ABOUT HERMAN AUERBACH’S PROBLEM ON FACTORS OF REAL POLYNOMIALS WITH CONNECTED ZERO SET COMPLEMENT

J. MAURICE ROJAS

In memory of Herman Auerbach, 26 October 1901 – 17 August 1942.

1. Introduction. Between September 4 and November 6 in 1936 Herman Auerbach posed...

Problem #148. Let \( P(x_1, \ldots, x_n) \) denote a polynomial with real coefficients. Consider the set of points defined by the equation \( P(x_1, \ldots, x_n) = 0 \). A necessary and sufficient condition for this set not to cut the Euclidean (real) space is: All the irreducible factors of the polynomial \( P \) in the real domain should be always nonnegative or always nonpositive.

We will interpret “not to cut” to mean that the real zero set of \( P \) has (non-empty) path-connected complement. We are unaware of any published solution to Problem #148 so we provide a self-contained solution below, using a reduction to...

Lemma 1.1. If \( Q \in \mathbb{R}[x_1, x_2] \) and each irreducible factor of \( Q \) (in \( \mathbb{R}[x_1, x_2] \)) is either always nonnegative on \( \mathbb{R}^2 \) or always nonpositive on \( \mathbb{R}^2 \) then the complement of the real zero set of \( Q \) is path-connected.

The example \((x_1 − x_2)^2\) shows the necessity of the sign condition on the irreducible factors.

2. From Auerbach’s Problem to Recent Research. Problem #148 naturally leads to important recent directions in algorithmic algebraic geometry: Polynomial factorization leads us naturally to the decomposition of algebraic sets in \( \mathbb{R}^n \) (and \( \mathbb{C}^n \)) into irreducible components and further fundamental topological questions. Nonnegativity leads us to optimization, sums of squares, and polynomial system solving.

Algorithms that are practical and efficient (as of early 2015) for multivariate polynomial factorization over \( \mathbb{C} \) are detailed in [Gao03, CL07]. Algorithms that take numerical instability into account (in the coefficients and/or the final answer) appear in [SVW04, Che04, GMYZ04, KMYZ08, Zen09]. Definitive references for background on algebraic sets (over \( \mathbb{R} \) and/or \( \mathbb{C} \)), and algorithms for determining their topological structure, include [BCR98, SW05, BPR10].

To date, all general algorithms for factoring univariate polynomials over \( \mathbb{R} \) have complexity super-linear in the degree. However, since a univariate polynomial with exactly \( t \) monomial terms has at most \( 2t − 1 \) real roots — a bound independent of the degree, thanks to Descartes’ Rule — one can ask for faster algorithms to at least count the degree 1 factors. Such algorithms, with complexity polynomial in the logarithm of the degree, were found in [BRS09, BHPR11, Sag14]. (Good bit complexity appears much more difficult to attain than good arithmetic complexity in this setting.) In the bivariate case, deciding whether an input degree 1 polynomial divides an input sparse polynomial can also be done in time polynomial in the logarithm in the degree [Ave09]. A deeper discussion of the role of sparsity in real analytic geometry can be found in [Kho91] and a remarkable connection to the \( \textbf{P} \) vs. \( \textbf{NP} \) problem can be found in [KPT15].

While nonnegative univariate polynomials are always sums of squares of polynomials, Theodore Motzkin observed in 1967, via the concrete example \( x_1^4x_2^2 + x_1^2x_2^4 \) \(-\) \( 3x_1^2x_2^2 + 1 \), that this equivalence fails for multivariate polynomials. The relationship between nonnegativity and sums of squares was advanced by Hilbert and Artin and, more recently, quantitative

\date{March 27, 2015.}

\textit{Key words and phrases.} exponential sum, amoeba, Hausdorff distance, tropical variety, complexity, metric.

Partially supported by NSF grant CCF-1409020.
estimates have been derived for how often nonnegative polynomials are sums of squares of polynomials. Such estimates are important because, when a polynomial is a sum of squares, its minimum can be found efficiently via semi-definite programming. This beautiful intersection of optimization, real algebraic geometry, and convexity is detailed in [BPT12] and the references therein.

3. Reducing Auerbach’s Problem to a Simplified Bivariate Case. Our key reduction to Lemma 1.1 hinges on the following fact:

**Lemma 3.2.** (Special case of [Sch00, Thm. 17, Pg. 75, Sec. 1.9]) Suppose \( x_1, \ldots, x_n, w_1, \ldots, w_{n-1}, y_1, \ldots, y_{n-1} \) are algebraically independent indeterminates and \( P \in \mathbb{R}[x_1, \ldots, x_n] \setminus \mathbb{R}[x_1] \) is irreducible in \( \mathbb{R}[x_1, \ldots, x_n] \). Then there is a polynomial \( \Phi \in \mathbb{R}[w_1, \ldots, w_{n-1}, y_1, \ldots, y_{n-1}] \setminus \{0\} \) with the following property: If \( \alpha_2, \beta_2, \ldots, \alpha_n, \beta_n \in \mathbb{R} \) and \( \Phi(\alpha_2, \ldots, \alpha_n, \beta_2, \ldots, \beta_n) \neq 0 \) then \( P(x_1, \alpha_2 x_2 + \beta_2, \ldots, \alpha_n x_2 + \beta_n) \) is irreducible in \( \mathbb{R}[x_1, x_2] \).

**Solution to Problem #148:** The case \( n = 1 \) follows immediately upon observing that, up to real affine transformations, the only irreducible non-constant polynomials in \( \mathbb{R}[x_1] \) are \( x_1 \) and \( x_1^2 + 1 \). So assume \( n \geq 2 \) and let \( Z \) be the zero set of \( P \) in \( \mathbb{R}^n \).

**(Sufficiency):** Suppose each irreducible factor of \( P \) is either always nonnegative on \( \mathbb{R}^n \) or always nonpositive on \( \mathbb{R}^n \). Let \( u = (u_1, \ldots, u_n) \) and \( v = (v_1, \ldots, v_n) \) be any two distinct points in \( \mathbb{R}^n \setminus Z \). Since \( Z \) is closed, \( u \) (resp. \( v \)) in fact lies in an open neighborhood \( U \) (resp. \( V \)) of points contained in the same connected component of \( \mathbb{R}^n \setminus Z \) as \( u \) (resp. \( v \)). Since the complement of any real algebraic hypersurface is open, Lemma 3.2 implies we can find \( \alpha_2, \beta_2, \ldots, \alpha_n, \beta_n \) such that the specialization \( Q(x_1, x_2) := P(x_1, \alpha_2 x_2 + \beta_2, \ldots, \alpha_n x_2 + \beta_n) \) satisfies:

(a) each irreducible factor \( P_i \) of \( P \) specializes to an irreducible factor \( Q_i \) of \( Q \) and (b) \( P_i \) is nonnegative on all of \( \mathbb{R}^n \) (resp. nonpositive on all of \( \mathbb{R}^n \)) if and only if \( Q_i \) is nonnegative on all of \( \mathbb{R}^2 \) (resp. nonpositive on all of \( \mathbb{R}^2 \)). In particular, the condition \( \Phi \neq 0 \) from Lemma 3.2 enables us to pick \( (\beta_2, \ldots, \beta_n) \) arbitrarily close to \((u_2, \ldots, u_n)\), and \((\alpha_2, \ldots, \alpha_n)\) arbitrarily close to \((v_2 - u_2, \ldots, v_n - u_n)\), so that both \( Q(u_1, 0) \) and \( Q(v_1, 1) \) are nonzero.

Let \( W \) denote the zero set of \( Q \) in \( \mathbb{R}^2 \) and note that

\[
H := \{(x_1, \alpha_2 x_2 + \beta_2, \ldots, \alpha_n x_2 + \beta_n) \mid (x_1, x_2) \in \mathbb{R}^2 \subset \mathbb{R}^n \}
\]

is a real 2-plane with the pair \( (H, H \cap Z) \) affinely equivalent to \( (\mathbb{R}^2, W) \). By Lemma 1.1 (and Conditions (a) and (b)), \( \mathbb{R}^2 \setminus W \) is path-connected, and thus \( H \setminus Z \) is path-connected. Moreover, by our choice of the \( \alpha_i \) and \( \beta_i \), both \( U \) and \( V \) intersect \( H \setminus Z \). So \( U \) and \( V \), and thus \( u \) and \( v \), are connected by a path in \( \mathbb{R}^n \setminus Z \).

**(Necessity):** Suppose now that \( \mathbb{R}^n \setminus Z \) is path-connected, but \( P \) has an irreducible factor \( P_i \) attaining both positive and negative values on \( \mathbb{R}^n \). Then \( P_i \) must be positive (resp. negative) at some point \( u_+ \) (resp. \( u_- \)) in \( \mathbb{R}^n \setminus Z \) since \( \mathbb{R}^n \setminus Z \) is open. By assumption, there is a path in \( (\gamma : [0, 1] \rightarrow \mathbb{R}^n \setminus Z \) connecting \( u_+ \) and \( u_- \). In particular, \( P_i(\gamma(0))P_i(\gamma(1)) < 0 \), so by the Intermediate Value Theorem, \( P_i(\gamma(s)) = 0 \) for some \( s \in (0, 1) \). In other words, \( \gamma([0, 1]) \) intersects \( Z \), which is a contradiction.

One can give a much shorter solution to Auerbach’s Problem, applying to arbitrary real-closed fields as well: Combine a higher-dimensional version of Proposition 3.3 below with [BCR98, Thm. 4.5.1]. The latter result, on real principal ideals, dates back to [DE70].
Our solution of Problem #148 is more elementary and, under Auerbach’s sign condition on irreducible factors, leads to the following construction for a path connecting any distinct \( u, v \in \mathbb{R}^n \setminus \mathbb{Z} \): Pick a random \( w \in \mathbb{R}^n \) and let \( \Gamma \) be the path obtained by joining the line segments \( uw \) and \( vw \). Then \( \Gamma \) lies in \( \mathbb{R}^n \setminus \mathbb{Z} \) with probability 1 (with respect to any bounded, continuous positive probability measure) or high probability (with respect to the uniform measure on \( \{-N, \ldots, N\}^n \) for \( N \) sufficiently large). This can be made precise by observing that the polynomial \( \Phi \) from Lemma 3.2 has degree \( O(d^2) \) (see, e.g., [Lec07, Thm. 6]).

To prove Lemma 1.1 we will apply the following two facts:

**Proposition 3.3.** If \( X \subset \mathbb{R}^2 \) is finite then \( \mathbb{R}^2 \setminus X \) is path connected. Moreover, we can connect any two points of \( \mathbb{R}^2 \setminus X \) with a smooth quadric curve \( \Gamma \subset \mathbb{R}^2 \setminus X \). ■

**Lemma 3.4.** Suppose \( f, g \in \mathbb{C}[x_1, x_2] \) have respective degrees \( d \) and \( e \), and no common factor of positive degree. Then \( f = g = 0 \) has no more than \( de \) solutions in \( \mathbb{C}^2 \). ■

Proposition 3.3 follows easily by using an invertible affine map to reduce to the special case of connecting \((0,0)\) and \((1,0)\) via the graph of \( cx_1(1-x_1) \) for suitable \( c \). The finiteness of \( X \) guarantees that all but finitely many \( c \) will work. Lemma 3.4 is a special case of Bézout’s Theorem (see, e.g., [Sha94]) but can also be easily derived from the basic properties of the univariate resultant (see, e.g., [Sch00, App. B]).

**Proof of Lemma 1.1:** Let \( W \) denote the real zero set of \( Q \) in \( \mathbb{R}^2 \). By Proposition 3.3 it clearly suffices to prove that, under the hypotheses of Lemma 1.1, \( W \) is finite. It clearly suffices to restrict to the special case where \( Q \) is non-constant and irreducible in \( \mathbb{R}[x_1, x_2] \). Note also that the irreducibility of \( Q \) and the assumption on the sign of \( Q \) are invariant under composition with any invertible real affine map.

Consider now any root \( \zeta = (\zeta_1, \zeta_2) \in \mathbb{R}^2 \) of \( Q \). If \( \delta := \begin{pmatrix} \frac{\partial Q}{\partial x_1}(\zeta) \ & \frac{\partial Q}{\partial x_2}(\zeta) \end{pmatrix} \neq 0 \) then, by composing with a suitable invertible real affine map, we may assume \( \delta = (1,0) \). In particular, by Taylor expansion, we see that \( Q \) changes sign in a non-empty horizontal line segment containing \( \zeta \). Therefore, every root of \( Q \) must satisfy \( \frac{\partial Q}{\partial x_1}(\zeta) = \frac{\partial Q}{\partial x_2}(\zeta) = 0 \).

Let \( Q_1, \ldots, Q_r \) be the factorization of \( Q \) over \( \mathbb{C}[x_1, x_2] \) into factors of positive degree, irreducible in \( \mathbb{C}[x_1, x_2] \). The Galois group \( G := \text{Gal}(\mathbb{C}/\mathbb{R}) \) has order 2, is generated by complex conjugation \((\cdot) \), and acts naturally on the \( Q_i \). In particular, \( G \) acts trivially on \( Q_i \) if and only if \( Q_i \in \mathbb{R}[x_1, x_2] \). So \( r \) must be even when \( r \geq 2 \), since \( Q \) is irreducible over \( \mathbb{R}[x_1, x_2] \). Furthermore, \( r \leq 2 \) since \( Q_i \bar{Q}_i \) is invariant under complex conjugation. So we either have \( r = 1 \) (with \( Q \) irreducible over \( \mathbb{C}[x_1, x_2] \)) or \( r = 2 \) (with \( Q_1 \neq Q_1 = Q_2 \neq Q_2 \)). A simple calculation then shows that, in either case, \( \frac{\partial Q}{\partial x_1} \) has no common factors with \( Q \). So \( W \) is finite by Lemma 3.4. ■

**Acknowledgements** I am grateful to Dan Mauldin for his invitation to write this brief commentary and Joe Buhler for bringing Auerbach’s problem to my attention. I also thank Zbigniew Szafraniec, Michel Coste, and Marie-Francoise Roy for pointing out [BCR98, Thm. 4.5.1]; and Guillaume Chèze and Erich Kaltofen for help with tracking down references to the fastest current factoring algorithms.

**References**


Department of Mathematics, Texas A&M University TAMU 3368, College Station, Texas 77843-3368, USA.

E-mail address: rojas@math.tamu.edu