NASH G MANIFOLD STRUCTURES OF COMPACT OR COMPACTIFIABLE $C^\infty G$ MANIFOLDS

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1. Introduction.

Let G be a compact affine Nash group. We say that a $C^\infty G$ manifold X *admits* a (resp. an *affine*, a *nonaffine*) *Nash G manifold structure* if there exists a (resp. an affine, a nonaffine) Nash G manifold Y such that X is $C^\infty G$ diffeomorphic to Y. In the present paper we consider Nash G manifold structures of compact or compactifiable $C^\infty G$ manifolds.

We have the following when X is compact.

Theorem 1. *Let G be a compact affine Nash group and let X be a compact $C^\infty G$ manifold with dim $X \geq 1$.*
(1)X admits exactly one affine Nash G manifold structure up to Nash G diffeomorphism.
(2)If G acts on X transitively then a Nash G manifold structure of X is unique up to Nash G diffeomorphism.
(3)If X is connected and the action on X is not transitive, then X admits a continuum number of nonaffine Nash G manifold structures.

In the non-equivariant category, M. Shiota in [4] proved that any compactifiable C^∞ manifold X admits a continuum number of nonaffine Nash manifold structures. When X is not compact but compactifiable, an affine Nash compactification of X is not unique, and the number of affine ones can be investigated by the cardinality of the Whitehead torsion of X [6]. Here an affine Nash compactification of X means an affine Nash manifold Y with boundary so that X is C^∞ diffeomorphic to the interior of Y.

We say that a $C^\infty G$ manifold X is *compactifiable as a $C^\infty G$ manifold* if there exists a compact $C^\infty G$ manifold Y with boundary so that X is $C^\infty G$ diffeomorphic to the interior of Y. We obtain the following.

Theorem 2. *Let G be a compact affine Nash group and let X be a non-compact compactifiable $C^\infty G$ manifold with dim $X \geq 1$.*
(1)X admits an affine Nash G manifold structure.
(2)X admits a continuum number of nonaffine Nash G manifold structures.

This paper consists of two parts. The first half is to investigate Nash G manifold structures of compact $C^\infty G$ manifolds. We consider Nash G manifold structures of compactifiable (not compact) $C^\infty G$ manifolds in the latter half.

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In this paper all Nash G manifolds and all Nash G maps are of class C^ω unless otherwise stated.

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2. Nash G manifolds.

First of all we recall the definition of Nash groups.

Definition 2.1. A group is called a (resp. an *affine*) *Nash group* if it is a (resp. an affine) Nash manifold and that the multiplication $G \times G \longrightarrow G$, the inversion $G \longrightarrow G$ are Nash maps.

We remark that one-dimensional Nash groups are classified by J.J. Madden and C.M. Stanton [2].

Let G be an affine Nash group. In this paper, a *representation* of G means a Nash group homomorphism $G \longrightarrow GL(\mathbb{R}^n)$ for some $\mathbb{R}^n$. Here a Nash group homomorphism means a group homomorphism which is a Nash map. We use a representation as a representation space.

Definition 2.2. Let G be an affine Nash group
(1)An affine Nash submanifold in some representation of G is called an *affine Nash G submanifold* if it is G invariant. A Nash manifold X with G action is said to be a *Nash G manifold* if the action map $G \times X \longrightarrow X$ is a Nash map.
(2)Let X and Y be Nash G manifolds. A Nash map $f : X \longrightarrow Y$ is called a *Nash G map* if it is a G map. We say that X is *Nash G diffeomorphic to* Y if there exist Nash G maps $f : X \longrightarrow Y, h : Y \longrightarrow X$ so that $f \circ h = id, h \circ f = id$.
(3)A Nash G manifold X is said to be *affine* if there exists an affine Nash G submanifold Y so that X is Nash G diffeomorphic to Y.

Tubular neighborhood theorem and collaring theorem are well known in the smooth equivariant category. They are proved in the Nash category by M. Shiota (Lemma 1.3.2 [7], Lemma 6.1.6 [7]). Since M. Shiota's proofs work in the equivariant Nash category, the following two propositions are obtained.

Proposition 2.3. *Let G be a compact affine Nash group and let X be an affine Nash G submanifold in a representation Ω of G. Then there exists a Nash G tubular neighborhood (U, p) of X in Ω, namely, U is an affine Nash G submanifold in Ω and the orthogonal projection $p : U \longrightarrow X$ is a Nash G map.* □

Proposition 2.4. *Let G be a compact affine Nash group. Any compact affine Nash G manifold X with boundary ∂X admits a Nash G collar, that is, there exists a Nash G imbedding $\phi : \partial X \times [0,1] \longrightarrow X$ so that $\phi|_{\partial X \times 0} = id_{\partial X}$, where the action on the closed unit interval $[0,1]$ is trivial.* □

3. Compact $C^\infty G$ manifolds.

Recall a theorem proved by K.H. Dovermann, M. Masuda, and T. Petrie [1], which is a partial solution of the equivariant Nash conjecture.

Theorem 3.1 [1]. *Let G be a compact affine Nash group and let X be a compact $C^\infty G$ manifold so that X is G cobordant to a nonsingular algebraic G set. Then X is $C^\infty G$ diffeomorphic to a nonsingular algebraic G set. Here an algebraic G set means a G invariant algebraic subset of some representation of G.* $\square$

Proof of Theorem 1. The disjoint union $X \amalg X$ is null cobordant. By Theorem 3.1, $X \amalg X$ is $C^\infty G$ diffeomorphic to a nonsingular algebraic G set in some representation Ω of G. Since a G invariant collection of connected components of a nonsingular algebraic G set is an affine Nash G submanifold in Ω, X admits an affine Nash G manifold structure $Y \subset \Omega$. Let Z be another affine Nash G manifold structure of X in Ω'. We have to prove Y is Nash G diffeomorphic to Z. Let f be a $C^\infty G$ diffeomorphism from Y to Z. Let F denote the composition of f with the inclusion $Z \longrightarrow \Omega'$. By [1] F can be approximated by a polynomial G map $q : Y \longrightarrow \Omega'$. By Proposition 2.3, we have a Nash G tubular neighborhood (U, p) of Z in Ω'. Since Y is compact, if the approximation is close then the image of q lies in U. Thus $k := p \circ q$ is an approximation of f. If the approximation is close then a Nash G map $k : Y \longrightarrow Z$ is a Nash G diffeomorphism. Therefore (1) is proved.

Next we prove (2). Let X_1, X_2 be two Nash G manifold structures (may not be affine) of X and let k be a $C^\infty G$ diffeomorphism from X_1 to X_2. Fix $x_1 \in X_1$, and let $x_2 = k(x_1)$. Then the map $f_i : G \longrightarrow X_i : f_i(g) = gx_i$ $(i = 1,2)$ is a surjective Nash G map because G acts on X_i $(i = 1,2)$ transitively, and $f_2 = k \circ f_1$.

To prove k is a Nash map, it is enough to show k is a C^0 Nash map. By [4] we can find a C^0 Nash imbedding I_i from X_i to some Euclidean space $\mathbb{R}^s$ $(i = 1,2)$. Let $X_i' = I_i(X_i)$ $(i = 1,2)$, $f_i' = I_i \circ f_i$ $(i = 1,2)$ and $k' = I_2 \circ k \circ I_1^{-1}$. Then $f_i' : G \longrightarrow X_i'$ $(i = 1,2)$ is a C^0 Nash map. Since G and X_i $(i = 1,2)$ are affine, there exists a finite semialgebraic open covering $\{O_t\}_t$ of G such that each $f_i'|O_t$ is semialgebraic. Therefore f_i' $(i = 1,2)$ is semialgebraic. Since k' is C^0 Nash if and only if k is C^0 Nash, we have only to show that k' is C^0 Nash.

Since f_i' $(i = 1,2)$ is a C^0 Nash map, there exist finite systems of coordinate neighborhoods $\{\phi_i : W_i \longrightarrow \mathbb{R}^m\}$ of G, $\{\psi_j : U_j \longrightarrow \mathbb{R}^n\}$ of X_1, and $\{\varphi_l : V_l \longrightarrow \mathbb{R}^n\}$ of X_2 such that , for any i, j and l, $\phi_i((f_1')^{-1}(U_j) \cap W_i)$, $\phi_i((f_2')^{-1}(V_l) \cap W_i)$ are semialgebraic, and that $\psi_j \circ f_1' \circ \phi_i^{-1} : \phi_i((f_1')^{-1}(U_j) \cap W_i) \longrightarrow \mathbb{R}^n$, $\varphi_l \circ f_2' \circ \phi_i^{-1} : \phi_i((f_2')^{-1}(V_l) \cap W_i) \longrightarrow \mathbb{R}^n$ are C^0 Nash maps, where m (resp. n) denotes the dimension of G (resp. X_1). We have only to show that each $\varphi_l \circ k' \circ \psi_j^{-1}$ is semialgebraic. For a map h, let $graph(h)$ denote the graph of h. For j and l, let

$$K = \bigcup_i graph(\psi_j \circ f_1' \circ \phi_i^{-1}) \times graph(\varphi_l \circ f_2' \circ \phi_i^{-1}).$$

Then K is semialgebraic in $(\mathbb{R}^m \times \mathbb{R}^n) \times (\mathbb{R}^m \times \mathbb{R}^n)$, hence the image K' of K by the projection $(\mathbb{R}^m \times \mathbb{R}^n) \times (\mathbb{R}^m \times \mathbb{R}^n) \longrightarrow \mathbb{R}^n \times \mathbb{R}^n$ is semialgebraic in $\mathbb{R}^n \times \mathbb{R}^n$. Since f_i' $(i = 1,2)$ is surjective and $f_2' = k' \circ f_1'$, $graph(\varphi_l \circ k' \circ \psi_j^{-1}) = K'$. Thus each $\varphi_l \circ k' \circ \psi_j^{-1}$ is semialgebraic. Hence k' is a C^0 Nash. Therefore k is a Nash G diffeomorphism.

Now we prove (3). By (1) we can assume that X is an affine Nash G submanifold of a representation Ω of G. For any $x \in X$, the orbit $G(x)$ of x is a $C^\infty G$ submanifold of Ω because G is compact. Moreover $G(x)$ is a semialgebraic set. Hence $G(x)$

is an affine Nash G submanifold in Ω. Since the action on G is not transitive and by Proposition 2.3, there exists some Nash G tubular neighborhood (U', p) of some orbit $G(x)$ in Ω with $X \neq U := U' \cap X$.

For $0 < c < 1$, set

$$a = 2^{2.5}(1+c)^2/(1-c)^2,$$
$$d = 2 + 2^{0.5}3a + a^2 - (a+\sqrt{2})\sqrt{a^2 + 2^{2.5}a}.$$

Then $a > 2^{2.5}, 1 < d < 2$. Suppose k is a Nash function satisfying

$$\sqrt{2}(x + k(x)) = (x - k(x))^2/a.$$

The graph of k comes to a rotation of the graph of $y = x^2/a$ with center at the origin. It follows from this and $a > 2^{2.5}$ that k and its Nash extension k' to

$$[1 - 2^{-0.25}\sqrt{a}, 1 + 2^{-0.25}\sqrt{a}](\supset (-1,3))$$

is well-defined, and that k' satisfies

$$k'[1 - 2^{-0.25}\sqrt{a}, 1 + 2^{-0.25}\sqrt{a}] = [1 - 2^{-0.25}\sqrt{a}, 1 + 2^{-0.25}\sqrt{a}],$$

the derivative of k' is negative, $k' \circ k' = id$.

Let

$$N_1 = (-\infty, d), N_2 = (0, \infty), N_3 = (0,1).$$

Define the Nash maps $h_1 : N_3 \longrightarrow N_1, h_2 : N_3 \longrightarrow N_2$ by

$$h_1(t) = t^2 + k(t)^2 \text{ and } h_2(t) = 2t - t^2.$$

Then h_1 and h_2 are Nash imbeddings so that $h_1(N_3) = (0,d), h_2(N_3) = (0,1)$. We can extend h_1 to

$$h_1' : [1 - 2^{-0.25}\sqrt{a}, 1 + 2^{-0.25}\sqrt{a}] \longrightarrow \mathbb{R}$$

as a Nash function such that the derivative vanishes at only 0 and that $h_1' = h_1' \circ k'$ because the derivative of k' is negative and $k' \circ k' = id$.

Applying Proposition 2.3 to the boundary $\partial\overline{U}$ of the closure $\overline{U}$ of U in X, there exists a Nash G collar $\phi : \partial\overline{U} \times [0,1] \longrightarrow \overline{U}$. Let $D(\varepsilon)$ $(0 < \varepsilon < 1)$ denote $\phi(\partial\overline{U} \times (0,\varepsilon))$. Take a Nash diffeomorphism $f : \mathbb{R} \longrightarrow (0,1)$ (e.g. the inverse map of the composition of $f : (0,1) \longrightarrow (-1,1) : f(x) = 2x - 1$ with $h : (-1,1) \longrightarrow \mathbb{R} : h(x) = x/(1-x^2)$). Set

$$U_1 = D(f(d)), U_2 = X - \overline{D(f(0))}, U_3 = D(f(1)) - \overline{D(f(0))}.$$

Then each U_i is an open affine Nash G submanifold of X. Let

$$H_1 = \phi \circ (id \times (f \circ h_1 \circ f^{-1})) \circ \phi^{-1} : U_3 \longrightarrow U_1,$$
$$H_2 = \phi \circ (id \times (f \circ h_2 \circ f^{-1})) \circ \phi^{-1} : U_3 \longrightarrow U_2.$$

We define X_c by the quotient topological space of the disjoint union $\amalg_{i=1}^3 U_i$, and the equivalence relation $x \sim H_1(x) \sim H_2(x)$ for $x \in U_3$ on the union. Then one can check that X_c is a Nash G manifold which is $C^\infty G$ diffeomorphic to X. Next we prove X_c is nonaffine. To prove this, we use the following lemma.

Lemma 3.2 (c.f. Remark 1.2.2.15 [7]). *Let f be a locally semialgebraic C^∞ map from a Nash manifold M to a Nash manifold N. If N is affine then f is a Nash map.* $\square$

Fix $0 < c < 1$ and $z \in S(f(1))$, where $S(f(1))$ denotes $\phi(\partial\overline{U} \times \{f(1)\})$. Let $\psi_c : (f(0), f(1)) \longrightarrow X_c$ be the composition

$$(f(0), f(1)) \longrightarrow S(f(1)) \times (f(0), f(1)) \longrightarrow U_3 \longrightarrow X_c,$$

where the first map is $x \longrightarrow (z, x)$, the second is the natural Nash G diffeomorphism from $S(f(1)) \times (f(0), f(1))$ to U_3, and the third is the natural imbedding from U_3 into X_c. Then ψ_c is an imbedding. We extend ψ_c as follows. Let l_{ci} $(i = 1, 2, 3)$ be the natural imbedding $U_i \longrightarrow X_c$ and let V_{ci} $(i = 1, 2, 3)$ denote its image. Then

$$p \circ k_1^{-1} \circ l_1^{-1} \circ \psi_c = f \circ h_1 \circ f^{-1}, p \circ k_2^{-1} \circ l_2^{-1} \circ \psi_c = f \circ h_2 \circ f^{-1} \text{ on } (f(0), f(1)),$$

where p denotes the projection $\partial\overline{U_3} \times (f(0), f(d)) \longrightarrow (f(0), f(d))$ and k_i $(i = 1, 2)$ stands for the natural imbedding $\partial\overline{U_3} \times (f(0), f(d)) \longrightarrow U_i$. We extend ψ_c to $(f(0), f(1 + \varepsilon))$ for small positive ε. It suffices to consider $p \circ k_2^{-1} \circ l_2^{-1} \circ \psi_c$ because the image of ψ_c lies in V_{c2} and $\lim_{t \to f(1)} \psi_c(t) \in V_{c2}$. Now $p \circ k_2^{-1} \circ l_2^{-1} \circ \psi_c = f(2f^{-1}(t) - (f^{-1}(t))^2)$ on $(f(0), f(1))$. Thus $p \circ k_2^{-1} \circ l_2^{-1} \circ \psi_c$ and ψ_c are extensible to $(f(0), f(2))$ and

$$p \circ k_2^{-1} \circ l_2^{-1} \circ \psi_c(t) = f(2f^{-1}(t) - (f^{-1}(t))^2) \text{ on } [f(1), f(2)).$$

Clearly we can extend ψ_c to $[f(0), f(1)]$, and $\psi_c((f(0), f(2)) \subset \psi_c([f(0), f(1)])$. Hence

$$\psi_{c0}^{-1} \circ \psi_c(t) = f(2 - f^{-1}(t)) \text{ on } [f(1), f(2)),$$

$f(1)$ is the only and nondegenerate critical point, where ψ_{c0} denotes the homeomorphism $\psi_c : [f(0), f(1)] \longrightarrow \psi_c([f(0), f(1)])$. In the same way, ψ_c can be defined on $(f(k'(1)), f(0)]$ satisfying

$$\psi_{c0}^{-1} \circ \psi_c(t) = f(k'(f^{-1}(t))) \text{ for } t \in (f(k'(1)), f(0)],$$

and the critical point is only $f(0)$ and nondegenerated. Repeating this argument, ψ_c is extensible on

$$(f(1 - 2^{-0.25}\sqrt{a}), f(1 + 2^{-0.25}\sqrt{a})),$$

and ψ_c is locally semialgebraic, the image of ψ_c is $\psi_c([f(0), f(1)])$, and that for any $e \in (f(0), f(1))$, $(\psi_{c0}^{-1} \circ \psi_c)^{-1}(e)$ is discrete and consists of infinitely many elements. The set of critical points of ψ_c is $(\psi_{c0}^{-1} \circ \psi_c)^{-1}(f(0)) \cup (\psi_{c0}^{-1} \circ \psi_c)^{-1}(f(1))$, and they are nondegenerate ones. Since ψ_c is locally semialgebraic and not semialgebraic and by Lemma 3.2, X_c is not affine.

Finally we prove that X_c is not Nash G diffeomorphic to $X_{c'}$ if $0 < c, c' < 1, \alpha = log f(c')/log f(c)$ is irrational. Assume that there exists a Nash G diffeomorphism $u : X_c \longrightarrow X_{c'}$. Then we have to prove $log f(c')/log f(c)$ is rational. Set

$$a = 2^{2.5}(1 + c)^2/(1 - c)^2, a' = 2^{2.5}(1 + c')^2/(1 - c')^2,$$
$$\psi_c : (f(1 - 2^{-0.25}\sqrt{a}), f(1 + 2^{-0.25}\sqrt{a})) \longrightarrow X_c,$$
$$\psi_{c'} : (f(1 - 2^{-0.25}\sqrt{a'}), f(1 + 2^{-0.25}\sqrt{a'})) \longrightarrow X_{c'}.$$

We also write

$$\psi_{c0} = \psi_c|[f(0), f(1)] : [f(0), f(1)] \longrightarrow \psi_c([f(0), f(1)]),$$

$$\psi_{c'0} = \psi_{c'}|[f(0), f(1)] : [f(0), f(1)] \longrightarrow \psi_{c'}([f(0), f(1)]),$$

Let L_1 be the composition of the diffeomorphism $S(f(1)) \times (f(-10d), f(10d)) \longrightarrow D(f(10d)) - \overline{D(f(-10d))}$ with the projection $D(f(10d)) \longrightarrow X_{c'}$, and let L_2 be the projection $S(f(1)) \times (f(-10d), f(-10d)) \longrightarrow S(f(1))$. By Lemma 3.2 and the infinite vibration of ψ_c, $L_2 \circ L_1^{-1} \circ u \circ \psi_c$ is constant. Let z' denote this constant. Clearly the images of $\phi(z' \times f(N_2))$ and $\phi(z' \times (f(1), f(d)))$ via $\pi_{c'}$ in $X_{c'}$ are affine Nash G submanifolds. Let k_c be the natural homeomorphism from $\overline{U_3}$ into X_c. Thus $u \circ k_c \circ \phi(z \times [f(0), f(1)])$ is not contained in these affine Nash G submanifolds because the image of ψ_c is not affine. This implies that

$$u \circ k_c \circ \phi(z \times [f(0), f(1)]) \subset k_{c'} \circ \phi(z' \times [f(0), f(1)]).$$

Applying the same argument to u^{-1}, we have

$$u^{-1} \circ k_{c'} \circ \phi(z' \times [f(0), f(1)]) \subset k_c \circ \phi(z \times [f(0), f(1)]).$$

Therefore

$$u \circ k_c \circ \phi(z \times [f(0), f(1)]) = k_{c'} \circ \phi(z' \times [f(0), f(1)]).$$

For any $e \in (f(0), f(1))$, let $(\psi_{c0}^{-1} \circ \psi_c)^{-1}(e) = \{e_i\}_{i \in \mathbb{Z}}$, $(\psi_{c'0}^{-1} \circ \psi_{c'})^{-1}(e) = \{e'_i\}_{i \in \mathbb{Z}}$. Then

[3.1] $$\lim_{i \to \infty} (f(1 + 2^{-0.25}\sqrt{a}) - e_{-i-2})/(f(1 + 2^{-0.25}\sqrt{a}) - e_{-i}) = f(c),$$

[3.2] $$\lim_{i \to \infty} (f(1 + 2^{-0.25}\sqrt{a'}) - e'_{-i-2})/(f(1 + 2^{-0.25}\sqrt{a'}) - e'_{-i}) = f(c'),$$

are obtained as follows. The map $t \longrightarrow f(k'(2 - f^{-1}(t)))$ has fixed points only at the end of the interval, it repels from $f(1 + 2^{-0.25}\sqrt{a})$, attracts to $f(1 - 2^{-0.25}\sqrt{a})$ and its derivatives at the latter point is $f(c)$. Thus $(f(1+2^{-0.25}\sqrt{a}) - e_{-i-2})/(f(1+2^{-0.25}\sqrt{a}) - e_{-i})$ converges $f(c)$ because $e_{-i-2} = f(k'(2 - f^{-1}(e_{-i})))$. Hence we have [3.1]. A similar argument shows [3.2]. Since

$$u \circ k_c \circ \phi(z \times [f(0), f(1)]) = k_{c'} \circ \phi(z' \times [f(0), f(1)]),$$

for a pair

$$e_0 \in (f(1 - 2^{-0.25}\sqrt{a}), f(1 + 2^{-0.25}\sqrt{a})) \text{ and}$$
$$e'_0 \in (f(1 - 2^{-0.25}\sqrt{a'}), f(1 + 2^{-0.25}\sqrt{a'})) \text{ with}$$
$$\psi_{c'}(e'_0) = u \circ \psi_c(e_0)$$

there exits a homeomorphism

$$\tau : (f(1 - 2^{-0.25}\sqrt{a}), f(1 + 2^{-0.25}\sqrt{a})) \longrightarrow (f(1 - 2^{-0.25}\sqrt{a}), f(1 + 2^{-0.25}\sqrt{a}))$$

so that $\tau(e_0) = e'_0$ and $\psi_{c'} \circ \tau = u \circ \psi_c$ on $(f(1-2^{-0.25}\sqrt{a}), f(1+2^{-0.25}\sqrt{a}))$. Remember that all critical points of $\psi_c, \psi_{c'}$ are nondegenerate. This shows that τ is of class C^ω. Therefore, by Lemma 3.2, τ is a Nash diffeomorphism. Set

$$\psi_{c0}^{-1} \circ \psi_c(e_0) = e, \psi_{c'0}^{-1} \circ \psi_{c'}(e_0) = e',$$

$$(\psi_{c0}^{-1} \circ \psi_c)^{-1}(e) = \{e_i\}_{i\in\mathbb{Z}},$$

$$(\psi_{c'0}^{-1} \circ \psi_{c'})^{-1}(e') = \{e'_i\}_{i\in\mathbb{Z}}.$$

Then τ satisfies

$$\tau(e_i) = e'_i \text{ for any } i \in \mathbb{Z} \text{ or },$$

$$\tau(e_i) = e'_{-i} \text{ for any } i \in \mathbb{Z}.$$

A map $f \circ (\text{translation}) \circ f^{-1}$ takes $(f(1-2^{-0.25}\sqrt{a}), f(1+2^{-0.25}\sqrt{a}))$ to $(f(0), f(2^{0.75}\sqrt{a}))$, and a similar map $f \circ (\text{translation}) \circ f^{-1}$ takes $(f(1-2^{-0.25}\sqrt{a'}), f(1+2^{-0.25}\sqrt{a'}))$ to $(f(0), f(2^{0.75}\sqrt{a'}))$, we may suppose that e_i and e'_i are converge to 0 as $i \longrightarrow \infty$. Assume that e and e' lie in $(f(0), f(1))$. Then it follows from [3.1] and [3.2] that

[3.3]
$$\lim_{i\to\infty} e_{-i-2}/e_{-i} = f(c),$$

[3.4]
$$\lim_{i\to\infty} e'_{-i-2}/e'_{-i} = f(c').$$

Let Z denote the Zariski closure of $graph(\tau)$. This is of dimension 1 because τ is semialgebraic. It is clear that Z contains all (e_i, e'_i). Let $P(x,y) = \sum_{j=1}^{s} \delta_j x^{\beta_j} y^{\gamma_j}$ ($\delta_j \in \mathbb{R}, \beta_j, \gamma_j \in \mathbb{N}$) be a defining polynomial of Z. Then

$$P(e_i, e'_i) = 0 \text{ for any } i \in \mathbb{Z}.$$

Since α is irrational,

[3.5]
$$\beta_i + \alpha\gamma_i \neq \beta_j + \alpha\gamma_j \text{ for } i \neq j.$$

Set

$$P_i(x,y) = x^{\beta_i} y^{\gamma_i}.$$

For each $n \in \mathbb{Z}$, let $E(n)$ denote the $s \times s$-matrix whose (i,j) entry is

$$P_i(e_{-n-2j+1}, e'_{-n-2j+1}).$$

Then

$$(\delta_1, \ldots \delta_l)E(n) = (P(e_{-n-1}, e'_{-n-1}), \ldots, P(e_{-n-2s+1}, e'_{-n-2s+1}) = 0.$$

In particular $\det E(n) = 0$. On the other hand, we have

$$\det E(n) = (\prod_{i=1}^{s} P_i(e_{-n-1}, e'_{-n-1})) \det F(n),$$

where $F(n)$ is the $s \times s$-matrix whose (i,j) entry is

$$P_i(e_{-n-2j+1}, e'_{-n-2j+1})/P_i(e_{-n-1}, e'_{-n-1}).$$

Now [3.3] and [3.4] mean that each entry of $F(n)$ converges to

$$(c^{\beta_i}(c')^{\gamma_i})^{j-1} = c^{(\beta_i+\alpha\gamma_i)(j-1)}$$

as $n \longrightarrow \infty$. Thus det $F(n)$ converges to a Vandermonde's determinant equals

$$\prod_{i<j}(c^{\beta_j+\alpha\gamma_j} - c^{\beta_i+\alpha\gamma_i}) \neq 0,$$

by [3.5]. Therefore det $E(n) \neq 0$ for large n. This proves the result. □

4. Compactifiable $C^\infty G$ manifolds.

The same argument of the proof of Theorem 1 (3) proves Theorem 2 (2). To prove Theorem 2 (1), we show a relative version of Theorem 3.1. After proving Theorem 4.2, we give a proof of Theorem 2 (1).

Definition 4.1. (1)An algebraic subset of a representation of G is said to be an *algebraic G set* if it is G invariant. Moreover we call it a *nonsingular algebraic G set* if it is nonsingular.
(2)Let X be a $C^\infty G$ manifold and let X' be a $C^\infty G$ submanifold of X. A pair (X, X') is called *algebraically G cobordant* if there exist a nonsingular algebraic G set Y, a nonsingular algebraic G subset Y' of Y, a G cobordism N between X and Y, and a G cobordism N' between X' and Y' such that N' is a $C^\infty G$ submanifold of N.

Theorem 4.2. *Let G be a compact affine Nash group, X a compact $C^\infty G$ manifold, and X' a compact $C^\infty G$ submanifold of X. If the pair (X, X') is algebraically G cobordant then there exist a nonsingular algebraic G set Z in $X \times \Omega$ for some representation Ω of G, a nonsingular algebraic subset Z' of Z, and a $C^\infty G$ diffeomorphism $\phi : X \longrightarrow Z$ with $\phi(X') = Z'$.*

For any $C^\infty G$ manifold X and $C^\infty G$ submanifold X' of X, the pair $(X \coprod X, X' \coprod X')$ is algebraically G cobordant. Therefore we have the next corollary because a G invariant collection of connected components of a nonsingular algebraic G set is an affine Nash G submanifold in some representation of G.

Corollary 4.3. *Let G be a compact affine Nash group, X a compact $C^\infty G$ manifold, and X' a compact $C^\infty G$ submanifold of X. Then there exist an affine Nash G manifold Y, an affine Nash G submanifold Y' of Y, and a $C^\infty G$ diffeomorphism $\phi : X \longrightarrow Y$ so that $\phi(X') = Y'$.* □

Proof of Theorem 4.2. By the proof of Theorem 1.3 [1], X' is G isotopic to a nonsingular algebraic G subset Z' of $X \times \Omega$ by an arbitrarily small isotopy, for some representation of G. Extending this isotopy, we may assume that it maps $X \times 0$ to some $C^\infty G$ manifold M in $X \times \Omega$ so that $M - X \times 0$ has compact closure and that the composition of the inclusion $M \longrightarrow X \times \Omega$ with the projection

$X \times \Omega \longrightarrow X$ is a $C^\infty G$ diffeomorphism. In particular $Z' \subset M$. Since Z' is compact and by Lemma 4.7 [1], one can find a proper G invariant polynomial ρ such that $\rho^{-1}(0) = Z'$. Let $\alpha : X \longrightarrow \Omega$ be a $C^\infty G$ map with compact support so that

$$M = \{(x,y) \in X \times \Omega | y = \alpha(x)\}.$$

Take a G invariant C^∞ function $\beta : X \times \Omega \longrightarrow [0,1]$ with compact support with $\beta(x,y) = 1$ when $|y| < 2|\alpha(x)|$. Let $\gamma : X \times \Omega \longrightarrow \Omega$ be

$$\gamma(x,y) = \beta(x,y)(y - \alpha(x)) + (1 - \beta(x,y))\rho^2(x,y)y.$$

Then 0 is a regular value of γ, $\gamma^{-1}(0) = M$, and γ is equal to the polynomial $\rho^2(x,y)y$ outside of a G invariant compact set. By Lemma 5.1 [1], one can C^1 approximates $\gamma(x,y) - \rho^2(x,y)y$ by an equivariant entire rational map $u : (X \times \Omega, Z') \longrightarrow (\Omega, 0)$. Here an entire rational map means a fraction of polynomial maps with nowhere vanishing denominator. This approximation is close on all $X \times \Omega$. Thus

$$w(x,y) = u(x,y) + \rho^2(x,y)y$$

is C^1 approximation of γ on $X \times \Omega$. Since ρ is proper and by equivariant Morse theory, there exists a $C^\infty G$ diffeomorphism from $Z := w^{-1}(0)$ to $M = \gamma^{-1}(0)$ fixing Z'. □

Proof of Theorem 2 (1). Since X is compactifiable, there exists a $C^\infty G$ manifold X' with boundary ∂X so that X is $C^\infty G$ diffeomorphic to the interior of X'. Let Y be the double of X'. Applying Corollary 4.3 to the pair $(Y, \partial X')$, one can find a representation Ω of G and a $C^\infty G$ imbedding $F : Y \longrightarrow \Omega$ such that $F(Y)$ and $F(\partial X')$ are affine Nash G manifolds. Hence $F(X)$ is an affine Nash G manifold. Therefore X admits an affine Nash G manifold structure. □

On the other hand, T. Petrie [3] proved that any nonsingular algebraic G set is compactifiable as a $C^\infty G$ manifold when G is an algebraic group. A similar proof shows the next theorem, because the number of connected components of the zeros of a Nash map is finite.

Theorem 4.4. *Let G be a compact affine Nash group. Then every affine Nash G manifold is compactifiable as a $C^\infty G$ manifold.* □

M. Shiota studied compactifications of Nash manifolds as either C^∞ manifolds [4] or Nash manifolds [5].

By Theorem 2 (1) and Theorem 4.4, we have the following.

Theorem 4.5. *Let G be a compact affine Nash group. Then a $C^\infty G$ manifold is compactifiable if and only if it admits an affine Nash G manifold structure.* □

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