Predicates and Quantifiers

Recall that the expression $x > 3$ is not a proposition. Why?

**$P(x)$ Notation:**
- We will use the propositional function notation $P(x)$ to denote the expression "$x$ has property $P$".
- As soon as $x$ is assumed to be some value then $P(x)$ has a truth value.

The goal of the section is to quantify such statements so that the result is a proposition. The process is very much in the spirit of the next example.

**Example:** Let $P(x)$ denote the statement "$x > 3$".

What are the truth values:
- i. $P(4)$ True or False?
- ii. $P(2)$ True or False?
- iii. $P(y)$ True or False?

**Example:** Let $Q(x,y)$ denote the statement "$x = y + 3$".

What are the truth values:
- i. $Q(7,4)$ True or False?
- ii. $Q(2,2)$ True or False?

### Quantifiers

**Def.** The **universe of discourse** for a math statement is the domain of that statement.

**Def.** The **universal quantification of $P(x)$** is the proposition "$P(x)$ is true for all values of $x$ in the universe of discourse."
- This proposition is denoted by $\forall x \ P(x)$.
- The proposition $\forall x \ P(x)$ is read as "for all $x \ P(x)$" or "for every $x \ P(x)$".
- The symbol $\forall$ is called the **universal quantifier**.

**Def.** The **existential quantification of $P(x)$** is the proposition "$There exists an element $x$ in the universe of discourse for which $P(x)$ is true.""
- This proposition is denoted by $\exists x \ P(x)$.
- The symbol $\exists$ is called the **existential quantifier**.
- The proposition $\exists x \ P(x)$ is read as "for some $x \ P(x)$" or "there exists an $x$ such that $P(x)$".
The Truth Values of $\forall x P(x)$ and $\exists x P(x)$

**Example 1:** Suppose that the universe of discourse for $x$ is the set of nonnegative integers $\{0, 1, 2, 3, 4, 5, \ldots\}$

What is the truth value of $\forall x (x > 0)$? ________

What is the truth value of $\exists x (x > 0)$? ________

**Example 2:** Suppose that the universe of discourse for $P(x)$ is the small set $\{x_1, x_2, x_3, x_4\}$.

Since $\forall x P(x) \iff P(x_1) \land P(x_2) \land P(x_3) \land P(x_4)$

when is $\forall x P(x)$ true? __________________________
when is $\forall x P(x)$ false? __________________________

Since $\exists x P(x) \iff P(x_1) \lor P(x_2) \lor P(x_3) \lor P(x_4)$

when is $\exists x P(x)$ true? __________________________
when is $\exists x P(x)$ false? __________________________

**Note:** The above observations also hold for infinite universe of discourse sets.

**Examples 3:**

<table>
<thead>
<tr>
<th>Where $P(x)$ denotes:</th>
<th>Universe of Discourse for $P(x)$</th>
<th>Truth value of $\exists x P(x)$</th>
<th>Truth value of $\forall x P(x)$</th>
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</thead>
<tbody>
<tr>
<td>$x = x + 3$</td>
<td>Real numbers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$x = x + 0$</td>
<td>Real numbers</td>
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<td>$0/x = 0$</td>
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<td>$0 - x = x$</td>
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<tr>
<td>$0 - x = x$</td>
<td>Natural numbers</td>
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</tr>
</tbody>
</table>

**Example 4:**

(i) What is the truth value of $[\forall x P(x) \rightarrow \exists x P(x)]$? ____________

(ii) What is the truth value of $[\exists x P(x) \rightarrow \forall x P(x)]$? ____________
Example 5: Let $P(x)$ denote the statement "$x^2 = 4$". Suppose that the universe of discourse is the set of real numbers.
- Which of the following is the English equivalent to $\exists x P(x)$
  (a) There is a real number $x$ such that $x^2 = 4$.
  (b) For every real number $x$ it is the case that $x^2 = 4$.
- What is the truth value of $\exists x P(x)$?

Example 6: Let $P(x,y)$ denote the statement "$x^2 = y$". Suppose that the universe of discourse is the set of real numbers.
- Which of the following is the English equivalent to $\forall x P(x)$?
  (c) There is a real number $x$ such that $x^2 = 4$.
  (d) For every real number $x$ it is the case that $x^2 = 4$.
- What is the truth value of $\forall x P(x)$?

Definition. A real number $x$ is a rational number if it can be expressed as the ratio of two integers $a$ and $b$ with $b$ not zero, that is if $x = \frac{a}{b}$, with $b \neq 0$.

Example 7: Let $Q(x)$ denote the statement "$x$ is a rational number ", and $I(y)$ denote the statement "$y$ is an integer. Assume the universe of discourse is the set of real numbers.
- $\exists y (Q(y) \land I(y))$
  - Which of the following is the English translation?
    (a) There is a rational number $y$ which is a rational number and also an integer.
    (b) There is a real number $y$ which is a rational number and also an integer.
    (c) Every real number $y$ is a rational and also an integer.
  - What is the truth value? __________

- $\forall y (Q(y) \land I(y))$
  - Which of the following is the English translation?
    (a) There is a rational number $y$ which is a rational number and also an integer.
    (b) There is a real number $y$ which is a rational number and also an integer.
    (c) Every real number $y$ is a rational or it is an integer.
    (d) Every real number $y$ is a rational and also an integer.
  - What is the truth value? __________
iii. \( \forall y (I(y) \rightarrow Q(y)) \)
- Which of the following is the English translation?
  (a) Every real number \( y \) is an integer and also a rational number.
  (b) There is a real number \( y \) such that if \( y \) is an integer then \( y \) is a rational number.
  (c) For any real number \( y \), if \( y \) is an integer then \( y \) is a rational number.
- What is the truth value? __________

iv. \( \forall y (\neg I(y) \rightarrow Q(y)) \)
- What is the English translation? ___________________________
- What is the truth value? __________

v. \( \forall y (Q(y) \rightarrow I(y)) \)
- What is the English translation? ___________________________
- What is the truth value? __________

**Example 8:** Assume the universe of discourse is the set of all students at UHD. Let \( C(x) \) be " \( x \) has a computer" and let \( F(x,y) \) be " \( x \) and \( y \) are friends."

i. Translate \( C(Judy) \) into English. __________________________

ii. Which is the English translation of \( \exists y (C(y) \land F(Judy, y)) \).
   (a) Judy has a friend who has a computer.
   (b) Judy has a computer and a friend.
   (c) There is a student who has a friend and a computer.

iii. Translate \( C(Judy) \land \exists y (C(y) \land F(Judy, y)) \) into English.
    ______________________________________________________________________

iv. Translate \( \forall x (C(x) \lor \exists y (C(y) \land F(x, y))) \) into English.
    ______________________________________________________________________

**Negations of Quantified Expressions**

**Example 9:** Consider the proposition "Every student in the class has taken a course in calculus."
- When is this proposition true? ________________
• Write the proposition in symbolic logic notation.

________________________________________
________________________________________

• Which of the following is the negation of "Every student in the class has taken a course in calculus."
(a) No student in the class has taken calculus.
(b) Some students in the class have not taken calculus
(c) Some student in the class has not taken calculus

• Write the negation of the proposition in symbolic logic notation.

________________________________________
________________________________________

• When is the negation of the proposition "Every student in the class has taken a course in calculus" true? _______________________

Fact: \[ \neg \forall x P(x) \iff \exists x \neg P(x) \]
\[ \neg \exists x P(x) \iff \forall x \neg P(x) \]

Example 10:
(iii) What is the truth value of \([\forall x P(x)] \lor [\neg \forall x P(x)]\)? ______________

(iv) What is the truth value of \([\forall x P(x)] \lor [\exists x \neg P(x)]\)? ______________

(v) What is the truth value of \([\forall x P(x)] \land [\exists x \neg P(x)]\)? ______________

Example 11: Show that \( \neg \exists x (P(x) \lor Q(x)) \equiv \forall x (\neg P(x) \land \neg Q(x)) \).