

**Exercise 1:** Argue that if  $\Delta_k^{\mathbf{P}} = \Sigma_k^{\mathbf{P}}$ , then  $\Delta_k^{\mathbf{P}} = \mathbf{PH}$ .

**Solution:** My plan is to prove that if  $\Delta_k^{\mathbf{P}} = \Sigma_k^{\mathbf{P}}$ , then  $\Delta_k^{\mathbf{P}} = \Pi_k^{\mathbf{P}}$ . This implies that  $\Sigma_k^{\mathbf{P}} = \Pi_k^{\mathbf{P}}$ , and we have seen in class that this implies  $\Sigma_k^{\mathbf{P}} = \Pi_k^{\mathbf{P}} = \mathbf{PH}$ .

For this, recall the recursive definition of these classes:

$$\begin{aligned}\Delta_k^{\mathbf{P}} &= \mathbf{P}^{\Sigma_{k-1}^{\mathbf{P}}}. \\ \Sigma_k^{\mathbf{P}} &= \mathbf{NP}^{\Sigma_{k-1}^{\mathbf{P}}}. \\ \Pi_k^{\mathbf{P}} &= \mathbf{co-NP}^{\Sigma_{k-1}^{\mathbf{P}}}.\end{aligned}$$

The inclusions  $\Delta_k^{\mathbf{P}} \subseteq \Sigma_k^{\mathbf{P}}$  and  $\Delta_k^{\mathbf{P}} \subseteq \Pi_k^{\mathbf{P}}$  clear from the definitions and have been discussed in class. Therefore, it is enough to prove

$$(1) \quad \Sigma_k^{\mathbf{P}} \subseteq \Delta_k^{\mathbf{P}} \implies \Pi_k^{\mathbf{P}} \subseteq \Delta_k^{\mathbf{P}}.$$

Suppose that  $\Sigma_k^{\mathbf{P}} \subseteq \Delta_k^{\mathbf{P}}$  and let  $X \in \Pi_k^{\mathbf{P}}$  be a language. Then,  $\overline{X} \in \Sigma_k^{\mathbf{P}} \subseteq \Delta_k^{\mathbf{P}}$ . However,  $\Delta_k^{\mathbf{P}}$  is closed under complement, because its languages can be decided deterministically in polynomial time with a  $\Sigma_{k-1}^{\mathbf{P}}$  oracle (in particular, the output bit can just be flipped). More formally, let  $M$  be a DTM that decides  $\overline{X}$  with access to a  $\Sigma_{k-1}^{\mathbf{P}}$  oracle. Then, a DTM  $M'$  that decides  $X$  with access to the same oracle can be constructed: Run  $M$  on the input and output the opposite of the answer given by  $M$ . This implies that  $X \in \Delta_k^{\mathbf{P}}$ , proving (1).

**Exercise 2:** Let  $A, B \subseteq \{0, 1\}^*$  be two languages. Show that if  $A \leq_m^l B$  and  $B \in \mathbf{NL}$ , then  $A \in \mathbf{NL}$ .

**Solution:** Recall that  $A \leq_m^l B$  means that there is a log-space computable function  $f$  (say, by a deterministic Turing machine  $D$ ) such that

$$(2) \quad x \in A \iff f(x) \in B.$$

On the other hand,  $B \in \mathbf{NL}$  means that there is a log-space non-deterministic Turing machine  $M$  such that  $M$  accepts  $x$  if and only if  $x \in B$ . Naïvely, a nondeterministic Turing machine  $N$  can be constructed that computes  $f(x)$  by running  $D$  and runs  $M$  on the output. However, this machine would not necessarily run in log-space, because it would need to write the output of  $f$  on one of its work tapes in order for  $M$  to read it. Instead, use a trick introduced in class: I construct the  $k$ th bit of  $f(x)$  whenever it is needed by  $M$ . To achieve this, in addition to the input and work tapes of  $D$ , and the output and work tapes of  $M$ , I need:

- A work tape  $K$  of which only one bit is used, which corresponds to the  $k$ th bit of  $f(x)$ . This serves as the output tape of  $D$  and the input tape of  $M$ . The head associated with this tape never moves.
- A work tape  $MC$  to store the position of the read head of  $M$ , and increment it or decrement it whenever the program of  $M$  moves the read head.
- A work tape  $DC$  to store the position of the write head of  $D$ , and increment it or decrement it whenever the program of  $D$  moves the write head.

More precisely, the machine works as follows:

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**Algorithm 1** Nondeterministic Turing Machine  $N$  that decides  $A$ 

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**Require:**  $x$

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1:  $MC \leftarrow 0$ 
2: for step  $S$  of a run of  $M$  do
3:   if  $S$  reads from the input then
4:      $DC \leftarrow 0$ 
5:     for step  $T$  of a run of  $D$  on the input  $x$  from its initial configuration do
6:       if  $T$  writes bit  $b$  to the output tape and  $DC = MC$  then
7:         Write  $b$  in  $K$ 
8:       end if
9:       Perform step  $T$ , without moving  $N$ 's write head or writing to its output tape
10:      if  $T$  moves the write head to the left then
11:         $DC \leftarrow DC - 1$ 
12:      else if  $T$  moves the write head to the right then
13:         $DC \leftarrow DC + 1$ 
14:      end if
15:    end for
16:  end if
17:  Perform step  $S$ , reading from  $K$  instead of the input tape, and never moving  $N$ 's read head
18:  if  $S$  moves the read head to the left then
19:     $MC \leftarrow MC - 1$ 
20:  else if  $S$  moves the read head to the right then
21:     $MC \leftarrow MC + 1$ 
22:  end if
23: end for
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Note that the machine  $N$  is a (non-deterministic, because the steps of the machine  $M$  used are non-deterministic) Turing machine that completely emulates the machine  $M$  on the input  $f(x)$ . Therefore, it accepts  $x$  if and only if  $M$  accepts  $f(x)$ , that is, if and only if  $x \in A$ . Furthermore, it only uses as much space as  $M$  and  $D$  together, plus the space used in the tapes  $MC$ ,  $DC$  and  $K$ . However,  $K$  is only one bit, and  $MC$  and  $DC$  can count only up to  $|f(x)|$ , which is polynomial in  $|x|$ , because  $D$  is a log-space machine. Therefore, the number of bits used by  $N$  is logarithmic in  $|x|$ . This concludes the proof that  $A \in \mathbf{NL}$ .