

MATHEMATICAL STRUCTURES (NMAI064)

summer term 2021/22

lecturer: Martin Klazar

LECTURE 9 (April 11, 2022)

AXIOM OF CHOICE AND ITS CONSEQUENCES:
NON-MEASURABLE SETS, THE WELL ORDERING
THEOREM, THE PROPHET PARADOX

- *The Axiom of Choice (AC)* is the requirement/axiom in set theory that

$$\forall A : \emptyset \notin A \Rightarrow \exists F : (F : A \rightarrow \bigcup A) \wedge (B \in A \Rightarrow F(B) \in B) .$$

As you certainly know, the *sum* $\bigcup A$ of A , is the set $\bigcup A$ such that $B \in \bigcup A \iff \exists C \in A : B \in C$. The notation $F : A \rightarrow B$, i.e., F is a *function (map) from A to B* , abbreviates the fact that F is a set of ordered pairs (C, D) such that always $C \in A$, $D \in B$, and for every $C \in A$ there exists exactly one $D \in B$ with $(C, D) \in F$.

Exercise 1 Show that the AC is equivalent with the claim that

$$\forall \text{ surjection } F : A \rightarrow B \exists G : B \rightarrow A \text{ s.t. } FG = F \circ G = \text{id}_B .$$

Exercise 2 Show that the AC is equivalent with the claim that for any set system $(A_i \mid i \in I)$ s.t. always $A_i \neq \emptyset$, there exists a map $F : I \rightarrow \bigcup_{i \in I} A_i$ s.t. always $F(i) \in A_i$ (“always” = $\forall i \in I$).

Exercise 3 Give a simple example to show that in the first formulation of the AC one cannot in general have injective function F .

- *Equivalences and partitions.* First let us review equivalence relations and set partitions. $R \subseteq A \times A$ is an *equivalence relation (on A)* if it is

- reflexive ($\forall a \in A : aRa$),
- symmetric ($\forall a, b \in A : aRb \Rightarrow bRa$), and
- transitive ($\forall a, b, c \in A : aRb \wedge bRc \Rightarrow aRc$).

A (*set*) *partition* of a set A is a set B s.t. $\emptyset \notin B$ and

$$(C, D \in B \Rightarrow C = D \vee C \cap D = \emptyset) \wedge \bigcup B = A .$$

For any equivalence relation R on a set A we define the *blocks of R* to be the sets

$$[a]_R := \{b \in A \mid aRb\}, \quad a \in A .$$

Exercise 4 Show that for any set A and any equivalence relation R on A ,

$$A/R := \{[a]_R \mid a \in A\}$$

is a partition of A .

Exercise 5 Show that for any set A and any partition P of A ,

$$R(P) := \{(a, b) \in A^2 \mid \exists B \in P : a, b \in B\}$$

is an equivalence relation on A .

Exercise 6 Show that for any set A , any equivalence relation S on A and any partition P of A ,

$$R(A/S) = S \quad \text{and} \quad A/R(P) = P .$$

Exercise 7 For $n \in \mathbb{N} = \{1, 2, \dots\}$ let B_n (the Bell number¹) be the number of all equivalence relations on an n -element set X . Why does B_n depend only on the cardinality of X and not on the elements of X ? Prove that for every n ,

$$B_n < B_{n+1} .$$

• *Non-measurable sets.* Let

$$S := \{(x, y) \in \mathbb{R}^2 \mid x^2 + y^2 = 1\}$$

be the *unit circle* in the Euclidean plane \mathbb{R}^2 . For any angle $\varphi \in [0, 2\pi)$ we denote by

$$F_\varphi : S \rightarrow S, \quad (x, y) \mapsto (?_x, ?_y) ,$$

the *counter-clockwise rotation around the origin by the angle φ* ; it is a bijection. An angle $\varphi \in [0, 2\pi)$ is *rational* if $\varphi/\pi \in \mathbb{Q}$. We denote the set of rational angles by $[0, 2\pi)_{\mathbb{Q}}$. Obviously, $[0, 2\pi)_{\mathbb{Q}}$ is a countable set.

¹Named after Eric T. Bell (1883–1960).

Exercise 8 Define the additive Abelian group $([0, 2\pi)_{\mathbb{Q}}, +)$ of addition modulo 2π . Find the above formulas $?_x$ and $?_y$ in the definition of F_{φ} and show that for any $\varphi, \varphi' \in [0, 2\pi)_{\mathbb{Q}}$,

$$F_{\varphi} \circ F_{\varphi'} = F_{\varphi + \varphi'} .$$

Show that for any fixed $x \in S$, the function $F_{\varphi}(x)$ is injective in the variable $\varphi \in [0, 2\pi)$.

For a subset $X \subseteq \mathcal{P}(S)$ of the power set of S (i.e. $\mathcal{P}(S)$ is the set of all subsets of S) with $S \in X$, we say that a map

$$\lambda: X \rightarrow [0, +\infty)$$

is an *arc length on X* if the following three conditions hold.

1. $\lambda(S) > 0$ — the whole unit circle has positive arc length.
2. For any pairwise disjoint sets $A_n \in X$, $n \in \mathbb{N}$, with $\bigcup_{n=1}^{\infty} A_n \in X$ one has that

$$\lambda\left(\bigcup_{n=1}^{\infty} A_n\right) = \sum_{n=1}^{\infty} \lambda(A_n)$$

— arc length is σ -additive.

3. For every $\varphi \in [0, 2\pi)$ and $A \in X$, if $F_{\varphi}[A] \in X$ then

$$\lambda(F_{\varphi}[A]) = \lambda(A)$$

— arc length is invariant under rotations.

Theorem 9 (a troublesome set) *There exists a set $X \subseteq S$ such that the set*

$$\{F_{\varphi}[X] \mid \varphi \in [0, 2\pi)_{\mathbb{Q}}\}$$

is a partition of S .

Proof. The relation \sim on S , defined by

$$a \sim b \iff \exists \varphi \in [0, 2\pi)_{\mathbb{Q}} : F_{\varphi}(a) = b ,$$

is by Exercise 10 an equivalence relation. We define $X \subseteq S$ by means of the AC by taking one representative element from each block of \sim . We show that for φ running in $[0, 2\pi)_{\mathbb{Q}}$ the sets $F_{\varphi}[X]$ are disjoint and partition S . Their union is S because each $s \in S$ lies in a block B

of \sim and thus $F_\varphi(r) = s$ for some $\varphi \in [0, 2\pi)_\mathbb{Q}$ for the representative $r \in X$ of B . If $F_\varphi[X] \cap F_{\varphi'}[X] \neq \emptyset$ for two distinct rational angles φ and φ' , then

$$F_\varphi(r) = F_{\varphi'}(r') \text{ for some } r, r' \in X .$$

Then $r \neq r'$ by the injectivity of $F_\varphi(x)$ in φ for fixed x (Exercise 8). Also,

$$F_{\varphi-\varphi'}(r) = r' \text{ for } \varphi - \varphi' \in [0, 2\pi)_\mathbb{Q}$$

(again by Exercise 8) and therefore $r \sim r'$, which is impossible for two distinct elements of X . It is clear that each set $F_\varphi[X] \neq \emptyset$. \square

Exercise 10 *Prove that the relation \sim on S defined in the previous proof is an equivalence relation.*

Corollary 11 (impossible arc length) *There is no arc length λ on the whole power set $\mathcal{P}(S)$.*

Proof. Indeed, suppose in the way of contradiction that

$$\lambda: \mathcal{P}(S) \rightarrow [0, +\infty)$$

is an arc length and consider the set $X \subseteq S$ of the previous theorem. Then we get by the theorem and by the three properties of any arc length the contradiction that

$$(0, +\infty) \ni \lambda(S) = \sum_{\varphi \in [0, 2\pi)_\mathbb{Q}} \lambda(F_\varphi[X]) = \sum_{\varphi \in [0, 2\pi)_\mathbb{Q}} \lambda(X) = 0 \text{ or } +\infty ,$$

the last value depending on whether $\lambda(X) = 0$ or is > 0 . \square

Exercise 12 *Show that if property 1 of arc length is not required, then the previous corollary does not hold.*

- *Well orderings.* A relation $\leq_X \subseteq X^2$ is a *linear order (on X)* if it is reflexive, transitive, weakly asymmetric ($a \leq_X b \wedge b \leq_X a \Rightarrow a = b$) and total ($\forall a, b \in X : a \leq_X b \vee b \leq_X a$). We say that a linear order \leq_X on X is a *well ordering (on X)* if every nonempty set $Y \subseteq X$ has the minimum (i.e., least) element $y \in Y$: for every $z \in Y$ one has that $y \leq_X z$.

Exercise 13 *Prove that minimum elements are unique.*

Exercise 14 Prove that any linear order (X, \leq_X) is a well ordering iff there is no infinite strictly descending chain $x_1 >_X x_2 >_X \dots$, $x_n \in X$ ($x >_X y$ means that $y \leq_X x$ and $y \neq x$).

Exercise 15 Assume that there is a well ordering on every set and deduce from this the AC.

Theorem 16 (Zermelo's theorem) The axiom of choice holds if and only if every set possesses a well ordering.

Proof. The “if” part is proven in Exercise 15. We prove the other implication, if the AC holds then every set possesses a well ordering. Let $X \neq \emptyset$ and $f: \mathcal{P}(X) \setminus \{\emptyset\} \rightarrow X$ be a *selector on X*, a function satisfying $f(A) \in A$ that is guaranteed by the AC. We consider the set

$$L := \{R \mid R \subseteq D(R)^2, D(R) \subseteq X, R \text{ is a linear order on } D(R)\}$$

of all linear orders R on subsets $D(R)$ of X . For any $R \in L$ we set

$$D_R := \{A \subseteq D(R) \mid x, y \in D(R), y \in A, xRy \Rightarrow x \in A\}.$$

So D_R is the set of all *downsets* in the linear order R . Let further

$$C := \{R \in L \mid A \in D_R, A \neq D(R) \Rightarrow f(X \setminus A) = \min_R(D(R) \setminus A)\}$$

be those linear orders R on subsets $D(R)$ of X , for which for every proper downset A in R the selector f chooses from its complement to X an element that is also the minimum element of the complement of A to $D(R)$. We show that C contains a well ordering of the whole set X . We have $C \neq \emptyset$ because, for example, $\{(f(X), f(X))\} \in C$.

Firstly we show that every $R \in C$ is a well ordering of $D(R)$. Let $R \in C$. For any nonempty $B \subseteq D(R)$ we set

$$A = \{y \in D(R) \setminus B \mid x \in B \Rightarrow yRx\}.$$

The set $D(R) \setminus A$ contains B and is therefore nonempty. Clearly, A is a downset in R . Thus

$$y := f(X \setminus A) = \min_R(D(R) \setminus A).$$

From the facts that $D(R) \setminus A \supset B$ and that y is the minimum element in $D(R) \setminus A$ we get that yRx for every $x \in B$. If $y \notin B$, we would

have $y \in A$ by the definition of A , which is impossible. Hence y is in B and is the minimum element of B , even of the superset $D(R) \setminus A$.

Secondly we show that for every two linear orders $R, S \in C$ one of them extends the other: $D(R) \in D_S \wedge R \subseteq S$ or $D(S) \in D_R \wedge S \subseteq R$. Let $R, S \in C$ be given; we set

$$A = \{x \in D(R) \cap D(S) \mid Rx = Sx \wedge R \cap (Rx \times Rx) = S \cap (Sx \times Sx)\}$$

(here $Rx = \{y \in D(R) \mid yRx\}$ and similarly for Sx). The set A consists exactly of the elements that determine the same downset in R and in S , that is moreover ordered in R and in S in the same way. We claim that $A \in D_R \cap D_S$ — A is a downset both in R and in S). Let

$$z, y, x \in X \text{ with } x \in A \text{ and } yRx .$$

Then ySx because $Rx = Sx$. If zRy then zSy and vice-versa (in both cases $y, z \in Rx = Sx$ and this set is ordered in the same way in R and in S). Thus $Ry = Sy$. This set is contained in $Rx = Sx$, and therefore it is ordered in the same way both in R and in S . Hence $y \in A$ and A is a downset in R . One shows in the same way that A is a downset in S .

Now if both $D(R) \setminus A$ and $D(S) \setminus A$ are nonempty, $y = f(X \setminus A)$ is the minimum element of $D(R) \setminus A$ with respect to R and it is also the minimum element of $D(S) \setminus A$ with respect to S , and so $Ry = A \cup \{y\} = Sy$. It is also clear that R and S give $A \cup \{y\}$ the same order (they add a new element y at the end), and so $y \in A$, which is a contradiction. Thus for example $A = D(R)$, $R \subseteq S$ and S extends R .

Thirdly we show that

$$T := \bigcup C \in C ,$$

and therefore C has (unique) inclusion-wise maximum element. By the previous paragraph, T is a linear order on $D(T) = \bigcup_{R \in C} D(R)$ and for $x, y \in D(T)$ we have xTy , if and only if xRy for some $R \in C$ with $x, y \in D(R)$. We check that T has the property defining C . Let $A \subseteq D(T)$ be a proper downset in T and let $b \in D(T) \setminus A$ be arbitrary. Thus $b \in D(R)$ for some $R \in C$. We show that $A \subseteq D(R)$. If $a \in A$ is arbitrary, then $a \in D(S)$ for some $S \in C$. If $D(S) \in D_R$,

then $a \in D(R)$. If $D(R) \in D_S$ and aSb , then again $a \in D(R)$. The case bSa does not occur (for then one would have $b \in A$). Hence $A \subseteq D(R)$ and $D(R) \setminus A \neq \emptyset$. Therefore the element $y = f(X \setminus A)$ is the minimum element in $D(R) \setminus A$ and yRb . Since b was arbitrary, y is the minimum element in $D(T) \setminus A$ and we see that $T \in C$.

In conclusion we show that $D(T) = X$, and T is therefore the sought-for well ordering of X . If $D(T) \neq X$, then we could extend T by the element $x := f(X \setminus D(T))$ to R :

$$D(R) := D(T) \cup \{x\} \quad \text{and} \quad yRx \quad \text{for every } y \in D(R) \quad (1)$$

— we add to T a new maximum element. It is clear that $R \in C$ (Exercise 17). Since R properly extends T , we have a contradiction with the maximality of T . \square

The previous proof is taken from a manuscript of A. Pultr.

Exercise 17 Show that the linear order R defined in equation (1) indeed belongs to C .

• *The prophet paradox.* Let (X, \leq_X) be a linear order. For any $a \in X$ and any map $f: X \rightarrow Y$ we denote by $f|_a$ the restriction of the map f to the set

$$\{b \in X \mid b <_X a\}.$$

For a linear order (X, \leq_X) and a family \mathcal{F} of functions $f: X \rightarrow Y$, an (X, \mathcal{F}) -prophet is a map

$$P: \{f|_a \mid f \in \mathcal{F}, a \in X\} \rightarrow Y.$$

The value $P(f|_a) \in Y$ is the *guess of P for f at a* . The prophet tries to guess from the values $f(b)$ for all $b <_X a$ the value $f(a)$ of f at a . If $P(f|_a) = f(a)$ then P *succeeds for f at a* , else P *errs for f at a* .

Exercise 18 Let $(X, \leq_X) := (\mathbb{R}, \leq)$ be the real numbers with the standard linear order and let

$$\mathcal{F} = C(\mathbb{R}) := \{f: \mathbb{R} \rightarrow \mathbb{R} \mid f \text{ is continuous}\}$$

be the set of all real functions that are continuous on \mathbb{R} . Find an $(\mathbb{R}, C(\mathbb{R}))$ -prophet that succeeds for f at a for every $f \in C(\mathbb{R})$ and every $a \in \mathbb{R}$.

On the other hand we have the following equally simple result.

Proposition 19 (all prophets err) For $n \in \mathbb{N}$, let

$$(X, \leq_X) = ([n], \leq) := (\{1, 2, \dots, n\}, \leq)$$

be the standard linear order on the first n natural numbers and let

$$\mathcal{F} := Y^{[n]} = \{\text{all maps from } [n] \text{ to } Y\},$$

where Y is a set with at least two elements. Then it is true that for every $([n], Y^{[n]})$ -prophet P there exists a function $f \in Y^{[n]}$ such that

$$\forall a \in [n] : P(f|_a) \neq f(a)$$

— P errs for f at its every argument $a \in [n]$.

Proof. Let $P : \{g \mid g : [m] \rightarrow Y, m \in \{0, 1, \dots, n-1\}\} \rightarrow Y$ be an $([n], Y^{[n]})$ -prophet; here $[0] := \emptyset$. We define the values $f(m)$ of the required function $f : [n] \rightarrow Y$ by induction on $m = 1, 2, \dots, n$. At the start we set $f(1) \in Y$ so that $f(1) \neq P(\emptyset)$ (which is possible as $|Y| \geq 2$). If $m \in [n]$, $m > 1$ and $f(1), f(2), \dots, f(m-1)$ are already defined, we set

$$f(m) \in Y \setminus \{P(f|_m)\}$$

(again, this is possible as $|Y| \geq 2$). It is clear that P errs for the function f at its every argument. \square

Exercise 20 What happens when $|Y| \leq 1$?

One might think that when in Exercise 18 the family of continuous functions is extended to the family $\mathcal{F} := \mathbb{R}^{\mathbb{R}}$ of all real function, one obtain a result similar to the previous proposition, namely that every prophet has to err for some troublesome function very often. Surprisingly, quite the opposite is the case under the assumption of AC: there exists a prophet that for every real function almost never errs.

Theorem 21 (the prophet paradox) Let $(X, \leq_X) := (\mathbb{R}, \leq)$ be the standard linear order of real numbers and let

$$\mathcal{F} := \mathbb{R}^{\mathbb{R}} = \{\text{all functions from } \mathbb{R} \text{ to } \mathbb{R}\}.$$

Then there exists an $(\mathbb{R}, \mathbb{R}^{\mathbb{R}})$ -prophet P such that

$\forall f \in \mathbb{R}^{\mathbb{R}} : \text{the set } \{a \in \mathbb{R} \mid P \text{ errs for } f \text{ at } a\} \text{ is at most countable.}$

Proof. We define P by means of the well ordering

$$(\mathbb{R}^{\mathbb{R}}, \preceq)$$

that exists under the assumption of AC by Theorem 16. For $g \in \mathbb{R}^{\mathbb{R}}$ and $a \in \mathbb{R}$ we set

$$P(g|_a) := g_0(a) \text{ where } g_0 := \min_{\preceq}(\{h \in \mathbb{R}^{\mathbb{R}} \mid h|_a = g|_a\}) .$$

Now let an $f \in \mathbb{R}^{\mathbb{R}}$ be given. We take the set

$$X := \{a \in \mathbb{R} \mid P(f|_a) \neq f(a)\} .$$

of errors of P for f . Let $a < b$ with $a \in X$ be two real numbers,

$$g_a := \min_{\preceq}(\underbrace{\{g \in \mathbb{R}^{\mathbb{R}} \mid g|_a = f|_a\}}_{M_a}) \text{ and } g_b := \min_{\preceq}(\underbrace{\{g \in \mathbb{R}^{\mathbb{R}} \mid g|_b = f|_b\}}_{M_b}) .$$

From $a < b$ we get that $M_b \subseteq M_a$ and $g_a \preceq g_b$. From

$$g_a(a) = P(f|_a) \neq f(a) = g_b(a)$$

we see that $g_a \neq g_b$. Thus $g_a \succ g_b$. We see that the linear order (X, \leq) (with the standard order \leq of real numbers) is a well ordering. Else, by Exercise 14, we would have in (X, \leq) an infinite strictly descending chain $a_1 > a_2 > \dots$, which would yield by the last argument an infinite strictly descending chain $g_{a_1} \succ g_{a_2} \succ \dots$ in $(\mathbb{R}^{\mathbb{R}}, \preceq)$. But the last chain does not exist because $(\mathbb{R}^{\mathbb{R}}, \preceq)$ is a well ordering. Since (X, \leq) is a well ordering, by the next Exercise 22 the set X is at most countable. \square

Exercise 22 Let (\mathbb{R}, \leq) be the standard linear order of real numbers and let $X \subseteq \mathbb{R}$ be such that the linear suborder

$$(X, \leq)$$

is a well ordering. Prove that then the set X is at most countable. *Hint: define an injection $f: X \rightarrow \mathbb{Q}$ (the fractions).*

The last theorem is taken from and many problems around existence of prophets with various properties are investigated in the book

Ch. S. Hardin and A. D. Taylor, *The Mathematics of Coordinated Inference*, Springer, 2013.

THANK YOU!

HOMEWORK: Exercises 7, 8, 14 and 22. Deadline is (by the end of the day) April 23, 2022. (To get “zápočet” for the tutorial, you should solve (or at least send in solutions of) at least half of the homework exercises.)