Theoretical Computer Science

Tutorial Week 9

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Agenda

- **Turing Machine**
  - formal definition
  - example

FSA (Formal definition)

Definition

A (complete) Finite State Automaton is a tuple $\langle Q, \Sigma, q_0, A, \delta\rangle$, where

Q is a finite set of *states*;
Σ is a finite *input alphabet*;
$q_0 \in Q$ is the *initial* state;
$A \subseteq Q$ is the set of *accepting* states;
$\delta : Q \times \Sigma \to Q$ is a (total) *transition* function.

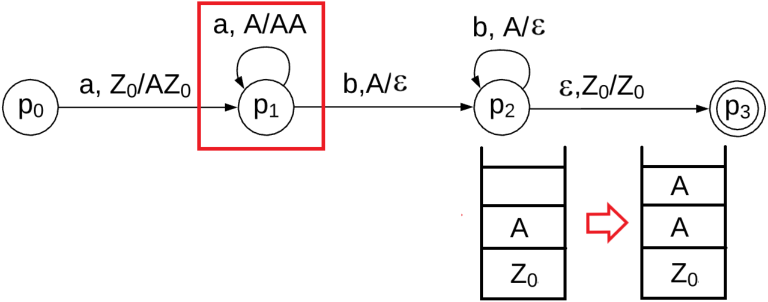
PDA (Formal Definition)

Definition

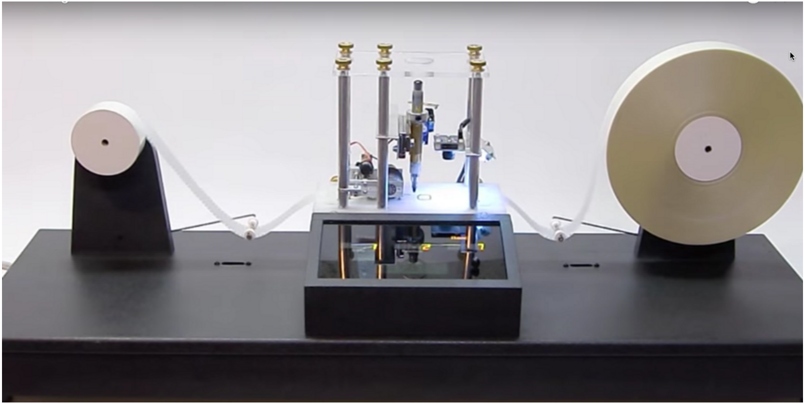
A (Deterministic) Pushdown Automaton (PDA) is a tuple $\langle Q, \Sigma, \Gamma, \delta, q_0, Z_0, A \rangle$, where

- Q is a finite set of states;
- Σ and Γ are the input and stack (finite) alphabets;
- $\delta : Q \times (\Sigma \cup \{\epsilon\}) \times \Gamma \rightarrow Q \times \Gamma^*$ is the (partial) transition function;
- $q_0 \in Q$ is the initial state;
- $Z_0 \in \Gamma$ is the initial stack symbol;
- $A \subseteq Q$ is the set of accepting states.

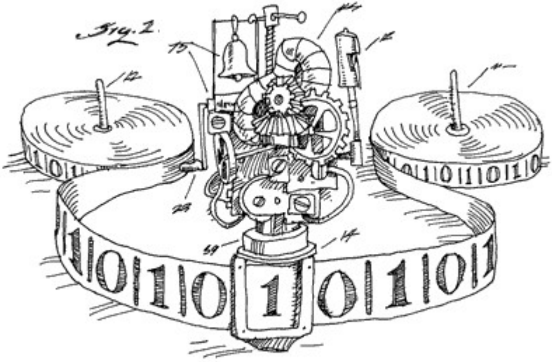
Pushdown automata



Turing Machine



Turing Machine



$\longleftarrow L \qquad S \qquad R \longrightarrow$

Turing Machine

Special symbols

R : move the head one position to the right
L : move the head one position to the left
S : stand still

Turing Machine

Special symbols

R : move the head one position to the right
L : move the head one position to the left
S : stand still

_ : a special blank symbol on the tapes

Turing Machine

Formal Definition

A Turing Machine (TM) (with 1-tape) is a tuple

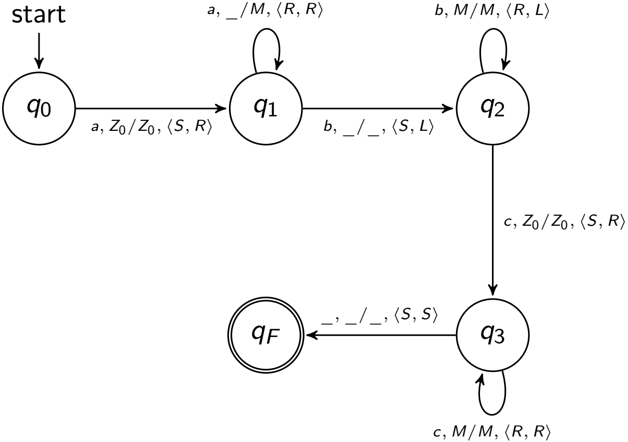
$$T = \langle Q, \Sigma, \Gamma, \delta, q_0, Z_0, F \rangle$$

where

- Q is a finite set of states;
- Σ is the input alphabet;
- Γ is the memory alphabet;
- $\delta : (Q - F) \times (\Sigma \cup \{\_\}) \times (\Gamma \cup \{\_\}) \to Q \times (\Gamma \cup \{\_\}) \times \{R, L, S\}^2$ is the transition function;
- $q_0 \in Q$ is the initial state;
- $Z_0 \in \Gamma$ is the initial memory symbol;
- $F \subseteq Q$ is the set of final states.

Example: Language $A^nB^nC^n$

A TM T that recognises the language $A^nB^nC^n = \{a^nb^nc^n \mid n > 0\}$



Is the string *aabbcc* recognised by T?

Agenda

- Turing Machine
  - **formal definition**
  - example

Turing Machine

Formal Definition

A Turing Machine (TM) (with k-tapes) is a tuple

$$T = \langle Q, \Sigma, \Gamma, \delta, q_0, Z_0, F \rangle$$

where

Q is a finite set of states;
Σ is the input alphabet;
Γ is the memory alphabet;
δ is the transition function;
$q_0 \in Q$ is the initial state;
$Z_0 \in \Gamma$ is the initial memory symbol;
$F \subseteq Q$ is the set of final states.

Transition Function

The transition function is defined as

$$\delta : (Q - F) \times (\Sigma \cup \{\_\}) \times (\Gamma \cup \{\_\})^k \to Q \times (\Gamma \cup \{\_\})^k \times \{R, L, S\}^{k+1}$$

Remarks:

- the transition function can be partial;
- no transition outgoing from the final states;
- the symbol $\_ \notin \Gamma \cup \Sigma$ is a special blank symbol on the tapes.

Moves

Moves are based on

- state of the control device,
- one symbol read from the input tape,
- k symbols, one for each memory tape.

Actions

- Change state,
- Write a symbol replacing the one read on each memory tape,
- Move the $k + 1$ heads.

Moves: Graphically

$$q \xrightarrow{i, \langle A_1, A_2, \ldots, A_k \rangle / \langle A'_1, A'_2, \ldots, A'_k \rangle, \langle M_0, M_1, \ldots, M_k \rangle} q'$$

- $q \in Q - F$ and $q' \in Q$
- i is the input symbol,
- A_j is the symbol read from the j^{th} memory tape,
- A'_j is the symbol replacing A_j,
- M_0 is the direction of the head of the input tape,
- M_j is the direction of the head of the j^{th} memory tape.

where $1 \leq j \leq k$

Configuration

A configuration (a snapshot) c of a TM with k memory tapes is the following $(k+2)$-tuple:

$$c = \langle q, x{\uparrow}y, \alpha_1{\uparrow}\beta_1, \ldots, \alpha_k{\uparrow}\beta_k \rangle$$

where

- $q \in Q$
- $x \in (\Sigma \cup \{\_\})^*$, $y = y' \cdot \_$ with $y' \in \Sigma^*$
- $\alpha_r \in (\Gamma \cup \{\_\})^*$ and $\beta'_r = \beta'_r \cdot \_$ with $\beta'_r \in \Gamma^*$ and $1 \leq r \leq k$
- $\uparrow \notin \Sigma \cup \Gamma$

Acceptance Condition

If $T = \langle Q, \Sigma, \Gamma, \delta, q_0, Z_0, F \rangle$ is a TM and $s \in \Sigma^*$,

$$s \text{ is accepted by } T, \text{ if } c_0 \vdash^* c_F$$

where

1. c_0 is an initial configuration defined as $c_0 = \langle q_0, \uparrow s, \uparrow Z_0, \ldots, \uparrow Z_0 \rangle$ where
   - $x = \epsilon$
   - $y = s\_$
   - $\alpha_r = \epsilon$, $\beta_r = Z_0$, for any $1 \leq r \leq k$.
2. c_F is a final configuration defined as $c_F = \langle q, s' \uparrow y, \alpha_1 \uparrow \beta_1, \ldots, \alpha_k \uparrow \beta_k \rangle$ where
   - $q \in F$
   - $x = s'$

$L(T) = \{s \in \Sigma^* \mid x \text{ is accepted by } T\}$

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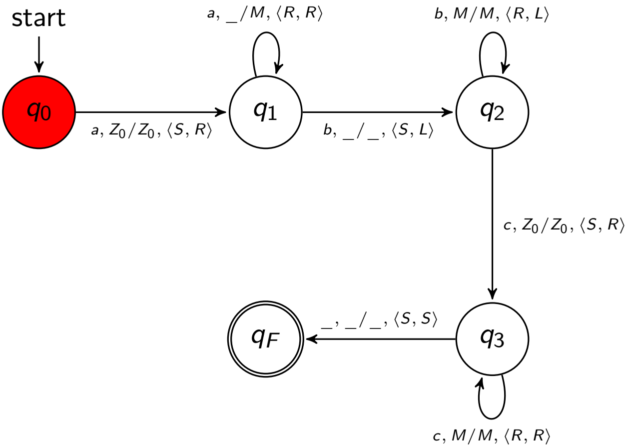
  - formal definition
  - **example**

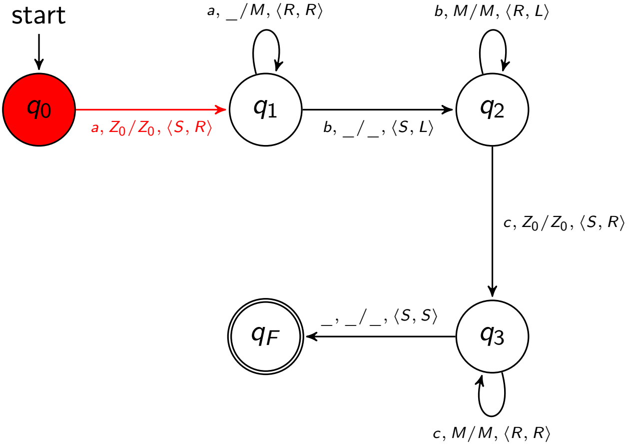
Example: Language $A^nB^nC^n$



Initial Configuration:

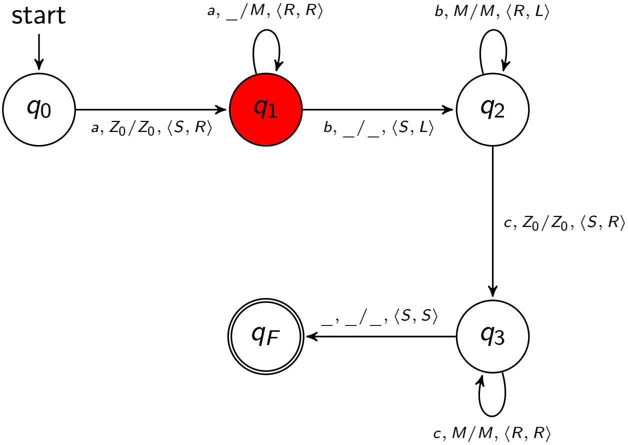
$$\langle q_0, \uparrow aabbcc, \uparrow Z_0\rangle$$

Example: Language $A^nB^nC^n$



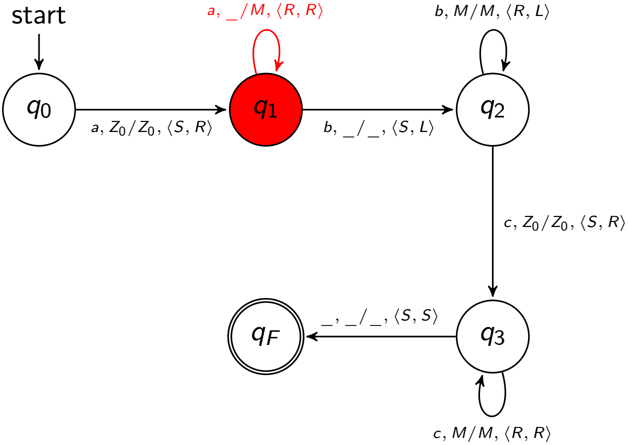
$$\langle q_0, \uparrow aabbcc, \uparrow Z_0\rangle \vdash$$

Example: Language $A^nB^nC^n$



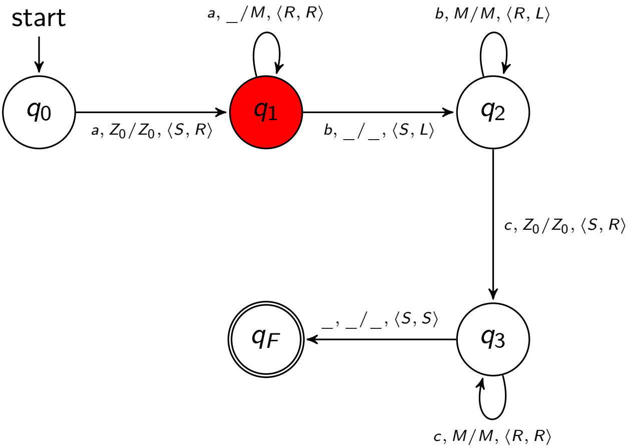
$$\langle q_0, \uparrow aabbcc, \uparrow Z_0\rangle \vdash \langle q_1, \uparrow aabbcc, Z_0\uparrow\rangle$$

Example: Language $A^nB^nC^n$



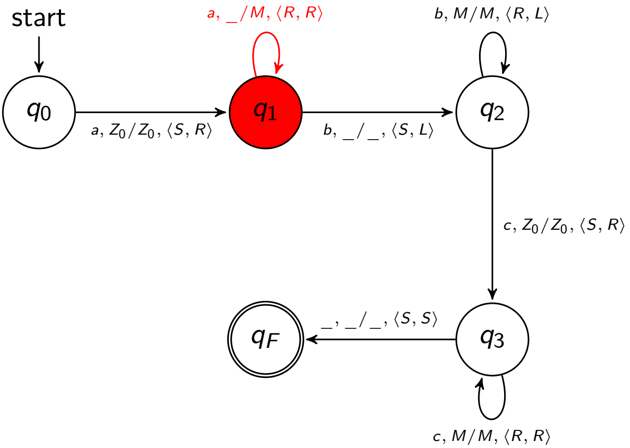
$$\ldots \vdash \langle q_1, \uparrow aabbcc, Z_0\uparrow\rangle \vdash$$

Example: Language $A^nB^nC^n$



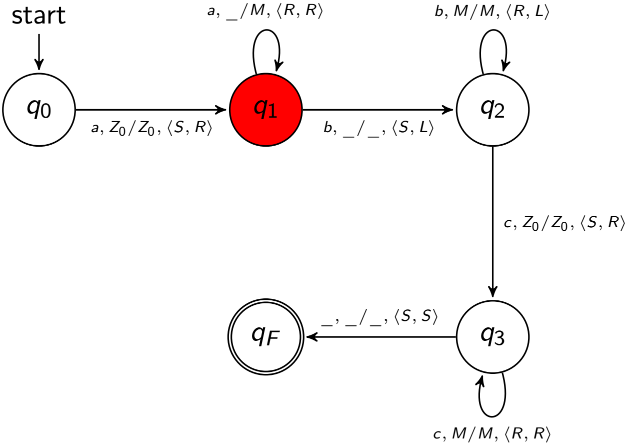
$$\ldots \vdash \langle q_1, \uparrow aabbcc, Z_0\uparrow\rangle \vdash \langle q_1, a\uparrow abbcc, Z_0M\uparrow\rangle$$

Example: Language $A^n B^n C^n$



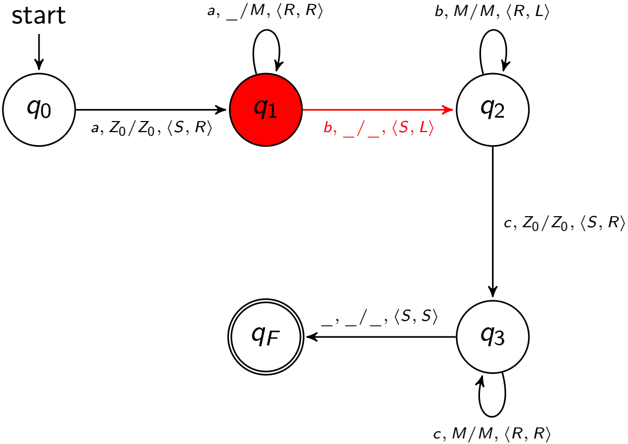
$$\ldots \vdash \langle q_1, a{\uparrow}abbcc, Z_0M{\uparrow} \rangle$$

Example: Language $A^nB^nC^n$



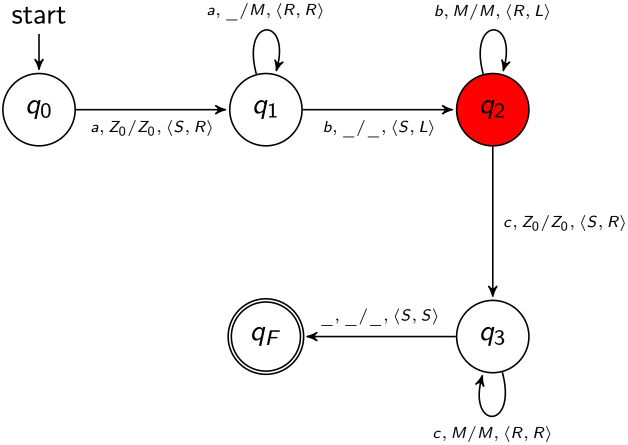
$$\ldots \vdash \langle q_1, a{\uparrow}abbcc, Z_0M{\uparrow}\rangle \vdash \langle q_1, aa{\uparrow}bbcc, Z_0MM{\uparrow}\rangle$$

Example: Language $A^nB^nC^n$



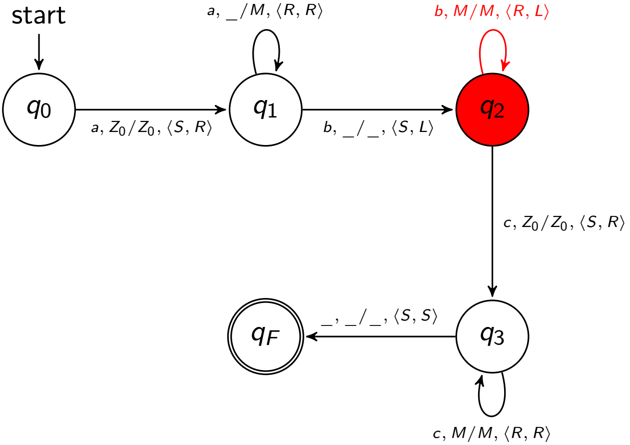
$$\ldots \vdash \langle q_1, aa{\uparrow}bbcc, Z_0MM{\uparrow}\rangle$$

Example: Language $A^nB^nC^n$



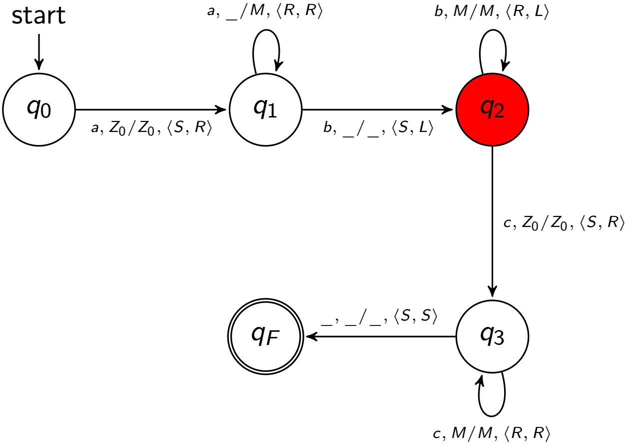
$$\ldots \vdash \langle q_1, aa{\uparrow}bbcc, Z_0MM{\uparrow}\rangle \vdash \langle q_2, aa{\uparrow}bbcc, Z_0M{\uparrow}M\rangle$$

Example: Language $A^n B^n C^n$



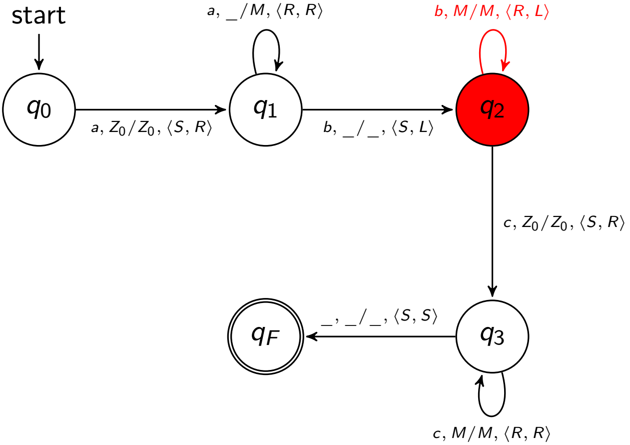
$$\ldots \vdash \langle q_2, aa{\uparrow}bbcc, Z_0M{\uparrow}M\rangle$$

Example: Language $A^n B^n C^n$



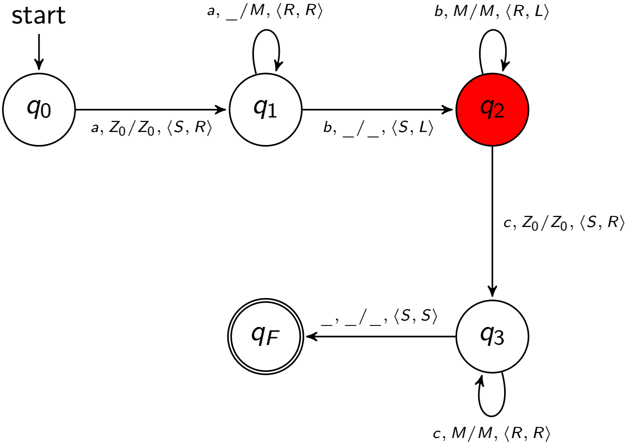
$$\ldots \vdash \langle q_2, aa{\uparrow}bbcc, Z_0M{\uparrow}M\rangle \vdash \langle q_2, aab{\uparrow}bcc, Z_0{\uparrow}MM\rangle$$

Example: Language $A^n B^n C^n$



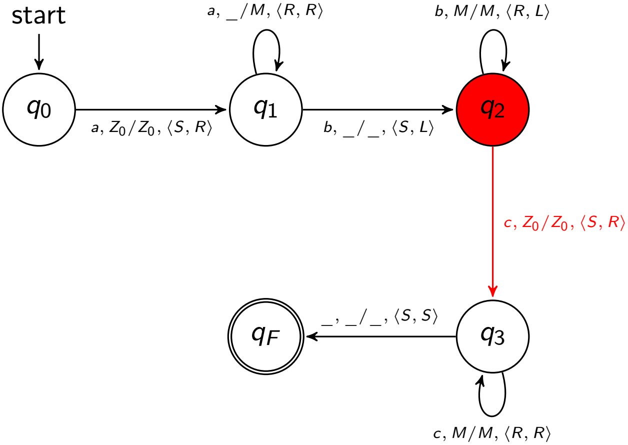
$$\ldots \vdash \langle q_2, aab{\uparrow}bcc, Z_0{\uparrow}MM\rangle$$

Example: Language $A^n B^n C^n$



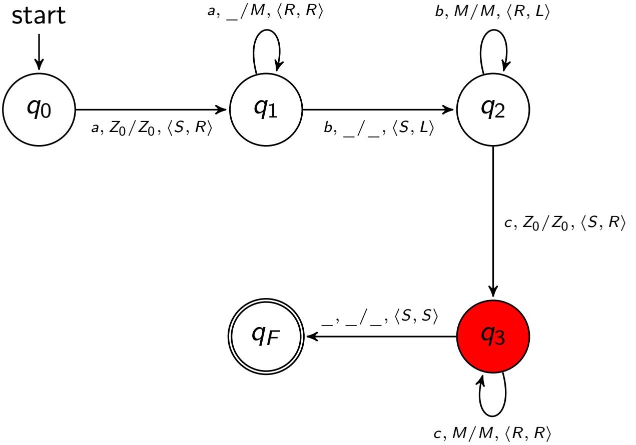
$$\ldots \vdash \langle q_2, aab{\uparrow}bcc, Z_0{\uparrow}MM \rangle \vdash \langle q_2, aabb{\uparrow}cc, {\uparrow}Z_0MM \rangle$$

Example: Language $A^n B^n C^n$



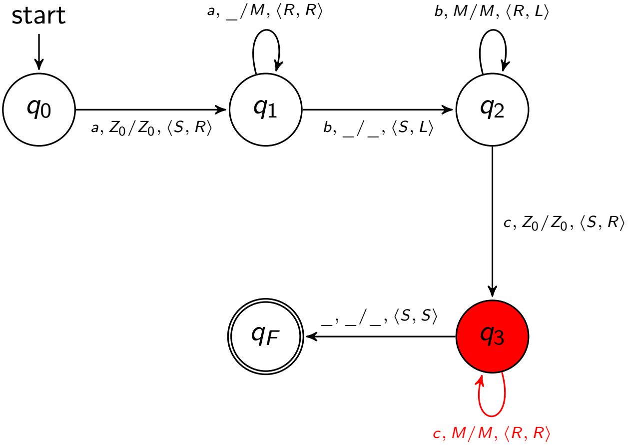
$$\ldots \vdash \langle q_2, aabb{\uparrow}cc, {\uparrow}Z_0MM\rangle$$

Example: Language $A^n B^n C^n$



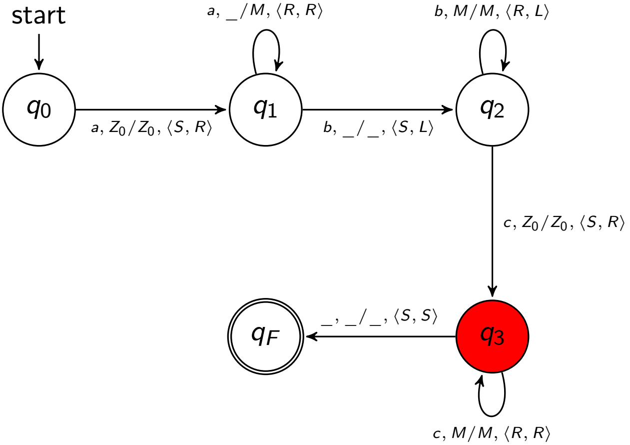
$$\ldots \vdash \langle q_2, aabb\uparrow cc, \uparrow Z_0MM\rangle \vdash \langle q_3, aabb\uparrow cc, Z_0\uparrow MM\rangle$$

Example: Language $A^nB^nC^n$



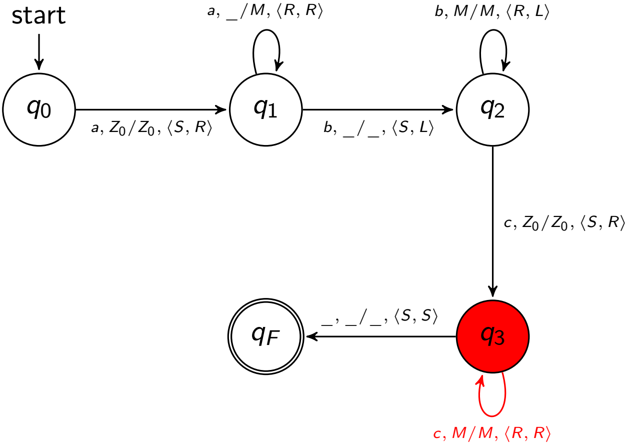
$$\ldots \vdash \langle q_3, aabb{\uparrow}cc, Z_0{\uparrow}MM\rangle$$

Example: Language $A^nB^nC^n$



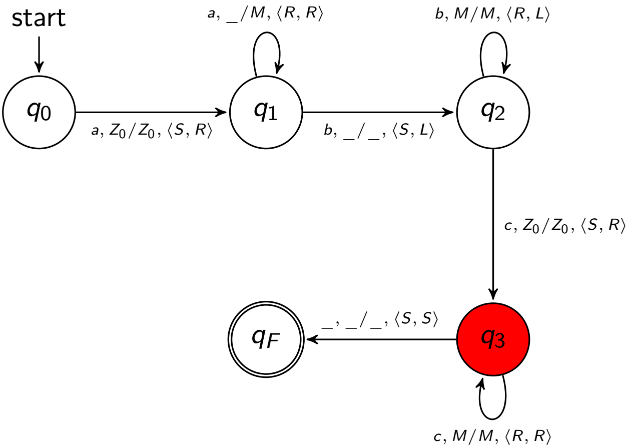
$$\ldots \vdash \langle q_3, aabb{\uparrow}cc, Z_0{\uparrow}MM\rangle \vdash \langle q_3, aabbc{\uparrow}c, Z_0M{\uparrow}M\rangle$$

Example: Language $A^nB^nC^n$



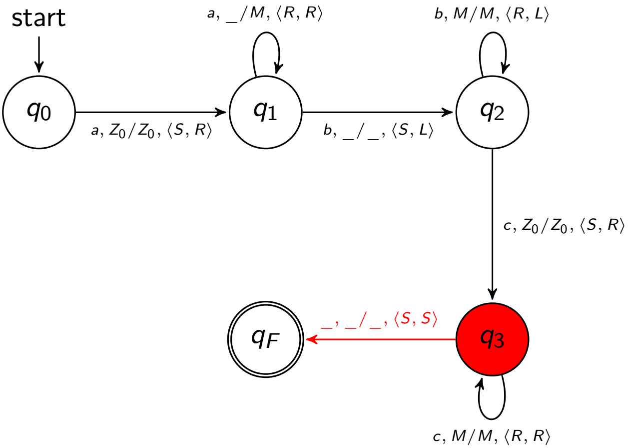
$$\ldots \vdash \langle q_3, aabbc{\uparrow}c, Z_0M{\uparrow}M\rangle$$

Example: Language $A^nB^nC^n$



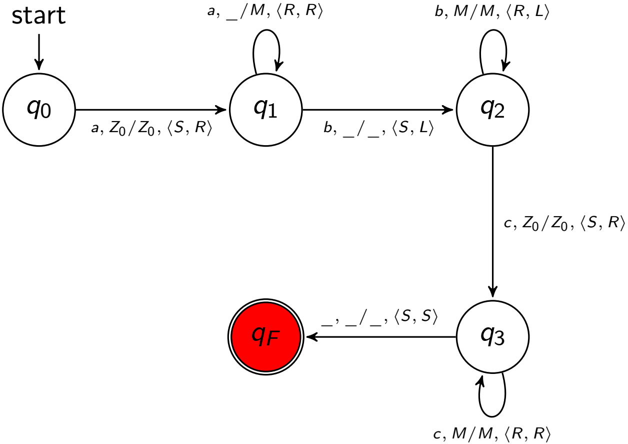
$$\ldots \vdash \langle q_3, aabbc{\uparrow}c, Z_0M{\uparrow}M\rangle \vdash \langle q_3, aabbcc{\uparrow}, Z_0MM{\uparrow}\rangle$$

Example: Language $A^nB^nC^n$



$$\ldots \vdash \langle q_3, aabbcc\uparrow, Z_0MM\uparrow\rangle$$

Example: Language $A^nB^nC^n$



$$\ldots \vdash \langle q_3, aabbcc\uparrow, Z_0MM\uparrow\rangle \vdash \langle q_F, aabbcc\uparrow, Z_0MM\uparrow\rangle$$

Example: Language $A^n B^n C^n$

$$\langle q_0, \uparrow aabbcc, \uparrow Z_0 \rangle \vdash^* \langle q_F, aabbcc\uparrow, Z_0 MM\uparrow \rangle$$

That is the string *aabbcc* recognised by T

Therefore, the TM recognize $\{a^n b^n c^n \mid n \in \mathbb{N}\}$

Thank you for your attention!