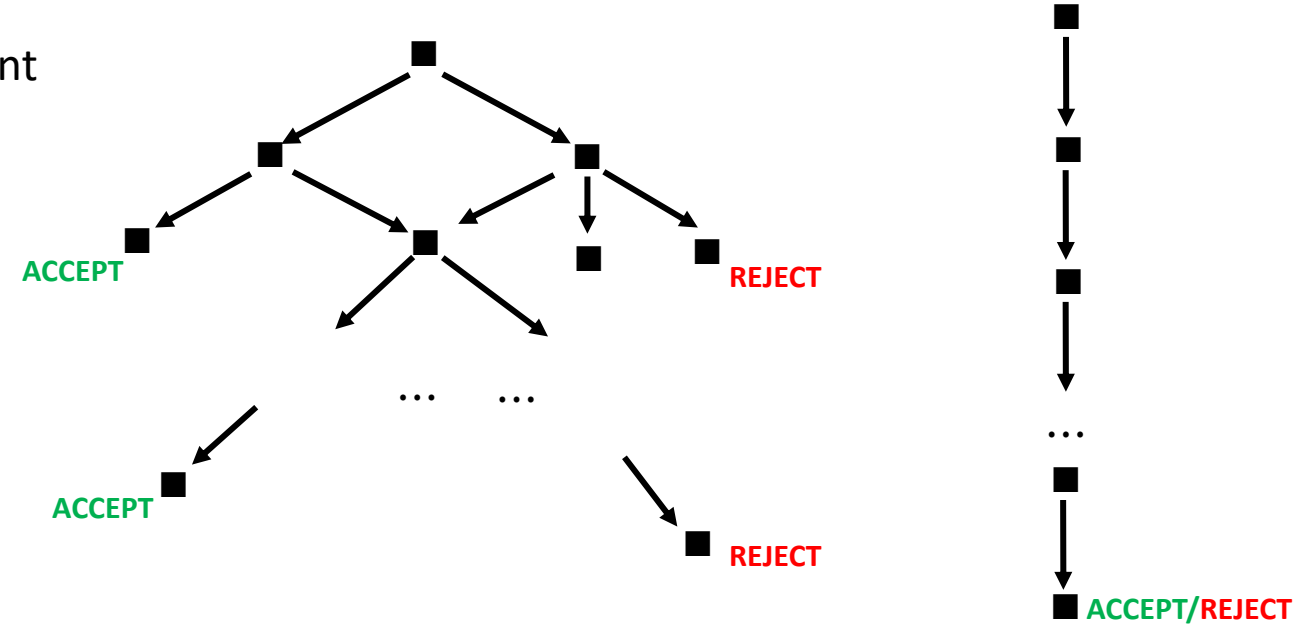
- The DTM searches from among the configurations of the NTM for an accepting configuration.
- Clearly an ordinary Depth First Search shouldn't work
- A branch of the configuration tree can be of infinite depth (when the TM loops forever for that sequence of configuration) and hence the DTM can miss a much shorter accepting configuration.

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Any NTM can be simulated by a 3-tape DTM



Input string w

Generate runs lexicographically

Simulate the run for i/p w

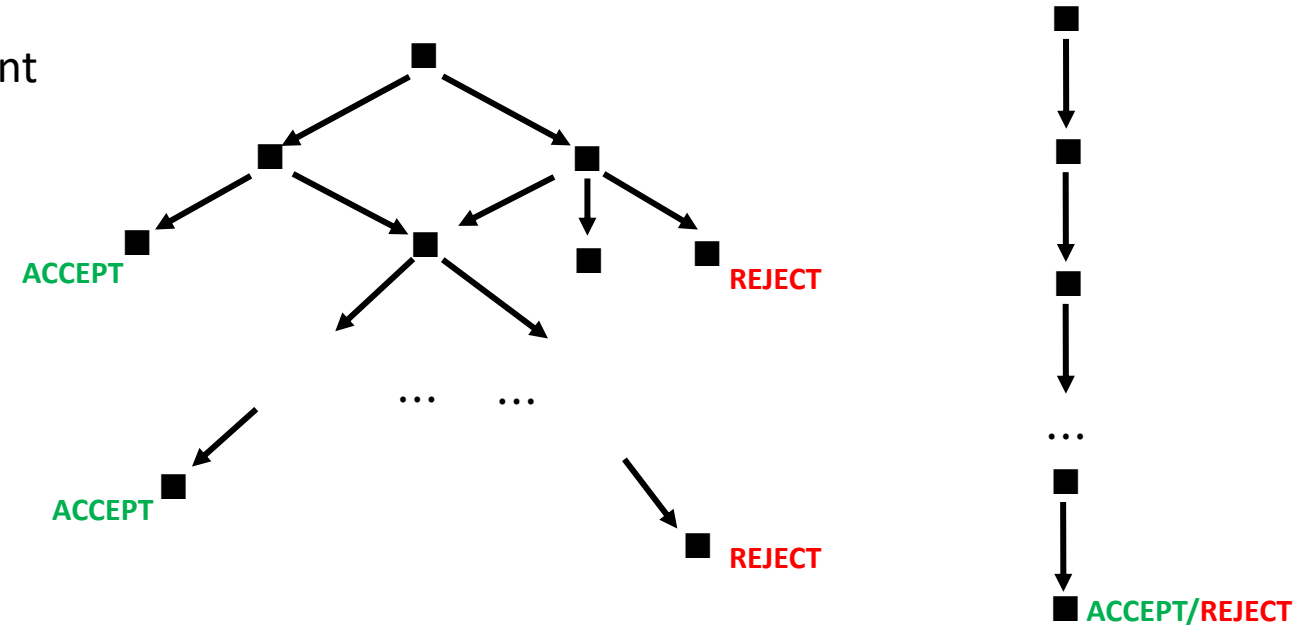
- Tape 1 holds the input string w .
- As for the content of Tape 2, note that we can always obtain a bound for the maximum number of nodes at any level of the configuration tree (say b).

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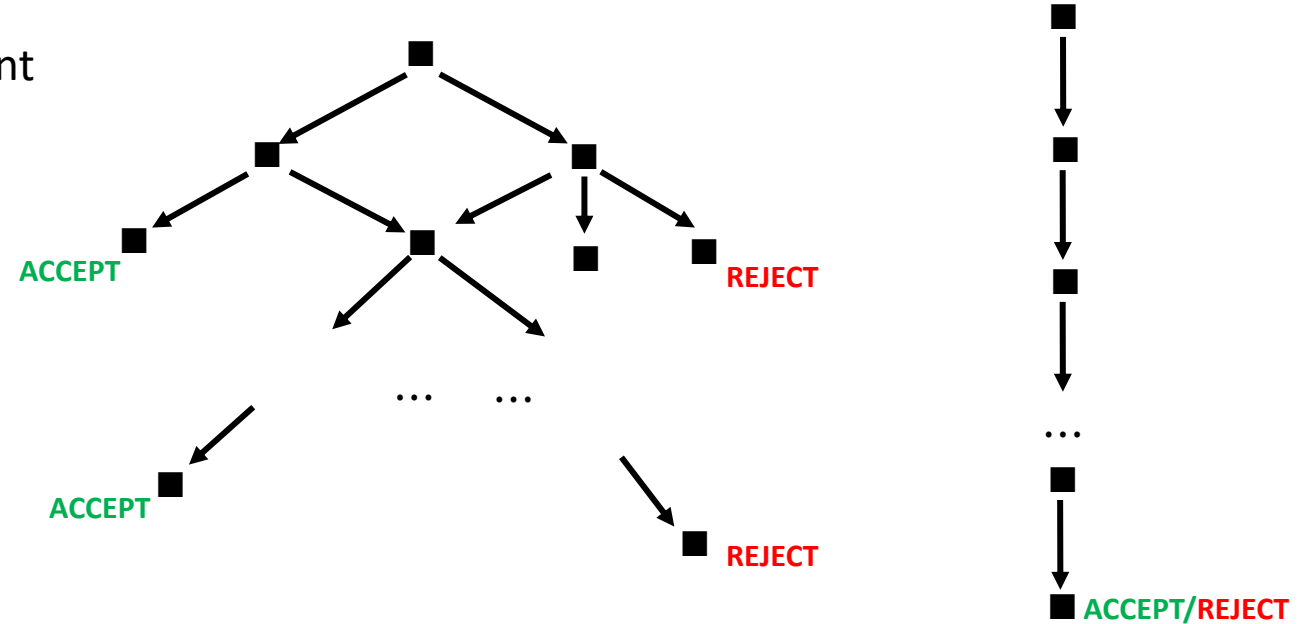
- Tape 1 holds the input string w .
- As for the content of Tape 2, note that we can always obtain a bound for the maximum number of nodes at any level of the configuration tree (say b).
- Let $C = \{1, 2, \dots, b\}$, then we can define a run by a string $s \in C$. E.g: 122: choose the first node from level 1, second node from level 2, third node from level 3.

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Simulate the run for i/p w

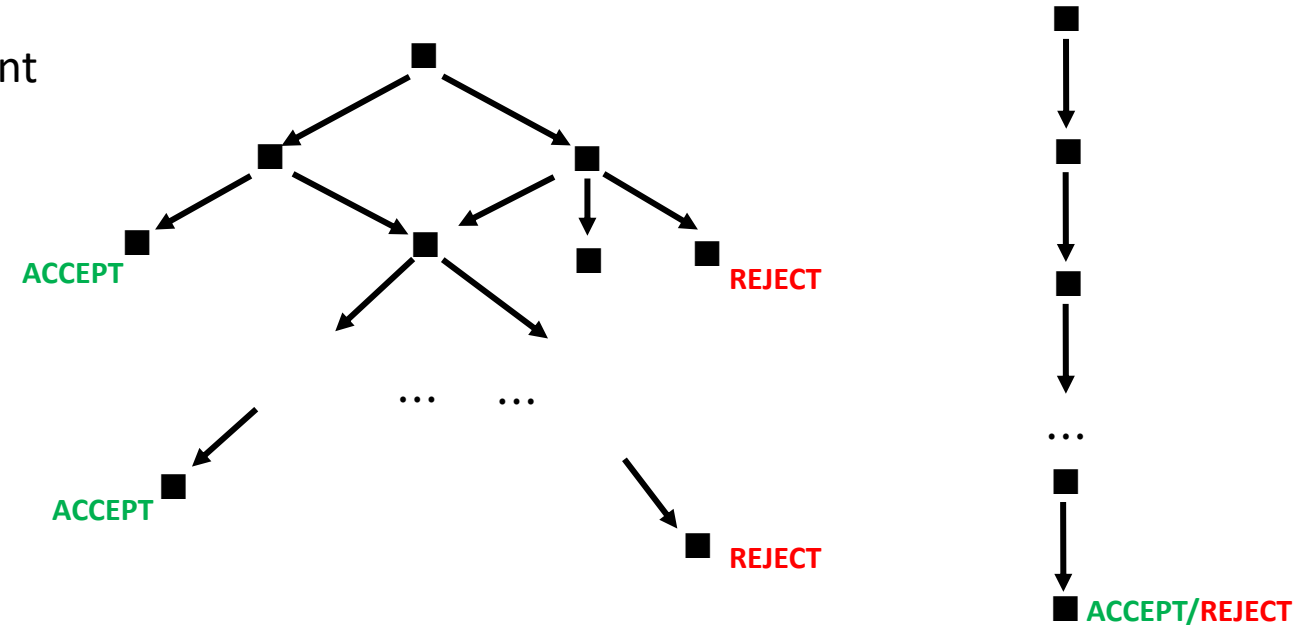
- Tape 1 holds the input string w .
- Tape 2 generates a string in $C = \{1, 2, \dots, b\}$ lexicographically: Generate all strings of length 1, then strings of length 2 and so on, i.e. $\{1, 2, \dots, b, 11, 12, 21, 22, \dots\}$.
- Some of these runs may be invalid or too short to lead to any accept/reject state.

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- Tape 1 holds the input string w .
- Tape 2 generates runs lexicographically
- Tape 3 simulates one branch of the configuration tree corresponding to the run generated in Tape 2.

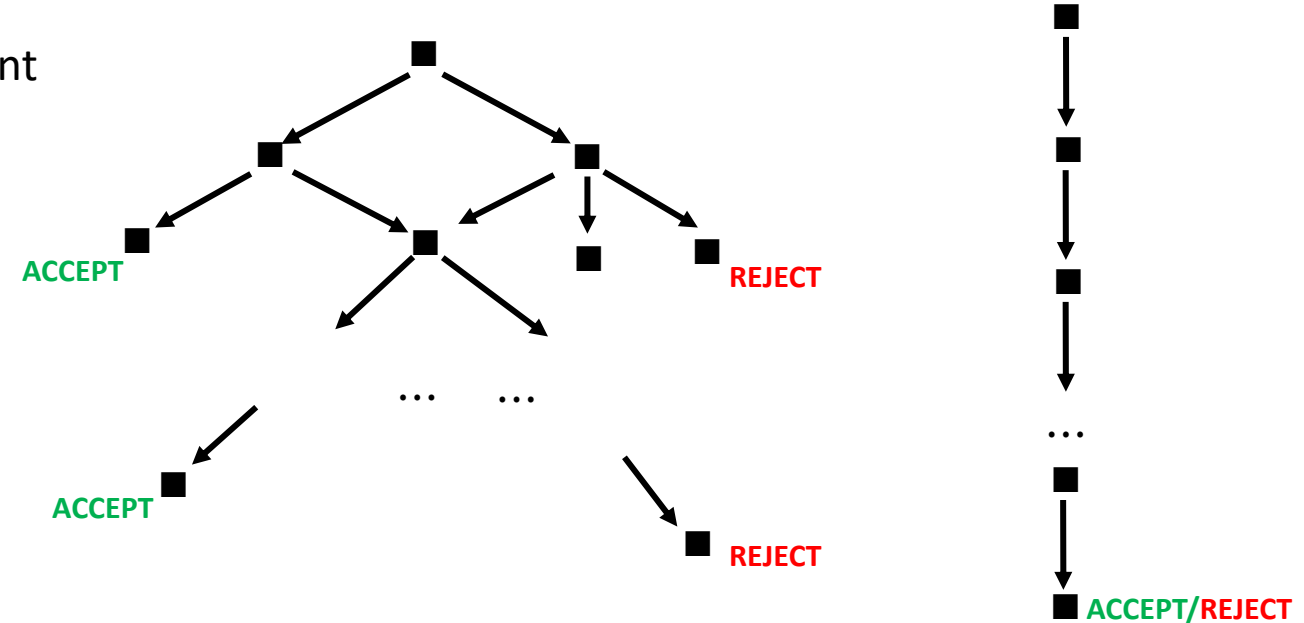


Variants of Turing Machine Models

Is the standard TM model \mathcal{M}_1 more powerful/equivalent to the following TM models where

- The head can move left, right or stay put?
- We have k read/write tapes instead of one?
- We have a two-way infinite tape, instead of one?
- **We introduce non-determinism?**

Any NTM can be simulated by a 3-tape DTM



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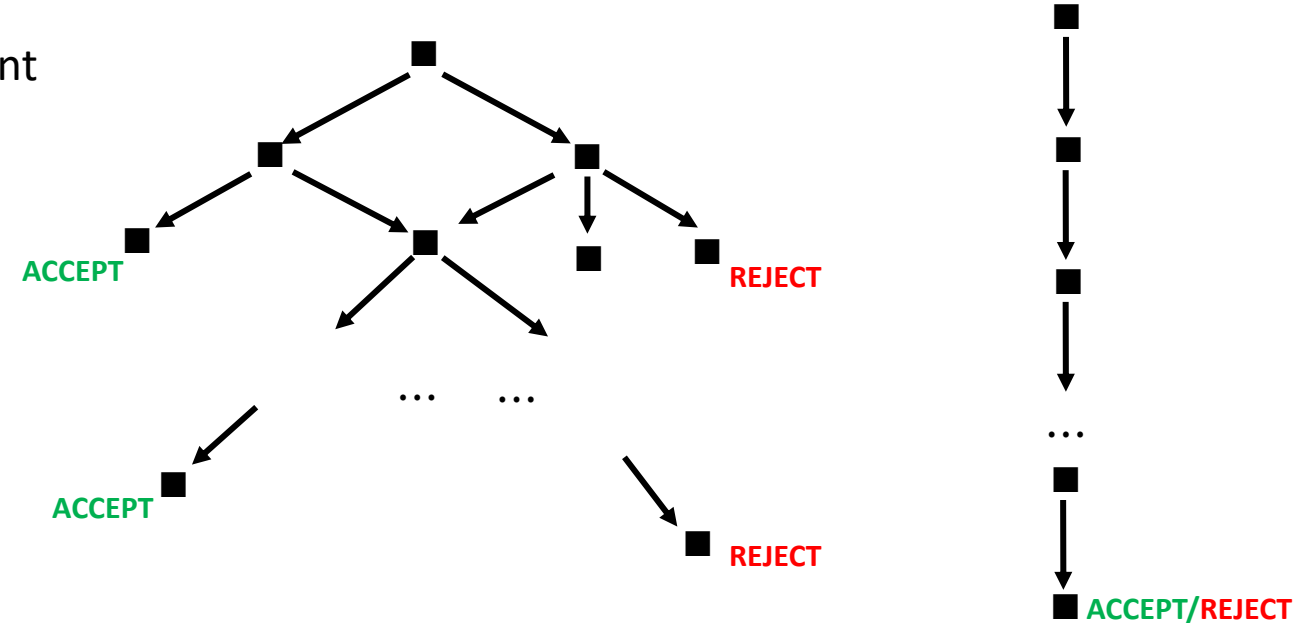
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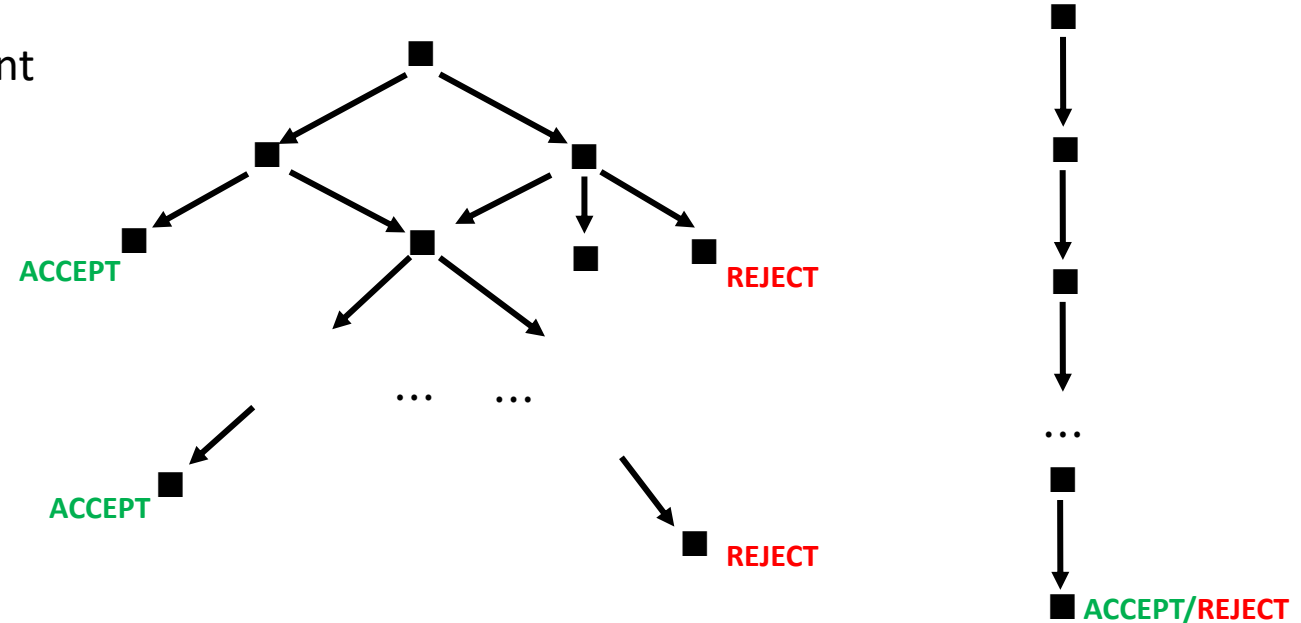
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- During the simulation, if the run in Tape 2 is found to be invalid, abort and generate the next lexicographic string

3-tape DTM \equiv 1-tape DTM \Rightarrow NTM \equiv DTM

Variants of Turing Machine Models

Variants of TM:

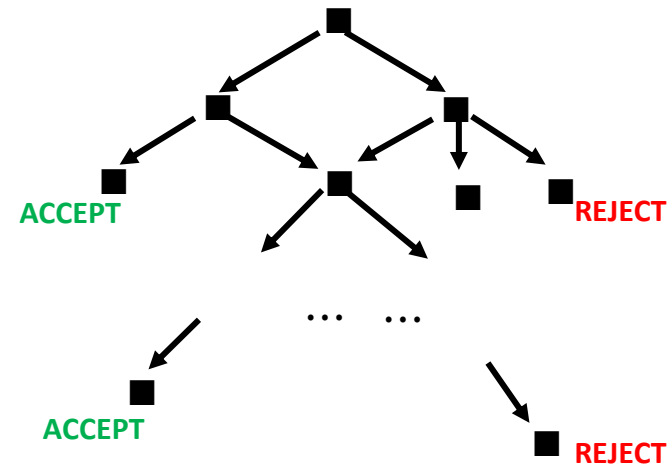
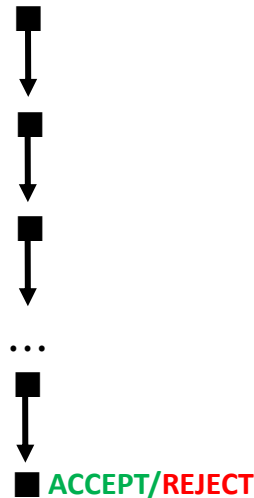
- **The head can move left, right or stay put?**
- **We have k read/write tapes instead of one?**
- **We have a two-way infinite tape, instead of one?**
- **TM with a printer attached?**
- **We introduce non-determinism?**



Key takeaway: A standard TM is quite robust. Adding extra power seems to make no difference in computing power

Variants of Turing Machine Models

- As an aside, although $NTM \equiv DTM$, a DTM may require several more steps to perform the same computation.
- For a moment, consider problems that are computable (TM halts on all inputs).
- For a given decision problem L , let for all input strings $|w| = n$, suppose \exists
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- For a given decision problem L , let for all input strings w such that $|w| = n$, suppose \exists
- **DTM** that halts within *DTIME* steps and outputs YES if $w \in L$ and NO if $w \notin L$.
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NP = Set of all problems for which *NTIME* is a polynomial in n .

Clearly, $P \subseteq NP$. However, is $P = NP$?

A million dollar problem

Thank You!