

# Computational Models — Lecture 11<sup>1</sup>

## Handout Mode

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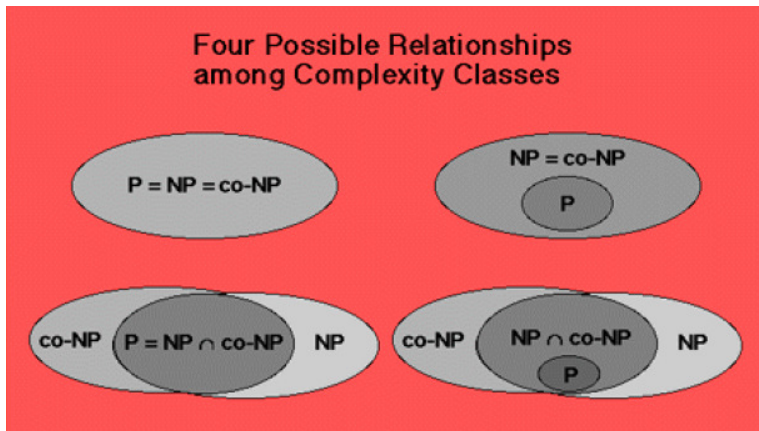
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<sup>1</sup>Based on frames by Benny Chor, Tel Aviv University, modifying frames by Maurice Herlihy, Brown University. With added modifications of Yishai Mansour.

## Ladies and Gentlemen, Boys and Girls

We are about to begin the fourth part of the course:

# Introduction to Computational Complexity



## Talk Outline

- ▶ Introduction to time complexity
  - ▶ The class  $\mathcal{P}$
  - ▶ The class  $\mathcal{NP}$
  - ▶ Verifiability
- 
- ▶ Sipser's book [7.1-7.3](#)

# Part I

## Introduction to Time Complexity

## How Long It takes to decide $L = \{0^m 1^m : m \geq 0\}$

Clearly  $L \in \mathcal{R}$ .

### Question 1

How much time does a **single-tape** TM need to decide  $L$ ?

### Algorithm 2 (Decider $M_1$ for $L$ )

On input string  $w$ :

1. Scan across tape and **Reject** if **0** is found to the right of a **1**.
2. While both **0**s and **1**s appear on tape, repeat the following:  
Scan across tape, crossing of a single **0** and a single **1** in each pass.
3. **Accept** if no **0**s and **1**s remain; otherwise **Reject**.

We analyze the time it takes to perform each of the three steps separately. In the following let  $n = |w|$ .

## Analyzing Step 1

*Scan across tape and **Reject** if 0 is found to the right of a 1. If not, return to starting point.*

- ▶ Scanning requires  $n$  steps.
- ▶ Re-positioning head requires  $n$  steps.
- ▶ Total is  $2n = O(n)$  steps.

## Analyzing Step 2

*While both 0s and 1s appear on tape, repeat the following*

*Scan across tape, crossing off a single 0 and a single 1 in each pass.*

- ▶ Each scan requires  $O(n)$  steps.
- ▶ Since each scan crosses off two symbols, the number of scans is at most  $n/2$ .
- ▶ Total number of steps is  $(n/2) \cdot O(n) = O(n^2)$ .

## Analyzing Step 3

*If 0s still remain after all 1s have been crossed out, or vice-versa, Reject. Otherwise, if the tape is empty, Accept.*

- ▶ Single scan requires  $O(n)$  steps.
- ▶ Total is  $O(n)$  steps.



## Total Cost

Total cost for three steps

1.  $O(n)$
2.  $O(n^2)$
3.  $O(n)$

which is  $O(n^2)$

## Deterministic Time

### Definition 3 (deterministic Time)

Let  $M$  be a **deterministic** TM, and let  $t : \mathbb{N} \mapsto \mathbb{N}$ . We say that  $M$  runs in time  $t(n)$ , if For **every** input  $x$  of length  $n$ , the number of steps that  $M(x)$  uses is **at most**  $t(n)$ .

### Question 4

What is a “step”?

### Definition 5 (DTIME)

For  $t : \mathbb{N} \mapsto \mathbb{N}$ , let  $\text{DTIME}(t(n)) =$   
 $\{L \subseteq \Sigma^* : L \text{ is } \mathbf{decided} \text{ by an } O(t(n))\text{-time } \mathbf{single\ tape\ TM}\}$

Note that  $t(n)$  running time, is also required for strings **not** in  $L$ .

# Language Encoding

- ▶ Let  $L = \{1^n : n \in \mathbb{N}\}$ .  
Is  $L$  in  $\text{DTIME}(n)$ ? in  $\text{DTIME}(n^{1/2})$ ? Proof?
- ▶ Let  $\text{PATH} = \{\langle G, s, t \rangle : G \text{ has directed path from } s \text{ to } t\}$   
Is  $L$  in  $\text{DTIME}(n)$ ? in  $\text{DTIME}(n^{1/2})$ ?
- ▶ The second question is **not well defined** w/o defining the **encoding** of strings into triplets  $\langle G, s, t \rangle$ .
- ▶ We typically define such encoding in the reverse direction: triplets into strings.
- ▶ Encoding may matter **much** — an **exponential** algorithm with respect to one encoding might turn to **linear** algorithm with respect to other encoding.

If not defined explicitly, we assume a “reasonable encoding”:

- ▶ Graphs encoding: **adjacency list** or **adjacency matrix**
- ▶ Integers encoding: **binary** encoding (and not **unary**)

## Relations among Time Classes

Let  $t_1, t_2 : \mathbb{N} \mapsto \mathbb{N}$  be two functions.

### Claim 6

If  $t_1(n) = O(t_2(n))$ , then  $\text{DTIME}(t_1(n)) \subseteq \text{DTIME}(t_2(n))$ .

Stated informally, more time does **not hurt**. But does it actually **help**?

### Claim 7

If  $t_1(n) \in O(t_2(n)/\log(n))$ , then  $\text{DTIME}(t_1(n)) \subsetneq \text{DTIME}(t_2(n))$ .

Informally, **sufficiently more time does help**

Proof – omitted.

Back to  $L = \{0^m 1^m \mid m \geq 0\} \in \text{DTIME}(n^2)$

We have seen that  $L \in \text{DTIME}(n^2)$ . Can we do **faster**?

### Algorithm 8 (Decider $M_2$ for $L$ )

On input string  $w$

1. Scan across tape and **Reject** if **0** is found to the right of a **1**.
2. Repeat the following while both **0**s and **1**s appear on tape:
  - 2.1 Scan across tape, checking whether total number of **0**s plus **1**s is even or odd. If odd, **Reject**.
  - 2.2 Scan across tape, crossing off every other **0** (starting with the first), and every other **1** (starting with the first) in each pass.
3. **Accept** if all string is crossed off; Otherwise **Reject**.

**Example:**  $w = 0^{13}1^{13}$

## Correctness of $M_2$

Let  $w = 0^{13}1^{13}$ .

▶  $w^i$  — the content of  $w$  after the  $i$ 'th pass (letting  $w^0 = w$ ).

▶  $\#_\sigma(x)$  — the number of  $\sigma$ 's in  $x$ .

·  $\#_0(w^0) = 13, \#_0(w^1) = 6, \#_0(w^2) = 3, \#_0(w^3) = 1$

●  $\#_b(w^i) = \lfloor \#_b(w) / 2^i \rfloor$

▶ Let  $P$  be the parity predicate:  $P(x) = 1$  iff  $x$  is odd.

·  $P(\#_0(w^0)) = 1, P(\#_0(w^1)) = 0, P(\#_0(w^2)) = 1, P(\#_0(w^3)) = 1.$

Note that  $1101$  is the binary representation of  $13 = \#_0(w^0)$ .

●  $P(\#_b(w^{i-1}))$  is the  $i$ 'th right-hand-side digit in binary representation of  $\#_b(w)$ .

▶ The check at beginning of the  $i$ 'th pass, detects whether  $P(\#_0(w^{i-1})) = P(\#_1(w^{i-1}))$ .

▶ Hence,  $M_2$  accepts  $w \implies \#_0(w) = \#_1(w)$ .  $\square$

## Running Time Analysis of $M_2$

### Algorithm 9 (Decider $M_2$ for L)

On input string  $w$

1. Scan across tape and **Reject** if 0 is found to the right of a 1.
2. Repeat the following while both 0s and 1s appear on tape:
  - 2.1 Scan across tape, checking whether total number of 0s plus 1s is even or odd. If odd, **Reject**.
  - 2.2 Scan across tape, crossing off every other 0 (starting with the first), and every other 1 (starting with the first) in each pass.
3. **Accept** if all string is crossed off; Otherwise **Reject**.

- ▶ One pass in each step (1,2,3) takes  $O(n)$  time.
- ▶ **Steps 1,3**: each executed once
- ▶ **Step 2** executed  $1 + \log_2 n$  times
- ▶ Total for **Step 2** is  $(1 + \log_2 n)O(n) = O(n \log n)$ .
- ▶ Grand total:  $O(n) + O(n \log n) = O(n \log n)$ .

## Further Improvements, Anybody?

### Question 10

Can the running time be made  $o(n \log n)$ ?

**Answer:** Not on a **single tape** TM...

### Theorem 11

$L \notin \text{DTIME}(o(n \log n))$  (i.e.,  $L \notin \text{DTIME}(g(n))$  for any  $g(n) \in o(n \log n)$ ).



$L \notin \text{DTIME}(o(n \log n))$

Fix an  $o(n \log n)$ -time TM  $M$ .

### Definition 12

For  $w \in \{0, 1\}^*$ , the **crossing sequence** of  $M(w)$  at location  $i$ , is the **sequence of states** used by the invocation of  $M$  on input  $w$ , when **moving** from  $i$  to  $(i + 1)$ , and from  $(i + 1)$  to  $i$ .

### Claim 13

For long enough  $w \in \{0, 1\}^*$ , the run  $M(w)$  has (at least) two **identical** crossing sequences.

### Claim 14 (Pumping Lemma for low running time TMs)

Let  $w = xyz$ , and assume that in  $M(w)$  locations  $|x|$  and  $|x + y|$  have **identical** crossing sequences, then  $M(w)$  and  $M(w' = (x, y^2, z))$  halt in the **same** state.

- ▶ Assume  $M$  is a decider for  $L$  and let  $w$  be a long enough word in  $L$ .
- ▶ Hence,  $M$  accepts  $w$ , but also a pumped version of  $w$ .
- ▶ But **all** pumped versions of  $w \in L$  are outside of  $L$  ...

## Proof of Claim 13 (beginning)

### Claim 15 (Restating Claim 13)

For long enough  $w \in \{0, 1\}^*$ , the run  $M(w)$  has (at least) two identical crossing sequences.

Let  $f(n) \in o(1)$  be such that running time on  $M$  on input  $w \in \{0, 1\}^n$  is at most  $f(n) \cdot n \cdot \log n$ .

Fix  $w \in \{0, 1\}^m$ , and consider the run  $M(w)$ .

- ▶ Let  $C$  be the subset of the first  $m$  locations on the tape that are visited at most  $2 \cdot f(m) \cdot \log m$  times.
- ▶ Let  $C'$  be the subset of the first  $m$  locations on the tape that are visited strictly greater than  $2 \cdot f(m) \cdot \log m$  times.
- ▶ We will show that  $|C'| \leq m/2$ , and since  $|C| + |C'| = m$ , we have that  $|C| \geq m/2$ :
- ▶ Assume for contradiction that  $|C'| > m/2$ .
- ▶ Let  $X(i)$  be the length of the crossing sequence at tape cell  $i$ .
- ▶  $f(m)m \log m \geq \sum_i X(i) \geq \sum_{i \in C} X(i) + \sum_{i \in C'} X(i) > 0 + (m/2) \cdot (2 \cdot f(m) \cdot \log m)$  (contradiction)

## Proof of Claim 13 (continued)

### Claim 16 (Restating Claim 13)

For long enough  $w \in \{0, 1\}^*$ , the run  $M(w)$  has (at least) two identical crossing sequences.

Let  $f(n) \in o(1)$  be such that running time on  $M$  on input  $w \in \{0, 1\}^n$  is at most  $f(n) \cdot n \cdot \log n$ .

Fix  $w \in \{0, 1\}^m$ , and consider the run  $M(w)$ .

- ▶ Let  $C$  be the subset of of the first  $m$  locations on the tape that are visited at most  $2 \cdot f(m) \cdot \log m$  times. Then  $|C| \geq m/2$  and every member of  $C$  has a crossing sequence of length at most  $2 \cdot f(m) \cdot \log m$ .
- ▶ Let  $D_t$  be the set of at most  $(|Q| + 1)^t$  possible crossing sequences of length at most  $t$ .
- ▶ For large enough  $m$ ,  $D_{2f(m) \cdot \log m}$  is smaller than  $m/2$  (since  $(|Q| + 1)^{2f(m) \cdot \log m} = m^{2f(m) \log |Q|} = m^{o(1)}$ )
- ▶ Hence, two of the locations in  $C$  share the same crossing sequence.  $\square$

## Proof idea for Claim 14

### Claim 17 (Restating Claim 14)

Let  $w = xyz$ , and assume that in  $M(w)$  locations  $|x|$  and  $|x + y|$  have identical crossing sequences, then  $M(w)$  and  $M(w' = (x, y^2, z))$  halt in the same state.

The **augment content** of a cell, contains its content (i.e., letter in  $\Sigma$ ), plus the **machine state**, if currently at this cell, and  $\perp$  otherwise.

Let  $M(w)_i$  stands for the augmented input of  $M(w)$  at location  $i$ .

### Claim 18

If in the execution,  $M(w)$  has spent  $k_1$  steps in the first  $|xy|$  locations, and  $k_2$  steps in locations  $|x| + 1, \dots$ . Then

- ▶ After  $M(w')$  spends  $k_1$  steps on the first  $|xy|$  locations,  
 $M(w)_{1, \dots, |xy|} = M(w')_{1, \dots, |xy|}$ .
- ▶ After  $M(w')$  spends  $k_2$  steps on locations  $|xy| + 1, \dots$ ,  
 $M(w)_{|x|+1, \dots} = M(w')_{|xy|+1, \dots}$ .

Proof: by induction on  $k_1 + k_2$  (and using Claim 14).(?)

## More on the “fooling”

- ▶ The first time  $M$  goes over  $x, y$  border into  $z$ , it is in same state as when goes over  $x, y, y$  border into  $z$ , so when gets to  $z$  in both inputs, will behave the same while in  $z$ .
- ▶ When gets back to cross left border of what was originally  $z$ , will also be in the same state.
- ▶ Why will it work the second, third, fourth, ...,  $n^{\text{th}}$  time it crosses the border?? (hint: definition of crossing sequence!)

## A Two-tape Decider for L

### Algorithm 19 (Two-tape Decider $M_3$ for L)

On input string  $w$ :

1. Scan across tape and **Reject** if 0 is found to the right of a 1.
2. Scan across 0s to first 1, copying 0s to tape 2.
3. Scan across 1s on tape 1 until the end. For each 1, cross off a 0. If no 0s left, **Reject**.
4. If any 0s left, **Reject**; otherwise **Accept**.

### Question 20

What is  $M_3$  running time?

## Complexity of Deciding $L = \{0^n 1^n\}$

- ▶ Single-tape  $M_1$ :  $O(n^2)$ .
- ▶ single-tape  $M_2$ :  $O(n \log n)$  (fastest possible!).

Hence  $L \in \text{DTIME}(O(n \log n))$ , but not in  $\text{DTIME}(O(f(n)))$  for  $f(n) \in o(n \log n)$

- ▶ Two-tape  $M_3$ :  $O(n)$ .

Important difference between complexity and computability:

- ▶ Computability: all reasonable models **equivalent** (Church-Turing)
- ▶ Complexity: choice of model **does** affect running time.

### Question 21

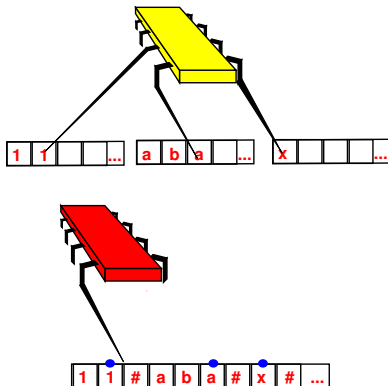
By **how much** does a model affect complexity?

## Multitape Speedup

Let  $t(n)$  be a function where  $t(n) \geq n$ , and let  $L \subseteq \Sigma^*$  be a language.

### Claim 22

Assume  $\exists$   $t(n)$ -time multitape TM that decides  $L$  with  $t(n) \geq n$ , then  $\exists$  an  $O(t(n)^2)$ -time single-tape TM that decides  $L$ .





## Reminder: Emulating Multi-Tape TMs

### Algorithm 23 (Single tape emulator $S$ for $k$ -tape $M$ )

On input  $w = w_1 \cdots w_n$ :

1. Write  $\# \overset{\bullet}{w}_1 w_2 \cdots w_n \# \overset{\bullet}{\ } \# \overset{\bullet}{\ } \# \cdots \#$  on tape.
  2. Scan tape from first  $\#$  to  $(k + 1)$ -st  $\#$  to read symbols under virtual heads.
  3. Rescan tape to write new symbols and move heads.
  4. If need to move virtual head onto  $\#$ , shift tape content to the right.
- ▶ For each step of  $M$ , the emulator  $S$  performs 2 scans and up to  $k$  rightward shifts
  - ▶ On input of length  $n$ ,  $M$  makes  $O(t(n))$  many steps, so active portion of each tape is  $O(t(n))$  long.
  - ▶ Total number of steps  $S$  makes:
    - ▶  $O(t(n))$  steps to simulate one step of  $M$ .
    - ▶ Initial tape arrangement  $O(n)$ .
    - ▶ Grand total:  $O(n) + O(t(n)^2) = O(t(n)^2)$  steps (recall  $t(n) > n$ ).

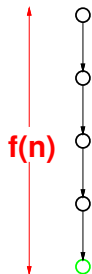
# Nondeterministic Time

## Definition 24 (nondeterministic Time)

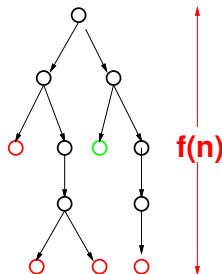
A **non-deterministic** TM  $N$  runs in time  $f(n)$ , where  $f: \mathbb{N} \mapsto \mathbb{N}$ , if for **every** input  $x$  of length  $n$ , the **maximum** number of steps that  $N$  uses on **any branch** of its computation tree on  $x$ , is **at most**  $f(n)$ .

Notice that also **non-accepting** branches must **reject** within  $f(n)$  many steps.

### deterministic



### nondeterministic



# Nondeterminism Speedup

## Claim 25

Suppose  $N$  is a **nondeterministic** TM that runs in time  $t(n)$  and decides the language  $L$ . Then there exists an  $2^{O(t(n))}$ -time **deterministic** TM  $D$  that decides  $L$ .

Note contrast with multi-tape result.

Proof's idea:  $D$  emulates  $N$ . Reminder

- ▶  $D$  tries all possible branches (say using BFS).
  - ▶ **Accept** if finds **any** accepting state.
  - ▶ **Reject** if **all** branches reject.
- ▶ Since  $N$  always stops, exactly one of two possibilities must occur.

## Emulation Details

We view the computation of  $N$  as a tree, whose nodes are configurations of the TM (i.e., state, head location and tape content).

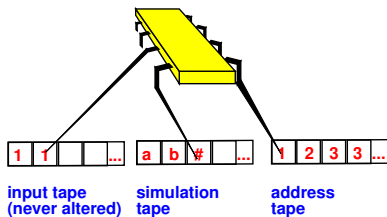
- ▶ Root is starting configuration,
- ▶ Fanout is at most some constant  $b$  (?),
- ▶ Depth at most  $\leq t(n)$ ,
- ▶ Total number of nodes  $O(b^{t(n)})$ ,
- ▶ Emulation time is  $O(b^{t(n)}) = O(2^{O(t(n))})$

## Remarks

### 1. Breadth-first search used in emulation

- ▶ Visit **each** node.
- ▶ May be improved upon by using depth-first search (is it OK?) or other tree search strategies.
- ▶ Still, doing this may save constants, but nothing substantial (?)

### 2. Simulation uses a three-tape machine.



Single-tape simulation:  $(2^{O(t(n))})^2 = 2^{O(2t(n))} = 2^{O(t(n))}$ .

## Polynomial is Good, Exponential is Bad

	10	20	30	40	50	60
$n$	.00001 second	.00002 second	.00003 second	.00004 second	.00005 second	.00006 second
$n^2$	.00001 second	.00004 second	.00009 second	.00016 second	.00025 second	.00036 second
$n^3$	.00001 second	.00008 second	.027 second	.064 second	.125 second	.216 second
$n^5$	.1 second	3.2 seconds	24.3 seconds	1.7 minute	5.2 minutes	13.0 minutes
$2^n$	.001 second	1.0 second	17.9 minutes	12.7 days	35.7 years	366 centuries
$3^n$	.059 second	58 minutes	6.5 years	3855 centuries	$2 \cdot 10^8$ centuries	$1.3 \cdot 10^{13}$ centuries

## Gaps Between Models

- ▶ At most **polynomial** gap in time to perform tasks between different deterministic models (single- vs. multi-tape TMs, TM vs. **RAM**, etc.)
- ▶ Apparently **exponential** gap in time to perform tasks between **deterministic** and **non-deterministic** models.

### Claim 26

All “reasonable” models of computation are polynomially equivalent.

Any one can simulate another with only **polynomial blowup** in running time.

### Fact 27

*Is a given problem solvable in*

- ▶ *Linear time? **model-specific**.*
- ▶ *Polynomial time? **model-independent**.*

# Part II

## The Class P



## The Class $\mathcal{P}$

$\mathcal{P}$  is the set of languages decidable in polynomial time on deterministic TMs.

### Definition 28 ( $\mathcal{P}$ )

$$\mathcal{P} = \bigcup_{c \geq 0} \text{DTIME}(n^c)$$

The class  $\mathcal{P}$  is important because:

- ▶ Invariant for all (deterministic) models of computation polynomially equivalent to TMs
  - ▶ not affected by particulars of model ...
  - ▶ go ahead, have another tape, they're pretty small and inexpensive
  - ...
- ▶ Roughly corresponds to **realistically solvable** (tractable) problems.
  - ▶ actually depends on context
  - ▶ going from exponential to polynomial algorithm usually requires major insight,
  - ▶ if you find an inefficient polynomial algorithm, you can often find a more efficient one.

## Known Problems in $\mathcal{P}$

- ▶ **Integer arithmetic:** Addition, subtraction, multiplication, division with remainder.
- ▶ **Modular arithmetic:** Exponentiation (RSA), inverse.
- ▶ **Integer Algorithms:** Greatest common divisor (gcd).
- ▶ **Operations research:** Maximum network flow, linear programming.
- ▶ **Algebra:** Matrix multiplication, computing determinants, matrix inversion, solving systems of linear equations, factoring polynomials.
- ▶ **Graph algorithms:** BFS and DFS in graphs, minimum spanning trees, finding Eulerian path.

# PATH

$\text{PATH} = \{\langle G, s, t \rangle : G \text{ has directed path from } s \text{ to } t\}$

## Theorem 29

$\text{PATH} \in \mathcal{P}$ .

## Algorithm 30 ( $M_1$ – Naive algorithm for PATH)

Input: an  $m$  nodes graph  $G$

For each path  $p$  in  $G$  of length  $\leq m$  : check if  $p$  goes from  $s$  to  $t$ .

## Question 31

What is the (time) complexity of  $M_1$ ?

- ▶ there are  $m^m$  possible paths
  - $\implies$  exponential in number of nodes
  - $\implies$  exponential in input size
- ▶ Oh, oh. Does not sound like  $\mathcal{P}$  to me ...

## Efficient Algorithm for PATH

### Algorithm 32 ( $M_2$ – efficient algorithm for PATH)

1. Place mark on  $s$ .
2. Repeat until no additional nodes marked:
  - 2.1 Scan edges of  $G$ .
  - 2.2 If edge  $(a, b)$  found from marked node  $a$  to unmarked node  $b$ , mark node  $b$ .
3. **Accept** if  $t$  is marked; otherwise **Reject**.

### Question 33

What is the complexity of  $M_2$ ?

- ▶ Steps 1 and 3 run once.
- ▶ Step 2 runs at most  $m$  times, because each time (except last) it marks at least one new node.

⇒ total number of steps is polynomial.

## Relative Primality

Two numbers are **relatively prime** if their *greater common deviser* (**gcd**) is 1 (i.e., the largest integer that divides them both).

- ▶  $\text{gcd}(10, 21) = 1 \implies 10$  and  $21$  **are** relatively prime
- ▶  $\text{gcd}(10, 22) = 2 \implies 10$  and  $22$  are **not** relatively prime

### Definition 34

$\text{RELPRIME} = \{\langle x, y \rangle : \text{gcd}(x, y) = 1\}$ .

### Theorem 35

$\text{RELPRIME} \in \mathcal{P}$ .

## Naive algorithm for RELPRIME

### Algorithm 36 (Naive algorithm for RELPRIME)

Input: integers  $x, y$ :

Search through all possible divisors of  $x, y$  and test divisibility.

- ▶ If  $x, y$  are give in **unary**:
  - ▶ Size of  $\langle x \rangle$  is  $x$
  - ▶ Testing all potential divisors of  $x, y$  is **polynomial**
- ▶ If  $x, y$  are give in **binary**
  - ▶ Size of  $\langle x \rangle$  is  $\log x$
  - ▶ Testing all potential divisors of  $x, y$  is **exponential**
- ▶ To analyze the running time of an algorithm that decides a language  $L$ , one should first say what is the **encoding** of  $L$ .
- ▶ Yet, we sometimes ignore that, and assume “reasonable encoding”
- ▶ The above algorithm is sometimes called **pseudo polynomial**.

## Euclid's Algorithm for Computing gcd

### Algorithm 37 ( $E$ )

On input  $\langle x, y \rangle$ :

1. Repeat until  $x = 0$ :
  - 1.1 If  $y > x$ , swap  $x$  and  $y$ .
  - 1.2  $x \leftarrow x \bmod y$
2. Output  $y$ .

### Claim 38

$E$  runs in polynomial-time and correctly computes the gcd function.

### Algorithm 39 ( $M$ for RELPRIME)

On input  $\langle x, y \rangle$ :

Accept iff  $E(x, y) = 1$ .

To prove that RELPRIME  $\in \mathcal{P}$ , we only need to prove Claim 38.

## Analyzing Euclid's Algorithm

We will only prove the running time part.

### Algorithm 40 ( $E$ )

On input  $\langle x, y \rangle$ :

1. Repeat until  $x = 0$ :
  - 1.1 If  $y > x$ , swap  $x$  and  $y$ .
  - 1.2  $x \leftarrow x \bmod y$
2. Output  $y$ .

- ▶ Each execution of Step 1 cuts  $x$  by **at least half** (case analysis with for  $y < x/2$  and  $x/2 \leq y < x$ )
- ▶ After each two executions **maximal** value is cut in **half**  
 $\implies$  number of stages is  $\min(\log_2 x, \log_2 y) \implies$  total running time is polynomial.

Consequently,  $\text{RELPRIME} \in \mathcal{P}$ .





# Part III

## The Class NP

## The Class $\mathcal{NP}$

### Definition 41 (NTIME)

For  $t \mapsto \mathbb{N} \mapsto \mathbb{N}$ , let  $\text{NTIME}(t(n)) = \{L \subseteq \Sigma^* : L \text{ is decided by an } O(t(n))\text{-time single tape NTM}\}$

$\mathcal{NP}$  is the set of languages decidable in polynomial time on non-deterministic TMs.

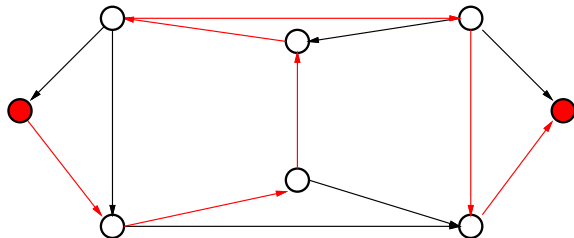
### Definition 42 ( $\mathcal{NP}$ )

$$\mathcal{NP} = \bigcup_{c \geq 0} \text{NTIME}(n^c)$$

The class  $\mathcal{NP}$  is important because:

- ▶ **Insensitive** to choice of reasonable non-deterministic computational model.
- ▶ Roughly corresponds to problems whose **positive solutions** are efficiently **verified**.

## Hamiltonian Path



A **Hamiltonian path** in a directed  $G$  visits each node **exactly** once.

$$\text{HAMPATH} = \{ \langle G, s, t \rangle : G \text{ has Hamiltonian path from } s \text{ to } t \}$$

### Question 43

How hard is it to decide **HAMPATH**?

Easy to obtain **exponential time** algorithm:

- ▶ Generate each potential path
- ▶ Check whether it is Hamiltonian