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 $p \implies \perp$;
• $p \vee q$ (p or q), as an abbreviation for $(\neg p) \implies q$;
• $p \wedge q$ (p and q), as an abbreviation for $\neg(p \implies (\neg q))$.

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. $((p \implies \bot) \implies \bot) \implies p$, 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 $\vdash t$.

Example. $\{p \implies q, q \implies r\} \vdash p \implies r$.
we deduce by the following:
(1) $[p \implies (q \implies r)] \implies [(p \implies q) \implies (p \implies r)]$; (axiom 2)
(2) $q \implies r$; (hypothesis)
(3) $(q \implies r) \implies (p \implies (q \implies r))$; (axiom 1)
(4) $p \implies (q \implies r)$; (mp on 2,3)
(5) $(p \implies q) \implies (p \implies r)$ (mp on 1,4);
(6) $p \implies q$; (hypothesis)
(7) $p \implies r$. (mp on 5,6)

Example. Let's now try to prove $\vdash p \implies p$. Axiom 1 and 3 probably don't help so look at axiom 2; if we make $(p \implies q)$ and $p \implies (q \implies r)$ something that's a theorem, and make $p \implies r$ to be $p \implies p$ then we are done. So we need to take $p = p, q = (p \implies p), r = p$. Now:
(1) $[p \implies ((p \implies p) \implies p)] \implies [(p \implies (p \implies p)) \implies (p \implies p)]$; (axiom 2)
(2) $p \implies ((p \implies p) \implies p)$; (axiom 1)
(3) $(p \implies (p \implies p)) \implies (p \implies p)$; (mp on 1,2)
(4) $p \implies (p \implies p)$; (axiom 1)
(5) $p \implies p$. (mp on 3,4)

Proofs are made easier by:

Proposition. (2, deduction theorem)
Let $S \subset L$, $p, q \in L$. Then $S \vdash (p \implies q)$ if and only if $(S \cup \{p\}) \vdash q$.

Proof. Forward: given a proof of $p \implies q$ from S, add the lines p (hypothesis), q (mp) to optaion a proof of q from $S \cup \{p\}$.
Backward: if we have proof $t_1, ..., t_n = q$ of q from $S \cup \{p\}$. We'll show that $S \vdash (p \implies t_i) \forall i$, so $p \implies t_n = q$.
If t_i is an axiom, then we have $\vdash t_i \implies (p \implies t_i)$, so $\vdash p \implies t_i$;
If $t_i \in S$, write down t_i, $t_i \implies (p \implies t_i)$, $p \implies t_i$ we get a proof of $p \implies t_i$ from S;
If $t_i = p$: we know $\vdash (p \implies p)$, so done;
If t_i obtained by mp: in that case we have some earlier lines t_j and $t_j \implies t_i$. By induction, we may assume $S \vdash (p \implies t_j)$ and $S \vdash (p \implies (t_j \implies t_i))$. Now we can write down $[p \implies (t_j \implies t_i)] \implies [(p \implies t_j) \implies (t_i)]$ by axiom 2, $p \implies (t_j \implies t_i)$, $p \implies t_j) \implies (p \implies t_i)$ (mp), $p \implies t_j$, $p \implies t_i$ (mp) to obtain $S \vdash (p \implies t_i)$.

These are all of the cases. So $S \vdash (p \implies q)$. ☐

This is why we chose axiom 2 as we did – to make this proof work.

Example. To show $\{p \implies q, q \implies r\} \vdash (p \implies r)$, it's enough to show that $\{p \implies q, q \implies r, p\} \vdash r$, which is trivial by mp.

Now, how are $\vdash$ and $\vDash$ related? We are going to prove the *completeness theorem*: $S \vdash t \iff S \vDash t$.

This ensures that our proofs are sound, in the sense that everything it can prove is not absurd ($S \vdash t$ then $S \vDash t$), and are adequate, i.e. our axioms are powerful enough to define every semantic consequence of S, which is not obvious ($S \vDash t$ then $S \vdash t$).

Proposition. (3)
Let $S \subset L$, $t \in L$. Then $S \vdash t \implies S \vDash t$.

Proof. Given a valuation v with $v(s) = 1\ \forall s \in S$, we want $v(t) = 1$.
We have $v(p) = 1\ \forall p$ axiom as our axioms are all tautologies (proven earier); $v(p) = 1\ \forall p \in S$ by definition of v; also if $v(p) = 1$ and $v(p \implies q) = 1$, then also $v(q) = 1$ (by definition of $\implies$). So $v(p) = 1$ for each line p of our proof of t from S. ☐

We say $S \subset L$ consistent if $S \nvdash \perp$. One special case of adequacy is: $S \vDash \perp \implies S \vdash \perp$, i.e. if S has no model then S inconsistent, i.e. if S is consistent then S has a model. This implies adequacy: given $S \vDash t$, we have $S \cup \{\neg t\} \vDash \perp$, so by our special case we have $S \cup \{\neg t\} \vdash \perp$, i.e. $S \vdash ((\neg t) \implies t)$ by deduction theorem, so $S \vdash \neg\neg t$. But $S \vdash ((\neg\neg t) \implies t)$ by axiom 3, so $S \vdash t$ (mp).

Theorem. (4)
Let $S \subset L$ be consistent, then S has a model.
The idea is that we would like to define valuation v by $v(p) = 1 \iff p \in S$, or more sensibly, $v(p) = 1 \iff S \vdash p$.
But maybe $S \nvdash p_3, S \nvdash \neg p_3$, but a valuation maps half of L to 1, so we want to 'grow' S to contain one of p or $\neg p$ for each $p \in L$, while keeping consistency.

Proof. Claim: for any consistent $S \subset L$, $p \in L$, $S \cup \{p\}$ or $S \cup \{\neg p\}$ consistent.
Proof of claim. If not, then $S \cup \{p\} \vdash \perp$ and $S \cup \{\neg p\} \vdash \perp$, then $S \vdash (p \implies \perp)$ (deduction theorem), i.e. $S \vdash \not p$, so $S \vdash \perp$ contradiction.

Now L is countable as each L_n is countable, so we can list L as $t_1, t_2, ...$ Put $S_0 = S$; set $S_1 = s_0 \cup \{t_1\}$ or $s_0 \cup (\neg t_1\}$ so that S_1 is consistent. Then set $S_2 = S_1 \cup \{t_2\}$ or $S_1 \cup \{\neg t_2\}$ so that S_2 is consistent, and continue likewise. Set $\bar{S} = S_0 \cup S_1 \cup S_2 \cup ...$ Then $\bar{S} \supset S$, and $\bar{S}$ is consistent (as each S_n is, and each proof is finite). $\forall p \in L$, we have either $p \in S$ or $(\neg p) \in S$. Also, $\bar{S}$ is *deductively closed*, meaning that is $\bar{S} \vdash p$ then $p \in \bar{S}$: if $p \notin \bar{S}$ then $(\neg p) \in \bar{S}$, so $\bar{S} \vdash p$, $\bar{S} \vdash (\not p)$ so $\bar{S} \vdash \perp$ contradiction.
Define $v : L \to \{0, 1\}$ by $p \to 1$ if $p \in \bar{S}$, 0 otherwise. Then v is a valuation: $v(\perp) = 0$ as $\perp \notin \bar{S}$; for $v(p \implies q)$:
If $v(p) = 1$, $v(q) = 0$: We have $p \in \bar{S}$, $q \notin \bar{S}$, and want $v(p \implies q) = 0$, i.e. $(p \implies q \notin \bar{S}$. But if $9p \implies q) \in \bar{S}$ then $\bar{S} \vdash q$ contradiction;
If $v(q) = 1$: have $q \in \bar{S}$, and want $v(p \implies q) = 1$, i.e. $(p \implies q) \int \bar{S}$. But $\vdash q \implies (p \implies q)$ so $\bar{S} \vdash (p \implies q)$;
If $v(p) = 0$: have $p \notin \bar{S}$, i.e. $(\neg p) \in \bar{S}$ and want $(p \implies q) \in \bar{S}$. So we need $(p \implies \perp) \vdash (p \implies q)$, i.e. $p \implies \perp, p \vdash q$ (deduction theorem). Thus it's enough to show that $\perp \vdash q$. But $(\neg\neg q) \implies q$, and $\vdash (\perp \implies (\neg\neg q))$ (axiom 3 and 1 − to see the second one, write $\neg$ explicitly using $\implies$ and $\perp$), so $\vdash (\perp \implies q)$, i.e. $\perp \vdash q$. □

Remark. Sometimes this is called 'completeness theorem'. The proof used P being countable to get L countable; in fact, result still holds if P is uncountable (see chapter 3).

By remark before theorem 4, we have

Corollary. (5, adequacy)
Let $S \subset L$, $t \in L$. Then if $S \vDash t$ then $S \vdash t$.

And hence,

Theorem. (6, completeness theorem)
Let $S \subset L$, $t \in L$. Then $S \vdash t \iff S \vDash t$.

Some consequences:

Corollary. (7, compactness theorem)
Let $S \subset L$, $t \in L$ with $S \vDash t$. Then $\exists$ finite $S' \subset S$ with $S' \vDash t$.
This is trivial if we replace $\vDash$ by $\vdash$ (as proofs are finite).

Special case for $t = \perp$: If S has no model then some finite $S' \subset S$ has no model. Equivalently,

Corollary. (7', compactness theorem, equivalent form)
Let $S \subset L$. If every finite subset of S has a model then S has a model.
This *isi* equivalent to corollary 7 because $S \vDash t \iff S \cup \{\neg t\}$ has no model and $S' \vDash t \iff S' \cup (\neg t)$ has no model.

Corollary. (8, decidability theorem)
There is an algorithm to determine (in finite time) whether or not, for a given finite $S \subset L$ and $t \in L$, we have $S \vdash t$.
This is highly non-obviuos; however it's trivial to decide if $S \models t$ just by drawing a truth table, and $\models \iff \vdash$.

3 Well-Orderings and Ordinals

Definition. A *total order* or *linear order* on a set X is a relation $<$ on X, such that
(1) Irreflexive: Not $x < x\ \forall x \in X$;
(2) Transitive: $x < y, y < z \implies x < z\ \forall x, y, z \in X$;
(3) Trichotomous: $x < y$ or $x = y$ or $y < x\ \forall x, y \in X$.
Note: two of (iii) cannot hold: if $x < y$, $y < x$ then $x < x$ by transitivity.
Write $x \leq y$ if $x < y$ or $x = y$, and $y > x$ if $x < y$.

We can also define total order in terms of $\leq$:
(1) Reflexive: $x \leq x\ \forall x \in X$;
(2) Transitive: $x \leq y, y \leq z \implies x \in z\ \forall x, y, z \in X$;
(3) Antisymmetric: $x \leq y, y \leq x \implies x = y\ \forall x, y \in X$;
(4) 'Tri'chotomous (although it's only two): $x \leq y$ or $y \leq x\ \forall x, y \in X$.

Example. $\mathbb{N}, \mathbb{Q}, \mathbb{R}$ with the usual orders are all total orders.
$\mathbb{N}^+$ the relation 'divides' is not a total order: for example we don't have any of $2|3, 3|2$ or $2 = 3$.
$\mathcal{P}(S)$ for some S (with $|S| \geq 2$ to be rigorous), with $x \leq y$ if $x \subseteq y$ is not a total order for the same reason.

A total order is a *well-ordering* if every (non-empty) subset has a least element, i.e. $\forall S \subset X, S \neq \phi \implies \exists x \in S, x \leq y \forall y \in S$.

Example. 1.$\mathbb{N}$ with the usual $<$ is a well ordering.
2.$\mathbb{Z}, \mathbb{Q}, \mathbb{R}$ with the usual $<$ are not well orderings.
3.$\mathbb{Q}^+ \cup \{0\}$ with the usual $<$ is not a well ordering (e.g. $(0, \infty) \subset \mathbb{Q}^+ \cup \{0\}$).
4.The set $\{1 - \frac{1}{n} : n = 2, 3, ...\}$ as a subset of $\mathbb{R}$ with the usual ordering is a well ordering. 5.The set $\{1 - \frac{1}{n} : n = 2, 3, ...\} \cup \{1\}$ as a subset of $\mathbb{R}$ with the usual ordering is a well ordering. 6.The set $\{1 - \frac{1}{n} : n = 2, 3, ...\} \cup \{2 - \frac{1}{n} : n = 2, 3, ...\}$ (same assumption) is a well ordering.

Remark. X is well-ordered iff there is no $x_1 > x_2 > x_3 > ...$ in X.
Clearly if there is such a sequence then $S = \{x_1, x_2, ...\}$ has no least element. Conversely, if $S \subset X$ has no least element, then for each element $x \in S$ there exists a $x' \in S$ with $x' < x$, so we can just pick $x, x', ...$ inductively.

Definition. We say total orders X, Y are *isomorphic* if there exists a bijection $f : X \to Y$ that is order-preserving, i.e. $x < y \iff f(x) < f(y)$.
For example, 1 and 4 above are isomorphic; 5 and 6 are isomorphic; 4 and 5 are not isomorphic (one has a greatest element, and the other doesn't).

Here comes the first reason why well orderings are useful:

Proposition. (1, Proof by induction)
Let X be well-ordered, and let $S \subset X$ be s.t. if $y \in S\ \forall y < x$ then $x \in S$ (each $x \in X$). Then $S = X$.
Equivalently, if $p(x)$ is a property s.t. $\forall x$: if $p(y) \forall y < x$ then $p(x)$, then $p(x) \forall x$.
(I think we must assert S to be non-empty here, but the lecturer didn't agree with me; need to check later.)

Proof. If $S \neq X$ then let x be the least element of $X \setminus S$. Then $x \notin S$. But $y \in S\ \forall y < x$, contradiction. □

A typical use:

Proposition. Let X, Y be isomorphic well-orderings. Then there is a *unique* isomorphism from X to Y.

Proof. Let f, g be isomorphisms. We'll show $f(x) = g(x)\ \forall x$ by induction. Thus we may assume $f(y) = g(y)\ \forall y < x$, and want $f(x) = g(x)$. Let a be the least element of $Y \setminus \{f(y) : y < x\}$. Then we must have $f(x) = a$: if $f(x) > a$, then some $x' > x$ has $f(x') = a$ by surjectivity, contradiction. The same shows $g(x)$ =least element of $Y \setminus \{g(y) : y < x\}$, but this is the same as a. So $f(x) = g(x)$. □

Remark. This is false for total orders in general. One example is, consider from $\mathbb{Z} \to \mathbb{Z}$, we could either take identity, or $x \to x - 5$; or from $\mathbb{R}$ to $\mathbb{R}$ we could take identity or $x \to x - 5$ or $x \to x^3$...

Definition. In a total order X, an *initial segment* I is a subset of X such that $x \in I, y < x \implies y \in I$.

Example. For any $x \in X$, set $I(x) = \{y \in X : y < x\}$. Then this is an initial segment.
Obviously, not every initial segment is of this form: for example, in $\mathbb{R}$ we can take $\{x : x \leq 3\}$; or in $\mathbb{Q}$, take $\{x : x^2 < 2\} \cup \{x < 0\}$ (this cannot be written as above form as $\sqrt{2} \notin \mathbb{Q}$.
Note: in a well-ordering, every proper initial segment *is* of the above form: let x be the least elemnt of $X \setminus I$. Then $y < x \implies y \in I$. Conversely, if $y \in I$, then we must have $y < x$: otherwise $x \in I$, contradiction.

Our aim is to show that every subset of a well-ordered X is isomorphic to an initial segment.
Note: this is very false for total orders: e.g. $\{1, 5, 9\} \subset \mathbb{Z}$, or $\mathbb{Q} \subset \mathbb{R}$. If we have $S \subset X$, Wwe would like to define $f : S \to X$ that sends the smallest of S to the smallest of X, then remove them from both sets and send the smallest of the remaining to the smallest of the remaining, etc... But to do this we need a theorem.

Theorem. (3, definition by recursion)
Let X be well-ordered, Y be a set, and $G : \mathcal{P}(X \times Y) \to Y$. Then $\exists f : X \to Y$ s.t. $f(x) = G(f|_{I_x})$ for all $x \in X$. Moreover, such f is unique.
Here we define the restriction as: for $f : A \to B$, and $C \subset A$, the restriction of f to C is $f|_C = \{(x, f(x)) : x \in C\}$. (I think the lecturer is regarding a function as subset of a cartesian product)
In defining $f(x)$, make use of $f|_{I_x}$, i.e. the values of $f(y), y < x$.

Proof. Existence: define 'h is an attempt' to mean: $h : I \to Y$, some initial segment I of X, and $\forall x \in I$ we have $h(x) = G(h|_{I_X})$. Note that is h, h' are

attempts, both defined at x, then $h(x) = h'(x)$ by induction on x. Since if $h(y) = h'(y) \forall y < x$ then $h(x) = h'(x)$.
Also, $\forall x \in X$ there exists an attempt defined at x by induction on x: we want attempt definde at x, given $\forall y < x$ there exists attempt defined at y. For each $y < x$, we have unique attempt h_y defined on $\{z : z \leq y\}$ (unique by what we just showed).
Let $h = \cup_{y<x} h_y$: an attempt defined on I_x. This is single-valued by uniqueness, so is indeed a function.
So $h' = h \cup \{(x, G(h))\}$ is an attempt defined at x.
Now set $f(x) = y$ if $\exists$ attempt h, defined at x, with $h(x) = y$ (single-valued).
Uniqueness: if f, f' suitable then $f(x) = f'(x) \forall x \in X$ (induction on X) – since if $f(y) = f'(y) \forall y < x$ then $f(x) = f'(x)$. □

A typical application:

Proposition. (4, subset collapse)
Let X be well-ordered, $Y \subset X$. Then Y is isomorphic to an initial segment of X. Moreover, such initial segment is unique.

Proof. To have f an isomorphism from y to an initial segment of X, we need precisely that $\forall x \in Y : f(x) = \min X \setminus \{f(y) : y < x\}$. So done (existence and uniqueness) by theorem 3.
Note that $X \setminus \{f(y) : y < x\} \neq \phi$, e.g. because $f(y) \leq y \ \forall y$ (induction), so $x \notin \{f(y) : y < x\}$. □

In particular, a well-ordered X cannot be isomorphic to a proper initial segment of X – by uniqueness in subset collapse, as X is isomorphic to X.

How do different well-orderings relate to each other?

We say $X \leq Y$ if X is isomorphic to an initial segment of Y. For example, $\mathbb{N} \leq \{1 - \frac{1}{n} : n = 2, 3, ...\} \cup \{1\}$.

Theorem. (5)
Let X, Y be well-orderings. Then $X \leq Y$ or $Y \leq X$.

Proof. Suppose $Y \not\leq X$. To obtain $f : X \to Y$ that is an isomorphism with an initial segment of Y, need $\forall x \in X : f(x) = \min Y \setminus \{f(y) : y < x\}$. So we are done by theorem 3.
Note that we cannot have $\{f(y) : y < x\} = X$, as then Y is isomorphic to I_x. □

Proposition. (6)
Let X, Y be well-orderings with $X \leq Y$ and $Y \leq X$. Then X and Y are isomorphic.

Proof. We have isomorphism f from X to an isomorphism of Y, and g the other way round. Then $g \circ f : X \to X$ is an isomorphism from X to an initial segment of X (i.s. of i.s. is i.s.), but that is impossible unless the initial segment is X

itself. So $g \circ f$ is identity (by uniqueness in subset collapse). Similarly, $f \circ g$ is identity on Y. □

New well-orderings from old:

Write $X < Y$ if $X \leq Y$ but X not isomorphic to Y. Equivalently, $X < Y$ iff X is isomorphic to a proper initial segment of Y. For example, if $X = \mathbb{N}$, $Y = \{1 - \frac{1}{n}\} \cup \{1\}$ then $X < Y$.

Make a bigger one: given well-ordered X, choose $x \notin X$, and set $x > y$ for all $y \in X$. This is a well-ordering on $X \cup \{x\}$: written X^+. Clearly $X < X^+$.

Put some together:
Let $(X, <_X)$ and $(Y, <_Y)$ be well-orderings. Say Y extends X if $X \subset Y$, and $<_X$, $<_Y$ agree on X, and X an initial segment of $(Y, <_Y)$.
Well-orderings $(X_i : i \in I)$ are nested if $\forall i, j \in I : X_i$ extends X_j or X_j extends X_i.

Proposition. (7)
Let $(X_i : i \in I)$ be a nested family of well-orderings. Then there exist well-ordering X with $X \geq X_i \ \forall i$.

Proof. Let $X = \cup_{i \in I} X_i$, with $x < y$ if $\exists i$ with $x, y \in X_i$ and $x <_i y$, Then $<$ is a well-defined total order on X. given $S \subset X$, $S \neq \phi$, choose i with $S \cap X_i \neq \phi$. Then $S \cap X_i$ has a minimal element (as X_i is well-ordered), which must also be a minimal element of S (as X_i an i.s. of X). Also, $X \geq X_i \forall i$. □

4 Ordinals

Are the well-orderings themselves well-ordered?

An ordinal is a well-ordered set, with two sell-ordered sets regarded as the same if they are isomorphic. (Just as a rational is an expression $\frac{M}{N}$, with $\frac{M}{N}$, $\frac{M'}{N'}$ regarded as the same if $MN' = M'N$. But, unlike for $\mathbb{Q}$, we cannot formalise by equivalence classes – see later).

If X is a well-ordering corresponding to ordinal X, say X has order-type α.

Example. For each $k \in \mathbb{N}$, write k for the order-type of the (unique) well-ordering of a set of size k, and write ω for order-type of $\mathbb{N}$. So, in $\mathbb{R}$, $\{1, 3, 7\}$ has order-type 3. $\{1 - \frac{1}{n} : n = 2, 3, ...\}$ has order-type ω. For X of o-t α and Y of o-t β, write $\alpha \leq \beta$ if $X \leq Y$ (this is independent of choice of X,Y).
Similarly for $\alpha < \beta$ etc.

We know: $\forall \alpha, \beta$, $\alpha \leq \beta$ or $\beta \leq \alpha$, and if $\alpha \leq \beta$, $\beta \leq \alpha$ then $\alpha = \beta$.

Theorem. Let α be an ordinal. Then the ordinals $< \alpha$ form a well-ordered set of order-type α. e.g. the ordinals $< \omega$ are $0, 1, 2, 3, ...$

Proof. Let X have o-t α. the well-orderings $< X$ are precisely (up to isomorphism) the proper initial segments of X, i.e. the $I_x, x \in X$.
But these are isomorphic to X itself, via $x \to I_x$. □

We often write I_α to be the set of ordinals less than α.

Proposition. (9)
Let S be a non-empty set of ordinals. Then S has a least element.

Proof. Choose $\alpha \in S$. If α minimal in S then done. If not, then $S \cap I_\alpha \neq \phi$, so have a minimal element of $S \cap I_\alpha$, which is therefore minimal in S. □

Theorem. (10, Burali-Forti paradox):
The ordinals do not form a set.

Proof. Suppose not, let X be set of all ordinals. Then X is a well-orderings, say order-type α. So X is isomorphic to I_α. But I_α is a proper i.s. of X. □

Given α, we have $\alpha^+ > \alpha$. Also, if $\{\alpha_i : i \in I\}$ is a set of ordinals, then there exists α with $\alpha \geq \alpha_i \forall i$ (by applying prop 7 to the nested family of $I_{\alpha_i}; i \in I$).

In fact, there is therefore a least upper bound for $\{\alpha_i : i \in I\}$ by applying prop 9 to the set $\{\beta \leq \alpha : \beta$ an upper bound for the $\alpha_i\}$. This is written $\sup\{\alpha_i : i \in I\}$, e.g. $\sup\{2, 4, 6, 8, ...\} = \omega$.

Some ordinals: $0, 1, 2, ..., \omega, \omega + 1$(officially ω^+),$\omega + 2$,...,
$\omega + \omega = \omega 2 = \sup\{\omega + 1, \omega + 2, ..., \}$, $\omega^2 + 1, \omega^2 + 2, ...,$

$\omega 3, ..., \omega 4, ..., ..., \omega\omega = \omega^2 = \sup\{\omega, \omega 2, \omega 3, ...\}$,
$\omega^2{+}1, ..., \omega^2{+}\omega, \omega^2{+}\omega{+}1, ...\omega^2{+}\omega 2, ..., \omega^2{+}\omega^2 = \omega^2 2, ..., \omega^2 3, ..., \omega^2 4, ..., \omega^2 5, ..., \omega^2\omega =$
$\omega^3, ...\omega^3 2, ..., \omega^4, ..., \omega^\omega = \sup\{\omega, \omega^2, \omega^3, ...\}$,
$\omega^\omega + 1, ..., \omega^\omega 2, ..., \omega^\omega\omega = \omega^{\omega+1}$,
$\omega^{\omega+2}, ..., \omega^{\omega+3}, ..., \omega^{\omega^2}, ..., \omega^{\omega^3}, ..., \omega^{\omega^\omega}, ...$
And as expected we have $\omega^{\omega^{\omega^{\omega^{\cdots}}}} = \sup\{\omega, \omega^2, \omega^3, ...\} := \varepsilon_0$, and then $\varepsilon_0 + 1, ...$, and then the whole thing again until $\varepsilon_1 = \varepsilon_0^{\varepsilon_0^{\cdots}}$.

However, although this thing looks quite magnificent, they are all just countable (as we have just done it). Is there an uncoutnable ordinal? In other words, is there an uncountable well-ordered set?

Theorem. (11)
There is an uncountable ordinal.

Proof.

$IDEA: take sup of all countable ordinals. However, this might not be a set.$

Let $R = \{A \in \mathcal{P}(\mathbb{N} \times \mathbb{N})\}$ s.t. A is a well-ordering of a subset of $\mathbb{N}$. Let S be image of R under 'order-type', i.e. S is the set of all order-types of well-orderings of some subset of $\mathbb{N}$. Then S is the set of all countable ordinals. Let ω_1 be $\sup S$. Then ω_1 is uncountable: otherwise, then $\omega_1 \in S$, so ω_1 would be the greatest member of S. But then $\omega_1 + 1$ is also in S. □

Note that, by contradiction, ω_1 is the *least* uncountable ordinal. ω_1 has some strange properties, e.g.
1. ω_1 is uncountable, but for any $\alpha < \omega_1$, we have $\{\beta : \beta < \alpha\}$ countable.
2. If $\alpha_1, \alpha_2, ... < \omega_1$ is any sequence, then it is bounded in ω_1: $\sup\{\alpha_1, ..., \alpha_2\}$ is countable, so is less than ω_1.

Similarly we have

Theorem. (11', Hartogs' lemma)
For any set X, there is an ordinal that does not inject into X.
To see that, just replace $\mathcal{P}(\mathbb{N} \times \mathbb{N})$ by $\mathcal{P}(X \times X)$ in the previous proof.

Write $\gamma(X)$ for the least such ordinal – e.g. $\gamma(\omega) = \omega_1$.

4.1 Successors and limits

Given ordinal α, does α (any set of order-type α, e.g. I_α) have a greatest element?
If yes: say β is that greatest element. Then $\gamma < \beta$ or $\gamma = \beta \implies \gamma < \alpha$, and $\gamma < \alpha \implies \gamma < \beta$ or $\gamma = \beta$ (as we can't have $\gamma > \beta$). In other words, $\alpha = \beta^+$. In that case, we call α a *successor*;
If not: then $\forall \beta < \alpha$, $\exists \gamma < \alpha$ s.t. $\gamma > \beta$. So $\alpha = \sup\{\beta : \beta < \alpha\}$. (this is false in general, e.g. $\omega + 5$). We call α a *limit*.

For example, 5 is a successor, $\omega + 5$ is a successor, ω is a limit, $\omega + \omega$ is a limit. (0 is a limit as well).

For ordinals α, β, define $\alpha + \beta$ by recursion on β (α fixed) by: $\alpha + 0 = \alpha$, $\alpha + \beta^+ = (\alpha + \beta)^+$, $\alpha + \lambda = \sup\{\alpha + \gamma : \gamma < \lambda\}$ for λ a non-zero limit.

For example, $\omega + 1 = (\omega + 0)^+ = \omega^+$, $\omega + 2 = \omega^{++}$, $1 + \omega = \sup\{1 + \gamma : \gamma < \omega\} = \omega$ – so addition is not commutative.

Officially, by 'recursion on the ordinals', we mean: define $\alpha + \gamma$ on $\{\gamma : \gamma \leq \beta\}$ (a set) recursively, plus uniqueness. Similarly for induction: if know $p(\beta) \forall \beta < \alpha \implies p(\alpha)$ (for each α), then must have $p(\alpha) \forall \alpha$. If not, say $p(\alpha)$ false: then look at $\{\beta \leq \alpha : p(\beta)$ false $\}$.

Note that $\beta \leq \gamma \implies \alpha + \beta \leq \alpha + \gamma$ (induction on γ). Also, $\beta < \gamma \implies \alpha + \beta < \alpha + \gamma$. Indeed, $\gamma \geq \beta^+$, so $\alpha + \gamma \geq \alpha + \beta^+ = (\alpha + \beta)^+ > \alpha + \beta$. However, $1 < 2$, but $1 + \omega = 2 + \omega$.

Proposition. (12)
$\alpha + (\beta + \gamma) = (\alpha + \beta) + \gamma \forall \alpha, \beta, \gamma$ ordinals.

Proof. Induction on γ:
0: $\alpha + (\beta + 0) = \alpha + \beta = (\alpha + \beta) + 0$.
Successors: $(\alpha + \beta) + \gamma^+ = ((\alpha + \beta) + \gamma)^+ = (\alpha + (\beta + \gamma))^+ = \alpha + (\beta + \gamma)^+ = \alpha + (\beta + \gamma^+)$.
λ a non-zero limit: $(\alpha + \beta) + \lambda = \sup\{(\alpha + \beta) + \gamma : \gamma < \lambda\} = \sup\{\alpha + (\beta + \gamma) : \gamma < \lambda\}$.

Claim: $\beta + \lambda$ is a limit.
Proof of claim: We have $\beta + \gamma = \sup\{\beta + \gamma : \gamma < \lambda\}$. But $\gamma < \lambda \implies \exists \gamma' < \lambda$ with $\gamma < \gamma' \implies \beta + \gamma < \beta + \gamma'$. So $\{\beta + \gamma : \gamma < \lambda\}$ does not have a greatest element.

Back to the main proof, now $\alpha + (\beta + \gamma) = \sup\{\alpha + \delta : \delta < \beta + \lambda\}$. So want $\sup\{\alpha + (\beta + \gamma) : \gamma < \lambda\{= \sup\{\alpha + \delta : \delta < \beta + \lambda\}$.
$\leq$: $\gamma < \lambda \implies \beta + \gamma < \beta + \lambda$, so LHS $\subset$ RHS;
$\geq$: $\delta < \beta + \lambda \implies \delta < \beta + \gamma$, some $\gamma < \lambda$ (definition of $\beta + \lambda$). So $\alpha + \delta \leq \alpha + (\beta + \gamma)$. □

Alternative viewpoint:

Above is the 'inductive' definition of +. Thereis also a synthetic definition: $\alpha+\beta$ is the order-type of $\alpha \sqcup \beta$ (α disjoint union β), with all of α coming before all of β.

Clearly we have $\alpha + (\beta + \gamma) = (\alpha + \beta) + \gamma$ with this definition (same order-type). We need:

Proposition. (13)
The synthetic and inductive definition of + coincide.

Proof. Write $\alpha + \beta$ for inductive, $\alpha +' \beta$ for synthetic. Do induction on β (α fixed).
0: $\alpha + 0 = \alpha = \alpha +' 0$:
Successors: $\alpha +' \beta^+ = (\alpha +' \beta)^+ = (\alpha + \beta)^+ = \alpha + \beta^+$;
λ a non-zero limit: $\alpha +' \gamma$ = order-type of $\alpha \sqcup \lambda$ = sup of order-type of $\alpha \sqcup \gamma$, $\gamma < \lambda$ (nest union, so order-type of union = sup − this was proved before) = $\sup(\alpha +' \gamma : \gamma < \lambda) = \sup(\alpha + \gamma : \gamma < \lambda) = \alpha + \lambda$. □

Normally we prefer to use synthetic than inductive, *if* we do have a synthetic definition available.

Ordinal multiplication:
Define $\alpha\beta$ recursively by:
$\alpha 0 = 0$, $\alpha(\beta^+) = \alpha\beta + \alpha$, $\alpha\lambda = \sup\{\alpha\gamma : \gamma < \lambda\}$ for λ a non-zero limit. e.g:
$\omega 1 = \omega 0 + \omega = 0 + \omega = \omega$;
$\omega 2 = \omega 1 + \omega = \omega + \omega$;
$\omega\omega = \sup\{0, \omega, \omega + \omega, \omega + \omega + \omega, ...\}$ (as in our big picture)
$2\omega = \sup\{2\gamma : \gamma < \omega\} = \omega$, so multiplication is not commutative.

Similarly, this also has a synthetic definition: $\alpha\beta$ is the order-type of $\alpha \times \beta$, with $(x, y) < (z, t)$ if either $y < t$ or $y = t$ and $x < z$. We can check that these coincide on the previous examples. Also we can see $\alpha(\beta\gamma) = (\alpha\beta)\gamma$ etc.

We can define ordinal exponentiation, powers, etc. Similarly. For example, let's define exponentiation:
$\alpha^0 = 1$, $\alpha^{\beta^+} = \alpha^\beta \cdot \alpha$, $\alpha^\lambda = \sup\{\alpha^\gamma : \gamma < \lambda\}$ for λ a non-zero limit.

Note that $\omega^1 = \omega$, $\omega^2 = \omega \cdot \omega$, and $2^\omega = \sup\{2^\gamma : \gamma < \omega\} = \omega$ (and is countable). This is different to what we expect from cardinality, but the notation in cardinality and here is different.

5 Posets and Zorn's lemma

A *Partially ordered* set or poset is a pair $(X, \leq)$ where X is a set and $\leq$ is a relation on X that is reflexive,transitive and antisymmetric. Write $x < y$ if $x \leq y, x \neq y$. In terms of $<$, a poset is irreflexive and transitive.

For example, any total order is a partial order; $\mathbb{N}^+$ with divides; for any set S, $\mathcal{P}(S)$, wiith $x \leq y$ if $x \subset y$; for any $X \subset \mathcal{P}(S)$, with same relation of $x \leq y$ if $x \subset y$ (e.g. all subspaces of a given vector space).

In general, a hasse diagram for a poset X consists of a drawing of the posets of X, with an upward line from x to y if y *covers* x, i.e. $y > x$, but no z that $y > z > x$.

Hasse diagrams can be useful to visualize a poset (e.g. $\mathbb{N}$, usual order), or useless (e.g. $\mathbb{Q}$, usual order).

In a poset X, a *chain* is a set $S \subset X$ that is totally ordered ($\forall x, y \in S : x \leq y$ or $y \leq x$).

Note: chains can be uncountable, e.g. in $(\mathbb{R}, \leq)$ take $\mathbb{R}$.

We say $S \subset X$ is an antichain if no two elmeent are related.

For $S \subset X$, an *upper bound* for S is an $x \in X$ s.t. $x \geq y \ \forall y \in S$.

Say X is a *least upper bound*, or *supremum* for S, if x is an upper bound for S, and $x \leq y$ for every upper bound y of S.

Write $x = \sup S$ or $x = \vee S$.

e.g. In $\mathbb{R}$, $\{x : x^2 < 2\}$ has 7 as least upper bound, and $\sup = \sqrt{2}$ (so $\sup S$ need not be in S). In $\mathbb{R}$, $\mathbb{Z}$ has no upper bound. In $\mathbb{Q}$, $\{x : x^2 < 2\}$ has 7 as an upper bound, but no least upper bound.

We say a poset is *complete* if every subset has a sup.

e.g. $(\mathbb{R}, \leq)$ is not complete: $\mathbb{Z}$ has no sup (so different to notion of 'completeness' from analysis);
$[0, 1]$ is complete; $(0, 1)$ is not complete: itself has no sup;
$\mathbb{P}(S)$ is always complete: $\{A_i : i \in I\}$ has sup $\cup_{i \in I} A_i$.

A function $f : X \to X$, where X is any poset, is order-preserving if $f(x) \leq f(y)$ $\forall x \leq y$.

e.g. on $\mathbb{N} :\ f(x) = x + 1$; on $[0, 1] : f(x) = \frac{1+x}{2}$ (halve the distance to 1); on $\mathbb{P}(S)$: $f(A) = A \cup \{i\}$ for some fixed $i \in S$.

not every order-preserving f has a fixed point ($f(x) = x$), e.g. $f(x) = x + 1$ on $\mathbb{N}$.

Theorem. (1, Knaster-Tarski fixed point theorem):

Let X be a complete poset. Then every order-preserving function $f : X \to X$ has a fixed point.

Proof. Let $E = \{x \in X : x \leq f(x)\}$, and put $s = \sup E$. To show $f(s) = s$, we'll show that $s \leq f(s)$ and $s \geq f(s)$.
$s \leq f(S)$: Enough to show $f(s)$ is an upper bound for E (as s the *least* upper bound). But $x \in E \implies x \leq s \implies f(x) \leq f(s) \implies x \leq f(x) \leq f(s)$.
$s \geq f(s)$: Enough to show $f(s) \in E$ (as s an upper bound). We know $s \leq f(s)$, and want $f(s) \leq f(f(s))$. But that's true because f is order preserving. □

Note: in any complete poset X, we have a greatest element $(xs.t.x \geq y\forall y)$, namely $\sup X$. A typical application of knaster-tarski:

Theorem. (2, schrӧder-bernstein theorem)
Let a, B be sets s.t. there exists injection $f : A \to B$ and an injection $g : B \to A$. Then there exists an bijection from A to B.

Proof. Seek partition $A = P \sqcup Q, B = R \sqcup S$ s.t. $f(P) = R$ and $g(S) = Q$. Then we are done: set h to be f on P, y^{-1} on Q, then $h : A \to B$ is a bijection.
i.e. we seek $P \subset A$ s.t. $A \setminus g(B \setminus f(P)) = P$. Define $\theta : \mathcal{P}(A) \to \mathcal{P}(A)$ via $P \to A \setminus g(B \setminus f(P))$. Then since $\mathcal{P}(A)$ is complete, θ order-preserving, there is a fixed point by K-T theorem. □

5.1 Zorn's Lemma

An element x in poset X is *Maximal* if no $y \in X$ has $y > x$.

Posets need not have a maximal element, for example $\mathbb{Z}, \mathbb{Q}, \mathbb{R}$.

Theorem. (3, Zorn's lemma)
Let X be a non-empty poset in which every chain has an u.b.. Then X has a maximal element.

Proof. Suppose not. Then for each $x \in X$ there is some $x' \in X$ with $x' > x$. Also, for any chain C we have an upper bound $u(C)$. Pick $x \in X$. Define $x_\alpha \in X$, each $\alpha < \gamma(x)$ ($\gamma(x)$ is the u.b.?) recursively by: $x_0 = x$, $x_{\alpha+1} = x'_\alpha$, $x_\lambda = u(\{x_\alpha : \alpha < \lambda\})$ for λ a non-zero limit (this is a chain by induction). Then $\alpha \to x_\alpha$ is an injection from $\gamma(X) to X$. □

A typical application of Zorn: does every vecotr space have a basis? Recall that a basis is a LI spanning set.

e.g. V = space of all real polynomials. We can take $1, x, x^2, ...$
Let V now be all real sequences. But $l_1 = (1, 0, 0, 0, ...)$, $l_2 = (0, 1, 0, 0, ...)$, then l_1, l_2 LI but not spanning! (recall span must be a finite linear combination!) It's easy to check that there is no countable basis. Also, it turns out that there is no

explicit basis.
$\mathbb{R}$ as a vector space over $\mathbb{Q}$. Basis is called a Hamel basis.

Theorem. (4) Every vector space V has a basis.

Proof. Let $X = \{A \subset V : A \text{ is LI}\}$, ordered by $\subset$. We seek a maximal element M of X (then we are done: if M does not span then choose $x \notin \langle M \rangle$, and now $M \cup \{x\}$ is LI, contradiction.
We have $X \neq \phi$, as $\phi \in X$.
Given a chain $\{A_i : i \in I\}$ in X, put $A = \cup_{i \in I} A_i$, then $A > A_i$ $\forall i$, so just need $A \in X$, i.e. A LI. Suppose A is not LI, hten $\sum_{i=1}^n \lambda_i x_i = 0$ for some $x_1, ..., x_n \in A$, and λ_i scalars not all zero. We have $x_i \in A_{i_1}, ..., x_n \in A_{i_n}$ for some $i_1, ..., i_n \in I$. But $A_{i_1}, ..., A_{i_n} \in A_{i_k}$, some k (as they are nested), contradicting A_{i_k} being LI. □

Note: the only actualy maths (i.e. linear alebra) in the proof was the 'then done' part.

Another application: completeness theorem when proposition language uncountable.

Theorem. (5)
Let $S \subset L(P)$, where P is any set. Then S consistent implies that S has a model.

Proof. We seek a maximal consistent $\bar{S} \supset S$. Then done: for each $t \in L(p)$ we have $\bar{S} \cup \{t\}$ or $\bar{S} \cup \{\neg t\}$ consistent (see chapter 1), hence $t \in \bar{S}$ or $\neg t \in \bar{S}$ by maximality of $\bar{S}$. Now define $v(t) = 1$ if $t \in \bar{S}$, 0 otherwise (as in chapter 1).
Let X be the set of all consistent subsets of $L(P)$, ordered by $\subset$. Then $X \neq \phi$, as $S \in X$. Given a non-empty chain $(T_i : i \in I)$ in X, put $T = \cup_{i \in I} T_i$. Then $T \supset T_i$ for each i, so we just need $T \in X$. We have $S \subset T$ as $T \neq \phi$. Also T is consistent: if $T \vdash \perp$, then $\{t_1, ..., t_n\} \vdash \perp$ for some $t_1, ..., t_n \in T$. We have $t_1 \in T_{i_1}, ..., t_n \in T_{i_n}$ for some $i_1, ..., i_n \in I$. But $T_{i_1}, ..., T_{i_n} \subset T_{i_k}$ for some k (nested), contradicting T_{i_k} being consistent. □

One more:

Theorem. (6, well-ordering principle)
Every set S can be well-ordered.
Note that this is very surprising for e.g $S = \mathbb{R}$.

Proof. Let $X = \{(A, R) : A \subset S \text{ and } R \text{ is a well-ordering of } A\}$. We order this by: $(A, R) \leq (A', R')$ if (A', R') extends (A, R). Then $X \neq \phi$, as $(\phi, \phi) \in X$. Given a chain $((A_i, R_i) : i \in I)$, we have $(\cup_{i \in I} A_i, \cup_{i \in I} R_i) \in X$, and extends each (A_i, R_i) from chapter 2. So by Zorn's lemma, X has a maximal element (A, R). We must have $A = S$: otherwise choose $x \in S \setminus A$ and take 'successor': well-order $A \cup \{x\}$ by putting $x > a$ $\forall a \in A$, contradicting maximality of (A, R). □

Remark. Proof of zorn was easy, but we used a lot of machinery there (ordinals, recursion, hartog's lemma).

5.2 Zorn's lemma and the axiom of choice

In proof of Zorn's kemma, we chose, for each $x \in X$, and $x' \supset x$, i.e. we made infinitely many arbitrary choices, even by time we get to x_ω. We did the same in part IA, to prove that a countable union of countable sets is countable. This is appealing to the axiom of choice, saying that we may choose an element of each set in a family of non-empty sets.

More precisely, the axiom of choice states that, if $(A_i : i \in I)$ is a family of sets, we have a choice function, meaning a function $f : I \to \cup_{i\in I} A_i$ s.t. $f(i) \in A_i\ \forall i$. This is of a different characterto the other set-building rules in that the object whose existence is asserted is not uniquely specified by its properties (unlike ,e.g., $A \cup B$).
So often one points out when one has used axiom of choice.

Note that AC is trivial $|I| = 1$ ($A \neq \phi$ means $\exists x \in A$). Similarly for I finite by induction. However, there is no derivation of AC from the other set-building rules for general I.

Also, we cannot prove ZL without AC because we can deduce AC from ZL:
Given family $(A_i : i \in I)$ of non-empty sets, a partial choice function is an $f : J \to \cup_{i\in I} A_i$ for some $J \subset I$, s.t. $f(j) \in A_j \forall j \in J$. Put $(J, f) \leq (J', f')$ if $J \subset J'$ and $f'|J = f$. This poset is not empty. Also, given a chain we have an upper bound being the union of them. So by ZL, there is a maximal of such. We must have $J = I$ in that case, as if not we can choose (???) $i \in I \setminus J$, $x \in A_i$ and put $J' = J \cup \{i\}$, $f' = f \cup \{(i, x)\}$. Contradiction.

Conclusion: ZL $\iff$ AC (in presence of the other set-building rules).

Also, we had $ZL \implies WO$, and $WO \implies AC$ trivially (well order $\cup i \in IA_i$ and let $f(i)$ be the least element of A_i). So we get $ZL \iff AC \iff WO$.

5.3 The Bourbaki-Witt theorem

Poset X is *chain-complete* if $X \neq \phi$ and every non-empty chain has a sup.
For example, any complete poset is chain-complete; any finite poset is chain-complete; and $\{A \subset V : A \text{ is LI}\}$, for a vector space V is also.

We say $f : X \to X$ is *inflationary* if $f(x) \geq x\ \forall x$.

Theorem. (Bourbaki-Witt)
X chain-complete, $f : X \to X$ inflationary. Then f has a fixed point.
Note that BW follows instantly from ZL: take maximal x, and now $f(x) \geq x \implies f(x) = x$.
However, we can prove BW without AC: we pick some $x_0 \in X$, then let $x_1 = f(x_0)$, $x_2 = f(x_1)$, ..., and let x_ω be the sup of them.

In chapter 2, we did not use AC, except in remark that well-ordering $\iff$ no decreasing sequence, and that ω_1 is not a countable sup.

In fact, it's easy to deduce ZL from BW (using AC). So we can view BW as the choice-free version of ZL.

6 Predicate Logic

Recall that a group is a set equipped with functions:
$M : A^2 \to A$ ('arity' (slots) 2) and inverse $iA \to A$ ('arity' 1), and a constant $e \in A$ (kind of 'arity' 0), s.t.

$$(\forall x, y, z \in A)(M(x, M(y, z)) = M(M(x, y), z)),$$
$$(\forall x \in A)(M(x, e) = x \wedge M(e, x) = x),$$
$$(\forall x \in A)(M(x, i(x)) = e \wedge M(i(x), x) = e)$$

And a poset is a set A equipped with a predicate (relation) $\leq$ (arity 2) $\subset A^2$ s.t

$$(\forall x \in A)(x \leq x),$$
$$(\forall x, y, z \in A)((x \leq y) \wedge (y \leq z) \implies x \leq z),$$
$$(\forall x, y \in A)((x \leq y \wedge y \leq x) \implies x = y)$$

We try to establish these correspondence between propositional logic and predicate logic: Language $\to$ e.g. language of groups (thinks like the definitions above);
Valuation $\to$ structure (set equipped with functions and relations of given arities);
Model of S (valuation making each $s \in S$ true) $\to$ model of S (structure in which each $s \in S$ holds);
$S \models t \to$ same (e.g. In language of groups, should have the above 3 definitions $\models M(e, e) = e$ etc);
$S \vdash t \to$ same (but a bit more complicated).

Let Ω (function symbols) and Π(relation symbols) be disjoint sets, and α (arity) : $\Omega \cup \Pi \to \mathbb{N}$. The *language* $L = L(\Omega, \Pi, \alpha)$ is the set of *formulae*, defined by:
• variables: $x_1, x_2, x_3, ...$ (can use x, y, etc);
• terms: defined inductively by:
(i) each variable is a term;
(ii) If $f \in \Omega$, $\alpha(f) = n$, and $t_1, ..., t_n$ are terms, then $ft_1...t_n$ is a term (and as always, we can add brackets, commas, etc). For example, in the language of groups: $\Omega = \{m, i, e\}$ of arities $2, 1, 0$, $\Pi = \phi$. Some terms: $x_1, m(x_1, x_2), e, m(e, e), m(x_1, i(x_1))$, etc.
• Atomic formulae, consists of:
(i) $\perp$;
(ii) $(s = t)$, any terms s, t;
(iii) $\phi(t_1, ..., t_n)$, any $\phi \in \Pi$, $\alpha(\phi) = n$, and terms $t_1, ..., t_n$.
Again use the language of groups as example: $m(x, y) = m(y, x)$, $m(x, i(x)) = e$;
In language of posets: $\Omega = \phi$, $\Pi = \{\leq\}$ of arity 2. We could take $x = y, x \leq y, x \leq x$.
• Formulae: defined inductively by:
(i) Each atomic formula is a formula;
(ii) If p, q are formulae, then so is $(p \implies q)$;
(iii) If p is a formulae, x is a variable, then $(\forall x)p$ is a formula.
e.g. in language of groupsL $(\forall x)(m(x, x) = e)$, $(\forall x)((m(x, x) = e) \implies$

$(\exists y)(m(y, y) = x))$ (note that we have not talked about $\exists$ yet; we'll do that later).
In language of posets: $(\forall x)(x \leq x)$.

Notes:
1. A formula is just a string of symbols.
2. We can now write $\neg p$ for $p \implies \perp$, and similarly for $p \wedge q$, $p \vee q$ etc, and $(\exists x)p$ for $\neg(\forall x)(\neg p)$.

A term is *closed* if it contains no variables. For example, $e, m(e, e), m(e, m(e, e))$. However, $m(x, i(x))$ is *not* closed.
An occurrence of variable x in formular p is *bound* if it is inside the brackets of '$\forall x$' quantifier. Otherwise, it is *free*.
For example, in $m(x, x) = e \implies (\exists y)(m(y, y) = x)$, each x is free and each y is bound.
Note that in some cases we can make a variable both free and bound: $(m(x, x) = e) \implies (\forall x)(\forall y)(m(x, y) = m(y, x))$. We see that x in LHS is free, but in RHS is bound (although it's not a very helpful expression).

A *sentence* is a formula without free variables: e.g., $(\forall x)(m(x, e) = x)$. For formula p, variable x, term t, the *substitution* $p[t/x]$ is obtained by replacing each free occurence of x with t.
For example, if p is $(\exists y)(m(y, y) = x)$, then $p[e/x]$ is $(\exists y)(m(y, y) = e)$.

Semantic entailment: An *L-structure* consists of a non-empty (see later wfor why) set A equipped with, for each $f \in \Omega$ with $\alpha(f) = m$, a function $f_A : A^m \to A$, and for each $\phi \in \Pi$, with $\alpha(\phi) = n$, a relation $\phi_A \subset A^n$.

For example, let L be the language of groups: an L-structure is a set A with functions $m_A : A^2 \to A$, $i_A : A \to A$, e_A an element of A (need not be a group! These have no 'meaning' yet).
Another example: L be the language of posets: an L-structure is a set A with a relation $\leq_A \subset A^2$.

We want to define the *interpretation* $p_A \in \{0, 1\}$ of a sentence p in structure A, e.g. $(\forall x)(m(x, x) = e)$ shold be 'true in A' if $\forall a \in A : m_A(a, a) = e_A$.
So: 'insert $\in A$ subsubscript A and say it aloud'.

Formal bit: For L-structure A, define *interpretation* of a closed term t to be $t_A \in A$, defined inductively by:
$(ft_1...t_n)_A = f_A(t_{1A}, ..., t_{nA})$ for any $f \in \Omega$, $\alpha(f) = n$, closed terms $t_1, ..., t_n$.
e.g. $m(e, i(e))_A = m_A(e_A, i_A(e_A))$ (and e_A already defined).

Atomic formulae: define $p_A \in \{9, 1\}$ for p atomic by:
(i) $\perp_A = 0$;
(ii)

$$(s = t)_A = \begin{cases} 1 & s_A = t_A \\ 0 & else \end{cases}$$

for s, t closed terms;

(iii)

$$\phi(t_1 ... t_n)_A = \begin{cases} 1 & (t_{1A}, ..., t_{nA}) \in \phi_A \\ 0 & else \end{cases}$$

for $\phi \in \Pi$, $\alpha(\phi) = n$, closed terms $t_1, ..., t_n$.

Sentences: p_A defined inductively by:
(i)

$$(p \implies q)_A = \begin{cases} 0 & p_A = 1, q_A = 0 \\ 1 & else \end{cases}$$

(ii)

$$((\forall i)_p)_A = \begin{cases} 1 & p[\bar{a}/x]_A = 1 \text{ for all } a \in A \\ 0 & else \end{cases}$$

where, for any $a \in A$, add constant symbol $\bar{a}$ to L, obtaining L', and make A an L'-structure by setting $\bar{a}_A = a$.

If p has free variables, we can define $p_A \subset A^{\text{number of free variables of } p}$.
e.g. if p is $(\exists y)(m(y,y) = x)$, then $p_A = \{a \in A : \exists b \in A \text{ with } m_A(b,b) = a\}$.

If $p_A = 1$, say p *true* in A, or p holds in A, or A is a *model* of p. For T a theoy (set of sentences), say T semantically entails p, written $T \vDash p$, if every model of T is a model of p.

p is a *tautology* if $\phi \vDash p$ (or just $\vDash p$), i.e. p holds in every L-structure. For example, $\vDash (\forall x)(x = x)$.

Examples: theory of groups: $\Omega = (m, i, e)$, $\Pi = \phi$. Let

$T = \{(\forall x)(\forall y)(\forall z)(m(x, m(y,z)) = m(m(x,y),z), (\forall x)(m(x,e) = x \wedge m(e,x) = x), (\forall x)(m(x,i(x)) = e \wedge m($

Then an L-structure is a model of $T \iff$ it is a group.

Say T 'axiomatises' the class of groups or 'axiomatises the theory of groups'.

Sometimes call the elements of T the 'axioms' of T.

Theory of fields: $\Omega = \{+, \times, -, 0, 1\}$. T is: abelian group under $(+, -, 0)$; X is commutative, associative, distributive under $+$; $(\forall x)(1x = x)$, $\neg(1 = 0)$, $(\forall x)((\neg(x = 0)) \implies (\exists y)(xy = 1))$. Then T axiomatises the class of fields. E.g., $T \vDash$ inverses are unique: $(\forall x)((\neg(x \neq 0)) \implies ((\forall y)(\forall x)((yx = 1 \wedge zx = 1) \implies y = z))$.

Theory of posets: $\Omega = \phi, \Pi = \{\leq\}$.

T is: $(\forall x)(x \leq x)$, $(\forall x)(\forall y)(\forall z)((x \leq y \wedge y \leq z) \implies x \leq z)$, $(\forall x)(\forall y)((x \leq y \wedge y \leq x) \implies x = y)$.

Theory of graphs: $\Omega = \phi$, $\Pi = \{a\}$ ('is adjacent to').

T is $(\forall x)(\neg a(x,x))$, $(\forall x)(\forall y)(a(x,y) \implies a(y,x))$.

Proofs:

Logical axioms:
(1) $p \implies (q \implies p)$ (any formulae p, q);
(2) $p \implies (q \implies r)) \implies ((p \implies q) \implies (p \implies r))$ (any formulae p, q, r);
(3) $(\neg\neg p) \implies p$ (any formula p);
(4) $(\forall x)(x = x)$; (any variable x);
(5) $(\forall x)(\forall y)(x = y) \implies (p \implies p[y/x]))$ (any variables x, y, formula p where y is a bound);
(6) $((\forall x)p) \implies p[t/x]$ (any variable x, term t, formula p with no variable in t occuring bound in p)
(7) $((\forall x)(p \implies q)) \implies (p \implies (\forall x)q)$ (any variable x, formulae p, q with x not occurring free in p).

As rules of deduction, we take:
Modus Ponens: From $p, p \implies q$ can deduce q;
Generalisation: From p can deduce $(\forall x)p$, if x does not occur free in any premise used to prove p.

For $S \subset L$, $p \in L$, a proof of p from S is a finite sequence of formulae, ending with p, s.t. each line is a logical axiom, or a member of S, or follows from earlier lines by MP or GEN. Write $S \vdash p$ ('S proves P') if there exists a proof of p from S.

Example: $\{x = y, x = z\} \vdash \{y = z\}$ (use axiom 5, with p being $'x = z'$).

1. $(\forall x)(\forall y)(x = y \implies (x = z \implies y = z))$ (axiom 5);
2. $(\forall x)(\forall y)(x = y \implies (x = z \implies y = z)) \implies (\forall y)(x = y \implies (x = z \implies y = z))$ (axiom 6, $t =' x'$);
3. $(\forall y)(x = y \implies (x = z \implies y = z))$ (MP on 1,2);
4. $(\forall y)(x = y \implies (x = z \implies y = z)) \implies (x = y \implies (x = z \implies y = z))$ (axiom 6);
5. $x = y \implies (x = z \implies y = z)$ (MP on 3,4);
6. $x = y$ (hypothesis)
7. $x = y \implies y = z$ (mp on 5,6)
8. $x \implies z$ (hypothesis)
9. $y = z$ (mp on 7,8).

Aim: $T \vdash p \iff T \models p$.

e.g. if p holds in every group then p can be proved from the three group axioms (completely obvious).

Proposition. (1, deduction theorem)
Let $S \subset L$, $p, q \in L$. Then $S \vdash (p \implies q) \iff S \cup \{p\} \vdash q$.

Proof. Forward: as for propositional logic, from $p \implies q$ write down p and apply MP to obtain $S \cup \{p\} \vdash q$;
Backward: as for propositional logic: the only new case is 'generalisation'. So in proof of q from $S \cup \{p\}$ we have something like r then $(\forall x)r$ (Gen), and have a proof of $p \implies r$ from S (induction), and we want $S \vdash p \implies (\forall x)r$. In proof of r from $S \cup \{p\}$, no premise had x free. So in proof of $p \implies r$ from S, no premise had x free. Hence $S \vdash (\forall x)(p \implies r$ (gen).

• If x does not occur free in p: we have $S \vdash p \implies (\forall x)r$ by axiom 6 and MP;
• If x does occur free in p: proof of r from $S \cup \{p\}$ cannot have used p. So in fact $S \vdash (\forall x)r$ whence $S \vdash (p \implies (\forall x)r)$ by axiom 1. □

Proposition. (2, soundness)
Let S be a set of sentences, p a sentence. Then if $S \vdash p$ then $S \vDash p$.

Proof. We have proof of p from S, and a model A of S, and we want $p_x = 1$. This is an induction down the lines of the proof. □

For adequacy, we want if $S \vDash p$, i.e. that if $S \cup \{\neg p\} \vDash \perp$, then $S \cup \{\neg p\} \vdash \perp$.

Theorem. (3, model existence lemma, or completeness theorem)
Let $S \subset L$ be a set of setences. Then S consistent implies that S have a model.
Ideas:
• 1. Build model out of language: let A be the set of closed terms of L, with operation line $(1+1) +_A (1+1) = (1+1) + (1+1)$;
• 2. Say for S be the theory of fields: $(1+1)+1 \neq 1+(1+1)$, but $S \vdash (1+1)+1 = 1+(1+1)$. So quotient out by $s \sim t$ if $S \vdash s = t$;
• 3. Suppose s is the fields of characteristic 2 or 3, i.e. field axioms, and the statement $1+1=0 \vee 1+1+1=0$. Then $S \nvdash 1+1=0$. So $[1+1] \neq [0]$, where $[\cdot]$ denotes the equivalent class unrder $\sim$. Also, $S \nvdash 1+1+1=0$, so $[1+1+1] \neq [0]$.

So our structure does not satisfy $1+1=0 \vee 1+1+1=0$. Then we need to extend S to maximal consistent.

• 4. If S is 'fields with a sqaure root of 2': field axioms + $(\exists x)(xx = 1+1)$. Maybe no closed term t has $[tt] = [1+1]$. So s lacks 'witnesses'.
Solution: for each $(\exists x|p$ in S, add new constant c to language, and add $p[c/x]$ to S. (e.g. $cc = 1+1$).
Now no longer maximal consistent, so go back to step 3.
Problem: this might not terminate.

Proof. We have consistent S in language $L_0 = L(\Omega, \Pi)$. Extend to maximal consistent S_1 (zorn), so for each sentence $p \in L$, we have $p \in S_1$, or $(\neg p) \in S_1$. Thus S_1 is complete (for every p, $S_1 \vdash p$ or $S_1 \vdash (\neg p)$). Add witnesses: for each $(\exists x)p$ in S_1, add new constant c and axiom $p[c/x]$. We obtain T_1 in language $L_1 = L(\Omega \cup C_1, \Pi)$ that has *witnesses* for S_1 (if $(\exists x)p \in S$, then some closed term t has $p[t/x] \in T_1$). It's easy to check T_1 consistent. Now extend T_1 to maximal consistent S_2 (in L). Add witnesses, obtaining T_2 in language $L_2 = L(\Omega \cup C_1 \cup C_2, \Pi)$.
Continue inductively.
Put $\bar{S} = S_1 \cup S_2 \cup ....$ In language $\bar{L} = L(\Omega \cup C_1 \cup C_2 \cup ...)$.
• $\bar{S}$ is consistent: If $\bar{S} \vdash \perp$, then some $S_n \vdash \perp$ (as proofs are finite), contradiction;
• $\bar{S}$ is complete: given sentence $p \in \bar{L}$, we have $p \in L_n$ for some n (as p mentions only finitely many constants), so $S_{n+1} \vdash p$ or $S_{n+1} \vdash (\neg p)$ (choice of S_{n+1}).
• $\bar{S}$ has witnesses (for itself): given $(\exists x)p \in \bar{S}$, we have $(\exists x)p \in S_n$ for some n. So $p[t/x] \in T_n$ for some closed term t (choice of T_n), whence $p[t/x] \in \bar{S}$. □

On set of closed terms of $\bar{L}$, define $s \sim t$ if $\bar{S} \vdash (s = t)$.

This is clearly an equivalent relationship. let A be the set of equivalent clases. Make A into an $\bar{L}$-structure by setting $f_A([t_1], ..., [t_2]) = [ft_1...t_n]$ (each $f \in \bar{\Omega}, \alpha(f) = n$, closed terms $t_1...t_n$), $\varphi_A = \{([t_1], ..., [t_n]) : \bar{S} \vdash \phi(t_1, ..., t_n)\}$ (each $\phi \in \Pi$, $\alpha(\phi) = n$, closed terms $t_1...t_n$).

Claim: $\phi_A = 1 \iff \bar{S} \vdash p$ for each setnence $p \in \bar{L}$. (Then done: A is a model of $\bar{S}$, so A is a model of S.

Proof. An easy induction:
Atomic sentences:
$\bot$: $\bot_A = 0$ and $\bar{S} \nvdash \bot$.
$s = t$:

$$\begin{aligned} \bar{S} \vdash (s = t) &\iff [s] = [t] \\ &\iff s_A = t_A \\ &\iff (s = t)_A = 1 \end{aligned}$$

$\phi(t_1...t_n)$: same.

Induction step:
$p \implies q$:

$$\begin{aligned} \bar{S} \vdash (p \implies q) &\iff \bar{S} \vdash (\neg p) \text{ or } \bar{S} \vdash q \\ &\iff p_A = 0 \text{ or } q_A = 1 (induction) \\ &\iff (p \implies q)_A = 1 \end{aligned}$$

where the second step is because, say if the forward direction doesn't hold, then $\bar{S} \vdash p$, $\bar{S} \vdash (\neg q)$ (since $\bar{S}$ is complete), but then $\bar{S} \vdash \neg(p \implies q)$, contradiction).

$(\exists x)p$:

$$\begin{aligned} \bar{S} \vdash (\exists x)p &\iff \bar{S} \vdash p[t/x] \\ &\iff p[t/x]_A = 1 \\ &\iff ((\exists x)p)_A = 1 \end{aligned}$$

for some closed term t. The last line is because A is the set of equivalent classes of closed terms. □

By remark before theorem 3 we have

Corollary. (4,adequacy)
If $S \models p$, then $S \vdash o$.

Hence:

Theorem. (5, Gödel's completeness theorem for first-order logic)
Let S be a set of sentences and p a sentence (in language L). Then $S \models p \iff S \vdash p$.
The proof is just soundness + adequacy.

Note:
• If L is countable (i.e $.\Omega, \Pi$ countable), then we don't need Zorn's lemma;
• 'First-order' means variables range over elements of our structure (not, e.g., subsets).

Theorem. (6, compactness)
Let $S \subset L$ be a set of sentences. Then if every finite subset of S has a model, then S has a model.

Proof. This is trivial if we replace $\models$ with $\vdash$ (as proofs are finite). □

Note: we have no decidability theorem – how to check if $S \models t$?

Some consequences of completeness/compactness:
Can we axiomatise the class of finite groups? In other words, we want some sentences S (in language of groups) s.t. a structure is a model for $S \iff$ it is a finite group.

However, this is not possible.

Corollary. (7)
the class of finite groups cannot be axiomatised (in language of groups).

Proof. Suppose S axiomatises finite groups. We add to S the sentences:

$$(\exists x_1)(\exists x_2)(\neg(x_1 = x_2))$$
$$(\exists x_1)(\exists x_2)(\exists x_3)(\neg(x_1 = x_2) \wedge \neg(x_1 = x_3) \wedge \neg(x_2 = x_3))$$
$$\ldots$$

which stands for $|G| \geq 2$, $|G| \geq 3$, etc.
Then ever finite subset has a model (e.g. $\mathbb{Z}_n$, n large). However, the set itself has no model – contradicting compactness. □

Similarly,

Corollary. (7')
Let S be a theory in a language L. Then if S has arbitrarily large finite models, then it has an infinite model.

Proof. Add sentences as in corollary 7, and apply compactness theorem. □

So we know *finiteness is not a first-order property.*

Corollary. (8, upward Löwenheim-Skolem theorem)
If a theory S has an infinite model, then it has an uncoutnable model.

Proof. Add uncoutnably many consttants $\{c_i : i \in I\}$ to the language, and add to S the set of sentences $c_i \neq c_j$ (for each distinct $i, j \in I$). Then any finite subset has a model. So the whole set has a model by compactness. □

Similarly, we could find a model into which $P(P(R))$ injects (choose $I = P(P(R))$). E.g., there exists an infinite field ($\mathbb{Q}$), so there exists field as big as $P(P(R))$.

Corollary. (9, downward Löwenheim-Skolem theorem):
Let S be a theory in countable language L. If S has a model, then it has a countable model.

Proof. The model constructed in theorem 3 is countable. □

6.1 Peano Arithmetic

We try to make the usual axioms for $\mathbb{N}$ into a first-order theory.
$L : \Omega = \{0, s, +, \times\}$, $\Pi = \phi$, axioms:
1. $(\forall x)(\neg s(x) = 0)$;
2. $(\forall x)(\forall y)(s(x) = s(y) \implies x = y)$;
3. $(\forall y_1)...(\forall y_n)[(p[0/x] \cap (\forall x)(p \implies p[s(x)/x])) \implies (\forall x)p]$.
(y_i in 3 are parameters).
4. $(\forall x)(x + 0 = x)$;
5. $(\forall x)(\forall y)(x + s(y) = s(x + y))$;
6. $(\forall x)(x + 0 = 0)$;
7. $(\forall x)(\forall y)(x \times (y) = (x + y) + x)$.

These axioms are called Peano Arithmetic or Formal Number Theory.

Note on axiom 3: first guess shold have been

$$(p[0/x] \cap (\forall x|(p \implies p[s(x)/x])) \implies (\forall x)p$$

But then missing properties like $x \geq y$ (y chosen earlier).

Then PA has an infinite model, so by upward L-S, PA has an uncountable model that is not isomorphic to $\mathbb{N}$ trivially. Doesn't this contradict the fact that the usual axioms characterise $\mathbb{N}$ uniquely?

Answer: axiom 3 is only 'first-order induction' – even in $\mathbb{N}$ itself, it refers to only countably many subsets (as opposed to true induction).

A subset $S \subset \mathbb{N}$ is called *definable* if there exists $p \in L$, free variable x, s.t. $\forall m \in \mathbb{N}$ we have: $m \in S \iff p[m/x]$ holds in $\mathbb{N}$ (where by m we mean $1 + 1 + ... + 1$ (m times)).

e.g. set of squares: $p(x)$ is $(\exists y)(yy = x)$;
set of primes: $p(x)$ is: $\neg(x = 0) \cap \neg(x = 1)\neg(\forall y)(y|x) \implies ((y = 1) \vee (y = x))$,
where $y|x$ is a short hand for $(\exists z)(yz = x)$, and by 1 we mean $s(0)$.
Powers of 2: $p(x)$ is $(\forall y)((y|x \wedge y\ prime) \implies (y = 2))$.

Exercise: powers of 4; challenge: powers of 6.

Is PA complete? in other words, for each sentence p, PA $\vdash p$ or PA $\vdash \neg p$?

Theorem. (Gödel's incompleteness theorem)
PA is not complete.
Take p with PA $\nvdash p$, $PA \nvdash \neg p$. We have p holding in $\mathbb{N}$ or $(\neg p)$ holding in $\mathbb{N}$.
Conclution: $\exists$ sentence p s.t. p is true in $\mathbb{N}$, but $PA \nvdash p$.

This does not contradict completeness; it shows that if p true in all models of PA, then PA $\vdash p$.

7 Set Theory

Aim: what does 'the universe of sets' look like?

Key starting point: view set theory as 'just another finite-order theory'.

7.1 Zermelo-Fraenkel set theory

We have L: $\Omega = \phi$, $\Pi = \{\varepsilon\}$, $\alpha(\epsilon) = 2$.

We'll have the ZF axioms: 2 to get started, 4 to build things, and 3 you might not think of at first.

Then a 'universe of sets' will mean a model (V, ϵ) of the ZF axioms.

1. *Axiom of extension*:
If two sets have the same mebmers, then they are equal:
$(\forall x)(\forall y)((\forall z)(z \in x \iff z \in y) \implies (x = y))$.

Note: converse is an instance of a logical axiom.

2. *Axiom of separtion*:
We can form a subset of a set, or precisely, given set x and property $p(z)$, we can form the set of all $z \in x$ such that $p(z)$ holds:
$(\forall t_1)...(\forall t_n)(\forall x)(\exists y)(\forall z)(z \in y \iff (z \in x \wedge p))$
This is actually an axiom scheme: for each formula p and free variables t_i.

Note: we do want parameters, e.g. to have $\{z \in x : t \in z\}$, t chosen earlier.

3. *Axiom of empty-set*:
There is a set with no members.
$(\exists x)(\forall y)(\neg y \in x)$.

We write ϕ for the unique (by extension axiom) such set x. This is just an abbreviation: so $p(\phi)$ means $(\exists x)((\forall y)(\neg y \in x) \wedge p(x))$.

Similarly, write $\{z \in x : p(z)\}$ for the set guaranteed by separation.

4. *Axiom of pair-set*:
We can form $\{x, y\}$.
$(\forall x)(\forall y)(\exists z)(\forall t)(t \in z \iff t = x \vee t = y)$.

We write $\{x, y\}$ for this set, and $\{x\}$ for $\{x, x\}$.
We can now define the 'ordered pair' (x, y) to be $\{\{x\}, \{x, y\}\}$.
It's easy to check that $(x, y) = (t, u) \implies x = t \wedge y = u$ (follows from axiom so far).
Say x is an ordered pair if $(\exists y)(\exists z)(x = (y, z))$, and we say f is a function to mean $(\forall x)(x \in f \implies x \text{ is an ordered pair}) \wedge (\forall x)(\forall y)(\forall z)((x, y) \in f \wedge (x, z) \in f \implies y = z)$.

Can now define the domain of a function as follows: write $x = Domf$ if (f is a function) $\wedge(\forall z)(z \in x \iff (\exists t)((z,t) \in f)))$.

And write $f : x \to y$ for (f is a function) $\wedge(x = Domf| \wedge (\forall z)((\exists t)((t,z) \in f) \implies z \in y))$.

5. *Axiom of union*:
We can form unions.
$(\forall x)(\exists y)(\forall z)(z \in y \iff (\exists t)(z \in t \wedge t \in x))$.

6. *Axiom of power-set*:
We can form power-sets.
$(\forall x)(\exists y)(\forall z)(z \in y \iff z \subset x)$.
Here by $z \subset x$ we mean $(\forall t)(t \in z \implies t \in x)$.

Notes:
1. write $\cup x$ and $\mathcal{P}(x)$ for these two sets. We can write $x \cup y$, etc.
2. No extra axiom needed for interseionts: we can form $\cap x$ $(x \neq \phi)$ as a subset of y any $y \in x$. So ok by separation.
3. We can now form $x \times y$ as a suitable subset of $\mathcal{P}\mathcal{P}(x \cup y)$ – since if $t \in x, u \in y$, then $(t,u) = \{\{t\},\{t,u\}\} \in \mathcal{P}\mathcal{P}(x \cup y)$. And then we can form the set of all functions from x to y, as a subset of $\mathcal{P}(x \times y)$.

The next three are more subtle:

7. *Axiom of infinity*:
So far, V (the branch symbol) must be inifinite. For example, write $x^+ = x \cup \{x\}$, then easy to check that $\phi, \phi^+, \phi^{++}, ...$ are all distinct. We often write 0 for ϕ, 1 for ϕ^+,2 for ϕ^{++}, etc. So $1 = \{0\}, 2 = \{0,1\}, 3 = \{0,1,2\}$,etc. But does the structure (V, ϵ) have an infinite set – e.g. x with $\phi \in x, \phi^+ \in x$, ...?

We say x is a successor set if $(\phi \in x) \wedge (\forall y)(y \in x \implies y^+ \in x)$.

Now let's state the axiom:
There is an infintie set/there is a successor set.
$(\exists x)$(x is a successor set).

Note that any intersection of successor sets is a successor set, so there exists a least one, called ω. This will be our version, in V, of the natural numbers.

Thus $(\forall x)(x \in \omega \iff (\forall y)(y$ a successor set $\implies x \in y))$.

Note that if $x \subset \omega$ is a successor set then $x = \omega$ by definition:
$(\forall x)(x \subset \omega \wedge \phi \in x \wedge (\forall y)(y \in x \implies y^+ \in x)) \implies x = \omega)$. This is induction: genuine induction, over all $x \subset \omega$ (as opposed to in PA).

Also, it's easy to check $(\forall x \in \omega)(\neg x^+ = \phi)$, and $(\forall x \in \omega)(\forall y \in \omega)(x^+ = y^+ \implies x = y)$.

Thus: ω satisfies (in V) all the usual axioms for the natural numbers.

Say x is finite if $(\exists y)(y \in \omega \wedge x$ bijects with $y)$.

And then x is countable if x is finite or x bijects with y.

8. *Axiom of Foundation*:
"Sets are build up from simpler sets". We want to disallow $x \in x$: note that $\{x\}$ has no ε-minimal member; and also disallow $x \in y \in x$: note $\{x, y\}$ has no ε-minimal element, etc. And we also want to disallow the infinite sequence $x_1 \in x_0$, $x_2 \in x_1$, $x_3 \in x_2$,..., in which case $\{x_0, x_1, ...\}$ has no ε-minimal element.

The axiom: every (non-empty) set has an ε-minimal element.
$(\forall x)(x \neq \phi \implies (\exists y)(y \in x \wedge (\forall z)(z \in x \implies z \notin y))$.

Bonus lecture on next Wednesday 1pm (proof of incompleteness theorem, consistency of ZF)

9. *Axiom of Replacement*:
We often say "for each $i \in I$ have A_i – take $\{A_i : i \in I\}$. However, how do we know they form a set? Alternatively, how do we know that $i \to A_i$ is a function? We want to say "the image of a set under something that looks like a function is a set".

A digression on classes:
Idea: $x \to \{x\}$ (for all x). This looks like a function, but it isn't: e.g. every function has a domain as functions are sets of ordered pairs, and the domain is just the left element of all those pairs. However, the 'domain' of $x \to \{x\}$ is not a set (the universal 'set').

For an L-structure V, a collection C of elements of V is called a *class* if there is a formula p, free variables x (and maybe more) s.t. $x \in C \iff p(x)$ holds in V. E.g. V is a class: take $p(x)$ to be $x = x$.

For any t, $\{x : t \in x\}$ is a class: take $p(x)$ to be $t \in x$.
Note that every set y is a class: take $p(x)$ to be $x \in y$.

If C is not a set (in V), i.e. $\not\exists y)(\forall x)(x \in y \iff p(x))$, say C is a proper class. E.g., V is a proper class, as is $\{x : x \text{ infinite}\}$, where by infinite we mean not finite.

Similarly, a function-class is a collection F of ordered pairs from V, s.t. for some formula p, free variables x, y (and maybe more), have $(x, y) \in F \iff p(x, y)$, and if $(x, y) \in F, (x, z) \in F$, then $y = z$.
For example, $x \to \{X\}$ is a function class: take $p(x, y)$ to be $y = \{x\}$.

—End of digression—

Let's now state the axiom of replacement: "the image of a set under a function-class is a set.
$(\forall t_1)...(\forall t_n)([(\forall x)(\forall y)(\forall z)((p \wedge p[z/y]) \implies y = z)] \implies [(\forall x)(\exists y)(\forall z)(z \in y \iff (\exists t)(t \in x \wedge p[t/x, z/y])])$
For each formula p, free variables $x, y, t_1, ..., t_n$, i.e., the image of x under p is a set.

Eg. for any set x, we can form $\{\{t\} : t \in x\}$ using function class $t \to \{t\}$.

This is a 'bad' example, as it didn't need replacement – see later for 'good' examples.

Those are the ZF axioms.

Note:
1: Sometimes separation is called 'comprehension', and sometimes fundation is called 'regularity'.
2. ZF axioms do not include AC: ZF + AC is called ZFC, where axiom of choice is: "every family of (non-empty) sets has a choice function" – $(\forall f)(f$ is a function $\wedge(\forall x)(x \in Domf \implies f(x) \neq \phi)) \implies (\exists y)(y$ is a function $\wedge Domy = Domf \wedge (\forall x)(x \in Domf \implies g(x) \in f(x))))$.

Goal: what does a model (V, ϵ) of ZF look like?

Remark: we haven't proved ZF consistent (i.e. $\exists$ model of ZF). Sadly, ZF $\nvdash$ "ZF has a model", i.e. it cannot be proved in ordinary maths (ZF or ZFC).

Say x is transitive if every member of x is itself a member of x: $(\forall y)((\exists z)(y \in z \wedge z \in x) \implies (y \in x)$, i.e. $\cup x \subset x$.

E.g. $2 = \{\phi, \{\phi\}\}$ is transitive; ω is transitive as $n = \{0, 1, ..., n-1\}$ $\forall n \in \omega$.

Lemma 1: every set x is contained in a transitive set.

Remarks: 1. Officially, let (V, ϵ) be a model of ZF. Then in V, ... holds, or equivalently, $ZF \vdash ....$
2. Any $\cap$ of transitive sets is transitive, so we'll then know that there exists a least transitive set containing x, called the transitive closure of x, written $TC(x)$.

Proof. We'll take $x \cup (\cup x) \cup (\cup\cup x)\cup) \cup\cup\cup x) \cup ...$ which is a set by union axiom, which is a set by replacement (a good example of replacement): $0 \to x, 1 \to \cup x$, etc. But why is this a function class?
To show that, define f is a an attempt to mean (recall we've done similar things before in chapter 2) $(f$ is a function $) \cap (Domf \in \omega) \cap (Domf \neq \phi) \cap (f(0) = x) \cap (\forall n)(n \in Domf \cap n \neq 0 \implies f(n) = \cup f(n-1))$. Then $(\forall n \in \omega)(\forall f)(\forall f')((f, f'$ attempts $\wedge n \in Domf') \implies f(n) = f'(n))$ (by ω-induction). And $(\forall n \in \omega)(\exists f)(f$ an attempt $\cap n \in Domf)$ (again, by ω-induction). So take $p(y, z)$ to be $(\exists f)(f$ an attempt $\cap\, y \in Domf \cap f(y) = z)$. □

We want foundation to be saying 'sets are built out of simpler sets'. If so, we would want: suppose $p(y) \forall y \in x$ implies $p(x)$, then $p(x) \forall x$.

Theorem. (2, principle of ϵ-induction): let p be a formula with free variables $t_1, ..., t_n, x$. Then $(\forall t_1)...(\forall t_n)((\forall x)((\forall y)(y \in x \implies p(y) \implies p(x)) \implies (\forall x)p(x))$. Note that formally, $p(y)$ should be $p[y/x]$, and $p(x)$ should just be p.

Proof. Given $t_1, ..., t_n$, have $p(y) \forall y \in x \implies p(x)$, and suppose $(\forall x)p(x)$ not true. So $(\exists x)(\neg p(x))$. We want ot say 'choose ϵ-minimal member of $\{x : \neg p(x))$, then contradiction'; however, this might not be a set – e.g. if $p(x)$ is $x \neq x$.

Let $t = TC(\{x\})$. So $x \in t$, and $\neg p(x)$. Let $u = \{y \in t : \neg p(y))$, and let y be an *epsilon*-minimal element of u. Then $\neg p(y)$. But $(\forall z \in y)p(z)$ (as $z \in y \implies z \in t$ and y is ϵ-minimal in u). □

Remarks: 1. we used existence of transitive closures (i.e. lemma 1).
2. In fact, ϵ-induction equivalent to foundatoin: as can deduce foundation from ϵ-induction (in the presence of the other ZF axioms): say x is regular if $(\forall y)(x \in y \implies y$ has an ϵ-minimal element). Foundation says every set is regular. To prove this by ϵ induction, given y regular $\forall y \in x$, we want to prove x is regular. For $x \in z$, if x minimal then done. Otherwise, some $y \in x$ has $y \in z$. But y is regular. So z has a minimal element.

How about recursion? we want '$f(x)$ defined in terms of the $f(y)$, $y \in x$'.

Theorem. (3, ϵ-recursion theorem)
Let G be a function-class ($(x, y) \in G \iff p(x, y)$ for some formula p), everywhere defined. Then there is a function-class F ($(x, y) \in F \iff q(x, y)$, for some formula q) s.t. $(\forall x)(F(x) = G(F|x))$. Moreover, F is unique.
Note: $F|x = \{(z, f(z)) : z \in x\}$ is a set, by replacement.

Proof. Say f is an attempt if: (f is a function) $\wedge$ ($Domf$ transitive) $\wedge$ $(\forall x)(x \in Domf \implies f(x) = G(f|x))$ ($f|x$ is defined, as $Domf$ is transitive).
Then $(\forall x)(f, f'$ attempts defined at $x \implies f(x) = f'(x))$ by ϵ-induction.
Since, if f, f' agree at all $y \in x$, then they agree at x.
Also, $(\forall x)(\exists$ attempt f defined at $x)$ by ϵ-induction.
Indeed, suppose $|forally \in x\ \exists$ attempt defined at y. So $\forall y \in x\ \exists$ unique attempt f_y defined on $TC(\{y\})$. Put $f = \cup_{y \in x} f_y$, and now put $f' = f \cup \{(x, G(f|x)\}$.
So done: take $q(x, y)$ to be $(\exists f)(f$ an attempt $\wedge x \in Domf \wedge f(x) = y)$. □

Note: ϵ-induction and ϵ-recursion proofs look very similar to induction and recursion from chapter 2.

What properties of the 'relation-class' ϵ (i.e. the formula $p(x, y) = x \epsilon y$) have we used?

1. p is well-founded: every non-empty set has a p-minimal element;
2. p is local: $(y : p(y, x))$ is a set, for each x.

So in fact we have p-induction and p-recursion for any $p(x, y)$ that is well-founde and local.

For a relation r on a set a, trivially r is local (as a is a set). So to have r-induction and r-recursion, just need r to be well-founded.

Thus induction and recursion from chapter 2 are special cases of this.

Can we 'model' a relation by ε?

E.g. let $a = \{a_1, a_2, a_3\}$ and $r = \{(a_1, a_2), (a_2, a_3)\}$.

Put $b = \{b_1, b_2, b_3\}$, where $b_1 = \phi$, $b_2 = \{\phi\}$, $b_3 = \{\{\phi\}\}$. Then $a_i r a_j \iff b_i r b_j \forall i, j$. Moreover, b transitive.

Say relation r on set a is extensional if $(\forall x, y \in a)((\forall z \in a)(zrx \iff zry) \implies x = y)$, e.g. above relation on above a, or relation ϵ on any transitive set.

Analogue of subset collapse is:

Theorem. (4, Mostowski's collapse theorem):
Let r be a relation on a set a that is well-founded and extensional. Then $\exists$ transitive b and bijection $f : a \to b$ s.t. $(\forall x, y \in a)(x \vee y \iff f(x) \in f(y))$. Moreover, b and f are unique.

Proof. Define $f(x) = \{f(y) : yrx\}$ a definition by r-recursion on the set a. (f is a function, not just a function-class, as it is an image of the set a).

Let $b = \{f(x) : x \in a\}$ (a set, by replacement).

Then b transitive (definition of f), and f surjective (definition of b). We need f injective, then also have $xry \iff f(x) \in f(y)$.

We'll show that $(\forall y)(f(y) = f(x) \implies y = x)$ holds $\forall x \in a$, by r-induction on x.

So given y with $f(y) = f(x)$, we want $y = x$, and may assume that $(\forall t)(\forall n)((t, n \in a \wedge trx \wedge f(y) = f(t)) \implies n = t)$.

From $f(y) = f(x)$, we have $\{f(n) : nry\} = \{f(t) : trx\}$, whence $\{n : nry\} = \{t : trx\}$.

Thus $x = y$ as r extensional.

Existence: if f, f' suitable then $(\forall x \in a)(f(x) = f''(x))$ by r-induction. □

An ordimal or Von Neumann ordinal is a transitive set that is well-orderd by ϵ. (or 'totally ordered, thanks to foundation)

e.g. $\phi, \{\phi\}$, any $n \in \omega$ (as $n = \{0, 1, 2, ..., \{n-1\}\}$), ω itself.

So mostowski tells us: any well-ordered X is order-isomorphic to a unique ordinal α. Say X has order-type α. (this was owed from chapter 2).

Remark (irrelevant): we know that for any ordinal α, have $\{\beta : \beta < \alpha\}$ is a well-ordered set of order-type α.

Hence, by definition of f in theorem 4, we have: $\alpha < \beta \iff \alpha \in \beta$.

So $\alpha = \{\beta : \beta < \alpha\}$.

So e.g. $\alpha^+ = \alpha \cup \{\alpha\}$, and $\sup\{\alpha_i : i \in I\} = \cup\{\alpha_i : i \in I\}$.

Picture of the universe:

"start with ϕ, and take $\mathbb{P}$ (power sets) many times. Define sets V_α for each ordinal α be recursion: $V_0 = \phi$, $V_{\alpha+1} = \mathbb{P}(V_\alpha)$, $V_\lambda = \cup_{\alpha<\lambda} V_\alpha$ for λ a non-zero limit. We want every set x to belong to some V_α.

Lemma. (5)
Each V_α is transitive.

Proof. Induction on α: 0 is trivial.
Successors: given $x \in y \in V_{\alpha+1}$, we have $y \in \mathbb{P}(V_\alpha)$, so $x \in V_\alpha$. So $x \subset V_\alpha$ (as V_α transitive), i.e. $x \in \mathbb{P}(V_\alpha) = V_{\alpha+1}$.
Limits: any union of transitive sets is transitive. □

Lemma. (6)
We have $V_\alpha \subset V_\beta$ whenever $\alpha \leq \beta$.

Proof. Induction on β (α fixed):
$\beta = \alpha$ is trivial.
Successors (β): given $V_\alpha \subset V_\beta$, we want $V_\alpha \subset \mathbb{P}(V_\beta)$. But $V_\beta \subset \mathbb{P}(V_\beta)$, $x \in V_\beta \implies x \subset V_\beta$ as that is transitive.
Limits are trivial as well as it is the union of all V_α below. □

Theorem. (7)
$(\forall x)(\exists \alpha)(x \in V_\alpha)$.
Slogan: $V = \cup_{\alpha \in ON} V_\alpha$, where ON is the class of ordinals. However that's not allowed, as we cannot take union over a class.
Notes: 1. $x \subset V_\alpha \iff x \in V_{\alpha+1}$.
2. If $x \subset V_\alpha$, then there exists least such α – called the rank of x. For example, $rank(\phi) = 0$, $rank(\{\phi\}) = 1$, $rank(\omega) = \omega$, and $rank(\alpha) = \alpha$ for all ordinals α (by induction).

Proof. We'll show $(\forall x)(\exists \alpha)(x \subset V_\alpha)$ by ϵ-induction. Given x, have $y \subset V_\alpha$ for some α (for each $y \in x$), so $y \subset V_{rank(y)}$, i.e. $y \in V_{rank(y)+1}$ for each $y \in x$.
Let $\alpha = \sup\{rank(y) + 1 : y \in x\}$. Then $x \subset V_\alpha$. □

Remark. 1. The V_α are called the Von-Neumann Hierarchy.
2. Proof gives: $rank(x) = \sup\{rank(y) + 1 : y \in x\}$ (this is the right way to think about rank). For example, what's the rank of $\{6\}$? For each ordinal the rank is itself, so $rank(6) = 6$. So $rank\{6\} = \sup\{rank(6) + 1\} = 7$.
3. (useless comment) Most of maths takes place in $V_{\omega+10}$, apart from order-types, etc. i.e. in this course.

8 Cardinals

Let's look at 'sizes' of sets. Work in ZFC.

We want to define $Card(x)$ so that $Card(x) = Card(y) \iff x \leftrightarrow y$, which is a short hand for 'there is a bijection from x to y'.

(Note: We cannot take $Card(x) = \{y : y \leftrightarrow x\}$, as this may not be a set.)

We do know $x \leftrightarrow \alpha$ for some ordinal α, so can define $Card(x)$ to be the least such α. Thus $Card(x) = Card(y) \iff x \leftrightarrow y$.

(In just ZF, use Scott trick: define the essential rank of x to be $essrank(x)$ =least rank of any $y \leftrightarrow x$, and then define $Card(x) = \{y \subset V_{essrank(x)} : y \leftrightarrow x\}$)

Say m is a cardinal or a cardinality if $m = Card(x)$ for some x.

For cardinals m, n, say $m \leq n$ if M injects into N for some M, N with $Card(M) = m$, $Card(N) = n$ (does not depend on choice of M and N).

Write $m < n$ if $m \leq n$ and $m \neq n$. For example, $Card(\omega) \leq Card(\mathbb{P}(\omega))$.

Note that if $m \leq n$, $n \leq m$, then $m = n$ (Schröder-Bernstein). So $\leq$ is a partial order, and even a total order (by well-ordering). However, in just ZF, this need not be a total ordering.