

Predicates and Quantifiers.

Predicates

Propositional logic, studied previously, cannot adequately express the meaning of all statements in mathematics and in natural language.

Examples?

“ x is greater than 5.”

“ x is greater than y .”

“ n is a prime number.”

“*user* is waiting.”

Def. A **predicate** is a proposition whose truth depends on the value of one or more variables.

Predicates

Quantifiers

Scope, bound variables

Nested quantifiers

Distributivity

Negation

Examples

Predicates

For convenience, we can give every predicate a name:

$$P(x) = "x \text{ is greater than } 5."$$

$$Q(x, y) = "x \text{ is greater than } y."$$

When the values of the variables are specified, the result is a simple proposition: Depending on the, the predicates are either true or false:

$$P(4) = F$$

$$P(10) = T$$

$$Q(2, 1) = T$$

Predicates

Quantifiers

Scope, bound variables

Nested quantifiers

Distributivity

Negation

Examples

How can we use predicates?

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

Let $C(x) = \text{"}x \text{ is playing chess."}$

There are three persons in the room: *Ed*, *Paul*, and *Tom*.

Ed and *Paul* are playing chess, and *Tom* is sleeping.

Formally: $C(\textit{Ed}) = T$, $C(\textit{Paul}) = T$, $C(\textit{Tom}) = F$.

How can we use predicates?

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

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Formally: $C(Ed) = T$, $C(Paul) = T$, $C(Tom) = F$.

Consider a proposition "Someone is playing chess in the room."

Is it true?

How can we use predicates?

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

Let $C(x) = \text{"}x \text{ is playing chess."}$

There are three persons in the room: *Ed*, *Paul*, and *Tom*.

Ed and *Paul* are playing chess, and *Tom* is sleeping.

Formally: $C(\textit{Ed}) = T$, $C(\textit{Paul}) = T$, $C(\textit{Tom}) = F$.

Consider a proposition "Someone is playing chess in the room."

Is it true?

Yes, because, for example, $C(\textit{Ed}) = T$.

How can we use predicates?

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

Let $C(x)$ = “ x is playing chess.”

There are three persons in the room: *Ed*, *Paul*, and *Tom*.

Ed and *Paul* are playing chess, and *Tom* is sleeping.

Formally: $C(Ed) = T$, $C(Paul) = T$, $C(Tom) = F$.

Another proposition “Everyone is playing chess in the room.”

How can we use predicates?

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

Let $C(x)$ = “ x is playing chess.”

There are three persons in the room: *Ed*, *Paul*, and *Tom*.

Ed and *Paul* are playing chess, and *Tom* is sleeping.

Formally: $C(Ed) = T$, $C(Paul) = T$, $C(Tom) = F$.

Another proposition “Everyone is playing chess in the room.”

It's false, because $C(Tom) = F$.

Always true or sometimes true ?

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

Let $P(x) = "x^2 \geq 0."$

Always true

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

Let $P(x) = "x^2 \geq 0."$

Always true:

"For all n , $P(n)$ is true."

"For all x , $x^2 \geq 0."$

" $P(n)$ is true for every n ."

" $x^2 \geq 0$ for every x ."

Always true

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

“For all x , $x^2 \geq 0$.”

An assertion that a predicate is always true is called
a *universal quantification*.

Always true or sometimes true?

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

Another predicate:

Let $Q(x) : "5x^2 - 7 = 0."$

It's true only when $x = \pm\sqrt{7/5}$.

Sometimes true

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

Let $Q(x) : "5x^2 - 7 = 0."$

It's true only when $x = \pm\sqrt{7/5}$.

Sometimes true:

"There exist an n such that
 $P(n)$ is true."

"There exist an x such that
 $5x^2 - 7 = 0."$

" $P(n)$ is true for some n ."

" $5x^2 - 7 = 0$ for some x ."

" $P(n)$ is true for at least one n ."

" $5x^2 - 7 = 0$ for at least one x ."

Sometimes true

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

“Exists an x such that $5x^2 - 7 = 0$ is true.”

An assertion that a predicate is true for some values of the
variable is called

an *existential quantification*.

Sentences can be ambiguous

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

“If you can solve *any* problem we come up with, then you get an A for the course.”

Is it a universal (for all), or an existential (for some) quantification?

Sentences can be ambiguous

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

The last sentence was ambiguous.
The right way to say it in math class:

Universal (always):

“You can solve *every* problem we come up with.”

Existential (sometimes):

“You can solve *at least one* problem we come up with.”

Mathematical notation

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

“For every x , it's true that $x + 1 > x$ ”

becomes

$$\forall x (x + 1 > x)$$

Mathematical notation

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

“For every x , $P(x)$ ”

becomes

$$\forall x (P(x))$$

Mathematical notation

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

“Exists x such that $x^2 = 4$ ”

becomes

$$\exists x (x^2 = 4)$$

Mathematical notation

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

“Exists x such that $P(x)$ ”

becomes

$$\exists x (P(x))$$

Mathematical notation

Universal:

$\forall x P(x)$ means that *for every* x , $P(x)$ is true.

Existential:

$\exists x P(x)$ means that there *exists* an x such that $P(x)$ is true.

We consider only those values of the variable x that belong to a given set called the *domain of discourse*, or the *universe of discourse*.

Predicates

Quantifiers

Scope, bound variables

Nested quantifiers

Distributivity

Negation

Examples

Example of the universe of discourse

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

For the predicate $Odd(x)$ and $Even(x)$, the universe of discourse is the set of all integers:

$\dots, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, \dots$

$Odd(x)$ is true for -5, -3, -1, 1, 3, 5, etc.

$Even(x)$ is true for -4, -2, 0, 2, 4, etc.

We consider only those values of the variable x that belong to a given set called the *domain of discourse*, or the *universe of discourse*.

To prove or disprove a quantification

Predicates

Quantifiers

Scope, bound variables

Nested quantifiers

Distributivity

Negation

Examples

Statement	When true?	When false?
$\forall x P(x)$	$P(x)$ is true for every x .	There is at least one <i>counterexample</i> x such that $P(x)$ is false.
$\exists x P(x)$	There is at least one x such that $P(x)$ is true.	$P(x)$ is false for every x .

Example

Let $P(x) = "x^2 > 0."$

The universe of discourse are all integer numbers.

Is it true or false that $\forall x P(x)$?

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

Example

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

Let $P(x) = "x^2 > 0."$

The universe of discourse are all integer numbers.

Is it true or false that $\forall x P(x)$?

To prove it, we must show that $P(x)$ is true for all integers.

To disprove, we have to find a counterexample for which it's false.

Example

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

Let $P(x) = "x^2 > 0."$

The universe of discourse are all integer numbers.

Is it true or false that $\forall x P(x)$?

To prove it, we must show that $P(x)$ is true for all integers.

To disprove, we have to find a counterexample for which it's false.

Counterexample:

$P(x)$ is false for $x = 0$. So, the quantified statement $\forall x P(x)$ is false.

Scope, variable binding

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

$$\forall x (P(x) \wedge Q(x))$$

The *scope* of the quantifier is the expression to which it's applied. Here, the scope is $P(x) \wedge Q(x)$. Quantifiers *bind* variables inside their scope.

\forall binds x in the logical expression $(P(x) \wedge Q(x))$.

Scope, variable binding

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

Why should we care?

$$\forall x (P(x) \wedge Q(x)) \wedge \exists y (R(y))$$

is equivalent to

$$\forall x (\underline{P(x) \wedge Q(x)}) \wedge \exists x (\underline{R(x)})$$

“Every dog has four legs and has a tail; and there exists a dog that barks.”

Scope, variable binding

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

If all variables are bound by a quantifier or set equal to a particular value then a statement is a proposition:

$\forall x (P(x) \wedge Q(z)) \wedge \exists y (R(y))$, and it's given that $z = 3.1415$.

x is bound by $\forall x$, y is bound by $\exists y$, and z is specified by the given equation.

So, this is a proposition.

Scope, variable binding

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

If a variable is not bound, it's called *free*.

$$\forall x (A(y) \wedge B(x)) \wedge \exists y (C(x, y) \rightarrow D(y)).$$

Scope, variable binding

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

If a variable is not bound, it's called *free*.

$$\forall \underline{x} (A(\underline{y}) \wedge B(\underline{x})) \wedge \exists \underline{y} (C(\underline{x}, \underline{y}) \rightarrow D(\underline{y})).$$

Only the first x is bound by $\forall x$.

This is not a proposition.

Nested quantifiers

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

Quantifiers are nested if one is within the scope of the other:

$$\forall x (\exists y (x + y = 0))$$

It reads as follows

“For every x exists y such that $x + y = 0$.”

We usually drop the external parentheses. Equivalent expression:

$$\forall x \exists y (x + y = 0)$$

Nested quantifiers

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

A few more examples (you know this formulas):

$$\forall x \forall y \forall z (x + (y + z) = (x + y) + z)$$

$$\forall x \forall y (x + y = y + x)$$

$$\forall w \forall x \forall y \forall z \left((y \neq 0 \wedge w \neq 0) \rightarrow \frac{x}{y} + \frac{z}{w} = \frac{xw + zy}{yw} \right)$$

Order of quantifiers

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

Does the order of quantifiers matter?

$$\forall x (\exists y (x + y = 0))$$

“For every x exists y such that $x + y = 0$.”

$$\exists y (\forall x (x + y = 0))$$

“Exists y such that for every x : $x + y = 0$.”

Order of quantifiers

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

Does the order of quantifiers matter?

$$\forall x (\exists y (x + y = 0))$$

“For every x exists y such that $x + y = 0$.”

$$\exists y (\forall x (x + y = 0))$$

“Exists y such that for every x : $x + y = 0$.”

The meaning of the two expressions is different. You cannot swap nested $\forall x$ and $\exists y$.

Order of quantifiers

However, we can swap two (or more) nested quantifiers of the same kind:

$$\forall x \forall y (x + y = y + x)$$

$$\forall y \forall x (x + y = y + x)$$

$$\exists x \exists y (x^y = 4)$$

$$\exists y \exists x (x^y = 4)$$

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

Order of quantifiers

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

These two statements are equivalent:

$$\forall w \exists x \forall y \forall z (P(w, x, y, z))$$

$$\forall w \exists x \underline{\forall z \forall y} (P(w, x, y, z))$$

But, these two statements are not equivalent:

$$\forall w \exists x \forall y \underline{\forall z} (P(w, x, y, z))$$

$$\forall w \underline{\forall z} \exists x \forall y (P(w, x, y, z))$$

Order of quantifiers

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

“For every even integer n greater than 2, there exist prime numbers p and q such that $n = p + q$.”

(Prime numbers are integers > 1 , divisible only by itself and 1.
They are 2, 3, 5, 7, 11, 13, 17, ...)

The universe of discourse:

n is an *even* integer, $n > 2$.

p and q are *prime* numbers.

$$\forall n \exists p \exists q (n = p + q)$$

Order of quantifiers

Swapping the order of different kinds of quantifiers (existential or universal) changes the meaning of a proposition.

$$\forall n (\exists p (\exists q (n = p + q)))$$

$$4 = 2 + 2$$

$$6 = 3 + 3$$

$$8 = 3 + 5$$

...

$$\exists p (\exists q (\forall n (n = p + q)))$$

$$4 \stackrel{?}{=} p + q$$

$$6 \stackrel{?}{=} p + q$$

...

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

Distributivity

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

$$\forall x (P(x) \wedge Q(x)) \equiv (\forall x P(x)) \wedge (\forall x Q(x))$$

we can distribute a universal quantifier \forall over a conjunction.

$$\exists x (P(x) \vee Q(x)) \equiv (\exists x P(x)) \vee (\exists x Q(x))$$

and we can distribute an existential quantifier \exists over a disjunction.

We **cannot** distribute \forall over a disjunction, or \exists over a conjunction.

Negating quantifiers

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

“It is not the case that everyone likes to snowboard.”

$$\neg(\forall x S(x))$$

“There exists someone who does not like to snowboard.”

$$\exists x (\neg S(x))$$

Negating quantifiers

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

“It is not the case that everyone likes to snowboard.”

$$\neg(\forall x S(x))$$

“There exists someone who does not like to snowboard.”

$$\exists x (\neg S(x))$$

To negate “ \forall ”:

$$\neg(\forall x S(x)) \equiv \exists x (\neg S(x))$$

Negating quantifiers

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

“There does not exist anyone who likes skiing over magma.”

$$\neg(\exists x M(x))$$

“Everyone dislikes skiing over magma.”

$$\forall x (\neg M(x))$$

Negating quantifiers

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

“There does not exist anyone who likes skiing over magma.”

$$\neg(\exists x M(x))$$

“Everyone dislikes skiing over magma.”

$$\forall x (\neg M(x))$$

To negate “ \exists ”:

$$\neg(\exists x M(x)) \equiv \forall x (\neg M(x))$$

Negating quantifiers

When negating more complex expressions with quantifiers, you “flip” the quantifier, and negate the expression to which the quantifier was applied.

$$\begin{aligned} & \neg(\forall z (\exists y (\forall x (P(x) \wedge Q(y, z)))))) \\ &= \exists z \neg(\exists y (\forall x (P(x) \wedge Q(y, z)))) \\ &= \exists z \forall y \neg(\forall x (P(x) \wedge Q(y, z))) \\ &= \exists z \forall y \exists x \neg(P(x) \wedge Q(y, z)) \\ &= \exists z (\forall y (\exists x (\neg P(x) \vee \neg Q(y, z)))) \end{aligned}$$

Predicates

Quantifiers

Scope, bound variables

Nested quantifiers

Distributivity

Negation

Examples

Example

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

“Everyone at Hunter College is smart.”

$$\forall x (AtHunter(x) \wedge Smart(x))$$

$$\forall x (AtHunter(x) \rightarrow Smart(x))$$

Example

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

“Everyone at Hunter College is smart.”

$\forall x (AtHunter(x) \wedge Smart(x))$ **Wrong!**

“Everyone is at Hunter College and is smart. No one is elsewhere.”

$\forall x (AtHunter(x) \rightarrow Smart(x))$

Example

“Someone at City College is smart.”

$$\exists x (AtCCNY(x) \wedge Smart(x))$$

$$\exists x (AtCCNY(x) \rightarrow Smart(x))$$

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

Example

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

“Someone at City College is smart.”

$$\exists x (AtCCNY(x) \wedge Smart(x))$$

$$\exists x (AtCCNY(x) \rightarrow Smart(x)) \textbf{Wrong!}$$

“There is someone, who is smart if he(he) is at City College.”

It is true if there is anyone who is not at City College, say in Boston.

Example

“All lions are fierce.”

“Some lions do not drink coffee.”

“Some fierce creatures do not drink coffee.”

Predicates:

$L(x)$ = x is a lion.

$C(x)$ = x drinks coffee.

$F(x)$ = x is fierce.

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

Example

Predicates

Quantifiers

Scope, bound
variables

Nested quantifiers

Distributivity

Negation

Examples

“All lions are fierce.”

“Some lions do not drink coffee.”

“Some fierce creatures do not drink coffee.”

Predicates:

$L(x)$ = x is a lion.

$C(x)$ = x drinks coffee.

$F(x)$ = x is fierce.

$$\forall x (L(x) \rightarrow F(x))$$

$$\exists x (L(x) \wedge \neg C(x))$$

$$\exists x (F(x) \wedge \neg C(x))$$