Give regular expressions for each of the following languages over the alphabet $\{0, 1\}$.

1 All strings containing the substring 000.

Solution: $(0+1)^*000(0+1)^*$

2 All strings *not* containing the substring 000.

Solution: $(1+01+001)^*(\varepsilon+0+00)$

Solution: $(\varepsilon+0+00)(1(\varepsilon+0+00))^*$

3 All strings in which every run of 0s has length at least 3.

Solution: $(1+0000^*)^*$

Solution: $(\varepsilon+1)((\varepsilon+0000^*)1)^*(\varepsilon+0000^*)$

4 All strings in which 1 does not appear after a substring 000.

Solution: $(1+01+001)^*0^*$

5 All strings containing at least three 0s.

Solution: $(0+1)^*0(0+1)^*0(0+1)^*0(0+1)^*$

Solution: $1^*01^*01^*0(0+1)^*$ or $(0+1)^*01^*01^*01^*$

6 Every string except 000. (**Hint:** Don't try to be clever.)

Solution: Every string $w \neq 000$ satisfies one of three conditions: Either $|w| < 3$, or $|w| = 3$ and $w \neq 000$, or $|w| > 3$. The first two cases include only a finite number of strings, so we just list them explicitly. The last case includes *all* strings of length at least 4.

$$\begin{gathered}\varepsilon+0+1+00+01+10+11\\ +001+010+011+100+101+110+111\\ +(1+0)(1+0)(1+0)(1+0)(1+0)^*\end{gathered}$$

Solution: $\varepsilon+0+00+\big(1+01+001+000(1+0)\big)(1+0)^*$

7 All strings w such that *in every prefix of* w, the number of 0s and 1s differ by at most 1.

Solution: Equivalently, strings that alternate between 0s and 1s: $(01+10)^*(\varepsilon+0+1)$

8 (**Hard.**) All strings containing at least two 0s and at least one 1.

Solution: There are three possibilities for how such a string can begin:

- Start with 00, then any number of 0s, then 1, then anything.
- Start with 01, then any number of 1s, then 0, then anything.
- Start with 1, then a substring with exactly two 0s, then anything.

All together: $000^*1(0+1)^* + 011^*0(0+1)^* + 11^*01^*0(0+1)^*$
Or equivalently: $\big(000^*1 + 011^*0 + 11^*01^*0\big)(0+1)^*$

Solution:

There are three possibilities for how the three required symbols are ordered:

- Contains a 1 before two 0s: $(0+1)^*\,1\,(0+1)^*\,0\,(0+1)^*\,0\,(0+1)^*$
- Contains a 1 between two 0s: $(0+1)^*\,0\,(0+1)^*\,1\,(0+1)^*\,0\,(0+1)^*$
- Contains a 1 after two 0s: $(0+1)^*\,0\,(0+1)^*\,0\,(0+1)^*\,1\,(0+1)^*$

So putting these cases together, we get the following:

$$\begin{aligned} &(0+1)^*\,1\,(0+1)^*\,0\,(0+1)^*\,0\,(0+1)^* \\ +\,&(0+1)^*\,0\,(0+1)^*\,1\,(0+1)^*\,0\,(0+1)^* \\ +\,&(0+1)^*\,0\,(0+1)^*\,0\,(0+1)^*\,1\,(0+1)^* \end{aligned}$$

Solution: $(0+1)^*\big(101^*0 +$ ~~010~~ $011^*0 + 01^*01\big)\,(0+1)^*$

9 (**Hard.**) All strings w such that *in every prefix of* w, the number of 0s and 1s differ by at most 2.

Solution: $\big(0(01)^*1 + 1(10)^*0\big)^* \cdot \big(\varepsilon + 0(01)^*(0+\varepsilon) + 1(10)^*(1+\varepsilon)\big)$

10 (**Really hard.**) All strings in which the substring 000 appears an even number of times. (For example, 0001000 and 0000 are in this language, but 00000 is not.)

Solution: Every string in $\{0,1\}^*$ alternates between (possibly empty) blocks of 0s and individual 1s; that is, $\{0,1\}^* = (0^*1)^*0^*$. Trivially, every 000 substring is contained in some block of 0s. Our strategy is to consider which blocks of 0s contain an even or odd number of 000 substrings.

Let X denote the set of all strings in 0^* with an even number of 000 substrings. We easily observe that $X = \{0^n \mid n = 1 \text{ or } n \text{ is even}\} = 0 + (00)^*$.

Let Y denote the set of all strings in 0^* with an *odd* number of 000 substrings. We easily observe that $Y = \{0^n \mid n > 1 \text{ and } n \text{ is odd}\} = 000(00)^*$.

We immediately have $0^* = X + Y$ and therefore $\{0,1\}^* = ((X+Y)1)^*(X+Y)$.

Finally, let L denote the set of all strings in $\{0,1\}^*$ with an even number of 000 substrings. A string $w \in \{0,1\}^*$ is in L if and only if an odd number of blocks of 0s in w are in Y; the remaining blocks of 0s are all in X.

$$L = \big((X1)^*Y1 \cdot (X1)^*Y1\big)^*\,(X1)^*X$$

Plugging in the expressions for X and Y gives us the following regular expression for L:

$$\Big(\big((0+(00)^*)1\big)^* \cdot 000(00)^*1 \cdot \big((0+(00)^*)1\big)^* \cdot 000(00)^*1\Big)^* \cdot \big((0+(00)^*)1\big)^* \cdot (0+(00)^*)$$

Whew!