A SURFACE IS TAME IF ITS COMPLEMENT IS 1-ULC

BY

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1. Introduction. In this paper we show that a 2-manifold $M$ in Euclidean 3-space $E^3$ is tame if $E^3 - M$ is uniformly locally simply connected.

A closed subset $X$ of a triangulated manifold $Y$ is tame if there is a homeomorphism of $Y$ onto itself taking $X$ onto a polyhedron (geometric complex) in $Y$. If there is no such homeomorphism, $X$ is called wild. Examples of 2-manifolds wildly embedded in $E^3$ are found in [1; 8; 6].

An $n$-manifold is a separable metric space each of whose points lies in a neighborhood homeomorphic to Euclidean $n$-space. An $n$-manifold-with-boundary is a separable metric space each of whose points lies in a neighborhood whose closure is a topological $n$-cell. If $M$ is an $n$-manifold-with-boundary, we use $\text{Int} M$ to denote the set of points of $M$ with neighborhoods homeomorphic to Euclidean $n$-space and $\text{Bd} D$ to denote $M - \text{Int} M$. For example, if $D$ is a disk, $\text{Bd} D$ is a simple closed curve which is the rim of the disk. If we have a manifold embedded in a larger space and treat the manifold as a subset rather than a space, we insist that it be closed. If $S$ is a 2-sphere embedded in $E^3$, we use $\text{Int} S$ and $\text{Ext} S$ to denote the bounded and unbounded components of $E^3 - S$. The double meaning of the symbol $\text{Int}$ should not lead to confusion.

A subset $X$ of a manifold-with-boundary is locally tame at a point $p$ of $X$ if there is a neighborhood $N$ of $p$ and a homeomorphism of $N$ (the closure of $N$) onto a cell that takes $X \cdot \overline{N}$ onto a polyhedron. If the manifold-with-boundary is triangulated, we say that $X$ is locally polyhedral at $p$ if there is a neighborhood $N$ of $p$ such that $X \cdot \overline{N}$ is a polyhedron.

Suppose $D$ is a disk. We say that a map of $\text{Bd} D$ into a set $Y$ can be shrunk to a constant in $Y$ if the map can be extended to take $D$ into $Y$. If each map of $\text{Bd} D$ into $Y$ can be shrunk to a constant in $Y$, we say that $Y$ is simply connected. Also, $Y$ is locally simply connected at a point $p$ of $\overline{Y}$ if for each neighborhood $U$ of $p$ there is a neighborhood $V$ of $p$ such that each map of $\text{Bd} D$ into $V \cdot Y$ can be shrunk to a point in $U \cdot Y$. A metric space $Y$ is uniformly locally simply connected (or 1-ULC) if for each $\varepsilon > 0$ there is a $\delta > 0$ such that each map of $\text{Bd} D$ into a $\delta$ subset of $Y$ can be shrunk to a point on an $\varepsilon$ subset of $Y$. If $\overline{Y}$ is a compact subset of a metric space, it can be shown that $Y$ is 1-ULC if it is locally simply connected at each point of $\overline{Y}$.

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The surfaces studied in solid geometry are tame. It is useful to have criteria for determining which surfaces are tame. We mention three such criteria.

1. A closed subset of a triangulated 3-manifold-with-boundary is tame if and only if it is locally tame at each of its points.

2. A 2-sphere in $E^3$ is tame if and only if it can be homeomorphically approximated from both sides.

3. A 2-manifold $M$ in a triangulated 3-manifold $M_3$ is tame if and only if $M_3 - M$ is locally simply connected at each point of $M$.

Criterion 1 is proved in [2] and [10]. Criterion 2 is proved in [5] and restated below as Theorem 0. Criterion 3 is Theorem 7 of the present paper.

The distance function is denoted by $\rho$. We shall make use of the following approximation theorem proved in [3].

**Approximation Theorem.** For each 2-manifold $M$ in a triangulated 3-manifold-with-boundary and each non-negative continuous function $f$ defined on $M$, there is a 2-manifold $M'$ and a homeomorphism $h$ of $M$ onto $M'$ such that

$$\rho(x, h(x)) \leq f(x) \quad (x \in M)$$

and $M'$ is locally polyhedral at $h(x)$ if $f(x) > 0$.

Another theorem that we shall use is the Side Approximation Theorem for 2-Spheres. It is proved by the same methods as the Approximation Theorem and its proof will be given in another paper [7].

**Side Approximation Theorem for 2-Spheres.** Each 2-sphere $S$ in $E^3$ can be polyhedrally approximated almost from either side—that is for each $\varepsilon > 0$ and each component $U$ of $E^3 - S$ there is a homeomorphism $h$ of $S$ onto a polyhedral 2-sphere such that

- $h$ moves no point more than $\varepsilon$ and
- $h(S)$ contains a finite collection of mutually exclusive disks each of diameter less than $\varepsilon$ such that $h(S)$ minus the sum of the disks lies in $U$.

If $A$ and $B$ are two sets and there is a homeomorphism of $A$ onto $B$ that moves no point by more than $\varepsilon$, we write

$H(A, B) \leq \varepsilon$.

The following theorem is proved in [5].

**Theorem 0.** A 2-sphere $S$ in $E^3$ is tame if it can be homeomorphically approximated from both sides—that is, for each $\varepsilon > 0$ and each component $U$ of $E^3 - S$, there is a 2-sphere $S'$ in $U$ such that

$$H(S, S') < \varepsilon.$$ 

To show that a 2-sphere is tame, a first step might be to show that the hypothesis of Theorem 0 is met. As a step toward proving that a 2-sphere in $E^3$ is tame if its complement is 1-ULC, we prove the following.
Theorem 1. If $S$ is a 2-sphere in $E^3$ such that $\text{Int } S$ is 1-ULC, then for each $\epsilon > 0$, $S$ can be homeomorphically approximated from $\text{Int } S$—that is, for each $\epsilon > 0$ there is a 2-sphere $S'$ in $\text{Int } S$ such that

$$H(S, S') < \epsilon.$$ 

Our plan for proving Theorem 1 is to get a special cellular decomposition $T$ of $S$, get a homeomorphism of $S$ onto itself that pulls the boundaries of the cells of the decomposition $T$ into $\text{Int } S$, and finally pull the cells themselves into $\text{Int } S$.

It is hoped that the serious reader will understand the why of the attack as well as the details. Hence, we give our over-all plan of attack first and reserve epsilonics to last so that the reader can see why these particular $\epsilon$'s are used. When we need a close approximation, we let it be an $\epsilon$, approximation and decide later how small the $\epsilon$, would need to be to make the details work.

2. Proof of Theorem 1. a. Special cellular decomposition $T$ of $S$. We need a cellular decomposition $T$ of $S$ with the following properties.

The mesh of $T$ is less than $\epsilon_1$ ($\epsilon_1$ is a small number whose size is to be described later).

The collection of 2-cells of $T$ is the sum of three subcollections $A_1, A_2, A_3$ such that no two elements of $A_i$ ($i = 1, 2, 3$) intersect each other.

That for each $\epsilon_i > 0$ there is such a cellular decomposition $T$ of $S$ follows from a consideration of a triangulation $T'$ of $S$ of mesh less than $\epsilon_i/2$. The vertices of $T'$ are swelled into 2-cells and become the elements of $A_1$. The parts of the 1-simplexes of $T'$ not in elements of $A_1$ are expanded into the elements of $A_2$. The closures of the parts of the 2-simplexes of $T'$ not in elements of $A_1$ or $A_2$ are the elements of $A_3$.

b. Pulling elements of $T$ partially into $S$. Suppose $T$ is a fixed special cellular decomposition of $S$ such as mentioned in the preceding section. The 1-skeleton of $T$ is the sum of the boundaries of the 2-cells in $T$ and is denoted by $K_1$. We select a small number $\epsilon_2$ whose size is described later. Then there is a polyhedral 2-sphere $S_1$ and a homeomorphism $h_1$ of $S$ onto $S_1$ such that

$h_1$ moves no point more than $\epsilon_2$,
$h_1(K_1) \subset \text{Int } S$, and
$S_1$ contains a finite collection of mutually exclusive $\epsilon_2$ disks such that $S_1$ minus the sum of the interiors of these disks lies in $\text{Int } S$.

That for each $\epsilon_2$ there are such an $S_1$ and an $h_1$ follows from the Side Approximation Theorem of 2-Spheres. We let $\epsilon_2/2$ be the $\epsilon$ in the statement of that theorem and $S_1$ be the $S'$ guaranteed by the conclusion of that theorem. The homeomorphism $h_1$ is the homeomorphism $h$ guaranteed by that theorem.
followed by a homeomorphism of $S_1$ onto itself that moves no point by more than $\varepsilon_2/2$ but pulls the image of $K_1$ off of the disks.

c. The next approximations to elements of $T$. For each 2-cell $D$ of $T$, $h_1(D)$ is a first approximation to $D$. We note that $h_1(D)$ is homeomorphically close to $D$ and $h_1(\text{Int } D)$ contains a finite collection $E_1, E_2, \ldots, E_n$ of mutually exclusive $\varepsilon_2$ disks such that $h_1(D) - \sum \text{Int } E_i \subset \text{Int } S$. We suppose that $h_1(\text{Bd } D)$ is a polygon.

The second approximation $h_2(D)$ to $D$ may not be quite as close homeomorphically to $D$ as is $h_1(D)$ but it will still be close. However, it will have the advantage that the components of $S \cdot h_2(D)$ will have diameters much smaller than $\varepsilon_2$ (which is an upper bound on the diameters of $E_1, E_2, \ldots, E_n$) and simple closed curves in $\text{Int } S$ near the components of $S \cdot h_2(D)$ can be shrunk to points in $\text{Int } S$ without hitting $h_1(K_1)$.

Let $\varepsilon_3$ be a very small positive number selected in a fashion to be described later and $S'$ be a polyhedral 2-sphere which is homeomorphically within $\varepsilon_3$ of $S$ and which contains a finite collection of mutually exclusive $\varepsilon_3$ disks such that $S'$ minus the sum of the interiors of these disks is contained in $\text{Int } S$. We select $\varepsilon_3$ so that $S' - h_1(D) \subset \sum \text{Int } E_i$ and suppose that $S' \cdot h_1(D)$ is the sum of a finite collection of mutually exclusive simple closed curves $J_1, J_2, \ldots, J_r$.

The $\varepsilon_2$ and $\varepsilon_3$ were selected so that each $J_i$ bounds a disk $F_i$ on $S'$ of small diameter. We suppose that these disks $F_i$ are ordered by size with the small ones first so that no $F_i$ contains an $F_{i+j}$.

The disk in $h_1(D)$ bounded by $J_1$ is first replaced by $F_1$ and then pushed slightly to one side of $S'$ so as to reduce the number of components with the intersection with $S'$. The process is continued by replacing disks in the adjusted $h_1(D)$ by $F_i$'s and then pushing slightly so as to get a polyhedral disk $h_2(D)$ which is close to $D$ homeomorphically and which lies on $\text{Int } S'$. We select $h_2$ so that it agrees with $h_1$ in a neighborhood of $\text{Bd } D$ and such that the components of $S \cdot h_2(D)$ are not much bigger than those of $S' \cdot h_1(D)$. By selecting $\varepsilon_3$ very small, we can insure that the components of $h_2(D) \cdot S$ are very small—in fact of diameter less than some preselected positive number $\varepsilon_4$.

Although we could have chosen the sum of the $h_2(D)$'s to be a 2-sphere, we did not insist on this since at the third approximation of $D$, there seems to be no easy way to prevent the approximating disks from intersecting at interior points of each.

d. Third approximation to $D$. Since each component of $S \cdot h_2(D)$ is of diameter less than $\varepsilon_4$, $h_2(\text{Int } D)$ contains a collection of mutually exclusive disks $E'_1, E'_2, \ldots, E'_m$ which cover $S \cdot h_2(D)$ such that each $\text{Bd } E'_i$ lies close to $S$ and is of diameter less than $\varepsilon_4$. Each $\text{Bd } E'_i$ lies in $\text{Int } S$ since $\text{Bd } D$ does.

Each $\text{Bd } E'_i$ is of such small diameter that it can be shrunk to a point on a small subset of $\text{Int } S$ where $\varepsilon_4$ and $\varepsilon_3$ have been selected so that this subset will not intersect $h_1(K_1) = h_2(K_1)$. Hence there is a map $g$ of $h_2(D)$ into $\text{Int } S$
such that $g h_3(D)$ lies close to $h_2(D)$, and $g$ is the identity in a neighborhood of $h_2(Bd D)$, $g h_3(D)$ intersects $h_2(K_1)$ only in $h_2(Bd D)$, and $g h_2(D)$ has no singular points near $g h_2(Bd D)$. It follows from Dehn's lemma as proved by Papakyriokopoulos [11] that for each neighborhood $U$ of the set of singular points of $g h_2(D)$, there is a homeomorphism $h_3$ of $D$ onto a polyhedral disk $h_3(D)$ in $g h_2(D) + U$ that agrees with $h_2$ in a neighborhood of $Bd D$. The third approximation to $D$ is $h_3(D)$. The advantage it has over $h_3(D)$ is that it lies in $Int S$. The only thing that makes $h_3(D)$ and $D$ homeomorphically close is that each is of small diameter and their boundaries are homeomorphically close.

e. The fourth approximation to $D$. Our task is now to untangle the $h_3(D)$'s so that their sum forms a 2-sphere in $Int S$. We recall that the collection of 2-cells of $T$ is the sum of three subcollections $A_1$, $A_2$, $A_3$ so that no two elements of any $A_i$ have a point in common. We will have enlarged the $h_1(D)$'s so little as we changed them to $h_2(D)$'s and then to $h_3(D)$'s that two $h_3(D)$'s will not intersect if the corresponding $D$'s do not intersect.

For each element $D$ of $A_1$, the fourth approximation $h(D)$ to $D$ is $h_3(D)$. We may suppose that for each element $D$ of $A_1$, the intersection of $h_3(Int D) = h(Int D)$ and the sum of the images under $h_3$ of the elements of $A_2$ is the sum of a finite collection of mutually exclusive simple closed curves $J_1, J_2, \cdots, J_r$ such that $J_i$ bounds a disk $G_i$ in $Int h(D)$ and the $J_i$'s are ordered according to the size of the disks $G_i$ they bound in $h(D)$, with the small ones coming first.

If $J_i$ lies in an $h_3(D')$ for an element $D'$ of $A_2$, we replace the disk in $h_3(D')$ by $G_i$ and shove this replaced disk slightly to one side of $h_3(D)$. This process is continued until for each element $D'$ of $A_2$, there is an $h$ defined on $D'$ so that $h(D)$ and the $h(D')$'s fit together only along their boundaries as they should.

Finally we turn to the elements of $A_3$. We suppose that for each element $D$ of $A_1+A_2$, $h(Int D)$ intersects the sum of the images under $h_3$ of the elements of $A_3$ in the sum of a collection of mutually exclusive simple closed curves. These simple closed curves are eliminated one by one, starting at the inside in a manner already described. For each element $D'$ of $A_3$, the resulting adjustment of $h_3(D')$ is called $h(D')$.

The sum of the $h(D)$'s is a 2-sphere in $Int S$. We note that $h = h_1 = h_2 = h_3$ on $K_1$. We will cause $h$ to be near the identity by picking the $\epsilon_i$'s so that the $D$'s and the $h(D)$'s are small and $h$ is near the identity on $K_1$.

f. Epsilontics. In this section we explain the sizes for $\epsilon_1$, $\epsilon_2$, $\epsilon_3$, $\epsilon_4$ and the reasons for these selections. We recall that

$\epsilon_1$ limits the mesh of $T$,

$\epsilon_2$ limits $h_1$ to be near the identity and limits the sizes of the $E_i$'s,

$\epsilon_3$ limits $S'$ to be near $S$ and limits the sizes of the disks in $S'$ such that $S'$ minus these disks lies in $Int S$, and
\( \varepsilon_4 \) limits the sizes of the components of \( h_2(D) \cdot S \).

We choose

\[ \varepsilon_1 < \varepsilon/8, \]

where \( \varepsilon \) is the number mentioned in the statement of Theorem 1. This is the only restriction we place on \( \varepsilon_1 \).

Let \( \delta_1 \) be a positive number so small that the distance between two elements of \( T \) without a common point is more than \( \delta_1 \).

Our goal is to choose \( \varepsilon_2, \varepsilon_3, \varepsilon_4 \) so that for each 2-cell \( D \) of \( T \), the following conditions are satisfied.

- \( h_1(D) \) lies in a \( \delta_1/6 \) neighborhood of \( D \).
- \( h_2(D) \) lies in a \( \delta_1/6 \) neighborhood of \( h_1(D) \).
- \( h_3(D) \) lies in a \( \delta_1/6 \) neighborhood of \( h_2(D) \).

This will insure that if \( D_1, D_2 \) are two 2-cells of \( T \) without a common point, then \( h_3(D_1) \cdot h_3(D_2) = 0 \).

Since each point of \( h_3(D) \) lies within \( 3\delta_1/6 \) of a point of \( D \) and \( \delta_1 < \varepsilon_1 \),

\[ \text{diameter } h_3(D) < \varepsilon_1 + \delta_1 < 2\varepsilon_1. \]

Since \( h = h_3 \) on elements of \( A_1 \),

\[ \text{diameter } h(D) < 2\varepsilon_1 \text{ if } D \text{ is an element of } A_1. \]

In changing from \( h_3 \) to \( h \) on elements \( D \) of \( A_2 \), the adjustment was made so that \( h(D) \) lies within \( 2\varepsilon_1 \) of \( h_3(D) \). Hence,

\[ \text{diameter } h(D) < 6\varepsilon_1 \text{ if } D \text{ is an element of } A_2. \]

For each element \( D \) of \( A_3 \),

\[ h(D) \text{ lies within } 6\varepsilon_1 \text{ of } h_3(D). \]

Since each point of \( h(D) \) lies within \( 6\varepsilon_1 \) of a point of \( h_3(D) \), this point in turn lies within \( 3\delta_1/6 \) of a point of \( D \), and diameter \( D < \varepsilon_1 \), we find that \( h \) moves no point as much as \( 8\varepsilon_1 \). This is the reason we selected \( \varepsilon_1 < \varepsilon/8 \).

Let \( \varepsilon_2 \) be a positive number so small that each subset of \( S \) of diameter \( 3\varepsilon_2 \) lies in a disk on \( S \) of diameter less than \( \delta_1/10 \). We note that

\[ \varepsilon_2 < \delta_1/30 < \delta_1/6. \]

Since \( \varepsilon_2 < \delta_1/6 \), for each 2-cell \( D \) of \( T \), \( h_1(D) \) lies in a \( \delta_1/6 \) neighborhood of \( D \). The more stringent condition that \( \varepsilon_2 < \delta_1/30 \) is used later to help insure that \( h_3(D) \) lies in a \( \delta_1/6 \) neighborhood of \( h_1(D) \).

Let \( \delta_2 \) be a positive number so small that for each 2-cell \( D \) of \( T \), \( \delta_2 \) is less than the distance between \( S \) and \( h_1(D) - \sum E_i \). We note that

\[ \delta_2 < \varepsilon_2. \]
Although we shall place more stringent conditions on $e_3$, we first consider the sizes of the components of $S' \cdot h_1(D)$ if we merely suppose

$$e_3 < \delta_2.$$ 

Let $X$ be a component of $S' \cdot h_1(D)$ and $h'$ be a homeomorphism of $S$ onto $S'$ that moves no point more than $e_2$. Then $X$ lies in an $E_\epsilon$ (which is of diameter less than $e_2$), $h'^{-1}(X)$ is of diameter less than $e_2 + 2e_3 < 3e_2$, $h'^{-1}(X)$ lies in a disk of diameter less than $\delta_1/10$, and the image of this disk under $h'$ is a disk in $S'$ of diameter less than $\delta_1/10 + 2e_3 < \delta_1/10 + 2\delta_1/30 = \delta_1/6$. Hence, the restrictions we have placed on $e_2$, $e_3$ are enough to insure that we can select $h_2$ so that $h_2(D)$ lies in a $\delta_1/6$ neighborhood of $h_1(D)$.

Let $e_4$ be a positive number so small that each simple closed curve in $E^3 - S$ of diameter less than $e_4$ can be shrunk to a point on a subset of $E^3 - S$ of diameter less than the minimum of $\delta_1/6$ and $\delta_2/2$. Note that $e_4$ does not depend on $e_2$. The $\text{Bd } E_i'$'s are selected to lie within $e_4 < \delta_2/2$ of $S$. Also, the $\text{Bd } E_i'$'s have diameters less than $e_4$ so that $gh_2(D)$ intersects $h_2(K_1)$ only in $h_3(\text{Bd } D)$. Furthermore, $h_3(D)$ lies in a $\delta_1/6$ neighborhood of $h_2(D)$.

The final restriction we place on $e_3$ is to insure that each component of $S \cdot h_2(D)$ is of diameter less than $e_4$. Let $\delta_3$ be a number so small that each $\delta_3$ subset of $S$ lies in a disk in $S$ of diameter less than $e_4$. We suppose

$$e_3 < \delta_3.$$ 

Each component $X$ of $S \cdot h_2(D)$ lies in $\text{Int } S'$ and is separated from the big component of $S - S'$ by a disk in $S'$ of diameter less than $e_3 < \delta_3$. Hence, diameter $X < e_4$.

3. **Conditions under which a 2-sphere is tame.** Tame 2-spheres in $E^3$ have uniformly locally simply connected complements. A converse is as follows.

**Theorem 2.** A 2-sphere $S$ in $E^3$ is tame if each component of $E^3 - S$ is 1-ULC.

**Proof.** It follows from Theorem 1 that for each positive number $\epsilon$ there is a 2-sphere $S'$ in $\text{Int } S$ such that

$$H(S, S') < \epsilon.$$ 

Similarly, it follows that there is a 2-sphere $S''$ in $\text{Ext } S$ such that

$$H(S, S'') < \epsilon.$$ 

That $S$ is tame then follows from Theorem 0.

**Corollary.** A 2-sphere $S$ in $E^3$ is tame if $E^3 - S$ is locally simply connected at each point of $S$.

4. **Retaining simple connectivity.** We shall be applying the Approximation Theorem to a 2-manifold to make part of the 2-manifold locally poly-
hedral. We are interested in seeing what this does to the local simple connectiv- 
ty of the complement. First we examine the effect of throwing away part of 
the 2-manifold.

**Theorem 3.** Suppose $M$ is a 2-manifold in $E^3$, $D$ is a disk in $M$, and $p$ is a 
point of $D$ at which $E^3 - M$ is locally simply connected. Then $E^3 - D$ is locally 
simply connected at $p$.

**Proof.** We only consider the case where $p \in \text{Bd} \ D$. Suppose $U$ is a given 
neighborhood of $p$. Let $V'$ be a neighborhood of $p$ such that each map of 
a circle into $V' \cdot (E^3 - M)$ can be shrunk to a point in $U \cdot (E^3 - M)$ and $V$ be a 
neighborhood of $p$ such that each pair of points of $V \cdot (M - D)$ lie in an arc in 
$V' \cdot (M - D)$. We show that if $E$ is a plane circular disk and $f$ is a map of 
Bd $E$ into $V \cdot (E^3 - D)$, then there is a map of $E$ into $U \cdot (E^3 - D)$ that agrees 
with $f$ on Bd $E$.

We want to simplify $f$ so that $M \cdot f(\text{Bd} \ E)$ does not have infinitely many 
components. Suppose $aa'$ is an arc on Bd $E$ and $bb'$ is an arc on $V \cdot (M - D)$ 
such that $f(a) = b$, $f(a') = b'$, and $bb' + f(aa')$ lies in a convex subset of $V - D$. 
Then there is a homotopy $F_t$ on aa' such that $F_0 = f$, $F_t$ is constant on $a$ and 
a', $F_t(aa') = bb'$, and each $F_t(aa')$ lies in $V - D$. Hence, we suppose with no 
loss of generality that $f^{-1}(M \cdot f(\text{Bd} \ E))$ is the sum of a finite number of arcs 
$a_1a_2$, $a_3a_4$, $\ldots$, $a_{2n-1}a_{2n}$ on Bd $E$ ordered so that there is no $a_t$ between any 
a_t and $a_{t+1}$.

Let $q$ be the center of $E$ and $f(q)$ be any point of $V \cdot (M - D)$. Extend $f$ to 
map the radius $qa_t$ of $E$ onto an arc in $V' \cdot (M - D)$ from $f(q)$ to $f(a_t)$. Since 
each component of $M$ divides $E^3$ into two pieces and any arc in $M$ can be 
approximated by arcs on either side of $M$, the map $f$ on the boundary of the 
sector $a_1a_{t+1}$ of $E$ can be extended to map an annulus ring in the sector 
one of whose boundary components is the boundary of the sector into 
$V' \cdot (E^3 - D)$ so that the image of the other boundary component of the 
anulus misses $M$. The map $f$ can be further extended to take the rest of the 
sector into $U \cdot (E^3 - M)$.

**Theorem 4.** Suppose $M$ is a 2-manifold in $E^3$, $D$ is a disk in $M$, $p$ is a 
point of $M$ at which $E^3 - M$ is locally simply connected, and $h$ is a homeomor-
phism of $M$ into $E^3$ such that $h$ is the identity on $D$ and $h(M)$ is locally poly-
hedral at each point of $h(M) - D$. Then $E^3 - h(M)$ is locally simply connected 
at $p$.

**Proof.** The only case we consider is the one in which $p$ is a point of Bd $D$. 
Suppose $U$ is a given neighborhood of $p$. Let $V'$ be a neighborhood of $p$ such 
that each closed set in $V' \cdot (h(M) - D)$ lies in a disk in $U \cdot (h(M) - D)$. It fol-
lows from Theorem 3 that there is a neighborhood $V$ of $p$ such that each map of 
a circle into $V \cdot (E^3 - D)$ can be shrunk to a point in $V' \cdot (E^3 - D)$. We show
that if \( E \) is a disk and \( f \) is a map of \( \text{Bd} \ E \) into \( V \cdot (E^3 - h(M)) \), then \( f \) can be extended to map \( E \) into \( U \cdot (E^3 - h(M)) \).

Let \( f' \) be a map of \( E \) into \( V' \cdot (E^3 - D) \) that is an extension of \( f \) on \( \text{Bd} \ E \). Let \( E' \) be the component of \( E - f'^{-1}(h(M) \cdot f(E)) \) containing \( \text{Bd} \ E \). With no loss of generality we suppose that \( E' \) is \( E \) minus a finite collection of mutually exclusive subdisks \( E_1, E_2, \ldots, E_n \) of \( E \).

Since \( f'(\text{Bd} \ E) \) lies on the interior of a polyhedral disk in \( U \cdot (h(M) - D) \), it is possible to adjust \( f' \) on disks in \( E \) slightly larger than the \( E_i \)‘s so as to take the larger disks slightly to one side of \( h(M) \). The adjusted \( f' \) is \( f \) and takes \( E \) into \( U \cdot (E^3 - h(M)) \).

**Question.** Would Theorem 4 be true if we supposed that \( D \) were merely a closed subset of \( M \) with only nondegenerate components rather than actually a disk in \( M \)?

5. **Enlarging a disk to a 2-sphere.** Not each disk in \( E^3 \) lies on a 2-sphere. An example of such a disk is obtained by taking a horizontal disk \( D \) in \( E^3 \); removing two circular holes from \( \text{Int} \ D \); adding tubes from the holes, one tube going up and the other down and around; and finally adding hooked disks as shown in [1]. The disk does not lie on a 2-sphere since its boundary cannot be shrunk to a point in the complement of the disk. Although it does not lie on a 2-sphere, it does lie on a torus as was pointed out to me by David Gillman. If instead of removing a pair of holes from the horizontal disk and replacing the holes with hooked wild disks, one had removed an infinite collection of pairs of holes converging to a boundary point of \( D \) and replaced each pair of holes with wild disks hooked over the boundary of \( D \), there would have resulted a wild disk in \( E^3 \) that does not lie on any 2-manifold in \( E^3 \).

The following result shows that each disk contains many small disks each of which lies on a 2-sphere.

**Theorem 5.** Suppose \( M \) is a 2-manifold in \( E^3 \), \( p \) is a point of \( M \), and \( U \) is a neighborhood of \( p \). Then there is a disk \( D \) in \( M \cdot U \) and a 2-sphere \( S \) in \( U \) such that \( p \in \text{Int} \ D \subseteq S \) and \( S \) is locally polyhedral at each point of \( S - D \).

**Proof.** Let \( E \) be a disk in \( M \) such that \( p \in \text{Int} \ E \) and \( C \) be a cube in \( U \) whose interior contains \( p \) and whose exterior contains \( \text{Bd} \ E \). Let \( D \) be a disk in \( M \cdot \text{Int} \ C \) such that \( p \in \text{Int} \ D \). It follows from the Approximation Theorem that there is a homeomorphism \( h \) of \( E \) into \( E^3 \) such that \( h \) is the identity on \( D \), \( h \) takes \( \text{Bd} \ E \) into \( \text{Ext} \ C \), and \( h(E) \) is locally polyhedral at each point of \( h(E) - D \). We suppose with no loss of generality that \( \text{Bd} \ C \cdot h(E) \) is the sum of a finite collection of mutually exclusive polygons.

Let \( E' \) be the component of \( h(E) - \text{Bd} \ C \) containing \( D \). It is topologically equivalent to a 2-sphere minus the sum of a finite collection of mutually exclusive disks. By adding polygonal disks in \( U \cdot (C + \text{Ext} \ C) \) to \( E' \), one obtains the required 2-sphere \( S \).

6. **Locally tame subsets of 2-manifolds.** A 2-sphere \( S \) in \( E^3 \) may not be
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locally tame at a point \( p \) even if \( E^3 - S \) is locally simply connected at \( p \) as shown by the following example.

**Example.** Consider a spherical 2-sphere \( S' \) and a sequence of mutually
exclusive spherical disks \( E_1, E_2, \ldots \) in \( S' \) converging to a point \( p \) of \( S' \). Fox
and Artin have described [8] a wild arc which is locally polyhedral except at
one end point. For each \( E_i \), let \( A_i \) be such an arc reaching out from the center
of \( E_i \) such that the arc is of diameter less than the radius of \( E_i \) and such that
\( A_i \) intersects \( S \) only at the polyhedral end of \( A_i \). By replacing each \( E_i \) in \( S \)
by a disk obtained by swelling up \( A_i \) as done in [7] one can obtain a 2-sphere
\( S \) such that \( E^3 - S \) is locally simply connected at \( p \) even though \( S \) is not locally
tame at \( p \).

**Theorem 6.** Suppose \( M_2 \) is a 2-manifold embedded in a 3-manifold \( M_3 \) and
\( U \) is an open subset of \( M_2 \) such that \( M_3 - M_2 \) is locally simply connected at each
point of \( U \). Then \( M_2 \) is locally tame at each point of \( U \).

**Proof.** Since local tameness is only a local property, we suppose that \( M_3 \)
is \( E^3 \) and \( U \) is all of \( M_2 \). If this were not the case already we would take a
homeomorphism \( h \) of a neighborhood of \( p \) in \( M_3 \) into \( E^3 \) such that this neigh-
borhood did not intersect \( M_3 - U \).

It follows from Theorem 5 that there is a disk \( D \) in \( M_3 \) and a 2-sphere \( S \)
such that \( p \in \text{Int } D \subset S \) and \( S \) is locally polyhedral at each point of \( S - D \). It
follows from Theorem 4 that \( E^3 - S \) is locally simply connected at each point
of \( S \). Since \( S \) is compact, \( E^3 - S \) is 1-ULC. Theorem 2 implies that \( S \) is tame.
Since \( S \) is tame, \( M_2 \) is locally tame at \( p \).

Since a closed set in a 3-manifold is tame if it is locally tame [2; 10] we
have the following result.

**Theorem 7.** A 2-manifold \( M_2 \) in a triangulated 3-manifold \( M_3 \) is tame if
and only if \( M_3 - M_2 \) is locally simply connected at each point of \( M_2 \).

**Corollary.** A 2-manifold \( M_2 \) in a 3-manifold \( M_3 \) is tame if \( M_3 - M_2 \) is
1-ULC.

7. Tame 2-manifolds-with-boundaries. In this section we extend our re-
results about 2-manifolds to 2-manifolds-with-boundaries.

**Theorem 8.** Suppose \( M_2 \) is a 2-manifold-with-boundary embedded in a 3-
manifold \( M_3 \) and \( U \) is an open subset of \( M_2 \) such that \( M_3 - M_2 \) is locally simply
connected at each point of \( U \). Then \( M_2 \) is locally tame at each point of \( U \).

**Proof.** Since we only look at \( M_2 \) locally, we suppose that \( M_2 \) is \( E^3 \) and
\( U \) is \( M_2 \). Since Theorem 6 takes care of points of \( \text{Int } M_2 \), we only show that
\( M_2 \) is locally tame at a point \( p \) of \( \text{Bd } M_2 \).

Let \( D \) be a disk in \( M_2 \) such that \( \text{Bd } D \cdot \text{Bd } M_2 \) is an arc containing \( p \) as a
non end point. An argument like that used in the proof of Theorem 3 shows
that $E^3 - D$ is locally simply connected at each point of $D$. We finish the proof of Theorem 8 by showing that $D$ is tame.

Since Theorem 6 shows that $D$ is locally tame at each point of $\text{Int } D$, it follows from [4; 9] that there is a homeomorphism $h$ of $E^3$ onto itself such that $h(D)$ is locally polyhedral at each point of $h(\text{Int } D)$. Hence, we suppose with no loss of generality that $D$ is locally polyhedral at each point of $\text{Int } D$.

By pushing $D$ to one side at points of $\text{Int } D$, one obtains a disk $D'$ such that $\text{Bd } D = \text{Bd } D'$, $D'$ is locally polyhedral at points of $\text{Int } D'$, and $D + D'$ bounds a topological cube $C$. Since $E^3 - \text{Bd } C$ is locally simply connected at each point of $\text{Bd } C$, it follows from either Theorem 2 or 6 that $\text{Bd } C$ is tame. Hence $D$ is tame and $M_2$ is locally tame at $p$.

8. Extensions of Theorem 0. As pointed out in [5], we can use Theorem 6 to extend Theorem 0 as follows.

**Theorem 9.** A 2-manifold $M_2$ in a 3-manifold $M_3$ is locally tame at a point $p$ of $M_2$ if there is a disk $D$ with $p \in \text{Int } D \subset M_2$ such that for each positive number $\epsilon$, there are disks $D', D''$ on opposite sides of $M_2$ such that

$$H(D, D') < \epsilon, \quad H(D, D'') < \epsilon.$$

**Proof.** Theorem 9 follows from Theorem 6 when we show that $M_3 - M_2$ is locally simply connected at each point of $\text{Int } D$.

Suppose $D$ is a disk, $q$ is a point of $\text{Int } D$, and $f$ is a map of $\text{Bd } D$ into a small subset of $M_3 - M_2$ near $q$. Suppose $f$ is extended to map $D$ into a small subset of $M_3$. Let $D'$, $D''$ be disks on opposite sides of $M_2$ which are homeomorphically close to $D$ and whose sum separates $f(\text{Bd } D)$ from $M_3 - f(D)$ in $f(E)$. If $E'$ is the component of $E - f^{-1}(D' + D'')$ containing $\text{Bd } D$, $f$ on $E'$ can be extended to map $D$ into a small subset of $f(E') + D' + D''$. Hence, $M_3 - M_2$ is locally simply connected at $q$.

Since locally tame closed subsets are tame in triangulated 3-manifolds [2; 10], we have the following as a corollary of Theorem 9.

**Corollary.** A 2-manifold $M_2$ in a triangulated 3-manifold $M_3$ is tame if and only if for each positive number $\epsilon$ the appropriate one of the following conditions is satisfied:

**Case 1.** If $M_2$ is two sided in some neighborhood $N$ of $M_2$ there are 2-manifolds $M', M''$ on opposite sides of $M_2$ in $N$ such that

$$H(M_2, M') < \epsilon, \quad H(M_2, M'') < \epsilon.$$

**Case 2.** If $M_2$ is one sided in each neighborhood of $M_2$ there is a connected double covering $M'$ of $M_2$ with projection map $\pi$ and a homeomorphism $h'$ of $M'$ into $M_3 - M_2$ such that

$$\rho(h(x), \pi(x)) < \epsilon, \quad x \in M'.$$
Neither Theorem 9 nor its corollary can be extended to 2-manifolds-with-boundaries. Besides having to speak with care about the two sides of a 2-manifold-with-boundary in a 3-manifold, one would have to contend with the example of Stallings [12] in which he describes an uncountable family of mutually exclusive wild disks in \( E^3 \). It would follow from an application of Theorem 9 that most of these disks are locally tame except on their boundaries.

References

6. ———, *A wild sphere each of whose arcs is tame*, Duke Math. J.

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