Contact Dehn surgery, symplectic fillings, and Property $P$ for knots

Hansjörg Geiges
Mathematisches Institut, Universität zu Köln
Weyertal 86–90, 50931 Köln, Germany

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1 Property $P$ for knots

According to a fundamental theorem of Lickorish and Wallace from the 1960s, every closed, orientable 3–manifold can be obtained by performing Dehn surgery on a link in the 3–sphere. Previous to the recent work of Perelman, which is expected to close the coffin on the Poincaré conjecture, it was a natural question for geometric topologists whether one might be able to produce a counterexample to that conjecture by a single Dehn surgery. This led to the definition of the following property, whose name is generally regarded as a little unfortunate.

**Definition.** A knot $K$ in $S^3$ has **Property P** if every nontrivial surgery along $K$ yields a non-simply-connected 3–manifold.

Our knots are always understood to be smooth, or at least tame, i.e. equivalent to a smooth one.

Let me briefly recall the notion of Dehn surgery along a knot $K$ in the 3–sphere $S^3$. Write $\nu K \cong S^1 \times D^2$ for a (closed) tubular neighbourhood of $K$. On the boundary $\partial(\nu K) \cong T^2$ of this tubular neighbourhood there are two distinguished curves (which we implicitly identify with the classes they represent in the homology group $H_1(T^2)$):

1. The meridian $\mu$, defined as a simple closed curve that generates the kernel of the homomorphism on $H_1$ induced by the inclusion $T^2 \to \nu K$.

2. The preferred longitude $\lambda$, defined as a simple closed curve that generates the kernel of the homomorphism on $H_1$ induced by the inclusion $T^2 \to C := \overline{S^3 \setminus \nu K}$.

This preferred longitude can also be characterised by the property that it has linking number zero with $K$. The knot $K$ bounds an embedded surface in $S^3$ (called a **Seifert surface** for $K$), and $\lambda$ can be obtained by pushing $K$ along that surface. For that reason, the trivialisation of the normal bundle of $K$ defined by $\lambda$ is called the **surface framing** of $K$. 
Given an orientation of $S^3$, orientations of $\mu$ and $\lambda$ are chosen such that $(\mu, \lambda)$ is a positive basis for $H_1(T^2)$, with $T^2$ oriented as the boundary of $\nu K$. In the contact geometric setting below, the orientation of $S^3$ will be the one induced from the contact structure.

Let $p,q$ be coprime integers. The manifold $K_{p/q}$ obtained from $S^3$ by Dehn surgery along $K$ with surgery coefficient $p/q \in \mathbb{Q} \cup \{\infty\}$ is defined as

$$K_{p/q} := \overline{S^3 \setminus \nu K} \cup_q S^1 \times D^2,$$

where the gluing map $g$ sends the meridian $\mu \times \partial D^2$ to $p\mu + q\lambda$. The resulting manifold is completely determined by the knot and the surgery coefficient.

A simple Mayer-Vietoris argument shows that $H_1(K_{p/q}) = \mathbb{Z}_{|p|}$. Therefore, saying that a knot $K$ has Property P is equivalent to

$$\pi_1(K_{1/q}) = 1 \text{ only for } q = 0.$$

(Observe that $p/q = \infty$ corresponds to a trivial surgery.)

**Example.** The unknot does not have Property P. Indeed, every $(1/q)$–surgery on the unknot yields $S^3$, which is seen as follows. If $K$ is the unknot, then the closure $C$ of $S^3 \setminus \nu K$ is also a solid torus. Write $\mu_C$ and $\lambda_C$ for meridian and preferred longitude on $\partial C$. We may assume $\mu = \lambda_C$ and $\lambda = -\mu_C$. When performing $(1/q)$–surgery on $K$, a solid torus is glued to $C$ by sending its meridian $\mu_0$ to $\mu + q\lambda = \lambda_C - q\mu_C$. Now, there clearly is a diffeomorphism of $C$ that sends $\mu_C$ to itself and $\lambda_C$ to $\lambda_C - q\mu_C$. It follows that the described surgery is equivalent to the one where we send $\mu_0$ to $\lambda_C = \mu$, which is a trivial $\infty$–surgery.

In the early 1970s, Bing and Martin, as well as González-Acuña, conjectured that every nontrivial knot has Property P. By work of Kronheimer and Mrowka [9], this is now a theorem.

**Theorem 1 (Kronheimer-Mrowka).** Every nontrivial knot in $S^3$ has Property P.

Before describing the role that contact geometry has played in the proof of this theorem, I want to indicate the importance of this theorem beyond the negative statement that counterexamples to the Poincaré conjecture cannot result from a single surgery.

**Proposition 2.** If two knots $K,K'$ in $S^3$ have homeomorphic complements and one of the knots has property P, then the knots are equivalent, i.e. there is a homeomorphism of $S^3$ mapping $K$ to $K'$.

**Proof.** According to a result of Edwards [3], two compact 3–manifolds with boundary are homeomorphic if and only if their interiors are homeomorphic. Thus, if $S^3 \setminus K$ is homeomorphic to $S^3 \setminus K'$, then there is a homeomorphism $\varphi: C \to C'$, where $C := \overline{S^3 \setminus \nu K}$ and $C' := \overline{S^3 \setminus \nu K'}$.

Suppose $K$ has Property P. This implies that there is a unique way of attaching a solid torus $S^1 \times D^2$ to $C$ such that the resulting manifold is the 3–sphere. Hence $\varphi$ extends to a homeomorphism $S^3 \to S^3$, i.e. the knots $K$ and $K'$ are equivalent. \qedsymbol
Observe that in this proof we only used the weaker property that nontrivial surgery along $K$ does not yield the standard 3-sphere. This had been proved earlier (for $K$ different from the unknot) by Gordon and Luecke [8]. Since the unknot is characterised by its complement being a solid torus, the result of Kronheimer and Mrowka (or the weaker one by Gordon and Luecke) yields the following corollary.

**Corollary 3.** If two knots in $S^3$ have homeomorphic complements, then the knots are equivalent. 

Of course, together with a positive answer to the Poincaré conjecture, the result of Gordon-Luecke implies that of Kronheimer-Mrowka.

### 2 Contact Dehn surgery

This section gives a brief report on joint work with Fan Ding [1]. Recall that a (coorientable) **contact structure** $\xi$ on a differential 3-manifold is a tangent 2-plane field defined as the kernel of a global differential 1-form $\alpha$ that satisfies the nonintegrability condition $\alpha \wedge d\alpha \neq 0$ (meaning that $\alpha \wedge d\alpha$ vanishes nowhere).

An example is the standard contact structure

$$\xi_{st} = \ker(x \, dy - y \, dx + z \, dt - t \, dz)$$

on $S^3 \subset \mathbb{R}^4$. This can also be characterised as the complex line in the tangent bundle of $S^3$ with respect to complex multiplication induced from the inclusion $S^3 \subset \mathbb{C}^2$.

I shall have to use a few notions from contact geometry without time for much explanation (tight and overtwisted contact structures, convex surfaces in contact 3-manifolds). For more details see the introductory lectures by Etnyre [5] or the **Handbook** chapter by the present author [7].

A (smooth) knot $K$ in a contact 3-manifold $(M, \xi)$ is called **Legendrian** if it is everywhere tangent to $\xi$. The normal bundle of such a knot has a canonical trivialisation, determined by a vector field along $K$ that is everywhere transverse to $\xi$. This will be referred to as the contact framing. We now consider Dehn surgery along $K$ with coefficient $p/q$ as before, but we define the surgery coefficient with respect to the contact framing.

It turns out that for $p \neq 0$, one can always extend the contact structure $\xi|_{M \setminus \nu K}$ to one on the surgered manifold in such a way that the extended contact structure is tight on the glued-in solid torus $S^1 \times D^2$. Moreover, subject to this tightness condition there are but finitely many choices for such an extension, and for $p/q = 1/k$ with $k \in \mathbb{Z}$ the extension is in fact unique. These observations hinge on the fact that $\partial(\nu K)$ is a convex surface, i.e. a surface admitting a transverse flow preserving the contact structure. On solid tori with convex boundary condition, tight contact structures have been classified by Giroux and Honda.

We can therefore speak sensibly of **contact** $(1/k)$--**surgery**. The following theorem is proved in [1].
Theorem 4. Let \((M, \xi)\) be a closed, connected contact 3–manifold. Then \((M, \xi)\) can be obtained from \((S^3, \xi_{st})\) by contact \((\pm 1)\)-surgery along a Legendrian link.

Remarks. (1) There is a related theorem, due to Lutz-Martinet in the early 1970s, cf. [7], saying that every (closed, orientable) 3–manifold admits a contact structure in each homotopy class of tangent 2–plane fields. The original proof is based on surgery along a link in \(S^3\) transverse to \(\xi_{st}\). For an alternative proof using Legendrian surgery see [2].

(2) From the topological point of view, surgeries with integer surgery coefficient are best, since they correspond to attaching 2–handles to the boundary of a 4–manifold. Thus, contact \((\pm 1)\)-surgeries are best from both the topological and contact geometric viewpoint.

(3) Contact \((-1/k)\)-surgery is the inverse of contact \((1/k)\)-surgery (along appropriately related knots).

(4) Contact \((-1)\)-surgery is symplectic handlebody surgery in the sense of Eliashberg and Weinstein, cf. [2], and preserves the property of being strongly symplectically fillable (see below).

3 Symplectic fillings

Contact geometry enters the proof of Theorem 1 via the notion of symplectic fillings. Observe that a contact 3–manifold \((M, \xi)\) is naturally oriented — the sign of the volume form \(\alpha \wedge d\alpha\) does not depend on the choice of 1–form \(\alpha\) defining a given \(\xi\); similarly, a symplectic 4–manifold \((W, \omega)\), i.e. with \(\omega\) a closed 2–form satisfying \(\omega^2 \neq 0\), is naturally oriented by the volume form \(\omega^2\).

Definition. (a) The symplectic 4–manifold \((W, \omega)\) is called a weak (symplectic) filling of the contact manifold \((M, \xi)\) if \(\partial W = M\) as oriented manifolds (outward normal followed by orientation of \(M\) gives orientation of \(W\)) and \(\omega|_{\xi} \neq 0\).

(b) The symplectic 4–manifold \((W, \omega)\) is called a strong (symplectic) filling of the contact manifold \((M, \xi)\) if \(\partial W = M\) and there is a Liouville vector field \(X\) defined near \(\partial W\), pointing outwards along \(\partial W\), and satisfying \(\xi = \text{ker}(\iota_X \omega|_{TM})\). Here Liouville vector field means that the Lie derivative \(\mathcal{L}_X \omega\), which is the same as \(d(i_X \omega)\) because of \(d\omega = 0\) and Cartan’s formula, is required to be equal to \(\omega\).

For instance, \((S^3, \xi_{st})\) is strongly filled by the standard symplectic 4–disc \(D^4\) with \(\omega_{st} = dx \wedge dy + dz \wedge dt\). The Liouville vector field here is the radial vector field \(X = r\partial_r/2\).

It is clear that every strong filling is also a weak filling. The converse is false: There are contact structures that are weakly but not strongly fillable; such examples are due to Eliashberg and Ding-Geiges.

The contact geometric result that allowed Kronheimer and Mrowka to conclude their proof of Property P was first proved by Eliashberg [4].

Theorem 5 (Eliashberg). Any weak symplectic filling of a contact 3–manifold embeds symplectically into a closed symplectic 4–manifold.
An alternative proof was given by Etnyre [6]. Both proofs rely on open book decompositions adapted to contact structures. Theorem 5 being a cobordism theoretic result, it is arguably more natural to give a surgical proof. Özbağçı and Stipsicz [10] were the first to observe that such a proof, based on Theorem 4, can indeed be devised. In the remainder of this section, I shall sketch this surgical argument.

Theorem 5 is proved by showing that any contact 3–manifold can be capped off symplectically, or has what is called a concave filling that can be glued to the given (convex) filling. (For instance, a strong concave filling corresponds to a Liouville vector field pointing inwards along the boundary.) Such a cap, attached to the (convex) symplectic filling of the contact manifold, gives the desired closed symplectic manifold.

(i) Strong fillings can be capped off: Let \((W, \omega)\) be a strong filling of \((M, \xi)\). By Theorem 4, there is a Legendrian link \(L = L^- \sqcup L^+\) in \((S^3, \xi_{st})\) such that contact \((-1)\)–surgery along the components of \(L^-\) and contact \((+1)\)–surgery along those of \(L^+\) produces \((M, \xi)\). By Remarks (3) and (4) we can attach symplectic 1–handles to the boundary \((M, \xi)\) of \((W, \omega)\) corresponding to contact \((-1)\)–surgeries that undo the contact \((+1)\)–surgeries along \(L^+\). The result will be a symplectic manifold \((W', \omega')\) strongly filling a contact manifold \((M', \xi')\), and the latter can be obtained from \((S^3, \xi_{st}) = \partial(D^4, \omega_{st})\) by performing contact \((-1)\)–surgeries (along \(L^-\)) only.

A handlebody obtained from \((D^4, \omega_{st})\) by attaching symplectic handles in this way is in fact a Stein filling of its boundary contact manifold, and for those a symplectic cap had been found earlier by Akbulut–Özbağçı and Lisca–Matić. The cap that fits on the Stein filling also fits on the strong filling \((W', \omega')\), since strongly convex and strongly concave fillings of a given contact manifold can always be glued together, using the Liouville flow to define collar neighbourhoods of the boundary.

(ii) Reduce the problem to the consideration of homology spheres only: Let \((W, \omega)\) be a weak filling of \((M, \xi)\). We want to attach a (weak) symplectic cobordism from \((M, \xi)\) to some integral homology sphere \(\Sigma^3\) with contact structure \(\xi'\), so as to get a weak filling of \((\Sigma^3, \xi')\) containing \((M, \xi)\) as a separating hypersurface.

We start from a contact surgery presentation of \((M, \xi)\) as in (i). For each component \(L_i\) of \(L\) we choose a Legendrian knot \(K_i\) in \((S^3, \xi_{st})\) only linked with that component, with linking number 1. These \(K_i\) can be chosen in such a way that surgery with framing \(-1\) relative to the contact framing is the same as surgery with coefficient 0 relative to the surface framing. (In case you know the term: The Thurston-Bennequin invariant of \(K_i\) can be chosen to be equal to 1). Performing these surgeries has the effect of killing all integral homology.

Since \(\omega\) is exact in the neighbourhood \(S^1 \times D^2 \times (-\varepsilon, 0]\) of a Legendrian knot in the boundary \((M, \xi)\) of \((W, \omega)\), these surgeries can be performed by attaching symplectic handles as in the case of a strong filling. The collection of these handles gives the desired (weak) symplectic cobordism.

(iii) Pass from a weak filling of a homology sphere to a strong filling: We
begin with the symplectic manifold \((W', \omega')\) with boundary \((\Sigma^3, \xi')\) constructed in (ii). We want to modify \(\omega'\) in a collar neighbourhood \(\Sigma^3 \times [0, 1]\) of the boundary \(\Sigma^3 \equiv \Sigma^3 \times \{1\}\) such that the resulting symplectic manifold is a strong filling of the new induced contact structure \(\xi''\) on the boundary. By (i) this can then be capped off.

Since \(H^2(\Sigma^3) = 0\), we can write \(\omega = d\eta\) with some 1–form \(\eta\) in a collar neighbourhood as described. (We see that it would be enough to have \(\Sigma^3\) a rational homology sphere.) Choose a 1–form \(\alpha\) on \(\Sigma^3\) with \(\xi' = \ker \alpha\) and \(\alpha \wedge \omega|_{\Sigma^3} > 0\), which is possible for a weak filling. Then set

\[
\tilde{\omega} = d(f\eta) + d(g\alpha)
\]
on \(\Sigma^3 \times [0, 1]\), where the smooth functions \(f(t)\) and \(g(t)\), \(t \in [0, 1]\), are chosen as follows: Fix a small \(\varepsilon > 0\). Choose \(f: [0, 1] \to [0, 1]\) identically 1 on \([0, \varepsilon]\) and identically 0 near 1. Choose \(g: [0, 1] \to \mathbb{R}_0^+\) identically 0 near 0 and with \(g'(t) > 0\) for \(t > \varepsilon/2\).

We compute

\[
\tilde{\omega} = f' dt \wedge \eta + f \omega + g' dt \wedge \alpha + g d\alpha,
\]
whence

\[
\tilde{\omega}^2 = ff' dt \wedge \eta \wedge \omega + f'g dt \wedge \eta \wedge d\alpha + f^2 \omega^2 + fg' \omega \wedge dt \wedge \alpha + fg \omega \wedge d\alpha + gg' dt \wedge \alpha \wedge d\alpha.
\]

The terms appearing with the factors \(f^2\), \(fg'\) and \(gg'\) are positive volume forms. By choosing \(g\) small on \([0, \varepsilon]\) and \(g'\) large compared with \(|f'|\), one can ensure that these positive terms dominate the three terms we cannot control. Then \(\tilde{\omega}\) is a symplectic form on the collar, and in terms of the coordinate \(s = \log g(t)\), the symplectic form looks like \(d(e^s \alpha)\) near the boundary, with Liouville vector field \(\partial_s\).

## 4 Proof of Property P for nontrivial knots

Here is a very rough sketch of the proof by Kronheimer and Mrowka. It relies heavily on pretty much everything known under the sun about gauge theory.

Let \(K\) be a nontrivial knot. It had been proved earlier by Culler-Gordon-Luecke-Shalen that \(\pi_1(K_{1/q})\) is nontrivial for \(q \notin \{0, \pm 1\}\). It therefore suffices to find a nontrivial homomorphism \(\pi_1(K_1) \to \text{SO}(3)\).

Arguing by contradiction, we assume that no such homomorphism exists. This implies the vanishing of the instanton Floer homology group \(HF(K_1)\). By the Floer exact triangle one finds that the group \(HF(K_0)\) vanishes likewise, and so does the Fukaya-Floer homology group.

For \(K\) nontrivial, results of Gabai say that \(K_0\) is different from \(S^1 \times S^2\) and admits a taut 2–dimensional foliation. Eliashberg and Thurston, in their theory of confoliations, deduce from this the existence of a symplectic structure on \(K_0 \times [-1, 1]\) weakly filling contact structures on the boundary components. According to Theorem 5, by capping off these boundaries we find a symplectic
manifold $V$ containing $K_0$ as a separating hypersurface (and satisfying some mild cohomological conditions).

Now, on the one hand, the Donaldson invariants of $V$ can be expressed as a pairing on the Fukaya-Floer homology group of $K_0$ and therefore have to vanish.

On the other hand, results of Taubes say that the Seiberg-Witten invariants of $V$ are nontrivial. By a conjecture of Witten, proved in the relevant case by Feehan-Leness, the Donaldson invariants are likewise nontrivial. This contradiction proves Theorem 1.

References


