Propositional Logic Intro

Note 1 **Proposition**: A statement with a truth value; it is either true or false.

Propositions can be combined to form more complicated expressions, using the following operations:

Operators		Quantifiers		Implication operations	
$\wedge$	and	$\forall$	for all	Implication	$P \implies Q$
$\vee$	or	$\exists$	there exists	Inverse	$\neg P \implies \neg Q$
$\neg$	not			Converse	$Q \implies P$
$\implies$	implies			Contrapositive	$\neg Q \implies \neg P$
$\equiv$	equivalent to				

Further, for an implication $P \implies Q$ where P is the *hypothesis* and Q is the *conclusion*, it is useful to know that $P \implies Q \equiv \neg P \vee Q$. Additionally, observe that any implication is logically equivalent to its contrapositive.

DeMorgan's Laws: The following identities can be helpful when simplifying expressions and distributing negations.

- $\neg(P \wedge Q) \equiv \neg P \vee \neg Q$
- $\neg(P \vee Q) \equiv \neg P \wedge \neg Q$
- $\neg(\forall x\, P(x)) \equiv \exists x(\neg P(x))$
- $\neg(\exists x\, P(x)) \equiv \forall x(\neg P(x))$

1 Propositional Practice

Note 1 Convert the following English sentences into propositional logic and the following propositions into English. State whether or not each statement is true with brief justification.

Recall that $\mathbb{R}$ is the set of reals, $\mathbb{Q}$ is the set of rationals, $\mathbb{Z}$ is the set of integers, and $\mathbb{N}$ is the set of natural numbers. The notation "$a \mid b$", read as "a divides b", means that a is a divisor of b.

(a) There is a real number which is not rational.

(b) All integers are natural numbers or are negative, but not both.

(c) If a natural number is divisible by 6, it is divisible by 2 or it is divisible by 3.

(d) $\neg(\forall x \in \mathbb{Q})(x \in \mathbb{Z})$

(e) $(\forall x \in \mathbb{Z})(((2 \mid x) \vee (3 \mid x)) \implies (6 \mid x))$

(f) $(\forall x \in \mathbb{N})((x > 7) \implies ((\exists a, b \in \mathbb{N})\ (a + b = x)))$

Solution:

(a) $(\exists x \in \mathbb{R})\ (x \notin \mathbb{Q})$, or equivalently $(\exists x \in \mathbb{R})\ \neg(x \in \mathbb{Q})$. This is true, and we can use π as an example to prove it.

(b) $(\forall x \in \mathbb{Z})\ (((x \in \mathbb{N}) \vee (x < 0)) \wedge \neg((x \in \mathbb{N}) \wedge (x < 0)))$. This is true, since we define the naturals to contain all integers which are not negative.

(c) $(\forall x \in \mathbb{N})\ ((6 \mid x) \implies ((2 \mid x) \vee (3 \mid x)))$. This is true, since any number divisible by 6 can be written as $6k = (2 \cdot 3)k = 2(3k)$, meaning it must also be divisible by 2.

(d) It is not the case that all rational numbers are integers. This is true, since we have rational numbers like $\frac{1}{2}$ that are not integers.

(e) Any integer that is divisible by 2 or 3 is also divisible by 6. This is false: 2 provides the easiest counterexample. Note that this statement is false even though its converse (part c) is true.

(f) If a natural number is larger than 7, it can be written as the sum of two other natural numbers. This is trivially true, since if $x = a + b$ we can take $a = x$ and $b = 0$.

(Aside: this is a reference to the very weak Goldback Conjecture (`https://xkcd.com/1310/`).)

2 Truth Tables

Note 1

Determine whether the following equivalences hold, by writing out truth tables. Clearly state whether or not each pair is equivalent.

(a) $P \wedge (Q \vee P) \equiv P \wedge Q$

(b) $(P \vee Q) \wedge R \equiv (P \wedge R) \vee (Q \wedge R)$

(c) $(P \wedge Q) \vee R \equiv (P \vee R) \wedge (Q \vee R)$

Solution:

(a) Not equivalent.

P	Q	$P \wedge (Q \vee P)$	$P \wedge Q$
T	T	T	T
T	F	T	F
F	T	F	F
F	F	F	F

(b) Equivalent.

P	Q	R	$(P \vee Q) \wedge R$	$(P \wedge R) \vee (Q \wedge R)$
T	T	T	T	T
T	T	F	F	F
T	F	T	T	T
T	F	F	F	F
F	T	T	T	T
F	T	F	F	F
F	F	T	F	F
F	F	F	F	F

(c) Equivalent.

P	Q	R	$(P \wedge Q) \vee R$	$(P \vee R) \wedge (Q \vee R)$
T	T	T	T	T
T	T	F	T	T
T	F	T	T	T
T	F	F	F	F
F	T	T	T	T
F	T	F	F	F
F	F	T	T	T
F	F	F	F	F

3 Implication

Note 0
Note 1

Which of the following implications are always true, regardless of P? Give a counterexample for each false assertion (i.e. come up with a statement $P(x,y)$ that would make the implication false).

(a) $\forall x \forall y P(x,y) \implies \forall y \forall x P(x,y)$.

(b) $\forall x \exists y P(x,y) \implies \exists y \forall x P(x,y)$.

(c) $\exists x \forall y P(x,y) \implies \forall y \exists x P(x,y)$.

Solution:

(a) True. For all can be switched if they are adjacent; since $\forall x, \forall y$ and $\forall y, \forall x$ means for all x and y in our universe.

(b) False. Let $P(x,y)$ be $x < y$, and the universe for x and y be the integers. Or let $P(x,y)$ be $x = y$ and the universe be any set with at least two elements. In both cases, the antecedent is true and the consequence is false, thus the entire implication statement is false.

(c) True. The antecedent says that there is an x, say x', where for every y, $P(x,y)$ is true. If the antecedent is true, then for every y one can choose $x = x'$, which will make the consequent true.