Complex roots of unity on the real plane

B.Zilber

April-July, 2003

We consider the theory of the structure

$$\mathbb{C}_{\mathbb{R},\text{roots}} = (\mathbb{C}, +, \cdot, R, U)$$

where R is a unary predicate for the real axis of the complex plane $\mathbb{C}$ and U the unary predicate for the complex roots of unity.

A weaker structure $(\mathbb{C}, +, \cdot, U)$ is known to be ω-stable (see [Z]). Anand Pillay asked if $\mathbb{C}_{\mathbb{R},\text{roots}}$ is well behaving in the context of real model theory, and this has been further discussed in [Mi].

We give here a complete axiomatisation of the theory of $\mathbb{C}_{\mathbb{R},\text{roots}}$ and prove that the theory allows elimination of quantifiers in a reasonable language. The elimination of quantifiers in fact shows that definable sets in the standard model are finite boolean combinations of some countable unions of semi-algebraic cells.

Let $U_0 = U(\mathbb{C})$, the complex roots of unity. We use the following **Lang property** of U_0 (see [L], Ch.I, s.6 for details):

For every polynomial $p(x_1, \dots, x_n)$ over $\mathbb{Q}(U_0)$ (the extension of $\mathbb{Q}$ by the roots of unity) there is a finite collection of cosets $S_1, \dots, S_k$ of algebraic subgroups of $(\mathbb{C}^*)^n$ given by a finite system of equations of the form

$$x^m = \gamma_m$$

for non-trivial monomials x^m and elements $\gamma_m \in U_0$ such that

$$\{a \in U_0^n : \ p(a) = 0\} = \bigcup_i S_i \cap U_0^n.$$

Let $T_{\mathbb{R},roots}$ be the theory of $\mathbb{C}_{\mathbb{R},roots}$ and $(F, +, \times, R, U)$ a model of the theory. Since $F = R + iR$, and $R = R(F)$ is a definable (formal real) subfield, a subset $S \subseteq F^n$ can be also vewed as a subset of R^{2n}. Call $S \subseteq F^n$ **semi-algebraic** if S is definable in the field structure $(R, +, \times)$.

Theorem 1 *The complete theory $T_{\mathbb{R},roots}$ of $\mathbb{C}_{\mathbb{R},roots}$ is given by the following axioms:*

1. *The universe F has a field structure, $F = R + iR$ with $i^2 = -1$ and R a real closed field;*

2. *U is a multiplicative divisible subgroup of F with n-torsion isomorphic to the cyclic group of order n;*

3. *for any $a \in U$ the unique representation*

$$a = s + it, \quad s, t \in R$$

   yields $s^2 + t^2 = 1$;

4. *the projection $\mathrm{pr}\ U$ of U on the 'real' axis R is dense in $[-1, 1]$, that is, for any $-1 \leq a < b \leq 1$ we have $(a, b) \cap \mathrm{pr}\ U \neq \emptyset$;*

5. *Lang's property holds for U, that is*

   for every polynomial $p(x_1, \ldots, x_n)$ over $\mathbb{Q}(U_0)$ there is a finite collection of cosets $S_1, \ldots, S_k$ of algebraic subgroups of $(F^*)^n$ given by finite system of equations of the form

$$x^m = \gamma_m$$

   for non-trivial monomials x^m and elements $\gamma_m \in U_0$ such that

$$\{a \in U^n : \ p(a) = 0\} = \bigcup_i S_i \cap U^n;$$

6. $R \setminus \mathrm{acl}(U)$ *is dense in* R, *that is for any* $a < b$ *in* R *and any semi-algebraic function* $f : (0,1)^n \to R$ *(with parameters)*

$$(a,b) \setminus f((\mathrm{pr}\ U)^n) \neq \emptyset.$$

The proof of the theorem follows from the lemmas below.

We write T for $T_{\mathbb{R},\mathrm{roots}}$.

Lemma 0.1 *Let* F *be a model of* T *and* A *a multipicatively independent over* U_0 *subset of* $U(F)$.

Then A *is algebraically independent over* U_0 *in the field theoretic sense.*

Proof Immediate from Lang's property. $\square$

Now let F and E be models of T. By Jonsson's theory there are saturated models $F' \succ F$ and $E' \succ E$ of some cardinality κ (with $2^\mu < \kappa$ for any $\mu < \kappa$) we may assume that $F' = F$ and $E' = E$ and want to prove that $F \cong E$.

Lemma 0.2 *Let* μ *be an ordinal less than* κ, $A_\mu \cup A^*_\mu$ *be a subset of* $R(F)$ $A^*_\mu \subseteq \mathrm{pr}\ U(F)$, $A_\mu \subseteq R(F)$, $\mathrm{card}\ A_\mu \leq |\mu|$, $\mathrm{card}\ A^*_\mu \leq |\mu|$, *such that*

(i) $A^*_\mu \subseteq \mathrm{pr}\ U(F)$ *is algebraically independent;*

(ii) A_μ *is algebraically independent over* $U(F)$.

Then

(a) $\mathrm{pr}\ U(F) \setminus \mathrm{acl} A^*_\mu \neq \emptyset$

(b) $R(F) \setminus \mathrm{acl}(U(F) \cup A_\mu) \neq \emptyset$

and

(c) for any $a^*_\mu \in \mathrm{pr}\ U(F) \setminus \mathrm{acl} A^*_\mu$ *and* $a_\mu \in R(F) \setminus \mathrm{acl}(U(F) \cup A_\mu)$ *the new sets* $A^*_{\mu+1} = A^*_\mu \cup \{a^*_\mu\}$ *and* $A_\mu = A_\mu \cup \{a_\mu\}$ *satisfy properties (i) and (ii).*

Proof (a) follows by saturatedness from the fact that $\mathrm{pr}\ U(F)$ is infinite.

(b) follows by saturatedness from axiom 6.

(c) is obvious from assumptions. $\square$

Corollary 1 *There exists a transcendence basis of F of the form $A \cup A^*$ with $A^* \subseteq \mathrm{pr}\ U(F)$, $A \subseteq R(F)$, $\mathrm{pr}\ U(F) \subseteq \mathrm{acl}A^*$, $\mathrm{card}\ A = \mathrm{card}\ A^* = \kappa$.*

For $X \subseteq R$ we denote $\mathrm{dcl}X$ the definable closure of X in the $(R, +, \times)$. We notice that dcl is just the closure under all semi-algebraic functions, that is the functions 0-definable in the formal reals.

We say that a bijection ϕ between subsets A and B of R is a semi-algebraic isomorphism if there is an extension of ϕ to a bijection $\phi : \mathrm{dcl}A \to \mathrm{dcl}B$ preserving semi-algebraic functions and $<$.

Lemma 0.3 *There exist transcendence bases $\tilde{A} \cup \tilde{A}^* \subseteq R(F)$ and $\tilde{B} \cup \tilde{B}^* \subseteq R(E)$ of F and E correspondingly with $\tilde{A}^* \subseteq \mathrm{pr}\ U(F)$, $\tilde{B}^* \subseteq \mathrm{pr}\ U(E)$, transcendence bases of $\mathrm{pr}\ U$ and a semi-algebraic isomorphism $\phi : \tilde{A} \cup \tilde{A}^* \to \tilde{B} \cup \tilde{B}^*$ such that $\phi(\tilde{A}) = \tilde{B}$.*

Proof Let

$$A \cup A^* = \{a_i : i < \kappa\} \cup \{a_i^* : i < \kappa\}$$

and

$$B \cup B^* = \{b_i : i < \kappa\} \cup \{b_i^* : i < \kappa\}$$

be transcendence bases of F and E correspondingly constructed by Corollary 1.

We construct $\tilde{A} \cup \tilde{A}^*$, $\tilde{B} \cup \tilde{B}^*$ and ϕ by transfinite induction.

Suppose that for $\mu < \kappa$

$$\tilde{A}_\mu \cup \tilde{A}_\mu^* = \{\tilde{a}_i : i < \mu\} \cup \{\tilde{a}_i^* : i < \mu\}$$

and

$$\tilde{B}_\mu \cup \tilde{B}_\mu^* = \{\tilde{b}_i : i < \mu\} \cup \{\tilde{b}_i^* : i < \mu\}$$

have been constructed with ϕ_μ given by the enumeration and

$$\mathrm{acl}(\tilde{A}_\mu \cup \tilde{A}_\mu^*) \supseteq \{a_i : i < \mu\} \cup \{a_i^* : i < \mu\}$$

and

$$\mathrm{acl}(\tilde{B}_\mu \cup \tilde{B}_\mu^*) \supseteq \{b_i : i < \mu\} \cup \{b_i^* : i < \mu\}.$$

By back-and-forth method it is enough to show that by letting $\tilde{a}^*_\mu$ equal to the first element of $A^* \smallsetminus \mathrm{acl}\tilde{A}^*_\mu$ and $\tilde{a}_\mu$ equal to the first element of $A \smallsetminus \mathrm{acl}(\mathrm{pr}\ U(F) \cup \tilde{A}_\mu)$ we can extend the isomorphism ϕ to $\tilde{A}_{\mu+1} \cup \tilde{A}^*_{\mu+1}$.

Denote $p^*_{\mu,A}$ the semi-algebraic type of $\tilde{a}^*_\mu$ over $\tilde{A}_\mu \cup \tilde{A}^*_\mu$ and $p^*_{\mu,B}$ the corresponding type over $\tilde{B}_\mu \cup \tilde{B}^*_\mu$. Notice that the types are given by collections of formulas of the form $f_1 < x < f_2$ for f_1, f_2 semi-algebraic terms over the parameters. Since the parameters of the two types are semi-algebraically conjugated, by elimination of quantifiers in real closed fields, $p^*_{\mu,B}$ is consistent. Also the type contains the condition $-1 < x < 1$ for its variable x. Since the projection pr (U) of U on R is dense in $[-1,1]$ and $p^*_{\mu,B}(R)$ is an intersection of intervals, the type is consistent with $x \in$ pr (U). By saturatedness we find $\tilde{b}^*_\mu \in U(E)$ realising $p^*_{\mu,B}$.

Now let $p_{\mu,A}$ be the semi-algebraic type of $\tilde{a}_\mu$ over $\tilde{A}^*_{\mu+1} \cup \tilde{A}_\mu$ and $p_{\mu,B}$ the correspondent type in E. Again, $p_{\mu,B}(R)$ is a given as an intersection of intervals. By axiom 6 this is finitely consistent with the collection of formulas saying that $x \notin \mathrm{acl}(U \cup \tilde{A}^*_{\mu+1} \cup \tilde{A}_\mu)$. Hence by saturatedness there exists

$$\tilde{b}_\mu \in R(F) \cap p_{\mu,B}(F) \smallsetminus \mathrm{acl}(U(F) \cup \tilde{A}^*_{\mu+1} \cup \tilde{A}_\mu).$$

$\square$

Proof of the Theorem. We extend the isomorphism ϕ of the bases of F and E of Lemma 0.3 can be extended to a semi-algebraic isomorphism $\bar{\phi} : F \to E$. Now let $A^U = \{a + i\sqrt{1-a^2} :\ a \in \tilde{A}^*\}$. Obviously $A^U \subseteq U(F)$ and is a maximal algebraically independent subset of $U(F)$. By Lemma 0.1 A^U is a maximal multiplicatively independent subset of $U(F)$.

Denote $G(A)$ the group generated by A^U and all the roots of any power of elements of A^U (the divisible hull of A^U. By definitions $G(A) = U(F)$. Define B^U and $G(B)$ similarly. $\bar{\phi}$ extends uniquely to a semi-algebraic isomorphism $A^U \to B^U$ and hence to $U(F) \to U(E)$. Further on we have a unique extension to a semi-algebraic isomorphism $\bar{\phi} : F \to E$. Since $\bar{\phi}$ preserves U, R and the field structure, we have the required isomorphism between the two models of T.$\square$

We now want to see $\mathbb{C}_{R,\mathrm{roots}}$ as a structure definable naturally in the reals. Let L^U be the definable extension of the language of the field of reals (including $<$) which contains a name $P_{f,k}(x_1,\ldots,x_m,y)$ for each definable predicate on R of the form

$$\exists v_1,\ldots,v_k \bigwedge_{i\le k} v_i\in \mathrm{pr}\, U \;\&\; y=f(x_1,\ldots,x_m,v_1,\ldots,v_k)$$

where f is a semi-algebraic function on R.

Notice that when $k=0$, $P_{f,k}(x_1,\ldots,x_m,y)$ is just a graph of f.

On the other hand, for $m=0$, $k=1$ and $f=\mathrm{id}$,

$$P_{\mathrm{id}}(y) \text{ iff } y\in \mathrm{pr}\, U,$$

and thus $U\subseteq R^2$ is definable in L^U. So $\mathbb{R}$ in the language L^U is essentially the same structure as $\mathbb{C}_{R,\mathrm{roots}}$.

Theorem 2 *$T_{\mathbb{R},\mathrm{roots}}$ has elimination of quantifiers in the language L^U.*

Proof

Claim. For any $\bar a$, a tuple in a model F of T, the L^U-quantifier-free type $q=$qftp$(\bar a)$ of the tuple is a complete type.

The theorem follows by compactness from the claim.

To prove the claim we assume that F is saturated and show that if $\bar b$ is a tuple satisfying q in any other saturated model E of the same cardinality, then there is an isomorphism $F\to E$ sending $\bar a$ to $\bar b$.

Up to enumeration we can assume that $\bar a=\langle a_1,\ldots,a_n\rangle$ with $\{a_1,\ldots,a_l\}$ algebraically independent over pr $U(F)$ and for each $i\in\{l+1,\ldots,n\}$, $P_{f_i,k}(a_1,\ldots,a_l,a_i)$ holds for some semi-algebraic f_i and some $k>0$. This effectively means that for some $a_1^*,\ldots,a_k^*\in \mathrm{pr}\, U(F)$ we have $a_i=f_i(a_1^*,\ldots,a_k^*,a_1,\ldots,a_l)$. By choosing k minimal possible we get $a_1^*,\ldots,a_k^*$ algebraically independent. Since l, the minimal k and corresponding f_i are all invariants of type q we have similar $\{b_1,\ldots,b_l,b_1^*,\ldots,b_k^*\}$ for $\bar b$.

Thus we can start the construction of bases by Lemma 0.2 by letting $A_l=\{a_1,\ldots,a_l\}$, $A_l^*=\{a_1^*,\ldots,a_k^*\}$ (assuming $l\ge k$) and $B_l=\{b_1,\ldots,b_l\}$, $B_l^*=\{b_1^*,\ldots,b_k^*\}$. Then the construction of Lemma 0.3 extends $A_l\cup A_l^*$

and $B_l \cup B_l^*$ to isomorphic bases and we can finish by an isomorphism of the structures as in the proof of Theorem 1. The ismomorphism $\phi : F \to E$ sending $\langle a_1^*, \ldots, a_k^*, a_1, \ldots, a_l \rangle$ to $\langle b_1^*, \ldots, b_k^*, b_1, \ldots, b_l \rangle$ we have thus constructed uniquely determines that $\phi(\bar{a}) = \phi(\bar{b})$, since type q tells how the tuple is coordinatised by the basis via semi-algebraic functions. This proves the claim and the theorem. □

References

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