Finite state automaton

Finite state automaton

Regular languages*: *RL

Deterministic pushdown automaton

Finite state automaton

Regular languages*: *RL

Deterministic pushdown automaton

Finite state automaton

Deterministic context-free languages: DCFL

Language L_3: $\{ w2w^R \mid w \in (0+1)^* \text{ i } |w|>1 \}$

$L_3 \in DCFL$ i $L_3 \notin RL$

Regular languages: RL

Non-deterministic pushdown automaton

Deterministic pushdown automaton

Finite state automaton

Deterministic context-free languages: *DCFL*

Language L_3: { $w2w^R$ | $w \in (0+1)^*$ i $|w|>1$ }

$L_3 \in DCFL$ i $L_3 \notin RL$

Regular languages: *RL*

Non-deterministic pushdown automaton

Deterministic pushdown automaton

Finite state automaton

Non-deterministic context-free languages: *NDCFL*

Language L_2: $\{ ww^R \mid w \in (0+1)^* \text{ i } |w|>1 \}$

$L_2 \in NDCFL$ i $L_2 \notin DCFL$

Deterministic context-free languages: *DCFL*

Language L_3: $\{ w2w^R \mid w \in (0+1)^* \text{ i } |w|>1 \}$

$L_3 \in DCFL$ i $L_3 \notin RL$

Regular languages: *RL*

Turing machine

Non-deterministic pushdown automaton

Deterministic pushdown automaton

Finite state automaton

Non-deterministic context-free languages: NDCFL

Language L_2: $\{ ww^R \mid w \in (0+1)^* \text{ i } |w|>1 \}$

$L_2 \in NDCFL$ i $L_2 \notin DCFL$

Deterministic context-free languages: DCFL

Language L_3: $\{ w2w^R \mid w \in (0+1)^* \text{ i } |w|>1 \}$

$L_3 \in DCFL$ i $L_3 \notin RL$

Regular languages: RL

Turing machine

Non-deterministic pushdown automaton

Deterministic pushdown automaton

Finite state automaton

Recursively enumerable languages

Non-deterministic context-free languages: NDCFL

Language L_2: $\{ ww^R \mid w \in (0+1)^* \text{ i } |w|>1 \}$

$L_2 \in NDCFL$ i $L_2 \notin DCFL$

Deterministic context-free languages: DCFL

Language L_3: $\{ w2w^R \mid w \in (0+1)^* \text{ i } |w|>1 \}$

$L_3 \in DCFL$ i $L_3 \notin RL$

Regular languages: RL

Lecture 11.

4 RECURSIVELY ENUMERABLE LANGUAGES 126

4.1 TURING MACHINE (TM) 126

4.1.1 Simple Turing machine 126

4.1.2 Programming techniques for Turing machines 133

Lecture outline

4 RECURSIVELY ENUMERABLE LANGUAGES 126
4.1 TURING MACHINE (TM) 126
4.1.1 Simple Turing machine 126
4.1.2 Programming techniques for Turing machines 133

Recursively enumerable languages

Recursively enumerable languages

- **Recursively enumerable language**

Recursively enumerable languages

- **Recursively enumerable language**
  - Turing machine

Recursively enumerable languages

- **Recursively enumerable language**
  - Turing machine
  - Most general computational model

Alan Turing

- **Born on 23 June 1912 in London**
- **Studied computer science, mathematics, philosophy, physics and biology**
- **As a student, in 1936, he published the work "*On Computable Numbers*" in which he presented the concept of the so-called Turing machine**

Alan Turing

- During the Second World War he worked as a cryptanalyst in the UK

- After the war, Turing worked at the National Physical Laboratory in London on the ACE (Automatic Computing Engine) project

- He later worked at the University of Manchester on the MADM (Manchester Automatic Digital Machine) project

Alan Turing

- **In 1951 he became a member of the Royal Society**
- **Died on 7 June 1954 in Wilmslow as a result of cyanide poisoning (alleged suicide)**

Lecture outline

4 RECURSIVELY ENUMERABLE LANGUAGES 126

4.1 TURING MACHINE (TM) 126

4.1.1 Simple Turing machine 126

4.1.2 Programming techniques for Turing machines 133

Simple Turing machine

Simple Turing machine

Finite automaton

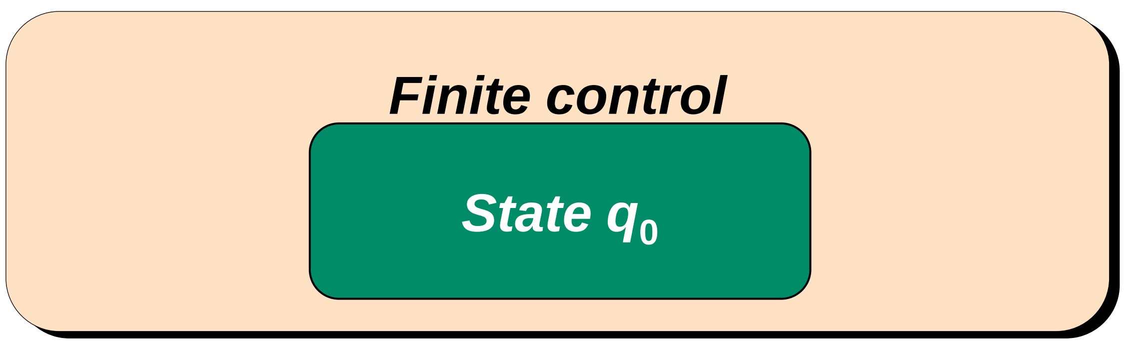
Simple Turing machine

Finite automaton

Finite control

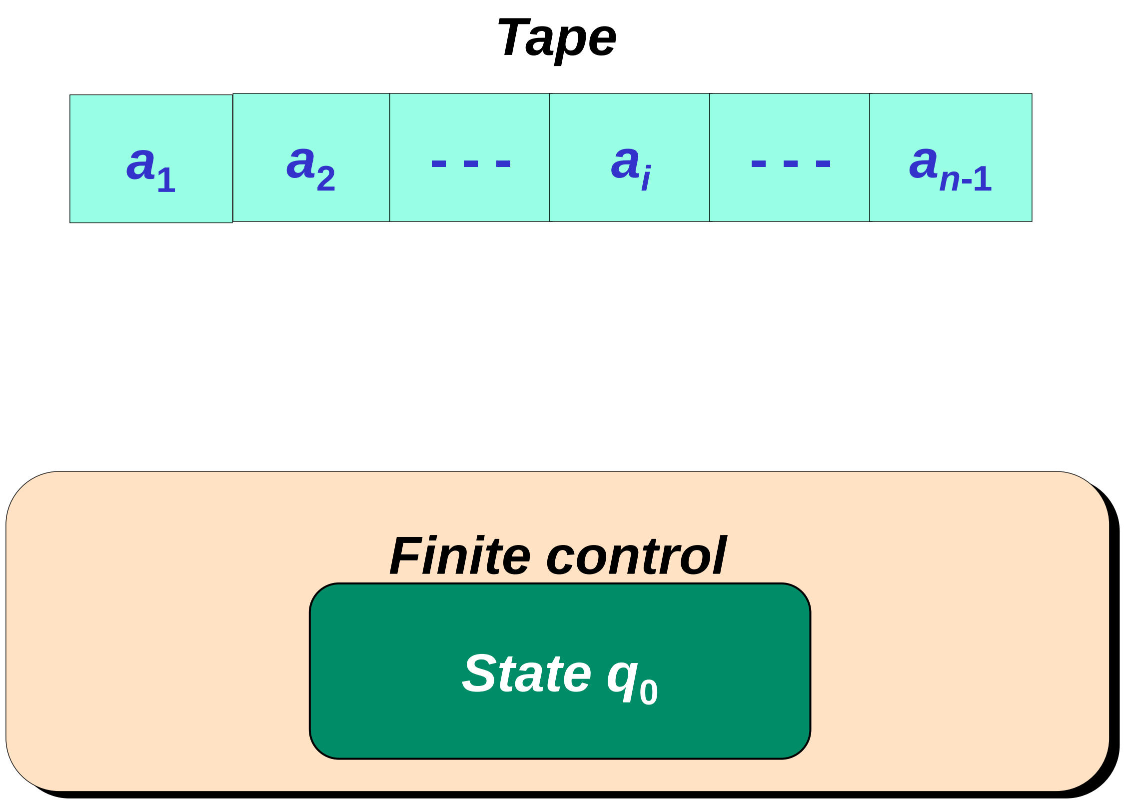
Simple Turing machine

Finite automaton

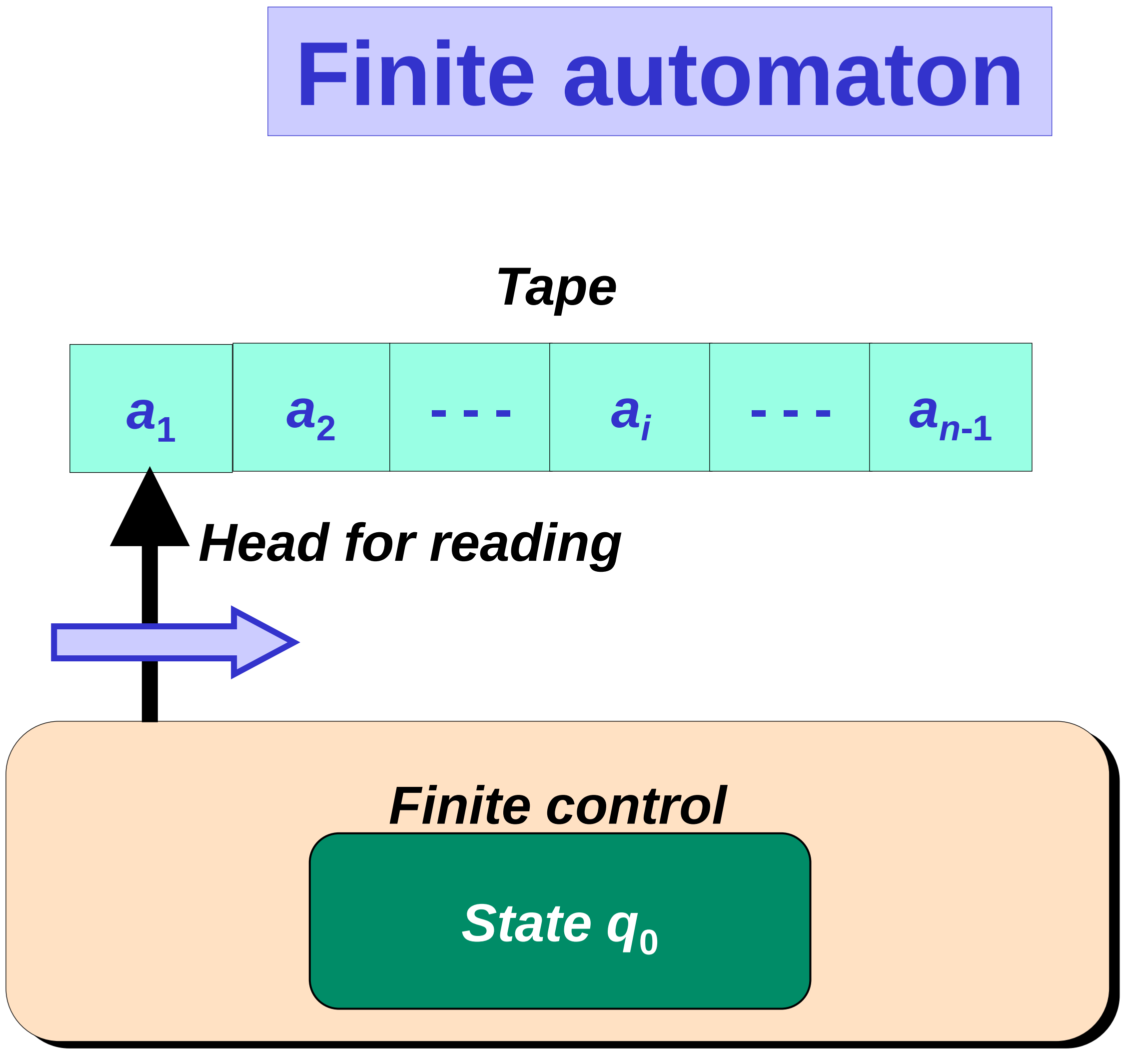


Simple Turing machine

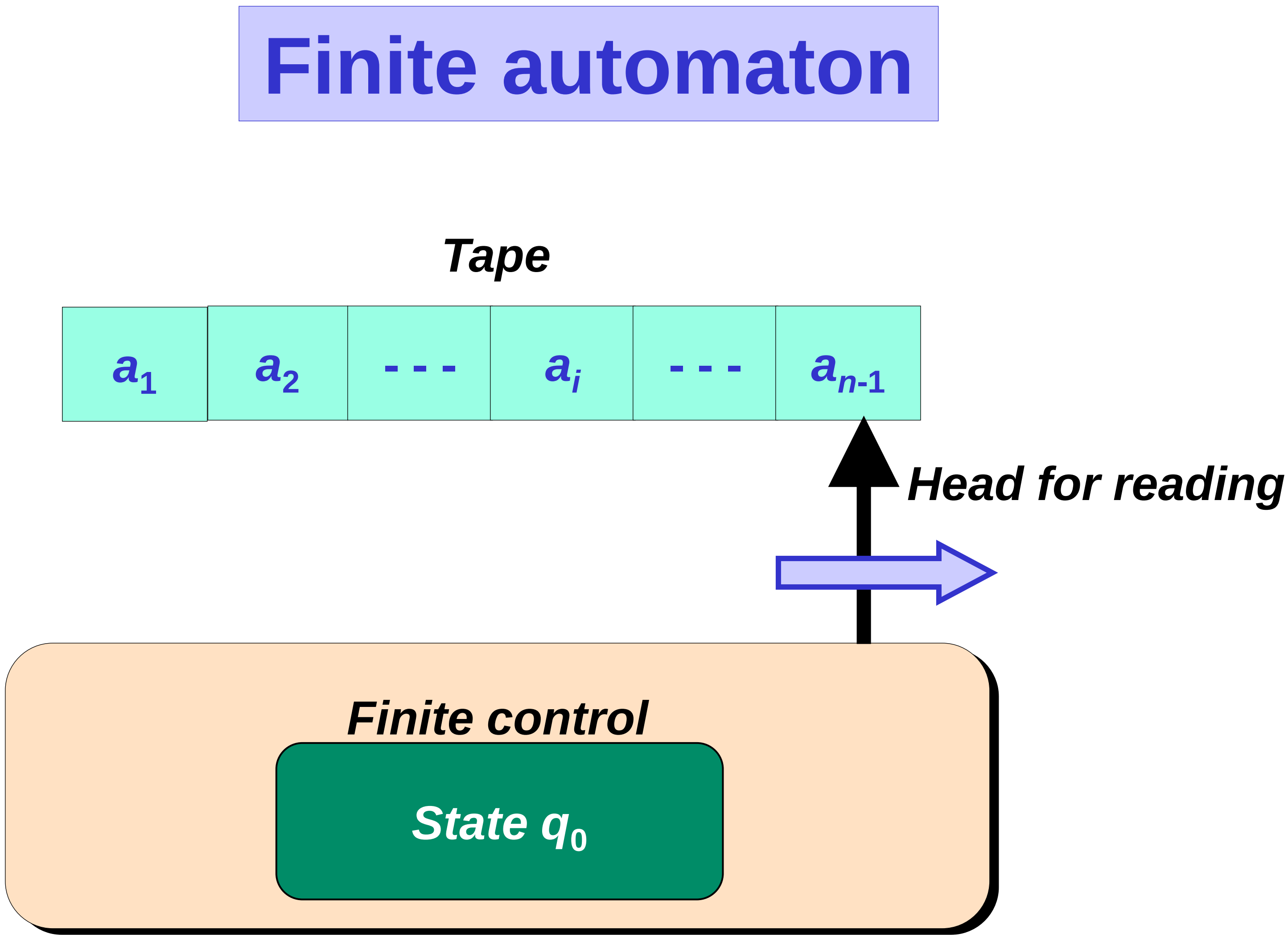
Finite automaton



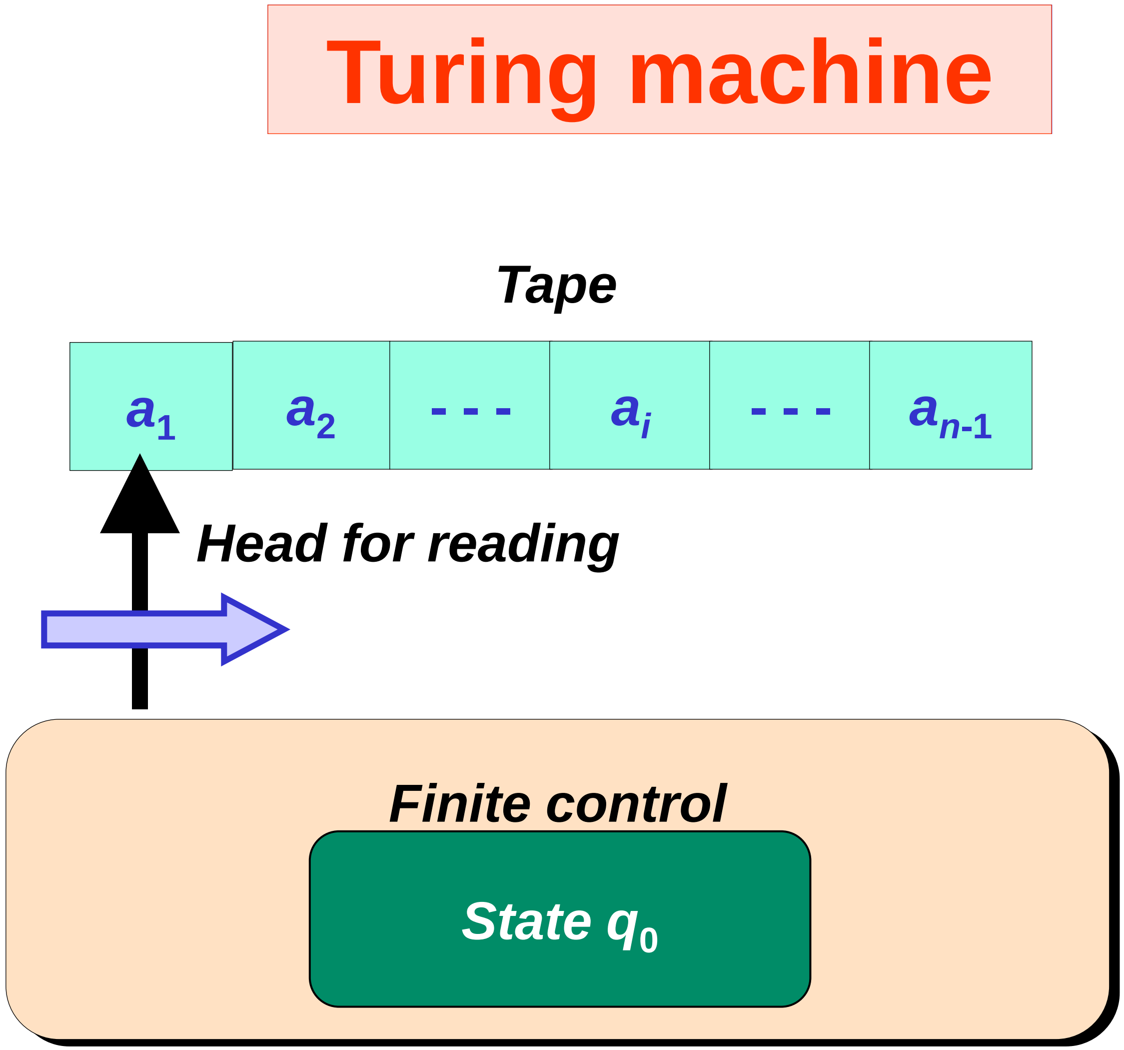
Simple Turing machine



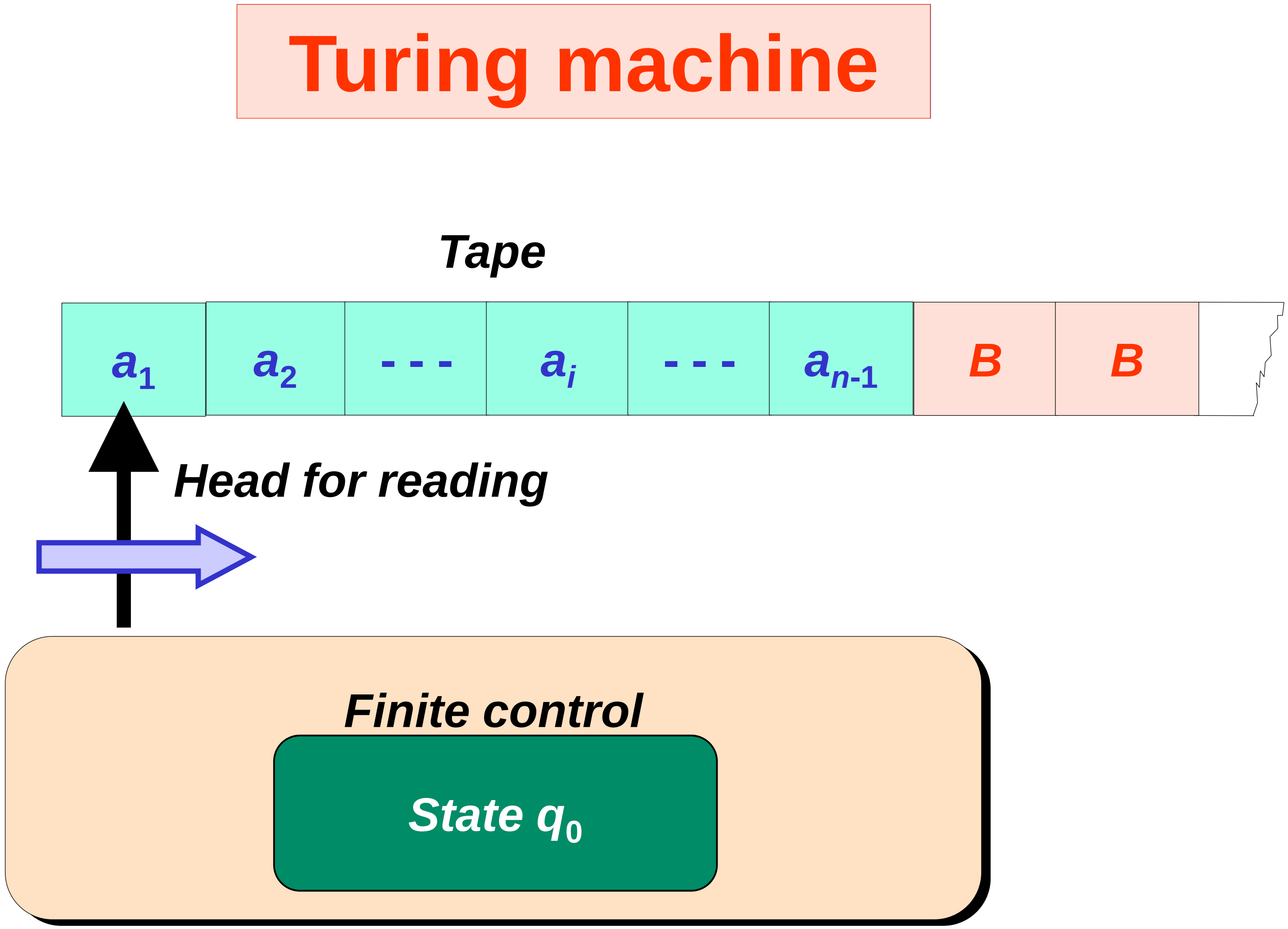
Simple Turing machine



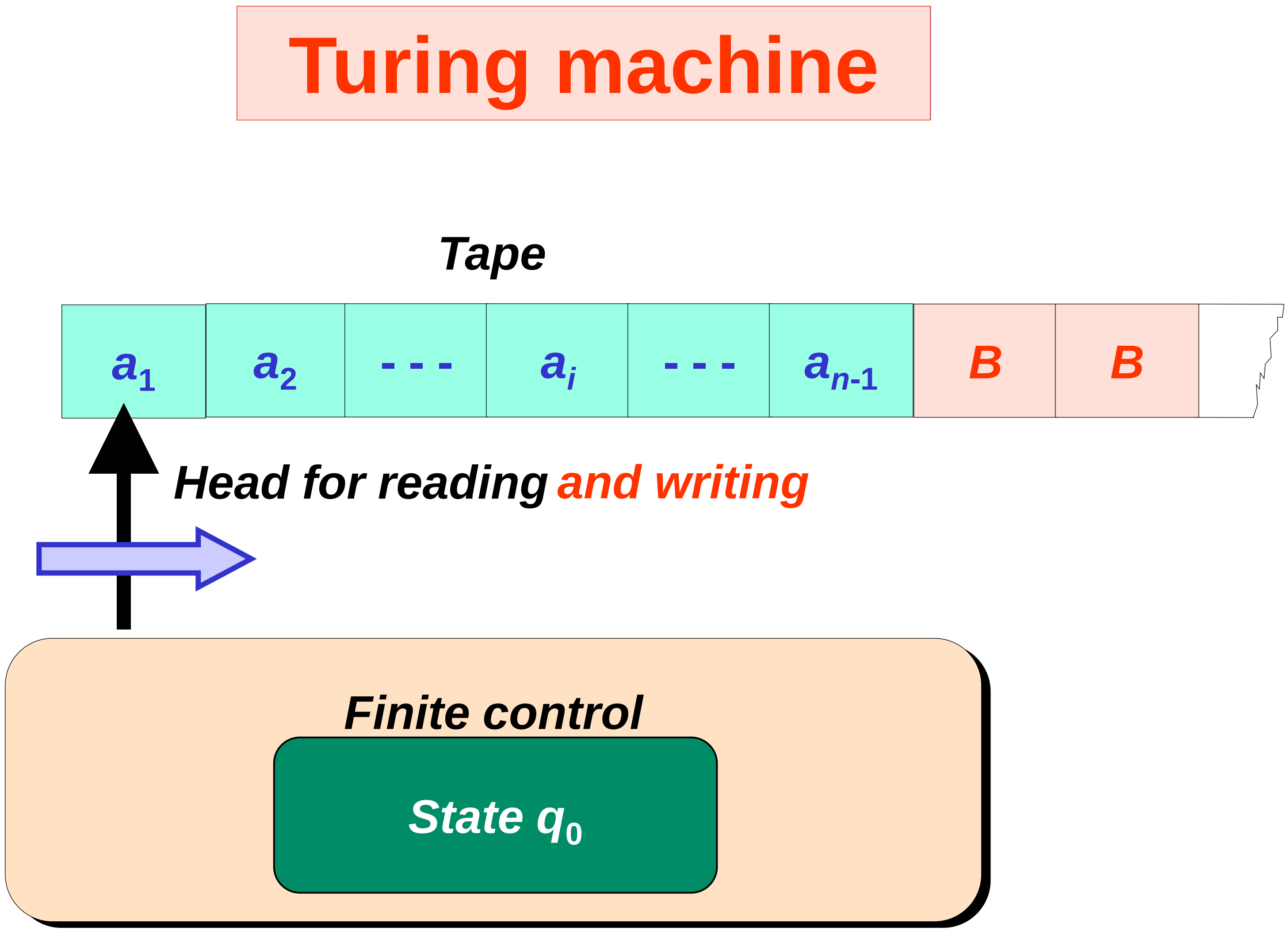
Simple Turing machine



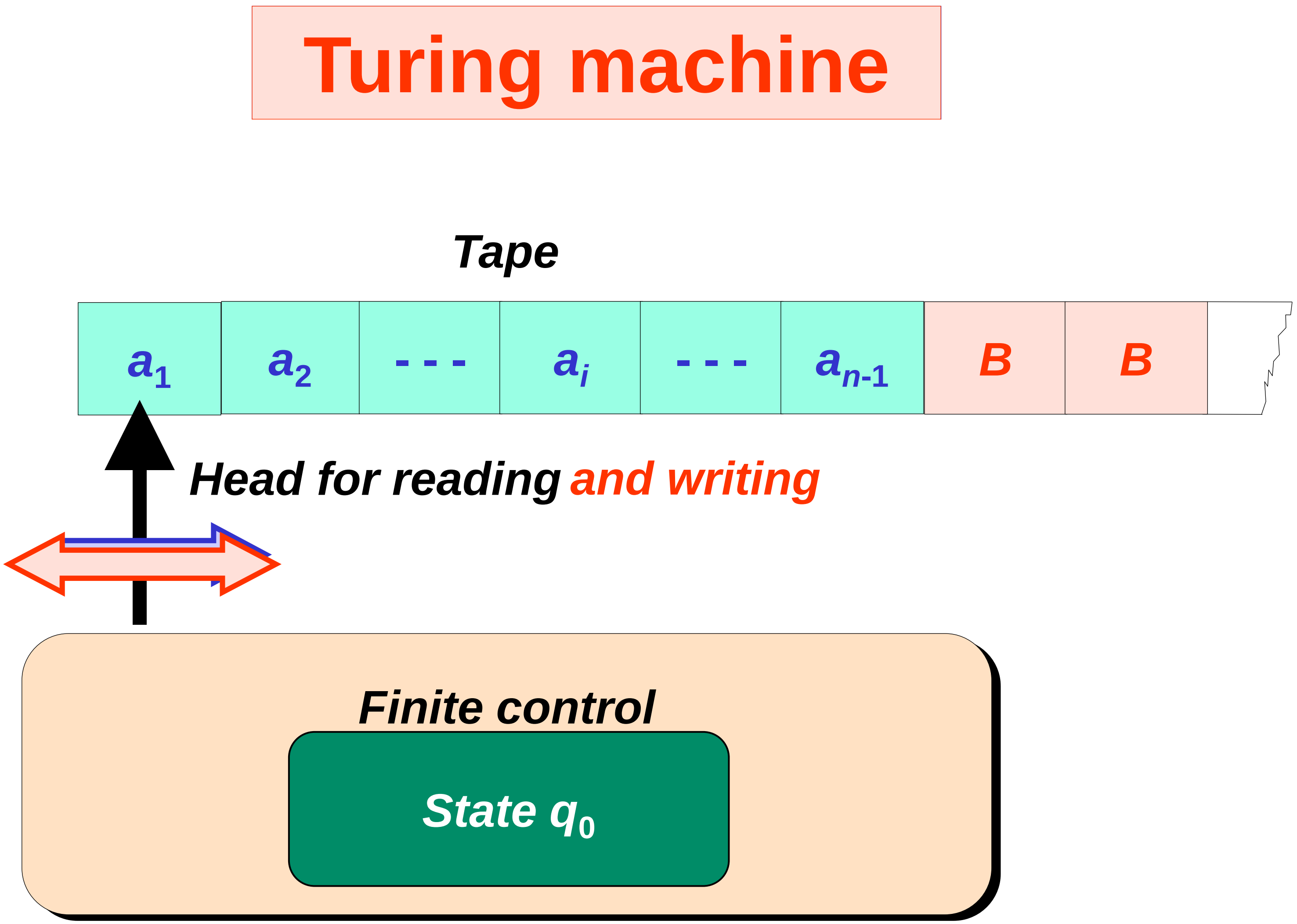
Simple Turing machine



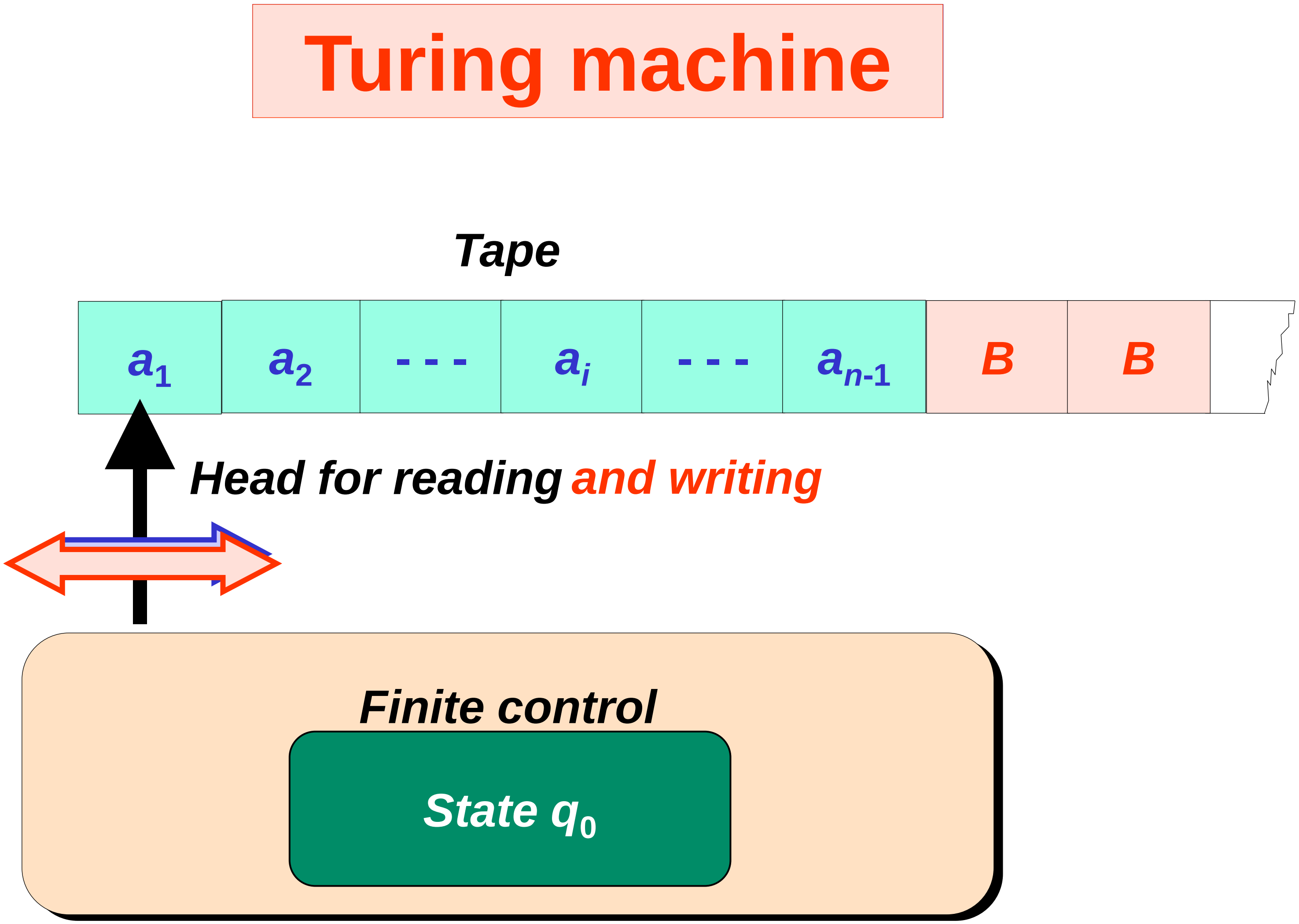
Simple Turing machine



Simple Turing machine



Simple Turing machine



Simple Turing machine

Simple Turing machine

- **Decision**

Simple Turing machine

- **Decision**
  - Input

Simple Turing machine

- **Decision**
  - Input
    1. **State**

Simple Turing machine

- **Decision**
  - Input
    1. **State**
    2. **Tape symbol**

Simple Turing machine

- **Decision**
  - Input
    1. **State**
    2. **Tape symbol**
  - Output

Simple Turing machine

- **Decision**
  - Input
    1. **State**
    2. **Tape symbol**
  - Output
    1. **New state**

Simple Turing machine

- **Decision**
  - Input
    1. **State**
    2. **Tape symbol**
  - Output
    1. **New state**
    2. **Symbol written on the tape**

Simple Turing machine

- **Decision**
  - Input
    1. **State**
    2. **Tape symbol**
  - Output
    1. **New state**
    2. **Symbol written on the tape**
    3. **Head movement direction (left or right)**

Simple Turing machine

Simple Turing machine

$$tm = (Q, \Sigma, \Gamma, \delta, q_0, B, F)$$

Simple Turing machine

$$tm = (Q, \Sigma, \Gamma, \delta, q_0, B, F)$$

Q - the finite set of states

Simple Turing machine

$$tm = (Q, \Sigma, \Gamma, \delta, q_0, B, F)$$

Q - the finite set of states

Γ - the complete set of tape symbols

Simple Turing machine

$$tm = (Q, \Sigma, \Gamma, \delta, q_0, B, F)$$

Q	- the finite set of states
Γ	- the complete set of tape symbols
$B \in \Gamma$	- the *blank* tape symbol

Simple Turing machine

$$tm = (Q, \Sigma, \Gamma, \delta, q_0, B, F)$$

Q	- the finite set of states
Γ	- the complete set of tape symbols
$B \in \Gamma$	- the *blank* tape symbol
$\Sigma \subseteq (\Gamma - \{ B \})$	- the finite set of input symbols

Simple Turing machine

$$tm = (Q, \Sigma, \Gamma, \delta, q_0, B, F)$$

Q	- **the finite set of states**
Γ	- **the complete set of tape symbols**
$B \in \Gamma$	- **the *blank* tape symbol**
$\Sigma \subseteq (\Gamma - \{ B \})$	- **the finite set of input symbols**
δ	- **the transition function**

Simple Turing machine

$$tm = (Q, \Sigma, \Gamma, \delta, q_0, B, F)$$

Q	- the finite set of states
Γ	- the complete set of tape symbols
$B \in \Gamma$	- the *blank* tape symbol
$\Sigma \subseteq (\Gamma - \{ B \})$	- the finite set of input symbols
δ	- the transition function

$$\delta : Q \times \Gamma \rightarrow Q \times \Gamma \times \{L, R\}$$

Simple Turing machine

$$tm = (Q, \Sigma, \Gamma, \delta, q_0, B, F)$$

Q	- the finite set of states
Γ	- the complete set of tape symbols
$B \in \Gamma$	- the *blank* tape symbol
$\Sigma \subseteq (\Gamma - \{B\})$	- the finite set of input symbols
δ	- the transition function
	$\delta : Q \times \Gamma \rightarrow Q \times \Gamma \times \{L, R\}$
$q_0 \in Q$	- the start state

Simple Turing machine

$$tm = (Q, \Sigma, \Gamma, \delta, q_0, B, F)$$

Q	- the finite set of states
Γ	- the complete set of tape symbols
$B \in \Gamma$	- the *blank* tape symbol
$\Sigma \subseteq (\Gamma - \{ B \})$	- the finite set of input symbols
δ	- the transition function
	$\delta : Q \times \Gamma \rightarrow Q \times \Gamma \times \{L, R\}$
$q_0 \in Q$	- the start state
$F \subseteq Q$	- the set of accepting states

Simple Turing machine

$$tm = (Q, \Sigma, \Gamma, \delta, q_0, B, F)$$

Q	- the finite set of states
Γ	- the complete set of tape symbols
$B \in \Gamma$	- the *blank* tape symbol
$\Sigma \subseteq (\Gamma - \{ B \})$	- the finite set of input symbols
δ	- the transition function
	$\delta : Q \times \Gamma \rightarrow Q \times \Gamma \times \{L, R\}$
$q_0 \in Q$	- the start state
$F \subseteq Q$	- the set of accepting states

$$\delta(q, V) = (p, Z, W)$$

Simple Turing machine

$$tm = (Q, \Sigma, \Gamma, \delta, q_0, B, F)$$

Q	- the finite set of states
Γ	- the complete set of tape symbols
$B \in \Gamma$	- the *blank* tape symbol
$\Sigma \subseteq (\Gamma - \{ B \})$	- the finite set of input symbols
δ	- the transition function
	$\delta : Q \times \Gamma \rightarrow Q \times \Gamma \times \{L, R\}$
$q_0 \in Q$	- the start state
$F \subseteq Q$	- the set of accepting states

$$\delta(q, V) = (p, Z, W)$$

$$q \in Q$$

Simple Turing machine

$$tm = (Q, \Sigma, \Gamma, \delta, q_0, B, F)$$

Q	- the finite set of states
Γ	- the complete set of tape symbols
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$q_0 \in Q$	- the start state
$F \subseteq Q$	- the set of accepting states

$$\delta(q, V) = (p, Z, W)$$

$$V \in \Gamma$$

Simple Turing machine

$$tm = (Q, \Sigma, \Gamma, \delta, q_0, B, F)$$

Q	- the finite set of states
Γ	- the complete set of tape symbols
$B \in \Gamma$	- the *blank* tape symbol
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	$\delta : Q \times \Gamma \rightarrow Q \times \Gamma \times \{L, R\}$
$q_0 \in Q$	- the start state
$F \subseteq Q$	- the set of accepting states

$$\delta(q, V) = (p, Z, W)$$

$$p \in Q$$

Simple Turing machine

$$tm = (Q, \Sigma, \Gamma, \delta, q_0, B, F)$$

Q	- the finite set of states
Γ	- the complete set of tape symbols
$B \in \Gamma$	- the *blank* tape symbol
$\Sigma \subseteq (\Gamma - \{ B \})$	- the finite set of input symbols
δ	- the transition function
	$\delta : Q \times \Gamma \to Q \times \Gamma \times \{L, R\}$
$q_0 \in Q$	- the start state
$F \subseteq Q$	- the set of accepting states

$$\delta(q, V) = (p, Z, W)$$

$$Z \in \Gamma$$

Simple Turing machine

$$tm = (Q, \Sigma, \Gamma, \delta, q_0, B, F)$$

Q	- the finite set of states
Γ	- the complete set of tape symbols
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	$\delta : Q \times \Gamma \rightarrow Q \times \Gamma \times \{L, R\}$
$q_0 \in Q$	- the start state
$F \subseteq Q$	- the set of accepting states

$$\delta(q, V) = (p, Z, W)$$

$$W \in \{L, R\}$$

Simple Turing machine

$$tm = (Q, \Sigma, \Gamma, \delta, q_0, B, F)$$

Q	- the finite set of states
Γ	- the complete set of tape symbols
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$q_0 \in Q$	- the start state
$F \subseteq Q$	- the set of accepting states

$$\delta(q, V) = (p, Z, W)$$

Simple Turing machine

Simple Turing machine

TM M = $(\{q_0, q_1, q_2, q_3, q_4\}, \{0, 1\}, \{0, 1, X, Y, B\}, \delta, q_0, B, \{q_4\})$

Simple Turing machine

TM M = $(\{q_0, q_1, q_2, q_3, q_4\}, \{0, 1\}, \{0, 1, X, Y, B\}, \delta, q_0, B, \{q_4\})$

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

Simple Turing machine

TM $M = (\{q_0, q_1, q_2, q_3, q_4\}, \{0, 1\}, \{0, 1, X, Y, B\}, \delta, q_0, B, \{q_4\})$

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8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	*B*	*B*

Simple Turing machine

TM $M = (\{q_0, q_1, q_2, q_3, q_4\}, \{0, 1\}, \{0, 1, X, Y, B\}, \delta, q_0, B, \{q_4\})$

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0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	*B*	*B*

Simple Turing machine

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9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	*B*	*B*

Simple Turing machine

TM M = $(\{q_0, q_1, q_2, q_3, q_4\}, \{0, 1\}, \{0, 1, X, Y, B\}, \delta, q_0, B, \{q_4\})$

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10. $\delta(q_3,B)=(q_4,B,R)$

X	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	*B*	*B*

Simple Turing machine

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10. $\delta(q_3,B)=(q_4,B,R)$

X	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	*B*	*B*

Simple Turing machine

TM $M = (\{q_0, q_1, q_2, q_3, q_4\}, \{0, 1\}, \{0, 1, X, Y, B\}, \delta, q_0, B, \{q_4\})$

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9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	0	0	0	0	0	0	0	*Y*	1	1	1	1	1	1	1	*B*	*B*

Simple Turing machine

TM M = $(\{q_0, q_1, q_2, q_3, q_4\}, \{0, 1\}, \{0, 1, X, Y, B\}, \delta, q_0, B, \{q_4\})$

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9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	0	0	0	0	0	0	0	*Y*	1	1	1	1	1	1	1	*B*	*B*

Simple Turing machine

TM $M = (\{q_0, q_1, q_2, q_3, q_4\}, \{0, 1\}, \{0, 1, X, Y, B\}, \delta, q_0, B, \{q_4\})$

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10. $\delta(q_3,B)=(q_4,B,R)$

X	0	0	0	0	0	0	0	*Y*	1	1	1	1	1	1	1	*B*	*B*

Simple Turing machine

TM M = ($\{q_0, q_1, q_2, q_3, q_4\}, \{0, 1\}, \{0, 1, X, Y, B\}, \delta, q_0, B, \{q_4\}$)

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9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	0	0	0	0	0	0	0	*Y*	1	1	1	1	1	1	1	*B*	*B*

Simple Turing machine

TM M = $(\{q_0, q_1, q_2, q_3, q_4\}, \{0, 1\}, \{0, 1, X, Y, B\}, \delta, q_0, B, \{q_4\})$

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9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	0	0	0	0	0	0	0	*Y*	1	1	1	1	1	1	1	*B*	*B*

Simple Turing machine

TM $M = (\{q_0, q_1, q_2, q_3, q_4\}, \{0, 1\}, \{0, 1, X, Y, B\}, \delta, q_0, B, \{q_4\})$

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	*X*	0	0	0	0	0	0	*Y*	1	1	1	1	1	1	1	*B*	*B*

Simple Turing machine

TM $M = (\{q_0, q_1, q_2, q_3, q_4\}, \{0, 1\}, \{0, 1, X, Y, B\}, \delta, q_0, B, \{q_4\})$

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	*X*	0	0	0	0	0	0	*Y*	1	1	1	1	1	1	1	*B*	*B*

Simple Turing machine

TM $M = (\{q_0, q_1, q_2, q_3, q_4\}, \{0, 1\}, \{0, 1, X, Y, B\}, \delta, q_0, B, \{q_4\})$

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	*X*	0	0	0	0	0	0	*Y*	*Y*	1	1	1	1	1	1	*B*	*B*

Simple Turing machine

TM $M = (\{q_0, q_1, q_2, q_3, q_4\}, \{0, 1\}, \{0, 1, X, Y, B\}, \delta, q_0, B, \{q_4\})$

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	*X*	0	0	0	0	0	0	*Y*	*Y*	1	1	1	1	1	1	*B*	*B*

Simple Turing machine

TM $M = (\{q_0, q_1, q_2, q_3, q_4\}, \{0, 1\}, \{0, 1, X, Y, B\}, \delta, q_0, B, \{q_4\})$

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	*X*	0	0	0	0	0	0	*Y*	*Y*	1	1	1	1	1	1	*B*	*B*

Simple Turing machine

TM $M = (\{q_0, q_1, q_2, q_3, q_4\}, \{0, 1\}, \{0, 1, X, Y, B\}, \delta, q_0, B, \{q_4\})$

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	*X*	*X*	*X*	*X*	*X*	*X*	*X*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*B*	*B*

Simple Turing machine

TM M = $(\{q_0, q_1, q_2, q_3, q_4\}, \{0, 1\}, \{0, 1, X, Y, B\}, \delta, q_0, B, \{q_4\})$

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	*X*	*X*	*X*	*X*	*X*	*X*	*X*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*B*	*B*

Simple Turing machine

TM $M = (\{q_0, q_1, q_2, q_3, q_4\}, \{0, 1\}, \{0, 1, X, Y, B\}, \delta, q_0, B, \{q_4\})$

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	*X*	*X*	*X*	*X*	*X*	*X*	*X*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*B*	*B*

Simple Turing machine

TM $M = (\{q_0, q_1, q_2, q_3, q_4\}, \{0, 1\}, \{0, 1, X, Y, B\}, \delta, q_0, B, \{q_4\})$

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	*X*	*X*	*X*	*X*	*X*	*X*	*X*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*B*	*B*

Simple Turing machine

TM $M = (\{q_0, q_1, q_2, q_3, q_4\}, \{0, 1\}, \{0, 1, X, Y, B\}, \delta, q_0, B, \{q_4\})$

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	*X*	*X*	*X*	*X*	*X*	*X*	*X*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*B*	*B*

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

q_0	0	0	1	1	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

q_0	0	0	1	1	*B*	*B*	*B*

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$

2. $\delta(q_1,0)=(q_1,0,R)$

3. $\delta(q_2,0)=(q_2,0,L)$

4. $\delta(q_1,1)=(q_2,Y,L)$

5. $\delta(q_2,X)=(q_0,X,R)$

6. $\delta(q_0,Y)=(q_3,Y,R)$

7. $\delta(q_1,Y)=(q_1,Y,R)$

8. $\delta(q_2,Y)=(q_2,Y,L)$

9. $\delta(q_3,Y)=(q_3,Y,R)$

10. $\delta(q_3,B)=(q_4,B,R)$

q_0

0	0	1	1	*B*	*B*	*B*

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$

2. $\delta(q_1,0)=(q_1,0,R)$ **4.** $\delta(q_1,1)=(q_2,Y,L)$

3. $\delta(q_2,0)=(q_2,0,L)$ **5.** $\delta(q_2,X)=(q_0,X,R)$

6. $\delta(q_0,Y)=(q_3,Y,R)$

7. $\delta(q_1,Y)=(q_1,Y,R)$

8. $\delta(q_2,Y)=(q_2,Y,L)$

9. $\delta(q_3,Y)=(q_3,Y,R)$ **10.** $\delta(q_3,B)=(q_4,B,R)$

X	q_1	0	1	1	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	q_1 0	1	1	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X 0 q_1 1 1 B B B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	0	q_1	1	1	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	q_2	0	Y	1	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	q_2	0	Y	1	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
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5. $\delta(q_2,X)=(q_0,X,R)$
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8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

q_2	X	0	Y	1	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
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8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

q_2	*X*	0	*Y*	1	*B*	*B*	*B*

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
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9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	q_0	0	Y	1	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
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9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	q_0	0	Y	1	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
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9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	X	q_1	Y	1	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
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8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	X	q_1	Y	1	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
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8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	X	Y	q_1	1	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	X	Y	q_1	1	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	*X*	q_2	*Y*	*Y*	*B*	*B*	*B*

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
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7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	X	Y	Y	B	B	B

q_2

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	q_2	X	Y	Y	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	q_2	*X*	*Y*	*Y*	*B*	*B*	*B*

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
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7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	*X*	q_0	*Y*	*Y*	**B**	**B**	**B**

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	X	q_0	Y	Y	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
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8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	X	Y	q_3	Y	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	*X*	*Y*	q_3	*Y*	*B*	*B*	*B*

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
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8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	X	Y	Y	q_3	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
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7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	X	Y	Y	q_3	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
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5. $\delta(q_2,X)=(q_0,X,R)$
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7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	X	Y	Y	B	q_4	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

q_0	0	0	1	B	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
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5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	q_1	0	1	B	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
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8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	0	q_1	1	B	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
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8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	q_2	0	Y	B	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
4. $\delta(q_1,1)=(q_2,Y,L)$
5. $\delta(q_2,X)=(q_0,X,R)$
6. $\delta(q_0,Y)=(q_3,Y,R)$
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8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

q_2	X	0	Y	B	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
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8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	q_0	0	Y	B	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
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9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	X	q_1	Y	B	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
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8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	*X*	*Y*	q_1	*B*	*B*	*B*	*B*

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
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8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

q_0	0	1	1	B	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
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8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X q_1	1	1	*B*	*B*	*B*	*B*

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
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8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

q_2	X	Y	1	B	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
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8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	q_0	Y	1	B	B	B	B

Simple Turing machine

1. $\delta(q_0,0)=(q_1,X,R)$
2. $\delta(q_1,0)=(q_1,0,R)$
3. $\delta(q_2,0)=(q_2,0,L)$
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6. $\delta(q_0,Y)=(q_3,Y,R)$
7. $\delta(q_1,Y)=(q_1,Y,R)$
8. $\delta(q_2,Y)=(q_2,Y,L)$
9. $\delta(q_3,Y)=(q_3,Y,R)$
10. $\delta(q_3,B)=(q_4,B,R)$

X	Y	q_3	1	B	B	B	B

The language of Turing machine

The language of Turing machine

TM configuration:

The language of Turing machine

TM configuration: α_1

The language of Turing machine

TM configuration: $\boxed{\alpha_1}$ q

The language of Turing machine

TM configuration: $\alpha_1 \; q \; \alpha_2$

The language of Turing machine

TM configuration: $\alpha_1 \; q \; \alpha_2$

$\delta(q, X_i) = (p, Y, L)$:

The language of Turing machine

TM configuration: $\alpha_1 \; q \; \alpha_2$

$\delta(q, X_i) = (p, Y, L)$:

$X_1 X_2 - - - X_{i-2} X_{i-1} \; q \; X_i X_{i+1} - - - X_n$

The language of Turing machine

TM configuration: $\alpha_1 \; q \; \alpha_2$

$\delta(q, X_i) = (p, Y, L)$:

$X_1 X_2 \,-\,-\,-\, X_{i-2} X_{i-1} \; q \; X_i X_{i+1} \,-\,-\,-\, X_n \succ$

The language of Turing machine

TM configuration: $\boxed{\alpha_1}\ q\ \boxed{\alpha_2}$

$\delta(q, X_i) = (p, Y, L)$:

$$X_1 X_2 \text{ - - - } X_{i-2} X_{i-1}\, q\, X_i X_{i+1} \text{ - - - } X_n \succ X_1 X_2 \text{ - - - } X_{i-2} \quad X_{i-1}\, q\, X_i X_{i+1} \text{ - - - } X_n$$

The language of Turing machine

TM configuration: $\alpha_1 \; q \; \alpha_2$

$\delta(q, X_i) = (p, Y, L)$:

$$X_1 X_2 \text{ - - - } X_{i-2} X_{i-1} \, q \, X_i X_{i+1} \text{ - - - } X_n \succ X_1 X_2 \text{ - - - } X_{i-2} \, p \, X_{i-1} \boxed{Y} X_{i+1} \text{ - - - } X_n$$

The language of Turing machine

TM configuration: $\boxed{\alpha_1}\ q\ \boxed{\alpha_2}$

$\delta(q, X_i) = (p, Y, L)$:

$$X_1 X_2 - - - X_{i-2} X_{i-1}\, q\, X_i X_{i+1} - - - X_n \succ X_1 X_2 - - - X_{i-2}\, p\, X_{i-1} \boxed{Y} X_{i+1} - - - X_n$$

$\delta(q, X_i) = (p, Y, R)$:

The language of Turing machine

TM configuration: $\boxed{\alpha_1}\ q\ \boxed{\alpha_2}$

$\delta(q, X_i) = (p, Y, L)$:

$X_1\, X_2 - - - X_{i-2}\, X_{i-1}\, q\, X_i\, X_{i+1} - - - X_n \succ X_1\, X_2 - - - X_{i-2}\, p\, X_{i-1}\, \boxed{Y}\, X_{i+1} - - - X_n$

$\delta(q, X_i) = (p, Y, R)$:

$X_1\, X_2 - - - X_{i-2}\, X_{i-1}\, q\, X_i\, X_{i+1} - - - X_n$

The language of Turing machine

TM configuration: $\boxed{\alpha_1}\ q\ \boxed{\alpha_2}$

$\delta(q, X_i) = (p, Y, L)$:

$$X_1\, X_2 - - - X_{i-2}\, X_{i-1}\, q\, X_i\, X_{i+1} - - - X_n \succ X_1\, X_2 - - - X_{i-2}\, p\, X_{i-1}\, \boxed{Y}\, X_{i+1} - - - X_n$$

$\delta(q, X_i) = (p, Y, R)$:

$$X_1\, X_2 - - - X_{i-2}\, X_{i-1}\, q\, X_i\, X_{i+1} - - - X_n \succ$$

The language of Turing machine

TM configuration: $\boxed{\alpha_1}\ q\ \boxed{\alpha_2}$

$\delta(q, X_i) = (p, Y, L)$:

$$X_1 X_2 - - - X_{i-2} X_{i-1}\, q\, X_i X_{i+1} - - - X_n \succ X_1 X_2 - - - X_{i-2}\, p\, X_{i-1} \boxed{Y} X_{i+1} - - - X_n$$

$\delta(q, X_i) = (p, Y, R)$:

$$X_1 X_2 - - - X_{i-2} X_{i-1}\, q\, X_i X_{i+1} - - - X_n \succ X_1 X_2 - - - X_{i-2} X_{i-1}\, q\, X_i \quad X_{i+1} - - - X_n$$

The language of Turing machine

TM configuration: $\boxed{\alpha_1}\; q \;\boxed{\alpha_2}$

$\delta(q, X_i) = (p, Y, L)$:

$$X_1\, X_2 \,\text{- - -}\, X_{i-2}\, X_{i-1}\, q\, X_i\, X_{i+1} \,\text{- - -}\, X_n \succ X_1\, X_2 \,\text{- - -}\, X_{i-2}\, p\, X_{i-1}\, \boxed{Y}\, X_{i+1} \,\text{- - -}\, X_n$$

$\delta(q, X_i) = (p, Y, R)$:

$$X_1\, X_2 \,\text{- - -}\, X_{i-2}\, X_{i-1}\, q\, X_i\, X_{i+1} \,\text{- - -}\, X_n \succ X_1\, X_2 \,\text{- - -}\, X_{i-2}\, X_{i-1}\, \boxed{Y}\, p\, X_{i+1} \,\text{- - -}\, X_n$$

The language of Turing machine

The language of Turing machine

$q_0\,0\,0\,1\,1 \succ X\,q_1\,0\,1\,1 \succ X\,0\,q_1\,1\,1 \succ X\,q_2\,0\,Y\,1 \succ$

$q_2\,X\,0\,Y\,1 \succ X\,q_0\,0\,Y\,1 \succ X\,X\,q_1\,Y\,1 \succ X\,X\,Y\,q_1\,1 \succ$

$X\,X\,q_2\,Y\,Y \succ X\,q_2\,X\,Y\,Y \succ X\,X\,q_0\,Y\,Y \succ X\,X\,Y\,q_3\,Y \succ$

$X\,X\,Y\,Y\,q_3 \succ X\,X\,Y\,Y\,B\,q_4$

The language of Turing machine

$q_0\,0\,0\,1\,1 \quad \succ \quad X\,q_1\,0\,1\,1 \quad \succ \quad X\,0\,q_1\,1\,1 \quad \succ \quad X\,q_2\,0\,Y\,1 \quad \succ$

$q_2\,X\,0\,Y\,1 \quad \succ \quad X\,q_0\,0\,Y\,1 \quad \succ \quad X\,X\,q_1\,Y\,1 \quad \succ \quad X\,X\,Y\,q_1\,1 \quad \succ$

$X\,X\,q_2\,Y\,Y \quad \succ \quad X\,q_2\,X\,Y\,Y \quad \succ \quad X\,X\,q_0\,Y\,Y \quad \succ \quad X\,X\,Y\,q_3\,Y \quad \succ$

$X\,X\,Y\,Y\,q_3 \quad \succ \quad X\,X\,Y\,Y\,B\,q_4$

$q_0\,0\,0\,1\,1$

The language of Turing machine

$q_0 0011 \succ X q_1 011 \succ X 0 q_1 11 \succ X q_2 0 Y 1 \succ$

$q_2 X 0 Y 1 \succ X q_0 0 Y 1 \succ X X q_1 Y 1 \succ X X Y q_1 1 \succ$

$X X q_2 Y Y \succ X q_2 X Y Y \succ X X q_0 Y Y \succ X X Y q_3 Y \succ$

$X X Y Y q_3 \succ X X Y Y B q_4$

$q_0 0011 \overset{*}{\succ}$

The language of Turing machine

$q_0\,0\,0\,1\,1 \succ X\,q_1\,0\,1\,1 \succ X\,0\,q_1\,1\,1 \succ X\,q_2\,0\,Y\,1 \succ$

$q_2\,X\,0\,Y\,1 \succ X\,q_0\,0\,Y\,1 \succ X\,X\,q_1\,Y\,1 \succ X\,X\,Y\,q_1\,1 \succ$

$X\,X\,q_2\,Y\,Y \succ X\,q_2\,X\,Y\,Y \succ X\,X\,q_0\,Y\,Y \succ X\,X\,Y\,q_3\,Y \succ$

$X\,X\,Y\,Y\,q_3 \succ X\,X\,Y\,Y\,B\,q_4$

$$q_0\,0\,0\,1\,1 \overset{*}{\succ} X\,X\,Y\,Y\,B\,q_4$$

The language of Turing machine

$q_0 0011 \succ X q_1 011 \succ X 0 q_1 11 \succ X q_2 0Y1 \succ$
$q_2 X 0Y1 \succ X q_0 0Y1 \succ XX q_1 Y1 \succ XXY q_1 1 \succ$
$XX q_2 YY \succ X q_2 XYY \succ XX q_0 YY \succ XXY q_3 Y \succ$
$XXYY q_3 \succ XXYYB q_4$

$$q_0 0011 \overset{*}{\succ} XXYYB q_4$$

$q_0 0011$

The language of Turing machine

$q_0\,0\,0\,1\,1 \succ X\,q_1\,0\,1\,1 \succ X\,0\,q_1\,1\,1 \succ X\,q_2\,0\,Y\,1 \succ$
$q_2\,X\,0\,Y\,1 \succ X\,q_0\,0\,Y\,1 \succ X\,X\,q_1\,Y\,1 \succ X\,X\,Y\,q_1\,1 \succ$
$X\,X\,q_2\,Y\,Y \succ X\,q_2\,X\,Y\,Y \succ X\,X\,q_0\,Y\,Y \succ X\,X\,Y\,q_3\,Y \succ$
$X\,X\,Y\,Y\,q_3 \succ X\,X\,Y\,Y\,B\,q_4$

$$q_0\,0\,0\,1\,1 \overset{*}{\succ} X\,X\,Y\,Y\,B\,q_4$$

$$q_0\,0\,0\,1\,1 \overset{13}{\succ}$$

The language of Turing machine

$q_0 0011 \succ X q_1 011 \succ X 0 q_1 11 \succ X q_2 0 Y 1 \succ$

$q_2 X 0 Y 1 \succ X q_0 0 Y 1 \succ X X q_1 Y 1 \succ X X Y q_1 1 \succ$

$X X q_2 Y Y \succ X q_2 X Y Y \succ X X q_0 Y Y \succ X X Y q_3 Y \succ$

$X X Y Y q_3 \succ X X Y Y B q_4$

$$q_0 0011 \overset{*}{\succeq} X X Y Y B q_4$$

$$q_0 0011 \overset{13}{\succeq} X X Y Y B q_4$$

The language of Turing machine

$$q_0 0011 \succ X q_1 011 \succ X0 q_1 11 \succ X q_2 0Y1 \succ$$
$$q_2 X0Y1 \succ X q_0 0Y1 \succ XX q_1 Y1 \succ XXY q_1 1 \succ$$
$$XX q_2 YY \succ X q_2 XYY \succ XX q_0 YY \succ XXY q_3 Y \succ$$
$$XXYY q_3 \succ XXYYB q_4$$

$$q_0 0011 \overset{*}{\succeq} XXYYB q_4$$

$$q_0 0011 \overset{13}{\succeq} XXYYB q_4$$

$$q_0 0011$$

The language of Turing machine

$$q_0 0 0 1 1 \succ X q_1 0 1 1 \succ X 0 q_1 1 1 \succ X q_2 0 Y 1 \succ$$
$$q_2 X 0 Y 1 \succ X q_0 0 Y 1 \succ X X q_1 Y 1 \succ X X Y q_1 1 \succ$$
$$X X q_2 Y Y \succ X q_2 X Y Y \succ X X q_0 Y Y \succ X X Y q_3 Y \succ$$
$$X X Y Y q_3 \succ X X Y Y B q_4$$

$$q_0 0 0 1 1 \overset{*}{\succ} X X Y Y B q_4$$

$$q_0 0 0 1 1 \overset{13}{\succ} X X Y Y B q_4$$

$$q_0 0 0 1 1 \overset{13}{\underset{M}{\succ}}$$

The language of Turing machine

$$q_0 0 0 1 1 \succ X q_1 0 1 1 \succ X 0 q_1 1 1 \succ X q_2 0 Y 1 \succ$$
$$q_2 X 0 Y 1 \succ X q_0 0 Y 1 \succ X X q_1 Y 1 \succ X X Y q_1 1 \succ$$
$$X X q_2 Y Y \succ X q_2 X Y Y \succ X X q_0 Y Y \succ X X Y q_3 Y \succ$$
$$X X Y Y q_3 \succ X X Y Y B q_4$$

$$q_0 0 0 1 1 \overset{*}{\succ} X X Y Y B q_4$$

$$q_0 0 0 1 1 \overset{13}{\succ} X X Y Y B q_4$$

$$q_0 0 0 1 1 \overset{13}{\underset{M}{\succ}} X X Y Y B q_4$$

The language of Turing machine

The language of Turing machine

TM $M = (Q, \Sigma, \Gamma, \delta, q_0, B, F)$ accepts the language:

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and $q_0 w$

The language of Turing machine

TM *M* = (Q, Σ, Γ, δ, q_0, B, F) accepts the language:

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$$\text{and } \ q_0 w \ \succ^{*}$$

The language of Turing machine

TM $M = (Q, \Sigma, \Gamma, \delta, q_0, B, F)$ accepts the language:

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The language of Turing machine

TM $M = (Q, \Sigma, \Gamma, \delta, q_0, B, F)$ accepts the language:

$$L(M) = \{\ w \ \mid \ w \in \Sigma^* \text{ and } q_0 w \overset{*}{\succ} \alpha_1 p \alpha_2,\ p \in F,\ \alpha_1 \text{ and } \alpha_2 \in \Gamma^*\}$$

The language of Turing machine

The language of Turing machine

- **Recursively enumerable languages**

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- **Recursively enumerable languages**
  - **Enumerable**
    - It is possible to construct a TM that outputs (enumerates) all strings from the language

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  - **String w is not in the language $L(M)$**
    - —It is possible that TM M never stops

The language of Turing machine

- **Recursively enumerable languages**
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  - **String $w \in L(M)$**
    - —TM *M* stops and accepts a string *w*
  - **String *w* is not in the language $L(M)$**
    - —It is possible that TM M never stops
- **Recursive languages**
    - —There exists a TM that halts on every given input

Computing functions with Turing machines

Computing functions with Turing machines

- **Integer $i \geq 0$**

Computing functions with Turing machines

- Integer $i \geq 0$
  - coded with a string 0^i

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- Integer $i \geq 0$
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- Integer function over k arguments $i1, i2, \ldots, ik$
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Computing functions with Turing machines

- Integer $i \geq 0$
  - coded with a string 0^i
- Integer function over k arguments $i1, i2, ..., ik$
  - coded with a string $0^{i1}\ 1\ 0^{i2}\ 1\ \text{---}\ 1\ 0^{ik}$
- TM halts and the tape contains 0^m
  - function result $f(i_1, i_2, ..., i_k) = m$

Computing functions with Turing machines

Computing functions with Turing machines

- **Partially recursive functions**
  - **TM might not halt**

Computing functions with Turing machines

- **Partially recursive functions**
  - **TM might not halt**
- **Total recursive functions**
  - **TM always halts for every input**

Computing functions with Turing machines

Computing functions with Turing machines

- **Function** $m \div n$

Computing functions with Turing machines

- **Function** $m \dot{-} n$
  - $m \geq n$
    - **Result of the function** $m \dot{-} n$ **is subtraction** $m - n$

Computing functions with Turing machines

- **Function** $m \dot{-} n$
  - $m \geq n$
    - Result of the function $m \dot{-} n$ is subtraction $m - n$
  - $m < n$
    - Result of the function $m \dot{-} n$ is **0**

Computing functions with Turing machines

Computing functions with Turing machines

$m \div n$

Computing functions with Turing machines

$m \div n$

Computing functions with Turing machines

m ÷ n

0^m **1** 0^n

Computing functions with Turing machines

m* ÷ *n

$0^m\ 1\ 0^n$

$$\delta(q_0, 0) = (q_1, B, R)$$

Computing functions with Turing machines

m **÷** ***n***

$0^m \, 1 \, 0^n$

$$\delta(q_0, 0) = (q_1, B, R)$$

$B \, 0^{m-1} \, 1 \, 0^n$

Computing functions with Turing machines

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Computing functions with Turing machines

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Computing functions with Turing machines

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Computing functions with Turing machines

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$BB\ 0^{m-2}\ 11\ \ 0^{n-1}$

Computing functions with Turing machines

$m \div n$

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$BB\ 0^{m-2}\ 11\ \ 0^{n-1}$

$BB\ 0^{m-2}\ 111\ \ 0^{n-2}$

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Computing functions with Turing machines

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$\delta(q_3, 0) = (q_3, 0, L)$
$\delta(q_3, B) = (q_0, B, R)$

$BB\ 0^{m-2}\ 11\ \ 0^{n-1}$

$BB\ 0^{m-2}\ 111\ \ 0^{n-2}$

$m > n$

Computing functions with Turing machines

$m \div n$

$0^m\ 1\ 0^n$

$$\delta(q_0, 0) = (q_1, B, R)$$

$B\ 0^{m-1}\ 1\ 0^n$

$$\delta(q_1, 0) = (q_1, 0, R)$$
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$BB\ 0^{m-2}\ 11\ \ 0^{n-1}$

$BB\ 0^{m-2}\ 111\ \ 0^{n-2}$

$m > n$

$B^{n+1}\ 0^{m-n-1}\ 1^{n+1}$

Computing functions with Turing machines

$m \div n$

$0^m\, 1\, 0^n$

$\delta(q_0, 0) = (q_1, B, R)$

$B\, 0^{m-1}\, 1\, 0^n$

$\delta(q_1, 0) = (q_1, 0, R)$
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$\delta(q_2, 0)=(q_3, 1, L)$
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$B\, 0^{m-1}\, 1\, 1\, 0^{n-1}$

$\delta(q_3, 1) = (q_3, 1, L)$
$\delta(q_3, 0) = (q_3, 0, L)$
$\delta(q_3, B) = (q_0, B, R)$

$BB\, 0^{m-2}\, 11\;\, 0^{n-1}$

$BB\, 0^{m-2}\, 111\;\, 0^{n-2}$

$m > n$

$B^{n+1}\, 0^{m-n-1}\, 1^{n+1}$

Computing functions with Turing machines

$m \div n$

$0^m\ 1\ 0^n$

$\delta(q_0, 0) = (q_1, B, R)$

$B\ 0^{m-1}\ 1\ 0^n$

$\delta(q_1, 0) = (q_1, 0, R)$
$\delta(q_1, 1) = (q_2, 1, R)$

$\delta(q_2, 0)=(q_3, 1, L)$
$\delta(q_2, 1)=(q_2, 1, R)$

$B\ 0^{m-1}\ 1\ 1\ 0^{n-1}$

$\delta(q_3, 1) = (q_3, 1, L)$
$\delta(q_3, 0) = (q_3, 0, L)$
$\delta(q_3, B) = (q_0, B, R)$

$BB\ 0^{m-2}\ 11\ \ 0^{n-1}$

$BB\ 0^{m-2}\ 111\ \ 0^{n-2}$

$m > n$

$B^{n+1}\ 0^{m-n-1}\ 1^{n+1}$

$\delta(q_2, B) = (q_4, B, L)$

Computing functions with Turing machines

$m \div n$

$0^{m}\,1\,0^{n}$

$\delta(q_0, 0) = (q_1, B, R)$

$B\,0^{m-1}\,1\,0^{n}$

$\delta(q_1, 0) = (q_1, 0, R)$
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$\delta(q_2, 0)=(q_3, 1, L)$
$\delta(q_2, 1)=(q_2, 1, R)$

$B\,0^{m-1}\,1\,1\,0^{n-1}$

$\delta(q_3, 1) = (q_3, 1, L)$
$\delta(q_3, 0) = (q_3, 0, L)$
$\delta(q_3, B) = (q_0, B, R)$

$BB\,0^{m-2}\,11\;\;0^{n-1}$

$BB\,0^{m-2}\,111\;\;0^{n-2}$

$m > n$

$B^{n+1}\,0^{m-n-1}\,1^{n+1}$

$\delta(q_2, B) = (q_4, B, L)$
$\delta(q_4, 1) = (q_4, B, L)$

Computing functions with Turing machines

$m \div n$

$0^m\ 1\ 0^n$

$\delta(q_0, 0) = (q_1, B, R)$

$B\ 0^{m-1}\ 1\ 0^n$

$\delta(q_1, 0) = (q_1, 0, R)$
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$\delta(q_3, 1) = (q_3, 1, L)$
$\delta(q_3, 0) = (q_3, 0, L)$
$\delta(q_3, B) = (q_0, B, R)$

$BB\ 0^{m-2}\ 11\ \ 0^{n-1}$

$BB\ 0^{m-2}\ 111\ \ 0^{n-2}$

$m > n$

$B^{n+1}\ 0^{m-n-1}\ 1^{n+1}$

$\delta(q_2, B) = (q_4, B, L)$
$\delta(q_4, 1) = (q_4, B, L)$
$\delta(q_4, 0) = (q_4, 0, L)$

Computing functions with Turing machines

$m \div n$

$0^m\ 1\ 0^n$

$\delta(q_0, 0) = (q_1, B, R)$

$B\ 0^{m-1}\ 1\ 0^n$

$\delta(q_1, 0) = (q_1, 0, R)$
$\delta(q_1, 1) = (q_2, 1, R)$

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$B\ 0^{m-1}\ 1\ 1\ 0^{n-1}$

$\delta(q_3, 1) = (q_3, 1, L)$
$\delta(q_3, 0) = (q_3, 0, L)$
$\delta(q_3, B) = (q_0, B, R)$

$BB\ 0^{m-2}\ 11\ \ 0^{n-1}$

$BB\ 0^{m-2}\ 111\ \ 0^{n-2}$

$m > n$

$B^{n+1}\ 0^{m-n-1}\ 1^{n+1}$

$\delta(q_2, B) = (q_4, B, L)$
$\delta(q_4, 1) = (q_4, B, L)$
$\delta(q_4, 0) = (q_4, 0, L)$
$\delta(q_4, B) = (q_6, 0, R)$

Computing functions with Turing machines

$m \div n$

$0^m \, 1 \, 0^n$

$\delta(q_0, 0) = (q_1, B, R)$

$B \, 0^{m-1} \, 1 \, 0^n$

$\delta(q_1, 0) = (q_1, 0, R)$
$\delta(q_1, 1) = (q_2, 1, R)$

$\delta(q_2, 0) = (q_3, 1, L)$
$\delta(q_2, 1) = (q_2, 1, R)$

$B \, 0^{m-1} \, 1 \, 1 \, 0^{n-1}$

$\delta(q_3, 1) = (q_3, 1, L)$
$\delta(q_3, 0) = (q_3, 0, L)$
$\delta(q_3, B) = (q_0, B, R)$

$BB \, 0^{m-2} \, 11 \;\; 0^{n-1}$

$BB \, 0^{m-2} \, 111 \;\; 0^{n-2}$

$m > n$

$B^{n+1} \, 0^{m-n-1} \, 1^{n+1}$

$\delta(q_2, B) = (q_4, B, L)$
$\delta(q_4, 1) = (q_4, B, L)$
$\delta(q_4, 0) = (q_4, 0, L)$
$\delta(q_4, B) = (q_6, 0, R)$

$B^n \, 0^{m-n}$

Computing functions with Turing machines

$m \div n$

$0^m \, 1 \, 0^n$

$$\delta(q_0, 0) = (q_1, B, R)$$

$B \, 0^{m-1} \, 1 \, 0^n$

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$B \, 0^{m-1} \, 1 \, 1 \, 0^{n-1}$

$$\delta(q_3, 1) = (q_3, 1, L)$$
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$BB \, 0^{m-2} \, 11 \;\; 0^{n-1}$

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Computing functions with Turing machines

$m \div n$

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$BB\ 0^{m-2}\ 11\ \ 0^{n-1}$

$BB\ 0^{m-2}\ 111\ \ 0^{n-2}$

$m \leq n$

Computing functions with Turing machines

$m \div n$

$0^m\ 1\ 0^n$

$\delta(q_0, 0) = (q_1, B, R)$

$B\ 0^{m-1}\ 1\ 0^n$

$\delta(q_1, 0) = (q_1, 0, R)$
$\delta(q_1, 1) = (q_2, 1, R)$

$\delta(q_2, 1)=(q_2, 1, R)$
$\delta(q_2, 0)=(q_3, 1, L)$

$B\ 0^{m-1}\ 1\ 1\ 0^{n-1}$

$\delta(q_3, 1) = (q_3, 1, L)$
$\delta(q_3, 0) = (q_3, 0, L)$
$\delta(q_3, B) = (q_0, B, R)$

$BB\ 0^{m-2}\ 11\ \ 0^{n-1}$

$BB\ 0^{m-2}\ 111\ \ 0^{n-2}$

$\boxed{m \leq n}$

$B^m\ 1^{m+1}\ 0^{n-m}$

Computing functions with Turing machines

$m \div n$

$0^m\ 1\ 0^n$

$\delta(q_0, 0) = (q_1, B, R)$

$B\ 0^{m-1}\ 1\ 0^n$

$\delta(q_1, 0) = (q_1, 0, R)$
$\delta(q_1, 1) = (q_2, 1, R)$

$\delta(q_2, 1)=(q_2, 1, R)$
$\delta(q_2, 0)=(q_3, 1, L)$

$B\ 0^{m-1}\ 1\ 1\ 0^{n-1}$

$\delta(q_3, 1) = (q_3, 1, L)$
$\delta(q_3, 0) = (q_3, 0, L)$
$\delta(q_3, B) = (q_0, B, R)$

$BB\ 0^{m-2}\ 11\ \ 0^{n-1}$

$BB\ 0^{m-2}\ 111\ \ 0^{n-2}$

$m \leq n$

$B^m\ 1^{m+1}\ 0^{n-m}$

Computing functions with Turing machines

$m \div n$

$0^m\ 1\ 0^n$

$\delta(q_0, 0) = (q_1, B, R)$

$B\ 0^{m-1}\ 1\ 0^n$

$\delta(q_1, 0) = (q_1, 0, R)$
$\delta(q_1, 1) = (q_2, 1, R)$

$\delta(q_2, 1)=(q_2, 1, R)$
$\delta(q_2, 0)=(q_3, 1, L)$

$B\ 0^{m-1}\ 1\ 1\ 0^{n-1}$

$\delta(q_3, 1) = (q_3, 1, L)$
$\delta(q_3, 0) = (q_3, 0, L)$
$\delta(q_3, B) = (q_0, B, R)$

$BB\ 0^{m-2}\ 11\ \ 0^{n-1}$

$BB\ 0^{m-2}\ 111\ \ 0^{n-2}$

$m \le n$

$B^m\ 1^{m+1}\ 0^{n-m}$

$\delta(q_0, 1)=(q_5, B, R)$

Computing functions with Turing machines

$m \div n$

$0^m\ 1\ 0^n$

$\delta(q_0, 0) = (q_1, B, R)$

$B\ 0^{m-1}\ 1\ 0^n$

$\delta(q_1, 0) = (q_1, 0, R)$
$\delta(q_1, 1) = (q_2, 1, R)$

$\delta(q_2, 1)=(q_2, 1, R)$
$\delta(q_2, 0)=(q_3, 1, L)$

$B\ 0^{m-1}\ 1\ 1\ 0^{n-1}$

$\delta(q_3, 1) = (q_3, 1, L)$
$\delta(q_3, 0) = (q_3, 0, L)$
$\delta(q_3, B) = (q_0, B, R)$

$BB\ 0^{m-2}\ 11\ \ 0^{n-1}$

$BB\ 0^{m-2}\ 111\ \ 0^{n-2}$

$m \leq n$

$B^m\ 1^{m+1}\ 0^{n-m}$

$\delta(q_0, 1)=(q_5, B, R)$
$\delta(q_5, 1)=(q_5, B, R)$

Computing functions with Turing machines

$m \div n$

$0^m\, 1\, 0^n$

$\delta(q_0, 0) = (q_1, B, R)$

$B\, 0^{m-1}\, 1\, 0^n$

$\delta(q_1, 0) = (q_1, 0, R)$
$\delta(q_1, 1) = (q_2, 1, R)$

$\delta(q_2, 1) = (q_2, 1, R)$
$\delta(q_2, 0) = (q_3, 1, L)$

$B\, 0^{m-1}\, 1\, 1\, 0^{n-1}$

$\delta(q_3, 1) = (q_3, 1, L)$
$\delta(q_3, 0) = (q_3, 0, L)$
$\delta(q_3, B) = (q_0, B, R)$

$BB\, 0^{m-2}\, 11\;\; 0^{n-1}$

$BB\, 0^{m-2}\, 111\;\; 0^{n-2}$

$m \le n$

$B^m\, 1^{m+1}\, 0^{n-m}$

$\delta(q_0, 1) = (q_5, B, R)$
$\delta(q_5, 1) = (q_5, B, R)$
$\delta(q_5, 0) = (q_5, B, R)$

Computing functions with Turing machines

$m \div n$

$0^m\ 1\ 0^n$

$\delta(q_0, 0) = (q_1, B, R)$

$B\ 0^{m-1}\ 1\ 0^n$

$\delta(q_1, 0) = (q_1, 0, R)$
$\delta(q_1, 1) = (q_2, 1, R)$

$\delta(q_2, 1)=(q_2, 1, R)$
$\delta(q_2, 0)=(q_3, 1, L)$

$B\ 0^{m-1}\ 1\ 1\ 0^{n-1}$

$\delta(q_3, 1) = (q_3, 1, L)$
$\delta(q_3, 0) = (q_3, 0, L)$
$\delta(q_3, B) = (q_0, B, R)$

$BB\ 0^{m-2}\ 11\ \ 0^{n-1}$

$BB\ 0^{m-2}\ 111\ \ 0^{n-2}$

$m \leq n$

$B^m\ 1^{m+1}\ 0^{n-m}$

$\delta(q_0, 1)=(q_5, B, R)$
$\delta(q_5, 1)=(q_5, B, R)$
$\delta(q_5, 0)=(q_5, B, R)$
$\delta(q_5, B)=(q_6, B, R)$

Computing functions with Turing machines

$m \div n$

$0^m\ 1\ 0^n$

$\delta(q_0, 0) = (q_1, B, R)$

$B\ 0^{m-1}\ 1\ 0^n$

$\delta(q_1, 0) = (q_1, 0, R)$
$\delta(q_1, 1) = (q_2, 1, R)$

$\delta(q_2, 1)=(q_2, 1, R)$
$\delta(q_2, 0)=(q_3, 1, L)$

$B\ 0^{m-1}\ 1\ 1\ 0^{n-1}$

$\delta(q_3, 1) = (q_3, 1, L)$
$\delta(q_3, 0) = (q_3, 0, L)$
$\delta(q_3, B) = (q_0, B, R)$

$BB\ 0^{m-2}\ 11\ \ 0^{n-1}$

$BB\ 0^{m-2}\ 111\ \ 0^{n-2}$

$m \leq n$

$B^m\ 1^{m+1}\ 0^{n-m}$

$\delta(q_0, 1)=(q_5, B, R)$
$\delta(q_5, 1)=(q_5, B, R)$
$\delta(q_5, 0)=(q_5, B, R)$
$\delta(q_5, B)=(q_6, B, R)$

B^{m+n+1}

Computing functions with Turing machines

Computing functions with Turing machines

$2 \div 1$

Computing functions with Turing machines

2 ÷ 1

$$q_0 0010 \succ Bq_1 010 \succ B0q_1 10 \succ B01q_2 0 \succ$$
$$B0q_3 11 \succ Bq_3 011 \succ q_3 B011 \succ Bq_0 011 \succ$$
$$BBq_1 11 \succ BB1q_2 1 \succ BB11q_2 \succ BB1q_4 1 \succ$$
$$BBq_4 1 \succ Bq_4 \succ B0q_6$$

Computing functions with Turing machines

$2 \div 1$

$q_0 0010$	$\succ$	$Bq_1 010$	$\succ$	$B0q_1 10$	$\succ$	$B01q_2 0$	$\succ$
$B0q_3 11$	$\succ$	$Bq_3 011$	$\succ$	$q_3 B011$	$\succ$	$Bq_0 011$	$\succ$
$BBq_1 11$	$\succ$	$BB1q_2 1$	$\succ$	$BB11q_2$	$\succ$	$BB1q_4 1$	$\succ$
$BBq_4 1$	$\succ$	Bq_4	$\succ$	$B0q_6$			

$2 \div 1 = 1$

Computing functions with Turing machines

$2 \div 1$

$q_0 0010 \succ Bq_1 010 \succ B0q_1 10 \succ B01q_2 0 \succ$
$B0q_3 11 \succ Bq_3 011 \succ q_3 B011 \succ Bq_0 011 \succ$
$BBq_1 11 \succ BB1q_2 1 \succ BB11q_2 \succ BB1q_4 1 \succ$
$BBq_4 1 \succ Bq_4 \succ B0q_6$

$2 \div 1 = 1$

$1 \div 2$

Computing functions with Turing machines

$2 \div 1$

$q_0 0010 \succ Bq_1 010 \succ B0q_1 10 \succ B01q_2 0 \succ$
$B0q_3 11 \succ Bq_3 011 \succ q_3 B011 \succ Bq_0 011 \succ$
$BBq_1 11 \succ BB1q_2 1 \succ BB11q_2 \succ BB1q_4 1 \succ$
$BBq_4 1 \succ Bq_4 \succ B0q_6$

$2 \div 1 = 1$

$1 \div 2$

$q_0 0100 \succ Bq_1 100 \succ B1q_2 00 \succ Bq_3 110 \succ$
$q_3 B110 \succ Bq_0 110 \succ BBq_5 10 \succ BBBq_5 0 \succ$
$BBBBq_5 \succ BBBBBq_6$

Computing functions with Turing machines

$2 \div 1$

$q_0 0010$	$\succ$	$Bq_1 010$	$\succ$	$B0q_1 10$	$\succ$	$B01q_2 0$	$\succ$
$B0q_3 11$	$\succ$	$Bq_3 011$	$\succ$	$q_3 B011$	$\succ$	$Bq_0 011$	$\succ$
$BBq_1 11$	$\succ$	$BB1q_2 1$	$\succ$	$BB11q_2$	$\succ$	$BB1q_4 1$	$\succ$
$BBq_4 1$	$\succ$	Bq_4	$\succ$	$B0q_6$			

$2 \div 1 = 1$

$1 \div 2$

$q_0 0100$	$\succ$	$Bq_1 100$	$\succ$	$B1q_2 00$	$\succ$	$Bq_3 110$	$\succ$
$q_3 B110$	$\succ$	$Bq_0 110$	$\succ$	$BBq_5 10$	$\succ$	$BBBq_5 0$	$\succ$
$BBBBq_5$	$\succ$	$BBBBBq_6$					

$1 \div 2 = 0$

Lecture outline

4 RECURSIVELY ENUMERABLE LANGUAGES 126

4.1 TURING MACHINE (TM) 126

4.1.1 Simple Turing machine 126

4.1.2 Programming techniques for Turing machines 133

Programming techniques for Turing machines

Programming techniques for Turing machines

- **States with multiple components**

Programming techniques for Turing machines

- **States with multiple components**

- **Tape symbols with multiple components**

Programming techniques for Turing machines

- **States with multiple components**
  - $[q_1, q_2, \ldots, q_n]$

- **Tape symbols with multiple components**

Programming techniques for Turing machines

- **States with multiple components**
  - **$[q_1, q_2, ..., q_n]$**
  - **Control components**
    - —**Define state/position of TM**
- **Tape symbols with multiple components**

Programming techniques for Turing machines

- States with multiple components
  - $[q_1, q_2, ..., q_n]$
  - Control components
    - —Define state/position of TM
  - Storage components
    - —Hold a finite amount of data

- Tape symbols with multiple components

Programming techniques for Turing machines

- **States with multiple components**
  - $[q_1, q_2, ..., q_n]$
  - **Control components**
    - —Define state/position of TM
  - **Storage components**
    - —Hold a finite amount of data

- **Tape symbols with multiple components**
  - $[a_1, a_2, ..., a_n]$

Programming techniques for Turing machines

- States with multiple components
  - $[q_1, q_2, ..., q_n]$
  - Control components
    - —Define state/position of TM
  - Storage components
    - —Hold a finite amount of data

- Tape symbols with multiple components
  - $[a_1, a_2, ..., a_n]$
  - Multiple *tracks* on the tape

Programming techniques for Turing machines

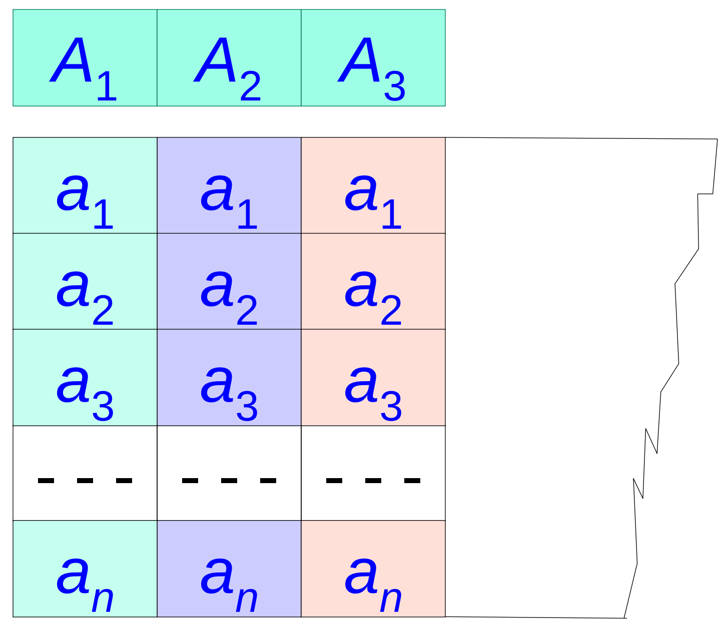
- **States with multiple components**
  - **[q_1, q_2, ..., q_n]**
  - **Control components**
    - —**Define state/position of TM**
  - **Storage components**
    - —**Hold a finite amount of data**

A_1	A_2	A_3

- **Tape symbols with multiple components**
  - **[a_1, a_2, ..., a_n]**
  - **Multiple *tracks* on the tape**

Programming techniques for Turing machines

- **States with multiple components**
  - **$[q_1, q_2, ..., q_n]$**
  - **Control components**
    - —Define state/position of TM
  - **Storage components**
    - —Hold a finite amount of data



- **Tape symbols with multiple components**
  - **$[a_1, a_2, ..., a_n]$**
  - **Multiple *tracks* on the tape**

States with multiple components

States with multiple components

- **Language *L***

States with multiple components

- Language *L*
  - **Set of strings where leftmost symbol does not appear elsewhere in the string**

States with multiple components

- **Language *L***
  - **Set of strings where leftmost symbol does not appear elsewhere in the string**
- **Composite states of the TM *M***

States with multiple components

- **Language *L***
  - **Set of strings where leftmost symbol does not appear elsewhere in the string**

- **Composite states of the TM *M***
  - **Two components [*q*, *a*]**

States with multiple components

- **Language *L***
  - **Set of strings where leftmost symbol does not appear elsewhere in the string**

- **Composite states of the TM *M***
  - **Two components [*q*, *a*]**
  - **Storage component *a***

States with multiple components

- Language *L*
  - Set of strings where leftmost symbol does not appear elsewhere in the string

- Composite states of the TM *M*
  - Two components [*q*, *a*]
  - Storage component *a*
    - —Holds leftmost symbol on the tape

States with multiple components

- **Language *L***
  - **Set of strings where leftmost symbol does not appear elsewhere in the string**
- **Composite states of the TM *M***
  - **Two components [*q*, *a*]**
  - **Storage component *a***
    - **—Holds leftmost symbol on the tape**
  - **Control component *q***

States with multiple components

- **Language *L***
  - **Set of strings where leftmost symbol does not appear elsewhere in the string**
- **Composite states of the TM *M***
  - **Two components [q, a]**
  - **Storage component a**
    - —**Holds leftmost symbol on the tape**
  - **Control component q**
    - —**Two values: q_0 and q_1**

States with multiple components

- Language L
  - Set of strings where leftmost symbol does not appear elsewhere in the string

- Composite states of the TM M
  - Two components $[q, a]$
  - Storage component a
    - —Holds leftmost symbol on the tape
  - Control component q
    - —Two values: q_0 and q_1
    - —State q_0: - TM M reads leftmost symbol and stores it in the storage component

States with multiple components

- **Language L**
  - **Set of strings where leftmost symbol does not appear elsewhere in the string**

- **Composite states of the TM M**
  - **Two components $[q, a]$**
  - **Storage component a**
    - —**Holds leftmost symbol on the tape**
  - **Control component q**
    - —**Two values: q_0 and q_1**
    - —**State q_0: - TM M reads leftmost symbol and stores it in the storage component**
    - —**State q_1: - TM M reads rest of the string and compares symbols with the symbol stored in the storage component**

States with multiple components

States with multiple components

- **Control component: q_0 and q_1**

States with multiple components

- **Control component: q_0 and q_1**
- **Storage component: 0, 1 and *B***

States with multiple components

- Control component: q_0 and q_1
- Storage component: **0**, **1** and ***B***
  - Set of composite states

States with multiple components

- **Control component: q_0 and q_1**
- **Storage component: 0, 1 and B**
  - **Set of composite states**

    $Q = \{[q_0, B], [q_0, 0], [q_0, 1], [q_1, B], [q_1, 0], [q_1, 1]\}$

States with multiple components

- **Control component: q_0 and q_1**
- **Storage component: 0, 1 and B**
  - **Set of composite states**

    $Q = \{[q_0, B], [q_0, 0], [q_0, 1], [q_1, B], [q_1, 0], [q_1, 1]\}$

- ***TM M =*** $(Q, \{0,1\}, \{0, 1, B\}, \delta, [q_0, B], B, \{[q_1, B]\})$

States with multiple components

- Control component: q_0 and q_1
- Storage component: **0**, **1** and B
  - **Set of composite states**

    $Q = \{[q_0, B], [q_0, 0], [q_0, 1], [q_1, B], [q_1, 0], [q_1, 1]\}$

- *TM M* = $(Q, \{0,1\}, \{0, 1, B\}, \delta, [q_0, B], B, \{[q_1, B]\})$

$\delta([q_0, B], 0\ ) =$

States with multiple components

- Control component: q_0 and q_1
- Storage component: **0**, **1** and ***B***
    - Set of composite states

      $Q = \{[q_0, B], [q_0, 0], [q_0, 1], [q_1, B], [q_1, 0], [q_1, 1]\}$

- *TM M* = $(Q, \{0,1\}, \{0, 1, B\}, \delta, [q_0, B], B, \{[q_1, B]\})$

$\delta([q_0, B], 0\ ) = ([q_1,\ \ ], 0, R)$

States with multiple components

- **Control component:** q_0 and q_1
- **Storage component:** 0, 1 and B
  - **Set of composite states**

    $Q = \{[q_0, B], [q_0, 0], [q_0, 1], [q_1, B], [q_1, 0], [q_1, 1]\}$

- *TM M* = $(Q, \{0,1\}, \{0, 1, B\}, \delta, [q_0, B], B, \{[q_1, B]\})$

$$\delta([q_0, B], 0) = ([q_1, 0], 0, R)$$

States with multiple components

- Control component: q_0 and q_1
- Storage component: 0, 1 and B
  - Set of composite states

    $Q = \{[q_0, B], [q_0, 0], [q_0, 1], [q_1, B], [q_1, 0], [q_1, 1]\}$

- TM $M = (Q, \{0,1\}, \{0, 1, B\}, \delta, [q_0, B], B, \{[q_1, B]\})$

$\delta([q_0, B], 0) = ([q_1, 0], 0, R)$

$\delta([q_0, B], 1) = ([q_1, \ \ ], 1, R)$

States with multiple components

- Control component: q_0 and q_1
- Storage component: 0, 1 and B
  - Set of composite states

    $Q = \{[q_0, B], [q_0, 0], [q_0, 1], [q_1, B], [q_1, 0], [q_1, 1]\}$

- TM $M = (Q, \{0,1\}, \{0, 1, B\}, \delta, [q_0, B], B, \{[q_1, B]\})$

$$\delta([q_0, B], 0) = ([q_1, 0], 0, R)$$

$$\delta([q_0, B], 1) = ([q_1, 1], 1, R)$$

States with multiple components

- Control component: q_0 and q_1
- Storage component: 0, 1 and B
  - Set of composite states

    $Q = \{[q_0, B], [q_0, 0], [q_0, 1], [q_1, B], [q_1, 0], [q_1, 1]\}$

- TM $M = (Q, \{0,1\}, \{0, 1, B\}, \delta, [q_0, B], B, \{[q_1, B]\})$

$\delta([q_0, B], 0) = ([q_1, 0], 0, R)$

$\delta([q_0, B], 1) = ([q_1, 1], 1, R)$

$\delta([q_1, 0], 1) = ([q_1, 0], 1, R)$

$\delta([q_1, 1], 0) = ([q_1, 1], 0, R)$

States with multiple components

- Control component: q_0 and q_1
- Storage component: 0, 1 and B
    - Set of composite states

      $Q = \{[q_0, B], [q_0, 0], [q_0, 1], [q_1, B], [q_1, 0], [q_1, 1]\}$

- TM $M = (Q, \{0,1\}, \{0, 1, B\}, \delta, [q_0, B], B, \{[q_1, B]\})$

$\delta([q_0, B], 0) = ([q_1, 0], 0, R)$

$\delta([q_0, B], 1) = ([q_1, 1], 1, R)$

$\delta([q_1, 0], 1) = ([q_1, 0], 1, R)$

$\delta([q_1, 1], 0) = ([q_1, 1], 0, R)$

States with multiple components

- Control component: q_0 and q_1
- Storage component: 0, 1 and B
    - Set of composite states

      $Q = \{[q_0, B], [q_0, 0], [q_0, 1], [q_1, B], [q_1, 0], [q_1, 1]\}$

- TM $M = (Q, \{0,1\}, \{0, 1, B\}, \delta, [q_0, B], B, \{[q_1, B]\})$

$$\delta([q_0, B], 0) = ([q_1, 0], 0, R)$$

$$\delta([q_0, B], 1) = ([q_1, 1], 1, R)$$

$$\delta([q_1, 0], 1) = ([q_1, 0], 1, R)$$

$$\delta([q_1, 1], 0) = ([q_1, 1], 0, R)$$

States with multiple components

- **Control component:** q_0 **and** q_1
- **Storage component:** **0, 1 and** B
  - **Set of composite states**

    $Q = \{[q_0, B], [q_0, 0], [q_0, 1], [q_1, B], [q_1, 0], [q_1, 1]\}$

- *TM M* = $(Q, \{0,1\}, \{0, 1, B\}, \delta, [q_0, B], B, \{[q_1, B]\})$

$\delta([q_0, B], 0) = ([q_1, 0], 0, R)$

$\delta([q_0, B], 1) = ([q_1, 1], 1, R)$

$\delta([q_1, 0], 1) = ([q_1, 0], 1, R)$

$\delta([q_1, 1], 0) = ([q_1, 1], 0, R)$

States with multiple components

- **Control component:** q_0 **and** q_1
- **Storage component:** **0, 1 and** B
  - **Set of composite states**

    $Q = \{[q_0, B], [q_0, 0], [q_0, 1], [q_1, B], [q_1, 0], [q_1, 1]\}$

- *TM M* = $(Q, \{0,1\}, \{0, 1, B\}, \delta, [q_0, B], B, \{[q_1, B]\})$

$\delta([q_0, B], 0) = ([q_1, 0], 0, R)$

$\delta([q_0, B], 1) = ([q_1, 1], 1, R)$

$\delta([q_1, 0], 1) = ([q_1, 0], 1, R)$

$\delta([q_1, 1], 0) = ([q_1, 1], 0, R)$

States with multiple components

- Control component: q_0 and q_1
- Storage component: 0, 1 and B
  - Set of composite states

    $Q = \{[q_0, B], [q_0, 0], [q_0, 1], [q_1, B], [q_1, 0], [q_1, 1]\}$

- TM $M = (Q, \{0,1\}, \{0, 1, B\}, \delta, [q_0, B], B, \{[q_1, B]\})$

$\delta([q_0, B], 0) = ([q_1, 0], 0, R)$

$\delta([q_0, B], 1) = ([q_1, 1], 1, R)$

$\delta([q_1, 0], B) = ([q_1, B], B, L)$

$\delta([q_1, 1], B) = ([q_1, B], B, L)$

$\delta([q_1, 0], 1) = ([q_1, 0], 1, R)$

$\delta([q_1, 1], 0) = ([q_1, 1], 0, R)$

States with multiple components

States with multiple components

- **TM *M***

States with multiple components

- **TM *M***
  - **Shift symbols over *n* cells using *n* storage components**

States with multiple components

- TM *M*
  - Shift symbols over *n* cells using *n* storage components

- 2-cell shift

States with multiple components

- TM *M*
  - Shift symbols over *n* cells using *n* storage components

- 2-cell shift
  - Composite states: $[q, R_1, R_2]$

States with multiple components

- TM *M*
  - Shift symbols over *n* cells using *n* storage components
- 2-cell shift
  - Composite states: [q, R_1, R_2]
    - —Control component q is q_1 or q_2

States with multiple components

- TM *M*
  - Shift symbols over *n* cells using *n* storage components

- 2-cell shift
  - Composite states: $[q, R_1, R_2]$
    - —Control component q is q_1 or q_2
    - —Storage components R_1 and R_2 hold tape symbols Γ

States with multiple components

States with multiple components

$$\delta([q_1, B, B], A_1\ \ ) = ([q_1, B,\ \ B\ \ \ ], B, R)$$

States with multiple components

$$\delta([q_1, B, B], A_1) = ([q_1, B, A_1], B, R)$$

States with multiple components

$\delta([q_1, B, B], A_1) = ([q_1, B, A_1], B, R)$

$\delta([q_1, B, A_1], A_2) = ([q_1, B, A_1], B, R)$

States with multiple components

$$\delta([q_1, B, B], A_1) = ([q_1, B, A_1], B, R)$$

$$\delta([q_1, B, A_1], A_2) = ([q_1, A_1, A_1], B, R)$$

States with multiple components

$$\delta([q_1, B, B], A_1) = ([q_1, B, A_1], B, R)$$

$$\delta([q_1, B, A_1], A_2) = ([q_1, A_1, A_2], B, R)$$

States with multiple components

$\delta([q_1, B, B], A_1) = ([q_1, B, A_1], B, R)$

$\delta([q_1, B, A_1], A_2) = ([q_1, A_1, A_2], B, R)$

$\delta([q_1, A_1, A_2], A_3) = ([q_1, A_1, A_2], A_3, R)$

States with multiple components

$$\delta([q_1, B, B], A_1) = ([q_1, B, A_1], B, R)$$

$$\delta([q_1, B, A_1], A_2) = ([q_1, A_1, A_2], B, R)$$

$$\delta([q_1, A_1, A_2], A_3) = ([q_1, A_1, A_2], A_1, R)$$

States with multiple components

$$\delta([q_1, B, B], A_1) = ([q_1, B, A_1], B, R)$$

$$\delta([q_1, B, A_1], A_2) = ([q_1, A_1, A_2], B, R)$$

$$\delta([q_1, A_1, A_2], A_3) = ([q_1, A_2, A_2], A_1, R)$$

States with multiple components

$$\delta([q_1, B, B], A_1) = ([q_1, B, A_1], B, R)$$

$$\delta([q_1, B, A_1], A_2) = ([q_1, A_1, A_2], B, R)$$

$$\delta([q_1, A_1, A_2], A_3) = ([q_1, A_2, A_3], A_1, R)$$

States with multiple components

$$\delta([q_1, B, B], A_1) = ([q_1, B, A_1], B, R)$$

$$\delta([q_1, B, A_1], A_2) = ([q_1, A_1, A_2], B, R)$$

$$\delta([q_1, A_1, A_2], A_3) = ([q_1, A_2, A_3], A_1, R)$$

$$\delta([q_1, A_1, A_2], B) = ([q_1, A_1, A_2], B, R)$$

States with multiple components

$$\delta([q_1, B, B], A_1) = ([q_1, B, A_1], B, R)$$

$$\delta([q_1, B, A_1], A_2) = ([q_1, A_1, A_2], B, R)$$

$$\delta([q_1, A_1, A_2], A_3) = ([q_1, A_2, A_3], A_1, R)$$

$$\delta([q_1, A_1, A_2], B) = ([q_1, A_1, A_2], A_1, R)$$

States with multiple components

$$\delta([q_1, B, B], A_1) = ([q_1, B, A_1], B, R)$$

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$$\delta([q_1, A_1, A_2], A_3) = ([q_1, A_2, A_3], A_1, R)$$

$$\delta([q_1, A_1, A_2], B) = ([q_1, A_2, A_2], A_1, R)$$

States with multiple components

$$\delta([q_1, B, B], A_1) = ([q_1, B, A_1], B, R)$$

$$\delta([q_1, B, A_1], A_2) = ([q_1, A_1, A_2], B, R)$$

$$\delta([q_1, A_1, A_2], A_3) = ([q_1, A_2, A_3], A_1, R)$$

$$\delta([q_1, A_1, A_2], B) = ([q_1, A_2, B], A_1, R)$$

States with multiple components

$\delta([q_1, B, B], A_1) = ([q_1, B, A_1], B, R)$

$\delta([q_1, B, A_1], A_2) = ([q_1, A_1, A_2], B, R)$

$\delta([q_1, A_1, A_2], A_3) = ([q_1, A_2, A_3], A_1, R)$

$\delta([q_1, A_1, A_2], B) = ([q_1, A_2, B], A_1, R)$

$\delta([q_1, A_1, B], B) = ([q_2, B, B], B, L)$

States with multiple components

$$\delta([q_1, B, B], A_1) = ([q_1, B, A_1], B, R)$$

$$\delta([q_1, B, A_1], A_2) = ([q_1, A_1, A_2], B, R)$$

$$\delta([q_1, A_1, A_2], A_3) = ([q_1, A_2, A_3], A_1, R)$$

$$\delta([q_1, A_1, A_2], B) = ([q_1, A_2, B], A_1, R)$$

$$\delta([q_1, A_1, B], B) = ([q_2, B, B], A_1, L)$$

States with multiple components

$$\delta([q_1, B, B], A_1) = ([q_1, B, A_1], B, R)$$

$$\delta([q_1, B, A_1], A_2) = ([q_1, A_1, A_2], B, R)$$

$$\delta([q_1, A_1, A_2], A_3) = ([q_1, A_2, A_3], A_1, R)$$

$$\delta([q_1, A_1, A_2], B) = ([q_1, A_2, B], A_1, R)$$

$$\delta([q_1, A_1, B], B) = ([q_2, B, B], A_1, L)$$

States with multiple components

$$\delta([q_1, B, B], A_1) = ([q_1, B, A_1], B, R)$$

$$\delta([q_1, B, A_1], A_2) = ([q_1, A_1, A_2], B, R)$$

$$\delta([q_1, A_1, A_2], A_3) = ([q_1, A_2, A_3], A_1, R)$$

$$\delta([q_1, A_1, A_2], B) = ([q_1, A_2, B], A_1, R)$$

$$\delta([q_1, A_1, B], B) = ([q_2, B, B], A_1, L)$$

States with multiple components

$\delta([q_1, B, B], A_1) = ([q_1, B, A_1], B, R)$

$\delta([q_1, B, A_1], A_2) = ([q_1, A_1, A_2], B, R)$

$\delta([q_1, A_1, A_2], A_3) = ([q_1, A_2, A_3], A_1, R)$

$\delta([q_1, A_1, A_2], B) = ([q_1, A_2, B], A_1, R)$

$\delta([q_1, A_1, B], B) = ([q_2, B, B], A_1, L)$

$\delta([q_2, B, B], A) = ([q_2, B, B], A, L)$

Tape symbols with multiple components

Tape symbols with multiple components

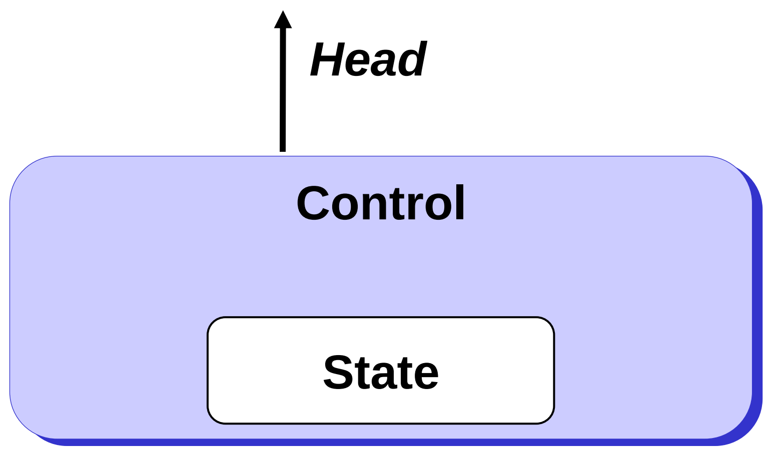
- **Language *L***

Tape symbols with multiple components

- **Language *L***
  - **Set of all prime numbers**

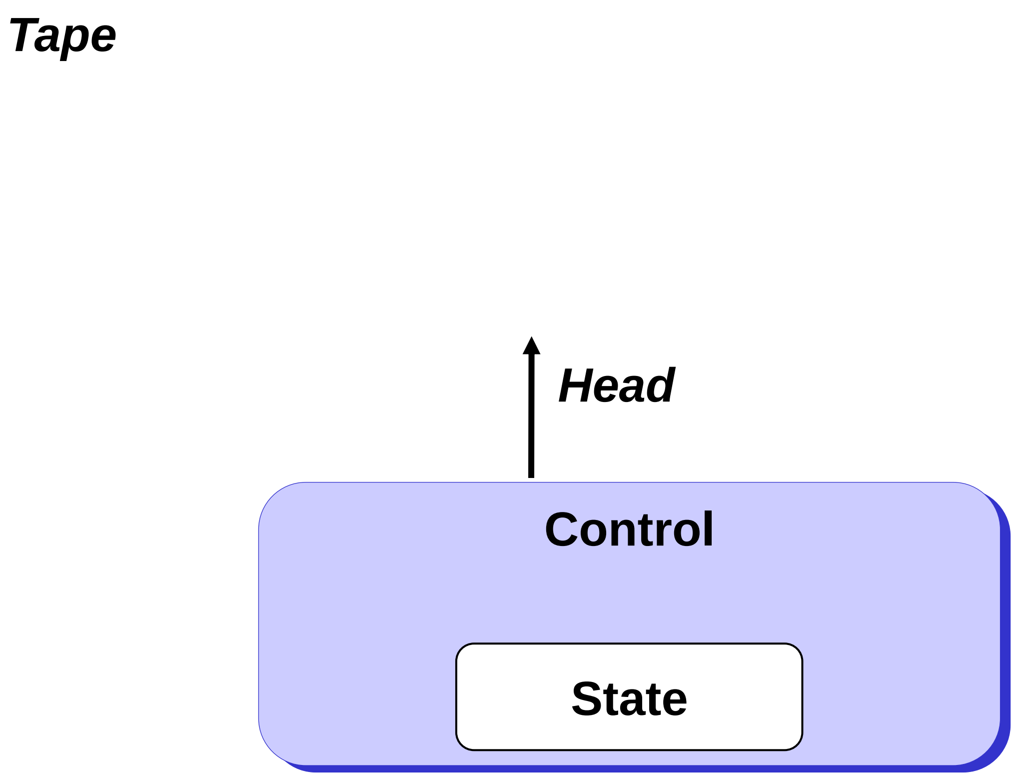
Tape symbols with multiple components

- Language *L*
  - Set of all prime numbers



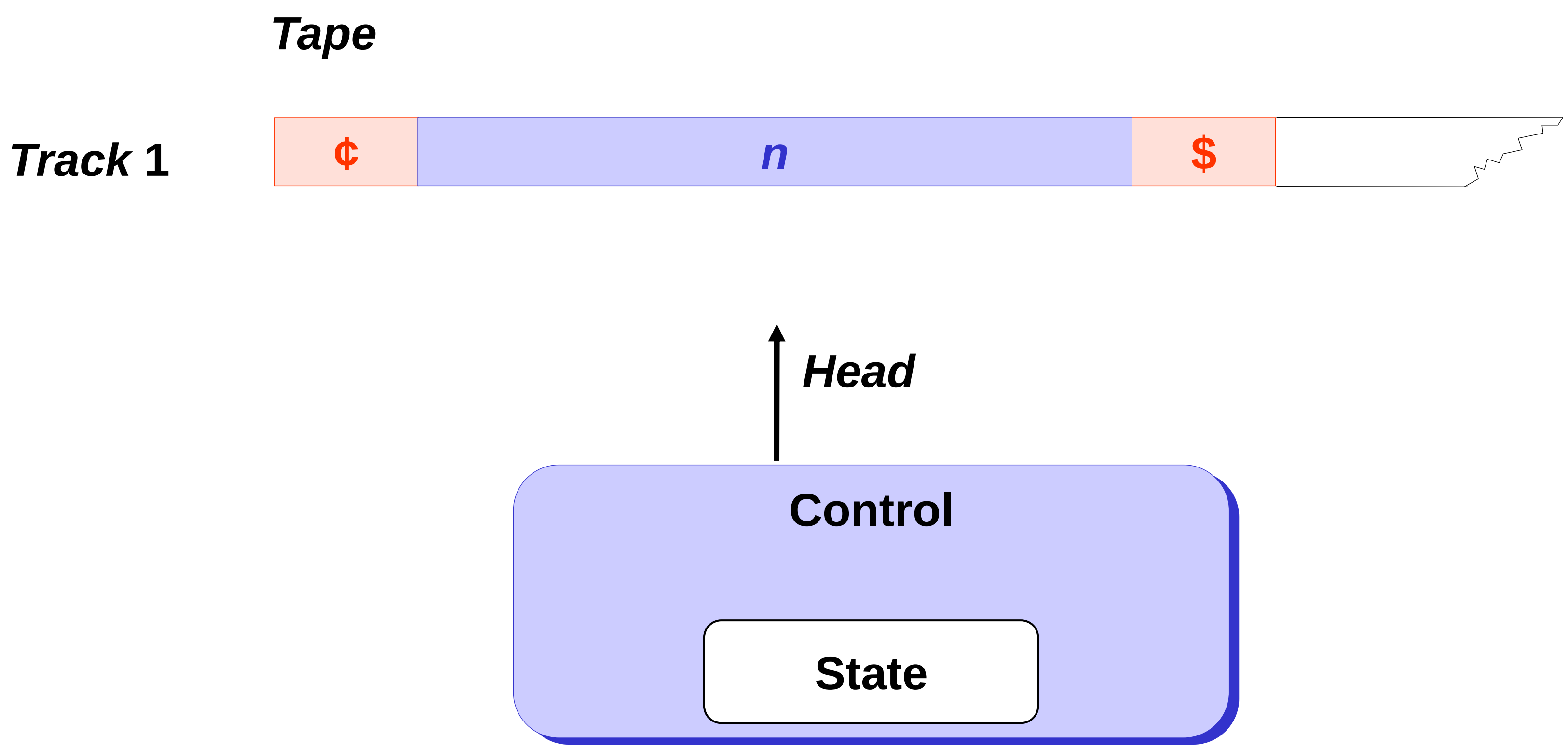
Tape symbols with multiple components

- Language *L*
  - Set of all prime numbers



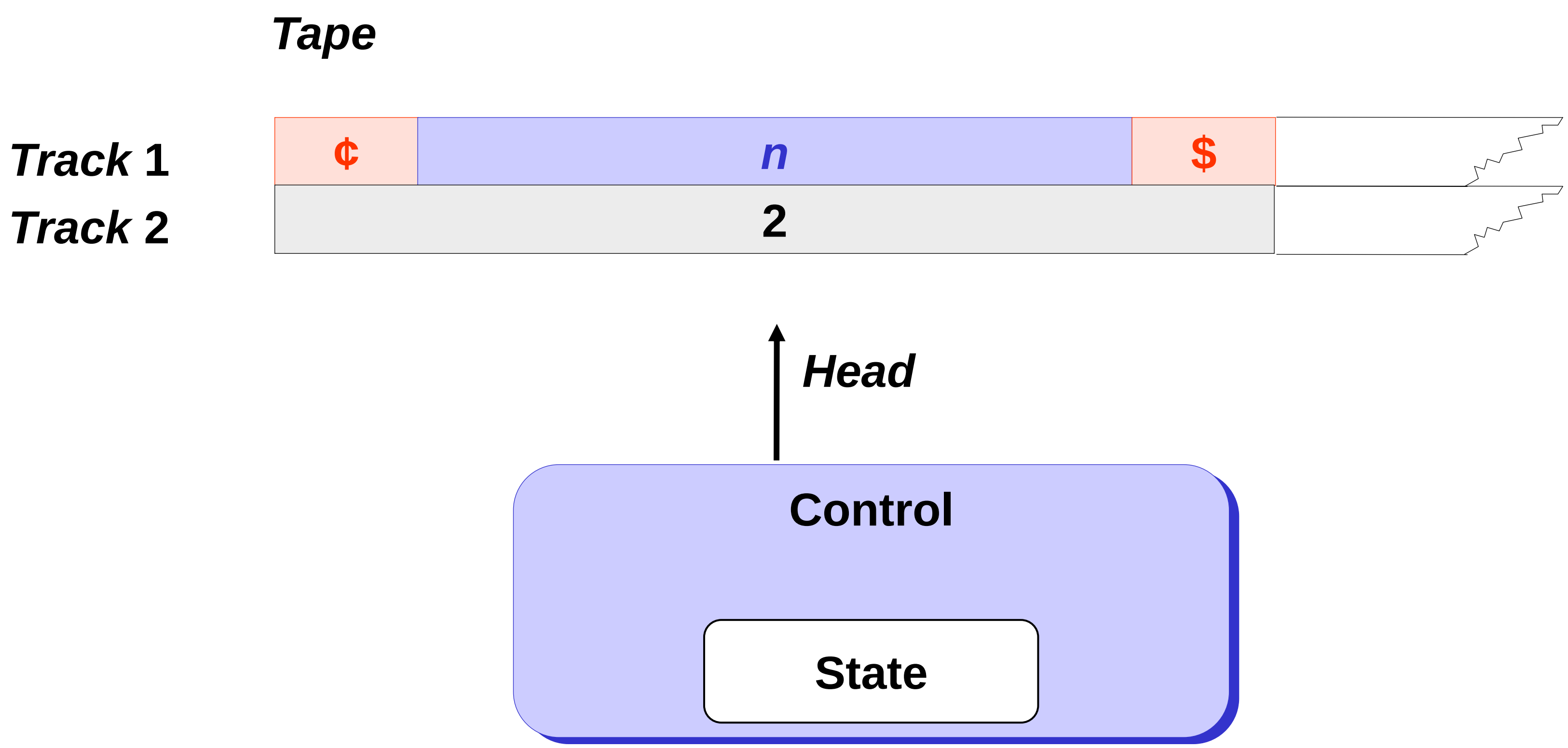
Tape symbols with multiple components

- Language *L*
  - Set of all prime numbers



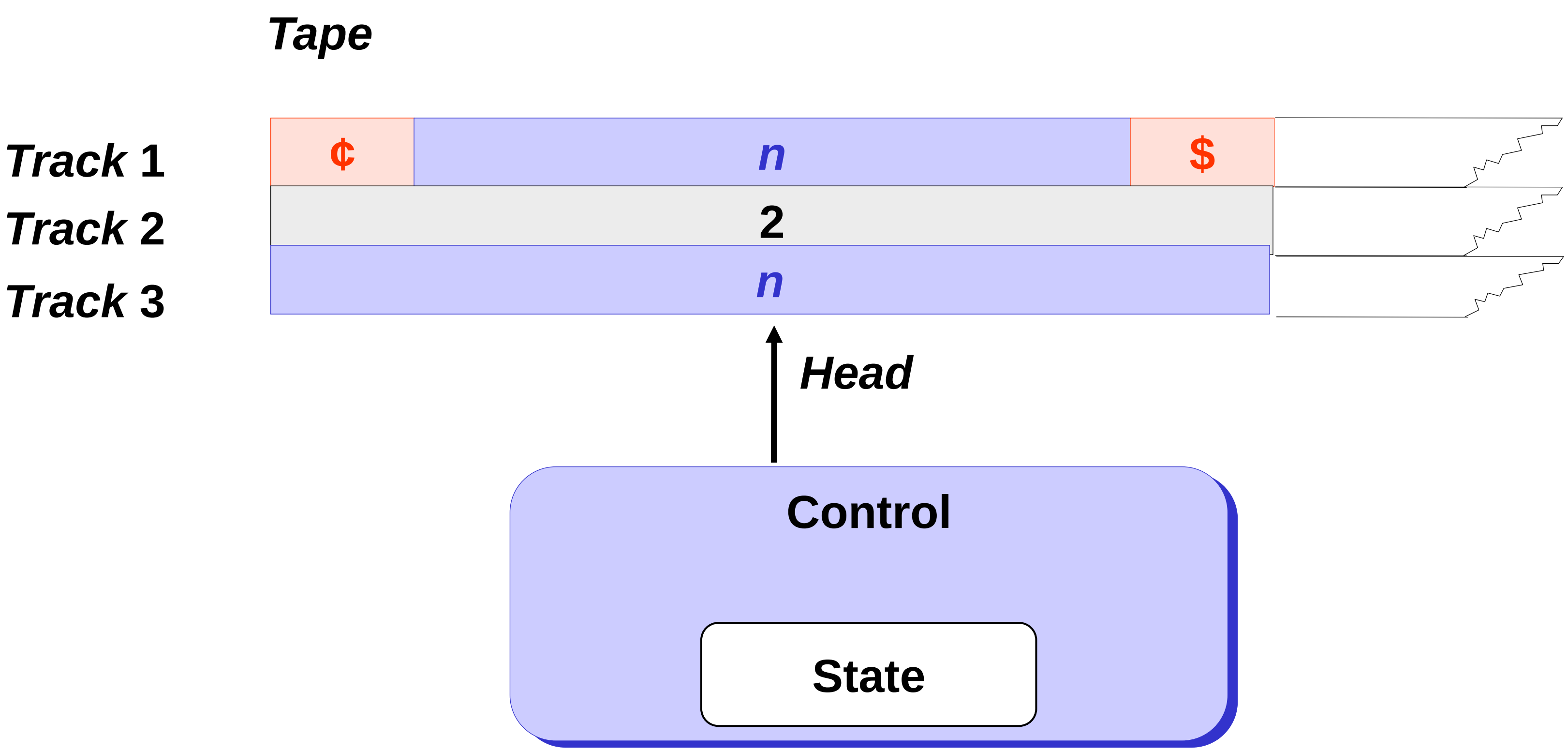
Tape symbols with multiple components

- Language *L*
  - Set of all prime numbers



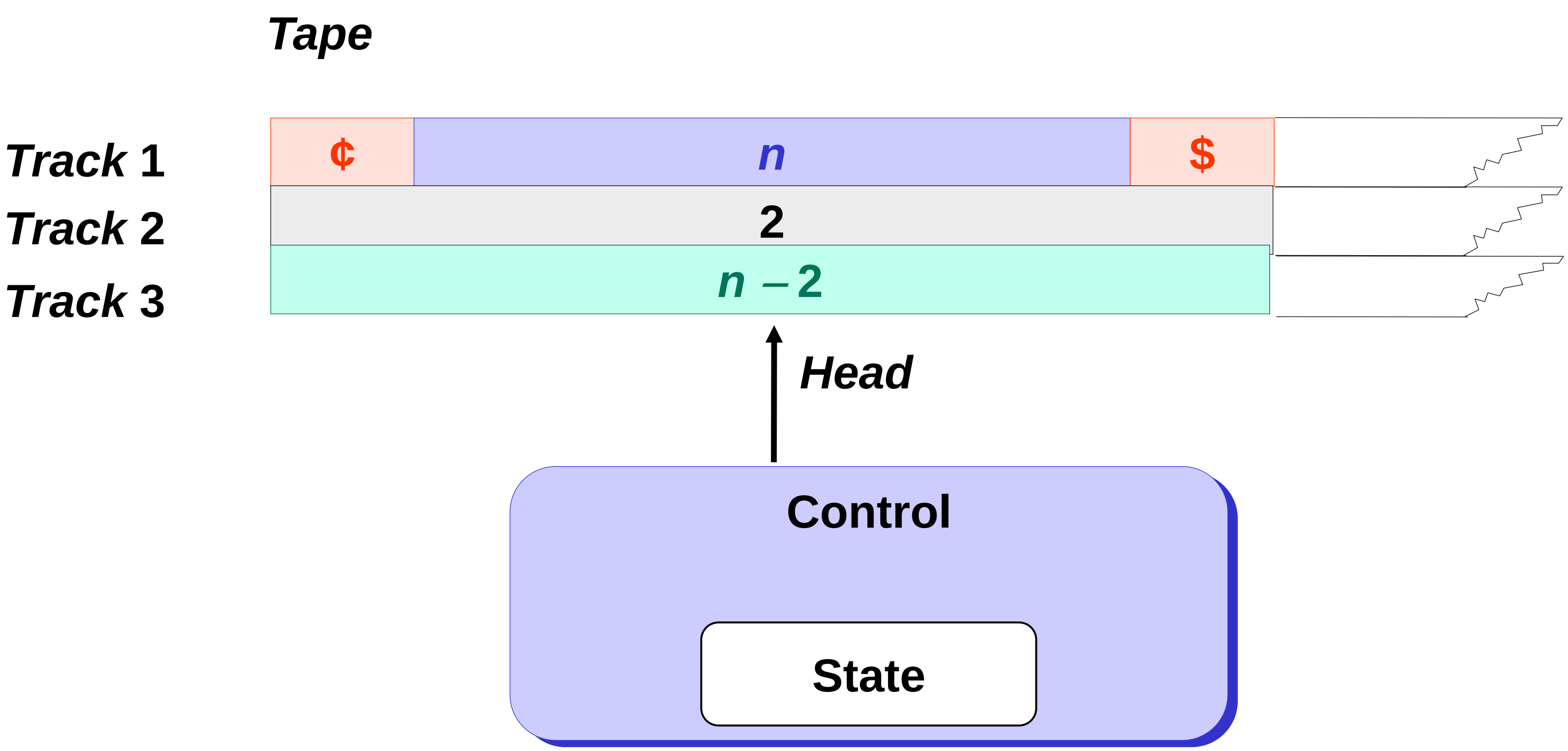
Tape symbols with multiple components

- **Language *L***
  - **Set of all prime numbers**



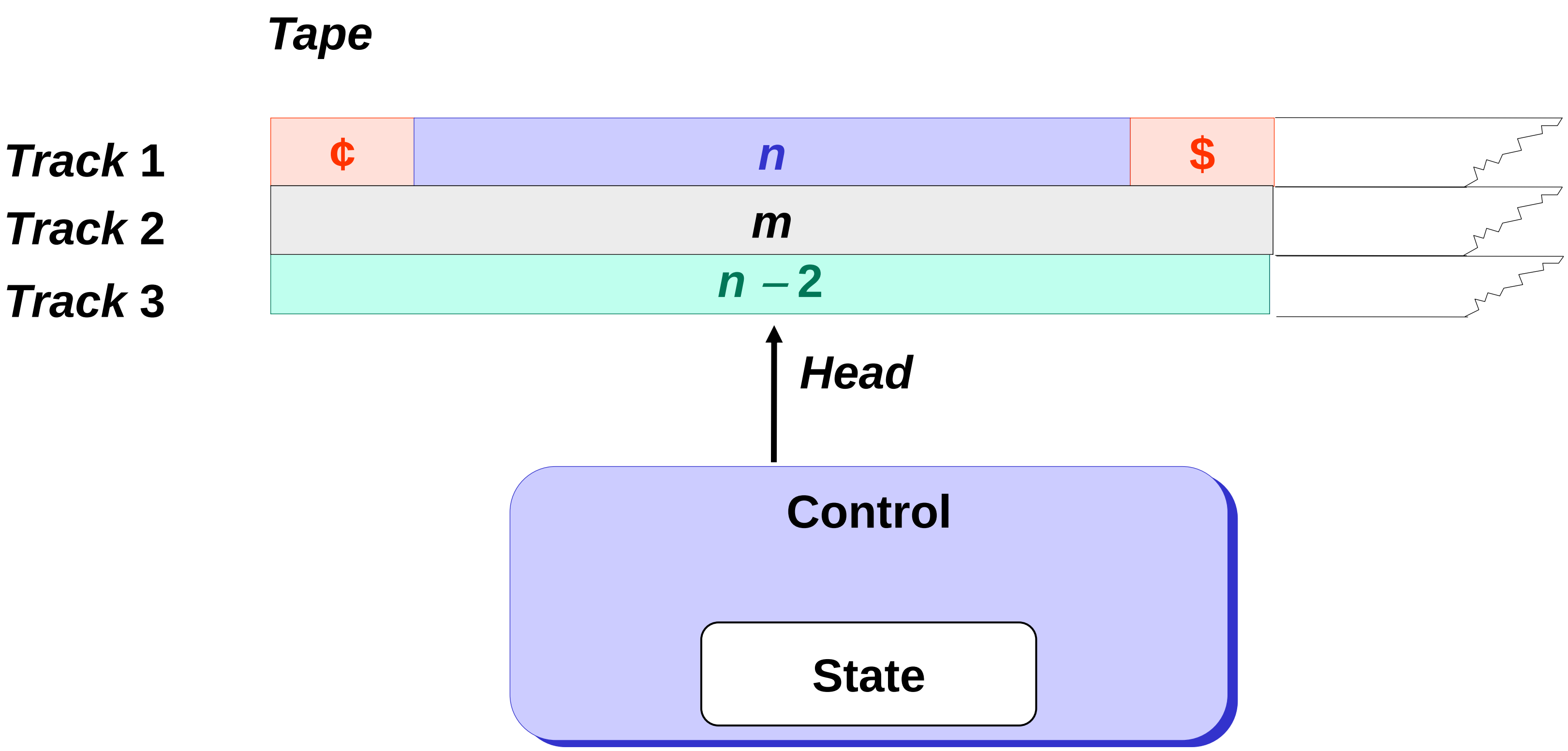
Tape symbols with multiple components

- Language *L*
  - Set of all prime numbers



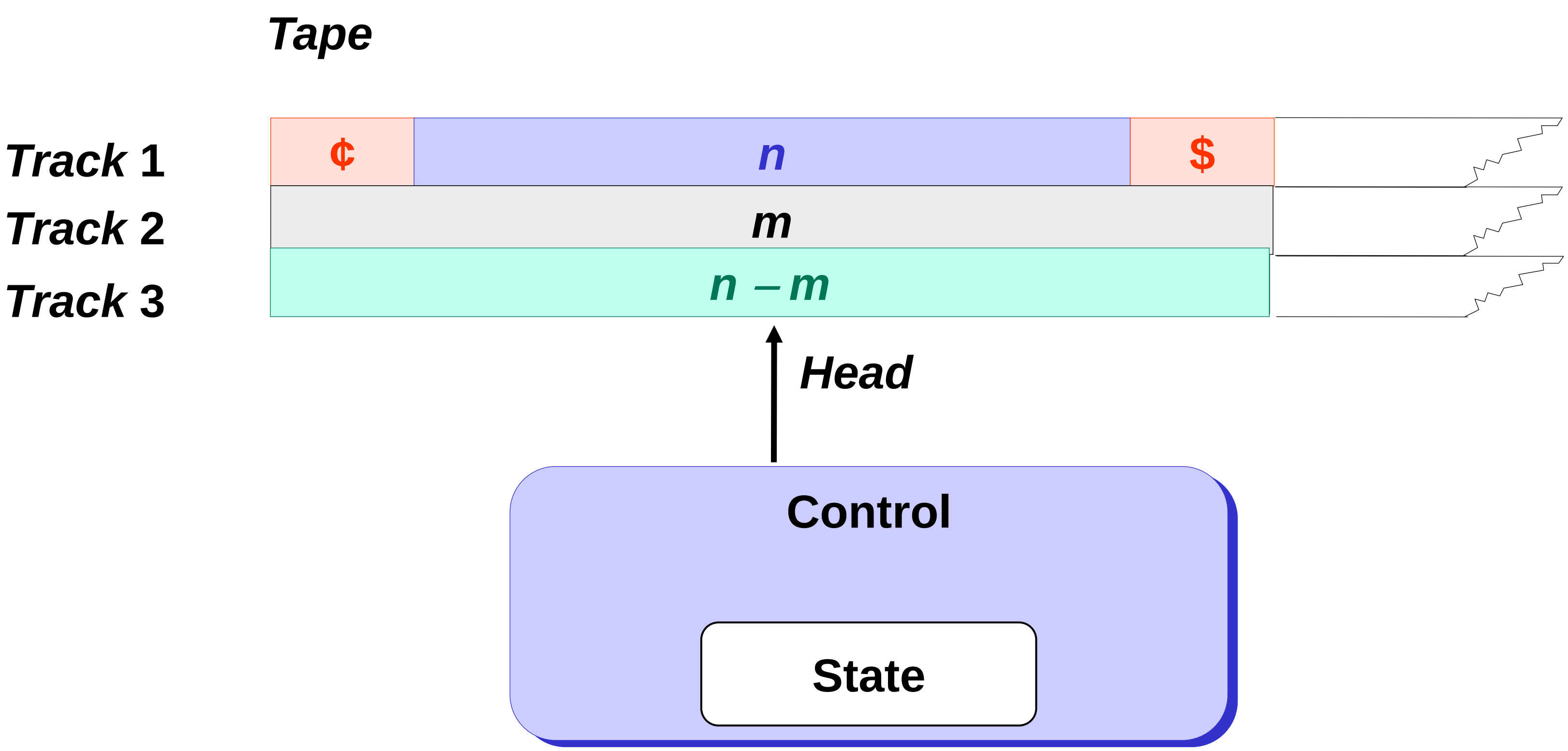
Tape symbols with multiple components

- **Language *L***
  - **Set of all prime numbers**



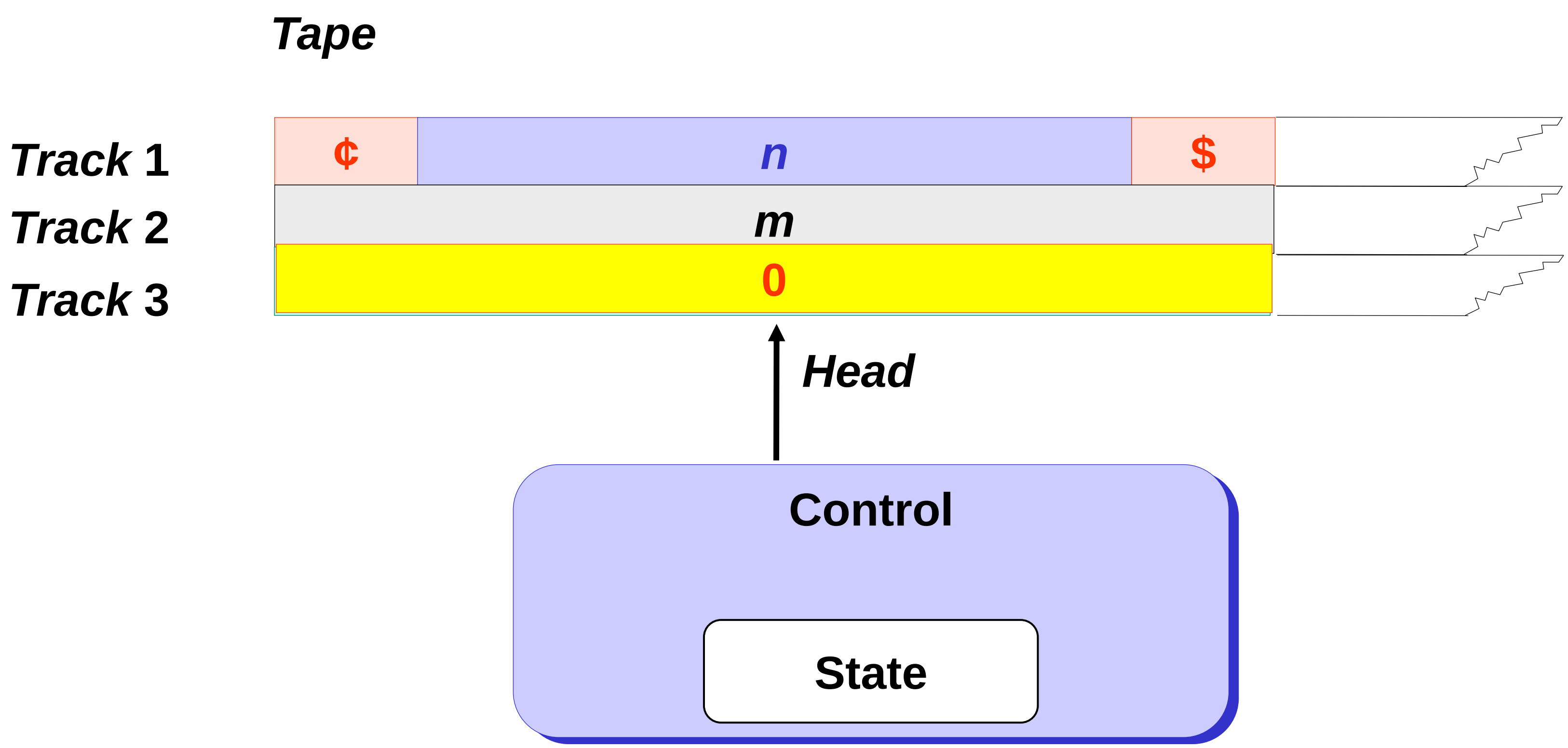
Tape symbols with multiple components

- Language *L*
  - Set of all prime numbers



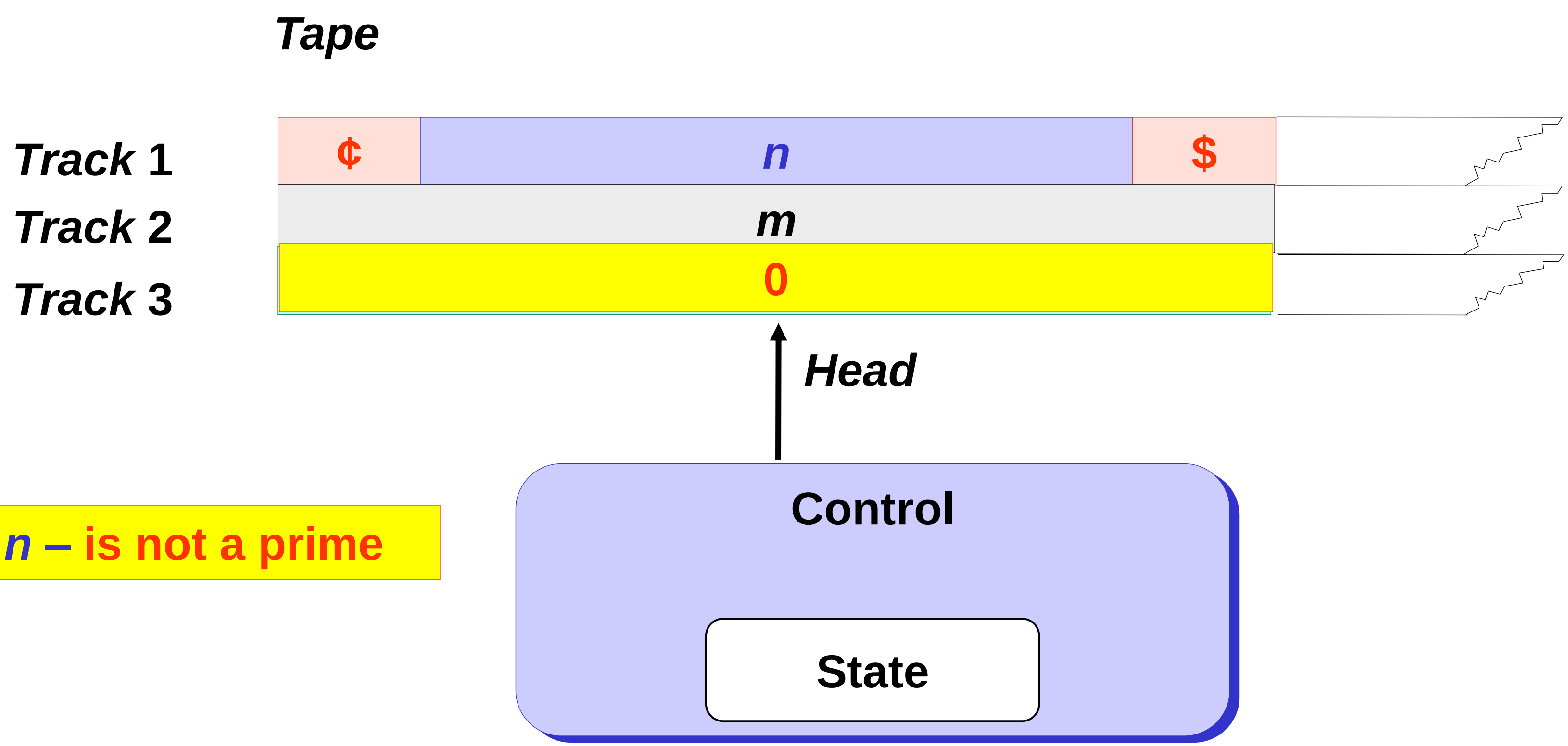
Tape symbols with multiple components

- Language *L*
  - Set of all prime numbers



Tape symbols with multiple components

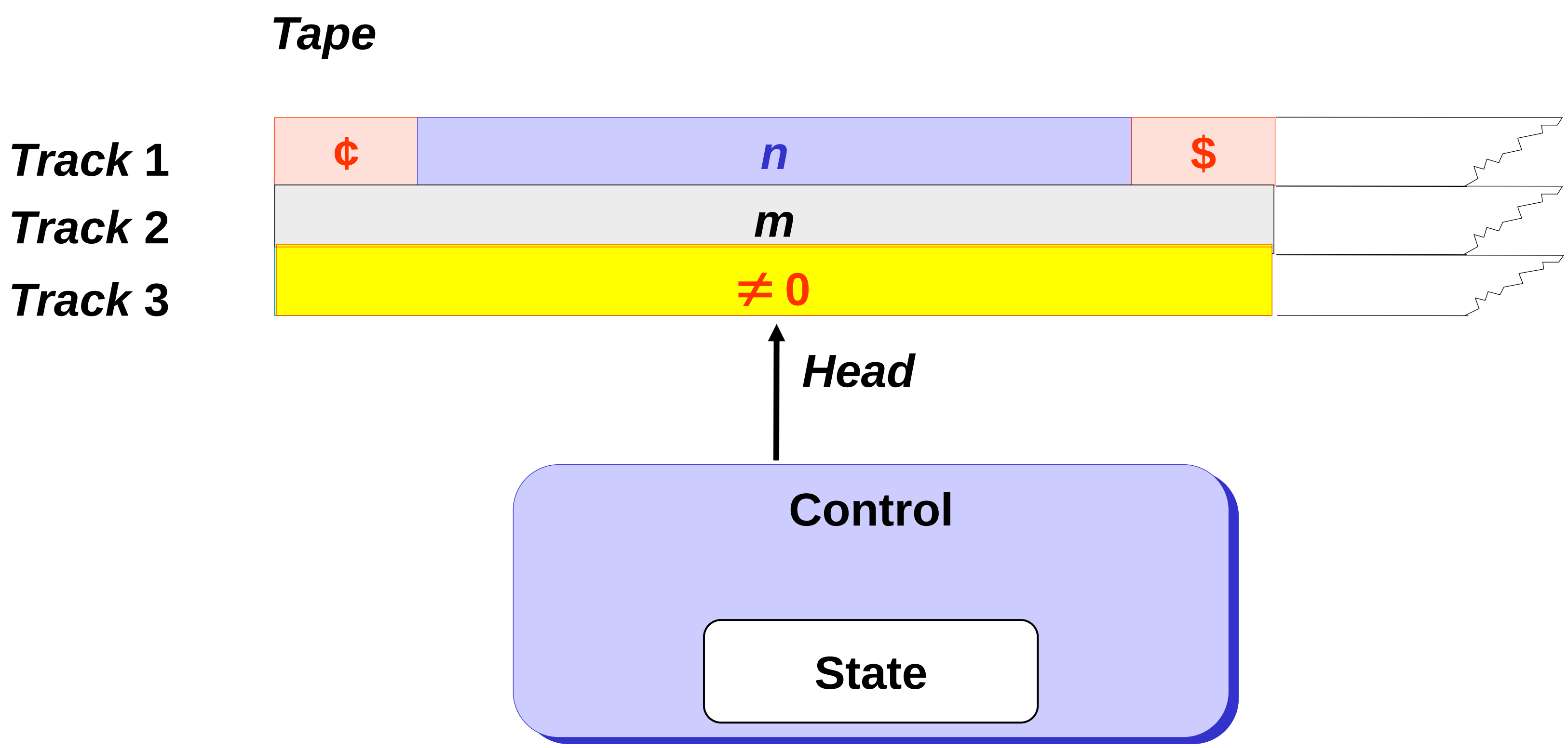
- Language *L*
    - Set of all prime numbers



n – is not a prime

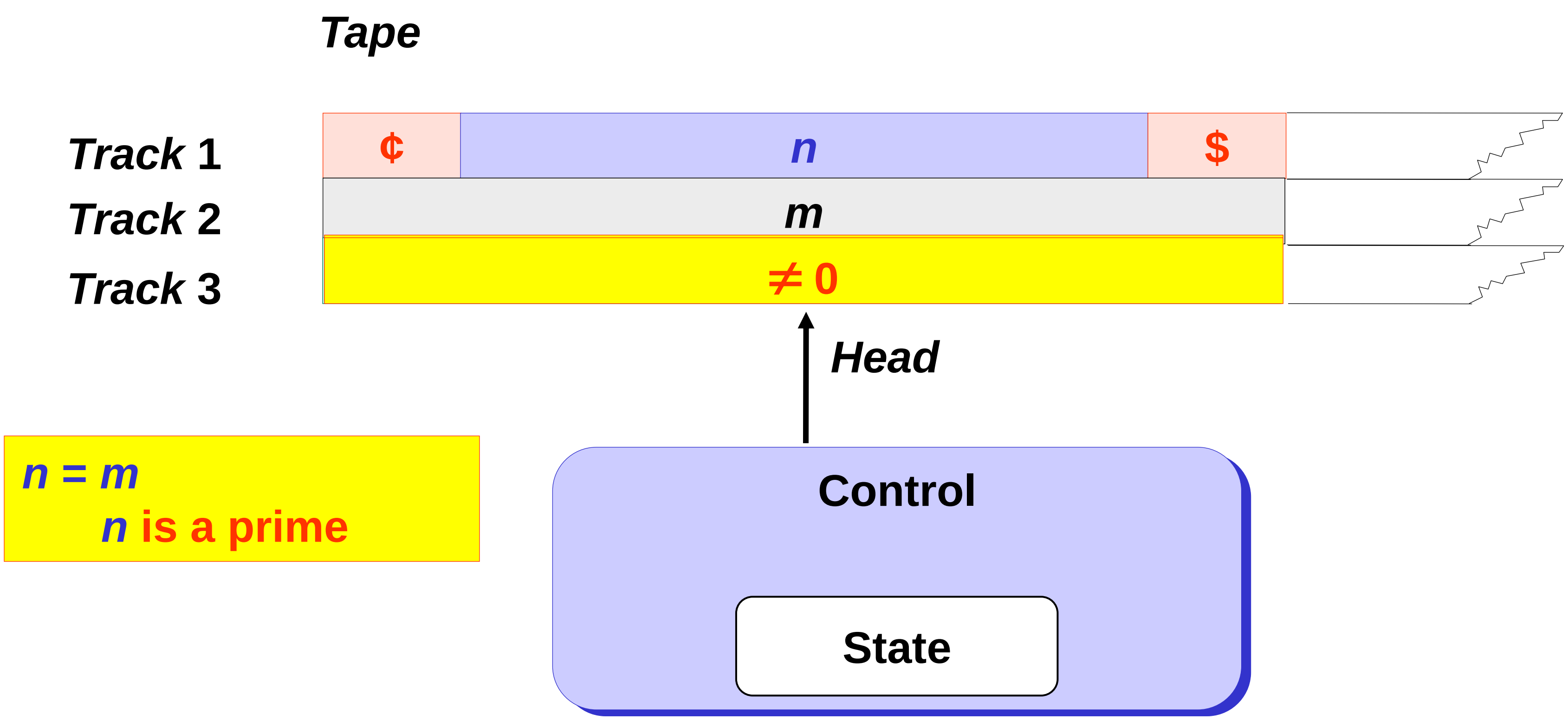
Tape symbols with multiple components

- **Language *L***
  - **Set of all prime numbers**



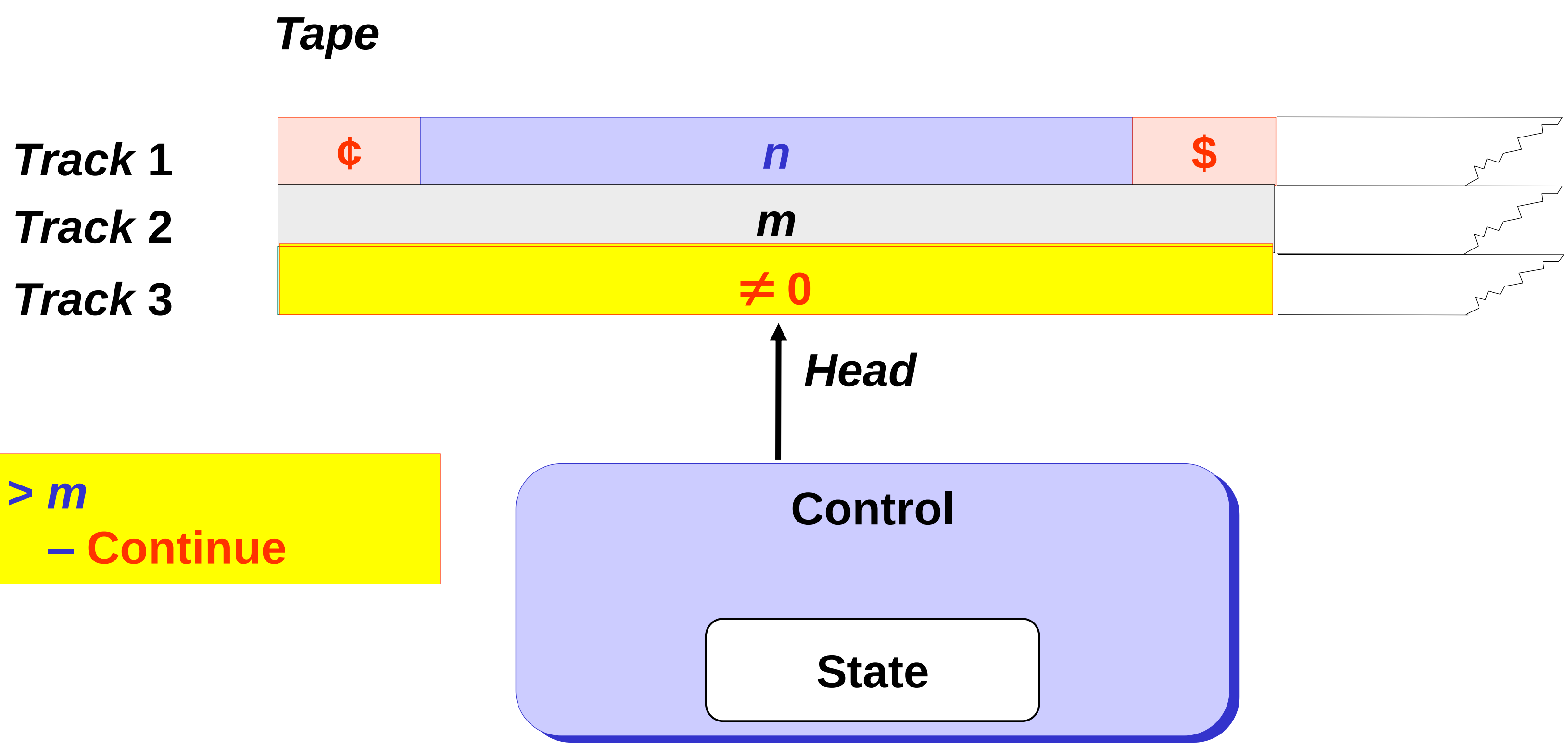
Tape symbols with multiple components

- Language *L*
  - Set of all prime numbers



Tape symbols with multiple components

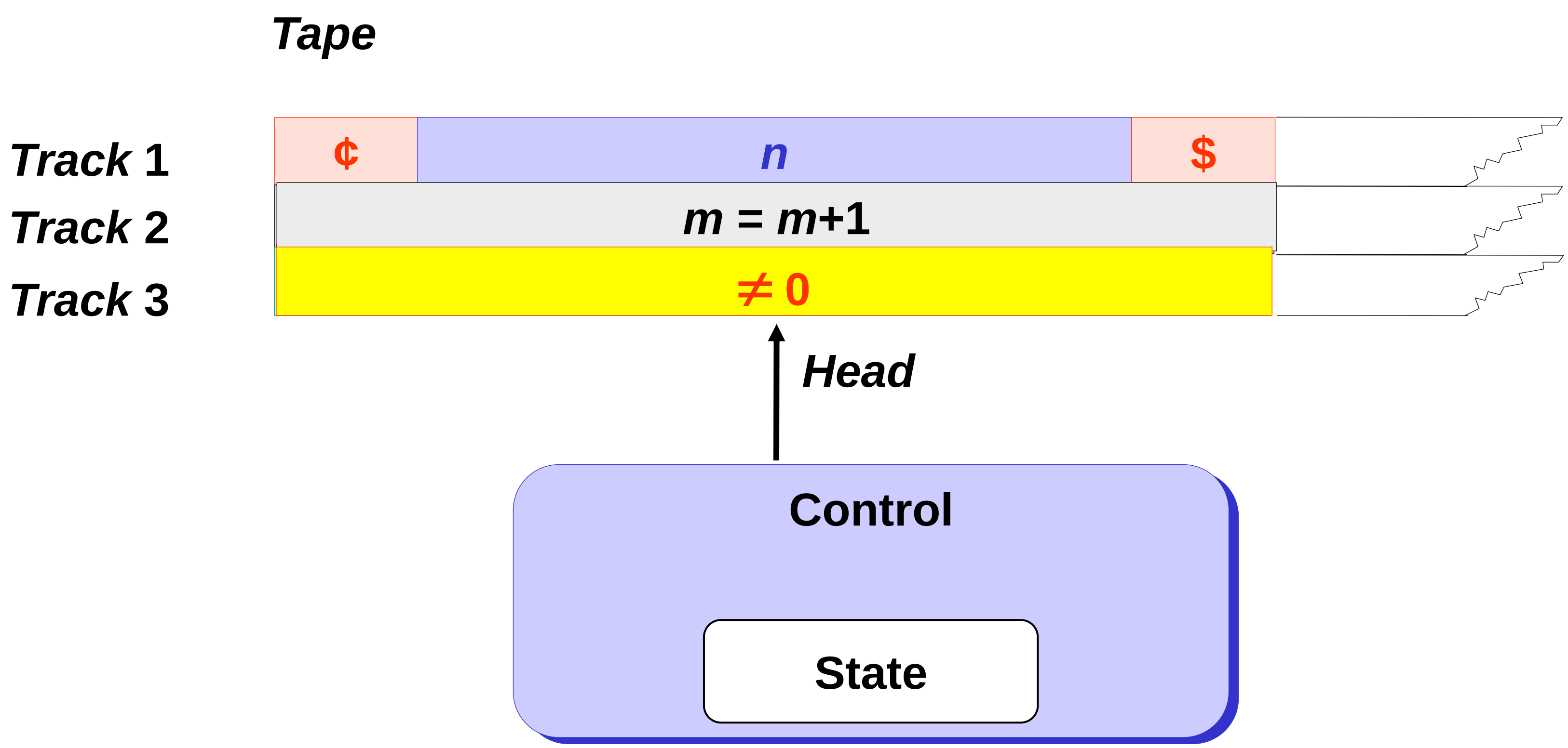
- **Language *L***
  - **Set of all prime numbers**



n > *m*
– Continue

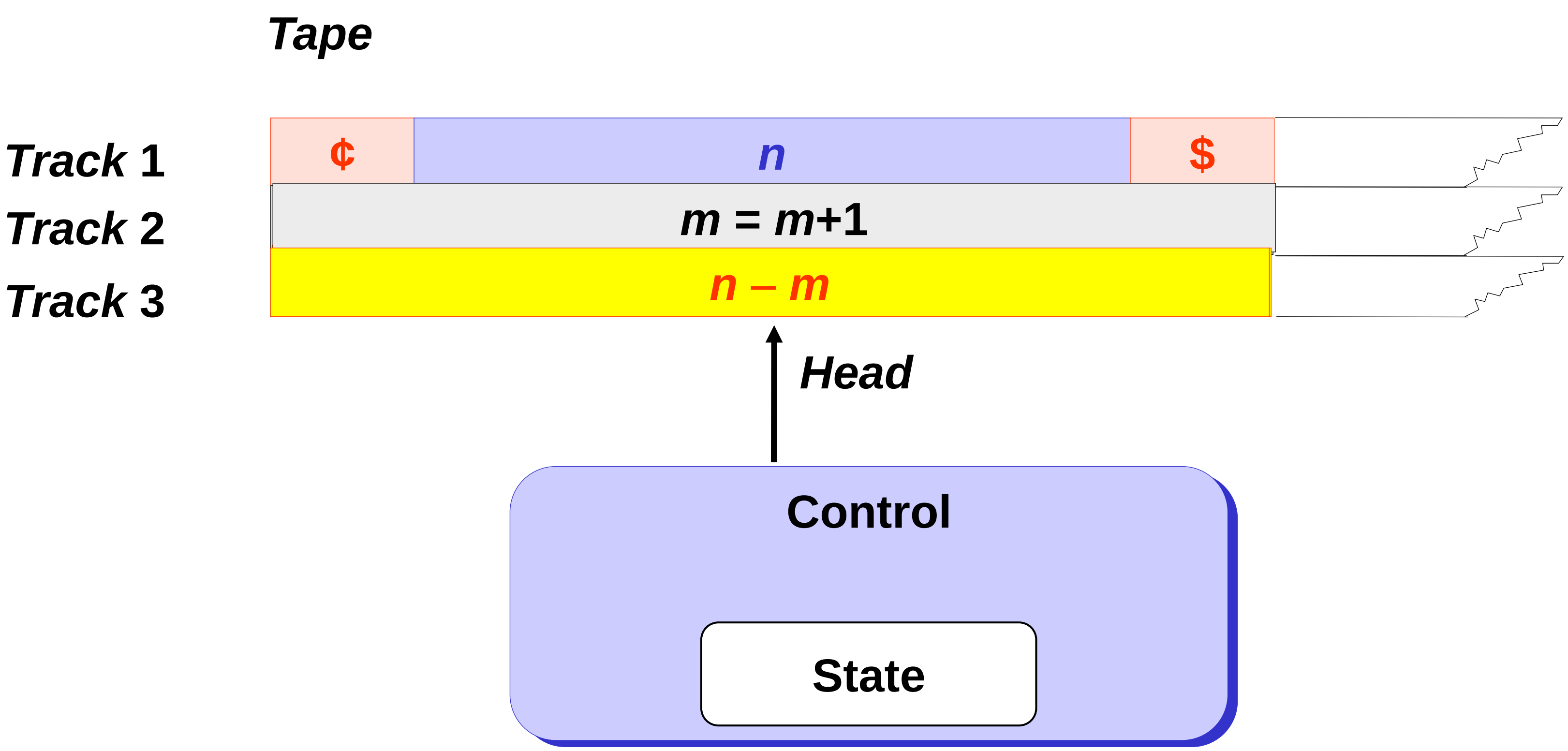
Tape symbols with multiple components

- **Language *L***
  - **Set of all prime numbers**



Tape symbols with multiple components

- Language *L*
  - Set of all prime numbers



Tape symbols with multiple components

- Language *L*
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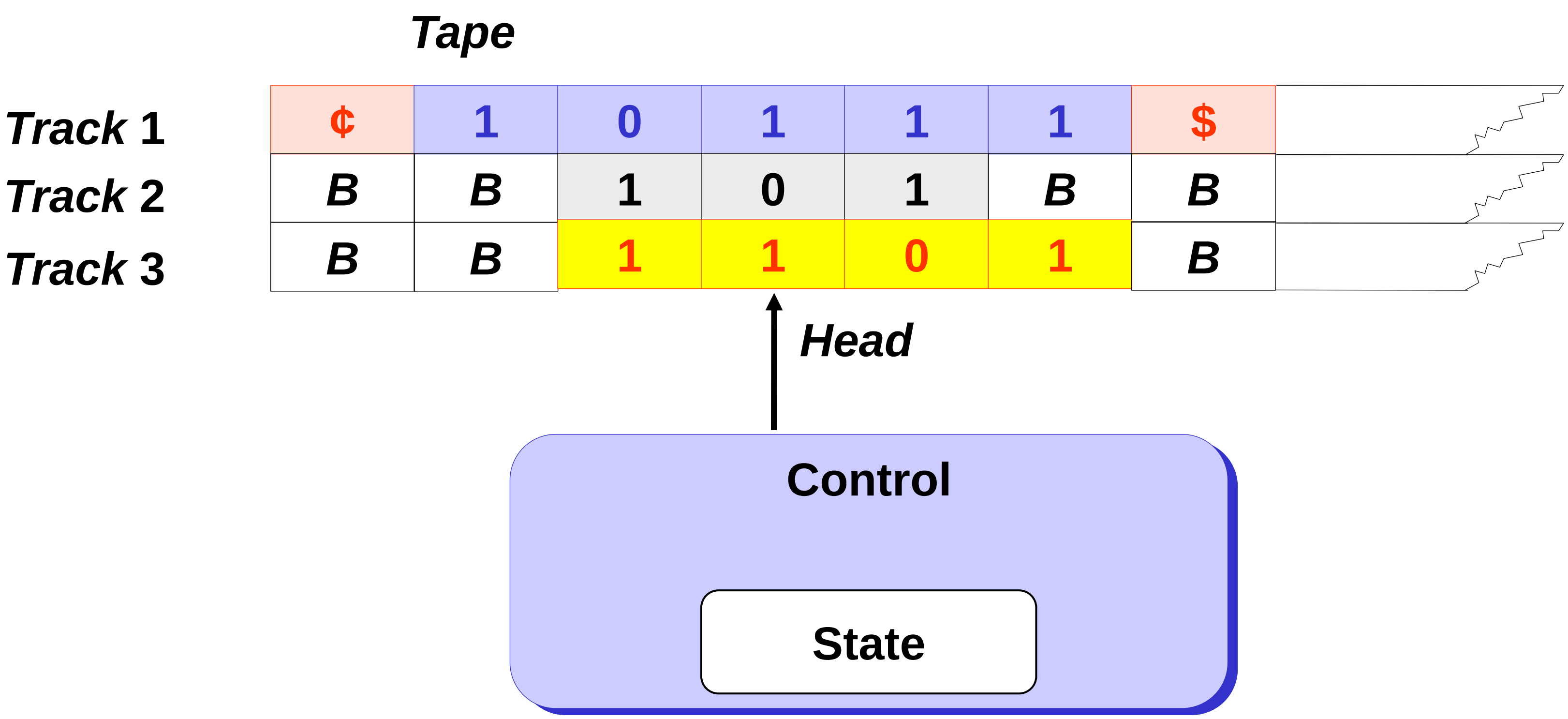

Tape symbols with multiple components

Tape symbols with multiple components

Repeating substrings

Tape symbols with multiple components

Repeating substrings

$\{wcw \mid w \in \Sigma^*\}$, $\{wcy \mid w, y \in \Sigma^*, w \neq y\}$, $\{ww^R \mid w \in \Sigma^*\}$, $w \in (a+b)^+$

Tape symbols with multiple components

Repeating substrings

$\{wcw \mid w\in\Sigma^*\}$, $\{wcy \mid w, y\in\Sigma^*, w\neq y\}$, $\{ww^R \mid w\in\Sigma^*\}$, $w\in(a+b)^+$

Comparing substrings

Tape symbols with multiple components

Repeating substrings

$\{wcw \mid w \in \Sigma^*\}$, $\{wcy \mid w, y \in \Sigma^*, w \neq y\}$, $\{ww^R \mid w \in \Sigma^*\}$, $w \in (a+b)^+$

Comparing substrings

$\{a^i b^i \mid i \geq 1\}$, $\{a^i b^j c^k \mid i \neq j$ ili $j \neq k\}$

Tape symbols with multiple components

Repeating substrings

$\{wcw \mid w \in \Sigma^*\}$ $\{wcy \mid w, y \in \Sigma^*, w \neq y\}$, $\{ww^R \mid w \in \Sigma^*\}$, $w \in (a+b)^+$

Comparing substrings

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$\{wcw \mid w \in \Sigma^*\}$ $\{wcy \mid w, y \in \Sigma^*, w \neq y\}$, $\{ww^R \mid w \in \Sigma^*\}$, $w \in (a+b)^+$

Comparing substrings

$\{a^i b^i \mid i \geq 1\}$, $\{a^i b^j c^k \mid i \neq j \text{ ili } j \neq k\}$

$Q = [q, d]$

Tape symbols with multiple components

Repeating substrings

$\{wcw \mid w \in \Sigma^*\}$ $\{wcy \mid w, y \in \Sigma^*, w \neq y\}$, $\{ww^R \mid w \in \Sigma^*\}$, $w \in (a+b)^+$

Comparing substrings

$\{a^i b^i \mid i \geq 1\}$, $\{a^i b^j c^k \mid i \neq j$ ili $j \neq k\}$

$Q = [q, d]$

q is $q_1, q_2, \ldots q_9$

Tape symbols with multiple components

Repeating substrings

$\{wcw \mid w \in \Sigma^*\}$ $\{wcy \mid w, y \in \Sigma^*, w \neq y\}$, $\{ww^R \mid w \in \Sigma^*\}$, $w \in (a+b)^+$

Comparing substrings

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$Q = [q, d]$

q is q_1, q_2, ... q_9

d is symbol a, b or blank B

Tape symbols with multiple components

Repeating substrings

$\{wcw \mid w \in \Sigma^*\}$ $\{wcy \mid w, y \in \Sigma^*, w \neq y\}$, $\{ww^R \mid w \in \Sigma^*\}$, $w \in (a+b)^+$

Comparing substrings

$\{a^i b^i \mid i \geq 1\}$, $\{a^i b^j c^k \mid i \neq j$ ili $j \neq k\}$

$Q = [q, d]$

q is q_1, q_2, ... q_9

d is symbol a, b or blank B

$\Gamma = [X, d]$

Tape symbols with multiple components

Repeating substrings

$\{wcw \mid w \in \Sigma^*\}$ $\{wcy \mid w, y \in \Sigma^*, w \neq y\}$, $\{ww^R \mid w \in \Sigma^*\}$, $w \in (a+b)^+$

Comparing substrings

$\{a^i b^i \mid i \geq 1\}$, $\{a^i b^j c^k \mid i \neq j$ ili $j \neq k\}$

$Q = [q, d]$

q is q_1, q_2, ... q_9

d is symbol a, b or blank B

$\Gamma = [X, d]$

X is B or $\surd$

Tape symbols with multiple components

Repeating substrings

$\{wcw \mid w \in \Sigma^*\}$ $\{wcy \mid w, y \in \Sigma^*, w \neq y\}$, $\{ww^R \mid w \in \Sigma^*\}$, $w \in (a+b)^+$

Comparing substrings

$\{a^i b^i \mid i \geq 1\}$, $\{a^i b^j c^k \mid i \neq j$ ili $j \neq k\}$

$Q = [q, d]$

q is $q_1, q_2, \ldots q_9$

d is symbol a, b or blank B

$\Gamma = [X, d]$

X is B or $\surd$

d is a, b, c or blank B

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

Tape symbols with multiple components

{wcw | $w \in \Sigma^*$}

B	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

B	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, B\ ], [\surd, d], R)$

Tape symbols with multiple components

{*wcw* | *w*∈Σ*}

B	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, B\ \ ], [\surd, d], R)$

Tape symbols with multiple components

{wcw | $w \in \Sigma^*$}

B	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, B\ ], [\surd, d], R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

B	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d\ ], [\surd, d], R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

B	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d\ ], \sqrt{}, d, R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d\ ], [\surd, d], R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d], [\surd, d], R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d\ ], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d\ ], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d\ ], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [B, d], L)$

Tape symbols with multiple components

{wcw | $w \in \Sigma^*$}

√	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
a	a	b	a	a	a	b	b	c	a	a	b	a	a	a	b	b	B	B

$\delta([q_1, B], [B, d]) = ([q_2, d\ ], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\ B\ , d], L)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d\ ], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\ \surd\ , d], L)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d\ ], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\ \surd\ , d], L)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\surd, d], L)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	B	B	B	B	B	B	B	B	√	B	B	B	B	B	B	B	B	B
a	a	b	a	a	a	b	b	c	a	a	b	a	a	a	b	b	B	B

$\delta([q_1, B], [B, d]) = ([q_2, d], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	B	B	B	B	B	B	B	B	√	B	B	B	B	B	B	B	B	B
a	a	b	a	a	a	b	b	c	a	a	b	a	a	a	b	b	B	B

$\delta([q_1, B], [B, d]) = ([q_2, d], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

Tape symbols with multiple components

{*wcw* | *w*∈Σ*}

√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d\ ], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\ \surd\ , d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [B, c]) = ([q_5, B], [B, c], L)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [B, c]) = ([q_5, B], [B, c], L)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [B, c]) = ([q_5, B], [B, c], L)$

$\delta([q_5, B], [B, d]) = ([q_6, B], [B, d], L)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [B, c]) = ([q_5, B], [B, c], L)$

$\delta([q_5, B], [B, d]) = ([q_6, B], [B, d], L)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	B	B	B	B	B	B	B	B	√	B	B	B	B	B	B	B	B	B
a	a	b	a	a	a	b	b	c	a	a	b	a	a	a	b	b	B	B

$\delta([q_1, B], [B, d]) = ([q_2, d\ ], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\ \surd\ , d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [B, c]) = ([q_5, B], [B, c], L)$

$\delta([q_5, B], [B, d]) = ([q_6, B], [B, d], L)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [B, c]) = ([q_5, B], [B, c], L)$

$\delta([q_5, B], [B, d]) = ([q_6, B], [B, d], L)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [B, c]) = ([q_5, B], [B, c], L)$

$\delta([q_5, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [B, d]) = ([q_6, B], [B, d], L)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [B, c]) = ([q_5, B], [B, c], L)$

$\delta([q_5, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [B, d]) = ([q_6, B], [B, d], L)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	B	B	B	B	B	B	B	B	√	B	B	B	B	B	B	B	B	B
a	a	b	a	a	a	b	b	c	a	a	b	a	a	a	b	b	B	B

$\delta([q_1, B], [B, d]) = ([q_2, d], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [B, c]) = ([q_5, B], [B, c], L)$

$\delta([q_5, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [B, d]) = ([q_6, B], [B, d], L)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	B	B	B	B	B	B	B	B	√	B	B	B	B	B	B	B	B	B
a	a	b	a	a	a	b	b	c	a	a	b	a	a	a	b	b	B	B

$\delta([q_1, B], [B, d]) = ([q_2, d], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [B, c]) = ([q_5, B], [B, c], L)$

$\delta([q_5, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [\surd, d]) = ([q_1, B], [\surd, d], R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [B, c]) = ([q_5, B], [B, c], L)$

$\delta([q_5, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [\surd, d]) = ([q_1, B], [\surd, d], R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	√	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [B, c]) = ([q_5, B], [B, c], L)$

$\delta([q_5, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [\surd, d]) = ([q_1, B], [\surd, d], R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	B	B	B	B	B	B	B	B	√	B	B	B	B	B	B	B	B	B
a	a	b	a	a	a	b	b	c	a	a	b	a	a	a	b	b	B	B

$\delta([q_1, B], [B, d]) = ([q_2, d], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [B, c]) = ([q_5, B], [B, c], L)$

$\delta([q_5, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [\surd, d]) = ([q_1, B], [\surd, d], R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	√	√	√	√	√	√	√	*B*	√	√	√	√	√	√	√	√	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d\ ], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\ \surd, d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [B, c]) = ([q_5, B], [B, c], L)$

$\delta([q_5, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [\surd, d]) = ([q_1, B], [\surd, d], R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	√	√	√	√	√	√	√	*B*	√	√	√	√	√	√	√	√	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d\ ], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\ \surd\ , d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [B, c]) = ([q_5, B], [B, c], L)$

$\delta([q_5, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [\surd, d]) = ([q_1, B], [\surd, d], R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	√	√	√	√	√	√	√	*B*	√	√	√	√	√	√	√	√	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d\ ], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\ \surd\ , d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [B, c]) = ([q_5, B], [B, c], L)$

$\delta([q_5, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [\surd, d]) = ([q_1, B], [\surd, d], R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	√	√	√	√	√	√	√	*B*	√	√	√	√	√	√	√	√	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d\ ], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\ \surd\ , d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [B, c]) = ([q_5, B], [B, c], L)$

$\delta([q_5, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [\surd, d]) = ([q_1, B], [\surd, d], R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	√	√	√	√	√	√	√	*B*	√	√	√	√	√	√	√	√	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d\ ], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\ \surd, d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [B, c]) = ([q_5, B], [B, c], L)$

$\delta([q_5, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [\surd, d]) = ([q_1, B], [\surd, d], R)$

$\delta([q_5, B], [\surd, d]) = ([q_7, B], [\surd, d], R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	√	√	√	√	√	√	√	*B*	√	√	√	√	√	√	√	√	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [B, c]) = ([q_5, B], [B, c], L)$

$\delta([q_5, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [\surd, d]) = ([q_1, B], [\surd, d], R)$

$\delta([q_5, B], [\surd, d]) = ([q_7, B], [\surd, d], R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	√	√	√	√	√	√	√	*B*	√	√	√	√	√	√	√	√	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [B, c]) = ([q_5, B], [B, c], L)$

$\delta([q_5, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [\surd, d]) = ([q_1, B], [\surd, d], R)$

$\delta([q_5, B], [\surd, d]) = ([q_7, B], [\surd, d], R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	√	√	√	√	√	√	√	*B*	√	√	√	√	√	√	√	√	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d\ ], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\ \surd, d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [B, c]) = ([q_5, B], [B, c], L)$

$\delta([q_5, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [\surd, d]) = ([q_1, B], [\surd, d], R)$

$\delta([q_5, B], [\surd, d]) = ([q_7, B], [\surd, d], R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	√	√	√	√	√	√	√	*B*	√	√	√	√	√	√	√	√	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d\ ], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\ \surd\ , d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [B, c]) = ([q_5, B], [B, c], L)$

$\delta([q_5, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [\surd, d]) = ([q_1, B], [\surd, d], R)$

$\delta([q_5, B], [\surd, d]) = ([q_7, B], [\surd, d], R)$

$\delta([q_7, B], [B, c]) = ([q_8, B], [B, c], R)$

$\delta([q_8, B], [\surd, d]) = ([q_8, B], [\surd, d], R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	√	√	√	√	√	√	√	*B*	√	√	√	√	√	√	√	√	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [B, c]) = ([q_5, B], [B, c], L)$

$\delta([q_5, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [\surd, d]) = ([q_1, B], [\surd, d], R)$

$\delta([q_5, B], [\surd, d]) = ([q_7, B], [\surd, d], R)$

$\delta([q_7, B], [B, c]) = ([q_8, B], [B, c], R)$

$\delta([q_8, B], [\surd, d]) = ([q_8, B], [\surd, d], R)$

Tape symbols with multiple components

$\{wcw \mid w \in \Sigma^*\}$

√	√	√	√	√	√	√	√	*B*	√	√	√	√	√	√	√	√	*B*	*B*
a	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*c*	*a*	*a*	*b*	*a*	*a*	*a*	*b*	*b*	*B*	*B*

$\delta([q_1, B], [B, d]) = ([q_2, d\ ], [\surd, d], R)$

$\delta([q_2, d], [B, e]) = ([q_2, d], [B, e], R)$

$\delta([q_2, d], [B, c]) = ([q_3, d], [B, c], R)$

$\delta([q_3, d], [\surd, e]) = ([q_3, d], [\surd, e], R)$

$\delta([q_3, d], [B, d]) = ([q_4, B], [\ \surd, d], L)$

$\delta([q_4, B], [\surd, d]) = ([q_4, B], [\surd, d], L)$

$\delta([q_4, B], [B, c]) = ([q_5, B], [B, c], L)$

$\delta([q_5, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [B, d]) = ([q_6, B], [B, d], L)$

$\delta([q_6, B], [\surd, d]) = ([q_1, B], [\surd, d], R)$

$\delta([q_5, B], [\surd, d]) = ([q_7, B], [\surd, d], R)$

$\delta([q_7, B], [B, c]) = ([q_8, B], [B, c], R)$

$\delta([q_8, B], [\surd, d]) = ([q_8, B], [\surd, d], R)$

$\delta([q_8, B], [B, B])=([q_9, B], [B, B], L)$