PROBLEMS AND EXERCISES

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1. Total degree and polyhedral homotopies

1.1. Conics in the plane. Consider the total degree family $\mathcal{F}(2,2)$, i.e. $n = 2$ and $(d_1, d_2) = (2, 2)$.

$$\mathcal{F}(2,2) = \begin{pmatrix} f_1 \\ f_2 \end{pmatrix} = \begin{pmatrix} a_{00} + a_{10}x + a_{01}y + a_{20}x^2 + a_{11}xy + a_{02}y^2 \\ b_{00} + b_{10}x + b_{01}y + b_{20}x^2 + b_{11}xy + b_{02}y^2 \end{pmatrix}$$

What is $\mathcal{N}_{\text{Béz}}$ in this example? Verify this by solving a random member of this family using `HomotopyContinuation.jl`.

There are strictly less than $\mathcal{N}_{\text{Béz}}$ solutions in the following two scenarios.

- Two or more solutions *coincide*. This happens if there are solutions to the overdetermined system

$$f_1 = f_2 = \det \begin{pmatrix} f_{1x} & f_{1y} \\ f_{2x} & f_{2y} \end{pmatrix} = 0 \quad \text{has a solution.}$$

  Prove (possibly using a computer algebra system) that this is equivalent to the vanishing of a nonzero polynomial in the coefficients of f_1, f_2. This polynomial is called the *discriminant*.
- there are solutions *at infinity*. To make this precise, we homogenize the equations:

$$\begin{pmatrix} a_{00}z^2 + a_{10}xz + a_{01}yz + a_{20}x^2 + a_{11}xy + a_{02}y^2 \\ b_{00}z^2 + b_{10}xz + b_{01}yz + b_{20}x^2 + b_{11}xy + b_{02}y^2 \end{pmatrix},$$

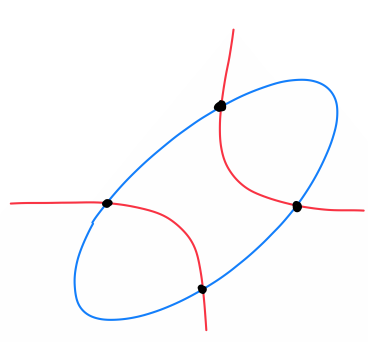

Figure 1. Two *generic* conics in the plane.

and consider solutions with $z = 0$. Geometrically, we replace our conics by their closures in $\mathbb{P}^2$. Show that there are solutions 'at infinity' if and only if

$$\det A_\infty = \det \begin{pmatrix} a_{20} & a_{11} & a_{02} & \\ & a_{20} & a_{11} & a_{02} \\ b_{20} & b_{11} & b_{02} & \\ & b_{20} & b_{11} & b_{02} \end{pmatrix} = 0.$$

What about the case where $f_1 = f_2 = 0$ has infinitely many solutions?

Construct two members of $\mathcal{F}(2,2)$ with 3 solutions, one with a solution at infinity, and one with a solution of multiplicity 2. Verify using `HomotopyContinuation.jl`.

1.2. **Systems supported on the square.** Consider the subfamily

$$\mathcal{F}_Q = \begin{pmatrix} f_1 = a_{00} + a_{10}x + a_{10}y + a_{11}xy \\ f_2 = b_{00} + b_{10}x + b_{10}y + b_{11}xy \end{pmatrix} \subset \mathcal{F}(2,2).$$

Use the previous exercise to show that $\mathcal{N}(Q) < \mathcal{N}_{\text{Béz}}$. Verify the formula $\text{MV}(P_1, P_2) = \text{Vol}_2(P_1 + P_2) - \text{Vol}_2(P_1) - \text{Vol}_2(P_2)$ for $P_1 = P_2 = [0,1]^2 \subset \mathbb{R}^2$. More generally, compute $\text{MV}(P_1, \ldots, P_n)$ with $P_i = [0,1]^n \subset \mathbb{R}^n$ for all i. This corresponds to a sparse family $\mathcal{F}_Q \subset \mathcal{F}(n, \ldots, n)$. Compare $\mathcal{N}(Q)$ for these systems with their Bézout number. For some n, solve a generic member of $\mathcal{F}_Q$ using a total degree and a polyhedral start system in `HomotopyContinuation.jl`.

1.3. **Asymptotic BKK and Bézout numbers.** This is an example taken from [Huber-Sturmfels]. Consider the family

$$\begin{pmatrix} a_1 + a_2 x + a_3 x^k y^k \\ b_1 + b_2 y + b_3 x^k y^k \end{pmatrix} \subset \mathcal{F}(2k, 2k).$$

Show that $\lim_{k\to\infty}(\mathcal{N}_{\text{BKK}}/\mathcal{N}_{\text{Béz}}) = 0$. Compare the computation time for the function `solve` in `HomotopyContinuation.jl` using the default option (`start_system = :polyhedral`) and the option `start_system = :total_degree` for random coefficients a, b and increasing values of k.

1.4. **Toric varieties and the BKK theorem.** Let $\mathcal{A} = \{\alpha_1, \ldots, \alpha_r\} \subset \mathbb{N}^n$ be a set of exponents such that $P = \text{Conv}(\mathcal{A})$ has dimension n. The *projective toric variety* $X_{\mathcal{A}}$ associated to $\mathcal{A}$ is the Zariski closure of the image of the monomial map

$$(x_1, \ldots, x_n) \mapsto (x^{\alpha_1} : \cdots : x^{\alpha_r}) \in \mathbb{P}^{r-1}.$$

Use the BKK theorem to relate the degree of $X_{\mathcal{A}}$ to the volume of P. The statement you obtain is known is *Kushnirenko's theorem*, which can be seen as a specialized version of the BKK theorem for *unmixed systems of equations*, for which $\mathcal{A}_i = \mathcal{A}, i = 1, \ldots, n$.

1.5. **Puiseux series solutions.** Consider the polynomial $f = tx^3 + 2x^2 + t \in K[x]$, where K is the field of Puiseux series with complex coefficients in the variable t. Compute the leading term of all solutions $x \in K$ to $f = 0$. That is, compute all possible $X \in \mathbb{C} \setminus \{0\}$ and $e \in \mathbb{Q}$ such that there is a solution $x(t) = Xt^e +$ higher order terms satisfying $f(x(t), t) = 0$.

Hint: substitute $x(t) = Xt^e +$ higher order terms in $f(x(t), t)$ and look for all exponents e for which at least two terms of $f(x(t), t)$ are of lowest order in t. Obtain X from the condition that these lowest order terms cancel. Can you give a graphical interpretation of the numbers e in terms of the Newton polygon of f?

1.6. **Solving binomial systems is easy.** Consider the system of equations over the field K of complex Puiseux series in t:

$$F = \begin{pmatrix} 1 + 2x^2y + 3xy^2 \\ 5 + 2tx + 4ty + 6txy \end{pmatrix} = 0.$$

How many solutions $(x(t), y(t))$ do you expect? Check that there exists a solution of the form $x(t) = Xt^{-1} +$ higher order terms and $y(t) = Yt^2 +$ higher order terms, where (X, Y) is the solution of

$$1 + 2X^2Y = 5 + 2X = 0.$$

Find $e_1, e_2 \in \mathbb{Q}$ such that $x(t) = Xt^{e_1} +$ higher order terms and $y(t) = Yt^{e_2} +$ higher order terms gives a solution for each $(X, Y) \in (\mathbb{C} \setminus \{0\})^2$ satisfying

$$2X^2Y + 3XY^2 = 5 + 6XY = 0.$$

To solve this *system of binomial equations*, we write it in the form

$$XY^{-1} = -3/2, \quad XY = -5/6. \tag{1.1}$$

We collect the exponent vectors in the columns of a matrix $A = \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix}$. There exist matrices $P, Q \in \mathbb{Z}^{2\times 2}$ with an inverse defined over Z (i.e. P and Q are *unimodular*) which diagonalize A

$$PAQ = \begin{pmatrix} s_1 & \\ & s_2 \end{pmatrix}. \tag{1.2}$$

This diagonal matrix is called the *Smith normal form* of A. Denote p_{ij}, q_{ij} for the entries of P and Q respectively. Show that the map $(\mathbb{C} \setminus \{0\})^2 \to (\mathbb{C} \setminus \{0\})^2$ given by

$$(U, V) \mapsto (U^{p_{11}}V^{p_{21}}, U^{p_{12}}V^{p_{22}})$$

is invertible. Use this change of coordinates on $(\mathbb{C} \setminus \{0\})^2$ and the identity (1.2) to reduce (1.1) to an equivalent system of equations

$$U^{s_1} = c_1, \qquad V^{s_2} = c_2.$$

Deduce that the number of solutions of (1.1) is $\det A$. Can you write down an algorithm for solving a system of binomial equations in the form (1.1) with exponent matrix $A \in \mathbb{Z}^{n\times n}$?

We have now found the leading term of 3 solutions to $F = 0$. Can you find the missing solution(s) as well?

2. Monodromy

Let $F_c(x)$ be a zero-dimensional parametrized polynomial system with variables $x_1, \ldots, x_n$ and parameters $c_1, \ldots, c_k$. Let $Z \xrightarrow{\pi} \mathbb{C}^k$ be the branched cover where $Z = \{(x, p) | F_p(x) = 0\}$ and $\pi : Z \to \mathbb{C}^k$ is the projection onto the parameters. Let d be the degree of this branched cover. Let U be the set of regular values of π and G_π the monodromy group based at some point $p \in U$.

(1) Show G_π is a group.
(2) Show G_π doesn't depend on the choice of $p \in U$ where you base monodromy loops.
(3) Show G_π is transitive if and only if Z has a unique irreducible component of maximal dimension.
(4) Explain why G_π being transitive is exactly the condition which allows `monodromy solve` to find all solutions to $\pi^{-1}(p)$.

(5) Suppose G_π is transitive. Show that G_π is 2-transitive if and only if the variety
$$\{(x_1, x_2, p) \mid x_1, x_2 \in \pi^{-1}(p), p \in \mathbb{C}^k\}$$
has two maximal dimensional irreducible components

(6) Suppose $F_c(x)$ is defined over the real numbers. Is it possible for a real path in U to produce a nontrivial monodromy permutation? Under which conditions can this happen?

(7) As explained in previous lectures, solving a system $G(x) = 0$ using homotopy methods requires one to embed $G(x)$ into a family of polynomial systems $F_c(x)$. Does the ability to solve $G(x)$ using monodromy depend on which family is chosen?

3. Witness Sets

(1) Prove the trace test for plane curves.

Hint: for one direction, it is useful to know that the monodromy group
$$\{(x, L) \mid x \in X \cap L\} \xrightarrow{\pi} \mathrm{Gr}(2,3)$$
$$(x, L) \mapsto L$$
is the full symmetric group

(2) Compute a witness set for
$$\mathrm{SO}(5) = \{M \in \mathrm{Mat}_{\mathbb{C}}(5, 5) \mid MM^T = \mathrm{id}, \det(M) = 1\}$$

(3) How many maximal dimensional irreducible components does
$$\mathrm{HSO}(4) = \{M \in \mathrm{Mat}_{\mathbb{C}}(4, 4) \mid MM^T = \mathrm{id}, \det(M) = 1, M_{i,i} = 0 \text{ for all } i\}$$
have? What are their degrees? How do they intersect?

(4) The Lüroth hypersurface $\mathfrak{L}$ is the hypersurface in the space of plane quartics parameterized by
$$(\mathbb{C}^3)^5 \to \mathbb{P}^{15}$$
$$(\ell_1, \ell_2, \ell_3, \ell_4, \ell_5) \mapsto \sum_{i=1}^{5} \prod_{j \neq i} \ell_j \text{ where } \ell_i = a_i x + b_i y + c_i$$
Compute a witness set for $\mathfrak{L}$. What is its degree?

4. Other

(1) A conic is the zero set of a quadratic polynomial
$$c(x, y) = a_1 x^2 + a_2 xy + a_3 y^2 + a_4 x + a_5 y + a_6$$
with $a_i \in \mathbb{C}$.

Emiris and Tzoumas showed that there are 184 complex circles that are tangent to 3 general conics C_1, C_2 and C_3. This means, that there are 184 complex solutions (a_1, a_2, r) such that there exists some $(x, y) \in \mathbb{C}^2$ with

$(x - a_1)^2 + (y - a_2)^2 = r$

$(x, y) \in C_i$ for $\leq i \leq 3$

$(x - a_1, y - a_2)$ spans the normal space of C_i at (x, y) for $1 \leq i \leq 3$.

(a) Define the polynomial system for 3 general conics and verify that this system has indeed 184 solutions. Use certification.

(b) Consider the three conics

$$\begin{aligned} C_1 &= \{y = -x^2 + 2x + 5\}, \\ C_2 &= \{y = 2x^2 + 5x - 8\}, \\ C_3 &= \{y = 8x^2 - 3x - 2\}. \end{aligned}$$

How many circles are tangent to these 3 conics? How many of them are real?

(c) Find a configuration of 3 conics with as many real solutions as possible. It is possible to find 184 real solutions?

(2) A real algebraic variety is the common zero set of polynomials $f_1, \dots, f_m \in \mathbb{R}[x_1, \dots, x_n]$ denoted by $X = V(f_1, \dots, f_m)$. A bottleneck of X is defined to be a pair of distinct points $x, y \in X$ such that $x - y$ is orthogonal to the tangent space $\mathrm{T}_x X$ and to $\mathrm{T}_y X$.

It was recently shown that a generic plane curve of degree d has $d^4 - 5d^2 + 4d$ bottleneck pairs. This is called the bottleneck degree of the curve.

Consider the curve $X = V(f)$ defined by

$$f = (x^4 + y^4 - 1)(x^2 + y^2 - 2) + x^5 y.$$

(a) Write down definining equations for computing all bottlenecks.
(b) What is the Bottleneck degree of X? How many real bottlenecks does it have?
(c) What are the coordinates smallest bottleneck pair?
(d) What effect do different start systems have on the number of paths necessary to track?

(3) Consider a general quartic surface $X \in \mathbb{C}^3$. This is defined by a random polynomial $f \in \mathbb{C}[x, y, z]$ of degree 4. HC.jl provides functions to sample random polynomials. We want to count the number of planes in three-space which are tangent to $f = 0$ in at least 3 points.

(a) Set up polynomial systems to compute all tritangent planes of a general quartic surface. (Hint you should obtain a polynomial system in 11 variables).
(b) Use monodromy to solve the system from (a).

(4) Extend the triangulation example from two to three (or more) cameras.

(5) Verify that the configurations of 5 conics at this link has 3264 real conics, which are simultaneously tangent to all 5 of them. Use certification methods to obtain a proof!