

Complexity Theory

Lecture 11

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<http://www.cl.cam.ac.uk/teaching/1112/Complexity/>

Inclusions

We have the following inclusions:

$$L \subseteq NL \subseteq P \subseteq NP \subseteq PSPACE \subseteq NPSpace \subseteq EXP$$

where $EXP = \bigcup_{k=1}^{\infty} TIME(2^{n^k})$

Moreover,

$$L \subseteq NL \cap co-NL$$

$$P \subseteq NP \cap co-NP$$

$$PSPACE \subseteq NPSpace \cap co-NPSpace$$

Establishing Inclusions

To establish the known inclusions between the main complexity classes, we prove the following.

- $SPACE(f(n)) \subseteq NSPACE(f(n))$;
- $TIME(f(n)) \subseteq NTIME(f(n))$;
- $NTIME(f(n)) \subseteq SPACE(f(n))$;
- $NSPACE(f(n)) \subseteq TIME(k^{\log n + f(n)})$;

The first two are straightforward from definitions.

The third is an easy simulation.

The last requires some more work.

Reachability

Recall the **Reachability** problem: given a *directed* graph $G = (V, E)$ and two nodes $a, b \in V$, determine whether there is a path from a to b in G .

A simple search algorithm solves it:

1. mark node a , leaving other nodes unmarked, and initialise set S to $\{a\}$;
2. while S is not empty, choose node i in S : remove i from S and for all j such that there is an edge (i, j) and j is unmarked, mark j and add j to S ;
3. if b is marked, accept else reject.

NL Reachability

We can construct an algorithm to show that the **Reachability** problem is in **NL**:

1. write the index of node a in the work space;
2. if i is the index currently written on the work space:
 - (a) if $i = b$ then accept, else
guess an index j ($\log n$ bits) and write it on the work space.
 - (b) if (i, j) is not an edge, reject, else replace i by j and return to (2).

We can use the $O(n^2)$ algorithm for **Reachability** to show that:

$$\text{NSPACE}(f(n)) \subseteq \text{TIME}(k^{\log n + f(n)})$$

for some constant k .

Let M be a nondeterministic machine working in space bounds $f(n)$.

For any input x of length n , there is a constant c (depending on the number of states and alphabet of M) such that the total number of possible configurations of M within space bounds $f(n)$ is bounded by $n \cdot c^{f(n)}$.

Here, $c^{f(n)}$ represents the number of different possible contents of the work space, and n different head positions on the input.

Configuration Graph

Define the *configuration graph* of M, x to be the graph whose nodes are the possible configurations, and there is an edge from i to j if, and only if, $i \rightarrow_M j$.

Then, M accepts x if, and only if, some accepting configuration is reachable from the starting configuration $(s, \triangleright, x, \triangleright, \epsilon)$ in the configuration graph of M, x .

Using the $O(n^2)$ algorithm for **Reachability**, we get that M can be simulated by a deterministic machine operating in time

$$c'(nc^{f(n)})^2 \sim c'c^{2(\log n + f(n))} \sim k^{(\log n + f(n))}$$

In particular, this establishes that $\text{NL} \subseteq \text{P}$ and $\text{NPSpace} \subseteq \text{EXP}$.

Savitch's Theorem

Further simulation results for nondeterministic space are obtained by other algorithms for **Reachability**.

We can show that **Reachability** can be solved by a *deterministic* algorithm in $O((\log n)^2)$ space.

Consider the following recursive algorithm for determining whether there is a path from a to b of length at most n (for n a power of 2):

$O((\log n)^2)$ space **Reachability** algorithm:

$\text{Path}(a, b, i)$

if $i = 1$ and $a \neq b$ and (a, b) is not an edge reject
 else if (a, b) is an edge or $a = b$ accept
 else, for each node x , check:

1. is there a path $a - x$ of length $i/2$; and
2. is there a path $x - b$ of length $i/2$?

if such an x is found, then accept, else reject.

The maximum depth of recursion is $\log n$, and the number of bits of information kept at each stage is $3 \log n$.

Savitch's Theorem - 2

The space efficient algorithm for reachability used on the configuration graph of a nondeterministic machine shows:

$$\text{NSPACE}(f(n)) \subseteq \text{SPACE}(f(n)^2)$$

for $f(n) \geq \log n$.

This yields

$$\text{PSPACE} = \text{NPSPACE} = \text{co-NPSPACE}.$$

Complementation

A still more clever algorithm for **Reachability** has been used to show that nondeterministic space classes are closed under complementation:

If $f(n) \geq \log n$, then

$$\text{NSPACE}(f(n)) = \text{co-NSPACE}(f(n))$$

In particular

$$\text{NL} = \text{co-NL}.$$