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APPROXIMATION THEOREMS AND NASH CONJECTURE

by Alberto TOGNOLI

Summary :

The purpose of this lecture is to illustrate some applications of Weierstrass' and Whitney's approximation theorems in their relative form.

In particular it will be mentioned how from these descends a theorem which affirms that the classification of the analytic fiber bundle on a coherent real analytic space coincides with the topological one.

Then, using Weierstrass' relative approximation theorem, an outline of the proof of the following fact will be given : every compact differentiable variety admits a structure of regular algebraic variety.

§ 1 . THE RELATIVE APPROXIMATION THEOREMS

a) Some definitions.

In this article we shall study only entities defined on the real field. Let U be an open set of $\mathbb{R}^n$, O_U denotes the sheaf of germs of the real analytic functions on U and $\Gamma(O_U)$ the ring of (global) sections of O_U .

A function $f \in \Gamma(O_U)$ is said algebraic if for any point $x \in U$ there exists a neighbourhood U_{x_0} and some polynomials $\alpha_i : \mathbb{R}^n \to \mathbb{R}$ such that

$$\sum_{i=0} (f(x))^i \alpha_i(x) = 0 , \forall x \in U_{x_0}$$

Let $\mathfrak{A}_U$ denote the sheaf of germs of algebraic functions.
Let V be a closed subset of U , V is said an analytic subset of U if the following condition is satisfied : for every $a \in V$ there exists an open neighbourhood U_a such that :

$$V \cap U_a = \{x \in U_a | f_1(x) = \dots = f_q(x) = 0 , f_i \in \Gamma(O_{U_a})\} .$$

Let V be an analytic subset of U and $\mathfrak{J}_V$ denote the ideal subsheaf of O_U of germs of the analytic functions that are identically zero on V .

Finally we denote $O_V = O_{U/\mathfrak{J}_V}$, the sheaf O_V is said the <u>sheaf of germs of analytic functions</u> on V .

In such a way, to any analytic set V of U , is associated a local ringed space.

Then a local ringed space (X,O_X) is said a <u>real analytic space if</u> :

I) X is paracompact.

II) (X,O_X) is locally isomorphic to a ringed space associated to an analytic subset of an open set of $\mathbb{R}^n$.

In a similar way we define <u>algebraic set</u> of U any closed set that, locally, is the set of zeros of algebraic functions, and we associate to any algebraic set V the sheaf $\mathfrak{A}_V = \mathfrak{A}_{U/\mathfrak{J}_V^a}$ of germs of algebraic functions restricted to V .

Finally a local ringed space (X,O_X) is said an <u>algebraic space</u> if it is paracompact and locally isomorphic to a ringed space associated to an algebraic set.

A closed set V of $\mathbb{R}^n$ is said an <u>affine variety</u> if there exist some polynomials $f_i : \mathbb{R}^n \to \mathbb{R}$ $i = 1,\dots,q$ such that $V = \{x \in \mathbb{R}^n | f_1(x) = \dots = f_q(x) = 0\}$.

Let V be an affine variety, we shall denote R_V the sheaf of germs of regular functions on V . Using affine varieties (V,R_V) as local models one defines <u>algebraic varieties</u> (see [1]).

If X , Y are real analytic spaces or algebraic spaces or algebraic varieties we shall use the term morphism (and isomorphism) of X into Y instead of morphism (and isomorphism) of ringed spaces. If X , Y are analytic spaces a morphism is usually said an analytic map.

Let U be an open set of $\mathbb{R}^n$, V an analytic set, $x_o \in V$ and V_{x_o} the germ of V at x_o .

We shall say that V is <u>regular in the point</u> x_o if it is possible to find $q = n - \dim V_{x_o}$ analytic functions $f_1,\dots,f_q$, defined on a neighbourhood U_{x_o} of x_o , such that :

I) $V \cap U_{x_o} = \{x \in U_{x_o} | f_1(x) = \dots = f_q(x) = 0\}$

II) $(df_1)(x_o),\dots,(df_q)(x_o)$ are linearly independent.

Let (X, O_X) be a real analytic space, we shall say that $x_o \in X$ is a <u>regular point</u> if there exists a neighbourhood B_{x_o} of x_o that is isomorphic to an analytic set containing only regular points. A point that is not regular is called <u>singular</u>. A similar definition of regular point is given for algebraic spaces and algebraic varieties.

Let (X , O_X) be a real analytic space (real algebraic variety) containing only regular points then X is called an analytic (algebraic) real <u>manifold</u>. An algebraic space that contains only regular points is called a <u>regular algebraic space</u>.

Let U be an open set of $\mathbb{R}^n$ and V an analytic (algebraic) subset of U ; it is a well known fact, (see [2],[3]), that in general the sheaf $\mathcal{J}_V$ $(\mathcal{J}^a_V)$ is not coherent considered as O_U - module $(\mathfrak{A}_U$ - module).

We shall say that an <u>analytic (algebraic) subset</u> of U is <u>coherent</u> if the sheaf $\mathcal{J}_V$ $(\mathcal{J}^a_V)$ is a coherent O_U - module $(\mathfrak{A}_U$ - module).

An <u>analytic (algebraic) space</u> is called coherent if any point $x_o \in X$ has a neighbourhood isomorphic to an analytic (algebraic) coherent subset of some open set of $\mathbb{R}^n$.

It is known that an algebraic space is coherent if and only if the associated real analytic space is coherent (see [3]). Finally we remember that any real analytic manifold and any regular algebraic space is coherent.

Let V be an affine variety of $\mathbb{R}^n$, $x_o \in V$ and $\mathcal{J}(V_{x_o})$, $(I(V_{x_o}))$ the rings of germs of analytic functions (and of polynomials) that are zero on the germ V_{x_o} of V at x_o (on V) .

Let O_{x_o} be the ring of germs of analytic functions defined in some neighbourhoods of x_o in $\mathbb{R}^n$.

We shall say that the point x_o is an <u>almost regular</u> point of V if $\mathcal{J}(V_{x_o})$ is generated, as O_{x_o} - module, by $I(V_{x_o})$.

An affine variety V is said <u>almost regular</u> if V is almost regular in any point.

It is easy to prove that x_o is an almost regular point of V if, and only if, the intersection of all the germs of complex analytic sets of $\mathbb{C}^n$ that contains V_{x_o} is the germ of a complex affine variety that contains V (see [4]). As a consequence we have that any regular point of V (considered as affine variety) is almost regular.

b) <u>The approximation theorems</u>.

In the suite we will give some applications of the following theorems :

THEOREM 1. - <u>Let</u> U <u>be open in</u> $\mathbb{R}^n$, V <u>a coherent analytic subset of</u> U <u>and</u> $g \in \Gamma(O_V)$ <u>an analytic function on</u> V . <u>Let</u> $\{K_n\}_{n\in\mathbb{N}}$ <u>be a sequence of compact</u>

sets in U such that :

$$K_n \subset \overset{\circ}{K}_{n+1} \quad , \quad \bigcup_{n\in\mathbb{N}} K_n = U \ .$$

Let $\{n_t\}_{t\in\mathbb{N}}$ be a sequence of positive integers.
Finally let $\{\varepsilon_t\}_{t\in\mathbb{N}}$ be a sequence of positive numbers.
Then for any function $f : U \to \mathbb{R}$ of class C^∞ such that $f|_V = g|_V$ there exists an analytic function $h : U \to \mathbb{R}$ with the following properties :

I) $\left| \dfrac{\partial^\alpha (f-h)(x)}{\partial x_1^{\alpha_1} \cdots\cdots \partial x_n^{\alpha_n}} \right| < \varepsilon_p$ for any $x \in K_{p+1} - K_p$ and $0 \leqslant \alpha < n_p$

II) $f|_V = h|_V$

THEOREM 2. - Let U be an open set of $\mathbb{R}^n$, V a compact affine almost regular variety contained in U . Suppose that V , considered as analytic set, is coherent and denote by $p : \mathbb{R}^n \to \mathbb{R}$ a polynomial function.
Let $f : U \to \mathbb{R}$ be a function of class C^∞ such that $f|_V = p|_V$, H a compact set of U and ε a positive number.
Then, for every positive integrer q , there exists a polynomial $h : \mathbb{R}^n \to \mathbb{R}$ such that :

I) $\left| \dfrac{\partial^\alpha (f-h)(x)}{\partial x_1^{\alpha_1} \cdots\cdots \partial x_n^{\alpha_n}} \right| < \varepsilon$, for any $x \in H$, $0 \leqslant \alpha < q$

II) $f|_V = h|_V$

THEOREM 3. - Let U be an open set of $\mathbb{R}^n$, V a compact, coherent affine almost regular variety contained in U and $p : U \to \mathbb{R}$ an algebraic function.
Let $f : U \to \mathbb{R}$ be a function of class C^∞ such that $f|_V = p|_V$, H a compact set of U and ε a positive number.
Then, for every positive integer q , there exists an algebraic function $h : U \to \mathbb{R}$ such that conditions I) and II) of theorem 2 are satisfied.

We shall give a sketch of the proof of theorem 2 .

Let $\mathbb{R}\{X_1,\ldots,X_n\}$, $\mathbb{R}[[X_1,\ldots,X_n]]$ be the ring of convergent power series and formal power series.

In the following on local rings we shall consider the M-adic topology and we shall denote by $\hat{A}$ the completion of A .

A ring A is said analytic (or formal) if $A = \mathbb{R}\{X_1,\dots,X_n\}/\mathfrak{J}$ ($A = \mathbb{R}[[X_1,\dots,X_n]]/\mathfrak{J}$) where $\mathfrak{J}$ is an ideal.

It is known that analytic and formal rings are local noetherian rings and Hausdorff spaces (with respect to M-adic topology).
From the last assertion the following equality is clear : for any ideal $\mathfrak{J}$ of an analytic or formal ring A we have

$$\hat{\mathfrak{J}} = \hat{A} \cdot \mathfrak{J} \overset{\text{def}}{=} \{x \in A \mid x = \sum_{i=1}^{q} \alpha_i g_i \ , \ \alpha_i \in \hat{A} \ , \ g_i \in \mathfrak{J}\} .$$

($\hat{A}\cdot\mathfrak{J}$ is dense in $\hat{\mathfrak{J}}$, but $\hat{A}\cdot\mathfrak{J}$ is an ideal, then closed, and we have $\hat{\mathfrak{J}} = \hat{A}\cdot\mathfrak{J}$).

Let U be an open set of $\mathbb{R}^n$, 0 the origin and suppose $0 \in U$. Let E be a set contained in U and g a function of class C^∞ defined in a neighbourhood of 0 ; we shall say that g has on E, in 0, a <u>zero</u> of <u>infinite order</u> if for any $p \in \mathbb{N}$ there exists a positive number C_p and a neighbourhood B_p of 0 such that on $B_p \cap E$ we have : $|g(x)| < C_p \cdot \|x\|^p$ where

$$x = (x_1,\dots,x_n) \ , \ \|x\| = \sum_{i=i}^{n} x_i^2 .$$

We remark that if g has a zero of infinite order on E in 0 then any function h having the same formal development has the same property.

Finally we shall denote by $\mathfrak{J}(E_0)$ the subset of $\mathbb{R}[[X_1,\dots,X_n]]$ of the elements associated to a germ of a C^∞ - function having a zero of infinite order on E in 0.

If E_0 is a germ of analytic set (algebraic variety) we shall denote by $\mathfrak{J}(E_0)$ ($P(E_0)$) the ring of germs of analytic functions (polynomials) that are zero on E_0.

It is clear that in the above definitions the choice of the origin as fixed point is inessential.

Using the above notation we have the following

LEMMA 1. - <u>Let V be an affine variety of $\mathbb{R}^n$ and $x \in V$ be an almost regular point, then we have</u>

$$\widehat{P(V_x)} = \widehat{\mathfrak{J}(V_x)} = \mathfrak{J}(V_x)$$

<u>Proof</u> : The first equality is a consequence of the definition of almost regular point, the second is proved in [6].

LEMMA 2. - Let V be an affine variety of $\mathbb{R}^n$, $x \in V$ be an almost regular point and suppose that V , considered as an analytic space, is coherent in x .
Let $f : U(x) \to \mathbb{R}$ be a function of C^∞ class defined on a neighbourhood $U(x)$ of x in $\mathbb{R}^n$.
If $f|_{U(x) \cap V} = 0$ there exist some polynomials $g_1,\dots,g_q$ and some C^∞ functions $\alpha_1,\dots,\alpha_q$, defined on a neighbourhood $U'(x)$ of x , such that :

$$f(y) = \sum_{i=i}^{q} \alpha_i(y)\ g_i(y) \quad , \quad \forall\, y \in U'(x) \quad \text{and} \quad g_i|_V \equiv 0 \ .$$

Proof : By hypothesis there exists a neighbourhood $D(x)$ of x in V and some polynomials $g_1,\dots,g_q$ such that : $g_i|_V = 0$, $i = 1,\dots,q$, for any $y \in D(x)$ the ring $\mathcal{J}(V_y)$ is generated by $g_1,\dots,g_q$.
For any $y \in D(x)$ the germ f_y of f is, in virtue of lemma 1, of the form

$$(1) \qquad f_y = \sum_{i=i}^{q} (\alpha_i)_y\ (g_i)_y \qquad \text{where} \quad (\alpha_i)_y \in \mathbb{R}[[X_1 ,\dots, X_n]] \ .$$

By a result of Malgrange (see [8]) from (1) we deduce that f_x is a linear combination of $(g_i)_x$ with C^∞ coefficients and the lemma is proved.

LEMMA 3. - Let V be an affine, compact, almost regular subvariety of $\mathbb{R}^n$ and $f : U \to \mathbb{R}$ a function of class C^∞ defined on a neighbourhood U of V .
Let K be a compact set of U , and suppose $f|_V \equiv 0$, then there exist some polynomials $g_1,\dots,g_q$ and some functions $\alpha_1,\dots,\alpha_q$ of class C^∞ defined on a neighbourhood U_K of K such that :

$$f(x) = \sum_{i=i}^{q} \alpha_i(x)\ g_i(x) \quad , \quad \forall\, x \in U_K \quad \text{and} \quad g_i|_V \equiv 0 \quad , \quad i = 1,\dots,q \ .$$

Proof : V is almost regular and compact then there exist some polynomials $g_1,\dots,g_q$ such that : $g_i|_V = 0$, $\{g_i\}_{i=1,\dots,q}$ generate $\mathcal{J}(V_x)$ for any $x \in V$ and if $x \notin V$ then there exists i such that $g_i(x) \neq 0$.
For any $x \in U$ there exists a neighbourhood U_x and some functions of class C^∞ : $\{\alpha_i^x\}_{i=1,\dots,q}$ such that

$$(1) \qquad f(y) = \sum_{j=1}^{q} \alpha_j^x(y)\ g_j(y) \quad , \quad \forall\, y \in U_x \ .$$

In fact, if $x \in V$, (1) is a consequence of lemma 2, if $x \notin V$ then there exists g_i such that $g_i(x) \neq 0$ and we can write $f(y) = f(y)/g_i(y) \cdot g_i(y)$.

So we have proved that there exists a finite open, (in $\mathbb{R}^n$), covering $\{U_i\}_{i=1,\ldots,s}$ of K and functions $\{\alpha_j^i\}_{\substack{j=1,\ldots,q \\ i=1,\ldots,s}}$ of class C^∞, such that we have : $f(y) = \sum_{j=1}^{q} \alpha_j^i(y)\, g_j(y)$, $\forall\, y \in U_i$.

Let $\{\rho_i\}_{i=1,\ldots,s}$ be a partition of unity of class C^∞ relative to the covering $\{U_i\}_{i=1,\ldots,s}$.

The we have :

$$f(x) = f(x) \cdot \sum_{i=1}^{s} \rho_i(x) = \sum_{i=1}^{s} \rho_i(x) \cdot \sum_{j=1}^{q} \alpha_j^i(x)\, g_j(x) =$$

$$= \sum_{i,j} \rho_i(x)\, \alpha_j^i(x) g_j(x) = \sum_{j=1}^{q} g_j(x) \cdot \sum_{i=1}^{s} \alpha_j^i(x)\, \rho_i(x) =$$

$$= \sum_{j=1}^{q} \alpha_j(x)\, g_j(x)$$

where $\alpha_j = \sum_{i=1}^{s} \alpha_j^i \rho_i$.

The functions α_j are of class C^∞ and the lemma is proved.

<u>Proof of theorem 2.</u> : We have $f - p|_V \equiv 0$ then it is enough to prove the theorem for the function $g = f - p$ such that $g|_V = 0$.

Lemma 3 affirms that there exist some polynomials $g_1,\ldots,g_q$ and C^∞ functions $\alpha_1,\ldots,\alpha_q$ defined on a neighbourhood U_K of K such that :

$$g(x) = \sum_{j=1}^{q} \alpha_j(x)\, g_j(x) \quad , \quad x \in U_K \quad \text{and} \quad g_j|_V \equiv 0 \; , \; j = 1,\ldots,q \; .$$

It is now possible, by the classical Weierstrass approximation theorem, to choose polynomials $\hat{\alpha}_j$ such that the polynome $\sum_{j=1}^{q} \hat{\alpha}_j\, g_j + p$ satisfies the conditions of theorem 2.

<u>Remark</u> : The proof of theorem 3 is quite similar.

The proof of theorem 1 is of the same type but more difficult because in general we need infinitely many elements of $\Gamma_V(\mathfrak{I})$ to generate $\mathfrak{I}(V_x)$, $x \in V$.

After we use Whitney's approximation theorem instead of Weierstrass theorem. Theorem 1 is contained in [20].

§ 2 . APPROXIMATION THEOREMS IN THE CASE OF MANIFOLDS

It is a natural problem to see if it is possible to deduce from theorems 1,2,3 some results of the following type :

1') let X , Y be two real analytic spaces and $f : X \to Y$ a continuous map, then f can be approached by analytic maps $f_i : X \to Y$ such that any f_i is in the same homotopy class of f .

2') let X , Y be two affine, compact varieties and $f : X \to Y$ a continuous map, then f can be approached by a sequence of morphisms.

3') let X , Y be two compact algebraic spaces and $f : X \to Y$ a continuous map, then f can be approached by a sequence of morphisms $f_n : X \to Y$ such that any f_n is in the same homotopy class of f .

It is also possible to see for "relative problem" of type 1'), 2'), 3').

In the next proposition we shall give a partial solution to problem 1').

PROPOSITION 1. - Let X be a coherent real analytic space and suppose that for any connected component X_i of X we have $\dim X_i < +\infty$.

Let Y be a real analytic manifold, $d : Y \times Y \to \mathbb{R}$ a continuous metric and $f : X \to Y$ a continuous map.

Then, for any $\varepsilon > 0$, there exists an analytic map $h : X \to Y$ such that : $d(f(x) , h(x)) < \varepsilon$, $\forall\, x \in X$ and h is homotopic to f .

Proof : We may suppose X connected.

There exists an analytic proper injective map $j : X \to \mathbb{R}^n$, $n = 2 \dim X + 1$, such that $j : X \to j(X)$ is homeomorphism and $j(X)$ is a coherent real analytic space (see [9]).

It is then clear that it is enough to solve the problem for the analytic subspace $j(X)$ of $\mathbb{R}^n$ and the function $f' = f \circ j^{-1}$, so in the following we shall suppose X subspace of $\mathbb{R}^n$.

It is known that Y may be considered as a submanifold of $\mathbb{R}^m$, $m \geqslant 2 \dim Y+1$ and there exists a tubular neighbourhood U of Y in $\mathbb{R}^m$.

By definition of tubular neighbourhood there exists an analytic map $p : U \to Y$ such that : $p(x) = x$, if $x \in Y$, and p is homotopic to the identity map $i : U \to U$.

Any continuous map $f : X \to Y$ may be approached by C^∞ maps $f'_i : X \to U \subset \mathbb{R}^m$ (see [10]) ; theorem 1 asserts that we can approach f'_i by analytic maps $f''_i : X \to U \subset \mathbb{R}^m$.

If f'_i is close enough to f and f''_i to f'_i the analytic map $f_i = p \circ f''_i : X \to Y$ approaches f in the required sense.

Finally it is easy to verify that if f''_i approaches enough f then f_i is homotopic to f .

The proposition is now proved.

The demonstration of proposition 1 points out that we obtain results of type 1'), 2'), 3') if the following conditions are satisfied :

a) X and Y are imbedded in some euclidian space ;

b) Y has a tubular neighbourhood.

So we can affirm that (at last following this way) we cannot solve the problem 1') if Y is singular (it is known that, if Y has at least a singular point, it is impossible to find a tubular neighbourhood).

Analogously we cannot solve problem 2') and we can solve problem 3') only if X and Y are isomorphic to algebraic subspaces of some euclidian space(*) and Y is regular at any point (the existence of tubular neighbourhoods for algebraic regular subspaces of $\mathbb{R}^n$ is proved in [3]).

It is not difficult to convince ourself that result 1'), if Y is singular, result 2'), result 3') if X or Y are not imbedded are false (at least in general)

For example let :

$$X = \{(x,y) \in \mathbb{R}^2 | x^2 + y^2 - 9 = 0\}$$

$$Y_1 = \{(x,y) \in \mathbb{R}^2 | x^2 + (y-1)^2 - 1 = 0\}$$

$$Y_2 = \{(x,y) \in \mathbb{R}^2 | x^2 + (y+1)^2 - 1 = 0\}$$

$Y = Y_1 \cup Y_2$ and $f : X \to Y$ the projection of X into Y from the origin 0 of $\mathbb{R}^2$.

It is easy to verify that :

f is continuous but for any analytic map $f' : X \to Y$ we have $f'(X) \subset Y_1$ or $f'(X) \subset Y_2$.

(*) In general a regular compact algebraic space is not isomorphic to a subspace of an euclidian space (see [3]).

So we conclude that f cannot be approximated by analytic map and any analytic map $f' : X \to Y$ is not homotopic to f .

About the problem 2') we remark the following : if it should be possible to obtain results of type 2') then we shall also have that two compact regular affine varieties are isomorphic if and only if they are C^∞ - isomorphic and this is false (*) (in fact for proving this last result we need a stronger version of 2') involving approximation of derivatives).

About the problem 3') we remark the circle S^1 may be considered as a real algebraic subspace of $\mathbb{R}^2$, and also with the algebraic structure induced by $\mathbb{R}$ identifying S^1 with $\mathbb{R}/\mathbb{Z}$. It is easy to verify that S^1 , endowed with the last structure, has no global algebraic function ; we shall denote $\hat{S}^1$ the circle with this last structure.

It is now clear that the identity map $i : \hat{S}^1 \to S^1$ cannot be approximated by morphisms of algebraic structures and any morphism is not homotopic to i .

Using theorem 1 in the relative form we can strenghten proposition 1 and we obtain :

THEOREM 4. - Let X be a real coherent analytic space, X' a coherent analytic subspace of X such that $\dim X' < +\infty$.

Let Y be a real analytic manifold, $d : Y \times Y \to \mathbb{R}$ a continuous metric and $f : X \to Y$ a continuous map such that $f|_{X'}$ is analytic.

Then for any $\varepsilon > 0$ there exists an analytic map $h : X \to Y$ such that :

$$f|_{X'} = h|_{X'} \ , \quad d(f(x) \, , h(x)) < \varepsilon \ , \quad \forall x \in X \text{ and } f \text{ is homotopic to } h \ .$$

The idea for proving theorem 4 is the following : let $X = \bigcup_{n \in \mathbb{N}} X_n$ the decomposition of X into irreducible components ; then one, using proposition 1 , approximate $f|_{X_1}$ by $f^1 : X_1 \to Y$, after, without changing $f^1|_{X_1 \cap X_2}$, one approximate $f|_{X_1 \cup X_2}$ ....

The family $\{X_n\}_{n \in \mathbb{N}}$ is locally finite so we can construct an analytic approximation of f .

Theorem 4 is proved in [11].

A problem tied to problem 1') is the following

1") Let X be a coherent real analytic space and $(B \xrightarrow{\pi} X \, , G \, , F)$ an analytic fiber bundle with structural Lie group G and fiber F . Suppose F is an analy-

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(*) In fact one proves that if two affine varieties X , X' are isomorphic then their complexifications are birationally equivalent.

tic manifold and $\gamma : X \to B$ be a continuous cross section.
We ask if it is possible to approach γ by analytic cross sections. A partial affirmative answer is given by

PROPOSITION 2. - Let X be an analytic manifold and $B \xrightarrow{\pi} X$ an analytic fiber bundle the fiber of which is a manifold. Let $d : B \times B \to \mathbb{R}$ be a continuous metric on B, X' a coherent analytic subspace of X and $\gamma : X \to B$ a continuous cross section such that $\gamma|_{X'}$ is analytic.
Then for any $\varepsilon > 0$ there exists an analytic cross section $\gamma_a : X \to B$ such that :

$\gamma_a|_{X'} = \gamma|_{X'}$, $d(\gamma(x), \gamma_a(x)) < \varepsilon$, $\forall x \in X$ and γ_a is homotopic to γ .

Proof : B is an analytic manifold then, by proposition 1 , the map $\gamma : X \to B$ may be approached by analytic maps $\gamma_i : X \to B$ such that $\gamma|_{X'} = \gamma_i|_{X'}$.

In general the maps $\alpha_i = \pi \circ \gamma_i : X \to X$ are not the identity but, if γ_i is close enough to γ (*), we know that α_i is an isomorphism of analytic manifolds.

It is now clear that $\hat{\gamma}_i = \gamma_i \circ \alpha_i^{-1} : X \to B$ is an analytic cross section of B and, if γ_i is close enough to γ , then $\hat{\gamma}_i$ satisfies the condition $d(\hat{\gamma}_i(x), \gamma(x)) < \varepsilon$, $\forall x \in X$.
If $x \in X'$ we have $\alpha_i(x) = x$ then $\hat{\gamma}_i(x) = \gamma_i(x) = \gamma(x)$. The proposition 1 asserts that, if γ_i is close enough to γ , there exists a homotopy γ_i^t tieing γ_i to γ ; it is clear that γ_i^t ties $\hat{\gamma}_i$ to γ .

The proof is acquired.

As a consequence of the theorem 4 and the proposition 2 we can prove the following

PROPOSITION 3. - Let X , $\dim X < +\infty$, be a real coherent analytic space and $B_t \xrightarrow{\pi} X$ a topological principal fibre bundle of structural group G . If G is a connected (or a compact) Lie group then there exists an analytic fiber bundle $B_a \xrightarrow{\pi_a} X$ that is topologically equivalent to B_t .

Let X be a real analytic manifold and G a Lie group.

Let $B_i \xrightarrow{\pi_i} X$, $i = 1,2$, be two analytic principal fiber bundles with structural group G , then B_1 is analytically isomorphic to B_2 if and only if B_1 is topologically isomorphic to B_2 .

(*) Here we need that γ_i and their "first derivative" approach γ and its first derivative and this is possible by theorem 1 .

Proof : It is known (see [10]), that if the Lie group G is connected then, in the bundle $B_t \to X$, the structural group may be reduced to a compact subgroup G' .

For any $n \in \mathbb{N}$ there exists a universal bundle $U(G',n) \to D(G',n)$ relative to the group G' ; it is known (see [10]) that the universal bundle $U(G',n) \to D(G',n)$ may be endowed of real analytic structure.

To prove the first part of the proposition it is enough to show that any continuous map $\varphi : X \to D(G',n)$, $n = \dim X$, is homotopic to an analytic map $\varphi_a : X \to D(G',n)$ and this is proved in proposition 1 .

To prove the second part of proposition we recall that, given the fiber bundles B_1 , B_2 , there exists another fiber bundle : $B_{1,2} \to X$ such that B_1 is topologically (analytically) isomorphic to B_2 if and only if $B_{1,2}$ has at least one continuous (analytic) section (for the construction of $B_{1,2}$ see [13]).

It is now clear that the proposition 2 proves the second part of this proposition.

Proposition 2 is a particular case of the following

THEOREM 5. - Let X be a real coherent analytic space, $\dim X < \infty$ and X' a coherent analytic subspace.

Let $B \xrightarrow{\pi} X$ be a real analytic fiber bundle of structural Lie group G and fiber the analytic manifold F

Let $d : B \times B \to \mathbb{R}$ a continuous metric, $\gamma : X \to B$ a continuous cross section such that $\gamma|_{X'}$ is analytic.

Then, if G is connected, for any $\varepsilon > 0$ there exists an analytic section $\gamma_a : X \to B$ such that :

$\gamma|_{X'} = \gamma_a|_{X'}$, $d(\gamma(x) , \gamma_a(x)) < \varepsilon$, $\forall x \in X$ and γ is homotopic to γ_a .

Remark : It is possible to prove a version of proposition 1 and 2 for compact regular algebraic sets of $\mathbb{R}^n$ (the proofs are formally the same).

Also a weak form of proposition 3 may be proved for the compact algebraic subsets of $\mathbb{R}^n$.

§ 3 . AN APPLICATION OF THEOREM 2

Let V be a compact differentiable submanifold of $\mathbb{R}^n$; J. Nash in [14], has put the following problems :

I) does it exist an affine regular variety V_a isomorphic (as differentiable manifold) to V ?

II) if there exists V_a , is it possible to realize V_a as a submanifold of $\mathbb{R}^n$ close to V ?

Nash has proved that there exists an affine variety V'_a such that V'_a has an analytic component V_a that solves problems I) and II). In the terminology we have introduced we can say that Nash has solved problems I) and II) with a regular compact algebraic set V_a . Using theorem 2 we can prove that the problem I) has an affirmative resolution and problem II) can be solved if $n > 2 \dim V$ (*) . We now shall give some definitions to explain problem II). Let L , L' be two linear r-dimensional subspaces of $\mathbb{R}^n$ and $x_1,\ldots,x_r$, $y_1,\ldots,y_{n-r}$ a system of orthogonal coordinates of $\mathbb{R}^n$ such that : $L = \{(x_1,\ldots,x_r , y_1,\ldots,y_{n-r}) | y_1=\ldots=y_{n-r}=0\}$. We shall say that L' is an ε-approximation of L if L' has equations of the form

$$y_i = \sum_{j=1}^{r} a_{ij} x_j + c_i \ , \ i = 1,\ldots,n-r$$

with the condition $\sum_{i,j} |a_{ij}|^2 + \sum c_i^2 < \varepsilon$

Let V be a compact differentiable manifold of dimension r differentiably embedded in $\mathbb{R}^n$. At each point $x \in V$ take the disc D_x of radius δ contained in the $n - r$ dimensional linear space orthogonal to V .

If δ is small enough it is known that the union of all these discs has the structure of a fibre bundle over V .

This bundle is called the <u>normal bundle of radius</u> δ (**) and it is denoted by $B(\delta)$.

The set $B(\delta)$ is an open neighbourbood of V in $\mathbb{R}^n$ and the projection $p : B(\delta) \to V$ defined by : $p(y) = x$ if $y \in D_x$ is a differentiable map.

Let V' be a differentiable manifold of $\mathbb{R}^n$, we shall say that V' <u>is an</u> ε-<u>approximation of</u> V if :

1°/ V' is contained in the tubular neighbourbood $B(\varepsilon)$ of V

2°/ $p : V' \to V$ is an isomorphism of the differentiable structures

3°/ for any $x \in V'$ the tangent linear variety to V' at x is an ε-approximation of the tangent linear variety to V at $p(x)$.

(*) The author conjectures that problem II) can be solved without any restriction on the codimension of V .

(**) $B(\delta)$ is also called the tubular neighbourbood of radius δ .

Let V be a differentiable submanifold of $\mathbb{R}^n$ we shall say that V has, (in $\mathbb{R}^n$) an algebraic ε-approximation if there exists an affine regular subvariety V' of $\mathbb{R}^n$ that is an ε-approximation of V .
We shall say that V admits algebraic approximation if, for any $\varepsilon > 0$, V has an algebraic ε-approximation.
A formulation of problem II is the following :
Any compact differentiable submanifold of $\mathbb{R}^n$ admits algebraic approximation ?
It is possible to prove the following

THEOREM 6. - Let V be a compact differentiable submanifold of $\mathbb{R}^n$, $n > 2 \dim V$, then V admits algebraic approximation.

COROLLARY. - Any compact differentiable manifold is isomorphic to a regular affine variety.

Theorem 6 is proved in [4] we shall give here an idea of the proof. We need the following

LEMMA. - Any compact differentiable manifold is in the same cobordism class of a compact, regular affine variety.

Proof : Let $P_n(\mathbb{R})$ be the n-projective space on the real numbers. We denote by $z_o,\dots,z_n$, $w_o,\dots,w_m$, $m \leqslant n$ two systems of coordinates of $P_n(\mathbb{R})$ and $P_m(\mathbb{R})$.
We put :

$$H_{n,m}(\mathbb{R}) = \{\{z_j\}\times\{w_j\} \in P_n(\mathbb{R}) \times P_m(\mathbb{R}) | w_o z_o + w_1 z_1 + \dots + w_m z_m = 0\}$$

It is known (see [16]) that the manifolds $P_n(\mathbb{R})$, $H_{nm}(\mathbb{R})$ are generators of cobordism ring.
Then to prove the lemma it is enough to show that $P_n(\mathbb{R})$ has a structure of regular affine variety.
Let us consider the map $\chi_{ik} : P_n(\mathbb{R}) \to \mathbb{R}$ defined by

$$\chi_{ik}(x_j) = x_i x_k / \sum_{j=o}^{n} x_1^2$$

It is easy to verify that the map $\chi : P_n(\mathbb{R}) \to \mathbb{R}^{(n+1)^2}$ defined by $\chi(x) = \{\chi_{ik}(x)\}_{i,k=o,\dots,n}$ is injective, of maximum rank at any point and the set $\chi(P_n(\mathbb{R}))$ is the regular affine subvariety W of $\mathbb{R}^{(n+1)}$ defined by the equations :

$$\sum_{i=o}^{n} \chi_{ii} = 1$$

$$\chi_{ik}\, \chi_{lr} = \chi_{il}\, \chi_{kr}$$

$$\chi_{ik} = \chi_{ki} \quad i,k,l,r = o,\dots,n .$$

So we have proved that $P_n(\mathbb{R})$ is isomorphic to W ; it is now easy to verify that W is regular affine subvarity of $\mathbb{R}^{(n+1)^2}$.

Let V_1 , V_2 be two differentiable manifolds and suppose that V_1 is in the same cobordism class of V_2 .

By Whitney's embedding theorems, (see [17]) , we may suppose that there exists a differential submanifold, with boundary W of $\mathbb{R}^{n+1}$ such that, if $x_1,\dots,x_{n+1}$ are coordinates in $\mathbb{R}^{n+1}$, we have :

1°/ $W \subset \{\{x_i\} | x_{n+1} \geq 0\}$, the boundary $\partial W = V_1 \cup V_2$ of W is equal to $W \cap \{\{x_i\} | x_{n+1} = 0\}$.

2°/ the set $\hat{W} = W \cup \{(x_1,\dots,x_{n+1}) | (x_1,\dots,-x_{n+1}) \in W\}$ is a differentiable submanifold of $\mathbb{R}^{n+1}$.

3°/ the hyperplane $x_{n+1} = 0$ cuts transversally $\hat{W}$.

Furthermore if V_1 is an affine regular variety we may suppose that W is the disjoint union of a regular affine subvariety V_1' of $\mathbb{R}^{n+1}$, isomorphic to V_1 , and of a differentiable submanifold V_2' isomorphic to V_2 .

The manifold W shall be said the <u>torus</u> constructed on V_1 and V_2 .

The idea of the proof of theorem 6 is the following : let V_2 be a compact differentiable manifold and V_1 a regular compact affine variety in the same cobordism class. Let $\hat{W}$ be the torus constructed on V_1 and V_2 . Then we approach $\hat{W}$ by an affine regular variety W' in such a way that the intersection of W' with the hyperplane $x_{n+1} = 0$ is composed by two analytic compact manifolds V_1' , V_2' that are ε -approximation of V_1 , V_2 for some ε .

But if in the approximation process we use theorem 2 instead of the classical Weierstrass theorem we can obtain $V_1 = V_1'$. So we have that $V_1' \cup V_2'$ is a regular affine subvariety of $\mathbb{R}^n$, $V_1' = V_1$ is an affine regular subvariety and we can conclude that V_2' is affine and an ε -approximation of V_2 .

BIBLIOGRAPHY

[1] SERRE (Jean-Pierre). - Faisceaux algébriques cohérents. Ann. of Math.61 (1955)

[2] CARTAN (Henri). - Variétés analytiques réelles et variétés analytiques complexes. Bull. Soc. Math. France, 85 (1957) pp. 77-99

[3] LAZZERI (F.), TOGNOLI (Alberto). - Alcune proprietà degli spazi algebrici. Annali Sc. Norm. Sup. di Pisa, Vol XXIV, (1970) pp. 597-632.

[4] TOGNOLI (Alberto). - Su una congettura di J. Nash. Annali Sc. Norm. Sup. di Pisa, vol. XXVII, (1973), pp. 167-185.

[5] WHITNEY (H.). - Analytic extension of differentiable functions defined on closed sets. Trans. Amer. Math. Soc. 36, n° 1 (1934), pp. 63-89.

[6] MALGRANGE (B.). - Sur les fonctions differentiables et les ensembles analytiques. Bull. Soc. Math. France 91 (1963), pp. 113-127.

[7] SERRE (Jean-Pierre). - Géométrie algébrique et géométrie analytique . Ann. Inst. Fourier t. 6 (1955-56) pp. 1-42.

[8] MALGRANGE (B.). - Division des distributions. I-IV, Séminaire Schwartz (1959-1960), n° 21-25.

[9] TOGNOLI (Alberto), TOMASSINI (G.). - Teoremi di immersione per gli spazi analitici reali. Annali Sc. Norm. Sup. di Pisa (1967), pp. 575-598.

[10] STEENROD (N.E.). - Topology of fibre bundles. Princeton Math. Series Univ. Press 1951.

[11] TOGNOLI (Alberto). - Teoremi di approssimazione per gli spazi analitici reali coerenti non immergibili in $\mathbb{R}^n$. Annali Sc. Norm. Sup. di Pisa (1971), vol. XXV, pp. 507-516.

[12] COEN (S.). - Sul rango dei fasci coerenti. Boll. U.M.I., Ser. III<u>a</u> (1967), pp. 373-382.

[13] CARTAN (Henri). - Espaces fibrés analytiques. Symposium Internecional de topologia algebraica (1958) Mexico.

[14] NASH (J.). - Real algebraic manifolds. Annals of Math., vol. 56 (1952) pp. 405-421.

[15] TOGNOLI (Alberto). - Sulla classificazione dei fibrati analitici reali. Annali Sc. Norm. Sup. di Pisa (1967), vol. XXI, pp. 709-744.

[16] MILNOR (J.). - On the Stiefel-Whitney numbers of complex manifolds and of spin manifolds.

[17] WHITNEY (H.). - Differentiable manifolds. Annals of Math., vol. 37, (1936), pp. 647-680.

[18] WALLACE(A.H.). - Algebraic approximation of manifolds. Proc. London Math. Soc. (3) 7 (1957) pp. 196-210.

[19] TOGNOLI (Alberto). - L'analogo del teorema delle matrici.... Annali Sc. Norm. Sup. di Pisa (1968), vol. XXII, pp. 527-558.

[20] TOGNOLI (Alberto). - Un teorema di approssimazione relativo, to appear on Bollettino dell'unione matematica italiana.

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