Logic and Set Theory

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0 Miscellaneous

Some introductory speech

1 Propositional logic

Let P denote a set of *primitive proposition*, unless otherwise stated, $P = \{p_1, p_2, ...\}$.

Definition. The *language* or *set of propositions* $L = L(P)$ is defined inductively by:
(1) $p \in L \; \forall p \in P$;
(2) $\perp \in L$, where $\perp$ is read as 'false';
(3) If $p, q \in L$, then $(p \implies q) \in L$. For example, $(p_1 \implies L)$, $((p_1 \implies p_2) \implies (p_1 \implies p_3))$.

Note that at this point, each proposition is only a finite string of symbols from the alphabet $(,), \implies, \perp, p_1, p_2, ...$ and do not really mean anything (until we define so).
By *inductively define*, we mean more precisely that we set $L_1 = P \cup \{\perp\}$, and $L_{n+1} = L_n \cup \{(p \implies q) : p, q \in L_n\}$, and then put $L = L_1 \cup L_2 \cup ....$

Each proposition is built up *uniquely* from 1) and 2) using 3). For example, $((p_1 \implies p_2) \implies (p_1 \implies p_3))$ came from $(p_1 \implies p_2)$ and $(p_1 \implies p_3)$. We often omit outer brackets or use different brackets for clarity.

Now we can define some useful things:
• $\neg p$ (not p), as an abbreviation for $p \implies L$;
• $p \vee q$ (p or q), as an abbreviation for $(\neg p) \implies q$;
• $p \wedge q$ (p and q), as an abbreviation for $(p \implies (\neg q))$.

These definitions 'make sense' in the way that we expect them to.

Definition. A *valuation* is a function $v : L \to \{0, 1\}$ s.t.
(1) $v(\perp) = 0$; (2)

$$v(p \implies q) = \begin{cases} 0 & v(p) = 1, v(q) = 0 \\ 1 & else \end{cases} \quad \forall p, q \in L$$

Remark. On $\{0, 1\}$, we could define a constant $\perp$ by $\perp = 0$, and an operation $\implies$ by $a \implies b = 0$ if $a = 1, b = 0$ and 1 otherwise. Then a valuation is a function $L \to \{0, 1\}$ that preserves the structure ($\perp$ and $\implies$), i.e. a homomorphism.

Proposition. (1) If v, v' are valuations with $v(p) = v'(p) \; \forall p \in P$, then $v = v'$ (on L).
(2) For any $w : P \to \{0, 1\}$, there exists a valuation v with $v(p) = w(p) \; \forall p \in P$.
In short, a valuation is defined by its value on p, and any values will do.

Proof. (1) We have $v(p) = v'(p) \; \forall p \in L_1$. However, if $v(p) = v'(p)$ and $v(q) = v'(q)$ then $v(p \implies q) = v'(p \implies q)$, so $v = v'$ on L_2. Continue inductively we have $v = v'$ on $L_n \forall n$.
(2) Set $v(p) = w(p) \; \forall p \in P$ and $v(\perp) = 0$: this defines v on L_1. Having defined v on L_n, use the rules for valuation to inductively define v on L_{n+1} so we can extend v to L. □

Definition. We say p is a *tautology*, written $\vDash p$, if $v(p) = 1$ $\forall$ valuations v. Some examples:
(1) $p \implies (q \implies p)$: a true statement is implies by anything. We can verify this by:

$v(p)$	$v(q)$	$v(q \implies p)$	$v(p \implies (q \implies p))$
1	1	1	1
1	0	1	1
0	1	0	1
0	0	1	1

So we see that this is indeed a tautology;
(2) $(\neg\neg p) \implies p$, i.e. $((p \implies \perp) \implies \perp) \implies p$, called the "law of excluded middle";

(3) $[p \implies (q \implies r)] \implies [(p \implies q) \implies (p \implies r)]$.
Indeed, if not then we have some v with $v(p \implies (q \implies r)) = 1$, $v(\implies (p \implies q) \implies (p \implies r)) = 0$. So $v(p \implies q) = 1$, $v(p \implies r) = 0$. This happens when $v(p) = 1$, $v(r) = 0$, so also $v(q) = 1$. But then $v(q \implies r) = 0$, so $v(p \implies (q \implies r)) = 0$.

Definition. For $S \subset L$, $t \in L$, say S *entails* or *semantically implies* t, written $S \vDash t$ if $v(s) = 1 \forall s \in S \implies v(t) = 1$, for each valuation v.
("Whenever all of S is true, t is true as well.")

For example, $\{p \implies q, q \implies r\} \vDash (p \implies r)$. To prove this, suppose not: so we have v with $v(p \implies q) = v(q \implies r) = 1$ but $v(p \implies r) = 0$. So $v(p) = 1$, $v(r) = 0$, so $v(q) = 0$, but then $v(p \implies q) = 0$.

If $v(t) = 1$ we say t is true in v or that v is a model of t.

For $S \subset L$, v is a model of S if $v(s) = 1$ $\forall s \in S$. So $S \vDash t$ says that every model of S is a model of t. For example, in fact $\vDash t$ is the same as $\phi \vDash t$.

2 Syntactic implication

For a notion of 'proof', we will need axioms and deduction rules. As axioms, we'll take:
1. $p \implies (q \implies p)\ \forall p, q \in L$;
2. $[p \implies (q \implies r)] \implies [(p \implies q) \implies (p \implies r)]\ \forall p, q, r \in L$; 3. $(\neg\neg p) \implies p\ \forall p \in L$.

Note: these are all tautologies. Sometimes we say they are 3 axiom-schemes, as all of these are infinite sets of axioms.

As deduction rules, we'll take just *modus ponens*: from p, and $p \implies q$, we can deduce q.

For $S \subset L$, $t \in L$, a *proof* of t from S cosists of a finite sequence $t_1, ..., t_n$ of propositions, with $t_n = t$, s.t. $\forall i$ the proposition t_i is an axiom, or a member of S, or there exists $j, k < i$ with $t_j = (t_k \implies t_i)$.

We say S is the *hypotheses* or *premises* and t is the *conclusion*.

If there exists a proof of t from S, we say S *proves* or *syntactically implies* t, written $S \vdash t$.

If $\phi \vdash t$, we say t is a *theorem*, written $\vdash t$.