

FOUNDATIONS OF COMPLEXITY THEORY

Lecture 15: P vs. NP and Diagonalisation

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Knowledge-Based Systems

TU Dresden, December 31, 2020

Review

Ladner's Theorem

Theorem 15.1 (Ladner, 1975): If $P \neq NP$, then there are problems in NP that are neither in P nor NP-complete.

Such problems are called **NP-intermediate**.

- No natural problem is known to be NP-intermediate
- Indeed, this would imply that $P \neq NP$

Lazy diagonalisation

A powerful proof idea:

- Don't try to construct a diagonalisation that tries to flip the behaviour for a TM \mathcal{M}_i that is given in the input
- Rather, for each \mathcal{M}_i that you want to be different from, keep on behaving “sufficiently different” for a large range of inputs – until the inputs given are big enough to detect a difference with \mathcal{M}_i (on much smaller inputs)
- To know which \mathcal{M}_i we are working on, simply recompute $f(0), f(1), \dots$ as far as possible in each step

We observed:

- Progress is really slow with this method.
- However, it does not matter how inefficient the actual computations are internally. Lazy diagonalisation has all the time in the world.

Schöning's Generalisation

Intermediate problems between other classes

Uwe Schöning established the following interesting generalisation of Ladner's approach:

Theorem 15.2 (Schöning 1982): Consider two classes C_1 and C_2 of decidable languages such that for either class C_k :

- We can effectively enumerate TMs $\mathcal{M}_0^k, \mathcal{M}_1^k, \dots$ that halt on all inputs and such that $C_k = \{\mathbf{L}(\mathcal{M}_i^k) \mid i \geq 0\}$.
- If $\mathbf{L} \in C_k$ and \mathbf{L}' differs from \mathbf{L} on only a finite number of words, then $\mathbf{L}' \in C_k$.

If there are decidable languages $\mathbf{L}_1 \notin C_1$ and $\mathbf{L}_2 \notin C_2$, then there is a decidable language $\mathbf{L}_d \notin C_1 \cup C_2$.

Moreover, if $\mathbf{L}_1 \in P$ and \mathbf{L}_2 is not trivial (i.e., $\mathbf{L}_2 \notin \{\emptyset, \Sigma^*\}$), then $\mathbf{L}_d \leq_p \mathbf{L}_2$.

This can be used for proving the existence of many other classes of intermediate problems.

The result has an elegant, not very long proof slightly different from our proof of Ladner's theorem, but using related ideas. See Uwe Schöning: A Uniform Approach to Obtain Diagonal Sets in Complexity Classes, *Theor. Comput. Sci.* 18, 95–103.

Example: Ladner's Theorem via Schöning

We obtain the previous result as a special case:

Corollary 15.3: Consider the classes $C_1 = \text{NPC}$ (NP-complete problems) and $C_2 = \text{P}$. We find that for either class C_k :

- We can effectively enumerate TMs $\mathcal{M}_0^k, \mathcal{M}_1^k, \dots$ that halt on all inputs and such that $C_k = \{\mathbf{L}(\mathcal{M}_i^k) \mid i \geq 0\}$.
- If $\mathbf{L} \in C_k$ and \mathbf{L}' differs from \mathbf{L} on only a finite number of words, then $\mathbf{L}' \in C_k$.

If $\text{P} \neq \text{NP}$, then $\mathbf{L}_1 = \emptyset \notin \text{NPC}$ and $\mathbf{L}_2 = \mathbf{SAT} \notin \text{P}$, hence there is a decidable language $\mathbf{L}_d \notin \text{NPC} \cup \text{P}$.

Moreover, as $\emptyset \in \text{P}$ and \mathbf{SAT} is not trivial, $\mathbf{L}_d \leq_p \mathbf{SAT}$ and hence $\mathbf{L}_d \in \text{NP}$.

Proof: Most properties are clear. The enumeration of NP-complete languages can be constructed by using ideas we have used to prove Ladner's theorem.

Enumerate all pairs of polytime TMs and polytime reductions, and construct a new machine for each pair: on input w , check if the reduction correctly reduces \mathbf{SAT} to the given TM for all inputs up to this length. If yes, behave like the TM; if no, behave like \mathbf{SAT} . Therefore, if a reduction is not working, the resulting machine will be like \mathbf{SAT} in all but a finite number of places.

□

Example: Separating coNP from NPC

We obtain another result as a special case:

Corollary 15.4: Consider the classes $C_1 = \text{NPC}$ (NP-complete problems) and $C_2 = \text{coNP}$. We find that for either class C_k :

- We can effectively enumerate TMs $\mathcal{M}_0^k, \mathcal{M}_1^k, \dots$ that halt on all inputs and such that $C_k = \{\mathbf{L}(\mathcal{M}_i^k) \mid i \geq 0\}$.
- If $\mathbf{L} \in C_k$ and \mathbf{L}' differs from \mathbf{L} on only a finite number of words, then $\mathbf{L}' \in C_k$.

If $\text{NP} \neq \text{coNP}$, then $\mathbf{L}_1 = \emptyset \notin \text{NPC}$ and $\mathbf{L}_2 = \mathbf{SAT} \notin \text{coNP}$, hence there is a decidable language $\mathbf{L}_d \notin \text{NPC} \cup \text{coNP}$.

Moreover, as $\emptyset \in \text{P}$ and \mathbf{SAT} is not trivial, $\mathbf{L}_d \leq_p \mathbf{SAT}$ and hence $\mathbf{L}_d \in \text{NP}$.

In words: There are problems in NP which are not in coNP and yet not NP-complete. This is a stronger statement than Ladner's theorem, but it also uses a stronger assumption (namely that $\text{NP} \neq \text{coNP}$).

Discussion: Schöning's Result

Many further classes of problems could be separated in this way.

The most critical questions for applying the theorem are:

- Can we really effectively enumerate TMs for the respective classes? (this is not trivial and not always true)
- Are the classes really closed under finite variations?
- Under which assumptions can we be sure that $\mathbf{L}_1 \notin C_1$ and $\mathbf{L}_2 \notin C_2$?

Hierarchies of intermediate problems

Another generalisation of Ladner's theorem comes about by applying similar arguments to find problems that are intermediate to, e.g., P and some intermediate problem.

This shows a lot of complicated structure in, e.g., NP:

- We can define classes of mutually \leq_p -reducible problems (even if not NP-complete), called **polynomial many-one degrees**
- These classes can be ordered by \leq_p on their representatives

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Fact 15.5: If $P \neq NP$, then the order of polynomial many-one degrees is dense and non-total.

Recall:

Dense: Between any two elements is another one distinct from both

Non-total: There are incomparable elements

The Limits of Diagonalisation

The Power of Diagonalisation

We have established powerful results using diagonalisation arguments:

- **Time and Space Hierarchy:** even fine-grained time and space classes differ
- **Ladner's Theorem:** NP-intermediate problems differ from both P and NP-complete

What next?

Are there any other interesting open questions about the potential difference of some complexity classes that we would like to resolve?

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Are there any other interesting open questions about the potential difference of some complexity classes that we would like to resolve?

How about separating P from NP?

- This has not been resolved using diagonalisation so far
- Indeed, we know some things that make it seem very unlikely that diagonalisation alone could succeed there

↪ Coming up next . . .

Review: Oracles

Recall the following definitions from Lecture 3:

Definition 3.15: An **Oracle Turing Machine** (OTM) is a Turing machine \mathcal{M} with a special tape, called the oracle tape, and distinguished states $q_?$, q_{yes} , and q_{no} . For a language \mathbf{O} , the **oracle machine** $\mathcal{M}^{\mathbf{O}}$ can, in addition to the normal TM operations, do the following:

Whenever $\mathcal{M}^{\mathbf{O}}$ reaches $q_?$, its next state is q_{yes} if the content of the oracle tape is in \mathbf{O} , and q_{no} otherwise.

Observe that invoking the oracle always takes one step only

Definition 3.16: A problem \mathbf{P} is **Turing reducible** to a problem \mathbf{Q} (in symbols: $\mathbf{P} \leq_T \mathbf{Q}$), if \mathbf{P} is decided by an OTM $\mathcal{M}^{\mathbf{Q}}$ with oracle \mathbf{Q} .

The following is immediate from the definition:

Proposition 15.6: Turing reducibility \leq_T is transitive.

Cook vs. Karp

One can talk about **polynomial-time Turing reductions**: if $\mathcal{M}^{\mathbf{Q}}$ is a polynomially time bounded OTM that decides \mathbf{L} we may write $\mathbf{L} \leq_T^p \mathbf{Q}$.

Polynomial Turing reductions are also known as **Cook reductions**, while polynomial many-one reductions are known as **Karp reductions**.

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Cook reductions are more powerful than Karp reductions, since they can make use of solutions to another problem many times within a single run, rather than only once at the very end. We observe:

Proposition 15.7: $\leq_p \subseteq \leq_T^p$.

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Proposition 15.7: $\leq_p \subseteq \leq_T^p$.

Example 15.8: It is easy to see that $\mathbf{TAUTOLOGY} \leq_T^p \mathbf{SAT}$, whereas $\mathbf{TAUTOLOGY} \not\leq_p \mathbf{SAT}$ is neither known nor expected.

Complexity classes with oracles

Definition 15.9: Consider a language $\mathbf{O} \subseteq \Sigma^*$:

- $P^{\mathbf{O}}$ is the set of all languages decidable by a deterministic polynomial-time OTM with oracle \mathbf{O} ,
- $NP^{\mathbf{O}}$ is the set of all languages decidable by a non-deterministic polynomial-time OTM with oracle \mathbf{O} .

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Some simple observations:

Proposition 15.10: If $\mathbf{O} \in P$ then $P^{\mathbf{O}} = P$.

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Proof: If $\mathbf{L} \in NP$, then there is a polynomial many-one reduction f from \mathbf{L} to \mathbf{SAT} , i.e., $w \in \mathbf{L}$ iff $f(w) \in \mathbf{SAT}$. A polytime OTM for \mathbf{L} , on input w , simply computes $f(w)$, and invokes the oracle to decide $f(w) \in \mathbf{SAT}$. □

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Proposition 15.12: $P^{\mathbf{O}}$ is closed under complement. In particular, $\text{coNP} \subseteq P^{\mathbf{SAT}}$, and $NP \neq P^{\mathbf{SAT}}$ unless $NP = \text{coNP}$.

Relativisation

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Proofs by diagonalisation typically **relativise**: they remain correct if TMs are allowed oracle calls. Indeed, our proofs so far only relied on two properties:

- TMs can be represented as strings (and therefore also iterated over)
- A TM can simulate another one (given as string) without much overhead

Both remain true when looking at machines for a (fixed) oracle **O**.

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Both remain true when looking at machines for a (fixed) oracle \mathbf{O} .

Example 15.13: Consider TMs that can use the Halting problem as an oracle. Such OTMs cannot decide the Halting problem for machines of their own type. Suppose for a contradiction that they could. We can then construct a diagonal TM \mathcal{D} that, on input $\langle \mathcal{M} \rangle$, simulates \mathcal{M} on $\langle \mathcal{M} \rangle$ and flips the result. \mathcal{D} on input $\langle \mathcal{D} \rangle$ leads to a contradiction.

Note: OTMs obtained by providing oracles for the Halting problem of a simpler type of (O)TM give rise to so-called **Turing jumps**. They produce some of the families of undecidable languages considered in the theory of computability.

The limits of diagonalisation

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A prominent example was discovered in the 1970s:

Theorem 15.14 (Baker, Gill, Solovay, 1975): The answer to $P \stackrel{?}{=} NP$ does not relativise: there are languages **A** and **B** such that $P^A = NP^A$ and $P^B \neq NP^B$.

Therefore, any proof that answers $P \stackrel{?}{=} NP$ must be based on some property of (normal) TMs that does not relativise.

Ironically, we will prove the second part of the theorem by diagonalisation!

Proving the theorem: $P^A = NP^A$

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Proof: It is not so hard to find a suitable **A** for the first part of the theorem: the power of the oracle must be such that deterministic and non-deterministic computations coincide.

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We know such complexity classes, e.g., PSpace. Therefore set **A** = **TRUE QBF**. Then:

$$NP^{\text{TRUE QBF}} \stackrel{(1)}{\subseteq} NPSpace \stackrel{(2)}{\subseteq} PSpace \stackrel{(3)}{\subseteq} P^{\text{TRUE QBF}}$$

Inclusion (1) follows from the observation that every nondeterministic OTM with oracle **TRUE QBF** running in polytime can be simulated by an NTM running in polynomial space. Inclusion (2) is Savitch's Theorem. (3) follows from the PSpace-hardness of **TRUE QBF**. Since $P^{\text{TRUE QBF}} \subseteq NP^{\text{TRUE QBF}}$, we obtain $NP^{\text{TRUE QBF}} = P^{\text{TRUE QBF}}$.

Proving the theorem: $P^B \neq NP^B$

Theorem 15.16 (Baker, Gill, Solovay, 1975): The answer to $P \stackrel{?}{=} NP$ does not relativise: there are languages \mathbf{A} and \mathbf{B} such that $P^{\mathbf{A}} = NP^{\mathbf{A}}$ and $P^{\mathbf{B}} \neq NP^{\mathbf{B}}$.

Proof (continued): To show $P^{\mathbf{B}} \neq NP^{\mathbf{B}}$, we define from an arbitrary language $\mathbf{C} \subseteq \Sigma^*$, a language $\mathbf{L}_{\mathbf{C}}$ as follows:

$$\mathbf{L}_{\mathbf{C}} = \{1^n \mid \text{there is } v \in \mathbf{C} \text{ with } |v| = n\}$$

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Proof (continued): To show $P^B \neq NP^B$, we define from an arbitrary language $C \subseteq \Sigma^*$, a language L_C as follows:

$$L_C = \{1^n \mid \text{there is } v \in C \text{ with } |v| = n\}$$

- Clearly, $L_C \in NP^C$: Given an input of form 1^n , an NTM can guess a suitable word v and use the C -oracle to check the guess
- Whether $L_C \in P^C$ or not depends on C . (We have already shown that $L_{\text{TRUE QBF}} \in P^{\text{TRUE QBF}}$ must hold)

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We will construct the required language B such that $L_B \notin P^B$.

We only consider the input alphabet $\Sigma = \{0, 1\}$. Let $\mathcal{M}_0, \mathcal{M}_1, \dots$ be some enumeration polynomial time-bounded OTMs (with oracle B , but this is immaterial for the description of the OTM) for Σ . Let p_i be a polynomial that provides a time bound for \mathcal{M}_i .

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Theorem 15.17 (Baker, Gill, Solovay, 1975): The answer to $P \stackrel{?}{=} NP$ does not relativise: there are languages \mathbf{A} and \mathbf{B} such that $P^{\mathbf{A}} = NP^{\mathbf{A}}$ and $P^{\mathbf{B}} \neq NP^{\mathbf{B}}$.

Proof (continued): We construct \mathbf{B} such that $L_{\mathbf{B}} = \{1^n \mid \text{there is } v \in \mathbf{B} \text{ with } |v| = n\} \notin P^{\mathbf{B}}$.

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In stage $i \geq 0$, do the following:

- Pick a number n such that (1) n is longer than the longest string w for which $w \in \mathbf{B}$ has been defined yet, and (2) $2^n > p_i(n)$.

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- Simulate the (deterministic) run of M_i on 1^n . For oracle calls, $w \stackrel{?}{\in} \mathbf{B}$:
 - If $w \stackrel{?}{\in} \mathbf{B}$ was already defined, answer as defined.
 - If $w \stackrel{?}{\in} \mathbf{B}$ was not defined before, answer **no** (and define $w \notin \mathbf{B}$).

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- For all w with $|w| \leq n$ where $w \stackrel{?}{\in} \mathbf{B}$ was not defined yet, define
 - $w \in \mathbf{B}$ if \mathcal{M}_i has rejected 1^n
 - $w \notin \mathbf{B}$ if \mathcal{M}_i has accepted 1^n

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Theorem 15.17 (Baker, Gill, Solovay, 1975): The answer to $P \stackrel{?}{=} NP$ does not relativise: there are languages A and B such that $P^A = NP^A$ and $P^B \neq NP^B$.

Proof (continued): We construct B such that $L_B = \{1^n \mid \text{there is } v \in B \text{ with } |v| = n\} \notin P^B$.

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- Simulate the (deterministic) run of M_i on 1^n . For oracle calls, $w \stackrel{?}{\in} B$:
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- For all w with $|w| \leq n$ where $w \stackrel{?}{\in} B$ was not defined yet, define
 - $w \in B$ if M_i has rejected 1^n
 - $w \notin B$ if M_i has accepted 1^n

Stage i therefore ends with $w \stackrel{?}{\in} B$ defined for all words w up to length n .

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Proof (continued): The definitions of stage i ensure that \mathcal{M}_i does not decide L_B , since (for the chosen n) we have $L_B(1^n) \neq \mathcal{M}_i(1^n)$:

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- If $1^n \in L(\mathcal{M}_i)$

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Proof (continued): The definitions of stage i ensure that \mathcal{M}_i does not decide L_B , since (for the chosen n) we have $L_B(1^n) \neq \mathcal{M}_i(1^n)$:

- If $1^n \in L(\mathcal{M}_i)$, then we have defined **B** to contain no words of length n , so $1^n \notin L_B$.

Proving the theorem: $P^{\mathbf{B}} \neq NP^{\mathbf{B}}$

Theorem 15.18 (Baker, Gill, Solovay, 1975): The answer to $P \stackrel{?}{=} NP$ does not relativise: there are languages \mathbf{A} and \mathbf{B} such that $P^{\mathbf{A}} = NP^{\mathbf{A}}$ and $P^{\mathbf{B}} \neq NP^{\mathbf{B}}$.

Proof (continued): The definitions of stage i ensure that \mathcal{M}_i does not decide $\mathbf{L}_{\mathbf{B}}$, since (for the chosen n) we have $\mathbf{L}_{\mathbf{B}}(1^n) \neq \mathcal{M}_i(1^n)$:

- If $1^n \in \mathbf{L}(\mathcal{M}_i)$, then we have defined \mathbf{B} to contain no words of length n , so $1^n \notin \mathbf{L}_{\mathbf{B}}$.
- If $1^n \notin \mathbf{L}(\mathcal{M}_i)$

Proving the theorem: $P^{\mathbf{B}} \neq NP^{\mathbf{B}}$

Theorem 15.18 (Baker, Gill, Solovay, 1975): The answer to $P \stackrel{?}{=} NP$ does not relativise: there are languages \mathbf{A} and \mathbf{B} such that $P^{\mathbf{A}} = NP^{\mathbf{A}}$ and $P^{\mathbf{B}} \neq NP^{\mathbf{B}}$.

Proof (continued): The definitions of stage i ensure that \mathcal{M}_i does not decide $\mathbf{L}_{\mathbf{B}}$, since (for the chosen n) we have $\mathbf{L}_{\mathbf{B}}(1^n) \neq \mathcal{M}_i(1^n)$:

- If $1^n \in \mathbf{L}(\mathcal{M}_i)$, then we have defined \mathbf{B} to contain no words of length n , so $1^n \notin \mathbf{L}_{\mathbf{B}}$.
- If $1^n \notin \mathbf{L}(\mathcal{M}_i)$, then there is a word w of length $|w| = n$ such that the run of \mathcal{M}_i on 1^n did not make an oracle call for $w \stackrel{?}{\in} \mathbf{B}$. This follows since there are 2^n words of this length, but at most $p_i(n) < 2^n$ oracle calls. Hence, we have defined $w \in \mathbf{B}$, so $1^n \in \mathbf{L}_{\mathbf{B}}$.

Proving the theorem: $P^B \neq NP^B$

Theorem 15.18 (Baker, Gill, Solovay, 1975): The answer to $P \stackrel{?}{=} NP$ does not relativise: there are languages \mathbf{A} and \mathbf{B} such that $P^{\mathbf{A}} = NP^{\mathbf{A}}$ and $P^{\mathbf{B}} \neq NP^{\mathbf{B}}$.

Proof (continued): The definitions of stage i ensure that \mathcal{M}_i does not decide \mathbf{L}_B , since (for the chosen n) we have $\mathbf{L}_B(1^n) \neq \mathcal{M}_i(1^n)$:

- If $1^n \in \mathbf{L}(\mathcal{M}_i)$, then we have defined \mathbf{B} to contain no words of length n , so $1^n \notin \mathbf{L}_B$.
- If $1^n \notin \mathbf{L}(\mathcal{M}_i)$, then there is a word w of length $|w| = n$ such that the run of \mathcal{M}_i on 1^n did not make an oracle call for $w \stackrel{?}{\in} \mathbf{B}$. This follows since there are 2^n words of this length, but at most $p_i(n) < 2^n$ oracle calls. Hence, we have defined $w \in \mathbf{B}$, so $1^n \in \mathbf{L}_B$.

Since $\mathbf{L}_B \neq \mathbf{L}(\mathcal{M}_i)$ holds for all polynomial time bounded deterministic OTMs \mathcal{M}_i with oracle \mathbf{B} , we obtain $\mathbf{L}_B \notin P^B$. □

Discussion: The proof of Baker/Gill/Solovay

Note 1: Our proof for $P^B \neq NP^B$ would work not just for P^B but for any $DTime(f)^B$ where $f \in o(2^n)$.

Discussion: The proof of Baker/Gill/Solovay

Note 1: Our proof for $P^{\mathbf{B}} \neq NP^{\mathbf{B}}$ would work not just for $P^{\mathbf{B}}$ but for any $DTime(f)^{\mathbf{B}}$ where $f \in o(2^n)$.

Note 2: The proof uses diagonalisation, but not as a method for specifying Turing machines. Indeed, we do not require \mathbf{B} to be computable (though it is), and we do not have to ensure that a particular resource-bounded TM can compute it.

Summary and Outlook

Ladner's theorem can be generalised to find intermediate problems elsewhere

Many results in complexity theory relativise to oracle TMs for some oracle (the same for all TMs considered)

The P vs. NP question does not relativise, as a famous result of Baker, Gill, and Solovay tells us

What's next?

- Generalising NTMs with alternation
- A hierarchy between NP and PSpace