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Autor(en): **Wei, Qiaoling**

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SUBTLETIES OF THE MINIMAX SELECTOR

by Qiaoling WEI

ABSTRACT. In this note, we show that the minimax and maximin critical values of a function quadratic nondegenerate at infinity are equal when defined in homology or cohomology with coefficients in a field. However, by an example of F. Laudenbach, this is not always true for coefficients in a ring and, even in the case of a field, the minimax-maximin depends on the field.

1. INTRODUCTION

Given a Lagrangian submanifold L in the cotangent bundle of a closed manifold M , obtained by Hamiltonian deformation of the zero section, the minimax selector introduced by J.-C. Sikorav [14] provides an almost everywhere defined section $M \rightarrow L$ of the projection $T^*M \rightarrow M$ restricted to L . As noticed by M. Chaperon [5, 6], this defines weak solutions of smooth Cauchy problems for Hamilton-Jacobi equations; in the classical case of a convex Hamiltonian, the minimax is a minimum and the minimax solution coincides with the viscosity solution, which is not always the case for nonconvex Hamiltonians. For a recent use of the minimax selector in weak KAM theory, see [1].

The minimax has been defined using homology or cohomology with various coefficient rings, for example \mathbf{Z} in [5, 15], \mathbf{Q} in [3] and \mathbf{Z}_2 in [13]. Also, in [15], the maximin was mentioned as a natural analogue to the minimax. But there is no evidence showing that all these critical values coincide. G. Capitanio has given a proof [3] that the maximin and minimax for homology with coefficients in \mathbf{Q} are equal, but the criterion he uses (Proposition 2 in [3]) is not correct — see Remark 3.11 hereafter.

In this note, we investigate the maximin and minimax for a general function quadratic at infinity, not necessarily related to Hamilton-Jacobi equations. We give both algebraic and geometric proofs that the minimax and maximin with coefficients in a field coincide; the geometric proof, based on Barannikov's Jordan normal form for the boundary operator of the Morse complex, improves our understanding of the problem. The Barannikov normal form also plays a crucial role in the proof of Arnold's 4 cusps conjecture [7].

A counterexample for coefficients in \mathbf{Z} , due to F. Laudenbach [11], is constructed using Morse homology; in this example, moreover, the minimax-maximin for coefficients in \mathbf{Z}_2 is not the same as for coefficients in \mathbf{Q} . However, if the minimax and maximin for coefficients in \mathbf{Z} coincide, then all three minimax-maximin critical values are equal.

2. MAXIMIN AND MINIMAX

HYPOTHESES AND NOTATION. We denote by X the vector space \mathbf{R}^n and by f a real function on X , *quadratic at infinity* in the sense that it is continuous and there exists a nondegenerate quadratic form $Q: X \rightarrow \mathbf{R}$ such that f coincides with Q outside a compact subset.

Let $f^c := \{x \mid f(x) \leq c\}$ denote the sub-level sets of f . Note that for c large enough, the homotopy types of f^c , f^{-c} do not depend on c , we may denote them as f^∞ and $f^{-\infty}$. Suppose the quadratic form Q has Morse index λ , then the homology groups with coefficient ring R are

$$H_*(f^\infty, f^{-\infty}; R) \simeq \begin{cases} R & \text{in dimension } \lambda \\ 0 & \text{otherwise.} \end{cases}$$

Consider the homomorphism of homology groups

$$i_{c*}: H_*(f^c, f^{-\infty}; R) \rightarrow H_*(f^\infty, f^{-\infty}; R)$$

induced by the inclusion $i_c: (f^c, f^{-\infty}) \hookrightarrow (f^\infty, f^{-\infty})$.

DEFINITION 2.1. If Ξ is a generator of $H_\lambda(f^\infty, f^{-\infty}; R)$, we let

$$\underline{\gamma}(f, R) := \inf\{c : \Xi \in \text{Im}(i_{c*})\},$$

i.e. $\underline{\gamma}(f, R) = \inf\{c : i_{c*}H_\lambda(f^c, f^{-\infty}; R) = H_\lambda(f^\infty, f^{-\infty}; R)\}$.

Similarly, we can consider the homology group

$$H_*(X \setminus f^{-\infty}, X \setminus f^{\infty}; R) \simeq \begin{cases} R & \text{in dimension } n - \lambda \\ 0 & \text{otherwise,} \end{cases}$$

and the homomorphism

$$j_{c*}: H_*(X \setminus f^c, X \setminus f^{\infty}; R) \rightarrow H_*(X \setminus f^{-\infty}, X \setminus f^{\infty}; R)$$

induced by $j_c: (X \setminus f^c, X \setminus f^{\infty}) \hookrightarrow (X \setminus f^{-\infty}, X \setminus f^{\infty})$.

DEFINITION 2.2. If Δ is a generator of $H_{n-\lambda}(X \setminus f^{-\infty}, X \setminus f^{\infty}; R)$, we let

$$\begin{aligned} \bar{\gamma}(f, R) &:= \sup\{c : \Delta \in \text{Im}(j_{c*})\} \\ &= \sup\{c : j_{c*}H_{n-\lambda}(X \setminus f^c, X \setminus f^{\infty}; R) = H_{n-\lambda}(X \setminus f^{-\infty}, X \setminus f^{\infty}; R)\}. \end{aligned}$$

LEMMA 2.3. *One has that*

$$\begin{aligned} \underline{\gamma}(f, R) &= \inf \max f := \inf_{[\sigma]=\Xi} \max_{x \in |\sigma|} f(x) \\ \bar{\gamma}(f, R) &= \sup \min f := \sup_{[\sigma]=\Delta} \min_{x \in |\sigma|} f(x), \end{aligned}$$

where σ is a relative cycle and $|\sigma|$ denotes its support. We call σ a descending (resp. ascending) simplex if $[\sigma] = \Xi$ (resp. $[\sigma] = \Delta$).

Proof. A descending simplex σ defines an element of $H_{\lambda}(f^c, f^{-\infty}; R)$ if and only if $|\sigma| \subset f^c$, in which case one has $\max_{x \in |\sigma|} f(x) \leq c$, hence $\underline{\gamma}(f, R) \geq \inf \max f$; choosing $c = \max_{x \in |\sigma|} f(x)$, we get equality. The case of $\bar{\gamma}$ is identical.

DEFINITION 2.4. $\underline{\gamma}(f, R)$ is called a *minimax* of f and $\bar{\gamma}(f, R)$, a *maximin*.

REMARK. As we shall see later, in view of Morse homology, these names are proper for excellent Morse functions.

One can also consider cohomology instead of homology and define

$$\begin{aligned} \underline{\alpha}(f, R) &:= \inf\{c : i_c^* \neq 0\}, & i_c^*: H^{\lambda}(f^{\infty}, f^{-\infty}; R) &\rightarrow H^{\lambda}(f^c, f^{-\infty}; R) \\ \bar{\alpha}(f, R) &:= \sup\{c : j_c^* \neq 0\}, & j_c^*: H^{n-\lambda}(X \setminus f^{-\infty}, X \setminus f^{\infty}; R) &\rightarrow H^{n-\lambda}(X \setminus f^c, X \setminus f^{\infty}; R). \end{aligned}$$

PROPOSITION 2.5 ([15], Proposition 2.4). *When X is R -oriented,*

$$\bar{\alpha}(f, R) = \underline{\gamma}(f, R) \quad \text{and} \quad \underline{\alpha}(f, R) = \bar{\gamma}(f, R).$$

Proof. We establish for example the first identity: one has the commutative diagram

$$\begin{array}{ccc}
 H_\lambda(f^c, f^{-\infty}; R) & \simeq & H^{n-\lambda}(X \setminus f^{-\infty}, X \setminus f^c; R) \\
 \downarrow i_{c*} & & \downarrow \\
 H_\lambda(f^\infty, f^{-\infty}; R) & \simeq & H^{n-\lambda}(X \setminus f^{-\infty}, X \setminus f^\infty; R) \\
 \downarrow & & \downarrow j_c^* \\
 H_\lambda(f^\infty, f^c; R) & \simeq & H^{n-\lambda}(X \setminus f^c, X \setminus f^\infty; R)
 \end{array}$$

where the horizontal isomorphisms are given by Alexander duality ([9], section 3.3) and the columns are exact. It does follow that i_{c*} is onto if and only if j_c^* is zero.

DEFINITION 2.6 ([8]). As long as X is finite dimensional, the *Clarke generalized derivative* of a locally Lipschitzian function $f: X \rightarrow \mathbf{R}$ can be defined as follows: by Rademacher's theorem, the set $\text{dom}(df)$ of differentiability points of f is dense in X ; we let $\partial f(x)$ be the convex hull of the set of limits of convergent sequences $df(x_n)$ with $\lim x_n = x$. A point $x \in X$ is called a *critical point* of f if $0 \in \partial f(x)$.

PROPOSITION 2.7. *If f is C^2 then $\underline{\gamma}(f, R)$ and $\overline{\gamma}(f, R)$ are critical values of f ; they are critical values of f in the sense of Clarke when f is locally Lipschitzian.*

Proof. Take $\underline{\gamma}$ for example: if $c = \underline{\gamma}(f, R)$ is not a critical value then, for small $\epsilon > 0$, $f^{c-\epsilon}$ is a deformation retract of $f^{c+\epsilon}$ via the flow of $-\frac{\nabla f}{\|\nabla f\|^2}$, hence $\underline{\gamma}(f, R) \leq c - \epsilon$, a contradiction. The same argument applies when f is only locally Lipschitzian, replacing ∇f by a pseudo-gradient [4].

LEMMA 2.8. *If f is locally Lipschitzian, then*

$$\overline{\gamma}(f, R) = -\underline{\gamma}(-f, R).$$

Proof. Using a (pseudo-)gradient of f as previously, one can see that $X \setminus f^c$ and $(-f)^{-c}$ have the same homotopy type when c is not a critical value of f . Otherwise, choose a sequence of non-critical values $c_n \nearrow c = \overline{\gamma}(f, R)$, then $-c_n \geq \underline{\gamma}(-f, R)$, taking the limit, we have $\overline{\gamma}(f, R) \leq -\underline{\gamma}(-f, R)$. Similarly, taking $c'_n \searrow \underline{\gamma}(-f, R)$, then $-c'_n \leq \overline{\gamma}(f, R)$, from which the limit gives us the reverse inequality $-\underline{\gamma}(-f, R) \leq \overline{\gamma}(f, R)$.

REMARK. The extension of the minimax selector to Lipschitzian functions is natural in the framework of Hamilton-Jacobi equations: even for smooth initial data, the minimax solution at time t is not smooth in general, but it is Lipschitzian; now, it can be interesting to take it as a new Cauchy datum.

The following two questions arise naturally:

- (1) Do we have $\underline{\gamma}(f, R) = \overline{\gamma}(f, R)$?
- (2) Do $\underline{\gamma}(f, R)$ and $\overline{\gamma}(f, R)$ depend on the coefficient ring R ?

Here are two obvious elements for an answer:

PROPOSITION 2.9. *One has $\underline{\gamma}(f, \mathbf{Z}) \geq \overline{\gamma}(f, \mathbf{Z})$.*

Proof. As the intersection number of Ξ and Δ is ± 1 , the support of any descending simplex σ must intersect the support of any ascending simplex τ at some point \bar{x} , hence $\max_{x \in |\sigma|} f(x) \geq f(\bar{x}) \geq \min_{x \in |\tau|} f(x)$.

PROPOSITION 2.10. *One has $\underline{\gamma}(f, \mathbf{Z}) \geq \underline{\gamma}(f, R)$ and $\overline{\gamma}(f, \mathbf{Z}) \leq \overline{\gamma}(f, R)$ for every ring R .*

Proof. A simplex σ whose homology class generates $H_\lambda(f^\infty, f^{-\infty}; \mathbf{Z})$ induces a simplex whose homology class generates $H_\lambda(f^\infty, f^{-\infty}; R)$, whence the first inequality and, mutatis mutandis, the second one.

THEOREM 2.11. *If \mathbf{F} is a field, then $\underline{\gamma}(f, \mathbf{F}) = \overline{\gamma}(f, \mathbf{F})$.*

Proof. By Proposition 2.5, it is enough to prove that

$$\underline{\gamma}(f, \mathbf{F}) = \underline{\alpha}(f, \mathbf{F}).$$

Recall that $\underline{\gamma}(f, \mathbf{F})$ (resp. $\underline{\alpha}(f, \mathbf{F})$) is the infimum of the real numbers c such that $i_{c*}: H_\lambda(f^c, f^{-\infty}; \mathbf{F}) \rightarrow H_\lambda(f^\infty, f^{-\infty}; \mathbf{F})$ is onto (resp. such that $i_c^*: H^\lambda(f^\infty, f^{-\infty}; \mathbf{F}) \rightarrow H^\lambda(f^c, f^{-\infty}; \mathbf{F})$ is nonzero). Now, as $H_\lambda(f^\infty, f^{-\infty}; \mathbf{F})$ is a one-dimensional vector space over \mathbf{F} , the linear map i_{c*} is onto if and only if it is nonzero, i.e. if and only if the transposed map i_c^* is nonzero.

REMARK. This proof is invalid for coefficients in \mathbf{Z} since a \mathbf{Z} -linear map to \mathbf{Z} , for example $\mathbf{Z} \ni m \rightarrow km, k \in \mathbf{Z}, k > 1$, can be nonzero without being onto; we shall see in Section 4 that Theorem 2.11 itself is not true in that case.

COROLLARY 2.12. *If $\underline{\gamma}(f, \mathbf{Z}) = \overline{\gamma}(f, \mathbf{Z}) = \gamma$ then $\underline{\gamma}(f, \mathbf{F}) = \overline{\gamma}(f, \mathbf{F}) = \gamma$ for every field \mathbf{F} .*

Proof. This follows at once from Theorem 2.11 and Proposition 2.10.

COROLLARY 2.13. *Let $\gamma \in \mathbf{R}$ have the following property: there exist both a descending simplex over \mathbf{Z} along which γ is the maximum of f and an ascending simplex over \mathbf{Z} along which γ is the minimum of f . Then, $\underline{\gamma}(f, \mathbf{Z}) = \overline{\gamma}(f, \mathbf{Z}) = \underline{\gamma}(f, \mathbf{F}) = \overline{\gamma}(f, \mathbf{F}) = \gamma$ for every field \mathbf{F} .*

Proof. We have $\underline{\gamma}(f; \mathbf{Z}) \leq \gamma \leq \overline{\gamma}(f; \mathbf{Z})$ by Lemma 2.3 and $\overline{\gamma}(f; \mathbf{Z}) \leq \underline{\gamma}(f; \mathbf{Z})$ by Proposition 2.9, hence our result by Corollary 2.12.

3. MORSE COMPLEXES AND THE BARANNIKOV NORMAL FORM

The previous proof of Theorem 2.11, though simple, is quite algebraic. We now give a more geometric proof, which we find more concrete and illuminating, based on Barannikov's canonical form of Morse complexes. It will provide a good setting for the counterexample in Section 4.

First, there is a continuity result for the minimax and maximin:

PROPOSITION 3.1 ([14, 16]). *If f and g are two continuous functions quadratic at infinity with the same reference quadratic form, then*

$$\begin{aligned} |\underline{\gamma}(f, R) - \underline{\gamma}(g, R)| &\leq |f - g|_{C^0} \\ |\overline{\gamma}(f, R) - \overline{\gamma}(g, R)| &\leq |f - g|_{C^0}. \end{aligned}$$

Proof. For $f \leq g$, from Lemma 2.3, it is easy to see that $\underline{\gamma}(f) \leq \underline{\gamma}(g)$. In the general case, this implies $\underline{\gamma}(g) \leq \underline{\gamma}(f + |g - f|) \leq \underline{\gamma}(f) + |g - f|_{C^0}$; exchanging f and g , we get $\underline{\gamma}(f) \leq \underline{\gamma}(g) + |f - g|_{C^0}$.

COROLLARY 3.2. *To prove Theorem 2.11, it suffices to establish it for excellent Morse functions $f: X \rightarrow \mathbf{R}$, i.e. smooth functions having only nondegenerate critical points, each of which corresponds to a different value of f .*

Proof. By a standard argument, given a non-degenerate quadratic form Q on X , the set of all continuous functions on X equal to Q off a compact subset contains a C^0 -dense subset consisting of excellent Morse functions; our result follows by Proposition 3.1.

To prove Theorem 2.11 for excellent Morse functions, we will use Morse homology.

HYPOTHESES. We consider an excellent Morse function f on X , quadratic at infinity¹); for each pair of regular values $b < c$ of f , we denote by $f_{b,c}$ the restriction of f to $f^c \cap (-f)^{-b} = \{b \leq f \leq c\}$.

MORSE COMPLEXES. Let

$$C_k(f_{b,c}) := \{\xi_\ell^k : 1 \leq \ell \leq m_k\}$$

denote the set of critical points of index k of $f_{b,c}$, ordered so that $f(\xi_\ell^k) < f(\xi_m^k)$ for $\ell < m$. Given a generic gradient-like vector field V for f such that (f, V) is Morse-Smale²), the *Morse complex* of $(f_{b,c}, V)$ over R consists of the free R -modules

$$M_k(f_{b,c}, R) := \left\{ \sum_\ell a_\ell \xi_\ell^k, \quad a_\ell \in R \right\}$$

together with the boundary operator $\partial: M_k(f_{b,c}, R) \rightarrow M_{k-1}(f_{b,c}, R)$ given by

$$\partial \xi_\ell^k := \sum_m \nu_{f,V}(\xi_\ell^k, \xi_m^{k-1}) \xi_m^{k-1}$$

where, with given orientations for the stable manifolds (hence co-orientations for unstable manifolds), $\nu_{f,V}$ is the intersection number of the stable manifold $W^s(\xi_\ell^k)$ of ξ_ℓ^k and the unstable manifold $W^u(\xi_m^{k-1})$ of ξ_m^{k-1} , i.e. the algebraic number of trajectories of V connecting ξ_ℓ^k and ξ_m^{k-1} ; note that

- $\nu_{f,V}(\xi_\ell^k, \xi_m^{k-1})$ is the same for all b, c with $f(\xi_\ell^k), f(\xi_m^{k-1})$ in $[b, c]$;
- $\nu_{f,V}(\xi_\ell^k, \xi_m^{k-1}) \neq 0$ implies $f(\xi_\ell^k) > f(\xi_m^{k-1})$: otherwise, the stable manifold of ξ_m^{k-1} and the unstable manifold of ξ_ℓ^k for V , which cannot be transversal because of their dimensions, would intersect, contradicting the genericity of V .
- $\nu_{f,V}(\xi_\ell^k, \xi_m^k) = 0$ for two distinct critical points of the same index.

This does define a complex, i.e. $\partial \circ \partial = 0$: see for example [10, 12]. The homology $HM_*(f_{b,c}, R) := H_*(M_*(f_{b,c}, R))$ is called the *Morse homology*³) of $f_{b,c}$.

¹) The theory applies as well to functions on a closed manifold, for example.

²) Being *Morse-Smale* means that the stable and unstable manifolds of all the critical points are transversal.

³) Morse homology is defined in general for any Morse function.

LEMMA 3.3 (Barannikov [2]). *If R is a field \mathbf{F} , then this boundary operator ∂ has a special kind of Jordan normal form as follows: each $M_k(f_{b,c}, \mathbf{F})$ has a basis*

$$(1) \quad \Xi_\ell^k := \sum_{i \leq \ell} \alpha_{\ell,i} \xi_i^k, \quad \alpha_{\ell,\ell} \neq 0$$

such that either $\partial \Xi_\ell^k = 0$ or $\partial \Xi_\ell^k = \Xi_m^{k-1}$ for some m , in which case no $\ell' \neq \ell$ satisfies $\partial \Xi_{\ell'}^k = \Xi_m^{k-1}$. If (Θ_ℓ^k) is another such basis, then $\partial \Xi_\ell^k = \Xi_m^{k-1}$ (resp. 0) is equivalent to $\partial \Theta_\ell^k = \Theta_m^{k-1}$ (resp. 0); in other words, the matrix of ∂ in all such bases is the same.

Proof. We prove existence by induction. Given nonnegative integers k, i with $i < m_k$, suppose that vectors Ξ_q^p of the form (1) have been obtained for all (p, q) with either $p < k$, or $p = k$ and $q \leq i$, possessing the required property that either $\partial \Xi_q^p = \Xi_{j_p(q)}^{p-1}$ (with $j_p(q) \neq j_p(q')$ for $q \neq q'$) or $\partial \Xi_q^p = 0$. If $\partial \xi_{i+1}^k = 0$ (e.g., when $k = 0$), we take $\xi_{i+1}^k := \Xi_{i+1}^k$ and continue the induction. Otherwise, $\partial \xi_{i+1}^k = \sum \alpha_j \Xi_j^{k-1}$, $\alpha_j \in \mathbf{F}$. Moving all the terms $\Xi_{j_k(q)}^{k-1} = \partial \Xi_q^k$, $q \leq i$ from the right-hand side to the left, we get

$$\partial(\xi_{i+1}^k - \sum_{q \leq i} \alpha_{j_k(q)} \Xi_q^k) = \sum_j \beta_j \Xi_j^{k-1}.$$

Let

$$\Xi_{i+1}^k := \xi_{i+1}^k - \sum_{q \leq i} \alpha_{j_k(q)} \Xi_q^k.$$

If $\beta_j = 0$ for all j , then $\partial \Xi_{i+1}^k = 0$ and the induction can go on. Otherwise,

$$\partial \Xi_{i+1}^k = \sum_{j \leq j_0} \beta_j \Xi_j^{k-1} =: \tilde{\Xi}_{j_0}^{k-1} \text{ with } \beta_{j_0} \neq 0;$$

as $\partial \tilde{\Xi}_{j_0}^{k-1} = \partial \partial \Xi_{i+1}^k = 0$, we can replace $\Xi_{j_0}^{k-1}$ by $\tilde{\Xi}_{j_0}^{k-1}$ and continue the induction⁴⁾.

DEFINITION 3.4. Under the hypotheses and with the notation of the Barannikov lemma, two critical points ξ_ℓ^k and ξ_m^{k-1} of $f_{b,c}$ are *coupled* if $\partial \Xi_\ell^k = \Xi_m^{k-1}$. A critical point is *free* (over \mathbf{F}) when it is not coupled with any other critical point.

In other words, ξ_ℓ^k is free if and only if Ξ_ℓ^k is a cycle of $M_k(f_{b,c}, \mathbf{F})$ but not a boundary, hence the following result:

⁴⁾ Note that if \mathbf{F} were not a field, this would not provide a basis for noninvertible β_{j_0} .

COROLLARY 3.5. *For each integer k , the Betti number $\dim_{\mathbf{F}} HM_k(f_{b,c}, \mathbf{F})$ is the number of free critical points of index k of $f_{b,c}$ over \mathbf{F} . \square*

THEOREM 3.6.

- (1) *The Barannikov normal form of the Morse complex of $f_{b,c}$ over \mathbf{F} is independent of the gradient-like vector field V .*
- (2) *So is the Morse homology $HM_*(f_{b,c}, R)$; it is isomorphic to $H_*(f^c, f^b; R)$.*
- (3) *For $b' \leq b < c \leq c'$, the inclusion $i: f^c \hookrightarrow f^{c'}$, restricted to the critical set $C_*(f_{b,c})$, induces a linear map $i_*: M_*(f_{b,c}, R) \rightarrow M_*(f_{b',c'}, R)$ such that $\partial \circ i_* = i_* \circ \partial$ and therefore a linear map $i_*: HM_*(f_{b,c}, R) \rightarrow HM_*(f_{b',c'}, R)$, which is the usual $i_*: H_*(f^c, f^b; R) \rightarrow H_*(f^{c'}, f^{b'}; R)$ modulo the previous isomorphism.*

Idea of the proof [10]. (1) Connecting two generic gradient-like vector fields V_0, V_1 for f by a generic family, one can prove that each of the Morse complexes defined by V_0 and V_1 is obtained from the other by a change of variables whose matrix is upper-triangular with all diagonal entries equal to 1.

(2) When there is no critical point of f in $\{b \leq f \leq c\}$, both $HM_*(f_{b,c}, R)$ and $H_*(f^c, f^b; R)$ are trivial (the flow of V defines a retraction of f^c onto f^b).

When there is only one critical point ξ of f in $\{b \leq f \leq c\}$, of index λ ,

$$HM_k(f_{b,c}, R) \simeq H_k(f^c, f^b; R) \simeq \begin{cases} R, & \text{if } k = \lambda, \\ 0 & \text{otherwise:} \end{cases}$$

the class of ξ obviously generates $HM_\lambda(f_{b,c}, R)$, whereas a generator of $H_\lambda(f^c, f^b; R)$ is the class of a cell of dimension λ , namely the stable manifold of ξ for $V|_{\{b \leq f \leq c\}}$; the isomorphism associates the second class to the first.

In the general case, one can consider a subdivision $b = b_0 < \dots < b_N = c$ consisting of regular values of f such that each $f_{b_i, b_{i+1}}$ has precisely one critical point. One can show that the boundary operator ∂ of the relative singular homology $\partial: H_{k+1}(f^{b_{i+1}}, f^{b_i}) \rightarrow H_k(f^{b_i}, f^{b_{i-1}})$ can be interpreted as the intersection number of the stable manifold of the critical point in $\{b_i \leq f \leq b_{i+1}\}$ and the unstable manifold of that in $\{b_{i-1} \leq f \leq b_i\}$, i.e., their algebraic number of connecting trajectories.

(3) The first claims are easy. The last one follows from what has just been sketched. \square

COROLLARY 3.7. *If f is an excellent Morse function quadratic at infinity, then it has precisely one free critical point ξ over \mathbf{F} ; its index λ is that of the reference quadratic form Q and*

$$\underline{\gamma}(f, \mathbf{F}) = f(\xi).$$

Proof. Clearly, the dimension of

$$HM_k(f, \mathbf{F}) = HM_k(f_{-\infty, \infty}, \mathbf{F}) \simeq H_k(f^\infty, f^{-\infty}; \mathbf{F}) = H_k(Q^\infty, Q^{-\infty}; \mathbf{F})$$

is 1 if $k = \lambda$ and 0 otherwise. The first two assertions follow by Corollary 3.5. To prove $\underline{\gamma}(f, \mathbf{F}) = f(\xi)$, note that $\underline{\gamma}(f)$ is the infimum of the regular values c of f such that the class of ξ in $HM_\lambda(f_{-\infty, \infty}, \mathbf{F})$ lies in the image of $i_{c*}: HM_\lambda(f_{-\infty, c}, \mathbf{F}) \rightarrow HM_\lambda(f_{-\infty, \infty}, \mathbf{F})$ by Theorem 3.6(3), which means $c \geq f(\xi)$.

PROPOSITION 3.8. *The excellent Morse function $-f_{b,c} = (-f)_{-c, -b}$ has the same free critical points over the field \mathbf{F} as $f_{b,c}$.*

Proof. Assuming V fixed, this is essentially easy linear algebra:

- One has $C_k(-f) = C_{n-k}(f)$ and the ordering of the corresponding critical values is reversed. Thus, the lexicographically ordered basis of $M_*(-f)$ corresponding to $(\xi_\ell^k)_{1 \leq \ell \leq m_k, 0 \leq k \leq n}$ is $(\xi_{m_{n-k}-\ell+1}^{n-k})_{1 \leq \ell \leq m_{n-k}, 0 \leq k \leq n}$.
- The vector field $-V$ has the same relations with $-f$ as V has with f , hence $\nu_{-f, -V}(\xi_{m_{n-k}-\ell+1}^{n-k}, \xi_{m_{n-(k-1)}-m+1}^{n-(k-1)}) = \nu_{f, V}(\xi_{m_{n-(k-1)}-m+1}^{n-(k-1)}, \xi_{m_{n-k}-\ell+1}^{n-k})$.

That is, the matrix of the boundary operator of $M_*(-f_{b,c})$ in the basis $(\xi_{m_{n-k}-\ell+1}^{n-k})$ is the matrix \tilde{M} obtained from the matrix A of the boundary operator of $M_*(f_{b,c})$ in the basis (ξ_ℓ^k) by symmetry with respect to the second diagonal (i.e. by reversing the order of both the lines and columns of the transpose of A).

Lemma 3.3 can be rephrased as follows: there exists a block-diagonal matrix

$$P = \text{diag}(P_0, \dots, P_n)$$

where each $P_k \in GL(m_k, \mathbf{F})$ is upper triangular, such that

$$(2) \quad P^{-1}AP = B$$

is a Barannikov normal form, meaning the following: the entries of the column of indices $\begin{smallmatrix} k \\ \ell \end{smallmatrix}$ are 0 except possibly one, equal to 1, which must lie on the line of indices $\begin{smallmatrix} k-1 \\ m \end{smallmatrix}$ for some m and be the only nonzero entry on this line. The normal form B is the same for every choice of P and V . Clearly, ξ_ℓ^k is a

free critical point of $f_{b,c}$ if and only if both the line and column of indices $\begin{smallmatrix} k \\ \ell \end{smallmatrix}$ of B are zero.

Equation (2) reads

$$(3) \quad \tilde{P} \tilde{A} \tilde{P}^{-1} = \tilde{B}.$$

Now, \tilde{P}^{-1} and $\tilde{P} = (\tilde{P}^{-1})^{-1}$ are block diagonal upper triangular matrices whose k^{th} diagonal block lies in $GL(m_{n-k}, \mathbf{F})$; therefore, by (3), as \tilde{B} is a Barannikov normal form for the ordering associated to $-f$, it is *the* Barannikov normal form of the boundary operator of $M_*(-f_{b,c})$, from which our result follows at once.

COROLLARY 3.9. *For any excellent Morse function f quadratic at infinity, the sole free critical point of $-f$ over \mathbf{F} is the free critical point ξ of f ; hence $\underline{\gamma}(f, \mathbf{F}) = f(\xi) = -(-f)(\xi) = -\underline{\gamma}(-f, \mathbf{F}) = \overline{\gamma}(f, \mathbf{F})$ by Corollary 3.7 and Lemma 2.8, which proves Theorem 2.11. \square*

Before we give an example where $\underline{\gamma}(f, \mathbf{Z}) > \overline{\gamma}(f, \mathbf{Z})$, here is a situation where this cannot occur:

PROPOSITION 3.10. *Assume that $M_*(f, \mathbf{Z})$ can be put into Barannikov normal form by a basis change (1) of the free \mathbf{Z} -module $M_*(f, \mathbf{Z})$:*

$$(4) \quad \Xi_\ell^k := \sum_{i \leq \ell} \alpha_{\ell,i}^k \xi_i^k, \quad \alpha_{\ell,i}^k \in \mathbf{Z}, \quad \alpha_{\ell,\ell}^k = \pm 1.$$

Then, $\underline{\gamma}(f, \mathbf{Z}) = \overline{\gamma}(f, \mathbf{Z}) = f(\xi)$, where ξ is the sole free critical point of f over \mathbf{Z} .

Proof. We are in the situation of the proof of Proposition 3.8 with $P_k \in GL(m_k, \mathbf{Z})$, which implies that the Barannikov normal form B of the boundary operator is the same for \mathbf{Z} as for \mathbf{Q} ; it does follow that there is a unique free critical point ξ of f over \mathbf{Z} (the same as over \mathbf{Q}) and that it is the unique free critical point of $-f$ over \mathbf{Z} ; moreover, the proof of Corollary 3.7 shows that $\underline{\gamma}(f, \mathbf{Z}) = \overline{\gamma}(f, \mathbf{Z}) = f(\xi)$. We conclude as in Corollary 3.9.

Now that the coefficients are in \mathbf{Z} , the classical method called *handle sliding* [10, 12] states that, under an additional condition imposed on the index of the change of basis in (4), namely $2 \leq k \leq n - 2$, the Barannikov normal form can be realized by a gradient-like vector field for f .

More precisely, let $P: M_*(f) \rightarrow M_*(f)$ be a transformation matrix where $P = \text{diag}(P_0, \dots, P_n)$ with each $P_k \in GL(m_k, \mathbf{Z})$ such that $P_k = id$ for $k = 0, 1$

or $n-1, n$, and P_k is upper triangular with ± 1 in the diagonal entries for $2 \leq k \leq n-2$. Then one can construct a gradient-like vector field V' such that, if the matrix of the boundary operator for a given gradient-like vector field V is A , then the matrix for V' is given by $B = P^{-1}AP$.

Roughly speaking, one modifies V , each time for one $i \leq \ell$, by sliding the stable sphere⁵⁾ $S_L(\xi_\ell^k)$ of ξ_ℓ^k for V so that it sweeps across the unstable sphere $S_R(\xi_i^k)$ of ξ_i^k with indicated intersection number. In other words, $S'_L(\xi_\ell^k)$ for the resulted V' is the connected sum of $S_L(\xi_\ell^k)$ and the boundary of a meridian disk of $S_R(\xi_i^k)$ described in section 4.4 of [10]. One may refer to the Basis Theorem (Theorem 7.6 in [12]) for a detailed construction of V' .

REMARK 3.11 (on the “proof” of Corollary 3.9 in [3]). Capitanio uses the following:

CRITERION. *A critical point ξ of f is free (over \mathbf{Q}) if and only if, for any critical point η incident to ξ , there is a critical point ξ' , incident to η , such that*

$$|f(\xi') - f(\eta)| < |f(\xi) - f(\eta)|,$$

where, given a generic gradient-like vector field V for f , two critical points are called incident if their algebraic number of connecting trajectories is nonzero.

Unfortunately, this is not true: one can construct a function $f: \mathbf{R}^{2n} \rightarrow \mathbf{R}$, $n \geq 2$, quadratic at infinity with Morse index n , having five critical points, two of index $n-1$ and three of index n , whose gradient vector field V defines the Morse complex

$$\partial \xi_1^n = \xi_2^{n-1}, \quad \partial \xi_2^n = \xi_1^{n-1}, \quad \partial \xi_3^n = 0.$$

This complex can be reformulated into

$$\begin{aligned} \partial \xi_1^n &= (\xi_2^{n-1} - \xi_1^{n-1}) + \xi_1^{n-1} \\ \partial(\xi_2^n + \xi_1^n) &= (\xi_2^{n-1} - \xi_1^{n-1}) + 2\xi_1^{n-1} \\ \partial(\xi_3^n + \xi_2^n) &= \xi_1^{n-1}. \end{aligned}$$

Hence, for a change of basis

$$\xi_2^{n-1} \mapsto \xi_2^{n-1} - \xi_1^{n-1}, \quad \xi_2^n \mapsto \xi_2^n + \xi_1^n, \quad \xi_3^n \mapsto \xi_3^n + \xi_2^n$$

⁵⁾ The stable and unstable spheres are $S_L(\xi_\ell^k) = W^s(\xi_\ell^k) \cap L$ and $S_R(\xi_i^k) = W^u(\xi_i^k) \cap L$ where $L = f^{-1}(c)$ for some $c \in (f(\xi_i^k), f(\xi_\ell^k))$.

one can construct a gradient-like vector field V' for f by sliding handles, such that

$$\partial\xi_1^n = \xi_2^{n-1} + \xi_1^{n-1}, \quad \partial\xi_2^n = \xi_2^{n-1} + 2\xi_1^{n-1}, \quad \partial\xi_3^n = \xi_1^{n-1}.$$

Obviously, ξ_3^n is the only free critical point, but ξ_2^n satisfies the criterion (with incidences under V'). \square

4. AN EXAMPLE OF LAUDENBACH

PROPOSITION 4.1. *There exists an excellent Morse function $f: \mathbf{R}^{2n} \rightarrow \mathbf{R}$ as follows:*

1. *it is quadratic at infinity and the reference quadratic form has index and coindex $n > 1$;*
2. *it has exactly five critical points: three of index n , one of index $n - 1$ and one of index $n + 1$;*
3. *its Morse complex over \mathbf{Z} is given by*

$$(5) \quad \begin{aligned} \partial\xi_1^{n-1} &= 0 \\ \partial\xi_1^n &= \xi_1^{n-1}, \quad \partial\xi_2^n = -2\xi_1^{n-1}, \quad \partial\xi_3^n = -\xi_1^{n-1} \\ \partial\xi_1^{n+1} &= \xi_2^n - 2\xi_3^n, \end{aligned}$$

hence, for any field \mathbf{F}_2 of characteristic 2 and any field \mathbf{F} of characteristic $\neq 2$,

$$(6) \quad \begin{aligned} \underline{\gamma}(f, \mathbf{Z}) = \underline{\gamma}(f, \mathbf{F}_2) = \overline{\gamma}(f, \mathbf{F}_2) &= f(\xi_3^n) \\ &> f(\xi_2^n) = \underline{\gamma}(f, \mathbf{F}) = \overline{\gamma}(f, \mathbf{F}) = \overline{\gamma}(f, \mathbf{Z}). \end{aligned}$$

Proof that (5) implies (6). The Morse complex of f over \mathbf{F}_2 is written

$$\begin{aligned} \partial\xi_1^{n-1} &= 0 \\ \partial\xi_1^n &= \xi_1^{n-1}, \quad \partial\xi_2^n = 0, \quad \partial(\xi_3^n + \xi_1^n) = 0 \\ \partial\xi_1^{n+1} &= \xi_2^n, \end{aligned}$$

implying that ξ_3^n is the only free critical point, hence, by Corollary 3.7,

$$\underline{\gamma}(f, \mathbf{F}_2) = \overline{\gamma}(f, \mathbf{F}_2) = f(\xi_3^n);$$

as $\underline{\gamma}(f, \mathbf{Z}) \geq \underline{\gamma}(f, \mathbf{F}_2)$ by Proposition 2.10 and $\underline{\gamma}(f, \mathbf{Z}) \leq f(\xi_3^n)$, we do have

$$\underline{\gamma}(f, \mathbf{Z}) = f(\xi_3^n).$$

Similarly (keeping the numbering of the critical points defined by f) the Morse complex of $-f$ over \mathbf{F} has the Barannikov normal form

$$\begin{aligned}\partial(-2\xi_1^{n+1}) &= 0 \\ \partial\xi_3^n &= -2\xi_1^{n+1}, \quad \partial(\xi_2^n + \frac{1}{2}\xi_3^n) = 0, \quad \partial(-\xi_3^n - 2\xi_2^n + \xi_1^n) = 0 \\ \partial\xi_1^{n-1} &= -\xi_3^n - 2\xi_2^n + \xi_1^n,\end{aligned}$$

showing that the free critical point is ξ_2^n ; hence, by Corollary 3.7 and Proposition 3.8,

$$\bar{\gamma}(f, \mathbf{F}) = \underline{\gamma}(f, \mathbf{F}) = f(\xi_2^n);$$

finally, as we have $\bar{\gamma}(f, \mathbf{Z}) \leq \bar{\gamma}(f, \mathbf{F})$ by Proposition 2.10, and $\bar{\gamma}(f, \mathbf{Z}) \geq f(\xi_1^n)$, we should prove $\bar{\gamma}(f, \mathbf{Z}) > f(\xi_1^n)$, which is obvious since ξ_1^n and ξ_1^{n+1} are boundaries in $M_*(-f, \mathbf{Z})$.

How to construct such a function f . It is easy to construct a function $f_0: \mathbf{R}^{2n} \rightarrow \mathbf{R}$ with properties (1) and (2) required in the proposition and whose gradient vector field V_0 provides a Morse complex given by

$$\begin{aligned}\partial\xi_1^{n-1} &= 0 \\ \partial\xi_1^n &= \xi_1^{n-1}, \quad \partial\xi_2^n = 0, \quad \partial\xi_3^n = 0 \\ \partial\xi_1^{n+1} &= \xi_3^n.\end{aligned}$$

For a change of basis

$$\xi_2^n \mapsto \xi_2^n - \xi_1^n, \quad \xi_3^n \mapsto \xi_3^n - 2(\xi_2^n - \xi_1^n)$$

one can construct a gradient-like vector field V' for f_0 by sliding handles, such that

$$\begin{aligned}\partial\xi_1^{n-1} &= 0 \\ \partial\xi_1^n &= \xi_1^{n-1}, \quad \partial\xi_2^n = -\xi_1^{n-1}, \quad \xi_3^n = -2\xi_1^{n-1} \\ \partial\xi_1^{n+1} &= -2\xi_2^n + \xi_3^n.\end{aligned}$$

Since (f_0, V') is Morse-Smale, the invariant manifolds of those critical points of the same index are disjoint, hence one can modify f_0 to f such that

- f has the same critical points as f_0 ;
- the ordering of critical points for f is $f(\xi_2^n) > f(\xi_3^n) > f(\xi_1^n)$;
- V' is a gradient-like vector field for f .

This can be realized by the preliminary rearrangement theorem (Theorem 4.1 in [12]).

In other words, we have made a change of critical points $\xi_2^n \leftrightarrow \xi_3^n$, hence obtain the required Morse complex in the proposition.

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Qiaoling Wei

Institut de Mathématiques de Jussieu, Université Paris 7
175 rue du Chevaleret
F-75013 Paris
France
e-mail: weiqiaoling@math.jussieu.fr