

Induction on Strings

7 Jan 2019

Instruction : Write the answers to the problems neatly in loose sheets with your name and roll number. Submit to the TA at the end of the class.

1. A palindrome can be defined as a string that reads the same forward and backward, or by the following definition.
 - (a) ϵ is a palindrome.
 - (b) If a is any symbol, then the string a is a palindrome.
 - (c) If a is any symbol and x is a palindrome, then axa is a palindrome.
 - (d) Nothing is a palindrome unless it follows from (a) through (c).

Prove by induction that the two definitions are equivalent.

Solution : Let the definition provided here be called *def1* while the usual definition of palindromes be termed as *def2*. Usual definition means that the string reads the same both forward and backward. Both definitions are equivalent implies, both definitions capture exactly the same subset of Σ^* . We prove this by induction on string length, the base case being the empty string.

For ϵ , it is part of *def1* (clause 1) while it trivially satisfies *def2*. Similar argument holds for strings of unit length (clause 2 in *def1*). For length 2 palindromes, they satisfy *def1* being of the type aa with $x = \epsilon$ (clause 3). Strings of type aa also satisfy *def2* being the same symbol repeated twice. Now let us assume both definitions to be equivalent upto strings of length $n > 2$ in Σ^* .

Consider a string σ with $|\sigma| = n + 1$ which is palindrome as per *def2*. That implies $\sigma = \sigma^R$ (applying *def2*). Hence it must be the case that σ starts and ends with same symbol. Hence $\exists \sigma' \in \Sigma^*, a \in \Sigma$ such that $\sigma = a\sigma'a$. Also, $\sigma = \sigma^R \Rightarrow a\sigma'a = (a\sigma'a)^R \Rightarrow a\sigma'a = a\sigma'^R a \Rightarrow \sigma' = \sigma'^R$. Thus σ' is palindrome as per *def2*. Since $|\sigma'| = n - 1$ and *def1*, *def2* are equivalent for string length upto n , we have σ' as palindrome also for *def1*. Now, applying clause 3 of *def1*, we have $\sigma = a\sigma'a$ as palindrome (as per *def1*).

Consider a string σ with $|\sigma| = n + 1$ which is palindrome as per *def1*. Since $n > 2$, we must have a palindrome x such that $|x| = n - 1$ and

$axa = \sigma$ for some symbol a . x should satisfy *def2* and hence $x = x^R$. So, $\sigma^R = (axa)^R = ax^R a = axa = \sigma$. This σ is also palindrome as per *def2*.

2. The strings of balanced parenthesis can be defined in at least two ways.

- (a) A string w over alphabet $\{ (,) \}$ is balanced if and only if:
 - i. w has an equal number of '('s as ')'s, and
 - ii. any prefix of w has at least as many '('s as ')'s.
- (b)
 - i. ϵ is balanced.
 - ii. If w is a balanced string, then (w) is balanced.
 - iii. If w and x are balanced strings, then so is wx .
 - iv. Nothing else is a balanced string.

Prove by induction on the length of a string that definitions (a) and (b) define the same class of strings.

Solution : Let P_Σ^n be the set of balanced parenthesis upto length $2n$. $P_\Sigma^0 = \{\epsilon\}$ which is trivially satisfying *def1* and *def2*. Let *def1* and *def2* agree upto P_Σ^n . Now $P_\Sigma^{n+1} = P_\Sigma^n \cup X$ with X being the set of balanced parenthesis of length exactly $2n + 2$.

Let $x \in X$ be a balanced parenthesis satisfying *def1*. Consider the prefix of x of length 1. As per condition 2 of *def1*, it has to be '('. (If the first symbol is ')', condition 2 is not satisfied.) As per condition 1 of *def1*, x has $n + 1$ '(' and $n + 1$ ')'. We now argue that the last symbol of x has to be ')'. Otherwise, if $x = x_1($, then x_1 is a prefix with $n + 1$ '(' and n ')' (violates condition 2). Hence, as per *def1* $x = (w)$ (has to start and end with '(' and ')' respectively). There are two options now.

- (a) w is a balanced string of length $2n$ as per *def1*. Then w is a balanced string also as per *def2* (the definitions agree upto length $2n$). Then x satisfies *def2* (clause2).
- (b) w is not a balanced string as per *def1*. This can only happen if clause 2 of *def1* is violated by w (clause 1 is satisfied). Let w_1 be the smallest such prefix of w with less '(' than ')'. Note that ' w_1 ' manages to be a prefix with at least as many '(' as ')'. Hence, in w_1 there is exactly one '(' less. Thus ' w_1 ' satisfies both conditions of *def1* (condition 2 is guaranteed by w_1 being the smallest possible violator). Thus w_1 is a balanced string as per *def1* (and hence *def2*). With $x = (w) = (w_1 w_2)$, what about w_2 ? Since condition 1 and 2 of *def1* are satisfied by both w_1 and w , they are also satisfied by w_2 . Still let us show that. Surely, w_2 has same number of '(' and ')' since both (w) and (w_1) are balanced. Consider any prefix σ of w_2 . Note, $(w_1 \sigma)$ has at least as many '(' as ')'. (w_1 has same number of '(' and ')'. Hence σ has at least as many '(' as ')'.)

Both (w_1) and w_2 are balanced as per both defs. Hence $x = (w)$ is balanced also as per *def2* (clause3).

Assume def2 and prove the reverse now.

3. Prove that any equivalence relation R on a set S partitions S into disjoint equivalence classes.

Solution :

Let, $x, y \in S$ and $[[x]]_R \cap [[y]]_R \neq \phi$ and suppose $z \in [[x]]_R$, $z \in [[y]]_R$

Hence by definition of Equivalence Class, $(x, z) \in R$, $(y, z) \in R$

Let $c \in [[x]]_R$ i.e. $(x, c) \in R$

By definition of Equivalence relation, R is symmetric. So, $(z, x) \in R$

By definition of equivalence relation, R is transitive. So,

$(z, x) \in R \wedge (x, c) \in R \Rightarrow (z, c) \in R$ and $(y, z) \in R \wedge (z, c) \in R \Rightarrow (y, c) \in R$

This gives $c \in [[y]]_R$ and hence, $[[x]]_R \subseteq [[y]]_R$

Considering $c \in [[y]]_R$, it can be proved that $[[y]]_R \subseteq [[x]]_R$ in similar way.

$[[x]]_R \subseteq [[y]]_R \wedge [[y]]_R \subseteq [[x]]_R \Rightarrow [[x]]_R = [[y]]_R$

Thus, $[[x]]_R \cap [[y]]_R \neq \phi \Rightarrow [[x]]_R = [[y]]_R$.

Following the above results, we can say, equivalence classes are either same or disjoint. Hence any equivalence relation R on a set S partitions S into disjoint equivalence classes.

4. Show that the following are equivalence relations and give their equivalence classes.

(a) R_1 on integers $\rightarrow iR_1j$ iff $i = j$.

(b) R_2 on people $\rightarrow pR_2q$ iff p and q were born on the same hour of same day of some year.

Solution :

(a) R_1 is a relation on set of integers \mathbb{Z} such that $iR_1j \Rightarrow i = j$

i. **Proof of Reflexivity:** Let, $a \in \mathbb{Z}$

As we can say $a = a \Rightarrow aR_1a$

ii. **Proof of Symmetry:** Let, $a, b \in \mathbb{Z}$ such that $a = b \Rightarrow aR_1b$

From $a = b$ we can say $b = a \Rightarrow bR_1a$

iii. **Proof of Transitivity:** Let, $a, b, c \in \mathbb{Z}$ such that $a = b, b = c \Rightarrow aR_1b, bR_1c$

As we can say $a = c \Rightarrow aR_1c$

Clearly this R_1 will divide \mathbb{Z} into as many equivalent classes as many integers are present in Integer set.

(b) R_2 is a relation on set of people \mathcal{P} such that $pR_2q \Rightarrow p$ and q were born on the same hour of same day of some year.

i. **Proof of Reflexivity:** Let, $p \in \mathcal{P}$

Then we can say p and p were born on the same hour of same day of some year. $\Rightarrow pR_1p$

- ii. **Proof of Symmetry:** Let, $p, q \in \mathcal{P}$ and pR_2q
 Then we can say q and p were born on the same hour of same day of some year. $\implies qR_1p$
- iii. **Proof of Transitivity:** Let, $p, q, r \in \mathcal{P}$ and pR_2q, qR_2r
 As $pR_2q \implies p$ and q were born on the same hour of same day of some year and $qR_2r \implies q$ and r were born on the same hour of same day of some year. then we can clearly say, p and r were born on the same hour of same day of some year. $\implies pR_1r$

Clearly this R_2 will divide \mathcal{P} into $365*24$ ($366*24$, for leap years) equivalence classes i.e. the number of hours in any year.