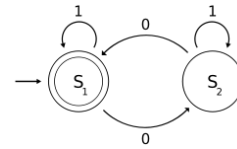


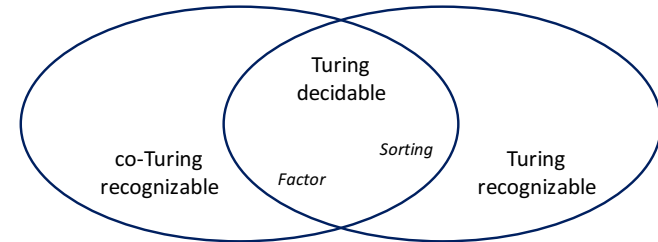
## Measuring Time Complexity

Sipser: Section 7.1 pages 275 - 284

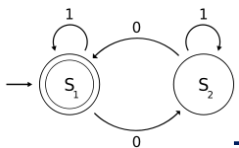
T - 1



## Solvable in Theory ...

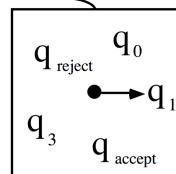
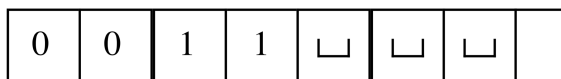


T - 2

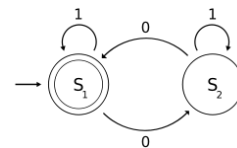


## Measuring Difficulty

How hard is it to recognize  $\{0^k1^k \mid k \geq 0\}$ ?



T - 3

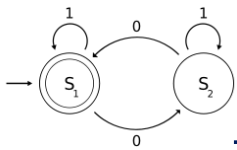


## An Algorithm

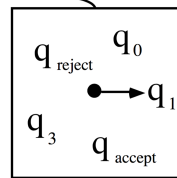
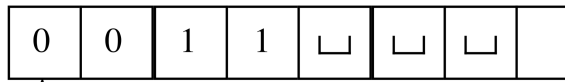
$M_1$  = "On input string  $w$ :

1. Scan across the tape and *reject* if a 0 is found to the right of a 1.
2. Repeat the following if both 0s and 1s remain.
3. Scan across tape, crossing off a single 0 and a single 1.
4. If either 0 or 1 remains, *reject*. Otherwise, *accept*."

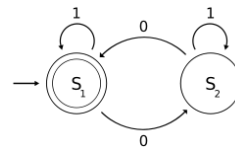
T - 4



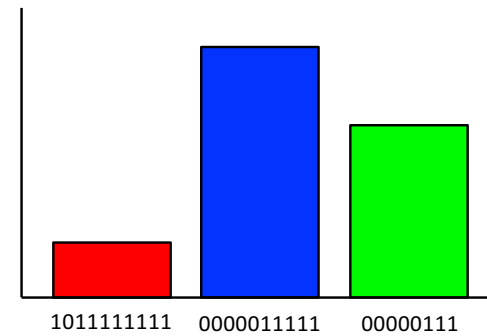
## Number of Steps Depends on Size of Input



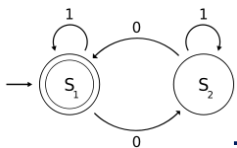
T-5



## The Good, the Bad, and the Average



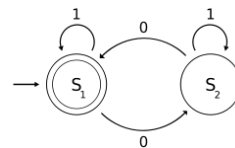
T-6



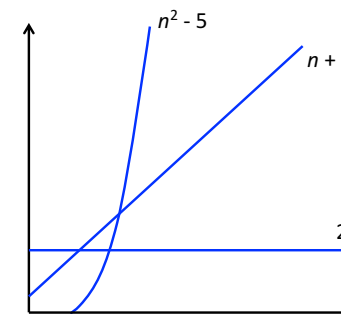
## Time Complexity

**Definition.** The *time complexity* of TM  $M$  is the function  $f: \mathbb{N} \rightarrow \mathbb{N}$ , where  $f(n)$  is the maximum number of steps that  $M$  uses on any input of length  $n$ .

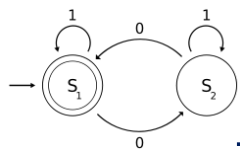
T-7



## Asymptotic Analysis



T-8



## Big O, Little o

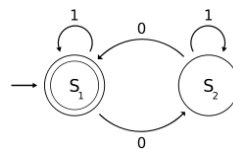
**Definition.** Consider  $f, g: \mathbb{N} \rightarrow \mathbb{R}^+$ . Say that  $f(n) = O(g(n))$  if positive integers  $c$  and  $n_0$  exist such that for every  $n \geq n_0$

$$f(n) \leq c g(n)$$

**Definition.** Consider  $f, g: \mathbb{N} \rightarrow \mathbb{R}^+$ . Say that  $f(n) = o(g(n))$  if

$$\lim_{n \rightarrow \infty} f(n)/g(n) = 0$$

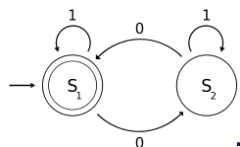
T - 9



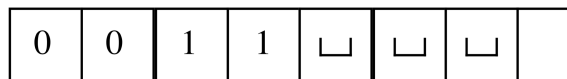
## True or False?

1.  $8n + 5 = O(n)$
2.  $8n + 5 = o(n)$
3.  $\sqrt{n} = o(n)$
4.  $\log_2 n = o(\ln n)$
5.  $n \log \log n = o(n \log n)$
6.  $n^2 = o(n \log n)$

T - 10



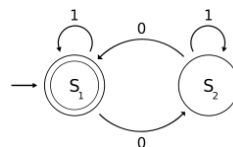
## The Verdict Please ...



$M_1 =$  "On input string  $w$ :

1. Scan across the tape and *reject* if a 0 is found to the right of a 1.
2. Repeat the following if both 0s and 1s remain.
3. Scan across tape, crossing off a single 0 and a single 1.
4. If either 0 or 1 remains, *reject*. Otherwise, *accept*."

T - 11



## Time Complexity Classes

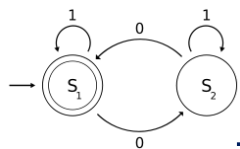
**Definition.** Let  $t: \mathbb{N} \rightarrow \mathbb{N}$  be a function. Define the time complexity class,  $\text{TIME}(t(n))$ , to be

$$\text{TIME}(t(n)) = \{ L \mid L \text{ is decided by } O(t(n)) \text{ time TM } \}$$

**Example.** The language  $\{ 0^k 1^k \mid k \geq 0 \} \in \text{TIME}(n^2)$ .\*

\* And  $\text{TIME}(n^3)$  and  $\text{TIME}(n^4)$  and ...

T - 12

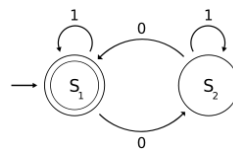


## Losing TIME Complexity

$M_2$  = "On input string  $w$ :

1. Scan across the tape and *reject* if a 0 is found to the right of a 1.
2. Repeat the following if both 0s and 1s remain.
3. Scan across tape, checking whether the total number of 0s and 1s remaining on the tape is even or odd. If odd, *reject*.
4. Scan again across tape, crossing off every other 0 and every other 1.
5. If no 0s or 1s remain, *accept*. Otherwise, *reject*."

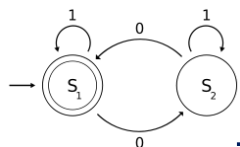
T - 13



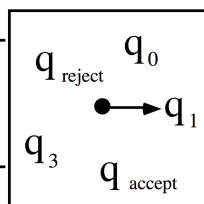
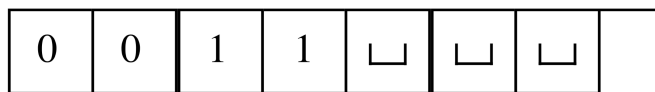
## Better Still???

**Theorem.** Let  $f: \mathbb{N} \rightarrow \mathbb{N}$  belong to  $o(n \log n)$ . If language  $A \in \text{TIME}(f)$ , then  $A$  is regular.

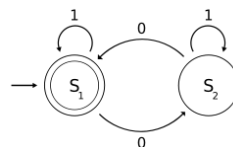
T - 14



## Ah, But What If We Had Two Tapes ...



T - 15



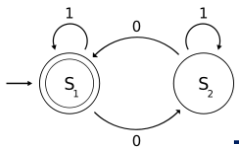
## Well, Then We Could Do Better Still!\*

**Theorem.** Let  $t(n)$  be a function, where  $t(n) \geq n$ . Then every  $t(n)$  time multitape Turing machine has an equivalent  $O(t^2(n))$  time single-tape Turing machine.

**Proof.** Compare the time complexity of the given multitape machine with the equivalent single tape machine that simulates it.

\* But only slightly.

T - 16



## How Costly Is Nondeterminism?

**Theorem.** Let  $t(n)$  be a function, where  $t(n) \geq n$ . Then every  $t(n)$  time nondeterministic single-tape Turing machine has an equivalent  $2^{\Omega(t(n))}$  time deterministic single-tape Turing machine.

**Proof.**

Compare the time complexity of the given nondeterministic machine with the equivalent single tape deterministic machine that simulates it.

