

Preliminaries

MT1/1

T : a complete consistent theory, in language L
with infinite models (countable)

that is, $T = \text{Th}(M)$, M : L -structure.
infinite

L denotes also the set of formulas of language L

$M = (|M|; \dots)$, but M also denotes $|M|$.
 $\emptyset \neq \uparrow$ universe of M (for brevity)

usually we omit $| \cdot |$ in $|M|$.

$M \supseteq A$: a set of parameters.

$L_n(A) = \{ \varphi(x_1, \dots, x_n, \bar{a}) : \varphi(\bar{x}, \bar{y}) \in L, \bar{a} \subseteq A \}$

$L(A) = \bigcup_n L_n(A)$, also $L(A)$: language L
extended by names for elements of A .

$L_n(A)$: Lindenbaum algebra.

[formally: on $L_n(A)$: $\varphi \sim \psi \Leftrightarrow T(A) \vdash \varphi \leftrightarrow \psi$
 $\Leftrightarrow M \models \varphi \leftrightarrow \psi$

here: $T(A) = \text{Th}(M, a)_{a \in A}$

a complete theory
in language $L(A)$.



$L_m(A)/\sim$: a Boolean algebra
(Lindenbaum algebra)

$$[\varphi]_{\sim} \wedge [\psi]_{\sim} = [\varphi \wedge \psi]_{\sim} \text{ etc.}$$

shorthand: $L_m(A)$ denotes also $L_m(A)/\sim$.

$S_m(A) = \{ \text{complete } n\text{-types over } A, \text{ in } \mathcal{M}_\mathcal{L} \}$
in variables x_1, \dots, x_n

consistent n -type over $A \mapsto$ proper filter in $L_m(A)$

An n -type $p(\bar{x})$ over A is complete if

$$L_m(A) \begin{cases} \cdot p(\bar{x}) : \text{consistent type} \\ \cdot \forall \varphi(\bar{x}) \in L_m(A) (\varphi(\bar{x}) \in p \text{ or } (\neg\varphi(\bar{x})) \in p) \end{cases}$$

$$S(A) := S_1(A)$$

(default)

$S_m(A)$: topological space :

for $\varphi(\bar{x}) \in L_m(A)$

$$[\varphi] = \{ p \in S_m(A) : \varphi \in p \}$$

basic open set [clopen]

closed and open

$S_m(A)$: compact Hausdorff space, 0-dimensional
(i.e. basis of clopen sets)

complete n -types / $A \leftrightarrow$ ultrafilters in $L_n(A)$ MT1/3

So $S_n(A) = S(L_n(A))$, the Stone space
of ultrafilters in $L_n(A)$

- the ~~type~~ topology on $S_n(A)$ = the Stone space topology.

For $p(\bar{x}) \in S_n(A)$

$$p(M) = \{ \bar{a} \in M^n : \bar{a} \text{ satisfies } p \}$$

$\bar{a} \models p$, i.e. $M \models \varphi(\bar{a})$ for every $\varphi(\bar{x}) \in p(\bar{x})$

- The same notation for arbitrary type (also incomplete)

- A formula $\varphi(\bar{x}) \in L(M)$: a special case of a type $\{ \varphi(\bar{x}) \}$.

$$\varphi(M) = \dots$$

- When $p \in S_n(A)$, $\bar{a} \subseteq M$ and $\bar{a} \models p$, then

$$p = \text{tp}^M(\bar{a}/A) = \{ \varphi(\bar{x}) \in L_n(A) : M \models \varphi(\bar{a}) \}$$

Example Assume $p(\bar{x})$: a consistent type over M .

Then $\exists N \supseteq M$ p is realized in N

i.e. $p(N) \neq \emptyset$.



From now on "a type" means "a consistent type". MT1/4

Def A type $p(\bar{x})$ over A is isolated, if:

$\exists \varphi(\bar{x}) \in L_n(A)$ $\left\{ \begin{array}{l} \textcircled{1} \varphi(\bar{x}) \text{ is consistent (wrt } T), \text{ i.e.} \\ \varphi(M) \neq \emptyset \Leftrightarrow T(A) \vdash \exists \bar{x} \varphi(\bar{x}) \end{array} \right.$

symbolically: $\varphi(\bar{x}) \vdash p(\bar{x}) \rightarrow \left\{ \begin{array}{l} \textcircled{2} \varphi(\bar{x}) \\ \forall \psi(\bar{x}) \in p(\bar{x}) \quad \varphi(M) \subseteq \psi(M) \\ \updownarrow \\ T(A) \vdash \varphi(\bar{x}) \rightarrow \psi(\bar{x}) \end{array} \right.$

• When $p(\bar{x})$: a complete type over A , then:

$p(\bar{x})$ is isolated $\Leftrightarrow p$ is isolated in $S_n(A)$
in the topological sense
(i.e. $\{p\}$ is open)

Tarski - Vaught test

Assume $A \subseteq M$. Then $A = |N|$ for some $N \prec M$ iff

$\forall \varphi(x) \in L_1(A) [\varphi(M) \neq \emptyset \Rightarrow \varphi(M) \cap A \neq \emptyset]$

Construction of an elementary submodel of M containing A :

• $A_n \subseteq M, n < \omega$, increasing chain of sets

recursive construction:

$$A_0 = A$$

$A_n \subseteq A_{n+1} \subseteq M$ such that $\forall \psi(x) \in L_1(A_n)$

$$[\psi(M) \neq \emptyset \Rightarrow \psi(M) \cap A_{n+1} \neq \emptyset]$$

$A_\infty = \bigcup_{n < \omega} A_n$ satisfies TV-test.

Omitting types theorem

MT1/5

Assume $p_n(\bar{x}_n)$, $n < \omega$: a family of non-isolated types in theory T , over \emptyset . Then:

$(\exists M \models T)$ M omits every p_n [i.e. $p_n(M) = \emptyset$]

Assume $M, N \models T$
 $\underset{A}{\cup}$

Def. $f: A \rightarrow N$ is elementary ($f: A \xrightarrow{\equiv} N$) if:

$$\forall \bar{a} \in A \forall \varphi(\bar{x}) \in L \quad (M \models \varphi(\bar{a}) \Leftrightarrow N \models \varphi(f(\bar{a})))$$

$$(\Leftrightarrow) \text{tp}^M(\bar{a}) = \text{tp}^N(f(\bar{a}))$$

Elementary diagram of $A \subseteq M$:

$$D_e(A) = T(A) = \text{Th}(M, a)_{a \in A}$$

Remark $f: A \rightarrow N$ is elementary $\Leftrightarrow (N, f(a))_{a \in A} \models T(A)$

Atomic diagram of $A \subseteq M$:

$$D_{\text{at}}(A) = \{ \varphi \in D_{\text{el}}(A) : \varphi \text{ is a quantifier free sentence} \}$$
$$= \{ \varphi(\bar{a}) \in L(A) : M \models \varphi(\bar{a}) \text{ and } \varphi(\bar{a}) : \text{q.f. sentence} \}$$

Remark $f: M \rightarrow N$ is a monomorphism (i.e.:

$$f: M \xrightarrow{\cong} f(M) \subseteq N$$

↑ substructure

$$\Leftrightarrow (N, f(a))_{a \in M} \models D_{\text{at}}(M).$$



Here always $f: M \rightarrow N$ denotes a monomorphism. MT 1/6

$M \subseteq N$: M is a submodel (substructure) of N

$M < N$: M is an elementary submodel of N , i.e.:

$$M \subseteq N \text{ and } \text{id}_M: M \xrightarrow{\equiv} N$$

Remark Assume $M < N$, $A \subseteq M$.

(1) Assume $p(\bar{x}) \subseteq L_m(A)$. Then

$p(\bar{x})$ is a consistent type in $M \Leftrightarrow p(\bar{x})$ is a consistent type in N

(2) Assume $A \subseteq B \subseteq M$

• If $p(\bar{x})$: a type over B , then $p \upharpoonright_A \stackrel{\text{def}}{=} p(\bar{x}) \cap L(A)$
a type over A

Let $r: S_m(B) \rightarrow S_m(A)$, $r(p) \stackrel{\text{def}}{=} p \upharpoonright_A$.

Then r : continuous and "onto".

(3) If $p(\bar{x})$: a type over A , then $\exists q(\bar{x}) \in S_m(A)$ $p(\bar{x}) \subseteq q(\bar{x})$

Saturation, universality, (strong) homogeneity.

Let $\kappa \in \mathbb{C}N$, $\kappa \neq \aleph_0$.

Def. (1) M κ -saturated if $\forall A \subseteq M$ $\forall p \in S_1(A)$ $p(M) \neq \emptyset$
(nasyrony) $|A| < \kappa$

M is saturated if M is $\|M\|$ -saturated

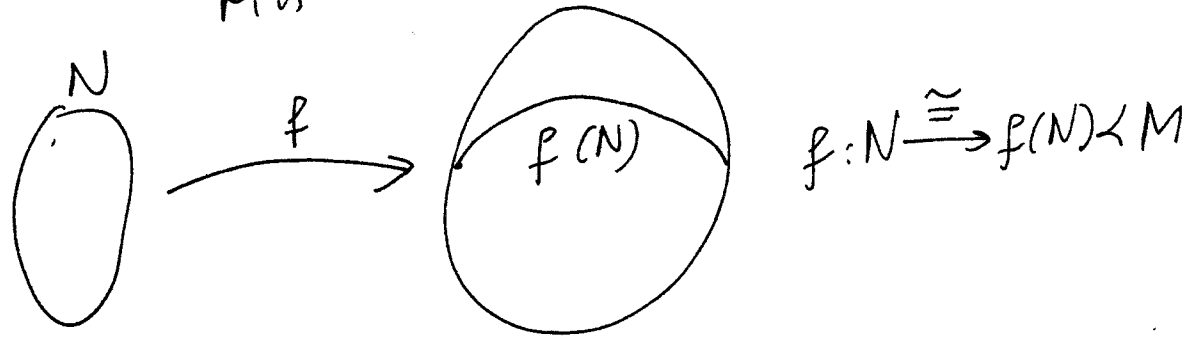
(2) M is κ -universal if $\forall N \equiv M$ ($\|N\| \leq \kappa \Rightarrow \exists f: N \xrightarrow{\equiv} M$)

↑
elementarily equivalent

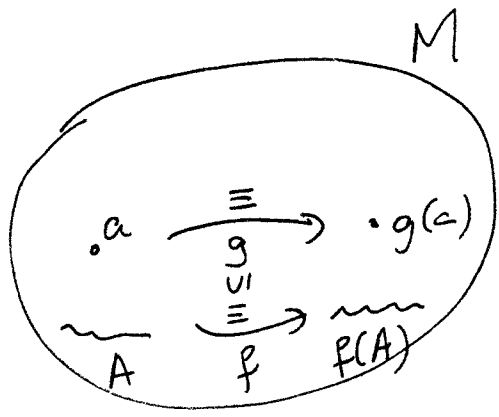
i.e. $\text{Th}(N) = \text{Th}(M)$

M : universal \Leftrightarrow $\|M\|$ -universal

MT1/7



(3) M : κ -homogeneous if $\forall A \subseteq M \forall a \in M \forall f: A \xrightarrow{\cong} M$
 $|A| < \kappa \quad \exists g: A \cup \{a\} \xrightarrow{\cong} M$
 homogeneous = $\|M\|$ -homogeneous.



4. M strongly κ -homogeneous if $\forall A \subseteq M \forall f: A \xrightarrow{\cong} M$
 $|A| < \kappa \quad \exists g: M \xrightarrow{\cong} M$

strongly homogeneous = strongly $\|M\|$ -homogeneous.

5. M is κ -compact if $(\forall 1$ -type $p(x)$ over $M)$
 $(|p| < \kappa \Rightarrow p(M) \neq \emptyset)$

Elementary chains of structures

Def $\langle M_\alpha : \alpha < \mu \rangle, \mu \in \text{Ord}$, : an elementary chain of structures if $(\forall \alpha < \beta < \mu) M_\alpha \prec M_\beta$.

Union of chain (when $\mu \in \text{Lim}$)

$$M_\mu = \bigcup_{\alpha < \mu} M_\alpha \quad ?$$

$$\cdot |M_\mu| := \bigcup_{\alpha < \mu} |M_\alpha|$$

$c \in L$ constant symbol

$$c^{M_\mu} = c^{M_\alpha} \text{ for } \alpha < \mu$$

P : relation symbol

$$P^{M_\mu}(a_1, \dots, a_n) \Leftrightarrow M_\alpha \models P(a_1, \dots, a_n) \text{ for } \alpha < \mu$$

$\bigcap_{\alpha < \mu} |M_\alpha|$
sufficiently large
[so that $\bar{a} \subseteq M_\alpha$]

$$\cdot f^{M_\mu}(\bar{a}) = b \Leftrightarrow M_\alpha \models f(\bar{a}) = b \text{ for } \alpha < \mu$$

sufficiently large

Fact (Tarski) $M_\alpha < M_\mu$ for all $\alpha < \mu$.

Proof (1) $M_\alpha \subseteq M_\mu$ (substructure): exercise

$$(2) \forall \varphi(\bar{x}) \in L \forall \alpha < \mu \forall \bar{a} \subseteq M_\alpha (M_\alpha \models \varphi(\bar{a}) \Leftrightarrow M_\mu \models \varphi(\bar{a}))$$

$$(a) \varphi \text{ atomic: } M_\alpha \subseteq M_\mu \checkmark$$

$$(b) \varphi = \psi_1 \wedge \psi_2, \varphi = \neg \psi : \text{easy}$$

$$(c) \varphi(\bar{x}) = \exists y \psi(\bar{x}, y)$$

$$M_\alpha \models \varphi(\bar{a}) \Rightarrow M_\alpha \models \psi(\bar{a}, b) \text{ for some } b \in M_\alpha$$

\Downarrow ind. assumption for ψ

$$M_\mu \models \psi(\bar{a}, b)$$

$$\Downarrow$$

$$M_\mu \models \varphi(\bar{a})$$

$$M_\mu \models \varphi(\bar{a}) \Rightarrow M_\mu \models \psi(\bar{a}, b) \text{ for some } b \in M_\mu$$

$$\exists y \psi(\bar{a}, y)$$

\Downarrow ind. assumption

$$b \in M_\beta \text{ for some } \alpha \leq \beta < \mu$$

$$M_\beta \models \psi(\bar{a}, b)$$

\Downarrow

$$M_\beta \models \varphi(\bar{a})$$

$$\Downarrow M_\alpha < M_\beta$$

$$M_\alpha \models \varphi(\bar{a})$$

Elementary directed systems of structures:

Let (I, \leq) : a directed set, i.e.:

(1) \leq : partial order on I

(2) $(\forall a, b \in I)(\exists c \in I)(a \leq c \wedge b \leq c)$

Example J : a set $\mapsto ([J]^{<\omega}, \leq)$: directed set.

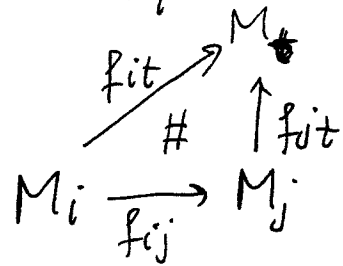
Directed system of structures:

$$\mathcal{M} = (M_i, f_{ij})_{i \leq j \in I}$$

connecting functions $f_{ij}: M_i \rightarrow M_j$, $f_{ii} = id_{M_i}$. such that

$$(\forall i \leq j \leq t \in I) f_{it} = f_{jt} \circ f_{ij}$$

(compatibility)



System \mathcal{M} is elementary if all f_{ij} are elementary.

Example Elementary chain $(M_\alpha)_{\alpha < \mu}$

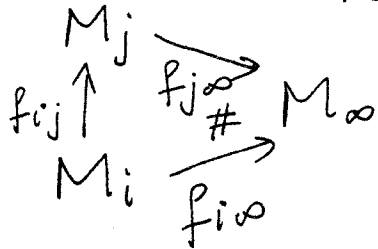
MT1/10

$\mathcal{M} = (M_\alpha, f_{\alpha\beta})_{\alpha \leq \beta < \mu}$ $f_{\alpha\beta} = id_{M_\alpha} : M_\alpha \xrightarrow{\cong} M_\beta$
elementary directed system of structures

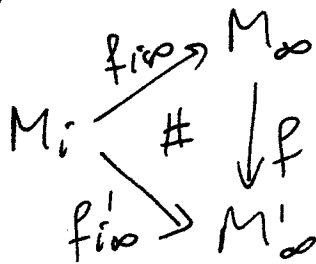
Direct limit of a directed system $\mathcal{M} : M_\infty = \varinjlim \mathcal{M}$

$(M_\infty, f_{i\infty})_{i \in I}$, where $f_{i\infty} : M_i \rightarrow M_\infty$ such that

(1) $\forall i \leq j \in I$ $f_{i\infty} = f_{j\infty} \circ f_{ij}$ [compatible with connecting functions]



(2) $(\forall (M'_\infty, f'_{i\infty})_{i \in I})$ satisfying (1) $\exists ! f : M_\infty \rightarrow M'_\infty$
(universality) $(\forall i \in I) f'_{i\infty} = f \circ f_{i\infty}$



Fact M_∞ exists (and is unique up to \cong).

If \mathcal{M} is elementary, then $f_{i,\infty} : M_i \xrightarrow{\cong} M_\infty$.

Proof 1. Construction of M_∞ :

$S := \dot{\bigcup}_{i \in I} |M_i|$: formally disjoint union.

\sim on S : an equivalence relation

$$M_i \quad M_j \quad \text{MTI/II}$$

$$\downarrow \quad \downarrow \quad \text{def}$$

$$x \sim y \Leftrightarrow f_{it}(x) = f_{jt}(y) \text{ for some } (= \text{every})$$

$$t \geq i, j$$

exercise: \sim is transitive.

$$|M_\infty| := S/\sim$$

- $\sim \upharpoonright |M_i|$: the equality (because f_{ij} : 1-1 (monomorphism))
- $f_{i\infty}(x) = x/\sim$, $f_{i\infty}: |M_i| \xrightarrow{1-1} |M_\infty|$.

L-structure on $|M_\infty|$:

- $c^{M_\infty} = c^{M_i}/\sim$
- $P^{M_\infty}(a_{i_1}/\sim, \dots, a_{i_m}/\sim) \Leftrightarrow M_t \models P(f_{i_1 t}(a_{i_1}), \dots, f_{i_m t}(a_{i_m}))$
 $a_{ij} \in M_{ij}$ for $t \geq i_1, \dots, i_m$
- f^{M_∞} : similarly

the rest is an exercise.

How to extend elementary mappings?

MT2/1

~~Def.~~ \mathbf{BA}_{lg} : Category of Boolean algebras

\mathbf{Comp}_0 : \mathbb{T} of compact Hausdorff 0-dimensional spaces

$$F: \mathbf{BA}_{lg} \rightarrow \mathbf{Comp}_0$$

$$G: \mathbf{Comp}_0 \rightarrow \mathbf{BA}_{lg}$$

$$F(A) = S(A)$$

$$G(X) = C(\text{open}(X))$$

F, G : contravariant functors "inverse" to each other

~~(F, G) is a duality of categories. (look it up)~~
Categories \mathbf{BA}_{lg} and \mathbf{Comp}_0 are dually equivalent.

A, B : Boolean algebras

$$f: A \rightarrow B \text{ homomorphism} \Rightarrow F(f): S(B) \rightarrow S(A)$$

$$F(f)(p) = f^{-1}[p]$$

continuous.

$$\text{Assume } f: A \xrightarrow{\cong} B$$

$$\begin{matrix} \cap & & \cap \\ T \neq M & , & N \neq T \end{matrix}$$

$$\text{Then } \hat{f}: L_n(A) \rightarrow L_n(B)$$

$$\hat{f}(\varphi(\bar{x}, \bar{a})) = \varphi(\bar{x}, f(\bar{a}))$$

homomorphism

of Boolean algebras.

even: monomorphism.

We skip $\hat{}$ in \hat{f} , so:

$$f: L_n(A) \rightarrow L_n(B) \text{ monomorphism}$$

$$f^*: S_n(B) \rightarrow S_n(A) \text{ epimorphism in } \mathbf{Comp}_0$$

i.e. continuous onto

Lemma (on extensions of elementary mappings) MT2/2

Assume $M, N \models T$, $A \subseteq M$, $B \subseteq N$, $f: A \xrightarrow{\equiv} B$ "onto".

Assume $\overset{\psi}{\underset{a}{\#}}, \overset{\psi}{\underset{b}{\#}}$, $p = \text{tp}(a/A)$, $q = \text{tp}(b/B)$.

Then $f \cup \{ \langle a, b \rangle \}$ is elementary $\Leftrightarrow f^*(q) = p$.

[here $f^*: S(B) \xrightarrow{\cong} S(A)$
homeomorphism]

Proof exercise.

Def. M is $(< \kappa_0)$ -universal $\Leftrightarrow \forall n \forall p \in S_n(\emptyset) p(M) \neq \emptyset$.

Remark $M: \kappa$ -universal $\Rightarrow M: (< \kappa_0)$ -universal.

Proof Let $p \in S_n(\emptyset)$.

Choose a countable $N \models T$ with $p(N) \neq \emptyset$.

$M: \kappa$ -universal $\Rightarrow \exists f: N \xrightarrow{\equiv} M$
 $\underset{a}{\cup} \neq p \mapsto \underset{f(a)}{\cup} \neq p$.

Thm. (1) $M: \kappa$ -saturated $\Rightarrow M: \kappa$ -homogeneous
and κ -universal.

(2) $M: \kappa$ -~~universal~~ ^{homogeneous} and $(< \kappa_0)$ -universal \Rightarrow
 $M: \kappa$ -saturated.

Proof. (1) κ -homogeneity of M :

Assume $f: A \xrightarrow{\equiv} M$, $A \subseteq M$, $|A| < \kappa$, $a \in M$.

We seek $b \in M$ s.t. $g = f \cup \{ \langle a, b \rangle \}$ elementary

MT2/3

\Updownarrow Lemma

$$f^*(tp(b/B)) = tp(a/A).$$

⊗ Let $p = tp(a/A)$, $q = (f^*)^{-1}(p) \in S_1(B)$

\uparrow
 $S_1(A)$

Let $b \in M$ (exists by κ -saturation)
 \uparrow
good. of M

• κ -universality of M :

Assume $N \equiv M$, $\|N\| \leq \kappa$.

We seek $f: N \xrightarrow{\equiv} M$.

Let $\{a_\alpha : \alpha < \mu\}$: an enumeration of N , $\mu = \|N\|$.

We define $f(a_\alpha)$ by induction on $\alpha < \mu$:

• Suppose $f(a_\beta)$ defined for all $\beta < \alpha$ so that

$$f: \{a_\beta : \beta < \alpha\} \xrightarrow{\equiv} M$$

Want to find $f(a_\alpha)$ so that

$$f: \{a_\beta : \beta \leq \alpha\} \xrightarrow{\equiv} M.$$

~~By the Lemma it is enough that~~

Let $p = tp(a_\alpha / \{a_\beta : \beta < \alpha\})$.

By the lemma it is enough to find $f(a_\alpha) \in M$

so that $f^*(tp(f(a_\alpha) / \{f(a_\beta) : \beta < \alpha\})) = p$.

So let $q_f = (f^*)^{-1}(p) \in S_{\kappa}(\underbrace{\{f(a_\beta) : \beta < \alpha\}}_{\text{power} < \kappa})$

(MT2/4)

M κ -saturated $\Rightarrow q_f$ realized in M .

Let $f(a_\alpha) \in M$ s.t. $f(a_\alpha) \neq q_f$.

(2) Assume M is κ -homogeneous & $(< \aleph_0)$ -~~saturated~~ ^{universal}.

Want: M : κ -saturated.

So: Let $A \subseteq M$, $|A| < \kappa$, $p \in S_{\kappa}(A)$. Show: $p(M) \neq \emptyset$.

Induction on $|A|$.

Case (a): $|A| < \aleph_0$.

N

$\exists N \supseteq M$ $p(N) \neq \emptyset$. So let $b \in p$.

Let $A^* = A \cup \{b\}$
 $\quad \quad \quad \cup \{a_1, \dots, a_k\}$

Let $q_f = t_p^N(a_1, \dots, a_k, b) \in S_{\kappa+1}(\emptyset)$

q_f is realized in M ($(< \aleph_0)$ -universality),

by $\langle \underbrace{a'_1, \dots, a'_k}_{A'}, b' \rangle$

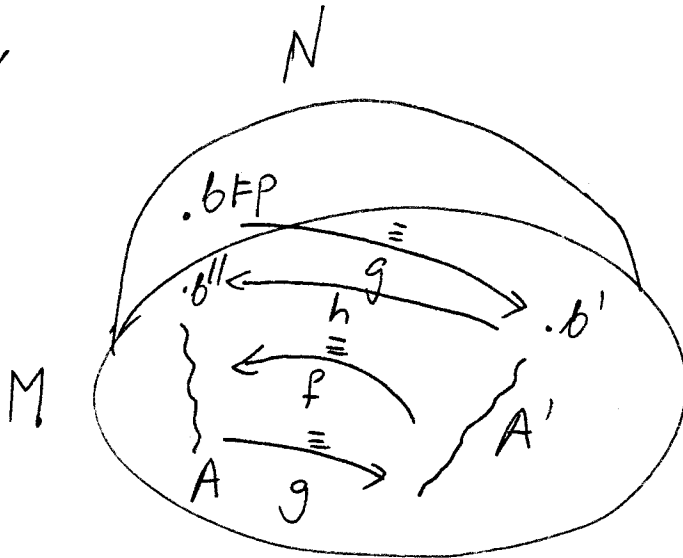
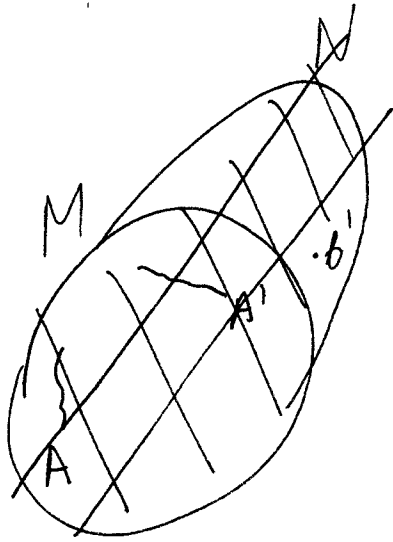
Let $g: A \cup \{b\} \rightarrow A' \cup \{b'\}$, $g(a_i) = a'_i$, $g(b) = b'$.

g : elementary.

$$\Rightarrow g \uparrow_A : A \xrightarrow{\cong} A'$$

$$\Downarrow f := (g \uparrow_A)^{-1} : A' \xrightarrow{\cong} A$$

M: κ -homogeneous $\Rightarrow \exists h : A' \cup \{b''\} \xrightarrow{\cong} A \cup \{b''\}$
for some $b'' \in M$.



$$\begin{array}{ccc} A \cup b & \xrightarrow{\cong} & A \cup b'' \\ g \downarrow \cong & & \cong \uparrow h \\ A' \cup b' & & \end{array}$$

Let $s = h \circ g$

$$s \uparrow_A = \underbrace{(h \uparrow_{A'})}_{\cong} \circ \underbrace{(g \uparrow_A)}_{(g \uparrow_A)^{-1}} = id_A$$

$$s^*(\cancel{tp(b''/A)}) = \cancel{tp(b''/A)}$$

$$s \uparrow_A = id_A \Rightarrow s^* : S(A) \xrightarrow{\cong} S(A)$$

\cong
 $id_{S(A)}$

$$\text{hence: } p = tp(b/A) \underset{\uparrow \text{Lemma}}{=} s^*(tp(b''/A)) \underset{\uparrow}{=} tp(b''/A)$$

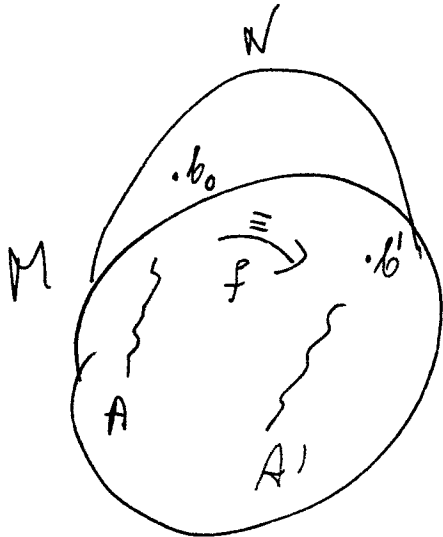
and $b'' \neq p$ $s^* = id_{S(A)}$

Case (b) $|A| = \mu$, $x_0 \leq \mu < \kappa$.

$A = \{a_\alpha : \alpha < \mu\}$, $p \in S_1(A)$.

$p \upharpoonright \emptyset \in S_1(\emptyset) \implies \exists b' \in M$ $b' \neq p \upharpoonright \emptyset$,
 $M: \langle x_0 \rangle$ -universal

$\exists N \supset M \exists b_0 \in N$
 $\begin{matrix} \pi \\ \downarrow \\ p \end{matrix}$



Will find $A' = \{a'_\alpha : \alpha < \mu\} \subseteq M$

s.t. $f: A b_0 \longrightarrow A' b'$
 given by $f(a_\alpha) = a'_\alpha$
 $f(b_0) = b'$

is elementary!

We find a'_α , $\alpha < \mu$ by induction on $\alpha < \mu$.

So suppose $\alpha < \mu$ and a'_β already defined for all $\beta < \alpha$

so that $\boxed{p \upharpoonright \{a_\beta : \beta < \alpha\} b_0} = \{a_\beta : \beta < \alpha\} b_0 \equiv \{a'_\beta : \beta < \alpha\} b'$
 $\equiv: f_0$

We look for a'_α .

Let $q = tp(a_\alpha / \{a_\beta : \beta < \alpha\} \cup \{b_0\})$

then $(f_0^*)^{-1}(q) \in S(\underbrace{\{a'_\beta : \beta < \alpha\} \cup \{b'\}}_{\text{power} < \mu \leq |A|})$

power $< \mu \leq |A|$

By the lemma it is enough that $a'_\alpha \neq (f_0^*)^{-1}(q)$.

But $M: \kappa$ -

M .

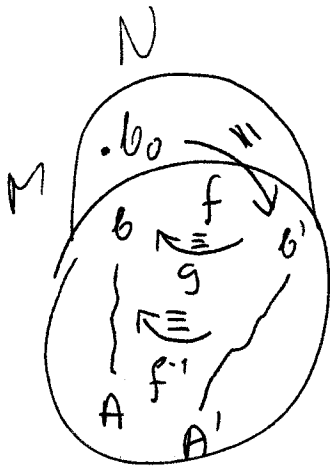
~~Let~~ By the inductive assumption on A :

MT2/7

$(f_0^*)^{-1}(q)$ is realized in M , so we are done with constructing A' .

Now: $f^{-1}: A' \xrightarrow{\cong} A$ in $M \leftarrow \kappa$ -homogeneous, so

$\exists \tilde{g}: A'b' \xrightarrow{\cong} Ab$ for some $b \in M$.



~~Let~~ Let $s = g \circ f$

$$s: Ab_0 \xrightarrow{\cong} Ab$$

$$s \uparrow_A = (g \uparrow_{A'}) \circ (f \uparrow_A) = id_A,$$

$$\parallel \quad (f \uparrow_A)^{-1} \quad \text{so } tp(b_0/A) = tp(b/A)$$

and p is realized in M .

Corollary

M is κ -saturated $\Leftrightarrow M$ is κ -homogeneous and κ -universal and κ -universal.

Proof \Rightarrow by Thm (1).

\Leftarrow κ -homogeneous + κ -universal \Rightarrow

κ -homogeneous + $(\langle \cdot \rangle_0)$ -universal \Rightarrow κ -saturated
Thm (2)

Properties of saturated models.

Thm. Assume $M, N \models T$ saturated models of the same power. Then $M \cong N$.

Proof $M = \{m_\alpha : \alpha < \kappa\}$, $N = \{n_\alpha : \alpha < \kappa\}$,
 $\kappa = \|M\| = \|N\|$. We find $f: M \xrightarrow{\cong} N$

back-and-forth method:

$$f = \bigcup_{\alpha < \kappa} f_\alpha \quad f_\alpha: M \xrightarrow{\cong} N \quad \text{s.t.}$$

partial, elementary

(1) $m_\alpha \in \text{Dom } f_{\alpha+1}$

$n_\alpha \in \text{Rng } f_{\alpha+1}$, $|f_\alpha| \leq 2 \cdot |\alpha|$

(2) $f_0 = \emptyset$

(3) For $\delta \in \text{Lim}$, $f_\delta = \bigcup_{\alpha < \delta} f_\alpha$.

(4) $f_{\alpha+1} = f_\alpha \cup \{ \langle \underset{\substack{\uparrow \\ N}}{m_\alpha}, m \rangle, \langle m, \underset{\substack{\uparrow \\ M}}{n_\alpha} \rangle \}$

Inductive step:

Suppose we have f_α . Want: $f_{\alpha+1}$.

Let $A_\alpha = \text{Dom } f_\alpha \subseteq M$, $B_\alpha = \text{Rng } f_\alpha \subseteq N$.

$$f_\alpha: A_\alpha \xrightarrow{\cong} B_\alpha$$

$$f_\alpha^{\leftarrow}: S(B_\alpha) \xrightarrow{\cong} S(A_\alpha).$$

"forth": Find $n \in N$ st. $f_\alpha \cup \{ \langle m_\alpha, n \rangle \}$ elementary MT2/9

$$\begin{array}{c} \Downarrow \\ (f_\alpha^*)^{-1}(tp(m_\alpha/A_\alpha)) = tp(n/B_\alpha). \end{array}$$

Let $p = tp(m_\alpha/A_\alpha)$.

So $(f_\alpha^*)^{-1}(p) \in S(B_\alpha)$ is realized in N by some n .

"~~back~~": similarly.
back

Thm Assume $M, N \models T$ are homogeneous, of the same power and $\forall n < \omega \forall p \in S_n(\emptyset) (p(M) \neq \emptyset \Leftrightarrow p(N) \neq \emptyset)$.
Then $M \cong N$.

Lemma Under the assumptions of the Thm,

$$\forall A \subseteq M \exists f: A \xrightarrow{\cong} N.$$

Proof. Induction on $|A|$.

Case (a) $|A| < \aleph_0$. $A = \{a_1, \dots, a_n\}$.

Let $p = tp(\langle a_1, \dots, a_n \rangle) \in S_n(\emptyset)$. realized in M
 \Downarrow
 realized in N

by some $\langle b_1, \dots, b_n \rangle \in N$.
 $f(a_i) = b_i$ is good.

Case (b) $|A| = \mu \geq \aleph_0$, $A = \{a_\alpha : \alpha < \mu\}$

We find $f(a_\alpha)$ by induction on $\alpha < \mu$.

Inductive step.

Suppose $\alpha < \mu$ and for every $\beta < \alpha$ we have $f(a_\beta)$

$$\text{s.t. } f : \{a_\beta : \beta < \alpha\} \xrightarrow{\equiv} N.$$

We shall find $f(a_\alpha) \in N$ s.t. $f : \{a_\beta : \beta \leq \alpha\} \xrightarrow{\equiv} N.$

Let $a_{<\alpha} := \{a_\beta : \beta < \alpha\}$. Likewise $a_{\leq\alpha}$.

$$|a_{\leq\alpha}| < \mu = |A|$$

By inductive assumption: $\exists g : a_{\leq\alpha} \xrightarrow{\equiv} N.$

$$\text{Then } f \circ g^{-1} : \underbrace{g(a_{<\alpha})}_N \xrightarrow{\equiv} \underbrace{f(a_{<\alpha})}_N$$

By homogeneity of N : $\exists f(a_\alpha) \in N$ s.t.

$$f \circ g^{-1} : \underbrace{g(a_{<\alpha}) \cup g(a_\alpha)}_{g(a_{\leq\alpha})} \xrightarrow{\equiv} f(a_{<\alpha}) \cup f(a_\alpha) = f(a_{\leq\alpha})$$

$$\text{Then } f = (f \circ g^{-1}) \circ g : a_{\leq\alpha} \xrightarrow{\equiv} N.$$

Proof of the theorem

$$\kappa := \|M\| = \|N\|$$

$f : M \xrightarrow{\cong} N$ constructed by back-and-forth method

$$f = \bigcup_{\alpha < \kappa} f_\alpha, \quad f_\alpha : M \xrightarrow{\cong} N \text{ (partial elementary), } \alpha < \kappa$$

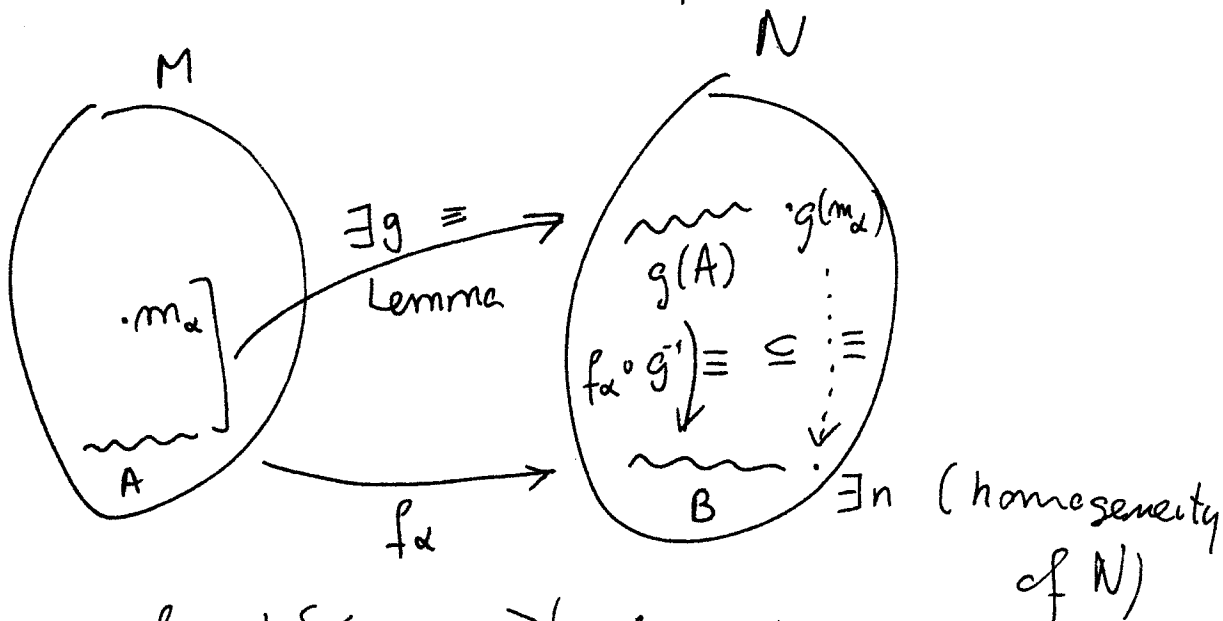
$|f_\alpha| \leq 2 \cdot |\alpha|$ + the same conditions as in the previous thm.

inductive step $f_\alpha \mapsto f_{\alpha+1}$

$A = \text{Dom } f_\alpha$

$B = \text{Rng } f_\alpha$

|"forth";



~~$f_\alpha \cup \{ \langle m_\alpha, n \rangle \}$ elementary~~

$h = (f_\alpha \circ g^{-1}) \upharpoonright_{g(A)} \cup \{ \langle g(m_\alpha), n \rangle \}$ elementary

$h \circ g : A \cup \{ m_\alpha \} \xrightarrow{\equiv} B \cup \{ n \} \subseteq N$

"back": similarly.

Constructions of models:

MT3/1

- Saturated \implies • (strongly) homogeneous $\bar{\equiv}$

Thm. $\underbrace{\kappa = 2^{<\kappa}, \kappa \in \text{Reg}}_{\kappa^{<\kappa} = \kappa}, \kappa > \aleph_0 \implies \exists \text{MFT}$
saturated, of power κ .

Proof

(*) $|S_i(A)| \leq 2^{|A| + \aleph_0}$, because: $|L_i(A)| = |A| + \aleph_0$

Here: $|A| < \kappa \implies |S_1(A)| \leq \kappa$.

Lemma NFT, $\|N\| \leq \kappa \implies X_N := \bigcup \{S_i(A) : A \subseteq N \ \& \ |A| < \kappa\}$
the set has power $\leq \kappa$.

Pf • $|\{A \subseteq N : |A| < \kappa\}| \leq \kappa^{<\kappa} = \kappa$.

• $|S_i(A)| \leq \kappa$ for such A .

Proof of the thm.

$M_\alpha, \alpha < \kappa$: elementary chain of models of T of power κ .

• M_0 : whatever

• $M_\delta = \bigcup_{\alpha < \delta} M_\alpha$, when $\delta < \kappa$ limit.

• $M_{\alpha+1} \supset M_\alpha$ such that $\forall p \in X_{M_\alpha} \ p(M_{\alpha+1}) \neq \emptyset$:

$$T' = \text{Th}(M_\alpha, m)_{m \in M_\alpha} \cup \bigcup_{\beta < \kappa} \{ \varphi(c_\beta) : \varphi(x) \in p_\beta \},$$

where $X_{M_\alpha} = \{ p_\beta : \beta < \kappa \}$

\uparrow
new constant symbols,

and T' in language $L(M_\alpha) \cup \{ c_\beta : \beta < \kappa \}$.

T^1 : consistent, has model of power κ : $M_{\alpha+1}$
such that $M_\alpha < M_{\alpha+1}$.

$M = \bigcup_{\alpha < \kappa} M_\alpha$: of power κ , saturated:

Let $A \subseteq M$, $|A| < \kappa$, and $p \in S_1^M(A)$
 $\kappa \in \text{Reg} \Rightarrow A \subseteq M_\alpha$ for some $\alpha < \kappa$. CW
↓

proof: $A = \{a_\beta : \beta < \mu\}$ for some $\mu < \kappa$.

$\forall \beta < \mu \exists \alpha_\beta < \kappa \ a_\beta \in M_{\alpha_\beta}$

$\{\alpha_\beta : \beta < \mu\} \subseteq \kappa$, $\mu < \text{cf}(\kappa) = \kappa$

$\Rightarrow \exists \alpha < \kappa \ \forall \beta < \mu \ \alpha_\beta < \alpha$
↑
 $A \subseteq M_\alpha$.

~~Let~~ $M_\alpha < M \Rightarrow p \in S_1^{M_\alpha}(A) = S_1^M(A)$

p realized in $M_{\alpha+1}$ by some $a \in M_{\alpha+1}$

$a \models p$ in $M_{\alpha+1} \Rightarrow a \models p$ in M .

$M_{\alpha+1} < M$

Monster model:

Let $\bar{\kappa}$: a large cardinal number.

"Ideal model" $M \models T$: saturated of power $\bar{\kappa}$

because: $\forall M \models T$ ($\|M\| < \bar{\kappa} \Rightarrow \exists M' < M \ M \cong M'$).

Advantages of saturated model M :

MT3/3

(i) universality

(ii) strong homogeneity

~~More~~ ^{More} Weakly (a bit):

(1) κ -universality

(2) strong κ -homogeneity

$\text{Aut}(M)$: the group of automorphisms of M

$\text{Aut}(M/A) = \{ f \in \text{Aut}(M) : f|_A = \text{id}_A \}$: automorphisms of M over A
 $A \subseteq M$

Lemma Assume M is strongly κ -homogeneous, κ -saturated, $A \subseteq M$, $|A| < \kappa$. Then:

(1) For $a, b \in M$ ($\text{tp}(a/A) \stackrel{!}{=} \text{tp}(b/A) \Leftrightarrow a, b$ are in the same orbit of $\text{Aut}(M/A)$ on M).

(2) [orbits $\text{Aut}(M/A)$ on M^n] $\xleftrightarrow[\text{onto}]{1:1}$ $S_n(A)$

Proof (1) \Leftarrow : $f \in \text{Aut}(M/A)$, $f(a) = b$

$$\Downarrow \text{tp}(a/A) = \text{tp}(b/A)$$

\Rightarrow : $\text{tp}(a/A) = \text{tp}(b/A) \Rightarrow f: Aa \xrightarrow{\equiv} Ab$

strong κ -homogeneity $f|_A = \text{id}_A, f(a) = b$

$|A| < \kappa \Rightarrow f \in g \in \text{Aut}(M), g \in \text{Aut}(M/A)$
 $g(a) = b$: a, b in the same orbit of $\text{Aut}(M/A)$

$$(2) M^n \supseteq \mathcal{O} \xrightarrow[\varphi]{(1)} p_{\mathcal{O}} \in S_n(A)$$

\uparrow
 orbit of
 $\text{Aut}(M/A)$

\parallel
 common
 type $tp(a/A)$
 for $a \in \mathcal{O}$.

$$\mathcal{P} : \{ \text{orbits of } \text{Aut}(M/A) \text{ on } M^n \}$$

$\downarrow \varphi$

$$S_n(A)$$

$$\mathcal{O}_1 \neq \mathcal{O}_2 \xrightarrow{(1)} p_{\mathcal{O}_1} \neq p_{\mathcal{O}_2} \quad \boxed{\text{so } \varphi: 1-1}$$

[if $p_{\mathcal{O}_1} = p_{\mathcal{O}_2}$ then let $a \in \mathcal{O}_1, b \in \mathcal{O}_2 \Rightarrow \exists g \in \text{Aut}(M/A)$

$M: \kappa$ -saturated $\Rightarrow \varphi$: "onto"

$$g(a) = b \quad \checkmark.]$$

Def Let $\bar{\kappa}$: a (large) cardinal number,

$M \models T$ monster model, if $M: \bar{\kappa}$ -saturated,
 (w.r. to $\bar{\kappa}$) strongly $\bar{\kappa}$ -homogeneous

Thm. Assume $\aleph_0 \leq \kappa \in \mathcal{C}N$. Then

$\exists M: \kappa$ -saturated ~~is~~ strongly $\bar{\kappa}$ -saturated.

Proof $M = \bigcup_{\alpha < \kappa^+} M_\alpha$: union of elementary chain
 s.t.:

(1) $M_0 \models T$ any

(2) $M_\delta = \bigcup_{\alpha < \delta} M_\alpha$ if $\delta \in \text{Lim}$,

(3) $M_{\alpha+1} \supset M_\alpha$ s.t.:

(a) $\forall p \in S_1(M_\alpha)$ p realized in $M_{\alpha+1}$

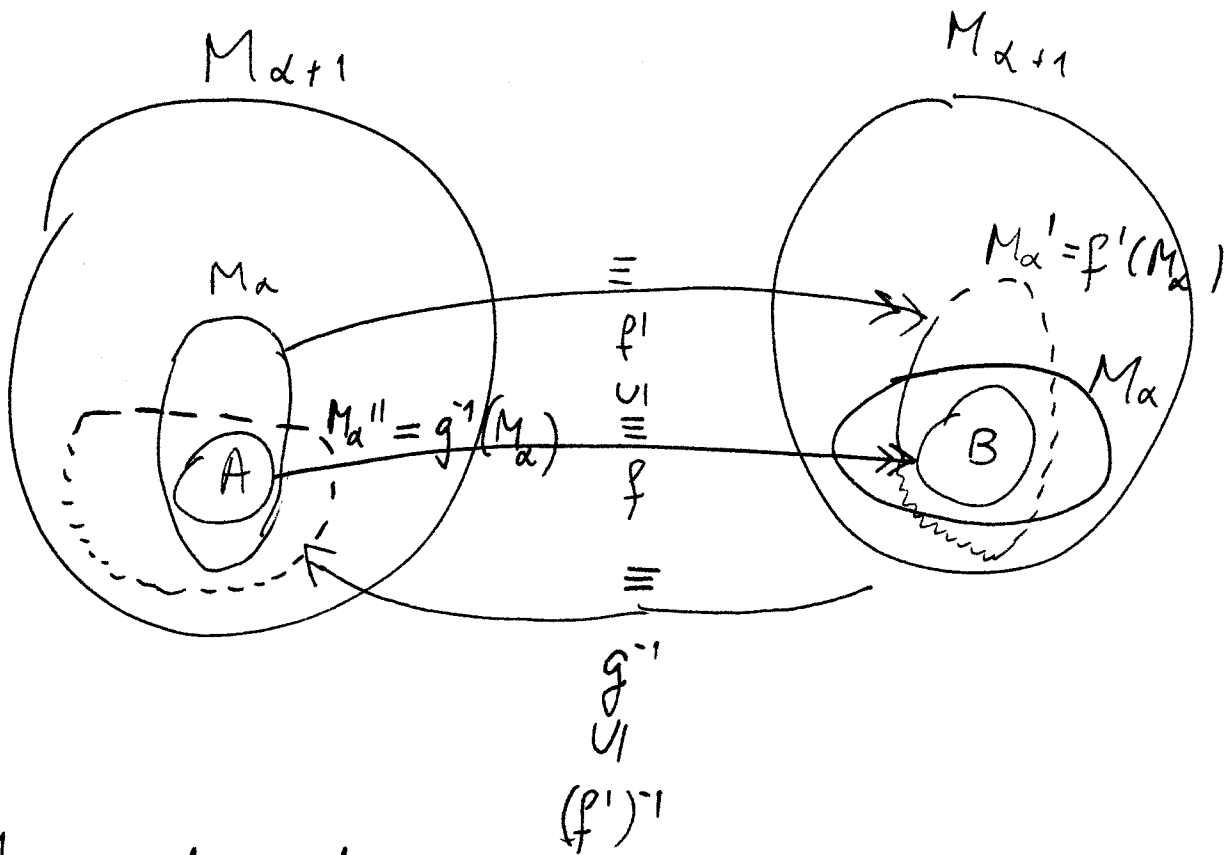
$$(b) \left(\forall f: A \xrightarrow{\equiv} B \right) \left(\exists g \geq f \right) \left(g: A' \xrightarrow{\equiv} B' \text{ in } M_{\alpha+1} \right)$$

$\begin{matrix} \cap & & \cap & & \cup & & \cup \\ M_\alpha & & M_\alpha & & M_\alpha & & M_\alpha \end{matrix}$

MT3/5.

It is enough ~~to~~ that $M_{\alpha+1}$ is $\|M_\alpha\|^+$ -saturated,
 To satisfy (a), (b). $M_{\alpha+1} \succ M_\alpha$

Proof of (b) for such $M_{\alpha+1}$:



I. M : κ -saturated: clear

II. M strongly κ -homogeneous:

Assume $A \subset M$, $|A| < \kappa$. Then $A \subseteq M_\alpha$, $B \subseteq M_\alpha$
 $f: A \xrightarrow{\equiv} M$ for some $\alpha < \kappa$.
 $B = f[A]$

• we construct

a sequence f_β , $\alpha \leq \beta < \kappa^+$:-

• increasing $f_\beta : M \xrightarrow{\equiv} M$

• ~~f_α~~ $f_\alpha \subseteq f_{\alpha+1}$ partial elementary

(*) $M_\beta \subseteq \text{dom } f_\beta \cap \text{rng } f_\beta$.

• ~~f_α~~ f_α constructed according to 3)(b)

$$f_\alpha : M_{\alpha+1} \xrightarrow{\equiv} M_{\alpha+1}$$

• $f_\beta : M_{\beta+1} \xrightarrow{\equiv} M_{\beta+1}$, as in 3.(b)

when β : successor.

• $f_\delta = \bigcup_{\beta < \delta} f_\beta$ when δ limit, still $f_\delta : M_\delta \xrightarrow{\equiv} M_\delta$.

$$f_\infty = \bigcup_{\alpha \leq \beta < \kappa^+} f_\beta, \quad f_\beta \in \text{Aut}(M), \quad f \subseteq f_\beta.$$

Assumptions let $\bar{\kappa}$: a cardinal number large enough
so that:

(1) We consider only small models of T

||
of power $< \bar{\kappa}$, or even $\ll \bar{\kappa}$

(2) We work within a monster model $\mathcal{M} \models T$ (w.r. to $\bar{\kappa}$)

(3) We consider only small models $M \prec \mathcal{M}$

||
of power $< \bar{\kappa}$, or even $\ll \bar{\kappa}$,

Consequences:

(1) For $M, N < \mathcal{M}$, $M \subseteq N \Leftrightarrow M < N$

(2) Convention: For $\bar{a} \in \mathcal{M}$
 $\vDash \varphi(\bar{a})$ means $\mathcal{M} \vDash \varphi(\bar{a})$

(3) For $A \subseteq M < \mathcal{M}$:

$$S_m^M(A) = S_m^{\mathcal{M}}(A) =: S_m(A)$$

Notation Assume $p(\bar{x}), q(\bar{x})$ types (small, over \mathcal{M})

• $p(\bar{x}) \vdash q(\bar{x}) \Leftrightarrow p(\mathcal{M}) \subseteq q(\mathcal{M})$
 "p implies q"

• $p(\bar{x}) \equiv q(\bar{x}) \Leftrightarrow p \vdash q \ \& \ q \vdash p$
 ↑
 equivalent

Special case: $p(\bar{x}) = \{ \varphi(\bar{x}) \}$.

$\varphi(\bar{x}) \vdash q(\bar{x})$: "φ isolates q".

Remark: Syntactically:

$$p(\bar{x}) \vdash q(\bar{x}) \Leftrightarrow \forall \varphi(\bar{x}) \in q \ \exists p_0(\bar{x}) \subseteq p(\bar{x}) \text{ finite} \\ \uparrow \quad \uparrow \\ \text{types over } A \quad T(A) \vdash \bigwedge p_0(x) \rightarrow \varphi(x)$$

Remark (exercise)

$$p(\bar{x}) \vdash q(\bar{x}) \Leftrightarrow \forall M \models T \text{ IA-saturated } p(M) \subseteq q(M).$$

Def. (reminder)

Let $p(\bar{x})$: a type over A .

p is isolated over $A \iff \exists \varphi(\bar{x}) \in L(A)$ $\varphi \vdash p$.
consistent (with T)

Thm (omitting types, Ehrenfeucht)

Assume $p_n(\bar{x}_n), n < \omega$: ~~non~~ a family of non-isolated types over \emptyset . Then $\exists M \models T \forall n \underbrace{p_n(M) = \emptyset}$,
 M omits p_n .

Lemma

Assume A is stable, $p_n(\bar{x}_n), n < \omega$: a family of non-isolated types over A , $\varphi(\bar{x}) \in L_1(A)$, $\varphi(M) \neq \emptyset$.

Then $\exists c \in \varphi(M) \forall n$ p_n non-isolated over $A \cup \{c\}$.
i.e. φ : consistent

Proof [Lemma \Rightarrow Thm]

By the lemma: $\exists \underbrace{\{a_n : n < \omega\}}_A \subseteq M$ s.t.

(1) A satisfies the TV-test A

(2) $p_n, n < \omega$: non-isolated over A .

Construction of $a_n, n < \omega$: recursion on n .

Let $\{ \varphi_n(x, \bar{y}) : n < \omega \}$: all formulas of L of this form.

Suppose $n < \omega$ and $\{a_i : i < n\} = a_{<n}$ already
 so that all $p_k, k < \omega$ still non-isolated over $a_{<n}$.

MT3/9

We consider a consistent formula $\varphi_n(x) \in L_1(a_{<n})$

By the Lemma we find $c \in \varphi_n(\mathcal{M})$ so that
 \downarrow
 a_n

all $p_k, k < \omega$, still non-isolated over $a_{\leq n}$.

• the formulas $\varphi_n(x), n < \omega$ may be chosen so that
 after ω steps:

$$\forall \varphi(x) \in L(A) \exists n \varphi = \varphi_n.$$

consistent

Then $A = \{a_n : n < \omega\}$ satisfies TV-test

$A = M \prec \mathcal{M}$, every p_k still non-isolated
 over A .

$$p_k(M) = \emptyset \text{ [if not,}$$

some $\bar{m} \models p_k$. then $\bar{m} \in \bar{a}_0$

$$(\bar{x}_k = \bar{m}) \vdash p_k(\bar{x}_k) \downarrow)$$

Proof of the Lemma.

Let $p(\bar{x})$: one of the types $p_n(\bar{x}_n)$.

Let $h(\bar{x}, y, \bar{a}) \in L(A)$

$$h(\bar{x}, c, \bar{a}) \vdash p(\bar{x}) \Leftrightarrow h(\mathcal{M}, c, \bar{a}) \subseteq p(\mathcal{M}).$$

$$\Leftrightarrow \forall \psi(\bar{x}) \in p(\bar{x}) \quad h(\mathcal{M}, c, \bar{a}) \subseteq \psi(\mathcal{M})$$

$$\Leftrightarrow \forall \psi \in p \quad \mathcal{M} \models \forall \bar{x} (h(\bar{x}, c, \bar{a}) \rightarrow \psi(\bar{x}))$$

$$\Leftrightarrow \forall \psi \in p \quad \psi_h(y) \in t_p(c/A)(y)$$

$$\text{where } \psi_h(y) = \forall \bar{x} (h(\bar{x}, y, \bar{a}) \rightarrow \psi(\bar{x}))$$

hence:

$$t_p(c/A) = t_p(c'/A) \Rightarrow [h(\bar{x}, c, \bar{a}) \vdash p \Leftrightarrow h(\bar{x}, c', \bar{a}) \vdash p]$$

$$h(\bar{x}, c, \bar{a}) \text{ consistent} \Leftrightarrow (\exists \bar{x} h(\bar{x}, y, \bar{a})) \in t_p(c/A)(y).$$

$$\text{Let } X_{h,p} = \{q \in S_1(A) : \text{For } c \models q, h(\bar{x}, c, \bar{a}) \vdash p(\bar{x}) \text{ and } h(\bar{x}, c, \bar{a}) \text{ consistent.}\}$$

"bad types"

$$\text{Let } q \in S_1(A) \text{ then} \quad \text{For } c \models q, h(\bar{x}, c, \bar{a}) \text{ consistent} \\ \Downarrow$$

$$q \in X_{h,p} \Leftrightarrow q(y) \in S_1(A) \cap [\exists \bar{x} h(\bar{x}, y, \bar{a})] \cap \bigcap_{\psi \in p} [\psi_h(y)]$$

$$\Downarrow \\ \text{For } c \models q, h(\bar{x}, c, \bar{a}) \vdash p(\bar{x})$$

(*) $X_{h,p}$: nowhere dense in $S_1(A)$.

Proof of (*): (a.a.)

Suppose $\theta(y) \in L_1(A)$ and $\emptyset \neq S_1(A) \cap [\theta] \subseteq X_{h,p}$.

$$\text{Let } \alpha(\bar{x}) = \exists y (h(\bar{x}, y, \bar{a}) \wedge \theta(y)) \\ \uparrow \\ L(A)$$

• $\alpha(\bar{x})$: consistent :

MT3 / M

Let $c \in \Theta(\mathcal{M})$

$$\Downarrow [\theta] \subseteq X_{n,p}$$

$$\mathcal{M} \models \exists \bar{x} h(\bar{x}, c, \bar{a}).$$

Let $\bar{d} \in \mathcal{M}$ s.t. $\mathcal{M} \models h(\bar{d}, c, \bar{a}).$

$$\bar{d} \text{ satisfies in } \mathcal{M} : \underbrace{\exists y h(\bar{x}, y, \bar{a})}_{\alpha(\bar{x})}$$

• $\alpha(\bar{x}) \vdash p(\bar{x})$, i.e. $\alpha(\mathcal{M}) \subseteq p(\mathcal{M}).$

Let $\bar{d} \in \alpha(\mathcal{M})$. So there is $c \in \mathcal{M}$ s.t.

$$\models h(\bar{d}, c, \bar{a}) \wedge \theta(c)$$

$$\Downarrow [\theta] \subseteq X_{n,d}$$

$$\forall \psi \in p \models \psi_n(c)$$

$$\forall \psi \in p \quad \underbrace{h(\bar{x}, c, \bar{a})}_{\Downarrow} \vdash \psi(\bar{x}) \Rightarrow h(\bar{x}, c, \bar{a}) \vdash p(\bar{x})$$

$$\neq \frac{\vdash}{\bar{d}} \Rightarrow \frac{\vdash}{\bar{d}} \quad \textcircled{y}$$

as: $p(\bar{x})$ non-isolated

$$\text{Let } X = \bigcup_{h,p_n} X_{h,p_n} \subseteq S_1(A).$$

meager. Let $q_i \in S_1(A) \cap [\varphi] \setminus X$

$c \models q_i$ good.

\textcircled{pf} (a.e) Suppose $p = p_n$ isolated over $A \cup \Sigma c \mathcal{L}$.

$$\exists h(\bar{x}, c, \bar{a}) \quad \underbrace{h(\bar{x}, c, \bar{a}) \vdash p(\bar{x})}_{\text{consistent}} \Rightarrow \underbrace{q_i \in X_{h,p_n}}_{\substack{\neq \\ \vdash(\bar{c}/A)}} \quad \Downarrow.$$

14.03.2022

Def T is quantifier eliminable if $\forall \varphi \in L \exists \psi \in L$

$$T \vdash \varphi \leftrightarrow \psi$$

ψ open
 \equiv q.f.

Def. For $p(\bar{x}) \in S_n(\emptyset)$ let $p_0(\bar{x}) = \exists \varphi(\bar{x}) \in p(\bar{x})$.

Remark T is q.e. $\Leftrightarrow \forall n \forall p \in S_n(\emptyset) p_0 \vdash p$ φ open.

Proof " \Rightarrow " Obvious. " \Leftarrow " Let $\varphi(\bar{x}) \in L$.

$$\bullet \forall p \in [\varphi] \cap S_n(\emptyset) \exists \psi \in p \quad p \in [\psi] \subseteq [\varphi]$$

Why? $p_0 \vdash p$
 $p_0 \vdash \varphi$

by compactness

\exists finite $p'_0 \subseteq p_0$ s.t.
 $p'_0 \vdash \varphi$, i.e.

$$p'_0(\mathcal{M}) \subseteq \varphi(\mathcal{M})$$

\Downarrow

$$\varphi(\mathcal{M}) = \left(\bigwedge_{\psi' \in p'_0} \psi' \right) (\mathcal{M}) \subseteq \varphi(\mathcal{M}) \rightsquigarrow \mathcal{M} \models \psi(\bar{x}) \rightarrow \varphi(\bar{x})$$

$$\varphi \vdash \varphi \Rightarrow [\varphi] \cap S_n(\emptyset) \subseteq [\varphi] \cap S_n(\emptyset)$$



Application $L = \{+, \cdot, 0, 1\}$: the language of rings.

ACF_p : the theory of algebraically closed fields of char p , in L .

Axioms:

1) field axioms

2) char $= p \neq 0$: $\underbrace{1 + \dots + 1}_p = 0$

2') $p = 0$: $\underbrace{1 + \dots + 1}_n = 0$ for $n \geq 1$

3) Every polynomial of deg n has a root:
 $0 < n$
 $\forall y_{n-1}, y_{n-2}, \dots, y_0 \exists x \quad x^n + y_{n-1}x^{n-1} + \dots + y_0 = 0.$

Fact ACF_p is complete.

Proof Let $M, N \models ACF_p$. Enough to show that $M \equiv N$. Let $\varepsilon > \|M\|, \|N\|$ and

let $M' \succ M, N' \succ N$.

power ε .

M', N' : uncountable acl fields of the same power and char

$$\begin{array}{c}
 \Downarrow \text{algebra} \\
 M' \cong N' \Rightarrow M' \equiv N' \\
 \quad \quad \quad \Downarrow \\
 \quad \quad \quad M \equiv N
 \end{array}$$

Fact ACF_p is q.e. (Chevalley, Tarski)

Proof (in \mathcal{M}) We will show that $\forall p \in S_n(\emptyset)$

$p_0 + p \Leftrightarrow p_0(\mathcal{M}) \subseteq p(\mathcal{M})$. Let $\bar{a} \models p_0$,

$\bar{b} \models p$, $\bar{a}, \bar{b} \in \mathcal{M}$. It's enough to prove

that $\exists f \in \text{Aut}(\mathcal{M}) f(\bar{a}) = \bar{b}$.

$$\begin{array}{l}
 \bar{a} = (a_1, \dots, a_n) \\
 \bar{b} = (b_1, \dots, b_n)
 \end{array}$$

Let $\langle \bar{a} \rangle, \langle \bar{b} \rangle$: the subfields with \mathbb{A}

of \mathcal{M} generated by \bar{a}, \bar{b} . $\bar{a}, \bar{b} \models p_0 \Rightarrow \langle \bar{a} \rangle \cong \langle \bar{b} \rangle$

$$\langle \bar{a} \rangle \cong \langle \bar{b} \rangle$$

\Downarrow unique \Downarrow

Some algebraic magic.

$$\mathcal{M} \cong \langle \bar{a} \rangle_0 \cong \langle \bar{b} \rangle_0 \subseteq \mathcal{M}$$

(fraction field)

$$\mathcal{M} \cong \underbrace{\langle \bar{a} \rangle_0^{\text{alg}}}_{F_a} \cong \underbrace{\langle \bar{b} \rangle_0^{\text{alg}}}_{F_b} \subseteq \mathcal{M}$$

(not unique)

$$\text{trdeg}(\mathcal{M}/\mathbb{F}_a) = \|\mathcal{M}\| = \text{trdeg}(\mathcal{M}/\mathbb{F}_b)$$

$$\begin{array}{ccc} \mathcal{M} \cong \mathbb{F}_a(X_\alpha, \alpha < \lambda)^{\text{alg}} & \Downarrow & \\ f \cong \downarrow & \curvearrowright & \cong \\ \mathcal{M} \cong \mathbb{F}_b(X_\beta, \beta < \lambda)^{\text{alg}} & & \end{array}$$

$$f \in \text{Aut}(\mathcal{M}), f(\bar{a}) = \bar{b}.$$



Types in $T = \text{ACF}_p$

Let $\mathcal{M} \models T$: a monster model.

subfield K , ^{UI} We will describe $S_n(K)$.
(small)

Let $\bar{a} \subseteq \mathcal{M}$, $|\bar{a}| = n$.

$$K[\bar{x}] \triangleright I(\bar{a}/K) = \{ f \in K[\bar{x}] : f(\bar{a}) = 0 \}$$

Remark 1) $\text{tp}(\bar{a}/K) = \text{tp}(\bar{a}'/K) \Leftrightarrow I(\bar{a}/K) = I(\bar{a}'/K)$

2) $\forall I \triangleleft K[\bar{x}]$ _{prime} $\exists \bar{a} \subseteq \mathcal{M} \ I(\bar{a}/K) = I$.

Proof 1) " \Rightarrow " $\text{tp}(\bar{a}/K) = \text{tp}(\bar{a}'/K) \Rightarrow \exists f \in \text{Aut}(\mathcal{M}/K)$
 $I(\bar{a}/K) = I(\bar{a}'/K) \stackrel{f}{=} f(\bar{a}) = \bar{a}'$

[alternatively: $f \in I(\bar{a}/K) \Leftrightarrow "f(\bar{x})=0" \in \text{tp}(\bar{a}/K)$]

" \Leftarrow " Assume $I(\bar{a}/K) = I(\bar{a}'/K) = I$.

$$K[\bar{a}] \cong_K K[\bar{x}] / I \cong K[\bar{a}']$$

$$\Downarrow$$

$$\exists f \in \text{Aut}(\mathcal{U}/K) \quad f(\bar{a}) = \bar{a}'$$

$$\Downarrow$$

$$\text{tp}(\bar{a}/K) = \text{tp}(\bar{a}'/K).$$

2) $K \subseteq K[\bar{x}] / I = K[\bar{a}] \cong \bar{a} = \bar{x} / I$ and $I(\bar{a}/K) = I$.

•
•
•

□

$$S_1(K) = \{ \text{tp}(a/K) : a \in \mathcal{M} \} : a \text{ top-space.}$$

$$\Downarrow$$

$$p(x) = \text{tp}(a/K), \quad I_p = I(a/K) \triangleleft K[x]$$

a) $I_p \neq \{0\}$, i.e. a is algebraic / K , so

$0 \neq f$ \Downarrow " $f(x) = 0$ " $\in p(x)$. In fact,

irreducible over K " $f(x) = 0$ " $\vdash p(x)$ (isolates)

Let $a' \in \mathcal{M}$ s.t. $f(a') = 0 \Rightarrow I(a'/K) \ni f \ni$

$$p = \text{tp}(a/K) = \text{tp}(a'/K) \Leftarrow I(a/K) = I(a'/K) \Leftarrow \begin{matrix} f \text{ generates} \\ I(a'/K) \end{matrix}$$

$p(x)$ here is called algebraic.

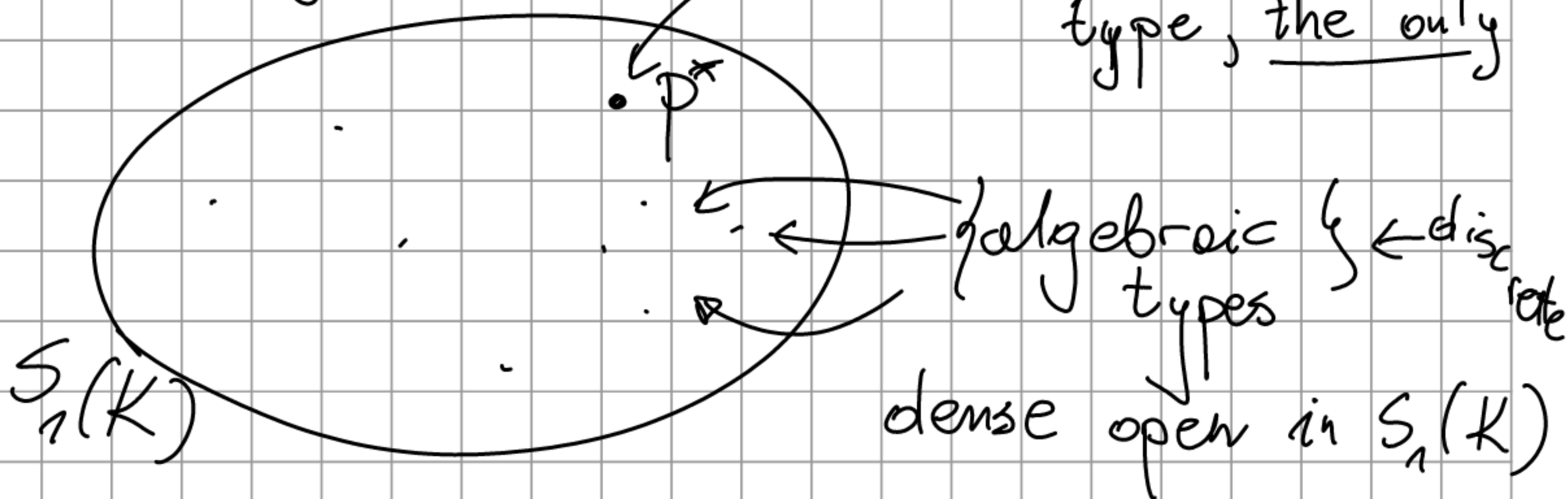
More generally (T : arbitrary)

Def $\varphi(\bar{x}) \in L(A)$ is called algebraic, if $0 < |\varphi(\mathcal{M})| < \aleph_0$, similarly for q : a type.

b) $I_p = \{0\}$: $p = \text{tp}(a/K)$ s.t. $a \in \mathcal{M}$ transcendental over K

↑
the transcendental type over K .

transcendental type, the only



If K cble then $S_n(K)$ cble

Corollary ACF_p is \aleph_0 -stable [recall: T is κ -stable $\Leftrightarrow \forall A \subseteq \mathcal{M}, |A| \leq \kappa$
 $|S_n(A)| \leq \kappa$]

Proof Let $A \subseteq \mathcal{M}$.
 A is abelian

$$A \subseteq K \subseteq \mathcal{M} \quad |S_n(A)| \leq |S_n(K)| = \aleph_0$$

\uparrow
 A is abelian subfield

Remark T is totally transcendental $\Leftrightarrow T: \aleph_0$ -stable

Proof " \Rightarrow " from def " \Leftarrow ": (A.a.) Let $\kappa > \aleph_0$.

Suppose $|A| \leq \kappa < |S_n(A)|$ for some $A \subseteq \mathcal{M}$.

Shall find $A_0 \subseteq A$ with $|S_n(A_0)| \geq 2^{\aleph_0}$.
 A_0 is abelian

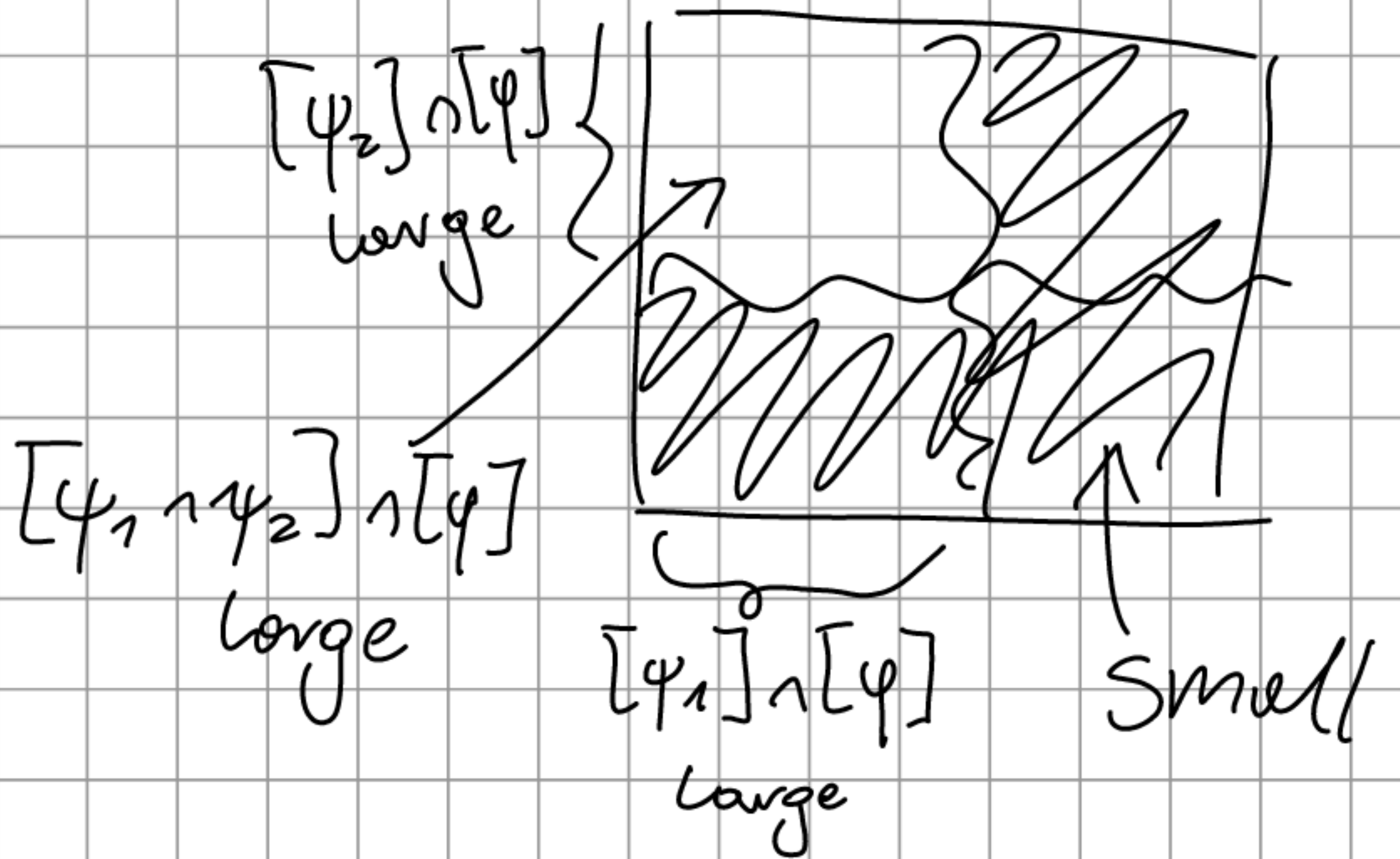
(def) $\varphi(x) \in L(A)$ is large iff $|S_n(A) \cap [\varphi]| > \kappa$
 otherwise: $\varphi(x)$ small.

(a) " $x=x$ " is large

(b) if $\varphi(x)$ is large, then $\exists \psi_1, \psi_2 \in L(A)$ large
 s.t. $\varphi(\mathcal{M}) = \psi_1(\mathcal{M}) \cup \psi_2(\mathcal{M})$

Pf. (b) if not then $\exists \psi \in L_n(A)$: $\psi \wedge \varphi$ is large
 is a complete type is $S_n(A) \cap [\psi]$

1° \mathcal{P}^* : consistent: $\psi_1, \psi_2 \in \mathcal{P}^* \Rightarrow \psi_1 \wedge \psi_2 \in \mathcal{P}^*$



2° \mathcal{P}^* : complete OK

$\mathcal{P}^* \in S_n(A) \cap [\phi]$: the only large type.

$$S_n(A) \cap [\phi] = \underbrace{\mathcal{P}^*}_{\text{large}} \cup \underbrace{\bigcup_{\substack{\psi \in L_n(A) \\ \psi \perp \phi}}}_{\leq \aleph} (S_n(A) \cap [\phi])_{\leq \aleph}$$

$> \aleph$

$\leq \aleph$

↘

c) a tree of large formulas in $L_1(A)$ $\varphi_\eta(x)$,
 $\eta \in 2^{<\omega}$ st. $\varphi_\eta(\mathcal{M}) = \varphi_{\eta_0}(\mathcal{M}) \cup \varphi_{\eta_1}(\mathcal{M})$
↑
by (b)

Let $A_0 \subseteq A$: the set of all params of $\varphi_\eta, \eta \in 2^{<\omega}$

Then $|A_0| \leq \aleph_0^{\aleph_0}$.

For $\eta = 2^{<\omega}$: $\mathcal{P}_\eta^0 = \{ \varphi_{\eta|n}(x) : x < \omega \}$: a consistent
 \mathcal{L} -type over A_0

When $\nu \neq \eta$
then $\mathcal{P}_\eta \neq \mathcal{P}_\nu$

$\mathcal{P}_\eta \in S_\eta(A_0)$

$$\Downarrow \quad |S_\eta(A_0)| \geq 2^{\aleph_0} > \aleph_0 \quad \Downarrow$$

21.03.2022

CONSTRUCTION OF SPECIAL MODELS: N, M ⊨ T

Def. M is atomic if $\forall \bar{a} \in M$ $\text{tp}(\bar{a}/\emptyset) = \text{tp}(\bar{a})$ is isolated.

(2) M is prime if $\forall N \models T \exists f: M \xrightarrow{\cong} N$

Example $T = \text{ACF}_p$, F_p : prime field of char p

a) F_p : atomic (exercise)

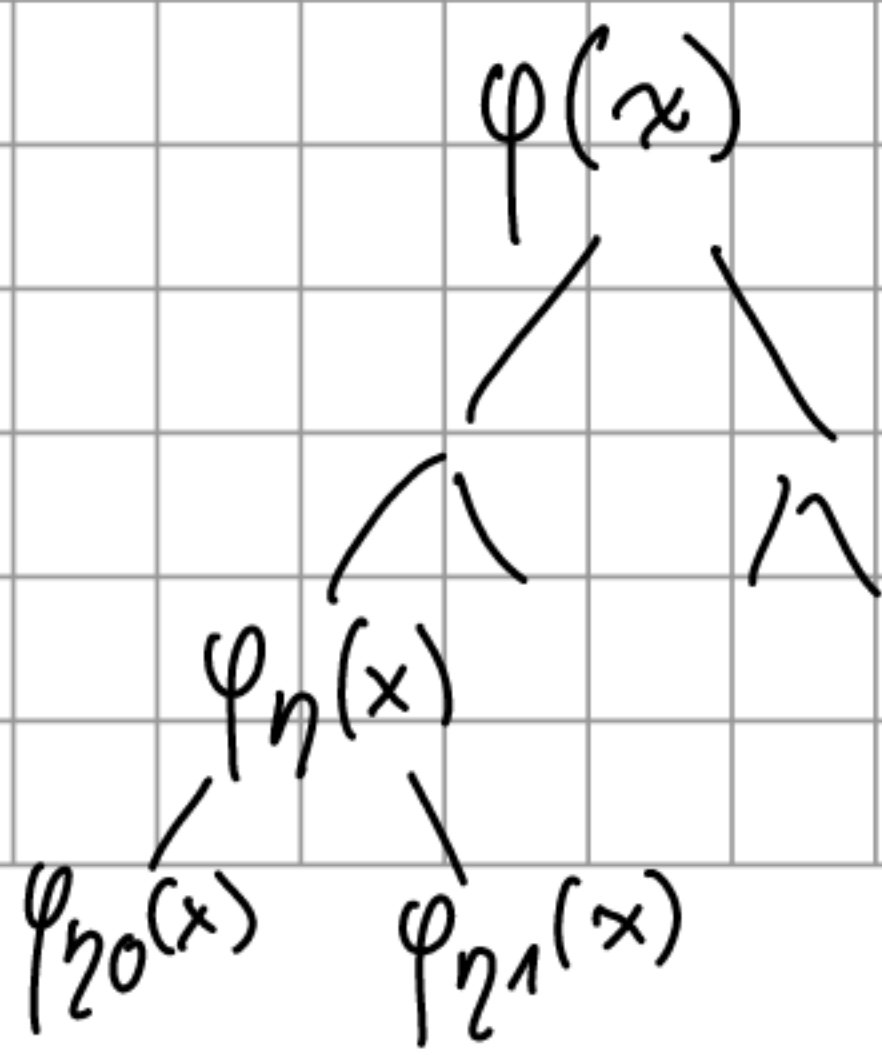
b) F_p : prime (exercise)

Thm. $T: \aleph_0$ -stable $\Rightarrow T$ has a prime model.

Lemma 1 $T: \aleph_0$ -stable $\Rightarrow \forall A \subseteq \mathcal{M}$ $\{ \text{isolated types} \} \subseteq S_n(A)$ dense

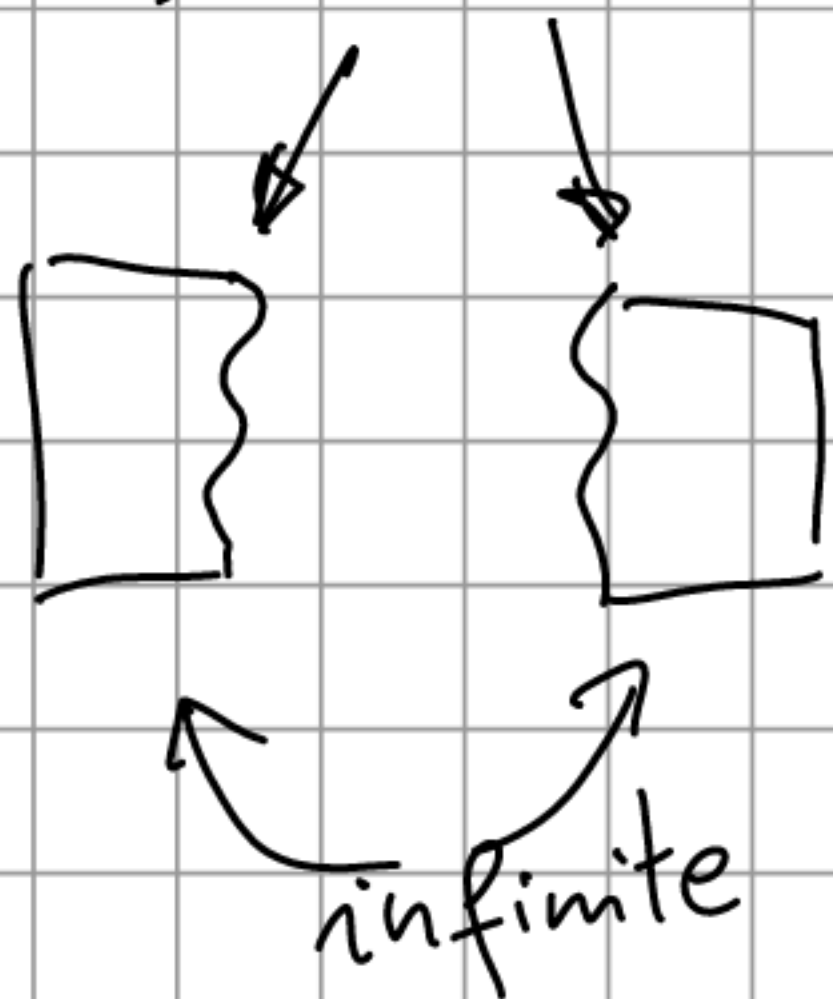
Pf. Suppose $\varphi(x) \in L_n(A)$ s.t. in $S_n(A) \cap [\varphi]$ (consistent with T)

there is no isolated types \Rightarrow a tree of formulas $\varphi_\eta(x) \in L_n(A)$, $\eta \in 2^{<\omega}$



\rightsquigarrow contradicts \aleph_0 -stability of T

clopen $\{ \} \subseteq S_1(A) \cap [\varphi]$



□

Lemma 2 $(a, b \in \mathcal{M})$ $tp(a)$ isolated and $tp(b/a)$ isolated

$\Leftrightarrow tp(ab)$ isolated

Pf " \Rightarrow ": $\varphi(x) \vdash tp(a), \psi(a, y) \vdash tp(b/a)(y)$

$p_a(y) \subseteq S_y(a)$

Then: $\varphi(x) \wedge \psi(x, y) \vdash tp(ab)$

Let $a', b' \in \mathcal{M}$ satisfy $\varphi(x) \wedge \psi(x, y)$

$\models \varphi(a') \Rightarrow tp(a') = tp(a) \Rightarrow \psi(a', y) \vdash p_{a'}(y)$

$\supseteq S_y(a')$

$\models \psi(a', b') \Rightarrow \models p_{a'}(b')$

\Downarrow

$ab \equiv a'b'$

and $tp(ab) = tp(a'b')$

" \Leftarrow ": $\Theta(x, y) \vdash \text{tp}(a, b)$.

(a) " $\exists y \Theta(x, y)$ " $\vdash \text{tp}(a)$.

because Let $a' \in \mathcal{M}$ satisfy " $\exists y \Theta(x, y)$ ".

So there is b' s.t. $\models \Theta(a', b')$

$\Rightarrow \text{tp}(ab) = \text{tp}(a', b') \Rightarrow \text{tp}(a) = \text{tp}(a')$.

(b) $\Theta(a, y) \vdash \text{tp}(b/a)(y)$

because: similar to (a) ▀

Proof of the thm. Construction of a prime model of T :

$A = \{a_n : n < \omega\} \subseteq \mathcal{M}$ so that:

1) A satisfies TV-test

2) $\forall n$ $\text{tp}(a_n/a_{<n})$ is isolated

At step n choose a_n : $[a_{<n} = \{a_k : k < n\}]$

Let $\varphi(x) \in L_n(a_{<n})$ consistent.

Let $a_n \in \varphi(\mathcal{M})$ s.t. $\text{tp}(a_n/a_{<n})$ is isolated (lemma 1)

Suitable choice of φ 's ensures (1).

$M \models T$ is prime. Let $N \models T$. We find

$f(a_n) \in N$ for $n < \omega$ s.t. \exists ^{arbitrary} $f: M \equiv \rightarrow N$.

At step n $f[a_{<n}] \subseteq N$ with $f: a_{<n} \equiv \rightarrow N$

Let $p(x) = \text{tp}(a_n/a_{<n})$ (isolated)

$$f^*(p)(x) \in S(f(a_{<n}))$$

isolated

too, hence realised by $f(a_n)$

$$f: a_{\leq n} \equiv \rightarrow N$$



Remark (1) A prime model $M \models T$ is atomic

(2) If $M \models T$ is atomic, then M prime

Corollary \hat{F}_p is atomic.

Proof of remark

(1) Let $p(\bar{x}) \in S_n(\emptyset)$ non-isolated. Will show

$p(M) = \emptyset$. Let $N \models T$ be omitting p .

$\exists f: M \xrightarrow{\cong} N \Rightarrow p(M) = \emptyset$.

(2) Let $M = \prod_T \{a_n : n < \omega\}$ atomic.

Then $\forall n$ $tp(a_n)$ is isolated

\Downarrow lemma 2
 $\forall n$ $tp(a_n/a_{<n})$ is isolated

\Downarrow pf of thm

M prime. □

Corollary A prime model of T is unique (up to \cong)

Proof Let $M, N \models T$ both prime $\stackrel{\text{remark}}{\Rightarrow} M, N$

are stable and atomic, so we have embeddings

in both directions, using back-and-forth

we get the iso.

Def $M \models T$ is minimal if $\neg \exists N \cong M$

Example $\hat{\mathbb{F}}_p$ is minimal.

Fact T has a prime model $\Leftrightarrow \forall n$ $\{ \text{isolated types} \} \subseteq S_n(\emptyset)$
dense

Proof " \Rightarrow ": Let $M \models T \Rightarrow M$: atomic prime

what we need

$N \models T$, then $\forall n \exists p \in S_n(\emptyset)$:
any $p(N) \neq \emptyset$
exercise | is dense in $S_n(\emptyset)$

" \Leftarrow ": Claim Assume $\bar{a} \subseteq M$ and $\text{tp}(\bar{a})$ is isolated.
finite

Then $\{ \text{isolated types} \} \subseteq S_n(\bar{a})$.
dense

Proof of claim Let $n = |\bar{a}|$, $\varphi(\bar{x}) \vdash \text{tp}(\bar{a})$.

Let $\psi(\bar{x}, y) \in L_{n+1}(\emptyset)$ s.t. $\psi(\bar{a}, y)$ is consistent.

We seek $q(y) \in S_1(A) \cap [\psi(\bar{a}, y)]$ isolated.

Let $\chi(\bar{x}, y) = \varphi(\bar{x}) \wedge \psi(\bar{x}, y)$.

By assumptions of $\Leftarrow \exists p(\bar{x}, y) \in S_{\bar{x}, y}(\emptyset) \cap [\chi(\bar{x}, y)]$.
isolated

Let $\bar{a}', b' \models p(\bar{x}, y)$. Then $\bar{a}' \models p(\bar{x}, y) \upharpoonright_{\bar{x}} = \text{tp}(\bar{a})$
 \wedge
 $\varphi(\bar{x})$

Let $f \in \text{Aut}(\mathcal{M}) : f(\bar{a}') = \bar{a}$
 $b = f(b')$

Then $\bar{a}'b' \stackrel{\equiv}{\underset{f}{\rightarrow}} \bar{a}b \Rightarrow \bar{a}b \models p(\bar{x}, y)$

so $\text{tp}(\bar{a}b)$ is isolated $\stackrel{(\text{lemma 2})}{\Rightarrow}$ $\text{tp}(b/\bar{a})$ is isolated
 \Downarrow
 $\psi(\bar{a}, y)$

So $q(y) = \text{tp}(b/\bar{a})$

Given $n \mapsto$ we construct a model $M = \{a_n : n < \omega\}$ s.t. $\forall n \text{ tp}(a_n/a_{<n})$ is isolated

\Downarrow lemma 2

M atomic dble $\Rightarrow M$ prime.

Corollary If $\forall n |S_n(\emptyset)| \leq \aleph_0$, then T has a prime model.

Corollary A prime model (of a dble T) is homogeneous (exercise).

The number of countable models of $T: I(T, \aleph_0), n(T).$

Remark $1 \leq n(T) \leq 2^{\aleph_0}$

$$M \models T \Rightarrow M \cong \underbrace{(N, \dots)}_{\leq 2^{\aleph_0} \text{ L-structures like that}}$$

Recall $n(T) = 1 \Leftrightarrow \forall n |S_n(\emptyset)| < \aleph_0$

($T: \aleph_0$ -categorical)

Vaught conjecture (1961)

$$n(T) > \aleph_0 \Rightarrow n(T) = 2^{\aleph_0}$$

Thm (M. Morley, 1971) $\aleph_0 < n(T) < 2^{\aleph_0} \Rightarrow n(T) = \aleph_1$

Thm (Vaught, 1961) $n(T) \neq 2$

Proof (A.a) suppose $n(T) = 2$.

$$n(T) < 2^{\aleph_0} \Rightarrow T \text{ small (i.e. } \forall n |S_n(\emptyset)| \leq \aleph_0)$$

⋮

25.03.2022

Example (Andrzej Ehrenfeucht) Theory with exactly 3 stable theories.

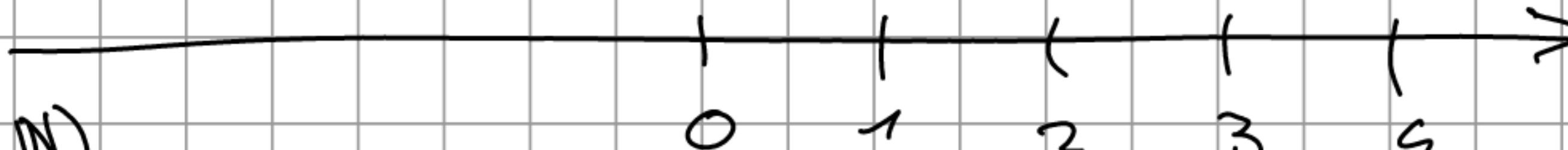
$T_0 = \text{Th}(\mathbb{Q}, \leq)$. Look at $T = T_0(N) = \text{Th}(\mathbb{Q}, \leq, n)_{n \in \mathbb{N}}$.

T_0 is q.e. $\Rightarrow T$ is also q.e.

$S_1^T(\emptyset) = S_1^{T_0}(N)$. The types in $S_1^T(N)$:

realised in (\mathbb{Q}, \leq, N)

isolated



- $p_i(x) \equiv \{x = i\}$, $i \in \mathbb{N}$
- $r_i(x) \equiv \{i-1 \leq x \leq i\}$, $i \in \mathbb{N}$, $-1 \approx -\infty$
- $s(x) \equiv \{x > i : i \in \mathbb{N}\}$

omitted

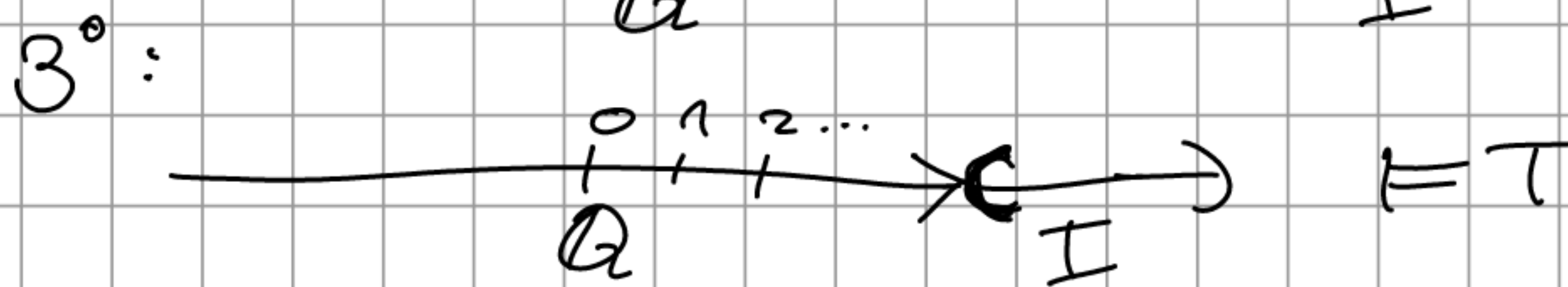
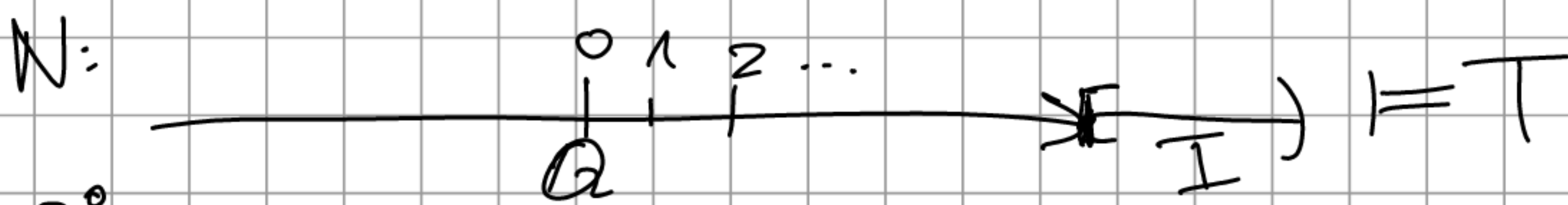
We will point 3 stable models $N \models T$.

1° $N = M$: prime model of T .

2° $s(N)$ has the minimal element.

3° $s(N)$ hasn't minimal element.

2°: $\mathbb{Q} \cup ([0,1) \cap \mathbb{Q})$:



Variants: 3, 4, 5, 6, ...

Problem Does there exist a stable T with $1 < n(T) < \aleph_0$?

Def ($A \subseteq \mathcal{M}$), $M \prec \mathcal{M}$ is prime over A if:

(1) $A \subseteq M$

(2) $\forall N \prec \mathcal{M} \exists f: M \xrightarrow{\cong} N: f|_A = \text{id}_A$

Equivalently M is a prime model of $T(A)$.

- If A is stable \rightarrow full description of prime models of $T(A)$.
- If A is unstable \rightarrow in general not much can be set

Thm \aleph_0 -stable $\implies \forall A \exists M \neq T(A)$
 \mathcal{M} prime

Proof $M = A \cup \{a_\alpha : \alpha < ?\}$

Construction of a_α 's s.t.:

(i) $A \cup \{a_\alpha : \alpha < ?\}$ satisfies the TV-test

(ii) $\forall \alpha < ?$ $\text{tp}(a_\alpha / A a_{<\alpha})$ is isolated.

At some point it has to terminate

(i.e. we cannot add more elements).

Claim Assume $N \not\prec \mathcal{M}$. Then $\forall \alpha \exists f: A \cup a_{<\alpha} \xrightarrow{\cong} N$

s.t. $f|_A = \text{id}_A$.

Proof We define $f(a_\beta)$ for all $\beta < \alpha$

by ind. on β so that $f|_A = \text{id}_A$ and $f: A a_{\leq \beta} \xrightarrow{\cong} N$.

Take $\beta < \alpha$ and suppose $\forall \beta' < \beta$ $f(a_{\beta'}) \downarrow$

so that the condition holds.

$p(x) = \text{tp}(a_\beta / A a_{<\beta})$ is isolated.

$f: A a_{<\beta} \xrightarrow{\cong} f[A a_{<\beta}] \subseteq N$

$f(p)$ is realised by c

$p(x) \in S_1(A a_{<\beta})$ isolated $\xrightarrow{f^*}$ $f(p) \in S_1(f[A a_{<\beta}])$ isolated

Now we put $f(a_\beta) = c$.

Claim ~~1~~

By the claim after some time we cannot get any more elements.

Additional property of the construction:

At the step α we consider a formula $\varphi(x) \in L(A_{\alpha, \alpha})$ with no consistent realisation in $A_{\alpha, \alpha}$, choose a_α s.t. $\models \varphi(a_\alpha)$.

Problems Is a prime model over A unique up to isomorphism over A ?

Answer: not always. However the prime model M over A constructed by the previous construction is unique up to \cong_A and it's called primary over A .

Thm M, N : primary over $A \Rightarrow M \cong_A N$.

Proof $M = A \cup \{a_\alpha : \alpha < \gamma\}$: an "isolated construction" of M over A , i.e. $\text{tp}(a_\alpha / A a_{\beta < \alpha})$ is isolated by a formula $\varphi_\alpha(x)$ over $A a_{\beta < \alpha}$ s.t. $C_\alpha \subseteq \gamma$

Def. $X \subseteq \gamma$ is closed if $\forall \alpha \in X \ C_\alpha \subseteq X$

Remark (1) $\alpha \in \gamma \Rightarrow \exists$ minimal $X \subseteq \alpha$ s.t. X is finite

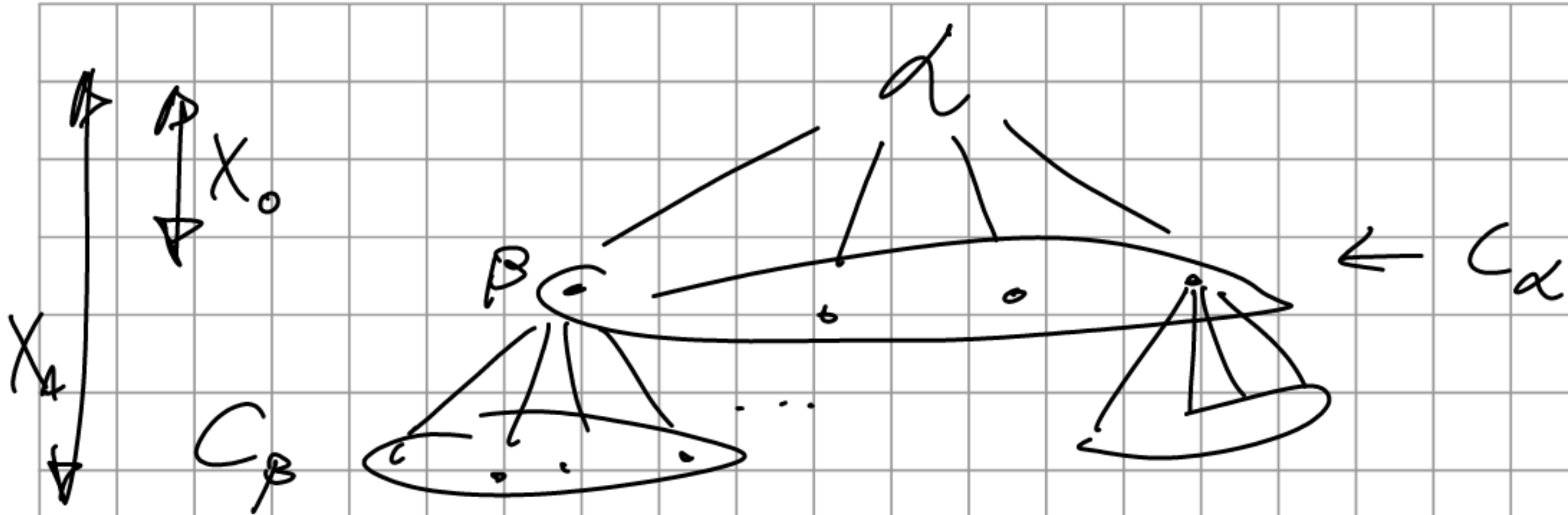
$\underbrace{X \cup \alpha}_\alpha$ is closed.

(2) A union of family of closed subsets of γ is closed.

Proof (remark) (2) is obvious.

(1): Take $X_0 = C_\alpha$, then $X_n = X_{n+1} \cup \bigcup_{\beta \in X_n} C_\beta$
 \uparrow
 finite because C_β finite

Then $X = \bigcup_n X_n$. Then $X \cup \alpha$ is finite and closed!



This tree has no infinite branch
 (because there are no infinite
 decreasing sequence of ordinals).

Remark II

Remark Assume X : closed. Then

$$A \cup \langle a_\alpha : \alpha \in X \rangle \overset{\text{concatenation}}{\uparrow} \langle a_\alpha : \alpha \in \gamma \setminus X \rangle$$

is an isolated construction over A .

Pf. (remark) as $A \cup \langle a_\alpha : \alpha \in X \rangle$ is an i -construction
 over A
 (by the fact that X is closed)

(2) Suppose that $\alpha < \gamma$ and $\alpha \notin X$. Will
 show that $\text{tp}(a_\alpha / A a_\chi a_{\chi \cap (\alpha)})$ is isolated.

$$\varphi_\alpha(A) \vdash \text{tp}(a_\alpha / A a_{<\alpha}) \vdash \text{tp}(a_\alpha / A a_{\alpha} a_{\alpha}^c \text{ } \dots)$$

↑ will show

Let $X_0 \subseteq X$ s.t. $X_0 \cap a \neq \emptyset$.
finite

Enough to show that $\text{tp}(a_\alpha / A a_{<\alpha}) \vdash \text{tp}(a_\alpha / A a_{<\alpha} a_{X_0})$

Wlog By the remark $X_0 \cup a$ is closed.

So: $A \cup \langle a_\beta : \beta < \alpha \rangle \wedge \langle a_\beta : \beta \in X_0 \rangle$ is

an i -construction over A , but for $\beta \in X_0$

$$\text{tp}(a_\beta / A a_{<\alpha} a_{(\beta) \cap X_0}) \vdash \text{tp}(a_\beta / A a_{<\beta})$$

Because $\varphi_\beta(x) \vdash$ and $\varphi_\beta \in$.

So it implies also $\text{tp}(a_\beta / A a_{<\alpha} a_{(\beta) \cap X_0})$.

$$\Rightarrow \text{tp}(a_\alpha / A a_{<\alpha} a_{(\beta) \cap X_0}) \vdash \text{tp}(a_\alpha / A a_{<\alpha} a_{(\beta) \cap X})$$

the
proof
of e123

(we switch a_α with a_β)

We just continue with induction on β

(start with $\beta = \min X_0$).

□

Claim M: Primary / A \Rightarrow atomic / A

Pf. Let $\bar{m} \subseteq M = A \cup \{a_\alpha : \alpha < \gamma\}$.

$\bar{m} \subseteq A \cup a_\chi, \chi \in \gamma$
finite closed

$A \cup a_\chi$: a partial i -construction.

\Downarrow
 $\text{tp}(a_\chi / A)$ is isolated

\Downarrow
 $\text{tp}(\bar{m} / A) \text{ --- } \parallel \text{ ---}$

claim \square

Pf (of thm) $M = A \cup \{a_\alpha : \alpha < \gamma\}$,

$N = A \cup \{b_\alpha : \alpha < \delta\}$: i -constructions / A.

We construct $f: M \xrightarrow{\cong} N$, $f = \bigcup_{\alpha} f_\alpha$: elementary.

(i) $\text{Dom } f_\alpha \supseteq A$, $\text{Rng } f_\alpha \supseteq A$, $f_\alpha \upharpoonright_A = \text{id}_A$

(ii) $|\text{Dom } f_\alpha \setminus A|, |\text{Rng } f_\alpha \setminus A| \leq |\alpha| \cdot \aleph_0$

(iii) $\beta \in \text{Lim } f_\beta = \bigcup_{\alpha < \beta} f_\alpha$

(iv) $a_\alpha \in \text{Dom } f_{\alpha+1}$, $b_{\alpha+1} \in \text{Rng } f_{\alpha+1}$.

(v) $\text{Dom } f_\alpha \setminus A = a_\chi$, $\text{Rng } f_\alpha \setminus A = b_\chi$,

where $X \subseteq \mathcal{I}$, $Y \subseteq \mathcal{J}$ are closed.

The recursive step from f_α to $f_{\alpha+1}$.

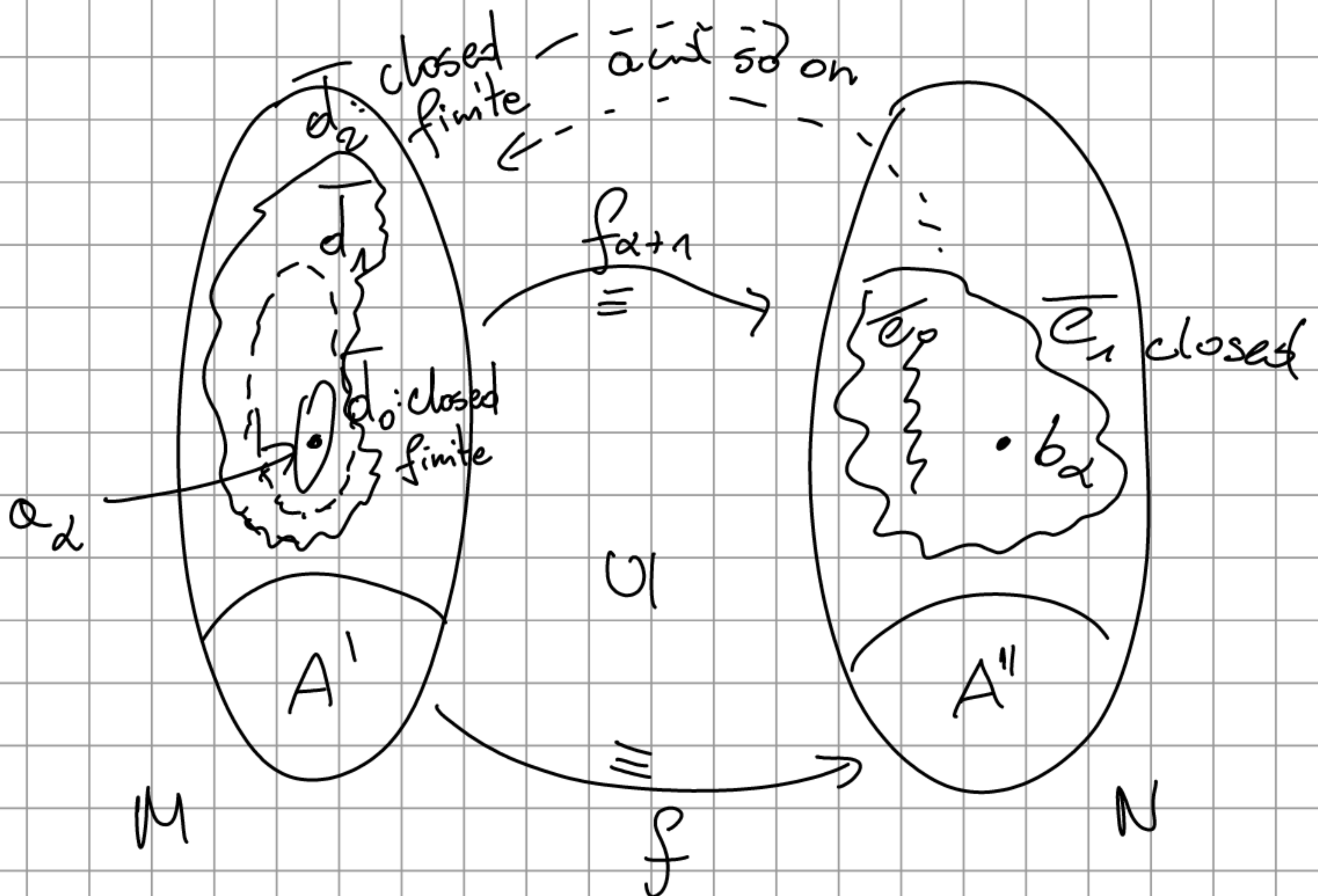
Let $A' = A \cup \text{Dom } f_\alpha$: an \mathcal{I} -construction over A ,

likewise $A'' = A \cup \text{Rng } f_\alpha$: $\text{---} \cup \text{---}$

and M is primary over A' (by the remark)

and N is primary over A'' .

$\wp(x) = \text{tp}(a_\alpha / A')$ is isolated, so $f_\alpha(p)$ is isolated too, therefore $\exists b \in N$ st. $f_\alpha(p) = \text{tp}(b / A'')$.



4.04.22

Def. (1) $\varphi(\bar{x}, \bar{a}) \in L_n(\bar{a})$ is algebraic if

$$0 < |\varphi(\mathcal{M})| < \aleph_0$$

(2) a type $p(\bar{x})$ (over \mathcal{M}) is algebraic if

$$0 < |p(\mathcal{M})| < \aleph_0$$

(3) $a \in \text{acl}(A)$ if $\text{tp}(a/A)$ is algebraic
algebraic closure

(4) $a \in \text{dcl}(A)$ if $a \in \mathcal{M}$ is the only
definable closure
realisation of $\text{tp}(a/A)$

Remark (1) $p(\bar{x})$: an algebraic type $\Leftrightarrow p(\bar{x}) \vdash \varphi(\bar{x})$

for some algebraic formula $\varphi(\bar{x})$

$$(2) |p(\mathcal{M})| = 1 \Leftrightarrow \exists \varphi (p \vdash \varphi \text{ and } |\varphi(\mathcal{M})| = 1)$$

Proof. 1 (\Leftarrow) $p(\mathcal{M}) \subseteq \varphi(\mathcal{M})$

(\Rightarrow) (a.a.) let $n \in \mathbb{N}$ arbitrary. Will show: $|p(\mathcal{M})| \geq n$.

Let $\bar{x}_1, \dots, \bar{x}_n$: disjoint tuples of variables,

$$|\bar{x}_i| = |\bar{x}|.$$

$\{ \varphi(\bar{x}_i) : \varphi(\bar{x}) \in p, i=1, \dots, n \} \cup \{ \bar{x}_i \neq \bar{x}_j : 1 \leq i < j \leq n \}$:

a consistent type.

\mathcal{J} is realised in \mathcal{M} so it has $\geq n$ realisations. \Downarrow

Fact $\text{acl}(A) = \bigcup \{ \varphi(\mathcal{M}) : \varphi(x) \in L_n(A) \text{ algebraic} \}$

$\text{dcl}(A) = \bigcup \{ \varphi(\mathcal{M}) : \varphi(x) \in L_n(A) \wedge |\varphi(\mathcal{M})| = 1 \}$

Remark Let $\varphi(\bar{x}) \in L_n(\mathcal{M})$. Then $\varphi(\bar{x})$ algebraic $\Leftrightarrow 0 < |\varphi(\mathcal{M})| < \aleph_0$

Proof $\mathcal{M} \models \mathcal{M}, |\varphi(\mathcal{M})| = k \Leftrightarrow \mathcal{M} \models (\exists!^k \bar{x}) \varphi(\bar{x})$
 $\Leftrightarrow \mathcal{M} \models (\exists!^k \bar{x}) \varphi(\bar{x}) \Leftrightarrow |\varphi(\mathcal{M})| = k$

Remark Let $A \subseteq \mathcal{M}$, then: $\text{tp}(ab/A)$ is algebraic
 $a, b \in \mathcal{M}$

$\Leftrightarrow \text{tp}(a/A)$ is algebraic and $\text{tp}(b/Aa)$ is algebraic

Pf. (\Rightarrow) $p(x, y) = \text{tp}(ab/A)$. Let $q(x) = p \upharpoonright_x$
 $= \text{tp}(a/A)$. Let $f: \mathcal{M}^2 \rightarrow \mathcal{M}$ projection

to the first coord. Then $f: p(\mathcal{M}) \rightarrow q(\mathcal{M})$

Why?

Take $a' \in q$, choose $g \in \text{Aut}(\mathcal{M}/A), g(a) = a'$,

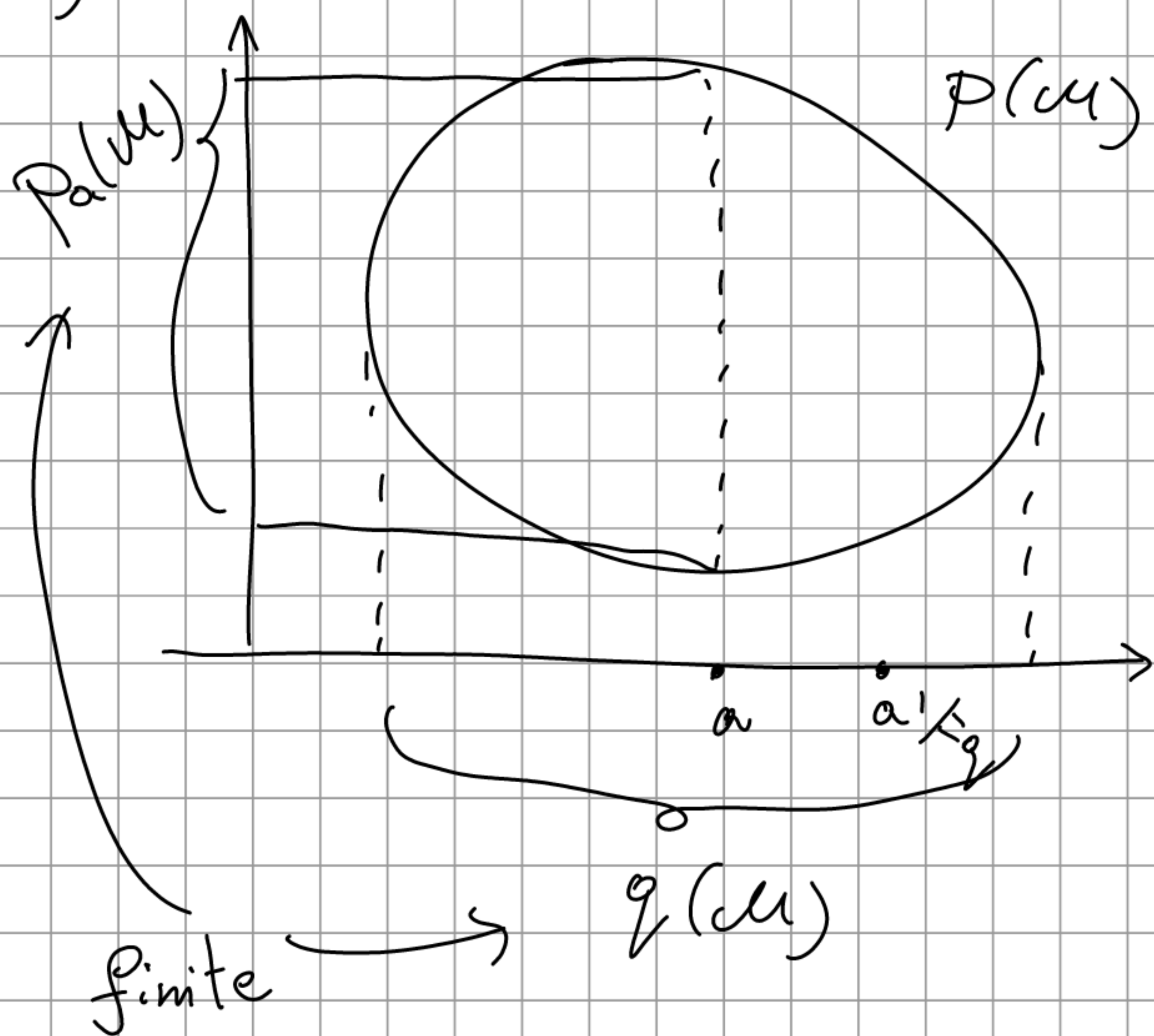
then $b' = g(b) \Rightarrow \text{tp}(ab/A) = \text{tp}(a'b'/A)$.

Then $|p(\mathcal{M})| < \aleph_0 \Rightarrow |p_q(\mathcal{M})| < \aleph_0$ and $(p_a(\mathcal{M}))^{\aleph_0}$

Let $p_a(y) = \text{tp}(b/Aa) = \{ \varphi(a, y) : \varphi(x, y) \in p \}$

Then $p_a(\mathcal{M}) = p(\mathcal{M})_a \leftarrow \text{"verticalization"}$
 this is finite

(\Leftarrow)



$p(\mathcal{M})_{a'} = q(p(\mathcal{M})_a)$ for any $q \in \text{Aut}(\mathcal{M}/A)$
 with $q(a) = a'$.

$p(\mathcal{M}) = \bigcup_{a' \models q} (\{a'\} \times p_{a'}(\mathcal{M})) : \text{finite} \quad \square$

Remark (1) ⁽ⁱ⁾ $A \subseteq \text{acl}(A)$, ⁽ⁱⁱ⁾ $\text{acl}(\text{acl}(A)) = \text{acl}(A)$,
⁽ⁱⁱⁱ⁾ $A \subseteq B \Rightarrow$ ^(iv) $\text{acl}(A) \subseteq \text{acl}(B)$ (a closure operator)
 $\text{acl}(A) = \bigcup_{\substack{A_0 \subseteq A \\ \text{finite}}} \text{acl}(A_0)$ (finite character)

(2) The same for dcl

Pf. 1 • $a \in \text{acl}(A) \Leftrightarrow a \in \varphi(\mathcal{U})$, $\varphi(x) \in L_1(A)$,
 so $\varphi \in L_1(A_0)$ for some $\substack{A_0 \subseteq A \\ \text{finite}}$, so (iv).

(ii): $a \in \text{acl}(\text{acl}(A)) \Rightarrow a \in \text{acl}(A \cup \bar{b})$,

for some $\bar{b} \subseteq \text{acl}(A) \Rightarrow \text{tp}(\bar{b}/A)$ algebraic

and $\text{tp}(a/\bar{b})$ algebraic $\stackrel{\text{remark}}{\Rightarrow} \text{tp}(a\bar{b}/A)$ is algebraic

$\Rightarrow \text{tp}(a/A)$ algebraic \Rightarrow

Example $T = \text{ACF}_p$, $A \subseteq \mathcal{U} \models T$. $\text{acl}(A) =$

the algebraic closure (in \mathcal{U}) of the field generated by A .



Measuring definable sets and types.

The Cantor-Bendixson rank.

Def. Let X : compact T_2 space.

$$\underbrace{X'}_{\text{CB-derivative}} = X \setminus \underbrace{\{\text{isolated points}\}}_{\text{open in } X} \Rightarrow X' \subseteq X \text{ closed}$$

Iteration: $X^{(\alpha+1)} = (X^{(\alpha)})'$, $X^{(\delta)} = \bigcap_{\alpha < \delta} X^{(\alpha)}$ where $\delta \in \text{Lim}$,
 $X^{(\infty)} = \bigcap_{\alpha \in \text{Ord}} X^{(\alpha)} = X^{(\beta)}$ for some $\beta < |w(X)|^+$
↑ the perfect core of X ↑ minimal cardinality of basis of X

Def CB: $X \rightarrow \text{Ord} \cup \{\infty\}$

$$\text{CB-rank } p = \begin{cases} \min \{\alpha \in \text{Ord} : p \notin X^{(\alpha+1)}\} & \text{if } p \notin X^{(\infty)} \\ \infty & p \in X^{(\infty)} \end{cases}$$

Now: $X = S(A)$: 0-dimensional (extremely disconnected).

Let: $\text{Clopen}(X) = \{V \subseteq X : V \text{ clopen}\}$.

Def. $CB: \text{Clopen}(X) \rightarrow \text{Ord} \cup \{\infty\}$: the smallest function (value-wise) s.t.: $CB(V) \geq \alpha + 1 \Leftrightarrow \forall n < \omega \exists V_1, \dots, V_n \subseteq V$ $\overset{\text{clopen}}{\text{disjoint}}$ $CB(V_i) \geq \alpha$. (also we define " $\geq \delta$ ")

Then $CB(V) := \min \{ \alpha : \neg CB(V) \geq \alpha + 1 \}$

Properties Let $U, V \subseteq X$ clopen.

(0) $CB(U) = -1 \Leftrightarrow U = \emptyset$

(1) $CB(U) = 0 \Leftrightarrow 0 < |U| < \aleph_0$

(2) $U \subseteq V \Leftrightarrow CB(U) \leq CB(V)$

(3) $CB(U \cup V) = \max \{ CB(U), CB(V) \}$

} Very easy

Pf. 3 Obv. $CB(U \cup V) \geq \max \{ CB(U), CB(V) \}$.

Now assume $CB(U \cup V) \geq \alpha \Rightarrow \max \{ CB(U), CB(V) \} \geq \alpha$.

Pf by ind on α . Base and limit easy.

Successor step $\alpha \rightarrow \alpha + 1$. Assume $CB(U \cup V) \geq \alpha + 1$.

So $\forall n \exists W_1, \dots, W_n \subseteq U \cup V$ $\overset{\text{clopen}}{\text{disjoint}}$ $\bigwedge_{i=1}^n CB(W_i) \geq \alpha$.

By ind hyp.: $\max\{CB(W_i \cap U), CB(W_i \cap V)\} \geq \alpha$.

So $\forall n \left(\exists W_1, \dots, W_n \subseteq U \bigwedge_{i=1}^n CB(W_i) \geq \alpha \right)$
 (or the same for V)

\Downarrow

$CB(U) \geq \alpha+1$ or $CB(V) \geq \alpha+1$.

- (4) $CB(V) \geq \alpha+1 \iff (\exists V_n \subseteq V, n < \omega) \bigwedge_n CB(V_n) \geq \alpha$
clopen disjoint
- (5) For $p \in X$ $CB(p) = \min\{CB(U) : p \in U \subseteq X\}$
clopen

Notation

In model theory: $X = S(A)$.

$$CB(a/A) := CB(\text{tp}(a/A))$$

$$CB(a/A) = 0 \iff \text{tp}(a/A) \text{ is isolated}$$

$$p \in S(A) \rightsquigarrow CB(p) = CB_A(p)$$

$$\varphi \in L(A) \rightsquigarrow [\varphi] \subseteq S(A) \rightsquigarrow CB_A(\varphi)$$

$$\parallel CB_A([\varphi] \cap S(A))$$

Morley rank "CB on $L(\mathcal{M})$, in $S(\mathcal{M})$ "

Def. RM: $L(\mathcal{M}) \rightarrow \{-1\} \cup \text{Ord} \cup \{\infty\}$:

the minimal function s.t. For $U \subseteq \mathcal{M}^n$
definable
[$\varphi(\bar{x}) \in L_n(\mathcal{M})$ identified with $U = \varphi(\mathcal{M}) \subseteq \mathcal{M}^n$]

$$(1) U = \emptyset \Rightarrow \text{RM}(U) = -1$$

$$(2) \text{ If } U \neq \emptyset, \text{ then } \text{RM}(U) \geq \alpha + 1$$

$$\Leftrightarrow \forall n < \omega \exists V_1, \dots, V_n \subseteq U \bigwedge_{i \leq n} \text{RM}(V_i) \geq \alpha$$

def. disjoint

Def. For $\varphi(\bar{x}) \in L(\mathcal{M})$, $\text{RM}(\varphi) = \text{RM}(\varphi(\mathcal{M}))$

• For a type $p(\bar{x})$ over \mathcal{M} (not necessarily complete)

$$\text{RM}(p) = \min \{ \text{RM}(\varphi) : p \vdash \varphi \}$$

$$= \min \{ \text{RM}(U) : p(U) \subseteq U \}$$

Remark (1) $\text{RM}(\varphi) = \text{CB}_{\mathcal{M}}(\varphi)$

(2) For $p \in S(\mathcal{M})$ $\text{RM}(p) = \text{CB}_{\mathcal{M}}(p)$

Here \mathcal{M} may be replaced with any

\aleph_0 -saturated $M \prec \mathcal{M}$.

Properties (1) $\varphi \vdash \psi \Rightarrow RM(\varphi) \leq RM(\psi)$

(2) $\rho \vdash \varphi \Rightarrow RM(\rho) \leq RM(\varphi)$

(3) $RM(\varphi \vee \psi) = \max\{RM(\varphi), RM(\psi)\}$

(4) $RM(\varphi) \geq \alpha + 1 \iff \left(\exists \varphi_n \vdash \varphi, n < \omega \right) \wedge_n RM(\varphi_n) \geq \alpha$
pairwise contradictory

(5) $\exists \delta \in Lim$, then $RM(\varphi) \geq \delta \iff (\forall \alpha < \delta) RM(\varphi) \geq \alpha$

Thm T is \aleph_0 -stable $\iff RM("x=x") < \infty$.

Pf. (\Rightarrow) (a.a.) $\exists f$ $tp(\bar{a}) = tp(\bar{b})$, then

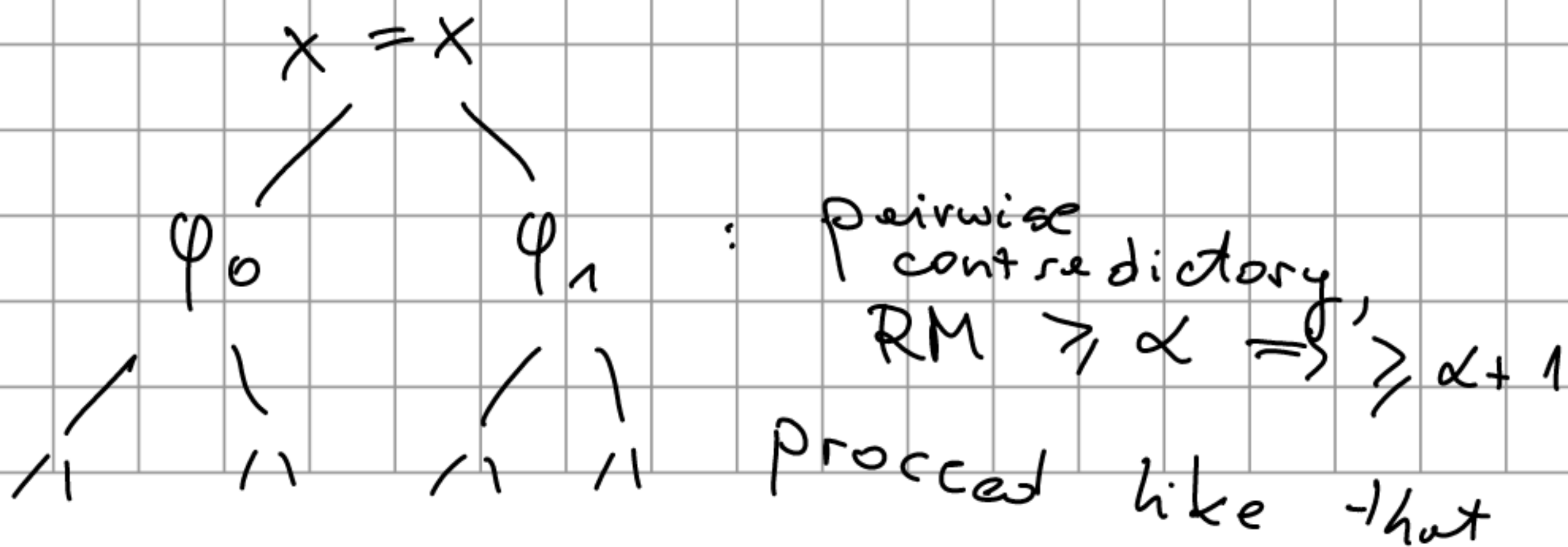
$$RM(\varphi(\bar{x}, \bar{a})) = RM(\varphi(\bar{x}, \bar{b}))$$

$$\exists f \in Aut(\mathcal{U}) \quad f(\bar{a}) = \bar{b} \Rightarrow f(\varphi(\mathcal{U}, \bar{a})) = \varphi(\mathcal{U}, \bar{b})$$

So $|Rng(RM)| \leq 2^{|\mathcal{U}|} \Rightarrow \exists \alpha \in Ord \forall \varphi [RM(\varphi) \geq \alpha$

$\Rightarrow RM(\varphi) = \infty$].

Suppose $RM("x=x") = \infty \Rightarrow \geq \alpha + 1$



We get 2^{10} many types over table set A
 $\Rightarrow T$ is not $\bigcup \bigcup$ -stable.