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Recent Advances in Topological Manifolds

Introduction

A topological $n$-manifold is a Hausdorff space which is locally $n$-Euclidean (like $\mathbb{R}^n$).

No progress was made in their study (unlike that in PL and differentiable manifolds) until 1968 when Kirby, Siebenmann and Wall solved most questions for high dimensional manifolds (at least as much as for the PL and differentiable cases).

Question: can compact $n$-manifolds be triangulated? Yes, if $n \leq 3$ (Moise 1950’s). This is unknown in general.

However, there exist manifolds (of dimension $\geq 5$) which don’t have PL structures. (They might still have triangulations in which links of simplices aren’t PL spheres.) There is machinery for deciding whether manifolds of dimension $\geq 5$ have a PL structure.

Not much is known about 4-manifolds in the topological, differentiable, and PL cases.

Question 2: the generalized Schönhflies theorem. Let $B^n = \{ x \in \mathbb{R}^{n+1} : \|x\| \leq 1 \}$, $S^n = \{ x \in \mathbb{R}^{n+1} : \|x\| = 1 \}$. Given an embedding $f : B^n \to S^n$ (i.e. a 1-1 continuous map), is $S^n \setminus f(B^n) \cong B^n$? No–the Alexander horned sphere.

Let $\lambda B^n = \{ x \in \mathbb{R}^{n+1} : \|x\| \leq \lambda \}$. Question 2': is $S^n \setminus f(\lambda B^n) \cong B^n$ (where $0 < \lambda < 1$)? Yes.

In 1960, Morton Brown, Mazur, and Morse proved the following: if $g : S^{n-1} \times [-1, 1] \to S^n$ is an embedding, then $S^n \setminus g(S^{n-1} \times \{0\})$ has 2 components, $D_1, D_2$, such that $D_1 \cong D_2 \cong B^n$, which implies 2' as a corollary. (The proof is easier than that of PL topology).

Question 3: the annulus conjecture. Let $f : B^n \to \text{Int } B^n$ be an embedding. Is $B^n \setminus f(\frac{1}{2} B^n) \cong B^n \setminus \frac{1}{2} B^n$ (i.e. $S^{n-1} \times I$)? In 1968, Kirby, Siebenmann, and Wall proved this for $n \geq 5$. This was already known for $n \leq 3$. The $n = 4$ case is still unknown.

Outline of course:

- Basic facts about topological manifolds
- Morton Brown’s theorem – the first “recent” result
Kirby’s trick: Homeo(M) is a topological group (with the compact-open topology). This is locally contractible: any homeomorphism h near 1 can be joined by a path in Homeo(M) to 1

Product structure theorem: if $M^n$ is a topological manifold and $M \times \mathbb{R}^k$ has a PL structure, then $M^n$ has a PL structure ($n \geq 5$).

sketch of proof of the annulus conjecture (complete except for deep PL theorems).

1 Basic Properties of Topological Manifolds

Let $\mathbb{R}^n_+ = \{(x_1, \ldots, x_n) \in \mathbb{R}^n : x_n > 0\}$. Identify $\mathbb{R}^{n-1}$ with

\[ \{(x_1, \ldots, x_n) \in \mathbb{R}^n : x_n = 0\} = \partial \mathbb{R}^n_+. \]

**Definition 1.1.** A (topological) n-manifold (with boundary) is a Hausdorff space $M$ such that each point of $M$ has a neighborhood homeomorphic to $\mathbb{R}^n_+$. The interior of $M$, $\text{Int} M$, is the set of points in $M$ which have neighborhoods homeomorphic to $\mathbb{R}^n$. The boundary of $M$, $\partial M = M \setminus \text{Int} M$.

$\text{Int} M$ is an open set in $M$, $\partial M$ is closed in $M$.

$M$ is an open manifold if it is non-compact and $\partial M = \emptyset$.

$M$ is a closed manifold if it is compact and $\partial M = \emptyset$.

**Example.** Any open subset of an n-manifold is an n-manifold.

Let $M$ be a connected manifold with $\partial M = \emptyset$. If $x, y \in M$ then there is a homeomorphism $h : M \to M$ with $h(x) = y$.

**Theorem 1.2** (Invariance of domain). Let $U, V \subset \mathbb{R}^n$ be subsets such that $U \cong V$. Then if $U$ is open in $\mathbb{R}^n$, then so is $V$.

**Corollary 1.3.** If $M$ is an N-manifold, then $\partial M$ is an $(n-1)$-manifold without boundary.

**Proof.** Suppose $x \in M$ and $f : \mathbb{R}^n_+ \to M$ be a homeomorphism onto a neighborhood $N$ of $x$ in $M$. Then

\[ x \in \partial M \iff x \in f(\mathbb{R}^{n-1}) \quad (1) \]

If $x \notin f(\mathbb{R}^{n-1})$, then $x \in f(\mathbb{R}^n_+ \setminus \mathbb{R}^{n-1}) \cong \mathbb{R}^n$, so $x \in \text{Int} M$ and $x \notin \partial M$.

If $x \notin \partial M$, then $x \in \text{Int} M$, i.e. there is a neighborhood $U$ of $x$ homeomorphic to $\mathbb{R}^n \subset f(\mathbb{R}^n_+)$. So there is a neighborhood $V$ of $x$ which is open in $M$ such that $V \subset U$, homeomorphic to an open set in $\mathbb{R}^n$. Therefore $f^{-1}(V) \subset \mathbb{R}^n_+ \subset \mathbb{R}^n$. By theorem 1.2, $f^{-1}(V)$ is open in $\mathbb{R}^n$.

Suppose $x \notin f(\mathbb{R}^{n-1})$. Then $f^{-1}(x) \in \mathbb{R}^{n-1}$, but then $f^{-1}(V)$ can’t be a neighborhood of $f^{-1}(x)$, so $f^{-1}(V)$ is not open. This is a contradiction, therefore $x \in f(\mathbb{R}^{n-1}) \implies x \in \partial M$.

Now suppose $y \in \partial M$. Let $g : \mathbb{R}^n_+ \to M$ be a homeomorphism onto a neighborhood $P$ of $y$ in $M$. $P$ contains an open neighborhood $W$ of $y$ in $M$. 

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Now $W \cap \partial M = W \cap g(\mathbb{R}^{n-1})$ by (1). Therefore $W \cap g(\mathbb{R}^{n-1})$ is a neighborhood of $y$ in $\partial M$ homeomorphic to an open set $N$, so $y$ has a neighborhood in $\partial M$ homeomorphic to $\mathbb{R}^{n-1}$, as required.

\[ \text{Corollary 1.4. If } M^m, N^n \text{ are manifolds then } M \times N \text{ is an } (m+n)\text{-manifold} \]

with $\partial (M \times N) = (\partial M \times N) \cup (M \times \partial N)$, i.e. $\text{Int}(M \times N) = \text{Int } M \times \text{Int } N$.

**Proof.** If $x \in M \times N$, then $x$ has a neighborhood homeomorphic to $\mathbb{R}_+^m \times \mathbb{R}_+^n \cong \mathbb{R}_+^{m+n}$, so $M \times N$ is an $(m+n)$-manifold.

Clearly $\text{Int } M \times \text{Int } N \subseteq \text{Int } (M \times N)$.

If $x \in (\partial M \times N) \cup (M \times \partial N)$, then $x$ has a neighborhood homeomorphic to $\mathbb{R}_+^m \times \mathbb{R}_+^n$, $\mathbb{R}_+^m \times \mathbb{R}_+^n$, or $\mathbb{R}_+^m \times \mathbb{R}_+^n$ all homeomorphic to $\mathbb{R}_+^{m+n}$ by a homeomorphism carrying $x$ to $\mathbb{R}_+^{m+n-1}$. By (1), $x \in (M \times N)$. Hence the result. \( \square \)

**Example.** Examples of manifolds:

- $\mathbb{R}^m$ is an $m$-manifold without boundary, open.
- $S^m$ is a closed $m$-manifold. (Stereographic projection gives neighborhoods.)
- $B^m$ is a compact $m$-manifold with boundary $S^{m-1}$.
- $\mathbb{R}^n_+$ is an $m$-manifold with boundary $\mathbb{R}^{n-1}$.
- Products of these,
- $\mathbb{C}P^m$, orthogonal groups $O(n)$ are manifolds.

These are all differentiable manifolds. There exist topological manifolds which do not possess a differentiable structure.

**Lemma 1.5.** If $X \subset S^n$ is homeomorphic to $B^k$, then $\tilde{H}_r(S^n \setminus X) = 0$ for all $r \in \mathbb{Z}$.

**Proof.** By induction on $k$. The lemma is true if $k = 0$: $S^n \setminus \{ \text{pt.} \} \cong \mathbb{R}^n$.

Assume true if $k = l$, we prove it for $k = l + 1$. Choose a homeomorphism $f : B^l \times I \cong B^{l+1} \to X$, suppose $\alpha \in \tilde{H}_r(S^n \setminus X)$. Take $t \in I$. By induction hypothesis, $\tilde{H}_r(S^n \setminus f(B^l \times \{ t \})) = 0$. Therefore $\alpha$ is represented by the boundary of some singular chain $c$ lying in $S^n \setminus f(B^l \times \{ t \})$. There is a neighborhood $N_t$ of $f(B^l \times \{ t \})$ in $S^n$ such that $c$ lies in $S^n \setminus N_t$.

Therefore there is an open interval $J_t \subset I$ containing $t$ such that $c$ lies in $S^n \setminus f(B^l \times J_t)$ since the unit interval is compact, we can cover by finitely many of the $J_t$'s. Therefore there is a dissection $0 = t_0 < t_1 < \cdots < t_k = 1$ such that $[t_{p-1}, t_p] \subset$ some $J_t$.

Let $\phi_{p,q} : \tilde{H}_r(S^n \setminus X) \to \tilde{H}_r(S^n \setminus f(B^l \times [t_p, t_q]))$ where $p < q$ and the map is induced by inclusion. Now $\phi_{p-1, p}(\alpha) = 0$ for all $p$.

Suppose inductively that $\phi_m(\alpha) = 0$ starts with $i = 1$. By the main inductive hypothesis, $\tilde{H}_r(S^n \setminus f(B^l \times \{ t_i \})) = 0$ for $s = r, r + 1$. The sets $S^n \setminus f(B^l \times [t_p, t_q])$ are open. We have the lattice
Proof. By induction on $k$. If $k = 0$, then $S^0 \setminus \{0\}$ is homeomorphic to $S^0$. If $0 < k < n$, then $S^n \setminus \{0\}$ is homeomorphic to $S^n$.

Choose a homeomorphism $f : S^l \to X$. Let $D_1, D_2$ be northern and southern hemispheres of $S^l$ so that $D_1 \cup D_2 = S^l$ and $D_1 \cap D_2 \cong S^{l-1}$. The sets $S^n \setminus X$, $S^n \setminus f(D_1)$, and $S^n \setminus f(D_1 \cap D_2)$ are open. We have the lattice

$$
\begin{array}{c}
S^n \setminus f(D_1) \\
\downarrow \\
S^n \setminus f(D_2)
\end{array}
\quad
\begin{array}{c}
S^n \setminus X \\
\downarrow \\
S^n \setminus f(D_1 \cap D_2)
\end{array}
$$

and the Mayer-Vietoris sequence

$$
0 \to \tilde{H}_r(S^n \setminus f(D_1 \cap D_2)) \to \tilde{H}_r(S^n \setminus f(D_1)) \oplus \tilde{H}_r(S^n \setminus f(D_2)) \to \tilde{H}_r(S^n \setminus X) \to 0
$$

since $\tilde{H}_r(S^n \setminus f(D_1)) \cong \tilde{H}_r(S^n \setminus f(D_2)) \cong 0$ by the previous lemma. The result follows from the inductive hypothesis.

**Lemma 1.6.** If $X \subset S^n$ is homeomorphic to $S^k$, then

$$
\tilde{H}_r(S^n \setminus X) \cong \tilde{H}_r(S^{n-k-1}) = \begin{cases} 
\mathbb{Z} & \text{if } r = n - k - 1, \\
0 & \text{otherwise.}
\end{cases}
$$

**Proof.** By induction on $k$. The result is true if $k = 0$, for $S^k \setminus \{0\}$ is homeomorphic to a pair of points $\cong S^{n-1}$. Now assume the result holds for $k = l - 1$ and try to prove it for $k = l$.

Choose a homeomorphism $f : S^l \to X$. Let $D_1, D_2$ be northern and southern hemispheres of $S^l$ so that $D_1 \cup D_2 = S^l$ and $D_1 \cap D_2 \cong S^{l-1}$. The sets $S^n \setminus X$, $S^n \setminus f(D_1)$, and $S^n \setminus f(D_1 \cap D_2)$ are open. We have the lattice

$$
\begin{array}{c}
S^n \setminus f(D_1) \\
\downarrow \\
S^n \setminus f(D_2)
\end{array}
\quad
\begin{array}{c}
S^n \setminus X \\
\downarrow \\
S^n \setminus f(D_1 \cap D_2)
\end{array}
$$

and the Mayer-Vietoris sequence

$$
0 \to \tilde{H}_{r+1}(S^n \setminus f(D_1 \cap D_2)) \to \tilde{H}_{r+1}(S^n \setminus f(D_1)) \oplus \tilde{H}_{r+1}(S^n \setminus f(D_2)) \to \tilde{H}_{r+1}(S^n \setminus X) \to 0
$$

since $\tilde{H}_{r+1}(S^n \setminus f(D_1)) \cong \tilde{H}_{r+1}(S^n \setminus f(D_2)) \cong 0$ by the previous lemma. The result follows from the inductive hypothesis.

**Corollary 1.7.** If $f : S^{n-1} \to S^n$ is 1-1 and continuous, then $S^n \setminus f(S^{n-1})$ has just two components.

**Proof.** By 1.6, $\tilde{H}_0(S^n \setminus f(S^{n-1})) \cong \tilde{H}_0(S^n) \cong \mathbb{Z}$. Therefore, $S^n \setminus f(S^{n-1})$ has two components.

**Corollary 1.8.** If $f : B^n \to S^n$ is 1-1 and continuous, then $f(\text{Int } B^n)$ is open in $S^n$.  

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Proof. By lemma 1.5, \( \tilde{H}_0(S^n \setminus f(B^n)) = 0 \), so \( S^n \setminus f(B^n) \) is connected. Now \( S^n \setminus f(S^{n-1}) = f(\text{Int } B^n) \cup S^n \setminus f(B^n) \), and \( f(\text{Int } B^n) \) and \( S^n \setminus f(B^n) \) are connected, while \( S^n \setminus f(S^{n-1}) \) is not (by corollary 1.7). Thus \( f(\text{Int } B^n) \) and \( S^n \setminus f(B^n) \) are the components of \( S^n \setminus f(S^{n-1}) \), and are closed in \( S^n \setminus f(S^{n-1}) \).

\( f(\text{Int } B^n) \) is open in \( S^n \setminus f(S^{n-1}) \), therefore open in \( S^n \). \( \square \)

Proof of theorem 1.2. We have \( U, V \subset \mathbb{R}^n \), a homeomorphism \( f : U \to V \), \( U \) open in \( \mathbb{R}^n \). Choose \( x \in U \). Then there exists a closed \( n \)-ball \( B^n \subset U \) with center \( x \) and a map \( g : \mathbb{R}^n \to S^n \) which is a homeomorphism onto \( g(\mathbb{R}^n) \) (e.g. the inverse of stereographic projection). We have that \( gf : U \to S^n \) is 1-1 and continuous, so by 1.7, \( gf(\text{Int } B^n) \) is open in \( S^n \) and \( f(B^n) \) is open in \( \mathbb{R}^n \).

Now \( f(x) \in f(\text{Int } B^n) \subset f(U) = V \), so \( V \) is a neighborhood of \( f(x) \). Since \( V = f(U) \), \( V \) is open in \( \mathbb{R}^n \). \( \square \)

2 The Generalized Schönflies Theorem

**Definition 2.1.** If \( M, N \) are manifolds, an embedding of \( M \) in \( N \) is a map \( f : M \to N \) which is a homeomorphism onto \( f(M) \). (If \( M \) is compact then any 1-1 continuous map \( f : M \to N \) is an embedding, but this is not true in general.)

**Theorem 2.2** (Morton Brown’s Schönflies Theorem). If \( f : S^{n-1} \times [-1, 1] \to S^n \) is an embedding, then each component of \( S^n \setminus f(X^{n-1} \times \{0\}) \) has closure homeomorphic to \( B^n \).

**Definition 2.3.** Let \( M \) be a manifold and \( X \subset \text{Int } M \). \( X \) is cellular if it is closed and, for any open set \( U \) containing \( X \) there is a set \( Y \subset U \) such that \( Y \cong B^n \) and \( X \subset Y \subset \text{Int } Y \).

**Example.** Any collapsible polyhedron in \( \mathbb{R}^n \) is cellular.

If \( f : B^n \to S^n \) is any embedding, then \( S^n \setminus f(B^n) \) is cellular.

**Lemma 2.4.** If \( M \) is a manifold and \( X \subset M \) is cellular, then \( M/X \) is homeomorphic to \( M \) by a homeomorphism fixed on \( \partial M \).

**Proof.** Since \( X \) is cellular, there is a \( Y_0 \subset \text{Int } M \) such that \( Y_0 \cong B^n \) and \( X \subset \text{Int } Y_0 \). \( Y_0 \) has a metric \( d \). Let \( U_r = \{ y \in Y_0 : d(X, y) < \frac{1}{r} \} \). Define \( Y_r \) inductively: assume \( Y_{r-1} \subset M \) is constructed with \( X \subset \text{Int } Y_{r-1} \). \( X \) is cellular implies that there is a \( Y_r \subset (\text{Int } Y_{r-1}) \cap U_r \) such that \( Y_r \cong B^n \) and \( X \subset \text{Int } Y_r \), where \( \text{Int } Y_r \) is the interior or \( Y_r \) in \( M \). We have

\[
Y_0 \supset \text{Int } Y_0 \supset Y_1 \supset \text{Int } Y_1 \supset \cdots \supset X = \bigcap_{r=0}^{\infty} Y_r.
\]

We construct homeomorphisms \( h_r : M \to M \) such that

i. \( h_0 = 1 \),
ii. $h_r|M\setminus Y_{r-1} = h_{r-1}|M\setminus Y_{r-1}$, and

iii. $h_r(Y_r)$ has diameter $< \frac{1}{2}$ with respect to the metric $d$.

Suppose $h_{r-1}$ is defined. Choose a homeomorphism $f : h_{r-1}(Y_{r-1}) \to B^n$. Now, $Y_r \subset \text{Int} Y_{r-1}$, so $f(h_{r-1}(Y_r)) \subset \text{Int} B^n$ and there is a $\lambda < 1$ and $\epsilon > 0$ such that $f(h_{r-1}(Y_r)) \subset \lambda B^n$ and $f^{-1}(\epsilon B^n)$ has diameter $< \frac{1}{2}$. There is a homeomorphism $g : B^n \to B^n$ such that $g|_{\partial B^n} = 1$ and $g(\lambda B^n) \subset \epsilon B^n$. Define $h_r : M \to M$ by

$$h_r(x) = \begin{cases} h_{r-1}(x) & \text{if } x \in M \setminus Y_{r-1}, \\ f^{-1}gfh_{r-1}(x) & \text{if } x \in Y_{r-1}. \end{cases}$$

To verify (3), note that

$$h_r(Y_r) \subseteq f^{-1}gfh_{r-1}(Y_{r-1})$$
$$\subseteq f^{-1}g\lambda B^n$$
$$\subseteq f^{-1}(\epsilon B^n)$$

has diameter $< \frac{1}{2}$.

Define $h(x) = \lim_{r \to \infty} h_r(x)$ for each $x \in M$. If $x \in M \setminus X$, then $x \in M \setminus Y_r$ for some $r$, and $h_r(x) = h_{r+1}(x) = \cdots = h(x)$ by (2), so $h(x)$ exists. Since $h_r(Y_r) \supset h_{r+1}(Y_r) \supset \cdots$, with diameter $h_r(Y_r) \to 0$, $\bigcap_{r=1}^{\infty} h_r(Y_r) = \{y\}$ for some $y \in M$. If $x \in X$, $h_r(x) \in h_r(Y_r)$, so $d(h_r(x), y) < \frac{1}{r}$ by (3), so $h_r(x) \to y$ as $r \to \infty$ and $h(x) = y$.

$h$ is continuous at $x \in M \setminus X$ because $h = h_r$ in a neighborhood of $x$ for some $r$. $h$ is continuous at $x \in X$ because $Y_r$ is a neighborhood of $x$ and $h(Y_r) \subset \frac{1}{2}$ neighborhood of $Y$. Thus $h$ induces a continuous map $h : M/X \to M$ with $h|_{\partial M} = 1$.

Since $h$ coincides with some $h_r$ outside $X$, $h|_{M \setminus X} = M\setminus \{y\}$ is a homeomorphism. $h(X) = y$, so $h$ is bijective. Further, $h|_{M \setminus X}$ is open: If $U$ is a neighborhood of $X$ is $M$, then $U \supset Y_r$ for some $r$, so $y \in h_r(Y_{r+1}) \subset \text{Int} h_r(Y_r) \subset h(U)$ and $h(U)$ is a neighborhood of $y$, so $h$ is open.

Therefore $h$ is a homeomorphism. $\Box$

Lemma 2.5. If $X \subset \text{Int} B^n$ is closed and $B^n/X$ is homeomorphic to some subset of $S^n$, then $X$ is cellular.

Proof. Let $f : B^n \to S^n$ induce an embedding $\tilde{f} : B^n/X \to S^n$. Suppose $f(x) = y$. Then $f(B^n) = \tilde{f}(B^n/X) \neq S^n$. (Apply theorem 1.2 to neighborhoods of points of $\partial B^n$). Let $U$ be any neighborhood of $X$ in $B^n$; $f(U)$ is a neighborhood of $y$ in $S^n$. $f(B^n)$ is a proper closed subset of $S^n$. There is a homeomorphism $h : S^n \to S^n$ such that $h|_V = 1$ for some neighborhood $V$ of $y$ and $h(f(B^n)) < f(U)$: there is a $Y \subset S^n$ such that $Y \cong B^n$ and $f(B^n) \subset \text{Int} Y$. Let $Z$ be a small convex ball with $y \in \text{Int} Z$. The radial map gives the homeomorphism.
Define $g : B^n \to B^n$ by

$$
g(x) = \begin{cases} f^{-1}h(x) & \text{if } x \notin X, \\ x & \text{if } x \in X. \end{cases}
$$

Here, $hf(x) \neq y$ implies that $f^{-1}hf(x)$ is well defined. $g$ is continuous since $h = 1$ in a neighborhood of $y$. Also, $g$ is 1-1. Now $g(B^n) \cong B^n$ and $g(B^n) \subset f^{-1}h(B^n) \subset f^{-1}(U) = U$, and $g = 1$ on a neighborhood of $X$. Therefore, $\text{Int } g(B^n) \supset X$ and $X$ is cellular. \hfill \Box

**Proof of Theorem 2.2.** $f : S^{n-1} \times [-1,1] \to S^n$ is an embedding, $S^n \setminus f(X^{n-1} \times \{0\})$ has two components, $D_+$ and $D_-$. Say $f(S^{n-1} \times \{-1\}) \subset D_-$. Let $X_+ = D_+ \setminus f(X^{n-1} \times (0,1))$ and $X_- = D_- \setminus f(X^{n-1} \times (-1,0))$.

Then $X_+ \cup X_-$ are both closed, and $X_+ \cup X_- = S^n \setminus f(X^{n-1} \times (-1,1))$. Note that $(S^n/X_+)/X_- \cong (S^{n-1} \times [0,1]/S^{n-1} \times \{0\})/S^{n-1} \times \{0\} \cong S^n$. Therefore there is a map $g : S^n \to S^n$ such that $g(X_+) = y_+$, $g(X_-) = y_-$, and $g|_{S^n \setminus (X_+ \cup X_-)}$ is a homeomorphism onto $S^n \setminus \{y_+, y_-\}$ where $y_+$ and $y_-$ are the poles of $S^n$.

$X_+ \cup X_-$ is a proper closed subset of $S^n$, so there exists $Y \subset S^n$ with $Y \cong B^n$ and $X_+ \cup X_- \subset \text{Int } Y$. Since $g(Y)$ is a proper closed subset of $S^n$, there is a homeomorphism $h : S^n \to S^n$ such that $h = 1$ on a neighborhood of $y_-$ and $h(g(Y)) \subset S^n \setminus \{y_+, y_-\}$.

Define $\phi : Y \to S^n$ by

$$
\phi(x) = \begin{cases} g^{-1}h(x) & \text{if } x \notin X_-, \\ x & \text{if } x \in X_. \end{cases}
$$

Since $h = 1$ on a neighborhood of $y_-$, $\phi$ is injective on $Y \setminus X_+$ and $\phi(X_+) = g^{-1}(y_+)$. Therefore $\phi$ induces an embedding $\phi : Y/X_+ \to S^n$, $Y \cong ??????????????????????

By lemma 2.5, $X_+$ is cellular.

$D_+$ is a manifold with $X_+ \subset D_+ = \text{Int } D_+$. By lemma 2.4, $D_+ \cong D_+/X_+ \cong S^{n-1} \times [0,1]/S^{n-1} \times \{0\} \cong B^n$. Similarly for $D_-$. \hfill \Box

**Corollary 2.6.** If $f, g : S^{n-1} \times [-1,1] \to S^n$ are embeddings, then there is a homeomorphism $h : S^n \to S^n$ such that

$$
hf|_{S^{n-1} \times \{0\}} = g|_{S^{n-1} \times \{0\}}.
$$

**Proof.** If $\phi : \partial B^n \to \partial B^n$ is a homeomorphism, then $\phi$ extends to a homeomorphism $\phi : B^n \to B^n$ in an obvious way along radii: $\phi(rx) = r\phi(x)$ for $0 \leq r < 1, x \in \partial B^n$. Therefore, if $Y_1, Y_2$ are homeomorphic to balls and $\phi : \partial Y_1 \to \partial Y_2$ is a homeomorphism, then $\phi$ extends to a homeomorphism $\phi : Y_1 \to Y_2$.

Let $D_+, D_-$ be the components of $S^n \setminus f(S^{n-1} \times \{0\})$ and $E_+, E_-$ be the components of $S^n \setminus g(S^{n-1} \times \{0\})$. Define $h|_{f(S^{n-1} \times \{0\})}$ to be $gf^{-1}$, so $h : \partial D_+ \to \partial E_+$. Since $D_+ \cong E_+ \cong B^n$, $h$ can be extended to a homeomorphism $h : D_+ \to E_+$. 

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Extend $h|_{\partial M} \rightarrow \partial E_-$ (already defined) to a homeomorphism $h|_{\partial E_-} \rightarrow \overline{E_-}$. We obtain a homeomorphism $h : S^n \rightarrow S^n$ with $hf|_{S^{n-1} \times \{0\}} = g|_{S^{n-1} \times \{0\}}$. 

**Definition 2.7.** A collar of $\partial M$ in $M$ is an embedding $f : \partial M \times I \rightarrow M$ such that $f(x,0) = x$ for $x \in \partial M$.

**Exercise.** $f(\partial M \times I)$ is a neighborhood of $\partial M$ in $M$.

**Remark.** From now on, we only consider metrizable manifolds, i.e., ones which are second countable.

**Exercise.** Compact manifolds are metrizable.

**Theorem 2.8** (Morton Brown). If $M$ is metrizable, then $\partial M$ has a collar in $M$.

If $U$ is an open set in $\partial M$, say that $U$ is collared if $U$ has a collar in the manifold $\text{Int } M \cup U$.

Let $V \subset U$ be a smaller open set and $\lambda : U \rightarrow I = [0,1]$ be a continuous map such that $\lambda(x) = 0$ iff $x \notin V$. Define a spindle neighborhood of $V$ in $U \times I$ to be

$$S(V, \lambda) = \{(x,t) \in U \times I : t < \lambda(x)\}.$$ 

$S(V, \lambda)$ is open, therefore a neighborhood of $V \times \{0\}$.

**Lemma 2.9.** Let $f : S(V, \lambda) \rightarrow U \times I$ be an embedding with $f|_{V \times \{0\}} = 1$. Then there is a homeomorphism $h : U \times I \rightarrow U \times I$ such that:

i. $hf = 1$ on $S(V, \mu)$ for some $\mu$ such that $\mu \leq \lambda$, and

ii. $h|_{(U \times I \setminus f(S(V, \lambda)))}$ is the identity.

**Proof.** Spindle neighborhoods form a base of neighborhoods of $V \times \{0\}$ in $U \times I$.

Suppose $V \times \{0\} \subset W$, $W$ open. Let $d$ be a metric on $U$ and define a metric $d$ on $U \times I$ by

$$d((x,t), (x',t')) = d(x,x') + |t-t'|.$$ 

Let $\nu(x) = \min\{d(x,U \times I \setminus W), d(x,U \setminus V)\}$. Then $(x,t) \in S(V, \nu)$ implies that $t < \nu(x)$, and so $(x,t) \in W$. Therefore $S(V, \nu) \subset W$.

There exists $\mu$ such that $S(V, 2\mu) \subset S(V, \frac{1}{2}\lambda) \cap f(S(V, \frac{1}{2}\lambda))$. There is an embedding $g : U \times I \rightarrow U \times I$ defined by

$$(x,t) \mapsto \begin{cases} (x,t) & \text{if } t \geq 2\mu(x), \\ (x,\mu(x) + \frac{1}{2}t) & \text{otherwise.} \end{cases}$$

$g$ has image $U \times I \setminus S(V, \mu)$ and $g|_{U \times I \setminus S(V, 2\mu)} = 1$.

Define $h : U \times I \rightarrow U \times I$ by

$$h(x) = \begin{cases} f^{-1}(x) & \text{if } x \in f(S(V, \mu)), \\ gfg^{-1}f^{-1}(x) & \text{if } x \in f(S(V, \lambda)) \setminus f(S(V, \mu)), \\ x & \text{otherwise.} \end{cases}$$

Continuity of $h$ is simply verified. In fact, $h$ is a homeomorphism such that $hf = 1$ on $S(V, \mu)$ and $h = 1$ off $f(S(V, \lambda))$. 

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Lemma 2.10. If $U, V \subset \partial M$ are collared, then $U \cup V$ is collared.

Proof. Let $f : U \times I \to M$, $g : V \times I \to M$ be collars. Choose $\lambda : U \cup V \to I$ so that $S(U \cap V, \lambda) \subset f^{-1}g(V \times I)$. Apply lemma 2.9 to the embedding
\[
g^{-1}f : S(U \cap V, \lambda) \to V \times I.
\]
There is an $S(U \cap V, \mu) \subset S(U \cap V, \lambda)$ and a homeomorphism $h : V \times I \to V \times I$ such that $hg^{-1}f|_{S(U \cap V, \mu)} = 1$. Then $gh^{-1}$ and $f$ agree on $S(U \cap V, \mu)$.

Define an open set $U_1 \subset U \times I$ by
\[
U_1 = \{x \in U \times I : d(x, (U \setminus V) \times \{0\}) < d(x, (V \setminus U) \times \{0\})\}.
\]
Define $V_1 \subset V \times I$ similarly. Let $U_2$ be
\[
U_2 = \{y \in M : d(y, U \setminus V) < d(y, V \setminus U)\}
\]
and define $V_2$ similarly. Then $U_1 \cap V_1 = \emptyset$ and $U_2 \cap V_2 = \emptyset$.

Put $U_3 = U_1 \cap f^{-1}(U_2)$, $V_3 = V_1 \cap h g^{-1}(V_2)$. Then $U_3, V_3$ are open, $U_3 \cap V_3 = \emptyset$, $f(U_3) \cap h g^{-1}(V_3) = \emptyset$, $(U \setminus V) \times \{0\} \subset U_3$, and $(V \setminus U) \times \{0\} \subset V_3$, so $W = U_3 \cup S(U \cap V, \mu) \cup V_3$ is a neighborhood of $(U \cup V) \times \{0\}$ in $(U \cup V) \times I$.

Define $\phi : W \to M$ by
\[
\phi(x) = \begin{cases} f(x) & \text{if } x \in U_3 \cup S(U \cap V, \mu), \\ gh^{-1}(x) & \text{if } x \in S(U \cap V, \mu) \cup V_3. \end{cases}
\]

Then $\phi$ is well defined, continuous, and 1-1.

There is a $\nu : U \cup V \to I$ such that $S(U \cup V, \nu) \subset W$. Define $\psi : (U \cup V) \times I \to M$ by $(x, t) \mapsto \phi(x, t\nu(x))$. This is continuous and 1-1, and hence an embedding by invariance of domain.

Proof of theorem 2.8. Collared sets cover $\partial M$ because if $x \in \partial M$, then there is a homeomorphism $f : \mathbb{R}^n \times [0, 1) \to M$ onto a neighborhood of $x$. We proved in corollary 1.3 that $f|$ restricts a neighborhood of $x$. Then $U$ has a collar given by $g : U \times I \to M$ sending $(y, t) \mapsto f(p_1 f^{-1}(y), t)$.

If $\partial M$ is compact, then $\partial M$ is collared by lemma 2.10. Before proceeding to the general case, we prove:

Lemma 2.11. Let $U_\alpha, \alpha \in A$ be a disjoint family of open collared sets. Then $\bigcup_{\alpha \in A} U_\alpha$ is collared.

Proof. Let $V_\alpha = \{y \in M : d(y, U_\alpha) < d(y, \bigcup_{\beta \neq \alpha} U_\beta)\}$. This is an open neighborhood of $U_\alpha$ in $M$, and $\alpha \neq \beta$ implies that $V_\alpha \cap V_\beta = \emptyset$.

Let $f_\alpha : U_\alpha \times I \to M$ be a collar of $U_\alpha$. Let $W_\alpha = f_\alpha^{-1}(V_\alpha)$, a neighborhood of $U_\alpha \times \{0\}$ in $U_\alpha \times I$. There are maps $\nu_\alpha : U_\alpha \to I$ such that $S(U_\alpha, \nu_\alpha) \subset W_\alpha$.

Define $g_\alpha : U_\alpha \times I \to M$ by
\[
g_\alpha(x, t) = f_\alpha(x, \frac{t
u_\alpha(x)}{2}) \in V_\alpha.
\]

Define $g = \bigcup g_\alpha : (\bigcup_{\alpha} U_\alpha) \times I \to M$. This is a collar of $\bigcup_{\alpha \in A} U_\alpha$ in $M$. 

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We have proved that if $X = \partial M$ then
i. $X$ is covered by collared sets,
ii. a finite union of collared sets is collared,
iii. a disjoint union of collared sets is collared, and
iv. open subsets of collared sets are collared.

Then (i)–(iv) together with $X$ metric imply that $X$ is collared.

Lemma 2.12. Any countable union of collared sets is collared.

Proof. It is enough to consider countable nested unions $U = \bigcup_{n=1}^{\infty} U_n$ with $U_1 \subset U_2 \subset \ldots$.

Put $V_n = \{ x \in U_n : d(x, X \setminus U_n) > 2^{-n} \}$. Then $U = \bigcup_{n=1}^{\infty} V_n$ since $x \in U_k$ means there is an $n > k$ such that $B(x; 2^{-n}) \subset U_k$. Therefore $d(x, X \setminus U_k) > 2^{-n}$, so $d(x, X \setminus U_n) > 2^{-n}$ and $x \in V_n$.

We have that $\bigcup_{n=1}^{\infty} V_n \subset \bigcup_{n=1}^{\infty} V_{n+1}$. Let $A_k = V_{2k+1} \setminus V_{2k-1}$ and $B_k = V_{2k+2} \setminus V_{2k}$. Then $A = \bigcup_{k=1}^{\infty} A_k$ is a disjoint union of collared sets, hence collared. Similarly for $B = \bigcup_{k=1}^{\infty} B_k$. Now $U = A \cup B \cup V_2$ is collared.

A family of subsets of $X$ is discrete if each $x \in X$ has a neighbourhood which intersects at most one member of the family. Call a family of subsets of $X$ $\sigma$-discrete if it is a countable union of locally finite discrete subfamilies (Kelley, p. 127).

Lemma 2.13. Every open cover of a metric space $X$ has a $\sigma$-discrete refinement.

Proof (cf Kelley, p. 129). Let $\mathcal{U}$ be an open cover of a metric space $X$. If $U \in \mathcal{U}$ let $U_n = \{ x \in U : d(x, X \setminus U) > 2^{-n} \}$. Then $d(U_n, X \setminus U_{n+1}) \geq 2^{-(n+1)}$.

Well order $\mathcal{U}$ by the relation $<$. Let $U_n^* = U_n \setminus \bigcup_{V < U} V_{n+1}$. If $U \neq V$ then $U < V$ or $U > V$. The first implies that $V_n^* \subset X \setminus U_{n+1}$, the second that $U_n^* \subset X \setminus V_{n+1}$, and in either case $d(U_n^*, V_n^*) \geq 2^{-(n+1)}$.

Let $U_n''$ be an open $2^{-(n+2)}$ neighborhood of $U_n^*$, similarly for $V_n'$. If $U \neq V$, then $U_n'' \cap V_n' = \emptyset$.

It is enough to prove that $\bigcup_{n \in \mathcal{U}} U_n'' = X$. If $x \in X$ let $U$ be the first (with respect to $<$) member of $\mathcal{U}$ containing $x$. Then $x \in U_n$ for some $n$ and so $x \in U_n^* \subset U_n''$. Now $\{ U_n'' \}$ is a $\sigma$-discrete refinement of $\mathcal{U}$.

□ (theorem 2.8)

References:

A shortened version of the second reference is included in the book “Topology of 3-manifolds.”
**Theorem 2.15.** There is a neighborhood continuous map proper.

**Remark.** There needn’t be an embedding \( G : M \times \mathbb{R}^{n-m} \rightarrow N \) such that \( G(y,0) = f(y) \) for all \( y \). Example. If \( S^1 \rightarrow \text{Möbius strip along the center line} \). This is locally flat but there is no embedding \( S^1 \times \mathbb{R} \rightarrow M \) agreeing with the previous one on \( S^1 \times \{0\} \).

**Exercise.** Suggest a generalization that does work.

Given two manifolds \( M^m, N^n \) let \( \mathcal{E}(M,N) \) be the set of embeddings of \( M \) in \( N \) with the compact-open topology. A continuous map \( f : X \rightarrow Y \) is proper if \( C \subseteq Y \) compact implies \( f^{-1}(C) \subseteq X \) is compact.

Let \( \mathcal{E}_p(M,N) \) be the set of embeddings which are proper maps. We will be interested in \( \mathcal{E}_p(\mathbb{R}^n \setminus \text{Int } B^n, \mathbb{R}^n) \), which consists of embeddings \( f : \mathbb{R}^n \setminus \text{Int } B^n \rightarrow \mathbb{R}^n \) onto neighborhoods of \( \infty \) by propriety.

Let \( \mathbb{R}^n \) be the one point compactification of \( \mathbb{R}^n \). \( f : \mathbb{R}^n \setminus \text{Int } B^n \rightarrow \mathbb{R}^n \) extends to a continuous map \( \widehat{f} : \mathbb{R}^n \setminus \text{Int } B^n \rightarrow \mathbb{R}^n \) with \( \widehat{f}(\infty) = \infty \) iff \( f \) is proper.

(In general, \( f : X \rightarrow Y \) extends to a continuous map \( \widehat{f} : \hat{X} \rightarrow \hat{Y} \) with \( \widehat{f}(\infty) = \infty \) iff \( f \) is proper.)

**Theorem 2.15.** There is a neighborhood \( U \) of 1 in \( \mathcal{E}(6B^n \setminus \text{Int } B^n, \mathbb{R}^n) \) and a continuous map \( \theta : U \rightarrow \mathcal{E}_p(\mathbb{R}^n \setminus \text{Int } B^n, \mathbb{R}^n) \) such that \( \theta(f)|_{S^{n-1}} = f|_{S^{n-1}} \).

**Proof.** Take \( U = \{ f \in \mathcal{E}(6B^n \setminus \text{Int } B^n, \mathbb{R}^n) : d(x, f(x)) < 1, x \in 6B^n \setminus \text{Int } B^n \} \). If \( f \in U \), then \( f(2B^n \setminus \text{Int } B^n) \subseteq \text{Int } 3B^n \setminus \{0\} \) and \( f(6B^n \setminus \text{Int } 5B^n) \subset f(7B^n \setminus \text{Int } 4B^n) \).

Define inductively \( f_k : (4k + 6)B^n \setminus \text{Int } B^n \rightarrow \mathbb{R}^n \) such that

i. \( f_0 = f \),

ii. \( f_{k+1}|_{(4k+5)B^n \setminus \text{Int } B^n} = f_k|_{(4k+5)B^n \setminus \text{Int } B^n} \),

iii. \( f_k((4r + 6)B^n \setminus \text{Int } (4r + 5)B^n) \subset \text{Int } (4r + 7)B^n \setminus (4r + 4)B^n \) for \( r \leq k \), and

iv. \( f_k \) depends continuously on \( f \).
Suppose $f_k$ is constructed. If $c, d \in (a, b)$ $(a, b, c, d \in \mathbb{R})$, let $\rho(a, b, c, d) : \mathbb{R}^n \to \mathbb{R}^n$ be the radial homeomorphism fixed outside $6B^n \setminus aB^n$ taking $cB^n$ onto $dB^n$.

Let $\rho_k(a, b, c, d) = \rho(4k + a, 4k + b, 4k + c, 4k + d)$.

Define $g_k : (4k + 6)B^n \setminus \text{Int } B^n \to \mathbb{R}^n$ by $g_k = \rho_k(3, 11, 4, 8)f_k\rho_k(1, 1, 2, 3)$. Define a homeomorphism $h_k : \mathbb{R}^n \to \mathbb{R}^n$ by
\[
  h_k(x) = \begin{cases} f_k\rho_k(1, 5\frac{1}{2}, 3, 5\frac{1}{2})f_k^{-1} & \text{if } x \text{ is in the image of } f_k, \\ x & \text{otherwise.} \end{cases}
\]

Let $\sigma_k : (4k + 10)B^n \to (4k + 6)B^n$ be a radial homeomorphism fixed on $(4k + 5)B^n$, sending $(4k + 6)B^n \to (4k + 5\frac{1}{2})B^n$ and $(4k + 9)B^n \to (4k + 5\frac{1}{2})B^n$.

Define $f_{k+1} = h_kg_k\sigma_k : (4k + 10)B^n \setminus \text{Int } B^n \to \mathbb{R}^n$. Check (ii): let $x \in (4k + 5)B^n$ so $\sigma_k(x) = x, \rho_k(1, 1, 2)(x) \in (4k + 2)B^n, y = f_k\rho_k(1, 1, 2)(x) \in (4k + 3)B^n$ (inductive hypothesis), $g_k(x) = \rho_k(3, 11, 4, 8)(y) = y$. XXXXXXXXXX

Similarly we can verify (iii). To prove (iv), that $f_k$ depends continuously on $f$, it is enough to show that $h_k$ depends continuously on $f_k$. Let $f_k'$ be near $f_k$, and let
\[
h_k' = \begin{cases} f_k'\rho_kf_k'^{-1} & \text{on } \text{Im } f \text{ where } \rho_k = \rho_k(1, 1, 2, 3), \\ 1 & \text{otherwise.} \end{cases}
\]

If $C$ is a compact set in $\mathbb{R}^n$, we must prove that $\sup_{x \in C} d(h_kx, h_k'x)$ can be made less than $\epsilon$ by requiring $d(f_ky, f_k'y) = \delta$ for all $y \in A_k, \epsilon > 0$.

Let $A_k = (4k + 6)B^n \setminus \text{Int } B^n = \text{domain of } f_k$. Given $\epsilon > 0$ there is an $\eta > 0$ such that $y, y' \in A$ and $d(y, y') < \eta$ imply $d(f_k\rho_k(y), f_k\rho_k(y')) < \frac{\epsilon}{2}$. Since $\rho_k$ is injective, there is a $\delta > 0$ such that $y, y' \in A$ and $d(y, y') < \eta$ imply $d(f_ky, f_ky') \geq \delta$. We suppose $\delta < \frac{\epsilon}{2}$. Suppose $d(f_ky, f_k'y) < \frac{\epsilon}{2}$ for all $y \in A$. Let $x \in C$. We split into cases:

i. $x \in \text{Im } f_k \cap \text{Im } f_k'$, say $x = f_ky_k = f_k'y_k$. Then $d(f_ky_k, f_k'y_k) = d(f_k'y_k, f_ky_k) < \frac{\epsilon}{2} < \delta$. Therefore $d(y, y') < \eta$, so $d(h_kx, h_k'x) = d(f_k\rho_ky_k, f_k'\rho_ky_k) \leq d(f_k\rho_ky_k, f_k\rho_ky_k) + d(f_k\rho_ky_k, f_k'\rho_ky_k) \leq \frac{\epsilon}{2} + \frac{\delta}{2} < \epsilon$

ii. If $x \in \text{Im } f_k \setminus \text{Im } f_k'$, say $x = f_k(y)$, then $d(x, f_k'y) < \frac{\epsilon}{2}$, so there is a $z \in \partial A$ such that $d(f_k'z, f_k'y) < \frac{\epsilon}{2}$ and $d(x, f_k'z) < \frac{\epsilon}{2}$. But $d(f_k'z, f_kz) < \frac{\epsilon}{2}$, so $d(x, f_kz) < \delta$, so $d(y, z) < \eta$. Therefore $d(h_kx, h_k'x) = d(f_k\rho_ky, x) \leq d(f_k\rho_ky, f_k\rho_kz) + d(f_kz, x) < \frac{\epsilon}{2} + \frac{\delta}{2} < \epsilon$.

Here we used the fact that $f_k\rho_kz = z$ since $z \in \partial A$. 12
iii. If $x \in \text{Im } f'_k \setminus \text{Im } f_k$, the proof is similar.

iv. If $x \not\in \text{Im } f'_k \cup \text{Im } f_k$, there is nothing to prove.

We have proved that $f_k \mapsto h_k$ is continuous. $f \mapsto f_{k+1}$ is continuous if $f \mapsto f_k$ is, so the induction is complete.

Define $\theta : U \to E_p(\mathbb{R}^n \setminus \text{Int } B^n, \mathbb{R}^n)$ by $\theta(f)(x) = f_k(x)$ for $k$ large and $x \in (4k+5)B^n$. Then $\theta(f)$ is proper (interleaving property (iii)). Also $\theta(f)$ is an embedding, so $\theta(f) \in E_p(\mathbb{R}^n \setminus \text{Int } B^n, \mathbb{R}^n)$. $\theta(f)$ depends continuously on $f$ because $f_k$ agrees with $f$ on $(4k+5)B^n$ and $f_k$ depends continuously on $f$. \hfill \Box

**Corollary 2.16.** If $0 < \lambda < 1$, there is a neighborhood $V$ of $1 \in \mathcal{E}(B^n \setminus \text{Int } \lambda B^n, \mathbb{R}^n)$ and a continuous map $\phi : V \to \mathcal{E}(B^n, \mathbb{R}^n)$ such that for all $f$, $\phi(f)|_{S^{n-1}} = f|_{S^{n-1}}$.

**Proof.** Let $\tilde{X}$ be the one point compactification of $X$. $g : X \to Y$ is proper iff $g$ extends to $\tilde{g} : \tilde{X} \to \tilde{Y}$ with $\tilde{g}(\infty) = \infty$.

**Example.** The map $g \mapsto \tilde{g}$ is not continuous, even if $X = Y = \mathbb{R}^n$.

We first prove that $f \mapsto \tilde{f}$ is continuous (XXXX seems to contradict the above). Suppose $f \in E_p(\mathbb{R}^n \setminus \text{Int } B^n, \mathbb{R}^n)$, $C \subset \mathbb{R}$ is compact, $U \subset \mathbb{R}^n$ is open, and $\tilde{f}(C) = U$. If $\infty \not\in C$, $C$ is a compact set in $\mathbb{R}^n \setminus \text{Int } B^n$ so $\{g \in E_p(\mathbb{R}^n \setminus \text{Int } B^n, \mathbb{R}^n) : g(C) \subset U \cap \mathbb{R}^n\}$ is a neighborhood of $f$, mapping into a given neighborhood of $\tilde{f}$.

If $\infty \in C$, then $\infty = \tilde{f}(\infty) \in U$ open in $\mathbb{R}^n$ and there is a $k$ such that $\mathbb{R}^n \setminus k B^n \subset U$. Since $f$ is proper, there is an $l$ such that $f^{-1}(2kB^n) \subset lB^n$. Let $N = \{g \in E_p(\mathbb{R}^n \setminus \text{Int } B^n, \mathbb{R}^n) : g(C \cap B^n) \subset U \cap \mathbb{R}^n, g(lS^{n-1}) \subset \mathbb{R}^n \setminus kB^n\}$. This is open in $E_p$ and contains $f$.

Now we have to show that $\tilde{g}(C) \subset U$ for all $g \in N$.

$$\tilde{g}(C) = g(C \cap B^n) \cup \tilde{g}(\mathbb{R}^n \setminus \text{Int } B^n) \subset U \cup \text{one of the complementary domains of } g(lS^{n-1}).$$

In fact $U \cup \text{outside domain } C \subset \mathbb{R}^n \setminus kB^n \subset U$. Hence the map $g \mapsto \tilde{g}$ is continuous.

$$\mathcal{E}(6B^n \setminus \text{Int } B^n, \mathbb{R}^n) \supset U \longrightarrow E_p(\mathbb{R}^n \setminus \text{Int } B^n, \mathbb{R}^n) \xrightarrow{\phi} E_p(\mathbb{R}^n \setminus \text{Int } B^n, \mathbb{R}^n)$$

There exists a homeomorphism $h : \widehat{\mathbb{R}^n} \to \mathbb{R}^n$ with

$$h(x) = \begin{cases} \frac{x}{||x||} & \text{if } x \neq 0, \infty, \\ \infty & \text{if } x = 0, \text{ and} \\ 0 & \text{if } x = \infty, \end{cases}$$
carrying $6B^n \setminus \text{Int } B^n$ onto $B^n \setminus \text{Int } \frac{1}{6}B^n$ taking $\mathbb{R}^n \setminus \text{Int } B^n \to B^n$. Hence the result. (XXXXXX: really?)

3 Properties of Tori

Definition 3.1. Let $\mathbb{Z}^n$ be the integer lattice in $\mathbb{R}^n$. Then $T^n = \mathbb{R}^n / \mathbb{Z}^n$ is the $n$-dimensional torus. Clearly $T^n \cong S^1 \times \cdots \times S^1$, $n$ copies of $S^1$.

Let $e : \mathbb{R}^n \to T^n$ be the projection map. If $a \in \mathbb{Z}^n$, let $\tau_a : \mathbb{R}^n \to \mathbb{R}^n$ send $x \mapsto a + x$.

Proposition 3.2. $e : \mathbb{R}^n \to T^n$ is a universal covering of $T^n$. If $X$ is a 1-connected space and $f : X \to T^n$ is any map the there is an $\tilde{f} : X \to \mathbb{R}^n$ such that $f = ef$. ($\tilde{f}$ is a lift of $f$.) If $f_1, f_2$ are lifts of $f$ then $f_1 = \tau_a f_2$ for some $a \in \mathbb{Z}^n$.

If $X$ is simply connected and $f : X \times T^n \to X \times T^n$ is a map, then there exists an $\tilde{f} : X \times \mathbb{R}^n \to X \times \mathbb{R}^n$ such that $ef = e\tilde{f}$.

Lemma 3.3. If $f$ is a homeomorphism, so is $\tilde{f}$; if $f$ is homotopic to the identity, then $\tilde{f}$ commutes with the covering translations.

Proof. Let $f$ be the homeomorphism and $g$ its inverse. We have

\[
e \tilde{g} = f e \tilde{g} = f e g e = e,
\]

so $\tilde{g} = \tau_a$ for some $a$. Similarly $\tilde{g} \tilde{f} = \tau_b$. Therefore $\tilde{f}$ is a homeomorphism.

Suppose $F : X \times T^n \times I \to X \times T^n$ has $F_0 = f$ and $F_1 = 1$. By 3.2 there is an $\tilde{F} : X \times \mathbb{R}^n \times I \to X \times \mathbb{R}^n$ with $e\tilde{F} = Fe$. We have

\[
e \tau_a \tilde{F} \tau_a = e \tilde{F} \tau_a = Fe \tau_a = Fe = e \tilde{F}.
\]

Therefore there is a $b \in \mathbb{Z}^n$ so that $\tau_{-a} \tilde{F} \tau_a = \tau_b \tilde{F}$. We have $e \tilde{F}_1 = F_1 e = e$, so $\tilde{F}_1 = \tau_c$ for some $c$. But $\tau_{-a} \tau_c \tau_a = \tau_b \tau_c$, therefore $b = 0$ and $\tau_c = 1$. Thus $\tau_{-a} \tilde{F} \tau_a = \tilde{F}$. Since $F_0 = f, \tilde{F}_0 = \tau_d f$ for some $d$. Therefore $\tilde{f}$ commutes with $\tau_d$.

Definition 3.4. Let $M, N$ be manifolds. An immersion $f : M \to N$ is a map such that each point $x \in M$ has a neighborhood $U_x$ with $f|_{U_x}$ an embedding. If $U_x$ can be chosen so that $f|_{U_x}$ is locally flat, then $f$ is a locally flat immersion.

Theorem 3.5. There is an immersion of $T^n \setminus \text{point}$ in $\mathbb{R}^n$. 

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Proof. \( T^n \setminus \text{pt} \) is an open parallelizable manifold. Therefore, by Hirsch’s theory of immersions there is a \( C^\infty \) immersion \( T^n \setminus \text{pt} \to \mathbb{R}^n \).

Alternately, regard \( T^n \) as the product of \( n \) circles, \( T = T^1 = \text{circle} \). Let \( J \) be a closed interval in \( T \). \( T^n \setminus J^n \cong T^n \setminus \text{pt} \). Assume inductively that there is an immersion \( f_n : T^n \setminus J^n \to \mathbb{R}^n \) such that \( f_n \times 1 : (T^n \setminus J^n) \times [-1,1] \to \mathbb{R}^n \times \mathbb{R} = \mathbb{R}^{n+1} \) extends to an immersion \( g_n : T^n \times [-1,1] \to \mathbb{R}^{n+1} \).

The induction starts with \( n = 1 \). Let \( \phi_0 : \overline{t \setminus J} \to [-1,1] \). Choose an embedding \( \phi : \mathbb{R} \times T \to \mathbb{R} \times \mathbb{R} \) such that if \((x,t) \in [-1,1] \times \overline{t \setminus J} \) then \( \phi(x,t) = (x,\phi_0(t)) \). Extend \( \phi_0^{-1} : [-1,1] \to \overline{t \setminus J} \) to an embedding \( \psi : \mathbb{R} \to T \).

Suppose \( f_n, g_n \) constructed. We have \( T^{n+1} \setminus J^{n+1} = (T^n \setminus J^n) \times T \cup T^n \times (T \setminus J) \). Define \( J^{n+1} : T^{n+1} \setminus J^{n+1} \to \mathbb{R}^{n+1} \) by

\[
J^{n+1} = (1_{\mathbb{R}^{n-1}} \times \phi)(f_n \times 1)T \cup (1 \times \psi)g_n(1_{\mathbb{R}^n} \times \psi^{-1})T.
\]

On \((T^n \setminus J^n) \times (T \setminus J)\), \( g_n = f_n \times 1 \) so \((1 \times \phi)g(1 \times \psi^{-1}) = (1 \times \psi)(f_n \times 1)(1 \times \psi^{-1}) = f_n \times 1 \). Let \( J' \triangleq T \setminus \phi(-\frac{1}{2}, \frac{1}{2}) \). \( J' \subseteq \text{Int } J' \).

We shall construct an immersion \( g'_{n+1} : T^{n+1} \times [-1,1] \to \mathbb{R}^{n+2} \) which agrees with \( f_{n+1} \times 1 \) on \( T^{n+1} \setminus (J')^{n+1} \times [-\frac{1}{2}, \frac{1}{2}] \). This will be enough, since \( T^{n+1} \setminus (J')^{n+1} \cong T^{n+1} \setminus J^{n+1} \).

Define \( \theta_t : C \to C \) \((= \mathbb{R}^2) \) by

\[
\theta_t(z) = \begin{cases} 
z & \text{if } |z| \leq \frac{1}{2}, \\
\pm \sqrt{|z| - \frac{1}{2}} & \text{if } \frac{1}{2} \leq |z| \leq \frac{3}{4}, \text{ and} \\
\pm \frac{3}{4} & \text{if } |z| \geq \frac{3}{4}.
\end{cases}
\]

Let \( J'' = T \setminus \psi(-\frac{1}{2}, \frac{3}{4}) \) and \( \lambda : T^n \to [0,1] \) be continuous such that \( \lambda|_{(J')^{n+1}} = 1 \) and \( \lambda|_{T^{n+1} \setminus (J')^{n+1}} = 0 \).

Define \( g'_{n+1} : T^{n+1} \setminus (J'' \times [-1,1]) \to \mathbb{R}^{n+1} \times \mathbb{R} \) by \( g'_{n+1}(x,t,u) = (1 \times \lambda(x))(\phi'_{n+1}(x,t), u) \) and define \( g_{n+1} : T^{n+1} \setminus (T \setminus [-1,1]) \to \mathbb{R}^n \times \mathbb{R} \) by \( g_{n+1}(x,t,u) = (J^{n+1} \times 1)(x, (\psi \times 1)\lambda(x)(\psi^{-1}(t), u)) \). Then \( g_{n+1}|_{T^{n+1} \setminus (J')^{n+1}} \) agrees with \( f_{n+1} \times 1 \). Define \( y_{n+1} \) to be the restriction of

\[
\sigma_{n+1}(1 \times \phi)\sigma_n(g_{n+1} \times 1)\sigma_{n+1}(1 \times \tau) : T^n \times T \times [1,1] \to \mathbb{R}^{n+2}
\]

where \( \sigma_j \) swaps the \( j \)th and \((j+1)\)th factors in the \((n+1)\)-fold product and \( \tau : [-1,1] \to [-1,1] \) changes sign.

This proof has no end XXXXXXXXXXXXXXXXXX

4 Local Contractibility

Definition 4.1. A space \( X \) is locally contractible if for each point \( x \in X \) and each neighborhood \( U \) of \( x \), there is a neighborhood \( V \) of \( x \) and homotopy \( H : V \times I \to U \) such that \( H_0 = 1 \) and \( H_1(V) = x \).

Let \( X^f \) be the set of paths in \( X \) ending at \( x \). It is enough to find a neighborhood \( V \) and map \( \phi : V \to X^f \) such that \( \phi(y) \) is a path from \( y \) to \( x \) and \( \phi(x) \)
is the constant path at \( x \). (Given an open neighborhood \( U \) of \( x \), \( U^I \) is the open set in \( X^I \) so that there is a neighborhood of \( x \) in \( X \) such that \( \phi(V') \subset U^I \).)

If \( M \) is a manifold, let \( \mathcal{H}(M) \) be the space of homeomorphisms of \( M \) together with the compact-open topology.

**Definition 4.2.** An *isotopy* of \( M \) is a path in \( \mathcal{H}(M) \). Equivalently, an isotopy is a homeomorphism \( H : M \times I \to M \times I \) such that \( p_2H = p_2 \). We say that \( H \) is an isotopy from \( H_0 \) to \( H_1 \), and \( H_0, H_1 \) are isotopic.

**Theorem 4.3** (Černavsky, Kirby). \( \mathcal{H}(\mathbb{R}^n) \) is locally contractible.

**Proof.** \( \mathcal{H}(\mathbb{R}^n) \) is a group, so it is enough to show that it is locally contractible at 1.

Choose an embedding \( i : 4B^n \to T^n \) and choose an immersion \( f : T^n \setminus i(0) \to \mathbb{R}^n \). \( T^n \setminus i(\text{Int } B^n) \) is compact, so there is a \( \delta > 0 \) such that for all \( x \in T^n \setminus i(\text{Int } B^n) \), \( f|_{N(x)} \) is injective. We may suppose \( \delta < d(i(3B^n \setminus \text{Int } 2B^n), i(4S^{n-1} \cup S^{n-1})) \). Since \( f \) is open \( \epsilon_x = d(f(x), \mathbb{R}^n \setminus N_0(f(x))) > 0 \) and \( \epsilon = \inf \{ \epsilon_x : x \in T^n \setminus i(\text{Int } B^n) \} > 0 \).

If \( x \in T^n \setminus i(\text{Int } B^n) \) and \( v \in \mathbb{R}^n \) are such that \( d(f(x), v) < \epsilon \) then there exists a unique \( u \in N_\delta(x) \) such that \( f(u) = v \).

Let \( h \in \mathcal{H}(\mathbb{R}^n) \). Suppose \( h \) is sufficiently small, then \( h \in \mathcal{H}(\mathbb{R}^n) \) such that \( f(h(x)) = f(x) \) for all \( x \in T^n \setminus i(\text{Int } B^n) \).

For \( x \in T^n \setminus i(\text{Int } 2B^n) \), let \( h'(x) \) be the unique point in \( N_\delta(x) \) such that \( f(h'(x)) = f(h(x)) \), \( h'(x) \in T^n \setminus i(\text{Int } B^n) \). Since \( f \) is an open immersion, \( h' \) is an open immersion. Let \( h''(x) \) be the unique point in \( N_\delta(h'(x)) \) such that \( f(h''(x)) = f(h(x)) \) which implies that \( h''(x) \neq h'(y) \), a contradiction. Therefore \( h' \) is an embedding depending continuously on \( h \in \mathcal{H}(\mathbb{R}^n) \).

Consider \( i^{-1}h'i : 3B^n \setminus \text{Int } 2B^n \to \text{Int } 4B^n \). By corollary 2.16 there is a neighborhood \( W \) of 1 in \( \mathcal{E}(3B^n \setminus \text{Int } 2B^n, \text{Int } 4B^n) \) and continuous map \( \phi : W \to \mathcal{E}(3B^n, \text{Int } 4B^n) \) such that \( \phi(w)|_{3S^{n-1}} = w|_{3S^{n-1}} \). Define \( h'' : T^n \to T^n \) by

\[
h''(x) = \begin{cases} h'(x) & \text{if } x \notin i(3B^n), \\ i\phi(i^{-1}h'i)^{-1}(x) & \text{if } x \in i(3B^n). \end{cases}
\]

Then \( h'' \) is a homeomorphism, depending continuously on \( h \in V \) where \( V = \{ h \in \mathcal{H}(\mathbb{R}^n) : h' \text{ is defined and } i^{-1}h'i \in W \} \). If \( V \) is sufficiently small, then \( h \in V \) implies that \( h'' \) is homotopic to 1.

Let \( e : \mathbb{R}^n \to T^n \) be the (universal) covering map. By 3.3 there exists a homeomorphism \( \tilde{h} : \mathbb{R}^n \to \mathbb{R}^n \) such that \( e\tilde{h} = h''e \). If \( V \) is sufficiently small, there is a unique choice of \( \tilde{h} \) such that \( d(h(0), 0) < \frac{1}{2} \). Then \( \tilde{h} \) depends continuously on \( h \). By 3.3, \( \tilde{h} \) commutes with covering translations. Let \( I = [0, 1] \): every point of \( \mathbb{R}^n \) can be moved into \( I^n \) by covering translations.

If \( A = \sup_{x \in I^n} d(\tilde{h}(x), x) < \infty \), we have \( d(\tilde{h}(x), x) \leq A \) for all \( x \in \mathbb{R}^n \), that is, \( \tilde{h} \) is a bounded homeomorphism of \( \mathbb{R}^n \).

Suppose without loss of generality that \( e(0) \notin i(4B^n) \). Choose once and for all \( r > 0 \) such that \( f|_{e(4B^n)} \) is injective and \( r < 1 \) and \( e(rB^n) \cap i(4B^n) = \emptyset \).
Define a homeomorphism $\rho : \text{Int } B^n \to \mathbb{R}^n$ fixed on $rB^n$ by

$$\rho(x) = \begin{cases} 
  x & \text{if } x \in rB^n, \\
  \frac{x-r}{|x-r|} & \text{if } x \notin rB^n.
\end{cases}$$

Then $\rho^{-1}\tilde{h}\rho$ is a homeomorphism from $\text{Int } B^n \to \text{Int } B^n$ fixed on $rB^n$. Suppose $|x| < 1$ is close to 1. Then $d(x, \rho^{-1}\tilde{h}\rho(x)) \leq \frac{2A(|x|-1)}{r^2-1} \to 0$ as $|x| \to 1$. So $\rho^{-1}\tilde{h}\rho$ extends to a homeomorphism of $B^n$, fixed on $\partial B^n$.

Define an isotopy $R_t$ of $B^n$ by

$$R_t(x) = \begin{cases} 
  x & \text{if } |x| \geq t, \\
  t\rho^{-1}\tilde{h}\rho(t^{-1}) & \text{if } |x| < t.
\end{cases}$$

Extend $f_\varepsilon : rB^n \to \mathbb{R}^n$ to a homeomorphism $\sigma : \text{Int } B^n \to \mathbb{R}^n$ (e.g. by Schönflies theorem). Choose $s$, $0 < s < r$. If $V$ is small enough, $h \in V$ implies that $\tilde{h}(sB^n) \subset \text{Int } tB^n$.

Define an isotopy $S_t$ of $\mathbb{R}^n$ by $S_t(x) = \sigma R_t \sigma^{-1}(x)$. This depends continuously on $h$. $S_0 = 1$, and $S_t|_{f_\varepsilon(sB^n)} = h|_{f_\varepsilon(sB^n)}$. Without loss of generality, $0 \in \text{Int } f_\varepsilon(sB^n)$. $S_t^{-1} h$ is 1 on a neighborhood of 0.

Define $F_t : \mathbb{R}^n \to \mathbb{R}^n$ by

$$F_t(x) = \begin{cases} 
  t^{-1}S_t^{-1}h(tx) & \text{if } t \neq 0, \\
  x & \text{if } t = 0.
\end{cases}$$

Define $H_t = S_t F_t$, i.e. $H_t(x) = S_t(F_t(x))$. This is an isotopy from 1 to $h$. $H_t$ depends continuously on $h \in V$, and $h = 1$ implies that $H_t = 1$. So $\mathcal{H}(\mathbb{R}^n)$ is locally contractible.

What about $\mathcal{H}(M)$ for (say) $M$ compact? (Use a handle decomposition.)

Let $\mathcal{E}(k\text{-handle})$ be the space of embeddings of $B^k \times B^n \to B^k \times \mathbb{R}^n$ leaving $(\partial B^k) \times B^n$ fixed.

**Theorem 4.4.** There is a neighborhood $V$ of 1 in $\mathcal{E}(k\text{-handle})$ and a homotopy $H : V \times I \to \mathcal{E}(k\text{-handle})$ such that

1. $H_t(1) = 1$ for all $t$,
2. $H_0(h) = h$ for all $h \in V$,
3. $H_t(h)|_{B^k \times \frac{1}{2}B^n} = 1$, and
4. $H_t(h)|_{\partial B^k \times B^n} = h|_{\partial B^k \times B^n}$ for all $t, h$.

**Proof.** Let $i : 4B^n \to T^n$ be a fixed embedding, $f : T^n \setminus \{0\} \to \text{Int } B^n$ a fixed immersion. Choose $0 < r < 1$ such that $f|_{e(rB^n)}$ is injective and $e(rB^n) \cap i(4B^n) = \emptyset$. Modify $f$ so that $f(e(\text{Int } rB^n)) \supset \frac{1}{2}B^n$.
XXX: this junk is all messed up: Let \( h \in \mathcal{E}(k \text{-handle}) \) be close to 1. Define a preliminary isotopy \( G \) from \( h \) to \( g \in \mathcal{E}(k \text{-handle}) \) such that XXXXXXX:

\[
G_t(x, y) = \begin{cases} 
(x, y) & \text{if } |x| \geq 1 - \frac{t}{2}, \\
((1 - \frac{t}{2})h_1((1 - \frac{t}{2})^{-1}x, y), h_2(x, y)) & \text{if } |x| \leq 1 - \frac{t}{2},
\end{cases}
\]

where \( h(x, y) = XXXXX \). \( G_0 = h, G_1 = g \) is an embedding fixed on \( B^n \setminus \frac{1}{2}B^k \times \frac{3}{4}B^n \). \( G \) depends continuously on \( h \) and

\[
G_{t}|B^k \times \partial B^n = h|B^k \times \partial B^n.
\]

As in 4.3 construct an embedding \( g^1 : B^k \times (T^n \setminus i(\text{Int } 2B^n)) \rightarrow B^k \times (T^n \setminus i(\text{Int } B^n)) \) such that \((1 \times f)g^1 = g(1 \times f)\) and \(g^1|B^n \setminus \frac{1}{2}B^k \times \partial T^n = 1\).

Put \( g^1|B^n \setminus \frac{1}{2}B^k \times \partial T^n = 1 \). This extends the \( g^1 \) defined above. Use 2.16 to extend \( g^1|B^n \setminus \frac{1}{2}B^k \times \partial T^n \rightarrow \) to an embedding \( g'' : \frac{1}{3}B^k \times i(3B^n) \rightarrow B^k \times i(4B^n) \) such that \( g'' = g^1 \) on \( \partial(\frac{1}{3}B^k \times i(3B^n)) \).

Let \( \tilde{g} : B^k \times \mathbb{R}^n \rightarrow B^k \times \mathbb{R}^n \) be such that \((1 \times e)\tilde{g} = g''(1 \times e) \) and \( \tilde{g}|\partial B^k \times B^n = 1 \). \( \tilde{g} \) is bounded, i.e., \( d(x, \tilde{g}(x)) \leq A \) for \( x \in B^k \times \mathbb{R}^n \). Extend \( \tilde{g} \) to a homeomorphism of \( \mathbb{R}^k \times \mathbb{R}^n \) by \( \tilde{g}|(\mathbb{R}^k \setminus B^k) \times \mathbb{R}^n = 1 \).

Define \( \rho : \text{Int}(2B^k \times 2B^n) \rightarrow \mathbb{R}^k \times \mathbb{R}^n \), a homeomorphism fixing \( B^k \times B^n \), by

\[
\rho(x, y) = \begin{cases} 
(x, y) & \text{if } (x, y) \in B^k \times B^n, \\
(2 - \max \{|x|, |y|\})^{-1}(x, y) & \text{otherwise}.
\end{cases}
\]

Then \( \rho^{-1}\tilde{g} \rho : \text{Int}(2B^k \times 2B^n) \rightarrow \text{Int}(2B^k \times 2B^n) \) extends to a homeomorphism of \( 2B^k \times 2B^n \) fixed on \( \partial(2B^k \times 2B^n) \). In fact, \( \rho^{-1}\tilde{g} \rho \) fixes \( (2B^k \setminus \text{Int } B^k) \times 2B^n \).

Thus \( \rho^{-1}\tilde{g} \rho \) defines a homeomorphism of \( B^k \times 2B^n \) fixed on \( \partial(B^k \times 2B^n) \). Define an isotopy \( R_t \) of \( B^k \times 2B^n \) by

\[
R_t(x, y) = \begin{cases} 
(x, y) & \text{if } \max \{|x|, \frac{1}{2}|y|\} \geq t, \\
\rho^{-1}\tilde{g} \rho(t^{-1}(x, y)) & \text{otherwise}.
\end{cases}
\]

Let \( \sigma : B^k \times 2B^n \rightarrow B^k \times \text{Int } B^n \) be an embedding with \( \sigma|B^k \times B^n = fe \). Now define an isotopy \( S_t \) of \( B^k \times B^n \) by

\[
S_t(x) = \begin{cases} 
\sigma R_t \sigma^{-1} & \text{if } x \in \text{Im } \sigma, \\
x & \text{otherwise}.
\end{cases}
\]

Then \( S_0 = 1 \) and \( S_t \) fixes \( \partial(B^k \times B^n) \).

Suppose \( V \) is so small that \( h \in V \) implies that \( \tilde{g} \) is defined and \( g(\frac{1}{2}B^n) \subset f e(\text{Int } rB^n) \). Then \( S_t|_{BV \times \frac{1}{2}B^n} = g \).

Define \( H_t : B^k \times B^n \rightarrow B^k \times \mathbb{R}^n \) by

\[
H_t(x) = \begin{cases} 
G_{2t}(x) & \text{if } 0 \leq t \leq \frac{1}{2}, \\
gS_{2t-1}(x) & \text{otherwise}.
\end{cases}
\]

This does what is required. \( \square \)
Lemma 4.5. If $C \subset \mathbb{R}^n$ is compact and $\epsilon > 0$, then $C$ lies in the interior of a handlebody with handles of diameter $< \epsilon$. Explicitly, there exist finitely many embeddings $h_i : B^k_i \times B^{n-k}_i \to \mathbb{R}^n$, $i = 1, 2, \ldots, l$, such that if $W_j = \bigcup_{i \in j} h_i(B^k_i \times \frac{1}{2}B^{n-k}_i)$ then

1. $h_i(B^k_i \times B^{n-k}_i) \cap W_{i-1} = h_i(\partial B^k_i \times B^{n-k}_i)$,
2. $W_i$ is a neighborhood of $C$, and
3. $h_i(B^k_i \times B^{n-k}_i)$ has diameter $< \epsilon$ and $h_i(B^k_i \times B^{n-k}_i) \subset N_\epsilon C$

Proof. Cover $C$ by a lattice of cubes of side $\frac{1}{2}\epsilon$. Since $C$ is compact, $C$ only needs a finite number of these cubes. Let $\gamma_1, \ldots, \gamma_t$ be all the faces of all the cubes meeting $C$.

Let $k_i = \dim \gamma_i$ and order $\gamma_i$ so that $k_0 < k_1 < \ldots < k_t$. Define a metric on $\mathbb{R}^n$ by $d((x_1, \ldots, x_n), (y_1, \ldots, y_n)) = \max_{1 \leq i \leq n} |x_i - y_i|$. Let

$$H_i = N_{2^{-i-1}}(\gamma_i) \setminus \bigcup_{j<i} N_{2^{-j-1}}(\gamma_j)$$

and $\frac{1}{2}H_i = H_i \cap N_{2^{-i-1}}(\gamma_i)$. Then $H_i \cap \gamma_i \cong \gamma_i$ (radial projection) $\cong B^k$ and clearly $H_i \cong (H_i \cap \gamma_i) \times B^{n-k}_i$. There exist homeomorphisms $h_i : B^k_i \times B^{n-k}_i \to H_i$ carrying $B^k_i \times \frac{1}{2}B^{n-k}_i$ onto $\frac{1}{2}H_i$ and $(\partial B^k_i) \times B^{n-k}_i$ onto $H_i \cap \bigcup_{j<i} \frac{1}{2}H_j$. Then $h_1, h_2, \ldots, h_t$ do what is required.

Addendum 4.6. If $D \subset C$ is compact, then we can select $h_{i_1}, \ldots, h_{i_m}$ so that (i) is still satisfied, and (ii) and (iii) are satisfied by $h_{i_1}, \ldots, h_{i_m}$ with respect to $D$ instead of $C$. That is, $\bigcup_{i=1} h_i(B^{k_i} \times \frac{1}{2}B^{n-k_i})$ is a neighborhood of $D$, $h_i(B^{k_i} \times B^{n-k_i})$ has diameter less than $\epsilon$ and is contained in $N_\epsilon(0)$.

Proof. Select $h_i$ iff $\gamma_i$ is a face of a cube which meets $D$.

Theorem 4.7 (Kirby-Edwards). Let $C, D$ be compact in $\mathbb{R}^n$ and $U, V$ be neighborhoods of $C, D$. Let $E$ be the space of embeddings of $U$ in $\mathbb{R}^n$ which restrict to 1 on $V$. There is a neighborhood $N$ of 1 in $E$ and a homotopy $H : N \times I \to H(\mathbb{R}^n)$ such that

1. $H_t(1) = 1$ for all $t$,
2. $H_t(0) = 1$ for all $g \in N$,
3. $H_t(g)|_{C} = g|_{C}$, and
4. $H_t(g)|_{D \cup (\mathbb{R}^n \setminus U)} = 1$ for all $t, g$.

Proof. Let $\epsilon = \min \{d(C, \mathbb{R}^n \setminus U), d(D, \mathbb{R}^n \setminus V)\}$. Cover $C \cup D$ by a handlebody in $U \cup V$ with handles of diameter $< \epsilon$. Let $h_1, \ldots, h_l$ be the handles, with $W_i$ as in 4.5. Select $h_{i_1}, \ldots, h_{i_m}$ to form a sub-handlebody covering $D$, contained in $V$. Let $X = \bigcup_{i} h_{i} (B^{k_i} \times B^{n-k_i})$. 

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Suppose inductively that we have constructed a neighborhood $N_{i-1}$ of 1 in $\mathcal{E}$ and a homotopy $H^{(i-1)} : N_{i-1} \times I \to \mathcal{H}(\mathbb{R}^n)$ such that (i) and (ii) are satisfied, $H^{(i-1)}_t(g)|_{\partial N_{i-1}} = g$, $H^{(i-1)}_t(1) = 1$, $H^{(i-1)}_0(g) = 1$, and $H^{(i-1)}_t(g)|_{X \cup (\mathbb{R}^n \setminus U)} = 1$.

If $h_i(B^{k_i} \times B^{n-k_i}) \subset X$, put $N_i = N_{i-1}$ and $H_i = H_{i-1}$. (This is consistent because if $h_i(B^{k_i} \times B^{n-k_i}) \cap h_j(B^{k_j} \times B^{n-k_j}) \neq \emptyset$ for $j < i$ then $h_j(B^{k_j} \times B^{n-k_j}) \subset X$.)

Now suppose $h_i(B^{k_i} \times B^{n-k_i}) \not\subset X$. Choose $N_i$ so small that

$$g^{-1}H^{(i-1)}_t(g)h_i(B^{k_i} \times \frac{3}{4}B^{n-k_i}) \subset h_i(B^{k_i} \times \text{Int } B^{n-k_i}).$$

Let $f = h_i^{-1}g^{-1}H^{(i-1)}_t(g)h_i : B^{k_i} \times \frac{3}{4}B^{n-k_i} \to B^{k_i} \times \text{Int } B^{n-k_i}$. Then $f$ fixes $(\partial B^{k_i}) \times \frac{3}{4}B^{n-k_i}$. Theorem 4.4 gives a continuously varying isotopy $H_i^t(g)$ such that

i. $H_i^t(1) = 1$,

ii. $H_i^t_0(g) = f$,

iii. $H_i^t_1(g)|_{B^{k_i} \times \frac{3}{4}B^{n-k_i}} = 1$, and

iv. $H_i^t_1(g)|_{\partial(B^{k_i} \times \frac{3}{4}B^{n-k_i})} = 1$.

Define

$$H_i^{(i)}(g)(x) = \begin{cases} (H_i^{(i-1)}(g)h_i f^{-1}(H_i^t(g))h_i^{-1}(x) & \text{if } x \in h_i(B^{k_i} \times \frac{3}{4}B^{n-k_i}), \\ H_i^{(i-1)}_t(g)(x) & \text{otherwise}. \end{cases}$$

Then $W_i = W_{i-1} \cup h_i(B^{k_i} \times \frac{1}{2}B^{n-k_i})$, $h_i(B_i^k \times \frac{3}{4}B^{n-k_i}) \cap X \subset h_i(\partial(B_i^k \times \frac{3}{4}B^{n-k_i}))$ completes the induction. $H = H^1$, $N = N^t$ do what is required.

**Theorem 4.8.** If $M$ is a compact manifold then $\mathcal{H}(M)$ is locally contractible.

**Proof.** First suppose $M$ is closed, $\partial M = \emptyset$. Cover $M$ by finitely many embeddings $f_i : \mathbb{R}^n \to M$, $i = 1, \ldots, l$. In fact, assume $M = \bigcup F_i(B^n)$.

Let $h : M \to M$ be a homeomorphism near 1. Define inductively an isotopy $H^{(i)}(h)$ of $M$ such that

i. $H^{(i)}_t(h)$ depends continuously on $h$,

ii. $H^{(i)}_1(h) = 1$,

iii. $H^{(i)}_0(h) = 1$, and

iv. $H^{(i)}_1(h)$ agrees with $h$ on $\bigcup_{j \leq i} f_j((1 + 2^{-i})B^n)$.
Suppose $H_t^{(i-1)}$ is defined. Let $C = (1 + 2^{-i})B^n$, $U = (1 + 2^{-(i-1)})B^n$, and let $D = f_i^{-1}(\bigcup_{j<i} f_j(C)) \cap 4B^n$, $V = f_i^{-1}(\bigcup_{j<i} f_j(U))$.

Suppose $h$ is so near 1 that $h^{-1}H_t^{(i-1)}(f_i(U)) \subset f_i(\mathbb{R}^n)$. Apply Theorem 4.7 to $g = f_i^{-1}h^{-1}H_t^{(i-1)}(f_i) : U \to \mathbb{R}^n$. If $h$ is sufficiently near 1, we get a continuously varying isotopy $H'(h)$ of $\mathbb{R}^n$ such that

i. $H'_t(1) = 1$ for all $t$,
ii. $H'_0(h) = 1$ for all $h$,
iii. $H'_t(h)|_C = h|_C$, and
iv. $H'_t(h)|_{D \cup (\mathbb{R}^n \setminus U)} = 1$ for all $t, h$.

Define $H^{(i)} = H^{(i)}(h)$ by

$$H^{(i)}_t(x) = \begin{cases} H_t^{(i-1)}f_i(H'_t(h))^{-1}f_i^{-1}(x) & \text{if } x \in f_i(\mathbb{R}) \\ H_t^{(i-1)}(x) & \text{otherwise.} \end{cases}$$

Then $H^{(i)}$ satisfies (i)–(iii) and completes the induction.

Now suppose $\partial M \neq \emptyset$. Let $\gamma : \partial M \times I \to M$ be a collar of $\partial M$ in $M$. $\mathcal{H}(\partial M)$ is locally contractible. If $h \in \mathcal{H}(M)$ is near 1 then we have an isotopy $H_t(h)$ of $\partial M$ with $H_0(h) = 1$, $H_1(1) = h|_{\partial M}$.

Define an isotopy $\overline{H}$ of $M$ by

$$\overline{H}_t(\gamma(x,u)) = \gamma(H_t(1-u)(x), u)$$

for $x \in \partial M, u \in I$, and

$$\overline{H}_t(y) = y$$

if $y \notin \gamma(\partial M \times \{0\})$. Then $\overline{H}_1$ is an isotopy of $M$ from $1$ to $\overline{H}_1$ where $\overline{H}_1$ agrees with $h$ on $\partial M$.

There exists an isotopy $G_t : M \to M$ from $\overline{H}_1$ to $G_1$ where $G_1$ agrees with $h$ on $\gamma(\partial M \times [0, \frac{1}{2}])$. Now the argument goes as for closed manifolds. □

**Exercise.** If $M$ is compact, then $\mathcal{H}(\text{Int } M)$ is locally contractible.

**Theorem 4.9 (Isotopy extension).** Let $M, N$ be $n$-manifolds with $M$ compact, $\partial N = \emptyset$, and $M \subset N$. Suppose we are given a path $H : I \to \mathcal{E}(M, N)$. $H_0 : M \to N$. If $U$ is a neighborhood of $\partial M$ in $M$, then there is an isotopy $\overline{H} : I \to \mathcal{H}(N)$ such that $\overline{H}_0 = 1$ and $\overline{H}_1|_{M \setminus U} = H|_{M \setminus U}$.

**Proof.** First use the method of 4.8 to generalize 4.7 to deal with compact $C, D \subset N$ (i.e. replace $\mathbb{R}^n$ by $N$.) Let $f \in \mathcal{E}(M, n)$. Then $f(M) \subset N$ is a neighborhood of $f(M \setminus U)$ (assume that $U$ is open), and there exists an open neighborhood $V_f$ of 1 in $\mathcal{E}(f(M), N)$ and a homotopy $F^{(f)} : V_f \times I \to \mathcal{H}(N)$ such that $F^{(f)}_1(g)|_{M \setminus U} = g|_{M \setminus U}$ for $g \in V_f$.

Let $W_f = \{gf : g \in V_f\}$. Then $W_f$ is an open neighborhood of $f$ in $\mathcal{E}(M, N)$. Now $\{W_f\}_{f \in \mathcal{E}(M, N)}$ is an open cover of $\mathcal{E}(M, N)$. There is a dissection $0 =
\[ t_0 < t_1 < \cdots < t_i = 1 \text{ of } I \text{ such that } H([t_{i-1}, t_i]) \text{ is contained in some } W_{t_i}, f_i \in \mathcal{E}(M, N). \]

Define \( \Pi_t \) for \( t_{i-1} \leq t \leq t_i \) by

\[
\Pi_t = F_{t_i}^r (H_t \circ f_i^{-1}) \left( F_{t_{i-1}}^r (H_{t_{i-1}} \circ f_{t_{i-1}}^{-1}) \right)^{-1} \Pi_{t_{i-1}}.
\]

Then \( \Pi_t = H_t \) on \( M \setminus U \).

Addendum 4.10. \( \Pi_t \) can be chosen to be the identity outside some compact set. (This is because 4.7 also produces isotopies of compact support.)

Corollary 4.11. Let \( f : B^n \hookrightarrow \text{Int } 2B^n \) be isotopic to \( 1 \). Then \( 2B^n \setminus f(\text{Int } 1/2 B^n) \cong 2B^n \setminus \text{Int } 1/2 B^n \).

Proof. Let \( H_t \) be an isotopy from \( 1 \) to \( f \). By 4.10 there is an isotopy \( \Pi_t \) of \( \text{Int } 2B^n \), fixed outside \( \lambda B^n \) for some \( \lambda < 2 \), such that \( \Pi_1 = f \) on \( 1/2 B^n \).

Therefore \( \tilde{H}_1 \) defines a homeomorphism \( 2B^n \setminus \text{Int } 1/2 B^n \rightarrow 2B^n \setminus f(\text{Int } 1/2 B^n) \).

5 Triangulation Theorems

Definition 5.1. An \( r \)-simplex in \( \mathbb{R}^n \) is the convex hull of \( r + 1 \) linearly independent points.

Let \( K \subset \mathbb{R}^n \) be compact. An embedding \( f : K \rightarrow \mathbb{R}^n \) is PL if \( K \) is a finite union of simplexes, each mapped linearly by \( f \).

If \( M \) is an \( n \)-manifold, a PL structure on \( M \) is a family \( \mathcal{F} \) of embeddings \( f : \Delta^n \rightarrow M \) such that

i. every point of \( M \) has a neighborhood of \( f(\Delta^n) \), \( f \in \mathcal{F} \),

ii. if \( f, g \in \mathcal{F} \), then \( g^{-1} f : f^{-1} g(\Delta^n) \rightarrow \mathbb{R}^n \) is PL, and

iii. \( \mathcal{F} \) is maximal with respect to (i) and (ii).

If \( M, N \) have PL structures \( \mathcal{F}, \mathcal{G} \), an embedding \( h : M \rightarrow N \) is PL if \( f \in \mathcal{F} \) implies \( hf \in \mathcal{G} \).

Example. The composite of 2 PL embeddings is PL, i.e. PL \( \cong \) is an equivalence relation.

A PL structure \( \mathcal{F} \) on \( M \) defines a PL structure \( \partial \mathcal{F} \) on \( \partial M \).

A compact \( n \)-manifold has PL structure iff it has a triangulation with the link of each vertex PL homeomorphic to \( \partial \Delta^n \).

We need 3 deep theorems from PL topology.

Proposition 5.2. i. Suppose \( M \) is a closed PL manifold which is homotopy equivalent to \( S^n \). If \( n \geq 5 \), then \( M \) is PL homeomorphic to \( S^n = \partial \Delta^{n+1} \).
ii. Call a non-compact manifold $W$ simply-connected at infinity if for every compact set $C \subset W$, there is a compact set $D \subset W$ such that any two loops in $W \setminus D$ are homotopic in $W \setminus C$. (Example: $\mathbb{R}^n$ is simply connected at infinity if $n \geq 3$.)

Suppose $W^n$ is an open PL manifold which is simply connected at infinity. If $n \geq 6$ then $W$ is PL homeomorphic to $\text{Int} V$ where $V$ is some compact PL manifold. XXXXXXXXXX

iii. Let $M$ be a closed PL manifold which is homotopy equivalent to $T^n$. Then some finite covering of $M$ is PL homeomorphic to $T^n = (\partial \Delta^2)^n$. (Proof in Wall’s book.)

**Theorem 5.3 (Annulus Conjecture).** If $h : B^n \to \text{Int} B^n$ is an embedding and $n \geq 6$, then $B^n \setminus h(\text{Int} \frac{1}{2} B^n) \cong B^n \setminus \text{Int} \frac{1}{2} B^n$.

**Proof.** Let $a \in T^n$ and let $f : T^n \setminus \{a\} \to \text{Int} B^n$ be a PL immersion such that $f(T^n \setminus \{a\}) \subset \frac{1}{2} B^n$. Let $h : B^n \to \text{Int} B^n$ be a topological homeomorphism:

we shall find a PL Structure $\mathcal{F}'$ on $T^n \setminus \{a\}$ such that $hf$ is PL with respect to $\mathcal{F}'$. Let $\mathcal{F}_0 = \{ \phi : \Delta^n \to T^n \setminus \{a\} : (hf)\phi$ is a PL embedding$\}$. Since $hf$ is an open immersion, $\{ \phi(\text{Int} \Delta^n) : \phi \in \mathcal{F}' \}$ covers $T^n \setminus \{a\}$. Extend $\mathcal{F}_0$ to a PL structure $\mathcal{F}'$ on $T^n \setminus \{a\}$. Let XXXXX. For $n \geq 3$, $(T^n \setminus \{a\})' \cong (T^n \setminus \{a\})$ so $(T^n \setminus \{a\})'$ is simply connected at infinity. Since $n \geq 6$, by 5.2 (ii) there is a compact PL manifold $w$ and PL homeomorphism $g : (T^n \setminus \{a\})' \to \text{Int} W$. There exists a PL collar $\gamma : \partial W \times I \to W$. Let $\epsilon > 0$ and $A$ be a neighborhood of $a$ in $T^n$ homeomorphic to $B^n$ and so small that

$$g^{-1}\gamma(\partial W \times I) \supset A \setminus \{a\} \supset g^{-1}\gamma(\partial W \times \{0\}).$$

The first and last sets are homotopy equivalent, so it follows that $\partial W \cong S^{n-1}$. By 5.2 (i) since $n \geq 6$, $\partial W$ is PL homeomorphic to $S^{n-1}$.

By Schönlies theorem, $\{a\} \cup g^{-1}\gamma(\partial W \times (0, \epsilon)) \cong B^n$. Extend $\mathcal{F}'|_{T^n \setminus \{a\} \cup g^{-1}\gamma(\partial W \times (0, \epsilon))}$ to a PL structure $\mathcal{F}''$ on $\{a\} \cup g^{-1}\gamma(\partial W \times (0, \epsilon))$.

By 5.2 (iii), there is a finite covering of $(T^n)'$ which is PL homeomorphic to $T^n$. Let $\epsilon'' : T^n \to (T^n)'$ be a finite cover. Let $\epsilon : T^n \to T^n$ be the corresponding cover of $T^n$. By the theory of covering spaces there exists a homeomorphism $\bar{h} : T^n \to T^n$ (not PL) such that $\epsilon = \epsilon'' \bar{h}$ (is homotopic to 1). Now let $h : \mathbb{R}^n \to \mathbb{R}^n$ be a homeomorphism such that $eh = \bar{h}e$. Then $d(x, h(x))$ is bounded uniformly for $x \in \mathbb{R}^n$.

Let $\rho : \text{Int} B^n \to \mathbb{R}^n$ be a PL “radial” homeomorphism (avoiding the “standard mistake”). Now $\eta = \rho^{-1}\bar{h}\rho : \text{Int} B^n \to \text{Int} B^n$ extends to a homeomorphism of $B^n$ fixing $\partial B^n$.

Let $U$ be a nonempty open set in $\text{Int} B^n$ such that $\epsilon\rho(U) \cap A = \emptyset$ and $\sigma = f\epsilon\rho[U]$ maps $U$ injectively into $\frac{1}{2} B^n$. Let $\sigma'' = hf\epsilon\rho[U] \to \text{Int} B^n$. Then $\sigma, \sigma''$ are PL embeddings and $\sigma''\eta = h\sigma$. The PL annulus conjecture is true (proof by regular neighborhood theory). There is an $n$-simplex $\Delta \subset U$.
such that \( \eta(\Delta) \) is contained in some \( n \)-simplex \( \Delta'' \subset \eta(U) \). Therefore by the PL annulus theorem, \( \frac{1}{2}B^n \setminus \sigma(\Delta) \cong \) the standard annulus \( \cong B^n \setminus \frac{1}{2}B^n \).

We have that \( B^n \setminus h(\text{Int } \frac{1}{2}B^n) \cong B^n \setminus h\sigma(\text{Int } \Delta) \) by gluing the standard annulus \( h(\frac{1}{2}B^n) \setminus h\sigma(\text{Int } \Delta) \) onto \( B^n \setminus h(\text{Int } \frac{1}{2}B^n) \). From there,

\[
B^n \setminus h\sigma(\text{Int } \Delta) \cong B^n \setminus \sigma''\eta(\text{Int } \Delta)
\cong \sigma''(\Delta'') \setminus \sigma''\eta(\text{Int } \Delta)
\cong \Delta'' \setminus \eta(\text{Int } \Delta)
\cong B^n \setminus \eta(\text{Int } \Delta)
\cong B^n \setminus \text{Int } \Delta
\cong B^n \setminus \text{Int } \frac{1}{2}B^n.
\]

\[\square\]

The proof depends only on knowing that given embeddings \( f, g : B^n \to T^n \) there exists an \( h : T^n \to T^n \) carrying \( f(\frac{1}{2}B^n) \) onto \( g(\frac{1}{2}B^n) \). If we could do this purely geometrically (i.e. without PL theory) for all dimensions, we would have then proved the annulus conjecture in all dimensions.

New notation: \( W \) is any manifold, \( ] \) is the subset \((\partial W \times I) \cup (W \times \{1\})\) of \( W \times I \).

**Theorem 5.4.** Let \( M \) be a PL manifold and let \( h : I \times B^k \times \mathbb{R}^n \to M \) be a homeomorphism which is PL on a neighborhood of \( ] \). If \( k + n \geq 6 \) then there is an isotopy \( H_t : I \times B^k \times \mathbb{R}^n \to M \) such that

i. \( H_0 = h \),

ii. \( H_1 \) is PL on \( I \times B^k \times B^n \), and

iii. \( H_t = h \) on \( ] \) and outside \( I \times B^k \times 2B^n \).

**Proof.** Let \( a \in T^n \) and let \( f : T^n \setminus \{a\} \to \mathbb{R}^n \) be a PL immersion. As in 5.3, let \( \mathcal{F}' \) be a PL structure on \( I \times B^k \times (T^n \setminus \{a\}) \) such that \( h(I \times f) : I \times B^k \times (T^n \setminus \{a\})' \to M \) is PL. Then \( \mathcal{F}' \) agrees with \( \mathcal{F} \) near \( ] \). Let \( A \) be a ball neighborhood of \( a \) in \( T^n \). First extend \( \mathcal{F}' \) over a neighborhood of \( \] \) in \( I \times B^k \times T^n \) (using the standard structure). As in 5.3 extend \( \mathcal{F}' \) over \( \{0\} \times B^k \times T^n \), obtaining a structure \( \mathcal{F}'' \). The following argument implies that we can extend \( \mathcal{F}'' \cup \mathcal{F}|_{I \times B^k \times (T^n \setminus A)} \) over a neighborhood of \( \{0\} \times B^k \times T^n \) in \( I \times B^k \times T^n \).

As in 5.3 extend this to a PL structure over \( I \times B^k \times T^n \) agreeing with the standard structure near \( ] \) and with \( \mathcal{F}' \) on \( I \times B^k \times (T^n \setminus A) \). We can take \( \mathcal{F}'' \) to be the standard structure near \( \{1\} \times B^k \times T^n \). Now \( \mathcal{F}'' \) is defined near \( \partial(I \times B^k \times A) \); we extend over \( I \times B^k \times A \) as in 5.3, obtaining a PL manifold \( (I \times B^k \times T^n)'' \). The inclusion \( (I \times B^k \times (T^n \setminus \{a\}))'' \hookrightarrow (I \times B^k \times T^n)'' \) is PL except on \( I \times B^k \times A \), and the identity map \( I \times B^k \times T^n \to (I \times B^k \times T^n)'' \) is PL near \( ] \).

Now we need another result from PL topology:
Proposition 5.5. Let \( W, V_1, V_2 \) be compact PL manifolds with \( \partial W = V_1 \cup V_2 \) and \( V_1 \cap V_2 = \partial V_1 = \partial V_2 \). Suppose the inclusions \( V_i \to W \) are homotopy equivalent. If \( \pi_1(W) \) is free abelian and \( \dim W \geq 6 \), then \( W \) is PL homeomorphic to \( V_1 \times I \).

Apply this result with \( W = (I \times B^k \times T^n)'', V_1 = ] \) and \( V_2 = (\{0\} \times B^k \times T^n)'' \). We obtain a PL homeomorphism \((I \times B^k \times T^n)'' \to ] \times I \). Since \([ \times I \cong I \times B^k \times T^n \) by a PL homeomorphism taking \((x, 0)\) to \( x \), we can find a PL homeomorphism \( g : I \times B^k \times T^n \to (I \times B^k \times T^n)'' \) which is the identity near \([ \).

Let \( \tilde{h} : I \times B^k \times \mathbb{R}^n \to I \times B^k \times \mathbb{R}^n \) be such that \( \epsilon \tilde{h} = g^{-1} \epsilon \) and \( \tilde{h} = 1 \) on \([ \). Then \( \tilde{h} \) is a bounded homeomorphism. Extend \( \tilde{h} \) over \([0, \infty) \times \mathbb{R}^k \times \mathbb{R}^n \) by putting \( \tilde{h} = 1 \) outside \( I \times B^k \times \mathbb{R}^n \). Extend further over \( \mathbb{R} \times \mathbb{R}^k \times \mathbb{R}^n \) by putting \( \tilde{h}(t, x, y) = (t, p_2\tilde{h}(0, x, y), p_3\tilde{h}(0, x, y)) \) for \( t \leq 0 \). Note that \( d(x, \tilde{h}(x)) \) remains bounded for \( x \in \mathbb{R} \times \mathbb{R}^k \times \mathbb{R}^n \).

Suppose \( 0 < r < 1, e(rB^n) \cap A = \emptyset, \) and \( f e|_{rB^n} \) is injective. We may also suppose \( f e(rB^n) \supset sB^n \) for some \( s > 0 \). There is a PL “radial” homeomorphism \( \rho : (-1, 2) \times \text{Int}(2B^n \times B^0) \to \mathbb{R} \times \mathbb{R}^k \times \mathbb{R}^n \) fixed near \( I \times B^k \times rB^n \). Then \( \tilde{\rho}\rho^{-1} \) extends to a homeomorphism of \([-1, 2] \times 2B^k \times B^n \) fixing the boundary. Let \( \eta = \tilde{\rho}\rho^{-1} \).

Note that \( I \times B^k \times B^n \times I \) is the join of \((\frac{1}{2}, 0, 0, \frac{1}{2}) \) to \((I \times I) \cup (I \times B^k \times B^n \times \partial I) \). Define a PL homeomorphism \( R \) of \( I \times B^k \times B^n \times I \) by \( R((\frac{1}{2}, 0, 0, \frac{1}{2}), (\frac{1}{2}, 0, 0, \frac{1}{2})) = (\frac{1}{2}, 0, 0, \frac{1}{2}), R((I \times I) \cup (I \times B^k \times B^n \times \{1\})) = 1, \) and \( R(I \times B^k \times B^n \times \{0\}) = \eta \), extending conewise. Then \( R \) defines a PL isotopy \( R_t \) of \( I \times B^k \times B^n, \) fixed near \([ \), with \( R_0 = \eta \) and \( R_1 = 1 \).

Let \( \sigma : I \times B^k \times B^n \to I \times B^k \times \mathbb{R}^n \) be a PL embedding which agrees with \( 1 \times f e \) near \( I \times B^k \times rB^n \). Then \( h\sigma\eta^{-1} \) agrees with \( b(1 \times f)\epsilon \rho \) near \( \eta(I \times B^k \times rB^n) \), so it is PL there.

\[
\begin{array}{ccc}
I \times B^k \times B^n & \xrightarrow{\eta} & I \times B^k \times B^n \\
\downarrow{\sigma} & & \downarrow{\sigma''} \\
I \times B^k \times \mathbb{R}^n & \xrightarrow{h} & M
\end{array}
\]

\( h\sigma\eta^{-1} \) is PL near \( \eta(I \times B^k \times rB^n) \). \( W = I \times B^k \times B^n \setminus \eta(I \times B^k \times rB^n) \) is a PL manifold (since it is an open subset of a PL manifold). If \( n \geq 3 \), \( W \) is simply connected at infinity, so if \( n \geq 3 \) the Browder-Levine-Livesay theorem (5.2B) implies that \( W \) is homeomorphic to an open subset of a compact manifold.

If \( n \leq 2 \), the same result, using instead Siebenmann’s XXXXXXX. It follows that \( \eta(I \times B^k \times rB^n) \) has a neighborhood which is a compact PL manifold such that \( \partial N \subseteq T \times B^k \times B^n \setminus N \) is a homotopy equivalence. Now the \( s \)-cobordism theorem (5.5) implies that \( T \times B^k \times B^n \setminus N \) is PL homeomorphic to \( T \times B^k \times B^n \setminus I \times B^k \times rB^n \).

It follows that there is a \( \sigma'' : I \times B^k \times B^n \to M \), a PL embedding such that \( \sigma''\eta = h\sigma \) near \( I \times B^k \times rB^n \) (regard \( T \times B^k \times B^n \setminus N \) as a collar of XXXXXX).
Let $R_t$ be an isotopy from $\eta$ to 1 rel $\sigma$. Define $S_t : I \times B^{k} \times \mathbb{R}^{n} \to M$ by

$$S_t(x) = \begin{cases} 
\sigma'' R_t \eta^{-1} (\sigma'')^{-1} h(x) & \text{if } h(x) \in \text{Im} \sigma'', \\
h(x) & \text{otherwise.}
\end{cases}$$

Then $S_0 = h$ and

$$S_1|_{I \times B^{k} \times \mathbb{R}^{n}} = \sigma'' R_1 \eta^{-1} \eta \sigma^{-1}$$

which is PL. $S_t = h$ on $\sigma$ and also outside $h^{-1}$ (the image of $\sigma''$) which is compact. Therefore $S_t = h$ on $\sigma$ and outside $I \times B^{k} \times \mathbb{R}^{n}$ for some $R > 0$. It is trivial to replace $S_t$ by an isotopy $H_t$ satisfying (i)–(iii).

**Theorem 5.6.** Let $C, D$ be closed subsets of $\mathbb{R}^{n}$ and let $U$ be an open neighborhood of $C$. Let $F$ be a PL structure on $U \times I \subset \mathbb{R}^{n} \times I$ which agrees with the standard PL structure near $(U \cap D) \times I$ and near $U \times \{0\}$. If $n \geq 6$, then there is an isotopy $H_t$ of $\mathbb{R}^{n} \times I$ such that

i. $H_0 = 1_{\mathbb{R}^{n} \times I}$,

ii. $H_1 : (U \times I, \text{standard}) \to (U \times I, F)$ is PL near $C \times I$, and

iii. $H_1 = 1$ near $(D \cup (\mathbb{R}^{n} \setminus U)) \times I$ and near $\mathbb{R}^{n} \times \{0\}$.

**Proof.** If $C, D$ are compact, this is deduced from 5.4 exactly as 4.7 was deduced from 4.4. For the general case, let $C_i = C \cap iB^n$, $U_i = U \cap (i + 1) \text{Int} B^n$, $D_i = D \cap (i + 1)B^n$. Suppose inductively that $H^{(i)}$ satisfies (i)–(iii) with respect to $C_i, D_i,$ and $U_i$.

Let $F_i = (H^{(i)})^{-1}(F)$: this is a PL structure on $U \times I$ which agrees with the standard PL structure near $(C_i \times I) \cup (D_i \cup (\mathbb{R}^{n} \setminus U_i)) \times I$ and near $U \times \{0\}$. Now apply the compact case to get an isotopy $H'_i$ satisfying (i)–(iii) with respect to $C_{i+1} \setminus C_i$, $U_{i+1} \setminus U_{i-2}$, $C_i \cup D_{i+1}$, $F_i$. Then $H^{(i+1)} = H^{(i)} H'_i$ satisfies (i)–(iii) with respect to $C_{i+1}, U_{i+1}, D_{i+1}, F_i$. Since $H'_i = 1$ on $(i - 1)B^n$, $H^{(i+1)} = H^{(i)}$ on $(i - 1)B^n$.

Now take $H_t = \lim_{i \to \infty} H^{(i)}$. This satisfies (i)–(iii) with respect to $C, D, U, F$.

**Theorem 5.7** (Product Structure Theorem). Let $M^n$ be a topological manifold, $C \subseteq M$ be a closed subset, and $U$ be an open neighborhood of $C$. Let $F_0$ be a PL structure on $U$, and let $G$ be a PL structure on $M \times \mathbb{R}^k$ such that $G$ agrees with $F_0 \times \mathbb{R}^k$ on $U \times \mathbb{R}^k$. If $n \geq 6$ then there is a PL structure $F$ on $M$ agreeing with $F_0$ on $C$ and a PL homeomorphism $(M \times \mathbb{R}^k, F \times \mathbb{R}^k) \to (M \times \mathbb{R}^k, G)$ which is isotopic to 1 by an isotopy fixing a neighborhood of $C \times \mathbb{R}^k$.

The proof is given below.

**Definition 5.8.** PL structures $F_1, F_2$ on $M$ are isotopic if there is a PL homeomorphism $h : (M, F_1) \to (M, F_2)$ which is isotopic to 1.
Let PL(M) be the set of isotopy classes of PL structures on M.

Corollary 5.9. If dim M ≥ 6, the natural map PL(M) → PL(M × ℝk) is a bijection. In particular, if M × ℝk has a PL structure and dim M ≥ 6, then M has a PL structure.

Lemma 5.10. Any two PL structures on ℝn (n XXXXXXX) are isotopic.

Proof. Let F be a PL structure on ℝn. By 5.2 (ii) (ℝn, F) is PL homeomorphic to Int W where W is a compact PL manifold with ∂W ⊆ Sn−1. By 5.2 (i), ∂W is PL homeomorphic to Sn−1. W is contractible, so by 5.2 (i), W is PL homeomorphic to Bn. W ∖ ∂ Bn ∼ S, so there exists a PL homeomorphism h : ℝn → Int Bn → Int W → (ℝn, F). We may assume h is orientation preserving. We must prove that h is isotopic to 1.

Let R > r > 0 be chosen so that h(rBn) ⊆ Int h(RBn). By the annulus theorem 5.3, there is a homeomorphism f : RBn ∖ Int rBn → RBn ∖ h(Int rBn) with f|∂(rBn) = 1. Since h is orientation preserving, and using the proof of 5.3, we can choose f so that f = h on ∂(rBn).

Extend f over ℝn by

\[ f(x) = \begin{cases} 
  x & \text{if } \|x\| \geq R, \\
  hx & \text{if } \|x\| < r.
\end{cases} \]

Since f = 1 outside RBn, f is isotopic to 1, so h is isotopic to f−1h. Since f−1h = 1 in rBn, f−1h is isotopic to 1. Therefore h is isotopic to 1 as required.

Proof of Theorem 5.7. Clearly, it is sufficient to prove for the case k = 1. Assume first that M = ℝn, G = a PL structure on ℝn × ℝ = ℝn+1. By 5.10, there exists an isotopy Ht such that H1 : ℝn+1 → (ℝn+1, G) is PL and Ht = 1 for t ≤ 1. H defines a homeomorphism H : ℝn × ℝ × I → ℝn × ℝ × I (sending (x, t) → (Ht(x, t))). Let H = H(standard PL structure). Then H agrees with the standard structure near ℝn × ℝ × {0} and with G on ℝn × ℝ × {1}. Apply theorem 5.6 to ℝn × ℝ × I with C, U, D, F replaced by ℝn × (−∞, 0], ℝn × (−∞, 12], 0, H|I × I.

We obtain an isotopy F0 on ℝn × ℝ × {1} such that F0 = 1, F1 = 1 outside ℝn × (−∞, 12] × XXX and F1 : (ℝn × (−∞, 12] × {1}, standard) → XXX is PL near ℝn × (−∞, 0] × {1}.

Let G′ = F−1(F), a PL structure on ℝn × ℝ. Then G′ agrees with G near ℝn × [1, ∞) and G′ agrees with the standard structure near ℝn × (−∞, 0]. ℝn × {0} is a PL submanifold of G′, U × {1} is a PL submanifold of G′, therefore G′ induces a PL structure on U × I. G′ is equal to the standard structure near U × {0}.

Apply Theorem 5.6 to C, U, 0, G′|I × I to obtain an isotopy Gt of ℝn × ℝ such that G1 : (U × I, standard) → (U × I, G′) is PL near C × I. Gt is I near ℝn × {0}.

Let g : ℝn → ℝ be defined by \(g(x, 1) = G(X XXX).\) Let G″ = (g × 1)G−1. Near C × I, G′′ agrees with (g × 1)(standard structure) = Fg × I.
Define $\mathcal{F} = G''|_{\mathbb{R}^n \times \{0\}}$. $\mathcal{F}$ agrees with $\mathcal{F}_0$ near $C$. XXXXXXX Remains constant isotopy (rel $C \times \mathbb{R}$) from $\mathcal{F} \times \mathbb{R}$ to $\mathcal{G}$.

Choose a PL isotopy (of embeddings) $j_i : \mathbb{R} \rightarrow \mathbb{R}$ such that $j_i = 1$ when $t \leq \frac{1}{4}$ and $j_i(\mathbb{R}) \subset (1, \infty)$. Let $J : \mathbb{R}^n \times \mathbb{R} \times I \rightarrow \mathbb{R}^n \times \mathbb{R} \times I$ be defined by $J(x, y, t) = (x, j_i(y), t)$. Then the PL structure $J^{-1}(\mathcal{G}'' \times I)$ agrees with $\mathcal{G}'' \times \{0\}$ on $\mathbb{R}^n \times \mathbb{R} \times \{0\}$ and agrees with $\mathcal{F}_0 \times \mathbb{R} \times I$ near $C \times \mathbb{R} \times I$.

Apply theorem 5.6 (using the fact that $\mathcal{G}''$ is isotopic to the standard structure by lemma 5.10) to obtain an isotopy from $\mathcal{G}''$ to $J^{-1}(\mathcal{G}'' \times \{1\})$, fixed near $C \times \mathbb{R}$. We have $J^{-1}(\mathcal{G}'' \times \{1\}) = J^{-1}(\mathcal{G} \times \{1\})$ (since $\mathcal{G}'' = G$ on $\mathbb{R}^n \times (1, \infty)$) and similarly $\mathcal{G}$ is isotopic to $J^{-1}(\mathcal{G} \times \{1\})$ (fixed near $C \times \mathbb{R}$). Therefore $\mathcal{G}, \mathcal{G}''$ are isotopic (relative to a neighborhood of $C \times \mathbb{R}$). Similarly, $\mathcal{G}, \mathcal{F} \times \mathbb{R}$ are isotopic fixing a neighborhood of $C \times \mathbb{R}$. Therefore $\mathcal{G}, \mathcal{F} \times \mathbb{R}$ are isotopic fixing a neighborhood of $C \times \mathbb{R}$.

For general $M$, with $\partial M = \emptyset$, we may assume WLOG that $M$ is connected. We know that $M$ is metrizable implies that $M$ is second countable. So $M = \bigcup_{i=1}^{\infty} f_i(B^n)$ where $f_i : \mathbb{R}^n \rightarrow M$ are embeddings. Let $C_i = C \cup f_1(B^n) \cup \cdots \cup f_i(B^n)$. Suppose inductively we have a PL structure $\mathcal{F}_{i-1}$ on a neighborhood of $C_{i-1}$ in $M$, extending $\mathcal{F}_0$ and a PL structure $\mathcal{G}_{i-1}$ on $M \times \mathbb{R}$ extending $\mathcal{F}_{i-1} \cup \mathbb{R}$ and isotopic to $\mathcal{G}$ by an isotopy fixed near $C \times \mathbb{R}$.

Apply the result for $M = \mathbb{R}^n$ to $\mathcal{F}' = f_i^{-1}(\mathcal{F}_{i-1})$ (near $C' = f_i^{-1}(C_{i-1})$) and $(f_i \times 1)^{-1}(\mathcal{G}_{i-1}) = \mathcal{G}'$. We obtain a PL structure $\mathcal{F}_i''$ on $\mathbb{R}^n$ (= $\mathcal{F}'$ near $C'$) and isotopy $H_i$ of $\mathbb{R}^n \times \mathbb{R}$ with $H_i = 1$ for $t \leq \frac{1}{4}$ and $H_i^{-1}(\mathcal{G}') = \mathcal{F}_i'' \times \mathbb{R}$, and $H_i$ fixes a neighborhood of $C'$.

$H$ defines a homeomorphism on $\mathbb{R}^n \times \mathbb{R} \times I$. Let $\mathcal{H} = H^{-1}(\mathcal{G}' \times I)$, $\mathcal{H}$ agrees with $\mathcal{G}'$ near $\mathbb{R}^n \times \mathbb{R} \times \{0\}$, with $\mathcal{F}_i'' \times \mathbb{R}$ on $\mathbb{R}^n \times \mathbb{R} \times \{1\}$, and near $C' \times \mathbb{R} \times I$. Apply theorem 5.6 to this: replace $C, U, D, \mathcal{F}$ by $B^n \times \mathbb{R}, \mathbb{R} \times \mathbb{R} \times I, \mathcal{H}$ to obtain a PL structure $\mathcal{G}_i''$ on $\mathbb{R}^n \times \mathbb{R}$ which agrees with $\mathcal{F}_i'' \times \mathbb{R}$ near $(C' \cup B^n) \times \mathbb{R}$ and which is isotopic to $\mathcal{G}'$ rel $(C' \cup (\mathbb{R}^n \setminus \text{Int } B^n)) \times \mathbb{R}$).

Define $\mathcal{F}_i = \mathcal{F}_{i-1} \cup f_i(\mathcal{F}_i'')$ and extend $(f_i \times 1)(\mathcal{G}_i'')$ to a structure $\mathcal{G}_i$ on $M \times \mathbb{R}$ agreeing with $\mathcal{G}_{i-1}$ off $f_i(B^n) \times \mathbb{R}$. Then $\mathcal{G}_i$ agrees with $\mathcal{F}_i \times \mathbb{R}$ near $C_i \times \mathbb{R}$ and $\mathcal{G}_i$ is isotopic to $\mathcal{G}_{i-1}$ fixing a neighborhood of $C_{i-1} \times \mathbb{R}$, so $\mathcal{F}_i = \mathcal{F}_{i-1}$ near $C_{i-1}$.

Since $\mathcal{F}_i = \mathcal{F}_{i-1}$ near $C_{i-1}$ there is a PL structure $\mathcal{F}$ on $M$ agreeing with $\mathcal{F}_i$ near $C_i$. $\mathcal{G}$ agrees with $\mathcal{F} \times \mathbb{R}$ near $C \times \mathbb{R}, \mathcal{F}$ agrees with $\mathcal{F}_0$ near XXXXXXXXXX. Since $\mathcal{G}_i$ is isotopic to $\mathcal{G}_{i-1}$ (fixing a neighborhood of $C_{i-1} \times \mathbb{R}$). Hence all isotopies can be pieced together to obtain an isotopy of $\mathcal{F} \times \mathbb{R}$ to $\mathcal{G}$, fixing a neighborhood of $C \times \mathbb{R}$.

This proves the product theorem when $M$ has no boundary.

If $M$ has nonempty boundary $\partial M$, then apply the theorem for $M$ unbounded to $\partial M$, and then to $\text{Int } M$ using a collaring argument. We seem to need $\dim M \geq 7$ to ensure $\dim \partial M \geq 6$.

In fact the theorem can be proved for all unbounded 5-manifolds and all 6-manifolds.

As an application, if $M$ is a topological manifold, we can embed $M$ in $\mathbb{R}^N$ with a neighborhood $E$ which fibers over $M$, i.e. there is a map $\phi : E \rightarrow M$ which
is locally the projection of product, with fiber $\mathbb{R}^n$ (structural group $\mathcal{H}(\mathbb{R}^n) = \text{Top}_n$).

Let $\nu = \phi$. A necessary condition for $M$ to have a PL structure is that $\nu$ come from a PL bundle over $M$. This is also sufficient if $\dim M \geq 6$.

$E(\nu)$ is an open subset of $\mathbb{R}^N$ so that it inherits a PL structure. Suppose there exists a PL bundle $\xi$ over $E(\nu)$ which is equivalent as a topological bundle to $\nu$. There exists a PL bundle $\eta$ over $E(\nu)$ such that $\xi \oplus \eta$ is trivial. The total space $E(\eta)$ is homeomorphic to $M \times \mathbb{R}^k$ and has a PL structure. By the product structure theorem, $M$ has a PL structure.

There exists a classifying space $B\text{Top}_n$ classifying such topological bundles by $[M, B\text{Top}_n]$. $n$ is immaterial, so take $B\text{Top} = \bigcup_{n=1}^{\infty} B\text{Top}_n$. Similarly for $B\text{PL}_n, B\text{PL}$. There is a natural map $B\text{PL}_n \rightarrow B\text{Top}$ which forgets the extra structure.

Therefore when $\dim M \geq 6$, $M$ has a PL structure if the map $\nu : M \rightarrow B\text{Top}$ factors (up to homotopy) as

$$
\begin{array}{c}
M \\
\downarrow \nu \\
B\text{PL} \\
\downarrow \rightarrow \\
B\text{Top}
\end{array}
$$

Therefore $M$ has a PL structure iff the classifying map of the stable normal bundle $\nu$ of $M$ lies in the image of $[M, B\text{PL}] \rightarrow [M, B\text{Top}]$.

To show that PL $\neq$ Top: let $k$ be an integer, and $p_k : T^n \rightarrow T^n$ be induced by $\mathbb{R}^n \rightarrow \mathbb{R}^n; x \mapsto kx$. Then $p_k$ is a $k^n$-fold covering (a fiber bundle with discrete fibers of $k^n$ XXXXXXXXXXXXXX). There exists a homeomorphism $h_k : T^n \rightarrow T^n$ such that

$$
\begin{array}{c}
T^n \\
\downarrow h_k \\
T^n \\
\downarrow p_k \\
T^n \\
\downarrow p_k \\
T^n
\end{array}
$$

for any given homeomorphism $h : T^n \rightarrow T^n$. There are $k^n$ such homeomorphisms. Since all covering translations of $p_k : T^n \rightarrow T^n$ are isotopic to 1, any two choices for $h_k$ are isotopic.

**Theorem 5.11.** If $h : T^n \rightarrow T^n$ is a homeomorphism homotopic to 1, then $h_k$ is topologically isotopic to 1 for sufficiently large $k$.

**Proof.** First isotope $h$ until $h(0) = 0$ (where $0 = e(0) \in T^n$.) Choose $h_k$ so that $h_k(0) = 0$. Let $\tilde{h}_k : \mathbb{R}^n \rightarrow \mathbb{R}^n$ be a homeomorphism such that $e\tilde{h}_k = h_k e$ and $\tilde{h}_k(0) = 0$. Since $h \simeq 1$, $\tilde{h}_1 = \tilde{h}$ is bounded. $\tilde{h}_k(x) = \frac{1}{k}\tilde{h}(x)$ because $p_k e\tilde{h}_k = p_k h_k e = h_k e$, $\tilde{h}_k(0) = 0$, and these characterize $\tilde{h}_k$. We have

$$
\sup_{x \in \mathbb{R}^n} d(x, \tilde{h}_k(x)) = \frac{1}{k} \left( \sup_{x \in \mathbb{R}^n} d(x, \tilde{h}(x)) \right) \rightarrow 0
$$
as \( k \to \infty \). So \( \sup_{y \in T^n} d(y, h_k(y)) \to 0 \) as \( k \to \infty \). But \( \mathcal{H}(T^n) \) is locally contractible by Theorem 4.8. Therefore if \( k \) is large enough, \( h_k \) is isotopic to 1.

But the behavior is different in the PL case:

**Proposition 5.12.** Let \( n \geq 5 \). There exists a PL homeomorphism \( h : T^n \to T^n \) such that \( h \simeq 1 \) and \( h_k \) is not PL isotopic to 1 for any odd \( k \).

**Exercise.** Show that if \( h : T^n \to T^n \) is PL and topologically isotopic to 1 but not PL isotopic to 1 then \( T^n \times I/(x, 0) \sim (h(x), 1) \) is topologically homeomorphic to \( T^{n+1} \) but not PL homeomorphic to \( T^{n+1} \).