A Short Review of Last Class
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Deterministic Time Classes
Computational Models - Lecture 11
Fall 04/05

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- Deterministic Time Classes
- NonDeterministic Time Classes
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- Relationship between Deterministic/Nondeterministic Time
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Deterministic Time Classes

NonDeterministic Time Classes

Relationship between Deterministic/Nondeterministic Time

The classe P
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The classe $P$
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The classe \( P \)
Examples of Problems in \( P \)
\( NTIME \) and the classe \( NP \)
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Relationship between Deterministic/Nondeterministic Time

The classe \( P \)

Examples of Problems in \( P \)

\( \text{NTIME} \) and the classe \( \text{NP} \)

Examples of Problems in \( \text{NP} \)
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- A Short Review of Last Class
- Deterministic Time Classes
- NonDeterministic Time Classes
- Relationship between Deterministic/Nondeterministic Time
- The classe P
- Examples of Problems in P
- NTIME and the classe NP
- Examples of Problems in NP
- Verifiability
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Deterministic Time Classes

NonDeterministic Time Classes

Relationship between Deterministic/Nondeterministic Time

The classe \( \mathbf{P} \)

Examples of Problems in \( \mathbf{P} \)

\( \text{NTIME} \) and the classe \( \mathbf{NP} \)

Examples of Problems in \( \mathbf{NP} \)

Verifiability

Sipser, Chapter 7
Short Review of Last Class

Three major topics:

- Undecidability of Tiling (Domino) Problems
- The Recursion Theorems.
- Unrestricted Grammars and TMs
Undecidability of Tiling Problems

Our domain is tilings of regions in the two dimensional plane by colored tiles. A tiling of any region in the plane is called legal if every edge shared by two tiles is colored by the same color.

An instance of the tiling problem consists of pairs: (set of tiles, initial tiling).

- A finite set \( \{S_1, \ldots, S_k\} \) of tiles, where each tile has rectangular shape, and each of its four edge is colored (colors on different edges need not be distinct).

- An initial tiling: A finite row of tiles \( \{R_1, \ldots, R_k\} \), such that for each \( j \), \( R_j \in \{S_1, \ldots, S_k\} \), and the consecutive row of tiles \( \{R_1, \ldots, R_k\} \) is legal.
Undecidability of Tiling Problems

\[ L_\varepsilon \triangleq \{ \langle M \rangle \mid M \text{ halts on the empty input string} \} . \]

**Theorem:** \( \overline{L_\varepsilon} \leq_m L_{\text{tile}} \).

Since \( L_\varepsilon \notin \mathcal{R} \) (why?), the reduction implies that \( L_{\text{tile}} \notin \mathcal{R} \) as well.
The Recursion Theorem

**Theorem:** Let $\varphi : \mathcal{N} \rightarrow \mathcal{N}$ be a total recursive function, thought of as a function from TM indices to TM indices. There exist an index $x_0$ such that for all $y$,

$$f_{x_0}(y) = f_{\varphi(x_0)}(y).$$

Such $x_0$ is called a **fixed point** of $\varphi$. The function $\varphi$ can be viewed as modifying TMs descriptions.
The Recursion Theorem: Proof

**Theorem:** Let $\varphi : \mathbb{N} \rightarrow \mathbb{N}$ be a total recursive function, thought of as a function from TM indices to TM indices. There is an index $x_0$ such that for all $y, f_{x_0}(y) = f_{\varphi(x_0)}(y)$.

**Proof (first half):**

- For each integer $i$ construct a TM, $M$, that on input $y$ computes $f_i(i)$.
- Then $M$ runs the $f_i(i)$-th TM on $y$.
- Let $g(i)$ be the index of $M$’s encoding.
- For all $i$ and $y$, $f_{g(i)}(y) = f_{f_i(i)}(y)$.
- Notice that $g : \mathbb{N} \rightarrow \mathbb{N}$ is a total computable function, even if $f_i(i)$ is not defined (in such case $f_i(i)$ on $y$ is not defined).
The Recursion Theorem: Proof?

Part of proof:

- For each integer $i$ construct a TM, $M$, that on input $y$ computes $f_i(i)$.
- Then $M$ runs the $f_i(i)$-th TM on $y$.
- Let $g(i)$ be the index of $M$’s encoding.
- For all $i$ and $y$, $f_{g(i)}(y) = f_{f_i(i)}(y)$. 
The Recursion Theorem: Proof？

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- For each integer $i$ construct a TM, $M$, that on input $y$ computes $f_i(i)$.
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- Let $g(i)$ be the index of $M$’s encoding.
- For all $i$ and $y$, $f_{g(i)}(y) = f_{f_i(i)}(y)$.

Complaint: But this is cheating. If $f_i(i)$ is undefined, neither is $g(i)$.
The Recursion Theorem: Proof ?!!!

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The Recursion Theorem: Proof ?!!!

Complaint: But this is cheating. If $f_i(i)$ is undefined, neither is $g(i)$.

Reply: Is that so? What about the following TM, $M_w$:

"on input $x$:
Run $\langle M \rangle$ on $w$
if halts, output $x^2 \mod 13"
The Recursion Theorem: Proof ?!!!

Complaint: But this is cheating. If $f_i(i)$ is undefined, neither is $g(i)$.

Reply: Is that so? What about the following TM, $M_w$:

"on input $x$:

Run $\langle M \rangle$ on $w$

if halts, output $x^2 \mod 13$.

Notice that $\langle M_w \rangle$ is well defined even if $\langle M \rangle$ does not halt on $w$.
Exactly the same is true for $g(i)$ being well defined even if $f_i(i)$ is undefined!
The Recursion Theorem

**Theorem:** Let $\varphi : \mathbb{N} \rightarrow \mathbb{N}$ be a total recursive function, thought of as a function from TM indices to TM indices. There exist an index $x_0$ such that for all $y$,

$$f_{x_0}(y) = f_{\varphi(x_0)}(y).$$

- The recursion theorem can be used to prove that $A_{\text{TM}}$ is undecidable.
- It can be used to prove Rice theorem.
- It can be used to prove existence of a self printing program, one that generates a copy of its own source text.
Unrestricted Grammars

- Set of rules $R \subset (V^*(V - \Sigma)V^* \times V^*)$

- In an Unrestricted Grammar, the left-hand side of a rule contains a string of terminals and non-terminals (at least one of which must be a non-terminal)

- Rules are applied just like CFGs:
  - Find a substring that matches the LHS of some rule
  - Replace with the RHS of the rule
Unrestricted Grammars

- To non-deterministically generate a string according to a given unrestricted grammar:
  - Start with the initial symbol
  - While the string contains at least one non-terminal:
    - Find a substring that matches the LHS of some rule
    - Replace that substring with the RHS of the rule
Unrestricted Grammars

Let $UG$ be the set of languages that can be described by an Unrestricted Grammar:

$UG = \{ L : \exists$ Unrestricted Grammar $G$ such that $L[G] = L \}$

Claim: $UG = RE$

To Prove:
- Show $UG \subseteq RE$
- Show $RE \subseteq UG$
$\mathcal{UG} \subseteq \mathcal{RE}$

- Given any Unrestricted Grammar $G$, we create a Turing Machine $M$ that accepts $L[G]$.

- $M$ will be non-deterministic, simulating derivations of $G$. 
$RE \subseteq UG$

- Given any language $L \in RE$, let $M$ be a deterministic Turing Machine that accepts it. We can create an Unrestricted Grammar $G$ such that $L[G] = L$

  - Grammar: Generates a string
  - Turing Machine: Works from string to accept state

- Two formalisms work in different directions
- Simulating Turing Machine with a Grammar can be difficult.
$RE \subseteq UG$

- Simulating Turing Machine with a Grammar can be difficult.
- Requires working backwards.
- Derivations works from short, accepting configuration, to initial configuration of $M$, and finally to the bare string, $w \in \Sigma^*$. 
Ladies and Gentlemen, Boys and Girls

We are about to begin the third part of the course:
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Introduction to Computational Complexity

![Diagram showing four possible relationships among complexity classes: P = NP = co-NP, NP = co-NP, P = NP \cap co-NP, and NP \cap co-NP = NP.](image)
Time Complexity

Consider

\[ A = \{0^n1^n | n \geq 0\} \]

Clearly this language is decidable.

**Question:** How much time does a single-tape TM need to decide it?
Time Complexity

$M_1$: On input string $w$,

1. Scan across tape and reject if 0 is found to the right of a 1.

2. While both 0s and 1s appear on tape, repeat the following
   \[\text{scan across tape, crossing of a single 0 and a single 1 in each pass.}\]

3. If no 0s and 1s remain, accept, otherwise reject.
Analysis (1)

We consider the three stages separately.

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.
Analysis (1)

We consider the three stages separately.

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.
- Repositioning head requires $n$ steps.
Analysis (1)

We consider the three stages separately.

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.
- Repositioning head requires $n$ steps.
- Total is $2n = O(n)$ steps.
Analysis (2)

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

- scan across tape, crossing of a single 0 and a single 1 in each pass.

- Each scan requires $O(n)$ steps.
Analysis (2)

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- scan across tape, crossing of 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 $n/2$. 
2. While both 0s and 1s appear on tape, repeat the following

- scan across tape, crossing of 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 $(n/2) \cdot O(n) = O(n^2)$. 
Analysis (3)

3. If 0s still remain after all 1s have been crossed out, or vice-versa, reject. Otherwise, if the tape is empty, accept.
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Single scan requires $O(n)$ steps.
Analysis (3)

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.
Final Analysis

Total cost for stages

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

which is $O(n^2)$
Deterministic Time

Let $M$ be a deterministic TM, and let

$$t : \mathbb{N} \rightarrow \mathbb{N}$$

We say that $M$ runs in time $t(n)$ if

- For every input $x$ of length $n$, 
Deterministic Time

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We say that $M$ runs in time $t(n)$ if

- For every input $x$ of length $n$,
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- is at most $t(n)$. 
Time Classes Definition

Let

\[ t : \mathbb{N} \rightarrow \mathbb{N} \]

be a function.

**Definition:**

\[ \text{DTIME}(t(n)) = \{ L \mid L \text{ is a language, decided by an } O(t(n))-\text{time TM} \} \]
Do It Faster, Please

We have seen that

- \( A = \{0^n1^n | n \geq 0\} \),
- \( A \in \text{DTIME}(n^2) \).

Can we do better, \textit{i.e.} faster?
Home Improvement

$M_2$: On input string $w$,

1. Scan across tape and reject if 0 is found to the right of a 1.

2. Repeat the following if both 0s and 1s appear on tape
   
   2.1 scan across tape, checking whether total number of 0s and 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. If no 0s or 1s remain, accept, otherwise reject.
Analysis

First, we verify that $M_2$ indeed halts.

- on each scan in step 2.2,
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Example: start with 13 0s and 13 1s,
Analysis

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- Example: start with 13 0s and 13 1s,
  - first pass: 6 0s and 6 1s are left
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- Same for 1s.

- Example: start with 13 0s and 13 1s,
  - first pass: 6 0s and 6 1s are left
  - second pass: 3 0s and 3 1s are left
Analysis

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- on each scan in step 2.2,
  - The total number of 0s is cut in half,
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- Example: start with 13 0s and 13 1s,
  - first pass: 6 0s and 6 1s are left
  - second pass: 3 0s and 3 1s are left
  - third pass: one 0s and one 1s are left
Analysis

First, we verify that $M_2$ indeed halts.

- on each scan in step 2.2,
  - The total number of 0s is cut in half,
  - and if there was a remainder, it is discarded.
  - Same for 1s.

- Example: start with 13 0s and 13 1s,
  - first pass: 6 0s and 6 1s are left
  - second pass: 3 0s and 3 1s are left
  - third pass: one 0s and one 1s are left
  - then no 0s and 1s are left.
Analysis

We now verify that $M_2$ is correct.

- Consider parity of 0s and 1s in 2.1,
Analysis

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  - odd, odd (13)
Analysis

We now verify that $M_2$ is correct.

- Consider parity of 0s and 1s in 2.1,
- example: start with 13 0s and 13 1s
  - odd, odd (13)
  - even, even (6)
Analysis

We now verify that $M_2$ is correct.

- Consider parity of 0s and 1s in 2.1,
- example: start with 13 0s and 13 1s
  - odd, odd (13)
  - even, even (6)
  - odd, odd (3)
Analysis

We now verify that $M_2$ is correct.

- Consider parity of 0s and 1s in 2.1,
- example: start with 13 0s and 13 1s
  - odd, odd (13)
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- The result, written right to left, is 1101, which is the binary representation of 13.
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- Each pass checks equality of one more bit.
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- example: start with 13 0s and 13 1s
  - odd, odd (13)
  - even, even (6)
  - odd, odd (3)
  - odd, odd (1)
- The result, written right to left, is 1101, which is the binary representation of 13.
- Each pass checks equality of one more bit.
- Inequality in any specific bit will be detected (total number of 0s and 1s will be odd).
Running Time

\( M_2 \): On input string \( w \),

1. Scan across tape and reject if 0 is found to the right of a 1.

2. Repeat the following if both 0s and 1s appear on tape
   2.1 scan across tape, checking whether total number of 0s and 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).

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- One pass in each stage (1, 2.1, 2.2, 3) takes \( O(n) \) time.
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- 2.2 eliminates half of 0s and 1s: \( 1 + \log_2 n \) times
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- total for 2 is \( (1 + \log_2 n)O(n) = O(n \log n) \).

Slides modified by Benny Chor, based on original slides by Maurice Herlihy, Brown University.
Running Time

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- One pass in each stage (1,2.1,2.2,3) takes $O(n)$ time.
- stage 1 and 3: each executed once
- 2.2 eliminates half of 0s and 1s: $1 + \log_2 n$ times
- total for 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:** Can the running time be made $o(n \log n)$?
Further Improvements, Anybody?

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**Answer:** Not on a single tape TM (proof omitted).
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**Question:** But why do we have to stick with single tape TMs?
Further Improvements, Anybody?

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**Answer:** Not on a single tape TM (proof omitted).

**Question:** But why do we have to stick with single tape TMs?

**Answer:** We don’t!
A Two Tape TM

\( M_3 \): 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.
A Two Tape TM

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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: What is the running time?
Complexity

Deciding \( \{0^n1^n\} \):

- single-tape \( M_1 \): \( O(n^2) \).
- single-tape \( M_2 \): \( O(n \log n) \) (fastest possible!).
- two-tape \( M_3 \): \( O(n) \).
Complexity

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- 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 run-time.
Complexity

Deciding $\{0^n1^n\}$:

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

Q: By how much does model affect complexity?
Models and Complexity

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

**Claim:** If a \( t(n) \)-time multitape TM decides \( L \), then \( \exists \) an \( O(t^2(n)) \)-time single tape TM that decided \( L \).
Reminder: Simulating MultiTape TMs

On input \( w = w_1 \cdots w_n \), single tape \( S \):

- puts on its tape \( \# w_1 w_2 \cdots w_n \# \)
Reminder: Simulating MultiTape TMs

On input $w = w_1 \cdots w_n$, single tape $S$:

- puts on its tape $\# w_1 w_2 \cdots w_n \# \# \# \# \cdots \#$
- scans its tape from first $\#$ to $k + 1$-st $\#$ to read symbols under “virtual” heads.
Reminder: Simulating MultiTape TMs

On input $w = w_1 \cdots w_n$, single tape $S$:

- puts on its tape $\# w_1 w_2 \cdots w_n \# \# \# \# \# \cdots \#$
- scans its tape from first $\#$ to $k + 1$-st $\#$ to read symbols under “virtual” heads.
- rescans to write new symbols and move heads.
Reminder: Simulating MultiTape TMs

On input \( w = w_1 \cdots w_n \), single tape \( S \):

- puts on its tape \( \# \ w_1 \ w_2 \cdots \ w_n \# \ \vdash \ # \ \vdash \ # \ \cdots \ # \)
- scans its tape from first \( \# \) to \( k + 1 \)-st \( \# \) to read symbols under “virtual” heads.
- rescans to write new symbols and move heads
- if \( S \) tries to move virtual head onto \( \# \), then \( M \) takes “tape fault” and re-arranges tape.
Complexity of Simulation

For each step of $M$, $S$ performs

- two scans
- 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 $M$. 
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- Grand total: $O(n) + O(t^2(n)) = O(t^2(n))$ steps,
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- Grand total: $O(n) + O(t^2(n)) = O(t^2(n))$ steps,
  under the reasonable assumption (why?) that $t(n) > n$. 

Slides modified by Benny Chor, based on original slides by Maurice Herlihy, Brown University. – p.36
Time Classes Definition, Again

Let

\[ t : \mathbb{N} \rightarrow \mathbb{N} \]

be a function.

**Definition:**

\[ \text{DTIME}(t(n)) = \{ L \mid L \text{ is a language, decided by an } O(t(n))-\text{time TM}\} \]
Relations among Time Classes

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

Claim: If $t_1(n) = \mathcal{O}(t_2(n))$ then

$$\text{DTIME}(t_1(n)) \subseteq \text{DTIME}(t_2(n)) .$$
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But does it actually help?
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- Claim: If $t_1(n) = O(t_2(n)/\log(n))$ then
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  Informally, **sufficiently more time does help.**

- **Proofs** – sophisticated diagonalizations (omitted).
Non-Deterministic Time

Let $N$ be a non-deterministic TM, and let $f : \mathcal{N} \rightarrow \mathcal{N}$

We say that $N$ runs in time $f(n)$ if

- For every input $x$ of length $n$,
**Non-Deterministic Time**

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- For every input $x$ of length $n$,
- the maximum number of steps that $N$ uses,
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- is at most $f(n)$. 
Deterministic vs. Non-Deterministic

deterministic

\[ f(n) \]

nondeterministic

\[ f(n) \]

Slides modified by Benny Chor, based on original slides by Maurice Herlihy, Brown University.
Deterministic vs. Non-Deterministic

**Deterministic**

![Deterministic Diagram]

**Nondeterministic**

Notice that non-accepting branches must reject within $f(n)$ many steps.
Models and Complexity

**Claim:** Suppose $N$ is a nondeterministic TM that runs in time $t(n)$ and decides the language $L$.

Then there is an $2^{O(t(n))}$-time deterministic TM, $D$, that decided $L$. 
Models and Complexity

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Then there is an $2^{O(t(n))}$-time deterministic TM, $D$, that decided $L$.

Note contrast with multi-tape result.
Simulation

Let $N$ be a non-deterministic TM running in $t(n)$ time. Want to describe the deterministic TM, $D$, simulating $N$.

Basic idea of simulation:

- $D$ tries all possible branches.
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Basic idea of simulation:

- $D$ tries all possible branches.
- If $D$ finds any accepting state, it accepts.
- If all branches reject, $D$ rejects.
- Notice $N$ has no looping branches, so exactly one of two possibilities must occur.
Simulation Details

\( N \)'s computation is a tree:

- root is starting configuration,
Simulation Details

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- each node has bounded fanout $\leq b$ (why?),
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- total number of leaves at most $b^{t(n)}$,
- total number of nodes in tree $O(b^{t(n)})$,
- time to arrive from root to any node is $O(t(n))$.

$\implies$ Time to visit all nodes is

$$O \left( t(n) \times b^{t(n)} \right) = O \left( 2^{O(t(n))} \right).$$
Remark

Breadth-first search used in simulation

- Inefficiently traverses from root to visit each node.
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Breadth-first search used in simulation

- Inefficiently traverses from root to visit each node.

- Can be improved upon by using depth-first search (why is it OK now?) or other tree search strategies.

- Still, doing this may save constants, but nothing substantial (why?)
Remark

Simulation uses three-tape machine.
Remark

Simulation uses three-tape machine.

Single-tape simulation:

\[ (2^{O(t(n))})^2 = 2^{O(2t(n))} = 2^{O(t(n))}. \]
Important Distinction

- At most *polynomial* gap in time to perform tasks between different deterministic models (single-vs. multi-tape TMs, TM vs. RAM, etc.)
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Important Distinction

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

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- *Apparently exponential* gap in time to perform tasks between deterministic and non-deterministic models.
The Good, the Bad, and the Ugly

Complexity differences: Polynomial is small; Exponential is large

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Polynomial is Good, Exponential is Bad

**Claim:** All “reasonable” models of computation are polynomially equivalent. Any one can simulate another with only *polynomial increase* in running time.
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**Question:** Is a given problem solvable in Linear time? model-specific.
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Any one can simulate another with only polynomial increase in running time.

**Question:** Is a given problem solvable in

- **Linear** time? model-specific.
- **Polynomial** time? model-independent.
- We are interested in computation, not in models *per se*!
The Class $P$

**Definition:** $P$ is the set of languages decidable in polynomial time on deterministic TMs.

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

- The class $P$ is important because:
The Class $P$

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  - Invariant for all models of computation polynomially equivalent to TMs.
  - Roughly corresponds to realistically solvable (tractable) problems.
The Class $P$

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- not affected by particulars of model . . .
The Class $P$

- Invariant for all models of computation polynomially equivalent to deterministic TMs
- not affected by particulars of model . . .
- go ahead, have another tape, they’re pretty small and inexpensive . . .
The Class $P$

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  - going from exponential to polynomial algorithm usually requires major insight,
The Class $P$

- 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.
Examples: Problems in $P$

- **Arithmetic**: Addition, subtraction, multiplication, division with remainder.
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Examples: Problems in $P$

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- **Integer Algorithms**: Greatest common divisor (gcd).
- **Operations research**: Maximum flow, linear programming,
- **Algebra**: Matrix multiplication, computing determinants, matrix inversion, solving systems of linear equations, factoring polynomials.
- **Graph algorithms**: DFS and DFS in graphs, minimum spanning trees, finding Eulerian path.
Typical analysis

- break algorithm into stages
- check that each stage is polynomial
- check that number of stages is polynomial
- Ergo, the algorithm is polynomial.
Encoding

For numbers
- binary good
- unary not realistic (exponentially longer)

For graphs
- list of nodes and edges (good)
- adjacency matrix (good)
Path

Given

- directed graph $G$
- nodes $s$ and $t$
- is there a path from $s$ to $t$?

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

Theorem:

\[ \text{PATH} \in P \]

When in doubt, try brute force.

**Question:** What is the complexity of this algorithm?
Complexity of PATH

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When in doubt, try brute force.

- let \( m \) be the number of nodes in \( G \)
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- examine each path in \( G \) of length \( \leq m \),

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Theorem:

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When in doubt, try brute force.

- let $m$ be the number of nodes in $G$
- any path from $s$ to $t$ need not repeat nodes
- examine each path in $G$ of length $\leq m$
- check if it goes from $s$ to $t$.

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Complexity of PATH

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- exponential in number of nodes
- exponential in input size
- Oh, oh. Does not sound like $P$ to me . . .
Complexity of PATH

Theorem:

\[ \text{PATH} \in P \]

1. Place mark on \( s \)
2. Repeat until no additional nodes marked:
   - scan edges of \( G \).
   - If edge \( (a, b) \) found from marked node \( a \) to unmarked node \( b \),
   - then mark node \( b \).
3. If \( t \) marked, accept, otherwise reject.

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Complexity of PATH

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     then mark $b$.
3. If $t$ marked, accept, otherwise reject.

How many stages?
- Stages 1 and 3 run once.
- Stage 2 runs at most $m$ times, because each time (except last) it marks at least one new node.

Total number of stages is polynomial.
Path

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2. Repeat until no additional nodes marked:
   - scan edges of $G$.
   - If edge $(a, b)$ found from marked $a$ to unmarked $b$,
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How much is each stage?
- Stages 1 and 3 polynomial.
- Stage 2 scans and marks nodes in graph, also polynomial.

Total time complexity is polynomial.
Relative Primality

Two numbers are relatively prime if 1 is the largest integer that evenly divides them both.

10 and 21 are relatively prime
Relative Primality

Two numbers are relatively prime if 1 is the largest integer that evenly divides them both.

- 10 and 21 are relatively prime
- 10 and 22 are not.

Definition:

\[ \text{RELPRIME} = \{ \langle x, y \rangle | \, x \text{ and } y \text{ are relatively prime} \} \]
Relative Primality

RELPRIME = \{ \langle x, y \rangle \mid x \text{ and } y \text{ are relatively prime} \}

First Idea: Search through all possible divisors of $x, y$ and test divisibility.
Relative Primality

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**First Idea**: Search through all possible divisors of \( x, y \) and test divisibility.

If \( x, y \) in unary:

- size of \( \langle x \rangle \) is \( x \)
- testing all potential divisors of \( x, y \) is polynomial
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If \( x, y \) in unary:
- size of \( \langle x \rangle \) is \( x \)
- testing all potential divisors of \( x, y \) is polynomial

If \( x, y \) in binary:
- size of \( \langle x \rangle \) is \( \log x \)
- testing all potential divisors of \( x, y \) is exponential
Relative Primality

\[ \text{RELPRIME} = \{ \langle x, y \rangle | \text{ } x \text{ and } y \text{ are relatively prime} \} \]

**First Idea**: Search through all possible divisors of \( x, y \) and test divisibility.

If \( x, y \) in unary:
- size of \( \langle x \rangle \) is \( x \)
- testing all potential divisors of \( x, y \) is polynomial

If \( x, y \) in binary:
- size of \( \langle x \rangle \) is \( \log x \)
- testing all potential divisors of \( x, y \) is exponential

**Important Notation**: Such algorithm is called pseudo-polynomial.
GCD

RELPRIME = \{ \langle x, y \rangle | \text{x and y are relatively prime} \}

Euclid’s greatest common divisor algorithm, \( E \):
On input \( \langle x, y \rangle \)

1. Repeat until \( y = 0 \)
   - \( x \leftarrow x \mod y \)
   - exchange \( x \) and \( y \)

2. output \( x \)

\( R \) for RELPRIME : on input \( \langle x, y \rangle \)

- Run \( E \) on \( \langle x, y \rangle \)
- if the result is 1, accept, otherwise reject.
Euclid’s Algorithm

Enough to check that Euclid’s Algorithm is polynomial.

- each execution of Stage 1 cuts $x$ by at least half (check details)
- after each loop $x < y$
- values swapped
- number of stages is $\min(\log_2 x, \log_2 y)$

total running time is polynomial.

Correctness holds (but should be verified).

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

♣

Slides modified by Benny Chor, based on original slides by Maurice Herlihy, Brown University.
**NTime Classes Definition**

Let

\[ f : \mathbb{N} \rightarrow \mathbb{N} \]

be a function.

**Definition:**

\[
\text{NTIME}(f(n)) = \{ L \mid L \text{ is a language, decided by an } O(f(n))-\text{time NTM} \}
\]
The Class $NP$

**Definition:** $NP$ is the set of languages decidable in polynomial time on non-deterministic TMs.

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

- The class $NP$ is important because:
The Class $NP$

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The Class \( NP \)

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\[
NP = \bigcup_{c \geq 0} \text{NTIME}(n^c)
\]

- The class \( NP \) is important because:
  - Invariant for all TMs with any number of tapes.
  - \( NP \) is insensitive to choice of reasonable non-deterministic computational model.
  - Roughly corresponds to problems whose positive solutions cannot be efficiently generated \((\Rightarrow \text{intractable})\), but can be efficiently checked.
A Hamiltonian path in a directed $G$ visits each node exactly once.
Hamiltonian Path

\[ \text{HAMPATH} = \{ \langle G, s, t \rangle | G \text{ has Hamiltonian path from } s \text{ to } t \} \]

**Question:** How hard is it to decide this language?
Hamiltonian Path

\[
\text{HAMPATH} = \{ \langle G, s, t \rangle | G \text{ has Hamiltonian path from } s \text{ to } t \}\]

Easy to obtain \textit{exponential time} algorithm:
- \textit{generate} each potential path
- \textit{check} whether it is Hamiltonian
The Class $\mathcal{NP}$

Here is an NTM that decides HAMPATH in poly time.

On input $\langle G, s, t \rangle$,

1. **Guess** and write down a list of numbers $p_1, \ldots, p_m$, where $m$ is number of nodes in $G$, and $1 \leq p_i \leq m$.

2. Check for repetitions in list. If any found, *reject*.

3. Check whether $p_1 = s$ and $p_m = t$. If either does not hold, *reject*.

4. For $i, 1 \leq i \leq m - 1$, check whether $(p_i, p_{i+1})$ is an edge in $G$. If any is not, *reject*. Otherwise accept.
On input \( \langle G, s, t \rangle \),

1. **Guess** and write down a list of numbers \( p_1, \ldots, p_m \ldots \)

2. Check for repetitions . . .

3. Check whether \( p_1 = s \) and \( p_m = t \) . . .

4. Check whether \( (p_i, p_{i+1}) \) is an edge in \( G \) . . .

- Stage 1 polynomial time
- Stages 2 and 3 simple checks.
- Stage 4 simple poly-time too.
Hamiltonian Path

This problem has one very interesting feature: polynomial verifiability.

- we don’t know a fast way to find a Hamiltonian path
Hamiltonian Path

This problem has one very interesting feature: polynomial verifiability.

- we don’t know a fast way to find a Hamiltonian path
- but we can check whether a given path is Hamiltonian in polynomial time.

In other words,

- verifying correctness of a path is much easier
- than determining whether one exists
Composite Numbers

A natural number is composite if it is the product of two integers greater than one.

\[ \text{COMPOSITES} = \{ x \mid x = pq \text{ for integers } p, q > 1 \} \]

- we don’t know a polynomial-time algorithm for deciding this problem*
- But we can easily verify that a number is composite (how?)

*Actually, in summer 2002, two Indian undergrads and their advisor found how to do this. However, let us pretend we’re still in 1/1/2002…
Verifiability

Not all problems are polynomially verifiable.

There is no known way to verify $\text{HAMPATH}$ in polynomial time.

In fact, we will see many examples where $L$ is polynomially verifiable, but its complement, $\overline{L}$, is not known to be polynomially verifiable.
Verifiability

A verifier for a language $A$ is an algorithm $\mathcal{V}$ where

$$A = \{ w | \mathcal{V} \text{ accepts } \langle w, c \rangle \text{ for some string } c \}$$

The verifier uses the additional information $c$ to verify $w \in A$. 
Verifiability

A verifier for a language $\mathcal{A}$ is an algorithm $\mathcal{V}$ where

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- We measure verifier run time by length of $w$. 
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- The string $c$ is called a certificate (or proof) for $w$ if $\mathcal{V}$ accepts $\langle w, c \rangle$. 
Verifiability

A verifier for a language $A$ is an algorithm $V$ where

$$A = \{ w \mid V \text{ accepts } \langle w, c \rangle \text{ for some string } c \}$$

- The verifier uses the additional information $c$ to verify $w \in A$.
- We measure verifier run time by length of $w$.
- The string $c$ is called a certificate (or proof) for $w$ if $V$ accepts $\langle w, c \rangle$.
- A polynomial verifier runs in polynomial time in $|w|$ (so $|c| \leq |w|^{O(1)}$).
Verifiability

A verifier for a language \( \mathcal{A} \) is an algorithm \( \mathcal{V} \) where

\[
\mathcal{A} = \{ w \mid \mathcal{V} \text{ accepts } \langle w, c \rangle \text{ for some string } c \}
\]

- The verifier uses the additional information \( c \) to verify \( w \in \mathcal{A} \).
- We measure verifier run time by length of \( w \).
- The string \( c \) is called a certificate (or proof) for \( w \) if \( \mathcal{V} \) accepts \( \langle w, c \rangle \).
- A polynomial verifier runs in polynomial time in \(|w|\) (so \(|c| \leq |w|^{O(1)}\)).
- A language \( \mathcal{A} \) is polynomially verifiable if it has a polynomial verifier.
Examples

For HAMPATH, a certificate for

\[ \langle G, s, t \rangle \in \text{HAMPATH} \]

is simply the Hamiltonian path from \( s \) to \( t \).

Can verify in time polynomial in \( |\langle G \rangle| \) whether given path is Hamiltonian.
Examples

For \textsc{composites}, a certificate for

\[ x \in \textsc{composites} \]

is simply one of its divisors.

Can verify in time polynomial in \(|x|\) if given divisor indeed divides \(x\).