You have 90 minutes to complete this exam. You may assume without proof any statement proved in class.

1. Find a regular expression for each of the following languages over \{0, 1\}:

   (1 pt) a. strings containing exactly two 0s;
   (1 pt) b. strings that begin or end with 00 or 11;
   (2 pts) c. strings containing both 11 and 010 as substrings;
   (2 pts) d. strings not containing the substring 110.

Solution.

   a. 1*01*01*
   b. \((00 \cup 11) \Sigma^* \cup \Sigma^*(00 \cup 11)\)
   c. \(\Sigma^*11\Sigma^*010\Sigma^* \cup \Sigma^*010\Sigma^*11\Sigma^*\)
   d. 0*(10^+)*1*
2 Prove or disprove:

(2 pts) a. if $L$ is regular and $L'$ is nonregular, then $L \cup L'$ is nonregular;

(3 pts) b. if $L$ is nonregular and both of $L'$ and $L \cap L'$ are regular, then $L \cup L'$ is nonregular.

Solution.

a. False. Take $L = \Sigma^*$ and let $L'$ be any nonregular language. Then $L \cup L' = \Sigma^*$ is regular.

b. True. We will prove the following contrapositive form: if $L'$, $L \cap L'$, and $L \cup L'$ are regular, then $L$ is also regular. This claim follows from the closure of regular languages under difference because

$$L = (L \cup L') \setminus (L' \setminus (L \cap L')).$$
3. Let $L_1$ and $L_2$ be languages recognized by DFAs with $n_1$ and $n_2$ states, respectively. Define $L = L_1 \cup L_2$. Prove that if $L$ is nonempty, then $L$ contains a string of length less than $\max(n_1, n_2)$.

**Solution.** By the argument in the pumping lemma, any DFA with $n$ states that accepts some string accepts some string of length less than $n$. This is because any accepted string of length at least $n$ must visit some state more than once and can therefore be shortened.

Now, let $L = L_1 \cup L_2$ be nonempty. Consider two cases.

- If $L_1$ is nonempty, then by the first paragraph $L_1$ contains a string of length less than $n_1$, the number of states in its DFA.
- Analogously, if $L_2$ is nonempty, then it contains a string of length less than $n_2$.

Either way, $L$ contains a string of length less than $\max(n_1, n_2)$.

4. Let $L$ be a nonempty language in which the shortest string has length $k$. Prove that $L$ cannot be recognized by a DFA with fewer than $k + 1$ states.

**Solution.** Take any string $w = w_1 w_2 \ldots w_k$ in $L$. We claim that the $k + 1$ strings

$$\varepsilon, \quad w_1, \quad w_1 w_2, \quad w_1 w_2 w_3, \quad \ldots, \quad w_1 w_2 w_3 \ldots w_k$$

are each in a different equivalence class of $\equiv_L$. Indeed, for any $i < j$,

$$(w_1 w_2 \ldots w_i)(w_{j+1} \ldots w_k) \notin L,$$

$$(w_1 w_2 \ldots w_j)(w_{j+1} \ldots w_k) \in L,$$

where the first line holds because that string is shorter than $k$.

Since $\equiv_L$ has at least $k + 1$ equivalence classes, the Myhill-Nerode theorem implies that any DFA for $L$ must have at least $k + 1$ states.
For each of the following languages over \{0, 1\}, determine whether it is regular, and prove your answer:

(2 pts)  
**a.** nonpalindromes;

(2 pts)  
**b.** odd-length strings with middle symbol 0;

(2 pts)  
**c.** strings that contain a substring of the form \( wuw \) where \( u \in \{0, 1\}^* \) and \( w \in \{0, 1\}^+ \);

(2 pts)  
**d.** strings with the property that in every prefix, the number of 0s and the number of 1s differ by at most 2.

**Solution.**

In each part, \( L \) stands for the language in question.

**a.** Nonregular. We showed in class that palindromes are a nonregular language. Since non-regular languages are closed under complement, nonpalindromes are also a nonregular language.

**b.** Nonregular. We claim that the infinite collection of strings \( 1^{2i-1}, i = 1, 2, 3, \ldots \), are each in a different equivalence class of \( \equiv_L \). Indeed, for \( i < j \), the language contains \( 1^{2i-1}0^{2i} \) but not \( 1^{2j-1}0^{2j} \). By the Myhill-Nerode theorem, \( L \) is nonregular.

**c.** Regular. The property of containing \( wuw \) for some nonempty \( w \) is equivalent to the property of having some symbol occur at least twice. Thus \( L \) is given by the regular expression \( L = \Sigma^*0\Sigma^*0\Sigma^* \cup \Sigma^*1\Sigma^*1\Sigma^* \), making it regular.

**d.** Regular. The language is given by the following DFA:

![DFA Diagram]