Complexity Theory

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Lecture 11

Lower Bounds for SAT

Agenda

- big picture
- **TISP**
- lower bound for satisfiability
- big picture

What is complexity all about?

- formalize the notion of computation
- ressource consumption of computations
- depending on input size
- in the worst-case
- computing precise solutions

complexity classes

separation
lower bounds

Satisfiability

We cannot rule out that SAT could be solved in

- linear time or
- logarithmic space

Situation similar for many **NP**-complete problems.

What about restricting time and space simultaneously?

TISP

Definition (TISP)

Let $S, T : \mathbb{N} \to \mathbb{N}$ be constructible functions. A language $L \subseteq \{0,1\}^*$ is in the complexity class **TISP**$(T(n), S(n))$ if there exists a TM M deciding L in time $T(n)$ and space $S(n)$.

Note: **TISP**$(T(n), S(n)) \neq$ **DTIME**$(T(n)) \cap$ **SPACE**$(S(n))$

Agenda

- big picture ✓
- TISP ✓
- lower bound for satisfiability
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Lower Bound for Satisfiability

Theorem

SAT $\notin$ **TISP**$(n^{1.1}, n^{0.1})$.

In order to decide SAT we need

- either more than linear time
- or more than logarithmic space
- due to completeness this translates to any other problem in **NP**
- stronger results known (see further reading)

Proof – Big Picture

Proof is by contradiction. So assume

0. $\mathrm{SAT} \in \mathbf{TISP}(n^{1.1}, n^{0.1})$
1. This implies $\mathbf{NTIME}(n) \subseteq \mathbf{TISP}(n^{1.2}, n^{0.2})$
2. This implies $\mathbf{NTIME}(n^{10}) \subseteq \mathbf{TISP}(n^{12}, n^{02})$ by padding
3. 1. also implies $\mathbf{NTIME}(n) \subseteq \mathbf{DTIME}(n^{1.2})$
4. which implies $\mathbf{\Sigma_2 TIME}(n^{8}) \subseteq \mathbf{NTIME}(n^{9.6})$
5. separately we can show $\mathbf{TISP}(n^{12}, n^{2}) \subseteq \mathbf{\Sigma_2 TIME}(n^{8})$
6. (2,4,5) together establish $\mathbf{NTIME}(n^{10}) \subseteq \mathbf{NTIME}(n^{9.6})$ contradicting the non-deterministic time hierarchy theorem

Proof – Part 1

- can be proven by careful observation of the Cook-Levin reduction.
- problem decided in **NTIME**$(T(n))$ can be formulated as satisfiability problem of size $T(n)\log(T(n))$
- every output bit of reduction computable in polylogarithmic time and space
- hence if SAT $\in$ **TISP**$(n^{1.1}, n^{0.1})$ then **NTIME**$(n) \subseteq$ **TISP**$(n^{1.2}, n^{0.2})$

Proof – Part 2 (padding)

- let $L \in \mathbf{NTIME}(n^{10})$
- define $L' = \{x1^{|x|^{10}} \mid x \in L\}$
- then $L' \in \mathbf{NTIME}(n)$
- by part 1 of proof: $L' \in \mathbf{TISP}(n^{1.2}, n^{0.2})$
- thus $L \in \mathbf{TISP}(n^{12}, n^{2})$

Proof – Part 3

By definition of **TISP**.

Proof – Part 4

Definition

A language L is in $\mathbf{\Sigma_2 TIME}(n^8)$ iff there exists a TM M running in time $\mathcal{O}(n^8)$ and constants c, d such that

$$x \in L \text{ iff } \exists u \in \{0,1\}^{c|x|^8}.\ \forall v \in \{0,1\}^{d|x|^8}.\ M(x,u,v) = 1$$

- let $L \in \mathbf{\Sigma_2 TIME}(n^8)$
- define $L' = \{(x,u) \mid \forall v \in \{0,1\}^{d|x|^8}.\ M(x,u,v) = 1\}$
- hence $\overline{L'} \in \mathbf{NTIME}(n^8)$
- by premise we obtain $\overline{L'} \in \mathbf{DTIME}(n^{1.2*8})$ and also L'
- since $L = \{\exists u \in \{0,1\}^{c|x|^8} \mid (x,u) \in L'\}$ we obtain $L \in \mathbf{NTIME}(n^{9.6})$

Proof – Part 5

- let $L \in \mathbf{TISP}(n^{12}, n^2)$
- then there exists a TM M such that $x \in \{0,1\}^n$ is accepted iff there is a path of length n^{12} in the configuration graph from C_{start} to C_{accept}
- where each configuration takes space $\mathcal{O}(n^2)$
- this is the case iff
  - there exist configurations $C_0, \ldots, C_{n^6}$ such that
  - $C_0 = C_{start}, C_{n^6} = C_{accept}$
  - for all $1 \leq i \leq n^6$ C_{i+1} is reachable from C_i in n^6 steps
- this implies $L \in \mathbf{\Sigma_2 TIME}(n^8)$
- which can be equivalently characterized using alternating TMs

Agenda

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- **TISP** ✓
- lower bound for satisfiability ✓
- big picture

Summary of today's result

- SAT cannot be decided in linear time and, simultaneously, logarithmic space
- neither can any other problem in **NP**
- lower bounds are hard
- nice combination of proof techniques
  - padding
  - reductions
  - splitting paths in the configuration graph

Further Reading

- AB, Theorem 5.11
- original lower bound by *Fortnow*, Time-space tradeoffs for satisfiability, CCC 1997.
- current record: SAT $\notin$ **TISP**$(n^c, c^{\mathcal{O}(1)})$ for any $c < 2\cos(\pi/7)$
- by *R. Williams* Time-space tradeoffs for counting NP solutions modulo integers, CCC 2007.

Big Picture so far