- Solutions must include the statements of the problems.
- The preferred format is LaTeX.
- Solution must be your own; homework must be handed in class and on time.

1. Let $\mathcal{X} = \mathbb{R}^2$ and $\mathcal{Y} = \{0, 1\}$. The set of hypothesis $\mathcal{H}$ is the class of concentric circles in $\mathbb{R}^2$: namely, the hypothesis h_r is the circle defined by $x^2 + y^2 \leqslant r^2$. A labeling function $f : \mathcal{X} \longrightarrow \mathcal{Y}$ defined a point P as a positive example if $f(P) = 1$ and a negative example if $f(P) = 0$. The realizability assumption means that a circle of radius r^* exists that contains all positive example.

   (a) Suppose that an ERM algorithm returns for a training sequence $S = \{(P_i, y_i) \mid 1 \leqslant i \leqslant m\}$ a circle h of radius $\bar{r}$. Prove that the error of this prediction rule is bounded above by the probability that no point in S belongs to the set $E = \{\mathbf{x} \in \mathbb{R}^2 \mid \bar{r} \leqslant \| \mathbf{x} \| \leqslant r^*\}$.

   (b) Prove that $\mathcal{H}$ is PAC-learnable and its sample complexity is bounded by

$$m_{\mathcal{H}}(\epsilon, \delta) \leqslant \left\lfloor \frac{\log \frac{1}{\delta}}{\epsilon} \right\rfloor.$$

   Hint: Use the inequality $(1 - \epsilon)^m \leqslant e^{-\epsilon m}$.

2. Consider the hypothesis class $\mathcal{H}$ of all Boolean conjunctions of d variables. Define $\mathcal{X} = \{0, 1\}^d$ and $\mathcal{Y} = \{0, 1\}$.

   A *literal* over the variables $x_1, \ldots, x_d$ is a Boolean function of the form x_i or $\overline{x_i}$ for some i, $1 \leqslant i \leqslant d$.

   A conjunction is any product of literals. For example, if the set of variables is $\{x_1, x_2, x_3, x_4, x_5\}$, a conjunction is a product of the form $x_2\overline{x_4}x_5$.

Consider the *hypothesis class of all conjunctions of literals over d variables*. The empty conjunction h_0 is interpreted as the all-positive hypothesis ($h_0(\mathbf{x}) = 1$ for all $\mathbf{x}$). Any conjunction which contains a variable and its negation (like $x_i \overline{x_i} x_j$, etc.) is interpreted as the all-negative hypothesis.

We assume realizability, which in this context, means that there exists a Boolean conjunction that generates the labels. Thus, each example $(\mathbf{x}, y) \in \mathcal{X} \times \mathcal{Y}$ consists of an assignment to the d Boolean variables and its truth value. For example, for $d = 3$ and the true hypothesis $f(\mathbf{x}) = x_1 \overline{x_2}$, the training set S may contain

$$((1,1,1),0),((1,0,1),1),((0,1,0),0),((1,0,0),1).$$

(a) Prove that $|\mathcal{H}| = 3^d + 1$.

(b) Prove that the hypothesis class of all conjunctions over d variable is PAC learnable and bound its sample complexity $m_{\mathcal{H}}(\epsilon, \delta)$.

(c) Design an algorithm (using pseudocode) that implements the ERM rule and whose time is polynomial in dm.