Complexity

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1 Repetition, NS hierarchy

1.1 Abbreviations

- TM - turing machine.
- DTM - deterministic turing machine.
- NTM - non-deterministic turing machine.
- DS - DSPACE
- NS - NSPACE
- DT - DTIME
- NT - NTIME

Theorem 1.1 (NT and DS relation).

$$\forall f : \mathbb{N} \to \mathbb{N} : NT(f(n)) \subseteq DS(f(n))$$

Proof. Construct TM with following algorithm:

1. k = 1
2. do
3. forall y vetev delky k
4. Simuluj M(x) dle y
5. If(Acc) prijmi
6. k++;
7. until vsechny simulace M(x) dle y ktera odmlitly // pokud vsechny vetve odmitli, neexistuje pr. vypocet
8. reject

M pracuje v case $g(n) = \mathcal{O}(f(n))$, vypocet v 4. skonci do g(n) kroku.
Prostor:
1) na ulozeni k potrebujeme g(n) prostoru, $k \leq g(n)$.
2) Na simulace M(x) dle y potrebujeme $\mathcal{O}(g(n))$ prostoru.
Korektnost:
Chceme aby det. TS prijimal stejny jazyk nako puvodni NTS. Pokud existuje pr. vypocet NTS, TS prijme dle nejakeho y. Opacne dojde k $k = g(n)$ a TS odmitne.
Zacykleni nemuze nastat, dle definice cas. slozitosti.
Technical details:
Constructed TM should have 2 tapes:
a) working tape
b) tape to store y (vector that encode branch of NTM) □

Note 1.2. If we are constrained to use single tape, any k tape machine can be compressed to 1 tape machine. We need 2 steps:

1. compress $\Sigma \to \Sigma^k$
2. How to deal with many heads of the original TM? $\Rightarrow$ simulate 1 step of the original machine by many steps in new TM. In total, time complexity is $\mathcal{O}(n^2)$ and space complexity is $\mathcal{O}(n)$.

Theorem 1.3 (NS and DT relation).

$$\forall f : \mathbb{N} \to \mathbb{N}, \forall L \in NS(f(n)) \Rightarrow \exists c_L : L \in DT\left(c_L^{f(n)}\right)$$

Proof. All accepting conf. leaves are bounded by the # of conf. However, # of all paths $2^{c_L^{f(n)}}$. How to avoid double exponent? $\Rightarrow$ Perform BFS in conf. graph. # of edges could be quadratic , however

$$\left(c_L^{f(n)}\right)^2 = \left(c_L^2\right)^{f(n)}$$

c_L^2 is another constant. □

Universal TM Input: (x, y), where x is Godel number of TM to be simulated. y is input of TM.
Alphabet: $\Sigma = \{0, 1\}$.
Working tapes: 3

1. Tape with transition table of M_x.
2. Tape with current state q
3. Working tape

If $S(n)$ is space used by $M_x \Rightarrow$ we need $\max(\lceil \log(t) \rceil, S(n), |x|)$.

Observation 1.4. If initial TM has k tapes and time complexity is $T(n)$ we can compress to 2 tapes with a cost of time complexity being $\mathcal{O}(T(n) \log(n))$.
// TODO write proof (moving blocks on tape)
Therefore simulating TM with multiple tapes could be reduces to 2 tapes, then simulate on Universal TM. Time complexity of Universal TM is dominated by finding the transition $\Rightarrow \mathcal{O}(|x| \cdot T(n))$.

Definition 1.5. Function f is *Space constructible* $\iff \exists$ TM with unary alphabet which marks exactly $|f(n)|$ cells on the working tape. E.g. $\log, e^x$, polynomials.

Theorem 1.6 (Space hierarchy). *Let S_1, S_2 are space constructible functions and*

$$S_1 \in o(S_2) \Rightarrow DS(S_1(n)) \subsetneq DS(S_2(n))$$

Proof. Construction by diagonalization $\Rightarrow$ find a language that is different from all in $\mathcal{O}(S_1)$. □

Definition 1.7. Function f is *Time constructible* $\iff \exists$ TM that does exactly $|f(n)|$ steps. You can think of it as alarm clock.

Note 1.8. Every time constructible function is space constructible.

Theorem 1.9 (Space hierarchy). *Let S_1, S_2 are time constructible functions and*

$$T_1 \cdot \log(T_1(n)) \in o(T_2) \Rightarrow DT(T_1(n)) \subsetneq DT(T_2(n))$$

Note that $\log(T_1(n))$ *is required because of k to 2 tapes compression.*

Proof. Construction by diagonalization $\Rightarrow$ find a language that is different from all in $\mathcal{O}(T_1)$. □

Theorem 1.10 (Savic). *Under some mild assumptions* (*space constructibility, functions bigger than* $\log(n)$) *following statement is true:*

$$NS(f(n)) \subseteq DS(f^2(n))$$

Proof. Find a path in configuration path. We cannot use neither BFS not DFS as the complexity is linear in edges which is exponential comparing to input. Therefore we use recursive algorithm which for all states K reachable by a path of length

$$\frac{c_L^{f(n)}}{2^i}$$

tries to find a path from $C_{init} \to K \to C_{accept}$.
As we divide path by 2 at every recursive call, recursion tree height is equal to $\log_2(n)$. Therefore time complexity is

$$\log_2(c_L^{f(n)}) = f(n) \cdot \log_2(c_L)$$

On each level of recursion we have to store C_{init}, K, C_{accept} which requires $\mathcal{O}(f(n))$ space. Having $\mathcal{O}(f(n))$ levels, total space complexity is $\mathcal{O}(f^2(n))$. □

Note 1.11. Time version of Savic would imply $P = NP$.

1.2 NS hierarchy

Lemma 1.12 (Translation lemma). *Let $S_1(n), S_2(n), f(n)$ be space constructible functions, also*

$$S_2(n) \geq n, f(n) \geq n$$

Then

$$NS(S_1(n)) \subseteq NS(S_2(n)) \Rightarrow NS(S_1(f(n))) \subseteq NS(S_2(f(n)))$$

Lemma allows to replace $n \to f(n)$.

Proof. Let $L_1 \in NS(S_1(f(n)))$ arbitrary, L_1 is recognized by NTS M_1 in space $S_1(f(n))$. We want to prove that $L_1 \in NS(S_2(f(n)))$ by constructing $L_2 \in NS(S_1(n))$ using padding. Define $L_2 := \{x\triangle^i | M_1 \text{ accepts } x \text{ in space } S_1(|x|+i)\}$. Where $\triangle$ is a new symbol, that $\notin$ initial Σ.
Algorithm of $M_2, L(M_2) = L_2$ on input $x\triangle^i$ is the following:

1. Mark $S_1(|x|+i)$ cells on tape.
2. Simulate M_1.
3. if($M_1(x)$ accept $\wedge$ did not use more space than marked in 1) then accept

From the construction, M_2 recognizes L_2 using $S_1(n)$ space. Consequently, $L_2 \in NS(S_1(n))$. Combining with assumption of the lemma

$$L_2 \in NS(S_2(n))$$

And there exists a TM M_3 that recognizes L_2 using $S_2(n)$ space.
The last step is to construct M_4 that recognizes L_1 using $S_2(f(n))$ space. M_4 has 2 working tapes and has following algorithm (M_4 on input x):

1. Mark $f(n)$ cells on 1st tape.
2. Mark $S_2(f(n))$ cells on 2nd tape. Using 1st tape as "input".
3. foreach $x\triangle^i, i = 0, 1, ...$
   simulate M_3 on input $x\triangle^i$. If head of M_3 is inside x M_4s head is in the same place. Otherwise, head of M_3 is inside padding, so M_4 uses counters to track M_3s position. Counter has length at most $1 + \log i$.
4. if($M_3(x)$ accept) then M_4 accept.
5. else if($1 + \log(i) \leq S_2(f(n))$) then $++i$;
   Counter did not overflow and is less than $S_2(f(n))$.
6. else if($1 + \log(i) > S_2(f(n))$) then reject;

If M_4 accepted input x, M_3 accepted $x\triangle^i$ for some $i \Rightarrow x\triangle^i \in L_2 \Rightarrow M_1$ accepts $x \Rightarrow x \in L_1$. On the other hand, if $x \in L_1 \Rightarrow x\triangle^i \in L_2$ for $i = f(|x|) - |x|$ therefore counter i requires

$$\log(f(|x|) - |x|) \leq S_2(f(|x|))$$

space.

□

Note 1.13. We can also prove Translation Lemma for DS, NT, DT.

Theorem 1.14 (NS hierarchy for polynomials). *Let $\varepsilon > 0, r > 1$. Then*

$$NS(n^r) \subsetneq NS(n^{r+\varepsilon})$$

Proof. From the density of rationals:

$$\exists s, t \in \mathbb{N} : r \leq \frac{s}{t} \leq \frac{s+1}{t} \leq r + \varepsilon$$

It is sufficient to prove that:

$$NS(n^{\frac{s}{t}}) \subsetneq NS(n^{\frac{s+1}{t}})$$

Assume by contradiction

$$NS(n^{\frac{s+1}{t}}) \subseteq NS(n^{\frac{s}{t}})$$

Now we use 1.12 for

$$S_1 = \frac{s+1}{t}, S_2 = \frac{s}{t}, f(n) = n^{(s+i)t}, i = 0, 1..., t$$

We get

$$\forall i : NS((n^{(s+i)t})^{(s+1)/t} \subseteq NS((n^{(s+i)t})^{s/t} \Rightarrow \forall i : NS(n^{(s+i)(s+1)}) \subseteq NS(n^{(s+i)s})$$

Now we write for all i:

- $i = 0 : NS(n^{s(s+1)}) \subseteq NS(n^{s^2})$
- $i = 1 : NS(n^{(s+1)(s+1)}) \subseteq NS(n^{(s+1)s})$
- ...
- $i = s : NS(n^{(s+1)2s}) \subseteq NS(n^{(2s)s})$

From the exponents we conclude that for every inequality right side is a subset of left side. So we get a chain of subsets and can use Savic theorem to get a contradiction:

$$NS(n^{(s+1)2s}) \subseteq NS(n^{s^2}) \subseteq DS(n^{2s*s}) \subsetneq DS(n^{2s*s+2s}) \subseteq NS(n^{(s+1)2s})$$

As the beginning and the end are the same sets and the chain of subsets has strict inclusion.

□

2 TM with Oracle

Definition 2.1. Oracle TM is a DTM with an Oracle A (where A is a language) differs from an ordinary DTM by the following:

- Oracle tape (with same alphabet as TM)
- 3 special states: QUERY, YES, NO
- In QUERY state TM moves to YES state if word on the oracle tape $\in A$ (moves to NO o/w). After the answer oracle tape is erased (to reuse space in Space complexity).
- Language of the accepted word by an oracle TM M is $L(M, A)$.

Note 2.2. For NTM definition works the same.

Note 2.3. Ordinary DTM is the same as oracle DTM with $A = \emptyset$.

Consider now a comparison of the oracle DTM, when oracle language A is *not fixed in advance*. Computation forms a tree, that branches at every QUERY.

Observation 2.4. Consider NTM vs Oracle DTM.
"⇒". If NTM M has language $L(M)$, set oracle language $A = L(M)$. "⇐". If oracle language is not recognizable (e.g. HALT), we cannot simulate such NTM.

Definition 2.5. *Turing reducibility* - let A,B languages. We say that A is (deterministically) Turing reducible to B in poly time if there $\exists$ an oracle DTM M working in poly time st

$$A = L(M, B), A \leq^T B$$

Example 2.6. $A \in P \Rightarrow A \leq^T \emptyset$. Since we have poly time algorithm without any oracle.

Definition 2.7. Let A be a language, then

$$\mathbb{P}(A) = \{B | B \leq^T A\}$$

Definition 2.8. Let C be a set of languages then

$$\mathbb{P}(C) = \{B | \exists A \in C : B \leq^T A\}$$

Observation 2.9.

$$\mathbb{P}(\mathbb{P}) = \mathbb{P}$$

Proof. $\mathbb{P} \subseteq \mathbb{P}(\mathbb{P})$. Let $A \in \mathbb{P}$, use A as an oracle with 1 QUERY or use empty oracle.
$\mathbb{P}(\mathbb{P}) \subseteq \mathbb{P}$. Let $B \in \mathbb{P}(\mathbb{P}) \iff \exists A \in \mathbb{P} \exists ODTM\ M : B = L(M, A)$.
To prove the inclusion, we have to construct ordinary DTM that recognizes A. Such TM $\overline{M}$ simulates M and whenever M enters QUERY state, simulate M' to check if word w on oracle tape $\in L(M') = A$.
Now we have to check time complexity.
M makes $P(|x|)$ queries (for p polynomial), as the total number of steps is polynomial. Each query word length is at most $p_w(|x|) = t$. Every query has at most $p_q(|t|)$ steps. In total, query is $p_q(p_w(|x|))$. And the total time complexity of the TM is $p(p_q(p_w(|x|)))$. Which is also polynomial. □

Definition 2.10. *Turing reducibility (non-deterministic)* - let A,B languages. We say that A is non-deterministically Turing reducible to B in poly time if there ∃ an oracle NTM M working in poly time st

$$A = L(M, B), A \leq^{NP} B$$

Definition 2.11. Let A be a language, then

$$\mathbb{NP}(A) = \{B | B \leq^{NP} A\}$$

Definition 2.12. Let C be a set of languages then

$$\mathbb{NP}(C) = \{B | \exists A \in C : B \leq^{NP} A\}$$

Note 2.13. Relativised definition also works for other classes, e.g. EXPTIME.

Definition 2.14.

$$PSPACE = \bigcup_{i=0}^{\infty} DS(n^i) = NPSPACE = \bigcup_{i=0}^{\infty} NS(n^i)$$

Where the 2nd equality holds because of Savic theorem.

Definition 2.15. $PSPACE(A) = \{B | B$ accepted by an oracle DTM working in poly space, st $B = L(M, A)\}$.
Also for class of languages C.

Note 2.16.

$$\mathbb{P} \subseteq \mathbb{NP} \subseteq PSPACE$$

Where last inclusion hold because of $NT(f(n))$ $subseteq DS(f(n))$.
Same proof but as for ordinary TM, but with oracle TM that shares same oracle language A.

Observation 2.17. What about $\mathbb{NP}(\mathbb{NP})$? Still an open question, depends on $\mathbb{P} = \mathbb{NP}$. We cannot simply plug NTM back to the original TM with oracle, as NTM serving as an oracle could have multiple accepting or rejecting leaves.

Definition 2.18. Consider a sequence

$$\Sigma_0^P, \Sigma_1^P, \Sigma_2^P, ...$$

Where $\Sigma_0^P = \mathbb{P}, \Sigma_{i+1}^P = \mathbb{NP}(\Sigma_i^P)$.
And Polynomial hierarchy(simplified) is:

$$PH = \bigcup_{i \geq 1} \Sigma_i^P$$

Theorem 2.19 (Polynomial hierarchy(simplified)).

$$PH \subseteq PSPACE$$

In plain words, PH is only smth in between NP and PSPACE.

Proof. By induction prove $\forall i : \Sigma_i \subseteq PSPACE$.

- $i = 0 \Rightarrow \mathbb{P} \subseteq PSPACE$
- $i \to i+1$, assume $\Sigma_i \subseteq PSPACE$.

By definition: $\Sigma_{i+1} = \mathbb{NP}(\Sigma_i)$ Then

$$\mathbb{NP}(\Sigma_i) \subseteq \mathbb{NP}(PSPACE)$$

We made set of oracles larger, set of recognized languages cannot shrink.
Now we use $\forall C : \mathbb{NP}(C) \subseteq PSPACE(C)$.
Therefore

$$\mathbb{NP}(C) \subseteq PSPACE(PSPACE) \subseteq PSPACE$$

Last inclusion is up to proof (similar to $\mathbb{P} = \mathbb{P}(\mathbb{P})$):

$$B \in PSPACE(PSPACE) \iff \exists A \in PSPACE \exists DTMM : B = L(M, A)$$

Where M works in poly space.

$$A \in PSPACE \iff \exists DTM\ M_A : A = L(M_A)$$

Where M_A works in poly space. Same in $\mathbb{P} = \mathbb{P}(\mathbb{P})$ proof replace oracle QUERY by DTM computation (which accepts or rejects)
The last thing is to check that used space is polynomial. Which is true since $\forall t \in QUERY$: $|t| \leq p(|x|)$ for some polynomial p. Space taken by DTM M' that computes the QUERY is $p_t(|t|) \leq p_t(p(|x|))$. Also, we can ask exponentially many QUERies, however the space is reused, therefore space is bounded by the largest QUERY. □