Foundations of Computing

Lecture 26 – Final Exam Review

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April 25, 2024

Outline

1. Lecture 25 Review
2. Complexity Theory
   - $\mathcal{P}$
   - $\mathcal{NP}$
   - Poly-time Reductions and $\mathcal{NP}$-Completeness
   - Interactive Proofs
   - Zero-Knowledge Proofs
3. Computability
   - Turing Machines and Decidable Languages
   - Languages Recognized by TMs
   - Undecidable Languages
   - Proofs by Reduction
4. Automata and Languages

Lecture 25 Review

- Zero-Knowledge Proofs
- Where's Waldo
- Puppy and Panda
- Graph Isomorphism
- 3-Coloring

We Are Done!

Welcome to the last lecture of CS 3313!!!

- Complete course evaluation form for 5 points on final exam

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Complexity Classes

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Important

Make sure you know the definitions and relationships between these complexity classes.

Asymptotic Notation – Big-O

Definition

Let $f, g : \mathbb{N} \to \mathbb{R}$, we say that $f(n) = O(g(n))$ if

- There exist positive integers c, n_0 s.t. for all $n \geq n_0$

$$f(n) \leq cg(n)$$

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- I.e., $n_0 = 6, c = 6$

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- Note that $f(n) = O(n^4)$

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- $\mathcal{P}$ corresponds to the class of "efficiently-solvable" problems
- $\mathcal{P}$ is invariant for all models of computation polynomially-equivalent to 1-tape TM
- $\mathcal{P}$ has nice closure properties

Problems in $\mathcal{P}$

- PATH
- RELPRIME
- Anything you saw in algorithms class

Outline

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Intuition

- $\mathcal{P}$ is the class of problems where you can find a solution in poly-time
- $\mathcal{NP}$ is the class of problems where you can verify a solution in poly-time
- Question: $\mathcal{P} \stackrel{?}{=} \mathcal{NP}$

The Class $\mathcal{NP}$ – Another Formulation

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- A verifier simulates the NTM by using the accepting branch as the witness

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Question: NP containing all L

Is $\mathcal{P} = \mathcal{NP} =$ co-$\mathcal{NP}$?

Problems in $\mathcal{NP}$

- CLIQUE

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- CLIQUE
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Problems in $\mathcal{NP}$

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- Satisfiability
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- Independent set
- and many more

Important

Make sure you know how to prove $L \in \mathcal{NP}$

Outline

Mapping Reductions

Mapping Reduction

Language A is mapping reducible to language B ($A \leq_m B$) if there is a computable function $f : \Sigma^* \to \Sigma^*$, where for every x,

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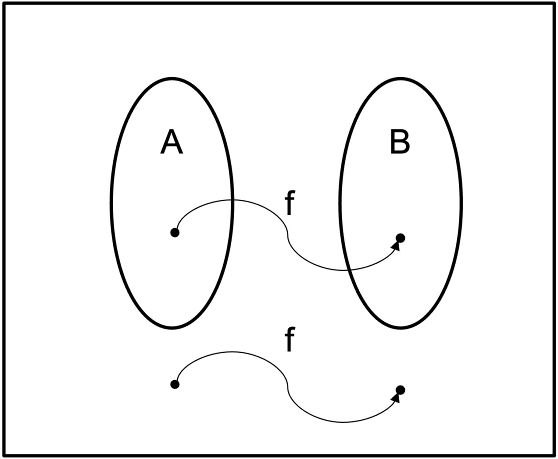
- Poly-time reductions give an efficient way to convert membership testing in A to membership testing in B
- If B has a poly-time solution so does A

Poly-time Mapping Reductions



f runs in time $poly(|x|)$ on all inputs x

Why Poly-Time Reductions

Theorem

If $A \leq_P B$ and $B \in \mathcal{P}$, then $A \in \mathcal{P}$

Proof:

- Let M be the poly-time TM deciding B
- Let f be the poly-time reduction from A to B
- Can construct M' deciding A:
  $M' =$ On input x:
  1. Compute $f(x)$
  2. Run $M(f(x))$ and output whatever M outputs

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     - If $x \in A$, $f(x) \in B$ so M accepts
     - If $x \notin A$, $f(x) \notin B$, so M rejects
     - Since both f and M are poly-time, $M(f(x))$ is also poly-time

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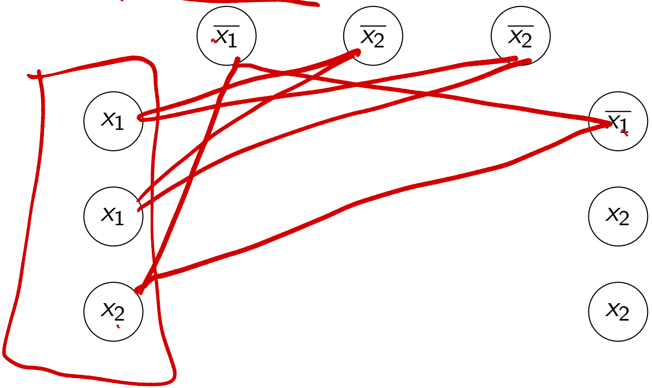

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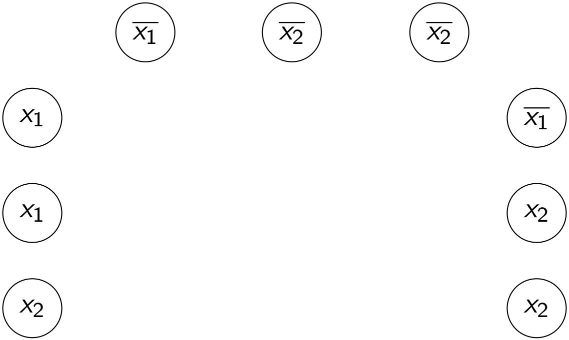

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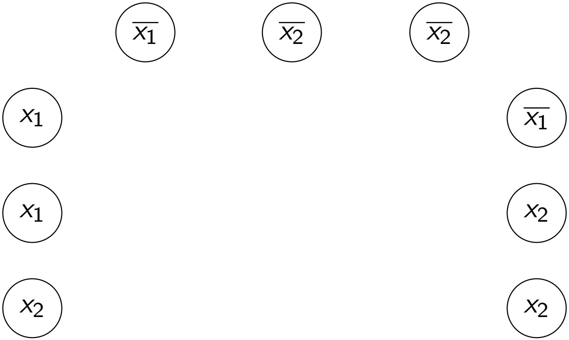

- If ϕ is satisfiable then G has a k-clique
- If G has a k-clique then ϕ is satisfiable

$\mathcal{NP}$-Completeness

Definition

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- For every language $A \in \mathcal{NP}$, $A \leq_P B$

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Theorem

If B is $\mathcal{NP}$-complete and $B \in \mathcal{P}$, then $\mathcal{P} = \mathcal{NP}$

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If B is $\mathcal{NP}$-complete and $B \leq_P C$ for $C \in \mathcal{NP}$, then C is $\mathcal{NP}$-complete

$\mathcal{NP}$-Complete Languages

1. SAT is $\mathcal{NP}$-complete

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7. More on the HW

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7. More on the HW

Important

Make sure you remember what direction the reduction should go.

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Definition

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1. (Completeness) If $x \in L$, then $\Pr[\langle P, V\rangle(x) = 1] = 1$
2. (Soundness) If $x \notin L$, then for any (possibly unbounded) P^*, we have $\Pr[\langle P^*, V\rangle(x) = 1] \leq 1/2$

$NP \subseteq IP$?

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Graph Non-Isomorphism

Question

How can we prove that two graphs G_0 and G_1 are NOT isomorphic?

$GNI \in co\text{-}NP$

1. $\forall x \notin GNI$, $\exists w$ s.t. $V(x, w) = 1$

   $w =$ the isomorphism

2. $\forall x \in GNI$, $\nexists w$ s.t. $V(x, w) = 1$

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Graph Non-Isomorphism

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How can we prove that two graphs G_0 and G_1 are NOT isomorphic?

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1. V chooses $b \leftarrow \{0, 1\}$, and applies a random permutation π to the vertices of G_b and sends this graph G^* to P input = (G_0, G_1)

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Why This Works:

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Why This Works:

1. (Completeness) Suppose that G_0 and G_1 are not isomorphic.

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   - Thus, $\Pr[b' = b] = 1/2$

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Question: What should V do?

- Suppose that V is deterministic:
- What if you allow V to be randomized:

Languages in $\mathcal{IP}$

- $\mathcal{P} \subseteq \mathcal{IP}$
- $\mathcal{NP} \subseteq \mathcal{IP}$
- Graph Non-Isomorphism $\in \mathcal{IP}$

Outline

1. Lecture 25 Review
2. Complexity Theory
   - $\mathcal{P}$
   - $\mathcal{NP}$
   - Poly-time Reductions and $\mathcal{NP}$-Completeness
   - Interactive Proofs
   - Zero-Knowledge Proofs
3. Computability
   - Turing Machines and Decidable Languages
   - Languages Recognized by TMs
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- There exists a poly-time *Simulator* S s.t.

$$\forall x \in L, \qquad VIEW_{V^*}(\langle P, V^* \rangle(x)) = S(x)$$

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4. V accepts iff $H = \pi'(G_{b'})$

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Exam

Exam Details:

- Tuesday, May 7, 10:20-12:20
- In the classroom
- 2 sheets (back-and-front) of notes are allowed

See you all there!