Lecture 1

Course Overview



























Algorithms vs Complexity Theory:



Algorithms focus on solving computation problems efficiently,



Algorithms vs Complexity Theory:



Algorithms focus on solving computation problems efficiently, while Complexity theory





Algorithms vs Complexity Theory:



Algorithms focus on solving computation problems efficiently, while Complexity theory studies inherent difficulty of problems.







Example: Given two numbers x and y, compute x.y.



Example: Given two numbers x and y, compute x.y.

- Design an algorithm to compute $x \cdot y$ that runs in T time.

Example: Given two numbers x and y, compute x.y.

• Design an algorithm to compute $x \cdot y$ that runs in T time.

Algorithms

Example: Given two numbers x and y, compute x.y.

- Design an algorithm to compute $x \cdot y$ that runs in T time. Algorithms
- Prove that no algorithm exists that runs in less than T time.

Example: Given two numbers x and y, compute x.y.

- Design an algorithm to compute $x \cdot y$ that runs in T time. 4 - - Algorithms
- Prove that no algorithm exists that runs in less than T time. \leftarrow Complexity Theory



Example: Given two numbers x and y, compute x.y.

- Design an algorithm to compute $x \cdot y$ that runs in T time. 4 - - Algorithms
- Prove that no algorithm exists that runs in less than T time. \leftarrow Complexity Theory



Example: Given two numbers x and y, compute x.y.

- Design an algorithm to compute $x \cdot y$ that runs in T time. 4 - - Algorithms
- Prove that no algorithm exists that runs in less than T time. \leftarrow Complexity Theory

computational problems



Example: Given two numbers x and y, compute x.y.

- Design an algorithm to compute $x \cdot y$ that runs in T time. 4 - - Algorithms
- Prove that no algorithm exists that runs in less than T time. \leftarrow Complexity Theory

computational problems w.r.t resources such as time,



Example: Given two numbers x and y, compute x.y.

- Design an algorithm to compute $x \cdot y$ that runs in T time. 4 - - Algorithms
- Prove that no algorithm exists that runs in less than T time. \leftarrow Complexity Theory

computational problems w.r.t resources such as time, space,



Example: Given two numbers x and y, compute x.y.

- Design an algorithm to compute $x \cdot y$ that runs in T time. 4 - - Algorithms
- Prove that no algorithm exists that runs in less than T time. \leftarrow Complexity Theory

computational problems w.r.t resources such as time, space, interactions,



Example: Given two numbers x and y, compute x.y.

- Design an algorithm to compute $x \cdot y$ that runs in T time. 4 - - Algorithms
- Prove that no algorithm exists that runs in less than T time. \leftarrow Complexity Theory

Central Goal of Complexity Theory: Proving non-existence of efficient algorithms for computational problems w.r.t resources such as time, space, interactions, randomness, etc.



Example: Given two numbers x and y, compute x.y.

- Design an algorithm to compute $x \cdot y$ that runs in T time. Algorithms
- Prove that no algorithm exists that runs in less than T time. \leftarrow Complexity Theory

- **Central Goal of Complexity Theory:** Proving non-existence of efficient algorithms for computational problems w.r.t resources such as time, space, interactions, randomness, etc.
 - Haven't been very successful







What we actually do in Complexity Theory:

Prove non-existence of efficient algorithms.



What we actually do in Complexity Theory:

• Prove non-existence of efficient algorithms. (E.g. *GeneralisedChess* \notin P)

- Prove non-existence of efficient algorithms. (E.g. *GeneralisedChess* \notin **P**)
- Interrelate different complexity questions. For instance,

- Prove non-existence of efficient algorithms. (E.g. *GeneralisedChess* \notin **P**)
- Interrelate different complexity questions. For instance, **Question:** Are problems P_1 and P_2 not solvable in polynomial time?

- Prove non-existence of efficient algorithms. (E.g. *GeneralisedChess* \notin **P**)
- Interrelate different complexity questions. For instance, **Question:** Are problems P_1 and P_2 not solvable in polynomial time? **Interrelation:** P_1 is not solvable in poly. time

- Prove non-existence of efficient algorithms. (E.g. *GeneralisedChess* \notin P)
- Interrelate different complexity questions. For instance, Question: Are problems P_1 and P_2 not solvable in polynomial time? Interrelation: P_1 is not solvable in poly. time $\iff P_2$ is not solvable in poly. time

- Prove non-existence of efficient algorithms. (E.g. *GeneralisedChess* \notin P)
- Interrelate different complexity questions. For instance, Question: Are problems P_1 and P_2 not solvable in polynomial time? Interrelation: P_1 is not solvable in poly. time $\iff P_2$ is not solvable in poly. time
- Classify problems based on the amount of resources required to solve them and compare those classes.

What we actually do in Complexity Theory:

- Prove non-existence of efficient algorithms. (E.g. *GeneralisedChess* \notin P)
- Interrelate different complexity questions. For instance, **Question:** Are problems P_1 and P_2 not solvable in polynomial time? Interrelation: P_1 is not solvable in poly. time $\iff P_2$ is not solvable in poly. time
- Classify problems based on the amount of resources required to solve them and compare those classes.

time, and polynomial space, respectively.

For instance, let X, Y, and Z be the set of problems solvable in logspace, polynomial



What we actually do in Complexity Theory:

- Prove non-existence of efficient algorithms. (E.g. *GeneralisedChess* \notin P)
- Interrelate different complexity questions. For instance, **Question:** Are problems P_1 and P_2 not solvable in polynomial time? Interrelation: P_1 is not solvable in poly. time $\iff P_2$ is not solvable in poly. time
- Classify problems based on the amount of resources required to solve them and compare those classes.

time, and polynomial space, respectively. Then, $X \subseteq Y \subseteq Z$.

For instance, let X, Y, and Z be the set of problems solvable in logspace, polynomial



Glimpses of this Course



Glimpses of this Course

We'll learn about the following and more in this course:


We'll learn about the following and more in this course:

• P vs NP:



We'll learn about the following and more in this course:

• **P** vs **NP**:

P = Set of problems that are polynomial-time solvable.

We'll learn about the following and more in this course:

- **P** vs **NP**:
 - **P** = Set of problems that are polynomial-time solvable.
 - **NP** = Set of problems whose solutions are polynomial-time verifiable.

We'll learn about the following and more in this course:

• **P** vs **NP**:

P = Set of problems that are polynomial-time solvable. **NP** = Set of problems whose solutions are polynomial-time verifiable.

For instance,

We'll learn about the following and more in this course:

• **P** vs **NP**:

P = Set of problems that are polynomial-time solvable. **NP** = Set of problems whose solutions are polynomial-time verifiable. For instance,

PATH: Given a graph G and $u, v \in G$, decide if there is a path from u to v.

We'll learn about the following and more in this course:

• **P** vs **NP**:

P = Set of problems that are polynomial-time solvable. **NP** = Set of problems whose solutions are polynomial-time verifiable. For instance,

- **PATH**: Given a graph G and $u, v \in G$, decide if there is a path from u to v.
- HAMPATH: Given a graph G, decide if G has a path that visits all the vertices of G.



We'll learn about the following and more in this course:

• **P** vs **NP**:

P = Set of problems that are polynomial-time solvable. **NP** = Set of problems whose solutions are polynomial-time verifiable. For instance, $PATH \in P$ and $HAMPATH \in NP$.

- **PATH**: Given a graph G and $u, v \in G$, decide if there is a path from u to v.
- HAMPATH: Given a graph G, decide if G has a path that visits all the vertices of G.



We'll learn about the following and more in this course:

• **P** vs **NP**:

P = Set of problems that are polynomial-time solvable. **NP** = Set of problems whose solutions are polynomial-time verifiable. For instance, **PATH**: Given a graph G and $u, v \in G$, decide if there is a path from u to v. HAMPATH: Given a graph G, decide if G has a path that visits all the vertices of G. $PATH \in P$ and $HAMPATH \in NP$.

• Are there problems solvable in $O(n^3)$ time that are not solvable in O(n) time?





• Given a directed graph G and $u, v \in G$, can we find whether $u \nleftrightarrow v$ in logspace?



Or is L = NL?



• Given a directed graph G and $u, v \in G$, can we find whether $u \nleftrightarrow v$ in logspace?

- Or is L = NL?
- Problems beyond NP. For instance,



• Given a directed graph G and $u, v \in G$, can we find whether $u \nleftrightarrow v$ in logspace?

- Or is L = NL?
- Problems beyond NP. For instance,



• Given a directed graph G and $u, v \in G$, can we find whether $u \rightsquigarrow v$ in logspace?

INDSET: Given a graph G and $k \in \mathbb{Z}^+$, decide if G has an independent set of size k.



- Or is L = NL?
- Problems beyond NP. For instance, Easily verifiable solutions to *INDSET* exist. (*INDSET* \in **NP**)

• Given a directed graph G and $u, v \in G$, can we find whether $u \rightsquigarrow v$ in logspace?

INDSET: Given a graph G and $k \in \mathbb{Z}^+$, decide if G has an independent set of size k.



- Or is L = NL?
- Problems beyond NP. For instance, Easily verifiable solutions to *INDSET* exist. (*INDSET* \in **NP**)

independent set of G is k.

• Given a directed graph G and $u, v \in G$, can we find whether $u \nleftrightarrow v$ in logspace?

INDSET: Given a graph G and $k \in \mathbb{Z}^+$, decide if G has an independent set of size k.

EXACT-INDSET: Given a graph G and $k \in \mathbb{Z}^+$, decide if the size of the largest



- Or is L = NL?
- Problems beyond NP. For instance, Easily verifiable solutions to *INDSET* exist. (*INDSET* \in **NP**)

independent set of G is k.

Easily verifiable solutions to EXACT-INDSET seem to not exist. (EXACT-INDSET $\in \Sigma_2^p$)

• Given a directed graph G and $u, v \in G$, can we find whether $u \rightsquigarrow v$ in logspace?

INDSET: Given a graph G and $k \in \mathbb{Z}^+$, decide if G has an independent set of size k.

EXACT-INDSET: Given a graph G and $k \in \mathbb{Z}^+$, decide if the size of the largest







• Can we use randomness to speed up the computation?



- Can we use randomness to speed up the computation?

P = Set of problems that are polytime solvable by deterministic algorithm.

- Can we use randomness to speed up the computation?
 - **P** = Set of problems that are polytime solvable by deterministic algorithm.
 - **BPP** = Set of problems that are polytime solvable by probabilistic algorithm.

• Can we use randomness to speed up the computation?

For instance,

- **P** = Set of problems that are polytime solvable by deterministic algorithm.
- **BPP** = Set of problems that are polytime solvable by probabilistic algorithm.

• Can we use randomness to speed up the computation?

For instance, **PRIMES**: Is *x* prime?

- **P** = Set of problems that are polytime solvable by deterministic algorithm.
- **BPP** = Set of problems that are polytime solvable by probabilistic algorithm.

• Can we use randomness to speed up the computation?

For instance,

PRIMES: Is x prime? (Is in **BPP**. Was shown to be in **P** after a long effort. [AKS'02])

- **P** = Set of problems that are polytime solvable by deterministic algorithm.
- **BPP** = Set of problems that are polytime solvable by probabilistic algorithm.



• Can we use randomness to speed up the computation?

For instance,

- **P** = Set of problems that are polytime solvable by deterministic algorithm.
- **BPP** = Set of problems that are polytime solvable by probabilistic algorithm.

PRIMES: Is x prime? (Is in **BPP**. Was shown to be in **P** after a long effort. [AKS'02]) **PIT (Polynomial Identity Testing)**: Given a multivariate polynomial with integer



• Can we use randomness to speed up the computation?

For instance,

- **P** = Set of problems that are polytime solvable by deterministic algorithm.
- **BPP** = Set of problems that are polytime solvable by probabilistic algorithm.

PRIMES: Is x prime? (Is in **BPP**. Was shown to be in **P** after a long effort. [AKS'02]) **PIT (Polynomial Identity Testing)**: Given a multivariate polynomial with integer coefficients, find whether there is an assignment of values to variables such that



• Can we use randomness to speed up the computation?

For instance,

polynomial evaluates to non-zero.

- **P** = Set of problems that are polytime solvable by deterministic algorithm.
- **BPP** = Set of problems that are polytime solvable by probabilistic algorithm.

PRIMES: Is x prime? (Is in **BPP**. Was shown to be in **P** after a long effort. [AKS'02]) **PIT (Polynomial Identity Testing)**: Given a multivariate polynomial with integer coefficients, find whether there is an assignment of values to variables such that



• Can we use randomness to speed up the computation?

For instance,

polynomial evaluates to non-zero. (Is in **BPP**, but not known to be in **P**.)

- **P** = Set of problems that are polytime solvable by deterministic algorithm.
- **BPP** = Set of problems that are polytime solvable by probabilistic algorithm.

PRIMES: Is x prime? (Is in **BPP**. Was shown to be in **P** after a long effort. [AKS'02]) **PIT (Polynomial Identity Testing)**: Given a multivariate polynomial with integer coefficients, find whether there is an assignment of values to variables such that





Grading:



Grading:

• 20% - Project (a presentation on a paper/topic in groups of two)

Grading:

- 20% Project (a presentation on a paper/topic in groups of two)
- 20% Best 2 out of 3 quizzes (Mostly MCQs and T/F)

paper/topic in groups of two) y MCQs and T/F)

Grading:

- 20% Project (a presentation on a paper/topic in groups of two)
- 20% Best 2 out of 3 quizzes (Mostly MCQs and T/F)
- 30% Minors (15% each)

paper/topic in groups of two) y MCQs and T/F)

Grading:

- 20% Project (a presentation on a paper/topic in groups of two)
- 20% Best 2 out of 3 quizzes (Mostly MCQs and T/F)
- 30% Minors (15% each)
- 30 % Major

paper/topic in groups of two) y MCQs and T/F)

Grading:

- 20% Project (a presentation on a paper/topic in groups of two)
- 20% Best 2 out of 3 quizzes (Mostly MCQs and T/F)
- 30% Minors (15% each)
- 30 % Major
- 0% Problem sets with solutions or solution links

Grading:

- 20% Project (a presentation on a paper/topic in groups of two)
- 20% Best 2 out of 3 quizzes (Mostly MCQs and T/F)
- 30% Minors (15% each)
- 30% Major
- 0% Problem sets with solutions or solution links

Book: Computational Complexity: A Modern Approach by Arora and Barak

Grading:

- 20% Project (a presentation on a paper/topic in groups of two)
- 20% Best 2 out of 3 quizzes (Mostly MCQs and T/F)
- 30% Minors (15% each)
- 30% Major
- 0% Problem sets with solutions or solution links

Book: Computational Complexity: A Modern Approach by Arora and Barak

Office Hours: Mail me to fix an appointment
Administrative Details

Grading:

- 20% Project (a presentation on a paper/topic in groups of two)
- 20% Best 2 out of 3 quizzes (Mostly MCQs and T/F)
- 30% Minors (15% each)
- 30 % Major
- 0% Problem sets with solutions or solution links

Book: Computational Complexity: A Modern Approach by Arora and Barak

Office Hours: Mail me to fix an appointment

Course Site: http://home.iitj.ac.in/~vimalraj/courses/ct/csl7140.html