

**TBD**

TBD

**Mohamed Noah Abdel Wahab**

Thesis for the attainment of the academic degree

**Master of Science**

at the TUM School of Computation, Information and Technology of the Technical University of Munich

**Supervisor:**

Prof. Dr. Marco Cicalese

**Advisor:**

Dr. Fumihiko Onoue

**Submitted:**

Munich, Date of submission



I hereby declare that this thesis is entirely the result of my own work except where otherwise indicated. I have only used the resources given in the list of references.

Munich, Date of submission

Mohamed Noah Abdel Wahab



# Abstract

## TODO (GENERAL STUFF).

1. Clean up Bibliography
2. ..
3. Replace s.t. with `\mid`
4. Complete List of symbols
5. Edit colors to fit TUMColors
6. Edit figures to smaller and increase font
7. ..

## Abstract

Nonlocal minimal surfaces confined within a cylinder exhibit unique behaviors dependent on external data. This thesis delves into these surfaces, which incorporate long-range spatial interactions compared to classical minimal surfaces. We consider two variations of the model discussed in [5], a minimal surfaces confined within a cylinder.

We investigate two scenarios: varying the height and width of data outside a separating slab. The results show that when the slab is wide, the minimal surface becomes disconnected from the data, while a narrow slab allows connection. This allows us to predict the behavior of similar models with symmetrically placed data. Additionally, the research reveals that for sufficiently narrow slabs, the surface “sticks” to the cylinder.

Finally, we present an example where the minimizer is completely disconnected from the external data, a phenomenon unique to nonlocal minimal surfaces. This work provides valuable insights into the behavior of these emerging mathematical objects and their interaction with external data.

## Zusammenfassung

In Zylindern eingeschlossene nichtlokale Minimalflächen zeigen ein einzigartiges Verhalten, das von externen Daten abhängt. Diese Arbeit befasst sich mit diesen Flächen, die im Vergleich zu klassischen Minimalflächen weitreichende räumliche Wechselwirkungen berücksichtigen. Wir betrachten zwei Varianten des in [5] diskutierten Modells, einer in einem Zylinder eingeschlossenen Minimalfläche.

Dabei untersuchen wir zwei Szenarien: die Variation der Höhe und der Breite von Daten außerhalb einer trennenden Platte. Die Ergebnisse zeigen, dass die Minimalfläche bei breiter Platte von den Daten getrennt wird, während eine schmale Platte eine Verbindung ermöglicht. Dies erlaubt uns, das Verhalten ähnlicher Modelle mit symmetrisch angeordneten Daten vorherzusagen. Darüber hinaus zeigt die Forschung, dass die Fläche bei ausreichend schmalen Platten am Zylinder “haftet”.

Schließlich präsentieren wir ein Beispiel, bei dem der Minimierer vollständig von den externen Daten getrennt ist, ein Phänomen, das für nichtlokale Minimalflächen einzigartig ist. Diese Arbeit liefert wertvolle Erkenntnisse über das Verhalten dieser neuen mathematischen Objekte und ihre Wechselwirkung mit externen Daten.

## List of symbols

$\mathbb{R}^n$	Euclidean space of dimension $n$
$\text{dist}(A, B)$	Distance between sets $A$ and $B$

# Contents

<b>Abstract</b>	<b>v</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Classical Minimal Surfaces . . . . .	1
1.2 Nonlocal Minimal Surfaces . . . . .	3
<b>2 Models</b>	<b>6</b>
2.1 Model 01 . . . . .	6
2.2 Model 02 . . . . .	10
<b>3 Disconnected Minimizer</b>	<b>15</b>
<b>Conclusion</b>	<b>23</b>
<b>Bibliography</b>	<b>24</b>





# 1 Introduction

**IDEA.** Idea: Start with short historical background

18th century: Lagrange, Euler

20th Century: DeGiorgi Perimeter and localized entity

2009 Caffarelli, Roquejoffre, Savin: Nonlocal minimal surfaces

Perimeter and nonlocal perimeter as the (semi)norm of an indicator function

Define the usual problem considered

Better regularity than classical minimal surfaces

Chapter 02

Model 01

Model 02

Combination of both

Chapter 03

Fully disconnected minimizer

Use the introduction in [9] as inspiration.

**TODO.** Add sources

What does “locally” mean here? And what do we minimize? The surface or the area the encompassed?

Rewrite the text

*Minimal surfaces*, characterized by locally minimizing their surface area, have captivated mathematicians for centuries. Dating back to the 18th century, mathematicians like *Euler* and *Lagrange* laid the foundation for the field. In an effort to describe these surfaces mathematically, they formulated the *Euler-Lagrange equations* in the late 18th century. These equations provide a powerful framework for identifying and characterizing minimal surfaces. Since the 19th century, many mathematicians contributed to the study of minimal surfaces, uncovering profound insights. Since then minimal surfaces found many applications in various fields beyond pure mathematics. From understanding physical phenomena like soap films and black holes to informing the design of optimal structures in engineering and architecture, the versatility of minimal surfaces continues to inspire exploration.

In this thesis, we want to explore a rather recent concept of minimal surfaces, namely *Nonlocal Minimal Surfaces*, which were first introduced by *Caffarelli*, *Roquejoffre*, and *Savin* in 2009. For that purpose, we will first give a short introduction to the theory of minimal surfaces in the context of this work.

## 1.1 Classical Minimal Surfaces

**CHECK.** Is this introduction enough and complete/correct?

The study of minimal surfaces concerns itself with finding the set with least surface area under certain constraints. But before we can formulate the usual problem, we have to define some tools.

**CHECK.** Do I need to cite this definition from [4]? Give a justification?

**Definition 1.1.** Let  $A \subset \mathbb{R}^n$  with smooth boundary, then the surface area or *perimeter* of  $A$  is given by

$$\text{Per}(A) := \sup \left\{ \int_{\partial A} \varphi \cdot \nu_A \, d\mathcal{H}^{n-1} \mid \varphi \in C_c^1(\mathbb{R}^n, \mathbb{R}^n), |\varphi| \leq 1 \right\},$$

where  $\nu_A$  is the outer normal to  $A$ .

To extend this definition to general measurable sets, we can use the divergence theorem and rewrite the integration over the boundary as an integration over the set itself. This removes the need for a smooth boundary and allows us to define the surface area for general sets.

**Definition 1.2.** Let  $A \subset \mathbb{R}^n$  be a Borel set, then the perimeter of  $A$  is given by

$$\text{Per}(A) := \sup \left\{ \int_A \text{div} \varphi \mid \varphi \in C_c^1(\mathbb{R}^n, \mathbb{R}^n), |\varphi| \leq 1 \right\}.$$

**TODO.** Rewrite this text

Not just for Minimization problem, but Perimeter of a set in some other set

In the minimization problem, we want to find some set  $E$  which minimizes the surface of some external data  $E_0$ . Since the surface area may be infinite, if  $E_0$  is unbounded, we can “localize”<sup>1</sup> the problem by just considering the part of  $\partial E$  in some bounded set  $\Omega$ .

**Definition 1.3.** Let  $A \subset \mathbb{R}^n$  be a Borel set and  $\Omega \subset \mathbb{R}^n$  bounded, then the perimeter of  $A$  relative to  $\Omega$  is given by

$$\text{Per}(A, \Omega) := \sup \left\{ \int_A \text{div} \varphi \mid \varphi \in C_c^1(\Omega, \mathbb{R}^n), |\varphi| \leq 1 \right\}.$$

Now we can formulate the usual problem.

**Definition 1.4 (Minimal Surface Problem).** Let  $\Omega \subset \mathbb{R}^n$  bounded and  $E_0 \subset \mathbb{R}^n$ , then we want to find  $E \subset \mathbb{R}^n$  such that  $E$  minimizes the perimeter of  $E_0$  relative to  $\Omega$ , i.e.

$$\text{Per}(E, \Omega) = \min \{ \text{Per}(A, \Omega) \mid A \setminus \Omega = E_0 \setminus \Omega \}.$$

This set  $E$  is then called a *minimal surface*.

**TODO.** Complete note

Case that  $E_0 \cap \Omega \neq \emptyset$ .

Give sources, that minimizer exists, thus minimal surfaces exist and say something about uniqueness

Note that in classical theory often one just has a contour over which one minimizes

**Note.** Usually  $E_0$  is chosen such that  $E_0 \cap \Omega = \emptyset$ , then we minimize over the set  $E$  such that  $E \setminus \Omega = E_0$ . If  $E_0 \cap \Omega \neq \emptyset$ , then we can minimize over..

**TODO.** Standard example of minimal surfaces (Plateau’s problem, soap bubble)

<sup>1</sup>Here “local” refers to the area in which we minimize

## 1.2 Nonlocal Minimal Surfaces

**TODO.** Do again, but start this time from the example of a soap bubble

Soap bubble, classical example, 2 dim surface..

Nanoscale, 3 dim, classical theory doesn't suffice anymore

Short construction of fractional perimeter a la Caffarelli [2]

Rewrite the text

Is the example fitting?

Emphasize that we are no longer just minimizing boundary but the set as well

Let us for now consider some set  $A \subset \mathbb{R}^n$  with smooth boundary, then to get its perimeter we have to take the supremum of

$$\int_{\partial A} \varphi \cdot \nu_A.$$

This is a local quantity, i.e. it only depends on the boundary of  $A$ . Thus if we want to minimize the perimeter of some set  $E$  with external data  $E_0$ , we are only interested in the behavior of the boundary of  $E$  close to and in  $\Omega$  and not in the contribution or the size of the external data. In many cases, this is enough to describe the behavior of the minimizer, but in some cases, this is not enough anymore. Take a soap bubble as an example, a standard example for a classical minimal surfaces. In our normal scaling, we can see the film of the soap bubble as a 2-dimensional object. But if we go to the molecular level, we see that the film is a 3-dimensional object. Thus we need to incorporate long-range correlation into our definition of perimeter and minimal surfaces. Caffarelli, Roquejoffre, and Savin did exactly that in 2009, when they introduced the concept of *nonlocal minimal surfaces* and *fractional perimeter* in [2].

**TODO.** What is the effect of  $s$ ?

Which definition is standard? Add note about other definitions

Maybe use the definition from [18], but it's without  $s$ , just with  $(1 - s)$  and with 2 in front. The 2 is just convention for the relation to the Gagliardo seminorm. Why not with  $s$ ? Can I define it with  $s$ ?

For the limiting behavior of  $\text{Per}_s()$  for  $s \rightarrow 0/1$  see [16]

**Definition 1.5 (Fractional Perimeter).** Let  $A \subset \mathbb{R}^n$  be a Borel set,  $s \in (0, 1)$ , then the  $s$ -perimeter of  $A$  to is given by

$$\text{Per}_s(A) := \int_A \int_{A^c} \frac{1}{|x - y|^{n+s}} dy dx.$$

Intuitively, we can understand the parameter  $s$  as the grade of nonlocality. For  $s$  big, we have a more local...

Just as in the classical case, we can define a relative fractional perimeter by removing the integration over the constant part..

$$\begin{aligned} & \int_A \int_{A^c} \frac{1}{|x - y|^{n+s}} dy dx \\ &= \int_{A \cap \Omega} \int_{A^c} \frac{1}{|x - y|^{n+s}} dy dx + \int_{A \setminus \Omega} \int_{A^c} \frac{1}{|x - y|^{n+s}} dy dx \\ &= \int_{A \cap \Omega} \int_{A^c} \frac{1}{|x - y|^{n+s}} dy dx + \int_{A \setminus \Omega} \int_{\Omega \setminus A} \frac{1}{|x - y|^{n+s}} dy dx + \int_{A \setminus \Omega} \int_{A^c \setminus \Omega} \frac{1}{|x - y|^{n+s}} dy dx \end{aligned}$$

While minimizing  $A$  relative to  $\Omega$  we can ignore the last term as it is constant and thus does not affect the minimization.

**Definition 1.6.** Let  $A, B \subset \mathbb{R}^n$  be Borel sets,  $s \in (0, 1)$ , then the interaction of  $A$  and  $B$  is given by

$$\mathcal{L}(A, B) := \int_A \int_{B^c} \frac{1}{|x - y|^{n+s}} dy dx.$$

**Definition 1.7** (Relative Fractional Perimeter). Let  $A \subset \mathbb{R}^n$  be a Borel set,  $\Omega \subset \mathbb{R}^n$  bounded and  $s \in (0, 1)$ , then the  $s$ -perimeter of  $A$  relative to  $\Omega$  is given by

$$\text{Per}_s(A, \Omega) := \mathcal{L}(A \cap \Omega, A^c) + \mathcal{L}(A \setminus \Omega, \Omega \setminus A).$$

**TODO.** Rewrite.. very bad  
Not precise enough

**Note.** In some literature, the fractional perimeter is sometimes defined with the factor 2 in front of the integral. This is just a convention to relate the Gagliardo seminorm

$$\|f\|_{W^{s,1}(\mathbb{R}^n)} = \int_{\mathbb{R}^n} \int_{\mathbb{R}^n} \frac{|f(x) - f(y)|}{|x - y|^{n+s}} dy dx$$

to the fractional perimeter. Notice that

$$\text{Per}_s(A) = \int_A \int_{A^c} \frac{1}{|x - y|^{n+s}} dy dx = \frac{1}{2} \int_{\mathbb{R}^n} \int_{\mathbb{R}^n} \frac{|\chi_A(x) - \chi_A(y)|}{|x - y|^{n+s}} dy dx = \frac{1}{2} \|\chi_A\|_{W^{s,1}(\mathbb{R}^n)},$$

i.e. the fractional perimeter is the seminorm of the indicator function of  $A$  up to a multiplicative constant.

In more recent literature like [18], the fractional perimeter is defined with the factor  $(1 - s)$  in front of the integral. This is based on the limiting behavior of the fractional perimeter for  $s \rightarrow 1^-$  as shown in [1] and [3]. In the latter, the authors have shown that for sets of finite *classical* perimeter, we have that  $(1 - s) \text{Per}_s(A, \Omega) \rightarrow c \text{Per}(A, \Omega)$  as  $s \rightarrow 1^-$  for some constant  $c$  depending on the dimension. In the former paper, the authors have shown the same behavior in sense of  $\Gamma$ -convergence and general measurable sets. In [18], the factor  $(1 - s)$  is used, to justify the fractional perimeter as a generalization of the classical perimeter.

In [9], the authors analyzed the behavior of  $s \text{Per}_s(A, \Omega)$  for  $s \rightarrow 0^+$ . They showed that not all sets have a limit for  $s \rightarrow 0^+$  and if a limit exists, then it relates to the volume of the sets.

Thus if we are interested in the limiting behavior, it would make sense to define Perimeter with the factor  $s(1 - s)$  in front of the integral. We will stick to the usual definition for convenience and add the factor  $s(1 - s)$ , when are interested in the limiting behavior.

**TODO.** give an example where classical theory doesn't suffice (cube rotated by 45 degree)  
Serra 2023 pixelled square

**TODO.** Add note about advantages/properties (e.g. Euler-Lagrange Viscos) of nonlocal minimal surfaces like better regularity properties and..

Add some sentences about stickiness property and that we are looking at a model precisely about that property.

Give some justification, why fractional perimeter can be seen as a generalization of the classical perimeter.

With these tools we can now define the nonlocal minimal surface problem.

**Definition 1.8** (Nonlocal Minimal Surface Problem). Let  $\Omega \subset \mathbb{R}^n$  bounded and  $E_0 \subset \mathbb{R}^n$ , then we want to find  $E \subset \mathbb{R}^n$  such that  $E$  minimizes the  $s$ -perimeter of  $E_0$  relative to  $\Omega$ , i.e.

$$\text{Per}_s(E, \Omega) = \min \{ \text{Per}_s(A, \Omega) \mid A \setminus \Omega = E_0 \setminus \Omega \}.$$

Over the last few years these nonlocal minimal surfaces have been an are of great interest. Various properties have been studied and many results have been obtained. Next to the better regularity properties, Euler-Lagrange equations, stickiness property, ..

**TODO.** Quick summary of Chapter 2 Quick summary of Chapter 3

In this thesis, we want to explore more on these surfaces and their properties. In Chapter 2, we will consider two models, analyze them on connectedness and try to understand the stickiness property and where the contribution lies to achieve stickiness. We will then derive the behavior of models similar to both, to get an understanding of general models of that form. In Chapter 3, we will discuss a natural question coming up while analyzing the models, namely the existence of a nontrivial minimizer in the case that the external data and the prescribed set are disconnected. We will provide an example where such a minimizer exists. This behavior is unique to nonlocal minimal surfaces.

## 2 Models

**TODO.** Rewrite the text

Add discussion about variation of models and why we are considering that

In this chapter we will consider two different models, which are variations of the model considered by Dipierro et al. in [5], where they considered the external data  $E_0$  as the complement of a slab in  $\mathbb{R}^n$  of width  $2M$  and the prescribed data  $\Omega$  as the cylinder of radius 1 and height  $2M$ . They showed that for  $M$  big enough the minimizer is disconnected which is consistent with the classical theory of minimal surfaces. When  $M$  is small enough, the minimizer is connected and even sticks to the boundary. The latter being a unique property of nonlocal minimal surfaces.

Here we will first consider a variation of the model, where we vary the width of the external data  $E_0$ . We observe similar behavior of the minimizer as in the original model. This is interesting in the sense of the stickiness property, since even for width of 1 we get stickiness to the boundary.

In the second model we will consider a variation of the height of the external data  $E_0$ . Again we observe similar behavior of the minimizer as in the original model, but for smaller heights, we cannot say a priori whether the minimizer is connected for small  $M$  as in the nonlocal case we could have a connected component of the minimizer which is fully disconnected from the rest of the minimizer. We will discuss this situation in Chapter 3.

### 2.1 Model 01

For  $n \geq 2$  consider the model as follows:

$$E_0 := \{(x', x_n) \in \mathbb{R}^{n-1} \times \mathbb{R} \text{ s.t. } |x'| \leq R, |x_n| \geq M\}$$

$$\Omega := \{(x', x_n) \in \mathbb{R}^{n-1} \times \mathbb{R} \text{ s.t. } |x'| \leq 1, |x_n| \leq M\}$$

for  $R \geq 1$  and  $M > 0$ . The Figure 2.1 illustrates the setting.

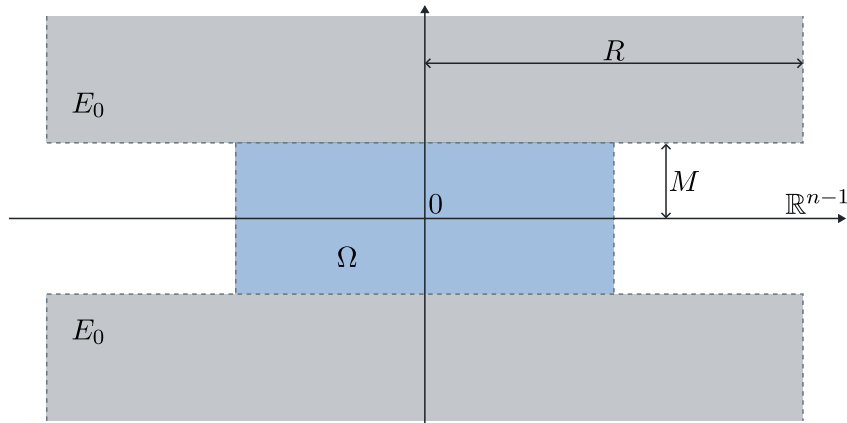


Figure 2.1

We state the following two results, which we will prove afterwards.

**Theorem 2.1.** For  $\Omega$  and  $E_0$  as given above and for all  $R \geq 1$ , then there exists  $M_0 \in (0, 1)$  depending only on the dimension and  $s$ , such that for any  $M \in (0, M_0)$ , the minimizer is  $E_M = E_0 \cup \Omega$ .

**Theorem 2.2.** For  $\Omega$  and  $E_0$  as given above and for all  $R \geq 1$ , then there exists  $M_0 > 1$  depending only on the dimension and  $s$ , such that for any  $M \geq M_0$ , the minimizer  $E_M$  is disconnected.

**TODO.** Elaborate and add source

Connect to classical minimal surfaces by observing disconnectedness of the minimizer, but when connected, the minimizer may “stick” to the boundary. Whereas classical minimal surfaces cannot stick to the boundary.

**TODO.** Rewrite

Improve the figure

For the first proof, we will follow a similar construction as in [5].

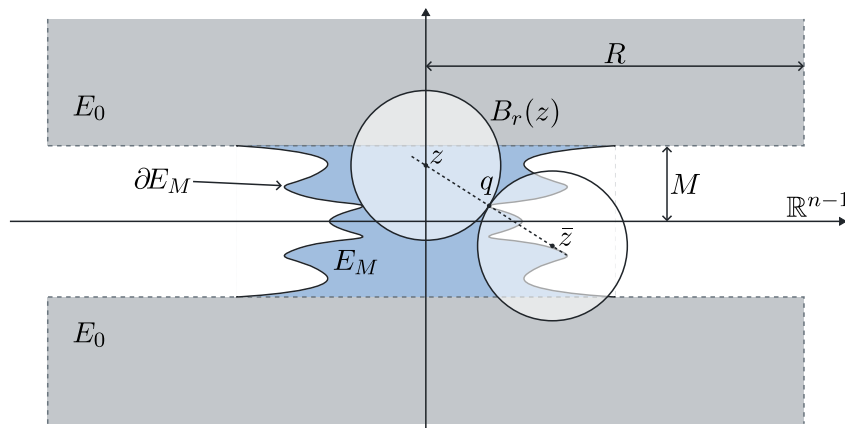
In [2] the authors have shown that nonlocal minimizer satisfy the Euler - Lagrange equation in the viscosity sense, i.e. if  $E$  is a minimizer, there exists some such that  $q \in \partial E$  and  $B_r(q + r\nu) \subset E$  for some  $r > 0$  and unit vector  $\nu \in \mathbb{R}^n$ , then

$$\int_{\mathbb{R}^n} \frac{\chi_{E^c}(y) - \chi_E(y)}{|y - q|^{n+s}} dy \geq 0. \quad (2.1)$$

In the proof we will assume that there exist a minimizer which is not  $E_0 \cup \Omega$ . To bring this assumption to a contradiction, we want to show that the left hand side of (2.1) is negative for  $M$  small enough. Thus, we have to construct some suitable ball such that we can apply the Euler - Lagrange equation. Constructing the ball by sliding it down from  $te_n$ . If the minimizer is not  $E_0 \cup \Omega$ , then at some point the ball will touch the minimizer for any  $0 < r < 1$  and a point  $q$ , then exists. Then we will split the domain into four parts and estimate each part to get the contradiction.

**TODO.** Improve the proof

*Proof of Theorem 2.1.* Proof by contradiction. Assume  $E_M$  is not  $E_0 \cup \Omega$ , then we can slide a ball of radius  $r$  down and at some point it will touch  $E_M$ . We consider the ball  $B_r(te_n)$ . Since  $E_M$  not cylindrical, there exists  $r_0 \in (0, 1)$  and  $t_0 > 0$  s.t.  $\partial B_{r_0}(t_0 e_n) \cap \partial E_M \neq \emptyset$  and  $B_{r_0}(te_n) \subset E_M$  for all  $t > t_0$ . See figure fig. 2.2.



**Figure 2.2**

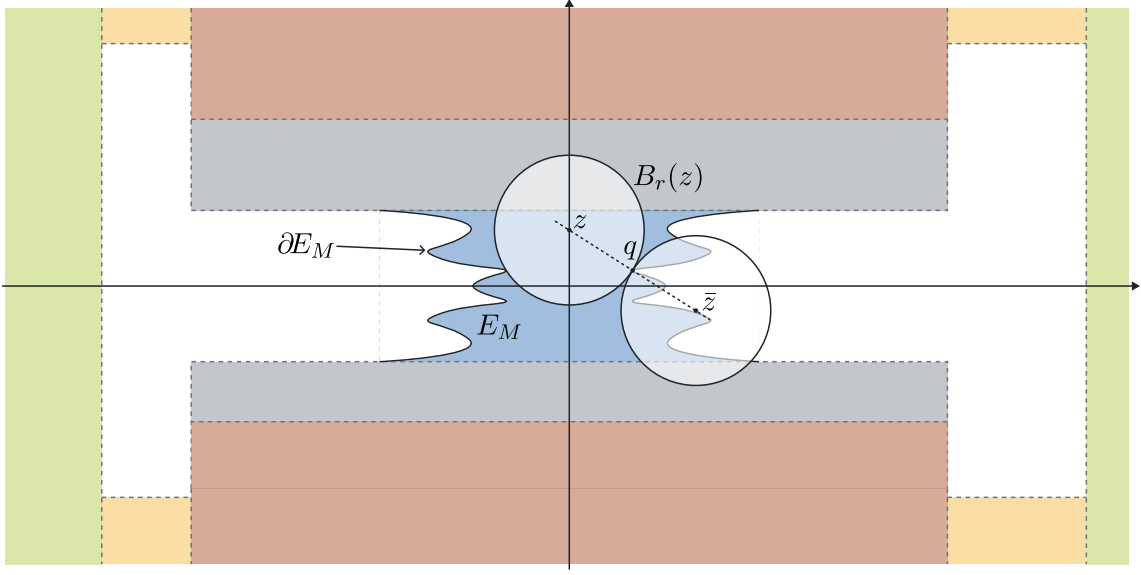
Since  $E_M$  is a minimizer it is also a variational solution and the inequality holds

$$\int_{\mathbb{R}^n} \frac{\chi_{E_M^c}(y) - \chi_{E_M}(y)}{|y - q|^{n+s}} dy \geq 0$$

whereas  $q \in \partial B_{r_0}(t_0 e_n) \cap \partial E_M$ .

We show that the left hand side is negative. Split the domain into four parts, as seen in the Figure fig. 2.3.

**CHECK.** Figure 2.3 looks good, but is this needed?



**Figure 2.3**

We define

$$A := \{(x', x_n) \text{ s.t. } |x' - q'| \geq R + 1\} \text{ Green Area}$$

$$B := \{(x', x_n) \text{ s.t. } |x'| < R, |x_n - q_n| > 2M\}$$

$$C := \{(x', x_n) \text{ s.t. } |x'| \geq R, |x' - q'| \leq R + 1, |x_n - q_n| > \Lambda M\}$$

$$\text{Everything else} \subset S := \{(x', x_n) \text{ s.t. } |x' - q'| \leq R + 1, |x_n - q_n| \leq \Lambda M\}$$

Integration over the first part:

$$\int_A \frac{\chi_{E^c} - \chi_E}{|y - q|^{n+s}} dy \stackrel{A \subseteq E^c}{=} \int_{|y'| > R+1} \frac{1}{|y|^{n+s}} dy \leq c(n) \int_{R+1}^{\infty} r^{-s-2} dy \leq c(n, s) R^{-(1+s)}$$

Integration over the second part:

$$\int_B \frac{\chi_{E^c} - \chi_E}{|y - q|^{n+s}} dy \stackrel{B \subseteq E}{=} - \int_B \frac{1}{|y - q|^{n+s}} dy \leq -c(n, s) M^{-s} \quad \text{Idea: Consider ball with factor } 2^{-n}$$

Integration over the third part:

$$\begin{aligned} \int_C \frac{\chi_{E^c} - \chi_E}{|y - q|^{n+s}} dy &\stackrel{C \subseteq E^c}{=} \int_C \frac{1}{|y - q|^{n+s}} dy \leq c(n) \int_{R-1}^{R+1} \int_{\Lambda M}^{\infty} \frac{r^{n-2}}{(r^2 + y_n^2)^{\frac{n+s}{2}}} dy_n dr \\ &\stackrel{r^2 \leq r^2 + y_n^2}{\leq} c(n) \int_{R-1}^{R+1} \int_{2\Lambda M}^{\infty} \frac{1}{(r^2 + y_n^2)^{\frac{s+2}{2}}} dy_n dr \stackrel{\text{convexity}}{\leq} \int_{R-1}^{R+1} \int_{\Lambda M}^{\infty} \frac{1}{(r + y_n)^{s+2}} dy_n dr \\ &\leq c(n, s) \int_{R-1}^{R+1} \frac{1}{(r + \Lambda M)^{s+1}} \leq c(n, s) (R - 1 + \Lambda M)^{-s} \leq c(n, s) (\Lambda M)^{-s} \end{aligned}$$

Integration over the fourth part:

Justification that we can estimate with  $S$ : Only negative part of the integration is fully in the set we want to estimate and the rest in  $S$  is positive.

We split  $S$  into four parts:

$$\text{i) } S \cap B_{\Lambda M}(q) \cap B_{r_0}(z)$$



- ii)  $S \cap B_{\Lambda M}(q) \cap B_{r_0}(\bar{z})$
- iii)  $S \cap (B_{\Lambda M}(q) \setminus (B_{r_0}(z) \cup B_{r_0}(\bar{z})))$
- iv)  $S \setminus B_{\Lambda M}(q)$

where  $\bar{z} := z + 2(q - z)$  and  $\Lambda > 4$  chosen big enough and  $M$  chosen small enough s.t.  $\Lambda M \leq 1$ .

We estimate the first and second part:

$$\begin{aligned} & \int_{S \cap B_{\Lambda M}(q) \cap B_{r_0}(z) \cup S \cap B_{\Lambda M}(q) \cap B_{r_0}(\bar{z})} \frac{\chi_{E^c} - \chi_E}{|y - q|^{n+s}} dy \\ & \leq \int_{S \cap B_{\Lambda M}(q) \cap B_{r_0}(z)} \frac{1}{|y - q|^{n+s}} dy - \int_{S \cap B_{\Lambda M}(q) \cap B_{r_0}(\bar{z})} \frac{1}{|y - q|^{n+s}} dy \leq 0 \end{aligned}$$

These two integrals cancel because of symmetry.

We estimate the third part:

$$\int_{S \cap (B_{\Lambda M}(q) \setminus (B_{r_0}(z) \cup B_{r_0}(\bar{z})))} \frac{\chi_{E^c} - \chi_E}{|y - q|^{n+s}} dy \leq \int_{P_{1, \Lambda M}} \frac{1}{|y - q|^{n+s}} dy \leq C \Lambda^{1-s} M^{1-s}$$

where we used lemma 3.1 in [6] with  $R = r_0 = 1$  and  $\lambda = \Lambda M$  (we can choose  $r_0 = 1$ , since if we can show the bound for  $r_0 = 1$  then it holds for all smaller balls as well).

We estimate the fourth part:

$$\int_{S \setminus B_{\Lambda M}(q)} \frac{\chi_{E^c} - \chi_E}{|y - q|^{n+s}} dy \leq \int_{B_{R+2} \setminus B_{\Lambda M}} \frac{1}{|y|^{n+s}} dy = c(n, s)((\Lambda M)^{-s} - (R+2)^{-s})$$

since  $S \subset B_{R+2}$  for  $R \geq 1$  since  $((\Lambda M)^2 + (R+1)^2)^{\frac{1}{2}} \leq (R^2 + 4R + 4)^{\frac{1}{2}} = R + 2$ .

Thus in total we get:

$$\begin{aligned} \int_{\mathbb{R}^n} \frac{\chi_{E^c} - \chi_E}{|y - q|^{n+s}} dy & \leq -c_1 M^{-s} + c_0(R^{-(1+s)} + (\Lambda M)^{-s} + (\Lambda M)^{-s} - (R+2)^{-s} + \Lambda^{1-s} M^{1-s}) \\ & \leq -c_1 M^{-s} (1 - \frac{c_0}{c_1} (R^{-(1+s)} M^s + 2\Lambda^{-s} - (R+2)^{-s} M^s + \Lambda^{1-s} M)) \end{aligned}$$

Choose  $\Lambda$  large and  $M$  small enough

$$\leq -c_2 M^{-s} < 0$$

■

Interesting to see, that the contribution of the cylinder of radius 1 is enough to get connectedness of the minimizer and even stickiness to the boundary. Also see, that the model seems (maybe prove that) to converge to the problem, considered in [5].

**TODO.** Complete proof of Theorem 2.2

*Proof of Theorem 2.2.* In theorems 1.2 in [5] the authors have shown that that  $\exists M_0 > 1$ , such that..

$$E_M \subset F_M \quad E_M^c \subset F_M^c$$

■

Whereas Theorem 2.2 is consistent with the classical theory of minimal surfaces, the behavior of the minimizer in Theorem 2.1 is unique to nonlocal minimal surfaces. In [5] the authors have shown that the minimizer exhibits similar behavior as we found in Theorem 2.1 for the model considered in this chapter, however interesting to see is that even in the case  $R = 1$  the minimizer is connected and even sticks to the boundary, for  $M$  small enough. This suggests that the contribution of the external data  $E_0$  above and below is enough to push the minimizer to the boundary of the prescribed set  $\Omega$ . In the proof we have seen that the width  $R$  is with negative exponents in the upper bound, thus if we choose  $R$  large enough,  $M_0$  increases.

## 2.2 Model 02

For  $n \geq 2$  consider the model as follows:

$$E_0 := \{(x', x_n) \in \mathbb{R}^{n-1} \times \mathbb{R} \text{ s.t. } |x_n| \geq R + M\}$$

$$\Omega := \{(x', x_n) \in \mathbb{R}^{n-1} \times \mathbb{R} \text{ s.t. } |x'| \leq 1, |x_n| \leq M\}$$

for  $R > 0$  and  $M > 0$ . The Figure 2.4 illustrates the setting.

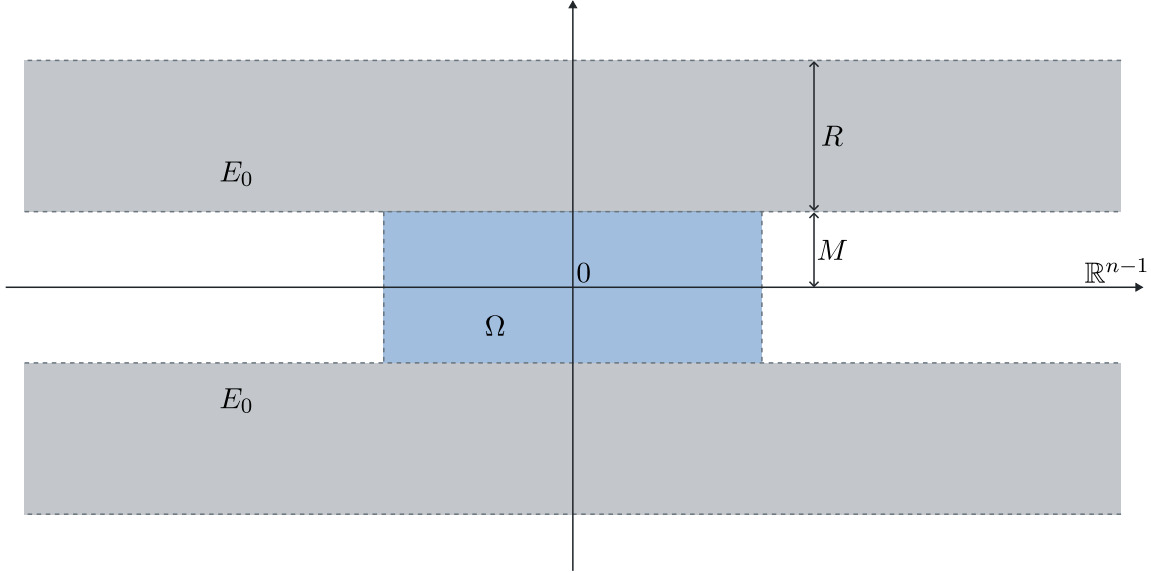


Figure 2.4

We state the following two results, which we will prove afterwards.

**TODO.** Specify  $R$

**Theorem 2.3.** Let  $\Omega$  and  $E_0$  as given above and for all  $R \geq 2$ , then there exists  $M_0 \in (0, 1)$  depending only on the dimension and  $s$ , such that for any  $M \in (0, M_0)$ , the minimizer is  $E_M = E_0 \cup \Omega$ . For  $R < 2$ , the cylinder  $A := \{(x', x_n) \in \mathbb{R}^{n-1} \times \mathbb{R} \text{ s.t. } |x'| \leq 1, |x_n| \leq M\}$  is in the minimizer, i.e.  $E_M \supset E_0 \cup A$ .

**Note.** Bound on  $R$  depends on the construction of the proof.

**TODO.** Elaborate

**Theorem 2.4.** For  $\Omega$  and  $E_0$  as given above and for all  $R > 0$ , then there exists  $M_0 > ..$  depending only on the dimension and  $s$ , such that for any  $M \geq M_0$ , the minimizer  $E_M$  is disconnected.

Again, similar proofs as in section 2.1.

Add some more discussion.

*Proof of Theorem 2.3.* We show that for every  $R > 0$  at least the tube  $\{|x_n| < r_0\}$  is in the minimizer for some  $r_0 > 0$ .

**TODO.** Edit proof to show cylinder is in minimizer and not assume that it's disconnected

We do that analogously to theorem 2.1 by contradiction. We assume that  $E_M$  is disconnected, thus we can slide a ball of radius  $r$  down and for all  $r_0 \in (0, 1)$  there exists a  $t_0 > 0$  s.t.  $\partial B_{r_0}(t_0 e_n) \cap \partial E_M \neq \emptyset$ . If

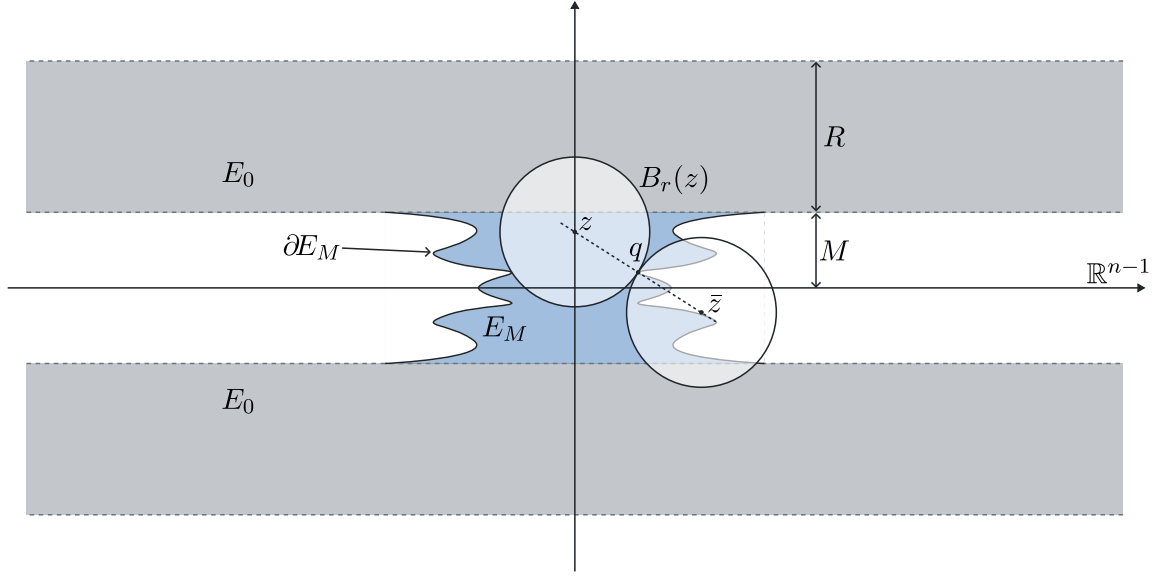


Figure 2.5

we can show that there exists a  $r_0$  s.t. this contradicts then the tube is in the minimizer. It is enough to show that for one  $r_0$  since if we can contradict this for one  $r_0$  then for all smaller there is no touching as well. For that we split into four parts as seen in the figure:

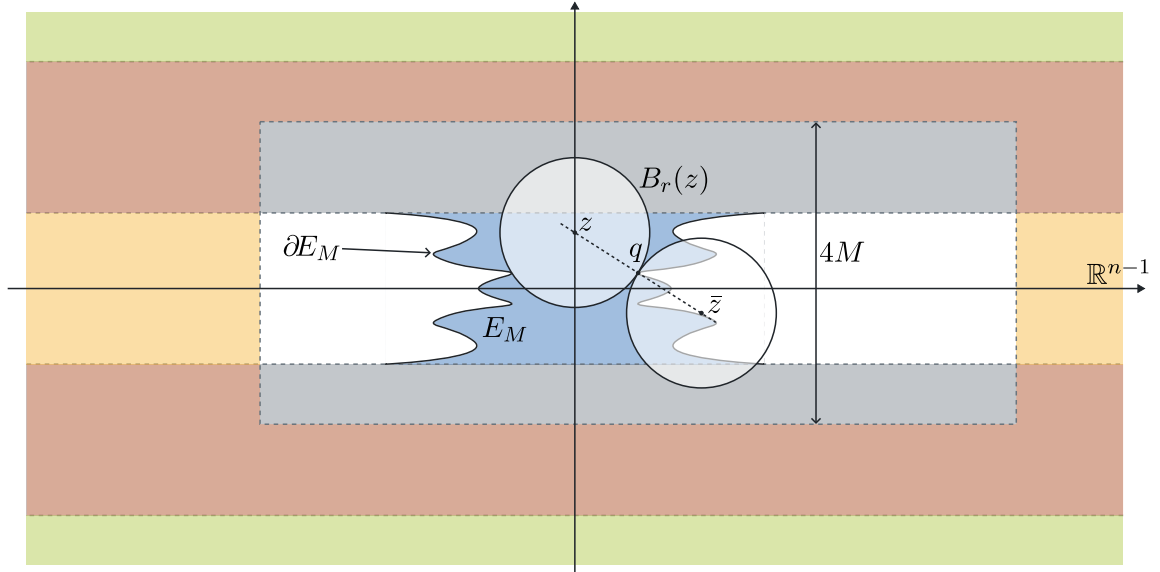


Figure 2.6

We define

$$\begin{aligned}
 A &:= \{(x', x_n) \text{ s.t. } |x_n| \geq M + R\} \\
 B &:= \{(x', x_n) \text{ s.t. } |x_n| \leq M, |x' - q'| > 2\} \\
 C &:= E_0 \setminus S \\
 S &:= \{(x', x_n) \text{ s.t. } |x_n - q_n| \leq M + R, |x' - q'| \leq 2\}
 \end{aligned}$$

Integration over the first part:

$$\begin{aligned}
\int_A \frac{\chi_{E^c} - \chi_E}{|y - q|^{n+s}} dy &\stackrel{A \subset E^c}{\leq} \int_{|y_n| \geq R} \frac{1}{|y|^{n+s}} dy \leq c(n) \int_0^\infty \int_R^\infty \frac{r^{n-2}}{(r^2 + y_n^2)^{\frac{n+s}{2}}} dy_n dr \\
&\leq c(n) \int_0^\infty \int_R^\infty \frac{1}{(r^2 + y_n^2)^{\frac{s+2}{2}}} dy_n dr \leq c(n) \int_0^\infty \int_R^\infty \frac{1}{(r + y_n)^{s+2}} dy_n dr \\
&= c(n, s) \int_0^\infty \frac{1}{(r + R)^{s+1}} dr = c(n, s) R^{-s}
\end{aligned}$$

Integration over the second part:

$$\begin{aligned}
\int_B \frac{\chi_{E^c} - \chi_E}{|y - q|^{n+s}} dy &\stackrel{B \subset E^c}{\leq} c(n) \int_0^M \int_2^\infty \frac{r^{n-2}}{(r^2 + y_n^2)^{\frac{n+s}{2}}} dr dy_n \\
&\leq c(n) \int_0^M \int_2^\infty \frac{1}{(r + y_n)^{s+2}} dr dy_n = c(n, s) \int_0^M \frac{1}{(2 + y_n)^{s+1}} dy_n \\
&= c(n, s) (2^{-s} - (2 + M)^{-s}) \leq c(n, s) 2^{-s}
\end{aligned}$$

Integration over the third part (here we need  $R > M$ ):

$$\int_C \frac{\chi_{E^c} - \chi_E}{|y - q|^{n+s}} dy = - \int_C \frac{1}{|y - q|^{n+s}} dy \leq -c(n) \int_{B_M(\dots)} \frac{1}{|y|^{n+s}} dy \leq -c(n, s) M^{-s}$$

Idea: Move part of the stripe outside, restrict to ball with radius  $M$  and multiply with  $\frac{1}{2}$  since not whole ball may be in the set. See

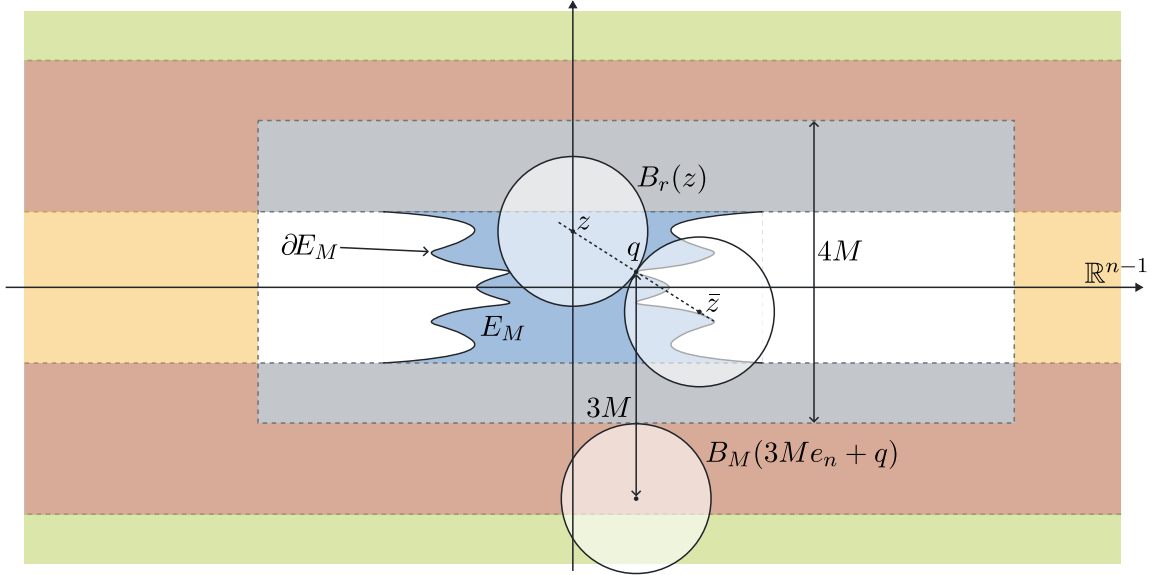


Figure 2.7 caption

Integration over the fourth part:

We split  $S$  into four parts:

- i)  $S \cap B_{\Lambda M}(q) \cap B_{r_0}(z)$
- ii)  $S \cap B_{\Lambda M}(q) \cap B_{r_0}(\bar{z})$
- iii)  $S \cap (B_{\Lambda M}(q) \setminus (B_{r_0}(z) \cup B_{r_0}(\bar{z})))$
- iv)  $S \setminus B_{\Lambda M}(q)$

where  $\bar{z} := z + 2(q - z)$  and  $\Lambda > 4$  chosen big enough and  $M$  chosen small enough s.t.  $\Lambda M \leq 1$ . Again the first and second part are in sum smaller than zero.

We estimate the third part:

$$\begin{aligned} & \int_{S \cap (B_{\Lambda M}(q) \setminus (B_{r_0}(z) \cup B_{r_0}(\bar{z})))} \frac{\chi_{E^c} - \chi_E}{|y - q|^{n+s}} dy \\ & \leq \int_{P_{r_0,1}} \frac{1}{|y|^{n+s}} dy + \int_{B_{\Lambda M} \setminus B_{r_0}} \frac{1}{|y|^{n+s}} dy \leq c(n, s)(r_0^{-s} - (\Lambda M)^{-s}) \end{aligned}$$

We estimate the fourth part:

$$\begin{aligned} & \int_{S \setminus B_{\Lambda M}(q)} \frac{\chi_{E^c} - \chi_E}{|y - q|^{n+s}} dy \\ & \leq c(n) \int_{\Lambda M}^{R+3} \frac{1}{r^{s+1}} dr \leq c(n, s)((\Lambda M)^{-s} - (R+3)^{-s}) \end{aligned}$$

Thus we estimate the domain  $S$  with

$$\int_S \frac{\chi_{E^c} - \chi_E}{|y - q|^{n+s}} dy \leq c(n, s)(r_0^{-s} - (R+3)^{-s}) \leq c(n, s)r_0^{-s}$$

Thus in total we get:

$$\begin{aligned} \int_{\mathbb{R}^n} \frac{\chi_{E^c} - \chi_E}{|y - q|^{n+s}} dy & \leq -c_0 M^{-s} + c_1(R^{-s} + 2^{-s} + r_0^{-s}) \\ & \leq -c_0 M^{-s} \left(1 - \frac{c_1}{c_0}(R^{-s} M^s + 2^{-s} M^s + r_0^{-s} M^s)\right) \end{aligned}$$

Now choose  $r_0 = \frac{R}{2}$  and at most 2

$$\leq -c_0 M^{-s} \left(1 - \frac{c_1}{c_0}(R^{-s} M^s + 2^{-s} M^s + \left(\frac{2M}{R}\right)^s)\right)$$

Choose  $\Lambda$  large and  $M$  small enogh

$$\leq -c_2 M^{-s} < 0$$

■

**TODO.** Elaborate

Discussion about connectedness in case of small  $R$  and refer to next chapter. Behavior unique to nonlocal minimal surfaces.

Talk about the contribution of the complement.

**TODO.** Complete proof of Theorem 2.4

*Proof of Theorem 2.4.* In theorems 1.2 in [5] the authors have shown that that  $\exists M_0 > 1$ , such that..

$$E_M \subset F_M \quad E_M^c \subset F_M^c$$

■

**TODO.** Ignore the existence of a disconnected part of the minimizer for now and come back to that in Chapter 3

**Theorem 2.5.** For  $\Omega$  and  $E_0$  as given above and for all  $R \geq 2$ , then there exists  $M_0 \in (0, 1)$  depending only on the dimension and  $s$ , such that for any  $M \in (0, M_0)$ , the minimizer is  $E_M = E_0 \cup \Omega$ .

We will prove this in a somehow similar manner than before, but this time we consider a ball of fixed radius  $R/4$  and slide it on the  $x_1$  direction. Since symmetries are preserved it is enough to consider  $x_1$ . We will push the ball outside from the origin and contradict the assumption, that if the minimizer is not  $E_0 \cup \Omega$ , by assuming the existence of the ball of radius  $R/4$  at  $(1 - R/4 - t)e_1 + he_n$  for some  $t \in (0, 1 - R/4)$  and all  $h \in (-M, M)$ . Then since the cylinder is in the minimizer, we can conclude that  $(1 - t)e_1 + he_n$  is in the boundary for any  $h$ , thus the minimizer is  $E_M = E_0 \cup \Omega$ .

*Proof of Theorem 2.5. ..* ■

**TODO.** Elaborate

Discussion about extending the model to arbitrary models with symmetric external data. Enough to consider discs of radius.. and height.. to have connectedness and even stickiness at some point.

New idea: If there is a minimizer  $E_M$ , can it ever be non sticky to the boundary?

Maybe able to give own interpretation of nonlocal minimal surfaces. Idea about Volume or Gravity?

### 3 Disconnected Minimizer

**IDEA.** Open this chapter with the train of thought motivated by model02

For the unbounded case, consider all dimensions and general  $r, R$  and just the upper bound.

For the bounded case consider  $n = 2$  to show, that even though we are positive at  $s = 0, 1$  we could still have negative values somewhere in between

Then give some interpretation if or how that helps or the consequences of that.

When discussing the connectedness of the second model in Chapter 2, we first just stated, that if  $R \geq 2$  the minimizer is connected and that if  $R < 2$  then at least the cylinder  $Z_R := B''_{R/2} \times (-M, M)$  is in the minimizer. This fact is not enough to for connectedness of the minimizer. To show connectedness, we would still need to show, that if there cannot exist a part of the minimizer that is fully detached from the cylinder and the external data.

Motivated by the fact, that in the classical case, if we have some external data  $E_0$  and some prescribed set  $\Omega$  that are fully disconnected, i.e.  $\text{dist}(E_0, \Omega) =: d > 0$ , then the minimizer is the external data itself, we wanted to prove the same thing for the nonlocal case as well.

Indeed, if we could show that, then the minimizer in the second model would be connected. Assume there exists a part of the minimizer that is not connected to the cylinder and the external data, i.e. there exists a set  $E_1$  such that  $\text{dist}(E_1, E_0 \cup Z_R) > 0$ . Then we can rewrite the fractional perimeter of  $E_M := E_0 \cup E_1$  relative to  $\Omega$  as follows:

$$\begin{aligned} \text{Per}_s(E_M, \Omega) &= \mathcal{L}(E_M \cap \Omega, E_M^c) + \mathcal{L}(E_M \setminus \Omega, \Omega \setminus E_M) \\ &= \mathcal{L}(E_1 \cup Z_R, E_M^c) + \mathcal{L}(E_0, \Omega \setminus (E_1 \cup Z_R)) \\ &= \mathcal{L}(E_1, E_M^c) + \mathcal{L}(Z_R, E_M^c) + \mathcal{L}(E_0 \cup Z_R, \Omega \setminus (E_1 \cup Z_R)) - \mathcal{L}(Z_R, \Omega \setminus (E_1 \cup Z_R)) \\ &= \text{Per}_s(E_M, \Omega \setminus Z_R) + \mathcal{L}(Z_R, (E_0 \cup Z_R)^c). \end{aligned} \quad (3.1)$$

Notice that the second term in (3.1) is now independent of  $E_1$ , thus to minimize  $\text{Per}_s(E_M, \Omega)$  we can minimize  $\text{Per}_s(E_M, \Omega \setminus Z_R)$  instead.

We define a sequence of prescribed sets  $\Omega_n$  such that  $\text{dist}(E_0 \cup Z_R, \Omega_n) = d/n$ , where  $d = \text{dist}(E_0 \cup Z_R, E_1)$ . Then for each  $n$  we are in the situation of fully disconnected external data, here  $E_0 \cup Z_R$  and prescribed set, here  $\Omega_n$ , and we could conclude

$$\text{Per}_s(E_M, \Omega \setminus Z_R) \leq \text{Per}_s(E_M, \Omega_n) \geq \text{Per}_s(E_0, \Omega_n) \searrow \text{Per}_s(E_0, \Omega \setminus Z_R).$$

As it turns out, this is not true in general and thus we cannot state connectedness just with the existence of the cylinder in the minimizer.

In the following, we will consider an example where depending on  $s$  the minimizer is not the external data itself, even though the external data and the prescribed set have nonzero distance.

**Example 3.1.** Let  $E_0 = B_2^c$  and  $\Omega = B_1$  in  $\mathbb{R}^2$ . Then we compare the fractional perimeter of  $E_0$  relative to  $\Omega$  with the fractional perimeter of  $E_0 \cup \Omega$  relative to  $\Omega$

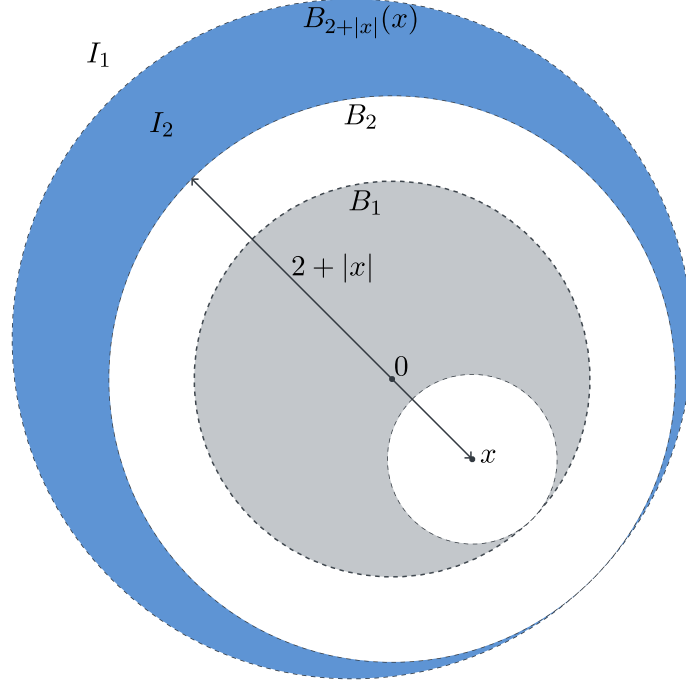
$$\text{Per}_s(E_0 \cup \Omega, \Omega) - \text{Per}_s(E_0, \Omega) = \text{Per}_s(B_1) - 2L(B_2^c, B_1) \quad (3.2)$$

and show that this difference is negative for  $s$  small enough.

For the first term we have by [14, Eq. (11)]

$$\text{Per}_s(B_1) = \frac{2^{2-s} \pi^{\frac{3}{2}} \Gamma(\frac{1-s}{2})}{s(2-s) \Gamma(\frac{2-s}{2})}.$$

We want to bound the second term from above and below. For that we will split the domain depending on  $x$ , see Figure 3.1.



**Figure 3.1** Split  $B_2^c$  depending on  $x$

Thus we have

$$\mathcal{L}(B_2^c, B_1) = \int_{B_1} \int_{B_2^c} \frac{1}{|x-y|^{2-s}} dy dx = \underbrace{\int_{B_1} \int_{B_{2+|x|}^c(x)} \frac{1}{|x-y|^{2-s}} dy dx}_{I_1} + \underbrace{\int_{B_1} \int_{B_{2+|x|}(x) \setminus B_2} \frac{1}{|x-y|^{2-s}} dy dx}_{I_2}.$$

We start with  $I_1$ :

$$\begin{aligned} I_1 &= \int_{B_1} \int_{B_{2+|x|}^c(x)} \frac{1}{|x-y|^{2+s}} dy dx \\ &= \int_{B_1} \int_{B_{2+|x|}^c} \frac{1}{|y|^{2+s}} dy dx \\ &= 4\pi^2 \int_0^1 \int_{2+r_1}^\infty \frac{r_1}{r_2^{1+s}} dr_2 dr_1 \\ &= \frac{4\pi^2}{s} \int_0^1 \left[ -\frac{r_1}{r_2^s} \right]_{2+r_1}^\infty dr_1 \\ &= \frac{4\pi^2}{s} \int_0^1 \frac{r_1}{(2+r_1)^s} dr_1 \\ &= \frac{4\pi^2}{s} \int_2^3 \frac{r_1-2}{r_1^s} dr_1 \\ &= \frac{4\pi^2}{s} \left[ \frac{r_1^{2-s}}{2-s} - 2 \frac{r_1^{1-s}}{1-s} \right]_2^3 \\ &= \frac{4\pi^2}{s(1-s)(2-s)} (2^{2-s} - (s+1)3^{1-s}). \end{aligned}$$



Thus for  $I_1$  we have

$$I_1 = \frac{4\pi^2}{s(1-s)(2-s)} (2^{2-s} - (s+1)3^{1-s}). \quad (3.3)$$

Now to  $I_2$ . Here the idea is to use radial coordinates again. Since the ntegral is radial symmetric with respect to  $x$ , we can fix  $x$  such that  $x = (r, 0)$  for  $r = |x|$ . Now for fixed  $x$  the domain of  $y$  is not radial symmetric anymore, thus we first have to compute the domain of  $\vartheta := \vartheta(r_1, r_2)$ .

We have two restrictions on  $y$ :

**TODO.** Give justifications of bounds

$$(1) \quad 4 \leq |x - y|^2 \leq (2 + 2|x|)^2$$

$$(2) \quad 2 - |x| \leq |y| \leq 2 + |x|$$

From the first restriction with  $|x| = r_1$ ,  $|y| = r_2$  and  $\vartheta$  the angle between  $x$  and  $y$  we get

$$\begin{aligned} 4 &\leq |x - y|^2 \leq (2 + 2r_1)^2 \\ \Leftrightarrow 4 &\leq r_1^2 + r_2^2 - 2r_1r_2 \cos(\vartheta) \leq 4(1 + r_1)^2 \\ \Leftrightarrow \frac{r_1^2 + r_2^2 - 4}{2r_1r_2} &\geq \cos(\vartheta) \geq \frac{r_1^2 + r_2^2 - 4(1 + r_1)^2}{2r_1r_2}. \end{aligned} \quad (3.4)$$

From the second restriction we get that the right - hand - side of (3.4) is always greater or equal to  $-1$ , thus we have

$$\frac{r_1^2 + r_2^2 - 4}{2r_1r_2} \geq \cos(\vartheta) \geq -1.$$

We will see, that for all  $r_1$  and  $r_2$  the argument is independent of  $\vartheta$ , thus we can integrate over  $\vartheta$  first. We then get

**TODO.** Argument for symmetry and how domain was chosen

$$\int_{-\vartheta}^{\vartheta} d\vartheta = 2\pi - 2 \arccos\left(\frac{r_1^2 + r_2^2 - 4}{2r_1r_2}\right).$$

For  $I_2$  we get then

**TODO.** Simplify computations?

Add arguments about splitting, change of variables, computationsteps etc

$$\begin{aligned}
I_2 &= \int_{B_1} \int_{B_{2+|x|}(x) \setminus B_2} \frac{1}{|x-y|^{2+s}} dy dx \\
&= \int_{B_1} \underbrace{\int_{B_{2+|x|} \setminus B_2(-x)} \frac{1}{|y|^{2+s}} dy}_{\text{radial symmetric w.r.t. } x} dx \\
&= 2\pi \int_0^1 \int_{2-r_1}^{2+r_1} \frac{r_1}{r_2^{1+s}} \int_{-\vartheta}^{\vartheta} d\vartheta dr_2 dr_1 \\
&= 2\pi \int_0^1 \int_{2-r_1}^{2+r_1} \frac{r_1}{r_2^{1+s}} \left( 2\pi - 2 \arccos \left( \frac{r_1^2 + r_2^2 - 4}{2r_1 r_2} \right) \right) dr_2 dr_1 \\
&= 4\pi^2 \int_0^1 \int_{2-r_1}^{2+r_1} \frac{r_1}{r_2^{1+s}} dr_2 dr_1 - 4\pi \int_0^1 \int_{2-r_1}^{2+r_1} \frac{r_1}{r_2^{1+s}} \arccos \left( \frac{r_1^2 + r_2^2 - 4}{2r_1 r_2} \right) dr_2 dr_1 \\
&= \frac{4\pi^2}{s(1-s)(2-s)} ((s+1)3^{1-s} - 3 + s) - \frac{4\pi^2}{s} \int_0^1 \frac{r_1}{(2-r_1)^s} dr_1 + \frac{4\pi}{s} \int_0^1 \int_{2-r_1}^{2+r_2} \frac{r_1}{r_2^{1+s}} \frac{r_2^2 - r_1^2 + 4}{\sqrt{4r_1^2 r_2^2 - (r_1^2 + r_2^2 - 4)^2}} dr_2 dr_1 \\
&= \underbrace{\frac{4\pi^2}{s(1-s)(2-s)} ((s+1)3^{1-s} - 2^{2-s})}_{-I_1} + \frac{4\pi}{s} \int_0^1 \int_{2-r_1}^{2+r_2} \frac{r_1}{r_2^{1+s}} \frac{r_2^2 - r_1^2 + 4}{\sqrt{4r_1^2 r_2^2 - (r_1^2 + r_2^2 - 4)^2}} dr_2 dr_1.
\end{aligned}$$

Thus we get for the second term in (3.2)

$$\mathcal{L}(E_0, E_1) = \frac{4\pi}{s} \int_0^1 \int_{2-r_1}^{2+r_2} \frac{r_1}{r_2^{1+s}} \frac{r_2^2 - r_1^2 + 4}{\sqrt{4r_1^2 r_2^2 - (r_1^2 + r_2^2 - 4)^2}} dr_2 dr_1.$$

We can now bound this term without losing too much information. For the upper bound, we will use that  $r_2 \geq 2 - r_1$  and for the lower bound we will use that  $r_2 \leq 2 + r_1$ . We then get

$$\begin{aligned}
\bullet \quad \mathcal{L}(E_0, E_1) &\leq \frac{4\pi}{s} \int_0^1 \int_{2-r_1}^{2+r_2} \frac{r_1}{(2-r_1)^s} \frac{1}{r_2} \frac{r_2^2 - r_1^2 + 4}{\sqrt{4r_1^2 r_2^2 - (r_1^2 + r_2^2 - 4)^2}} dr_2 dr_1 \\
&= \frac{4\pi}{s} \int_0^1 \frac{r_1}{(2-r_1)^s} \left[ \arccos \left( \frac{r_1^2 + r_2^2 - 4}{2r_1 r_2} \right) \right]_{2-r_1}^{2+r_2} dr_1 \\
&= \frac{4\pi^2}{s} \int_0^1 \frac{r_1}{(2-r_1)^s} dr_1 \\
&= \frac{4\pi^2}{s(1-s)(2-s)} (2^{2-s} - 3 + s)
\end{aligned}$$

and

$$\begin{aligned}
\bullet \quad \mathcal{L}(E_0, E_1) &\geq \frac{4\pi}{s} \int_0^1 \int_{2-r_1}^{2+r_2} \frac{r_1}{(2+r_1)^s} \frac{1}{r_2} \frac{r_2^2 - r_1^2 + 4}{\sqrt{4r_1^2 r_2^2 - (r_1^2 + r_2^2 - 4)^2}} dr_2 dr_1 \\
&= \frac{4\pi^2}{s} \int_0^1 \frac{r_1}{(2+r_1)^s} dr_1 \\
&= \frac{4\pi^2}{s(1-s)(2-s)} (2^{2-s} - (s+1)3^{1-s}).
\end{aligned}$$

Thus we have that

$$\frac{2^{2-s} \pi^{\frac{3}{2}} \Gamma(\frac{1-s}{2})}{s(2-s) \Gamma(\frac{2-s}{2})} - \frac{8\pi^2}{s(1-s)(2-s)} (2^{2-s} - 3 + s) \leq \text{Per}_s(E_1) - 2\mathcal{L}(E_0, E_1) \leq \frac{2^{2-s} \pi^{\frac{3}{2}} \Gamma(\frac{1-s}{2})}{s(2-s) \Gamma(\frac{2-s}{2})} - \frac{8\pi^2}{s(1-s)(2-s)} (2^{2-s} - (s+1)3^{1-s})$$

**TODO.** Give justification, that both sides are continuous w.r.t.  $s$  and conclude  
Maybe draw a picture

**Example 3.2** (Continuation of Example 3.1). Let us now consider the same setting as in Example 3.1, but instead with the external data  $E_1 = B_{2+T} \setminus B_2$  for  $T > 0$  large enough. Notice, that this change just adds one additional term compared to before

$$\mathcal{L}(B_{2+T} \setminus B_2, B_1) = \mathcal{L}(B_2^c, B_1) - \underbrace{\int_{B_{2+T}^c} \int_{B_1} \frac{1}{|x-y|^{2-s}} dx dy}_{I_3}$$

We will bound  $I_3$  from above and below.

The upper bound

$$\begin{aligned} \int_{B_1} \int_{B_{2+T-|x|}^c(x)} \frac{1}{|x-y|^{2-s}} dy dx &\leq 4\pi^2 \int_0^1 \int_{2+T-r_1}^\infty \frac{r_1}{r_2^{1-s}} dr_2 dr_1 \\ &= \frac{4\pi^2}{s} \int_0^1 \frac{r_1}{(2+T-r_1)^s} dr_1 \\ &= \frac{4\pi^2}{s(1-s)(2-s)} [(2+T)^{2-s} - (3-s+T)(1+T)^{1-s}] \end{aligned}$$

and the lower bound

$$\begin{aligned} \int_{B_1} \int_{B_{2+T+|x|}^c(x)} \frac{1}{|x-y|^{2-s}} dy dx &\geq 4\pi^2 \int_0^1 \int_{2+T+r_1}^{2+T+r_1} \frac{r_1}{r_2^{1-s}} dr_2 dr_1 \\ &= \frac{4\pi^2}{s} \int_0^1 \frac{r_1}{(2+T+r_1)^s} dr_1 \\ &= \frac{4\pi^2}{s(1-s)(2-s)} [(2+T)^{2-s} - (1+s+T)(3+T)^{1-s}] \end{aligned}$$

Thus we have the bounds

$$\text{Per}_s(E_0 \cup \Omega, \Omega) - \text{Per}_s(E_0, \Omega) \leq (\text{add upper bound}) + \frac{4\pi^2}{s(1-s)(2-s)} [(2+T)^{2-s} - (3-s+T)(1+T)^{1-s}]$$

$$\text{Per}_s(E_0 \cup \Omega, \Omega) - \text{Per}_s(E_0, \Omega) \geq (\text{add lower bound}) + \frac{4\pi^2}{s(1-s)(2-s)} [(2+T)^{2-s} - (1+s+T)(3+T)^{1-s}]$$

**TODO.** Add picture and more explanation

Notice that the limits for  $s \searrow 0$  and  $s \nearrow 1$  are independent of  $T$  and that for  $s \nearrow 1$  the limit is the same as in the unbounded case. For  $s \searrow 0$  however we have a different limit than in the unbounded case.

**TODO.** Add limit for  $s \searrow 0$ , independent of  $T$  and show that for  $T$  large enough the difference is negative for some interval of  $s$ .

**TODO.** Go from the example to the general case

We will consider the following setting once with unbounded data and once with bounded data: Let  $n \geq 1$  and  $r, R, T > 0$ , such that  $r < R$ . Take the external data  $E_0 = B_R^c$  in the unbounded case and  $E_0 = B_T \setminus B_R$  in the bounded case. Define the prescribed set  $\Omega = B_r$ .

**CHECK.** Is that correct?

Elaborate

In [3] the authors have shown that for  $s \nearrow 1$  the fractional perimeter approaches the classical perimeter. Thus, we can expect that for  $s$  large enough the minimizer should be the external data itself. In [9] the authors have shown that for bounded sets with nonzero distance and  $s$  small enough the minimizer is the external data itself as well.

**Theorem 3.3.** Let  $n \geq 2$  and  $0 < r < R$ . Let  $E_0 = B_R^c$  and  $\Omega = B_r$ , then there exists a  $s_0 \in (0, 1)$  such that for all  $s \in (0, s_0)$  the minimizer is not the external data itself.

**Theorem 3.4.** Let  $n \geq 2$  and  $0 < r < R$  and  $R + T > 0$ . Let  $E_0 = B_{R+T} \setminus B_R$  and  $\Omega = B_r$ , then there exists  $s_0, s_1 \in (0, 1)$  such that for all  $s \in (s_0, s_1)$  and  $T$  large enough the minimizer is not the external data itself and for  $s$  small and large enough the minimizer is the external data.

We will proof that the minimizer is not the external data itself by comparing the fractional perimeter of  $E_0$  with the fractional perimeter of  $E_0 \cup \Omega$ .

*Proof of Theorem 3.3.*

$$\text{Per}_s(E_0 \cup \Omega, \Omega) - \text{Per}_s(E_0, \Omega) = \text{Per}_s(\Omega) - 2L(E_0, \Omega) \quad (3.5)$$

For the first term we have by [14, Eq. (11)]

$$\text{Per}_s(\Omega) = \text{Per}_s(B_r) = \frac{2^{1-s} \pi^{\frac{n-1}{2}} n \omega_n \Gamma(\frac{1-s}{2})}{s(n-s)} r^{n-s} = \frac{2^{2-s} \pi^{n-\frac{1}{2}}}{s(n-s)} \frac{\Gamma(\frac{1-s}{2})}{\Gamma(\frac{n-s}{2}) \Gamma(\frac{n}{2})} r^{n-s}$$

with  $\omega_n = \frac{\pi^{\frac{n}{2}}}{\Gamma(\frac{n}{2}+1)}$ .

The second term we will bound from below to get an upper bound for (3.5).

$$\begin{aligned} \mathcal{L}(E_0, E_1) &= \mathcal{L}(B_r, B_R^c) = \int_{B_r} \int_{B_R^c} \frac{1}{|x-y|^{n-s}} dy dx \\ &\geq \int_{B_r} \int_{B_{R+|x|}^c(x)} \frac{1}{|x-y|^{n-s}} dy dx \\ &= \int_{B_r} \int_{B_{R+|x|}^c} \frac{1}{|y|^{n-s}} dy dx \\ &= \frac{4\pi^n}{(\Gamma(\frac{n}{2}))^2} \int_0^r \int_{R+r_1}^\infty \frac{r_1^{n-1}}{r_2^{1+s}} dr_2 dr_1 \\ &= \frac{4\pi^n}{(\Gamma(\frac{n}{2}))^2} \frac{1}{s} \int_0^r \frac{r_1^{n-1}}{(R+r_1)^s} dr_1 \\ &= \frac{4\pi^n}{(\Gamma(\frac{n}{2}))^2} \frac{1}{ns} \frac{r^{n-1}}{R^s} {}_2F_1(s, n; n+1; -\frac{r}{R}). \end{aligned}$$

**TODO.** Add source

In the last step we used the the following identity (source) for the hypergeometric function

$$B(b, c-b) {}_2F_1(a, b; c; z) = \int_0^1 t^{b-1} (1-t)^{c-b-1} (1-tz)^{-a} dt \quad \text{for } \Re(c) > \Re(b) > 0,$$

where  $B$  is the beta function. In our case we have  $a = s$ ,  $b = n$ ,  $c = n + 1$  and  $z = -\frac{r}{R}$ , thus

$$\begin{aligned} \int_0^r \frac{r_1^{n-1}}{(R+r_1)^s} dr_1 &= \frac{r^n}{R^s} \int_0^1 r_1^{n-1} (1 + \frac{r}{R} r_1)^{-s} dr_1 \\ &= \frac{r^n}{R^s} B(n, 1) {}_2F_1(s, n; n+1; -\frac{r}{R}) = \frac{r^n}{nR^s} {}_2F_1(s, n; n+1; -\frac{r}{R}). \end{aligned}$$

Thus we can bound (3.5) from above by

$$\text{Per}_s(E_0 \cup \Omega, \Omega) - \text{Per}_s(E_0, \Omega) \leq \frac{2^{2-s} \pi^{n-\frac{1}{2}}}{s(n-s)} \frac{\Gamma(\frac{1-s}{2})}{\Gamma(\frac{n-s}{2})\Gamma(\frac{n}{2})} r^{n-s} - \frac{8\pi^n}{(\Gamma(\frac{n}{2}))^2} \frac{r^n}{snR^s} {}_2F_1(s, n; n+1; -\frac{r}{R}). \quad (3.6)$$

**TODO.** Rewrite

Since we are interested in the behavior of (3.5) depending on  $s$  we multiply (3.6) by  $s(1-s)$  to deal with the singularities at  $s = 0$  and  $s = 1$

$$s(1-s)(\text{Per}_s(E_0 \cup \Omega, \Omega) - \text{Per}_s(E_0, \Omega)) \leq \frac{2^{3-s} \pi^{n-\frac{1}{2}}}{n-s} \frac{\Gamma(\frac{3-s}{2})}{\Gamma(\frac{n-s}{2})\Gamma(\frac{n}{2})} r^{n-s} - \frac{8\pi^n}{(\Gamma(\frac{n}{2}))^2} \frac{r^n}{nR^s} (1-s) {}_2F_1(s, n; n+1; -\frac{r}{R}). \quad (3.7)$$

**TODO.** Add source

Since  $\Gamma$  is continuous for all positive reals and  ${}_2F_1$  is continuous for  $|z| \leq 1$ , the right hand side of (3.7) is continuous for all  $s \in (0, 1)$ . Now take the limit for  $s \searrow 0$  and  $s \nearrow 1$

$$\lim_{s \searrow 0} s(1-s)(\text{Per}_s(E_0 \cup \Omega, \Omega) - \text{Per}_s(E_0, \Omega)) = -\frac{4\pi^n}{n} \frac{1}{(\Gamma(\frac{n}{2}))^2} r^n < 0 \quad (3.8)$$

and

$$\lim_{s \nearrow 1} s(1-s)(\text{Per}_s(E_0 \cup \Omega, \Omega) - \text{Per}_s(E_0, \Omega)) = \frac{4\pi^{n-\frac{1}{2}}}{n-1} \frac{1}{\Gamma(\frac{n-1}{2})\Gamma(\frac{n}{2})} r^{n-1} > 0.$$

Now we know for  $s \nearrow 1$  that  $(1-s)\text{Per}_s(E, \Omega)$  is approaching the classical perimeter, thus in (3.8) is actually an equality. Thus we can conclude that there exists a  $s_0 \in (0, 1)$  such that for all  $s \in (0, s_0)$  the minimizer is not the external data itself. ■

*Proof of Theorem 3.4.* We consider again the difference

$$\text{Per}_s(E_0 \cup \Omega, \Omega) - \text{Per}_s(E_0, \Omega) = \text{Per}_s(\Omega) - 2\mathcal{L}(E_0, \Omega) = \text{Per}_s(B_{R+T} \setminus B_R) - 2\mathcal{L}(B_R^c, B_r) + 2\mathcal{L}(B_{R+T}^c, B_r) \quad (3.9)$$

We can use the upper bound from the proof of Theorem 3.3 for the first 2 terms in (3.9). The third term we will bound from above

$$\begin{aligned}
\mathcal{L}(B_{R+T}^c, B_r) &= \int_{B_r} \int_{B_{R+T}^c} \frac{1}{|x-y|^{n-s}} dy dx \\
&\leq \int_{B_r} \int_{B_{R+T-|x|}^c} \frac{1}{|x-y|^{n-s}} dy dx \\
&= \frac{4\pi^n}{(\Gamma(\frac{n}{2}))^2} \int_0^r \int_{R+T-r_1}^\infty \frac{r_1^{n-1}}{r_2^{1+s}} dr_2 dr_1 \\
&= \frac{4\pi^n}{(\Gamma(\frac{n}{2}))^2} \frac{1}{s} \int_0^r \frac{r_1^{n-1}}{(R+T-r_1)^s} dr_1 \\
&= \frac{4\pi^n}{(\Gamma(\frac{n}{2}))^2} \frac{1}{ns} \frac{r^n}{(R+T)^s} {}_2F_1(s, n; n+1; -\frac{r}{R+T}).
\end{aligned}$$

Thus we can bound (3.9) from above by

$$\begin{aligned}
&\text{Per}_s(E_0 \cup \Omega, \Omega) - \text{Per}_s(E_0, \Omega) \\
&\leq \frac{2^{2-s}\pi^{n-\frac{1}{2}}}{s(n-s)} \frac{\Gamma(\frac{1-s}{2})}{\Gamma(\frac{n-s}{2})\Gamma(\frac{n}{2})} r^{n-s} - \frac{8\pi^n}{(\Gamma(\frac{n}{2}))^2} \frac{r^n}{sn} \left( \frac{1}{R^s} {}_2F_1(s, n; n+1; -\frac{r}{R}) - \frac{1}{(R+T)^s} {}_2F_1(s, n; n+1; -\frac{r}{R+T}) \right).
\end{aligned} \tag{3.10}$$

**TODO.** Argument for continuity

Now we multiply by  $s(1-s)$  to deal with the singularities at  $s=0$ ,  $s=1$  and let  $s \searrow 0$  and  $s \nearrow 1$

$$\lim_{s \searrow 0} s(1-s)(\text{Per}_s(E_0 \cup \Omega, \Omega) - \text{Per}_s(E_0, \Omega)) = \frac{4\pi^n}{n} \frac{1}{(\Gamma(\frac{n}{2}))^2} r^n > 0$$

and

$$\lim_{s \nearrow 1} s(1-s)(\text{Per}_s(E_0 \cup \Omega, \Omega) - \text{Per}_s(E_0, \Omega)) = \frac{4\pi^{n-\frac{1}{2}}}{n-1} \frac{1}{\Gamma(\frac{n-1}{2})\Gamma(\frac{n}{2})} r^{n-1} > 0.$$

Notice, that the limits are independent of  $R$  and  $T$ . Also both limits are positive. Nonetheless for  $T$  big enough, there will exist some interval in  $(0, 1)$  such that the difference is negative.

**TODO.** Elaborate or justify

The upper bound (3.10) is continuous in  $T$  for all  $s \in (0, 1)$  and for  $T \rightarrow \infty$ , the third term vanishes. Thus for  $s, T$  large enough, the upper bound behaves similar to the upper bound in the proof of Theorem 3.3. Thus there exists some  $s \in (0, 1)$  such that the difference is negative.

Since the limit for  $s \searrow 0$  is independent of  $T$  and positive and by [9, Eq. (3.2)] we have that  $s \mathcal{L}(B_{R+T} \setminus B_r, B_r) \rightarrow 0$  for  $s \searrow 0$ . Thus the limits in  $s=0$  and  $s=1$  are not only upper bounds but exact values.

Thus we can conclude, that there exists an interval  $(s_0, s_1)$  such that for all  $s \in (s_0, s_1)$  the minimizer is not the external data itself. ■

**TODO.** Give some conclusion and interpretation of these results

When comparing both theorems and their proofs, we notice that the example with bounded external data doesn't seem to converge to the example of unbounded external data. At least in the limit for  $s \searrow 0$ . This is interesting, as this entails, that if we want to analyze the limiting behavior of a minimizer for  $s \searrow 0$  we cannot restrict the boundary data to be bounded or unbounded.

# Conclusion

discussion of the results, comparison to classical case, open problems, future work,...

1. Change of Topology in the models (barrier construction)
2. Cubic construction for arbitrary external data
3. Existence of  $s_0$  for all external data and prescribed sets
4. Minimizer touching the boundary of the prescribed set (Calculations with of 3. with arbitrary parameter shows, no)
5. Can we give an estimate of the amount of connected components?

# Bibliography

- [1] L. Ambrosio, G. D. Philippis, and L. Martinazzi. “Gamma-convergence of nonlocal perimeter functionals”. In: *Manuscripta Mathematica* 134.3–4 (Oct. 2010), 377–403. ISSN: 1432-1785. DOI: 10.1007/s00229-010-0399-4. URL: <http://dx.doi.org/10.1007/s00229-010-0399-4>.
- [2] L. A. Caffarelli, J. M. Roquejoffre, and O. Savin. *Nonlocal minimal surfaces*. 2009. arXiv: 0905.1183 [math.AP].
- [3] L. Caffarelli and E. Valdinoci. “Uniform estimates and limiting arguments for nonlocal minimal surfaces”. In: *Calculus of Variations and Partial Differential Equations* 41.1 (2011), pp. 203–240. ISSN: 1432-0835. DOI: 10.1007/s00526-010-0359-6. URL: <https://doi.org/10.1007/s00526-010-0359-6>.
- [4] M. Cozzi and A. Figalli. “Regularity Theory for Local and Nonlocal Minimal Surfaces: An Overview”. In: *Nonlocal and Nonlinear Diffusions and Interactions: New Methods and Directions: Cetraro, Italy 2016*. Ed. by M. Bonforte and G. Grillo. Cham: Springer International Publishing, 2017, pp. 117–158. ISBN: 978-3-319-61494-6. DOI: 10.1007/978-3-319-61494-6\_3. URL: [https://doi.org/10.1007/978-3-319-61494-6\\_3](https://doi.org/10.1007/978-3-319-61494-6_3).
- [5] S. Dipierro, F. Onoue, and E. Valdinoci. *(Dis)connectedness of nonlocal minimal surfaces in a cylinder and a stickiness property*. 2020. arXiv: 2010.00798 [math.AP].
- [6] S. Dipierro, O. Savin, and E. Valdinoci. “Graph properties for nonlocal minimal surfaces”. In: *Calculus of Variations and Partial Differential Equations* 55.4 (2016), p. 86. ISSN: 1432-0835. DOI: 10.1007/s00526-016-1020-9. URL: <https://doi.org/10.1007/s00526-016-1020-9>.
- [7] S. Dipierro, O. Savin, and E. Valdinoci. “Boundary behavior of nonlocal minimal surfaces”. In: *Journal of Functional Analysis* 272.5 (2017), pp. 1791–1851. ISSN: 0022-1236. DOI: 10.1016/j.jfa.2016.11.016. URL: <https://www.sciencedirect.com/science/article/pii/S0022123616303858>.
- [8] S. Dipierro, O. Savin, and E. Valdinoci. *A strict maximum principle for nonlocal minimal surfaces*. 2023. arXiv: 2308.01697 [math.AP].
- [9] S. Dipierro et al. *Asymptotics of the  $s$ -perimeter as  $s \searrow 0$* . 2012. arXiv: 1204.0750 [math.AP].
- [10] C. B. Enrico Valdinoci and L. Lombardini. “Complete stickiness of nonlocal minimal surfaces for small values of the fractional parameter”. In: *Ann. Inst. H. Poincaré Anal. Non Linéaire* 36.3 (2019), pp. 655–703. DOI: 10.1016/J.ANIHPC.2018.08.003.
- [11] A. Figalli et al. “Isoperimetry and Stability Properties of Balls with Respect to Nonlocal Energies”. In: *Communications in Mathematical Physics* 336.1 (2014), 441–507. ISSN: 1432-0916. DOI: 10.1007/s00220-014-2244-1. URL: <http://dx.doi.org/10.1007/s00220-014-2244-1>.
- [12] R. L. Frank, E. H. Lieb, and R. Seiringer. *Hardy-Lieb-Thirring inequalities for fractional Schroedinger operators*. 2006. arXiv: math/0610593 [math.SP].
- [13] N. Fusco, V. Millot, and M. Morini. *A quantitative isoperimetric inequality for fractional perimeters*. 2011. arXiv: 1012.0051 [math.AP].
- [14] J. Haddad and M. Ludwig. *Affine Fractional Sobolev and Isoperimetric Inequalities*. 2022. arXiv: 2207.06375 [math.MG].
- [15] L. Lombardini. *Approximation of sets of finite fractional perimeter by smooth sets and comparison of local and global  $s$ -minimal surfaces*. 2016. arXiv: 1612.08237 [math.AP].



- [16] M. Ludwig. “Anisotropic fractional perimeters”. In: *Journal of Differential Geometry* 96.1 (Jan. 2014). ISSN: 0022-040X. DOI: 10.4310/jdg/1391192693. URL: <http://dx.doi.org/10.4310/jdg/1391192693>.
- [17] A. C. Ponce and D. Spector. *A Boxing Inequality for the Fractional Perimeter*. 2018. arXiv: 1703.06195 [math.FA].
- [18] J. Serra. “Nonlocal minimal surfaces: recent developments, applications, and future directions”. In: *SeMA Journal* (2023). ISSN: 2281-7875. DOI: <https://doi.org/10.1007/s40324-023-00345-1>.