Irregular solutions: Sketch

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1 Preliminaries. Existence of classical minimizers

1.1 Minimizers in finite-dimensional optimal problems

The classical approach to variational problems assumes that the optimal trajectory is a differentiable curve – a solution to the Euler equation that, in addition, satisfies the Weierstrass and Jacobi tests. In this chapter, we consider the variational problems which solutions do not satisfy necessary conditions of optimality. Either the Euler equation does not have solution, or Jacobi or Weierstrass tests are not satisfied at any stationary solution. If this is a case, the extremal cannot be found from necessary conditions. We have met such solution in the problem of minimal surface (Goldschmidt solution, Section **??**).

As always, we point to an analogy of irregular solutions in finite-dimensional minimization problems. Consider such a problem of minimization of a scalar function $F(x)$ of a vector $x \in R_n$,

$$\min_{x \in R_n} F(x).$$

The infimum of F may correspond to the regular stationary point where gradient is zero $\nabla F(x) = 0$ and Hessian $\nabla^2 F(x)$ is positively defined. This case is an analog of optimality of a stationary solution for which Legandre and Jacobi conditions safisfied. The infimum may also correspond to an irregular point x where $\nabla F(x)$ is not defined (as in the case $F(x) = |x|$), or its norm is unbounded, $\|\nabla F(x)\| \to \infty$ (as in the case $F(x) = \sqrt{|x|}$), or x can be improper, $\|x\| \to \infty$ (as in the case $F(x) = |x|^{-1}$); in the last case, a minimizing sequence x_n diverges.

In variational problems, the minimizing functions $u(x)$ belong to more complex than R_n sets and and they are bounded by additional requirements of differentiability. It is natural to expect irregular solutions to those problems and to meet diverse causes for these irregularities.

Irregular limits of minimizing sequences A minimization problem always can be solved by *a direct method* that is by constructing a corresponding minimizing sequence, the functions $u^s(t)$ with the property $I(u^s) \geq I(u^{s+1})$. The functionals $I(u^s)$ form a monotonic sequence of real number that converges to a real or improper limit. In this sense, every variational problem can be solved, but the limiting solution $\lim_{s\to\infty} u^s$ may be irregular; in other terms, it may not exist in an assumed set of functions. Especially, derivation of Euler equation uses an assumption that the minimum is a differentiable function. This assumption leads to complications because the set of differentiable functions is open and the limits of sequences of differentiable functions are not necessary differentiable functions themselves.

We list several types of minimizing sequences that one meets in variational problems

Example 1.1 (Various limits of functional sequences)

- The sequence of infinitely differentiable function

$$\phi_n(x) = \frac{n}{\sqrt{\pi}} \exp\left(-\frac{x^2}{n^2}\right)$$

  when $n \to \infty$ tends to the δ function, $\phi_n(x) \to \delta(x)$, which is not a function but a distribution. Its value is zero in all point but $x = 0$ and the integral of $\phi_n(x)$ over the real axis it is equal to one for all n.

- The limit $H(x)$ of the sequence of antiderivatives of these infinitely differentiable functions is a discontinuous function (Heaviside function)

$$H(x) = \int_{-\infty}^{x} \phi_n(t)dt = \begin{cases} 0 & \text{if } x < 0 \\ 1 & \text{if } x > 1 \end{cases}$$

- The limit of the sequence of oscillating functions

$$\lim_{n\to\infty} \sin(nx)$$

  does not exist for any $x \neq 0$.

- The sequence
$$\phi_n(x) = \frac{1}{\sqrt{n}}\sin(nx)$$
converges to zero pointwise, but the limit of the sequence of the derivatives $\phi_n(x)' = \sqrt{n}\cos(nx)$ does exist and the sequence is unbounded everywhere.

These or similar functional sequences often represent minimizing sequences in variational problems. Here we give a brief introduction to several methods aimed to deal with such "exotic" solutions, that do not correspond to solutions of Euler equation.

Regularization and relaxation The possible nonexistence of minimizer poses several challenging questions. Some criteria are needed to establish which problems have a classical solution and which do not. These criteria analyze the type of Lagrangians and result in existence theorems.

There are two alternative ideas in handling problems with nondifferentiable minimizers. The admissible class of minimizers can be enlarged and closed in such a way that the "exotic" limits of minimizers would be included in the admissible set. This procedure called *relaxation* and underlined in the Hilbert's quotation, has motivated the introduction of theory of distributions and the corresponding functional spaces, as well as development of relaxation methods. Below, we consider several ill-posed problems that require rethinking of the concept of a solution.

Alternatively, the minimization problem can be constrained so that the "exotic" behavior of the solutions is penalized and the minimizer will avoid it; this approach is called *regularization*. It forces the problem to select a classical solution at the expense of increasing the value of the objective functional. When the penalization decreases, the solution tends to the solution of the original problem, remaining conventional. An example of this approach is the *viscosity solution* developed for dealing with the shock waves.

1.2 Existence of a differentiable minimizer in a variational problem

We formulate here a list of conditions guarantying the smooth classical solution to a variational problem.

1. The Lagrangian grows superlinearly with respect to u':
$$\lim_{|u'|\to\infty} \frac{F(x,u,u')}{|u'|} = \infty \quad \forall x, u(x) \tag{1}$$
This condition forbids any finite jumps of the optimal trajectory $u(x)$; any such jump leads to an infinite penalty in the problem's cost.

2. The cost of the problem goes to infinity when $|u| \to \infty$. This condition forbids a blow-up of the solution.

3. The Lagrangian is convex with respect to u':

$$F(x,u,u') \quad \text{is a convex function of } u' \quad \forall x, u(x)$$

at the optimal trajectory u. This condition forbids infinite oscillations because they would increase the cost of the problem.

Let us outline the idea of the proof:

1. First two conditions guarantee that the limit of any minimizing sequence is bounded and has a bounded derivative. The cost of the problem goes to infinity when either the function or its derivative tend to infinity at a set of nonzero measure.

2. It is possible to extract a weakly convergent subsequence $u^S \rightharpoonup u^0$ from a weakly bounded minimizing sequence. Roughly, this means that the subsequence $u^\epsilon(x)$ in a sense approximates a limiting function u^0, but may wiggle around it infinitely often.

3. The convexity of $F(.,.,u')$ ensures that a minimizing sequence is not wiggling.

   More exactly, we use the property of *lower weakly semicontinuity* of the objective functional $I(u)$. The lower weakly semicontinuity states that

   $$\lim_{u^S \rightharpoonup u^0} I(u^s) \geq I(u^0)$$

   The following examples illustrate the relation between weak limits:

   Example 1.2 Consider sequence $u^s = \sin(s\,x)$; the weak limit of $\{u^s\}$ is zero. $\sin(s\,x) \rightharpoonup 0 \quad s \to \infty$, or

   $$\lim_{s\to\infty} \int_a^b \psi(x) u^s(x) dx = 0 \quad \forall \psi \in L_1([a,b])$$

   Compute the weak limit of the square of $u^2(x)$

   $$I_1(u^s, \psi) = \int_0^1 (u^s)^2 \psi(x) dx \quad \forall \psi \in L_1([a,b])$$

   We have

   $$\lim_{s\to\infty} \int_0^1 \sin^2(s\,x)\psi(x)dx = \frac{1}{2} \lim_{s\to\infty} \int_0^1 (1-\cos(2s\,x)\psi(x)dx = \frac{1}{2}\int_0^1 \psi(x)dx$$

   and we observe that

   $$\lim_{weak} u^2(x) = \frac{1}{2}$$

   . Therefore,

   $$\lim_{u^S \rightharpoonup u^0} I_1(u^s) > I(u^0) = 0$$

The weak limit of the equence $(u^s)^4 - (u^s)^2$ equals $-\frac{1}{4}$ and is smaller than $I_2(0)$,

$$\lim_{u^s \rightharpoonup u^0} I_2(u^s) < I(u^0) = 0$$

The "wiggling" minimizing sequence u^s increases the value of the first functional and decrease the value of the second. The fist functional corresponds to convex integrand and is weakly lower semicontinuous.

The convexity of Lagrangian eliminates the possibility of wiggling, because the cost of the problem with convex Lagrangian is smaller for a smooth function than on any close-by wiggling function by virtue of Jensen inequality. The functional of a convex Lagrangian is lower weakly semicontinuous.

2 Solutions with an unbounded derivative. Regularization

2.1 Lagrangians of linear growth

A minimizing sequence may tend to a discontinuous function if the Lagrangian growth slowly with the increase of u'. Here we investigate discontinuous solutions of Lagrangians of linear growth. Assume that the Lagrangian F satisfies the limiting equality

$$\lim_{|u'| \to \infty} \frac{F(x, u, u')}{|u'|} \leq \beta u \tag{2}$$

where β is a nonnegative constant.

Considering the scalar case (u is a scalar function), we assume that the minimizing sequence tends to a finite discontinuity (jump) and calculate the impact of it for the objective functional. Let a miniming sequence u^ϵ of differentiable functions tend to a discontinuous at the point x_0 function, as follows

$$\begin{aligned} u^\epsilon(x) &= \phi(x) + \psi^\epsilon(x) \\ \psi^\epsilon(x) &\rightharpoonup \alpha H(x - x_0), \quad \beta \neq 0 \end{aligned}$$

where ϕ is a differentiable function with the bounded everywhere derivative, and H is the Heaviside function.

Assume that functions ψ^ϵ that approximate the jump at the point x_0 are piece-wise linear,

$$\psi^\epsilon(x) = \begin{cases} 0 & \text{if } x < x_0 - \epsilon \\ \frac{\alpha}{\epsilon}(x - x_0 + \epsilon) & \text{if } x_0 - \epsilon \leq x \leq x_0 \\ \alpha & \text{if } x > x_0. \end{cases}$$

The derivative $(\psi^\epsilon)'$ is zero outside of the interval $[x_0 - \epsilon, x_0]$ where it is equal to a constant,

$$\psi' = \begin{cases} 0 & \text{if } x \notin [x_0 - \epsilon, x_0] \\ \frac{\alpha}{\epsilon} & \text{if } x \in [x_0 - \epsilon, x_0] \end{cases}$$

The Lagrangian is computed as

$$F(x,u,u') = \begin{cases} F(x,\phi,\phi') & \text{if } x \notin [x_0-\epsilon, x_0] \\ F\left(x, \phi+\psi^\epsilon, \phi' + \frac{\alpha}{\epsilon}\right) = \frac{\alpha\beta}{\epsilon} + o\left(\frac{1}{\epsilon}\right) & \text{if } x \in [x_0-\epsilon, x_0] \end{cases}$$

Here, we use the condition (2) of linear growth of F.

The variation of the objective functional is

$$\int_a^b F(x,u,u')dx \le \int_a^b F(x,\phi,\phi')dx + \alpha\beta.$$

We observe that the contribution $\alpha\beta$ due to the discontinuity of the minimizer is finite when the magnitude $|\alpha|$ of the jump is finite. Therefore, discontinuous solutions are tolerated in the problems with Lagrangian of linear growth: They do not lead to infinitely large values of the objective functionals. To the contrary, the problems with Lagrangians of superlinear growth $\beta = \infty$ do not allow for discontinuous solution because the penalty is infinitely large.

Remark 2.1 The problems of Geometric optics and minimal surface are or linear growth because the length $\sqrt{1+u'^2}$ linearly depends on the derivative u'. To the contrary, problems of Lagrange mechanics are of quadratic (superlinear) growth because kinetic energy depends of the speed $\dot{q}$ quadratically.

2.2 Examples of discontinuous solutions

Example 2.1 (Discontinuities in problems of geometrical optics) We have already seen in Section ?? that the minimal surface problem

$$I_0 = \min_{u(x)} I(u), \quad I(u) = \int_o^L u\sqrt{1+(u')^2}dx, \quad u(-1)=1, \quad u(1)=1, \tag{3}$$

can lead to a discontinuous solution (Goldschmidt solution)

$$u = -H(x+1) + H(x-1)$$

if L is larger than a threshold.

Particularly, the Goldschmidt solution corresponds to zero smooth component $u(x) = 0$, $x = (a,b)$ and two jumps M_1 and M_2 of the magnitudes $u(a)$ and $u(b)$, respectively. The smooth component gives zero contribution, and the contributions of the jumps are

$$I = \frac{1}{2}\left(u^2(a) + u^2(b)\right)$$

The next example (Gelfand & Fomin) shows that the solution may exhibit discontinuity if the superlinear growth condition is violated even at a single point.

Example 2.2 (Discontinuous extremal and viscosity-type regularization) Consider the minimization problem

$$I_0 = \min_{u(x)} I(u), \quad I(u) = \int_{-1}^{1} x^2 u'^2 dx, \quad u(-1) = -1, \quad u(1) = 1, \tag{4}$$

We observe that $I(u) \geq 0 \ \forall u$, and therefore $I_0 \geq 0$. The Lagrangian is convex function of u', and the third condition is satisfied. However, the second condition is violated in $x = 0$:

$$\lim_{|u'|\to\infty} \left.\frac{x^2 u'^2}{|u'|}\right|_{x=0} = \lim_{|u'|\to\infty} x^2|u'|\Big|_{x=0} = 0$$

The functional is of sublinear growth at only one point $x = 0$.

Let us show that the solution is discontinuous. Assume the contrary, that the solution satisfies the Euler equation $(x^2 u')' = 0$ everywhere. The equation admits the integral

$$\frac{\partial L}{\partial u'} = 2x^2 u' = C.$$

If $C \neq 0$, the value of $I(u)$ is infinity, because then $u' = \frac{C}{2x^2}$, the Lagrangian becomes

$$x^2 u'^2 = \frac{C^2}{x^2} \quad \text{if } C \neq 0.$$

and the integral of Lagrangian diverges. A finite value of the objective corresponds to $C = 0$ which implies that $u_0'(x) = 0$ if $x \neq 0$. Accounting for the boundary conditions, we find

$$u_0(x) = \begin{cases} -1 & \text{if } x < 0 \\ 1 & \text{if } x > 0 \end{cases}$$

and $u_0(0)$ is not defined.

We arrived at the unexpected result that violates the assumptions used when the Euler equation is derived: $u_0(x)$ is discontinuous at $x = 0$ and u_0' exists only in the sense of distributions:

$$u_0(x) = -1 + 2H(x), \quad u_0'(x) = 2\delta(x)$$

This solution delivers absolute minimum ($I_0 = 0$) to the functional, is not differentiable and satisfies the Euler equation in the sense of distributions,

$$\int_{-1}^{1} \frac{d}{dx} \left.\frac{\partial L}{\partial u'}\right|_{u=u_0(x)} \phi(x) dx = 0 \quad \forall \phi \in L_\infty[-1, 1]$$

Regularization A slightly perturb the problem (regularization) yields to the problem that has a classical solution and this solution is close to the discontinuous solution of the original problem. This time, regularization is performed by adding to the Lagrangian a stabilizer, a strictly convex function $\epsilon\rho(u')$ of superlinear growth.

Consider the perturbed problem for the Example 4:

$$I_\epsilon = \min_{u(x)} I_\epsilon(u), \quad I_\epsilon(u) = \int_{-1}^{1} \left(x^2 u'^2 + \epsilon^2 u'^2\right) dx, \quad u(-1) = -1, \quad u(1) = 1, \tag{5}$$

Here, the perturbation $\epsilon^2 u'$ is added to the original Lagrangian $\epsilon^2 u'$; the perturbed Lagrangian is of superlinear growth everywhere.

The first integral of the Euler equation for the perturbed problem becomes

$$(x^2 + \epsilon^2)u' = C, \quad \text{or } du = C\frac{dx}{x^2 + \epsilon^2}$$

Integrating and accounting for the boundary conditions, we obtain

$$u_\epsilon(x) = \left(\arctan \frac{1}{\epsilon}\right)^{-1} \arctan \frac{x}{\epsilon}.$$

When $\epsilon \to 0$, the solution $u_\epsilon(x)$ converges to $u_0(x)$ although the convergence is not uniform at $x = 0$.

Unbounded solutions in constrained problems The discontinuous solution often occurs in the problem where the derivative satisfies additional inequalities $u' \geq c$, but is unbounded. In such problems, the stationary condition must be satisfied everywhere where derivative is not at the constrain, $u' > c$. The next example shows, that the measure of such interval can be infinitesimal.

Example 2.3 (Euler equation is meaningless) Consider the variational problem with an inequality constraint

$$\max_{u(x)} \int_0^\pi u' \sin(x) dx, \quad u(0) = 0, \; u(\pi) = 1, \; u'(x) \geq 0 \; \forall x.$$

The minimizer should either corresponds to the limiting value $u' = 0$ of the derivative or satisfy the stationary conditions, if $u' > 0$. Let $[\alpha_i, \beta_i]$ be a sequence of subintervals where $u' = 0$. The stationary conditions must be satisfied in the complementary set of intervals $(\beta_i, \alpha_{i+1}])$ located between the intervals of constancy. The derivative cannot be zero everywhere, because this would correspond to a constant solution $u(x)$ and would violate the boundary conditions.

However, the minimizer cannot correspond to the solution of Euler equation at any interval. Indeed, the Lagrangian L depends only on x and u'. The first integral $\frac{\partial L}{\partial u'} = C$ of the Euler equation yields to an absurd result

$$\sin(x) = \text{ constant } \quad \forall x \in [\beta_i, \alpha_{i+1}]$$

The Euler equation does not produce the minimizer. Something is wrong!

The objective can be immediately bounded by the inequality

$$\int_0^\pi f(x)g(x)dx \leq \left(\max_{x\in[0,\pi]} g(x)\right) \int_0^\pi |f(x)|dx.$$

that is valid for all functions f and g if the involved integrals exist. We set $g(x) = \sin(x)$ and $f(x) = |f(x)| = u'$ (because u' is nonnegative), account for the constraints

$$\int_0^\pi |f(x)| dx = u(\pi) - u(0) = 1 \quad \text{ and } \max_{x \in [0,\pi]} \sin(x) = 1,$$

and obtain the upper bound

$$I(u) = \int_0^\pi u' \sin(x) dx \leq 1 \quad \forall u.$$

This bound corresponds to the minimizing sequence u_n that tends to a Heaviside function $u_n(x) \to H(x - \pi/2)$. The derivative of such sequence tends to the δ-function, $u'(x) = \delta(x - \pi/2)$. Indeed, immediately check that the bound is realizable, substituting the limit of u_n into the problem

$$\int_0^\pi \delta\left(x - \frac{\pi}{2}\right) \sin(x) dx = \sin\left(\frac{\pi}{2}\right) = 1.$$

The reason for the absence of a stationary solution is the openness of the set of differentiable function. This problem also can be regularized. Here, we show another way to regularization, by imposing an additional pointwise inequality $u'(x) \leq \frac{1}{\gamma}\ \forall x$ (Lipschitz constraint). Because the intermediate values of u' are never optimal, optimal u' alternates the limiting values:

$$u'_\gamma(x) = \begin{cases} 0 & \text{if } x \notin \left[\frac{\pi}{2} - \gamma, \frac{\pi}{2} + \gamma\right], \\ \frac{1}{2\gamma} & \text{if } x \in \left[\frac{\pi}{2} - \gamma, \frac{\pi}{2} + \gamma\right], \end{cases}$$

The objective functional is equal to

$$I(u_\gamma) = \frac{1}{2\gamma} \int_{\frac{\pi}{2}-\gamma}^{\frac{\pi}{2}+\gamma} \sin(x) dx = \frac{1}{\gamma} \sin(\gamma)$$

When γ tends to zero, I_M goas to its limit

$$\lim_{\gamma \to 0} I_\gamma = 1,$$

the length γ of the interval where $u' = \frac{1}{2\gamma}$ goes to zero so that $u'_\gamma(t)$ weakly converges to the δ-function for u', $u'_\gamma(t) \rightharpoonup \delta\left(x - \frac{\pi}{2}\right)$.

This example clearly demonstrates the source of irregularity: The absence of the upper bound for the derivative u'. The constrained variational problems are studied in the control theory; they are are discussed later in Section **??**.

2.3 Regularization by penalization

Regularization as smooth approximation The smoothing out feature of regularization is easy demonstrated on the following example of a quadratic approximation of a function by a smoother one.

Approximate a function $f(x)$ where $x \in \mathcal{R}$, by the function $u(x)$, adding a quadratic stabilizer; this problem takes the form

$$\min_u \int_{-\infty}^{\infty} [\epsilon^2 (u')^2 + (u - f)^2] dx$$

The Euler equation

$$\epsilon^2 u'' - u = -f \tag{6}$$

can be easily solved using the Green function

$$G(x, y) = \frac{1}{2\epsilon} \exp\left(-\frac{|x - y|}{\epsilon}\right)$$

of the operator in the left-hand side of (6). We have

$$u(x) = \frac{1}{2\epsilon} \int_{-\infty}^{\infty} \exp\left(-\frac{|x - y|}{\epsilon}\right) f(y) dy$$

that is the expression of the averaged f. The smaller is ϵ the closer is the average to f.

Quadratic stabilizers Besides the stabilizer $\varepsilon u'^2$, other stabilizers can be considered: The added term εu^2 penalizes for large values of the minimizer, $\varepsilon (u'')^2$ penalizes for the curvature of the minimizer and is insensitive to linearly growing solutions. The stabilizers can be inhomogeneous like $\varepsilon (u - u_{\text{target}})^2$; they force the solution stay close to a target value. The choice of a specific stabilizer depends on the physical arguments (see Tikhonov).

For example, solve the problem with the Lagrangian

$$F = \epsilon^4 (u'')^2 + (u - f(x))^2$$

Show that $u = f(x)$ if $f(x)$ is any polynomial of the order not higher than three. Find an integral representation for $u(f)$ if the function $f(x)$ is defined at the interval $|x| \leq 1$ and at the axis $x \in R$.

2.4 Complement: Regularization of a finite-dimensional linear problem

As the most of variational methods, the regularization has a finite-dimensional analog. It is applicable to the minimization problem of a convex but not strongly convex function which may have infinitely many solutions. The idea of regularization is to slightly perturb the function by small but a strictly convex term; the perturbed problem has a unique solution to matter how small the perturbation is. The numerical advantage of the regularization is the convergence of minimizing sequences.

Let us illustrate ideas of regularization by studying a finite dimensional problem. Consider a linear system

$$Ax = b \tag{7}$$

where A is a square $n \times b$ matrix and b is a known n-vector.

We know from linear algebra that the Fredholm Alternative holds:

- If $\det A \neq 0$, the problem has a unique solution:

$$x = A^{-1}b \quad \text{if } \det A \neq 0 \tag{8}$$

- If $\det A = 0$ and $Ab \neq 0$, the problem has no solutions.

- If $\det A = 0$ and $Ab = 0$, the problem has infinitely many solutions.

In practice, we also deal with an additional difficulty: The determinant $\det A$ may be a "very small" number and one cannot be sure whether its value is a result of rounding of digits or it has a "physical meaning." In any case, the errors of using the formula (8) can be arbitrary large and the norm of the solution is not bounded.

To address this difficulties, it is helpful to restate linear problem (7) as an extremal problem:

$$\min_{x \in R^n} (Ax - b)^2 \tag{9}$$

This problem does have at least one solution, no matter what the matrix A is. This solution coincides with the solution of the original problem (7) when this problem has a unique solution; in this case the cost of the minimization problem (9) is zero. Otherwise, the minimization problem provides "the best approximation" of the non-existing solution.

If the problem (7) has infinitely many solutions, so does problem (9). Corresponding minimizing sequences $\{x^s\}$ can be unbounded, $\|x^s\| \to \infty$ when $s \to \infty$.

In this case, we may select a solution with minimal norm. We use the *regularization*, passing to the perturbed problem

$$\min_{x \in R^n} (Ax - b)^2 + \epsilon x^2$$

The solution of the last problem exists and is unique. Indeed, we have by differentiation

$$(A^T A + \epsilon I)x - A^T b = 0$$

and

$$x = (A^T A + \epsilon I)^{-1} A^T b$$

We mention that

1. The inverse exists since the matrix $A^T A$ is nonnegative defined, and ϵ is positively defined. The eigenvalues of the matrix $(A^T A + \epsilon I)^{-1}$ are not smaller than ϵ^{-1}

2. Suppose that we are dealing with a well-posed problem (7), that is the matrix A is not degenerate. If $\epsilon \ll 1$, the solution approximately is $x = A^{-1}b - \epsilon(A^2 A^T)^{-1} b$ When $\epsilon \to 0$, the solution becomes the solution (8) of the unperturbed problem, $x \to A^{-1}b$.

3. If the problem (7) is ill-posed, the norm of the solution of the perturbed problem is still bounded:
$$\|x\| \leq \frac{1}{\epsilon}\|b\|$$

Remark 2.2 Instead of the regularizing term ϵx^2, we may use any positively define quadratic $\epsilon(x^T P x + p^T x)$ where matrix P is positively defined, $P > 0$, or other strongly convex function of x.

3 Infinitely oscillatory solutions: Relaxation

3.1 Nonconvex Variational Problems.

Consider the variational problem

$$\inf_u J(u), \quad J(u) = \inf_u \int_0^1 F(x, u, u')dx, \quad u(0) = a_0, \ u(1) = a_1 \tag{10}$$

with Lagrangian $F(x, \boldsymbol{y}, \boldsymbol{z})$ and assume that the Lagrangian is nonconvex with respect to $\boldsymbol{z}$, for some values of z, $z \in \mathcal{Z}_{\mathrm{f}}$.

Definition 3.1 We call the *forbidden region* $\mathcal{Z}_{\mathrm{f}}$ the set of $\boldsymbol{z}$ for which $F(x, \boldsymbol{y}, \boldsymbol{z})$ is not convex with respect to $\boldsymbol{z}$.

The Weierstrass test requires that the derivative u' of an extremal never assume values in the set $\mathcal{Z}_{\mathrm{f}}$,
$$u' \notin \mathcal{Z}_{\mathrm{f}}. \tag{11}$$
On the other hand, a stationary trajectory u may be required by Euler equations to pass through this set. Such trajectories fail the Weierstrass test and must be rejected. We conclude that the true minimizer (the limit of a minimizing sequence) is not a classical differentiable curve, otherwise it would satisfy both the Euler equation and the Weierstrass test.

We will demonstrate that a minimizing sequence tends to a “generalized curve.” It consists of infinitely many infinitesimal zigzags. The derivative of the minimizer ”jumps over” the forbidden set, and does it infinitely often. Because of these jumps, the derivative of a minimizer stays outside of the forbidden interval but its average can take any value within or outside the forbidden region. The limiting curve – the minimizer – has a dense set of points of discontinuity of the derivative.

Example of a nonconvex problem Consider a simple variational problem that yields to an irregular solution [**?**]:

$$\inf_u I(u) = \inf_u \int_0^1 G(u, u')dx, \quad u(0) = u(1) = 0 \tag{12}$$

where

$$G(u,v) = u^2 + \begin{cases} (v-1)^2, & \text{if} \quad v \geq \frac{1}{2} & \text{Regime 1} \\ \frac{1}{2} - v^2 & \text{if} \quad -\frac{1}{2} \leq v \leq \frac{1}{2} & \text{Regime 2} \\ (v+1)^2 & \text{if} \quad v \leq -\frac{1}{2} & \text{Regime 3} \end{cases} . \tag{13}$$

The graph of the function $G(.,v)$ is presented in **??**B; it is a nonconvex differentiable function of v of superlinear growth.

The Lagrangian G penalizes the trajectory u for having the speed $|u'|$ different from ± 1 and penalizes the deflection of the trajectory u from zero. These contradictory requirements cannot be resolved in the class of classical trajectories.

Indeed, a differentiable minimizer satisfies the Euler equation (**??**) that takes the form

$$\begin{array}{ll} u'' - u = 0 & \text{if} \quad |u'| \geq \frac{1}{2} \\ u'' + u = 0 & \text{if} \quad |u'| \leq \frac{1}{2}. \end{array} \tag{14}$$

The Weierstrass test additionally requires convexity of $G(u,v)$ with respect to v; the Lagrangian $G(u,v)$ is nonconvex in the interval $v \in (-1,\ 1)$ (see **??**). The Weierstrass test requires the extremal (14) to be supplemented by the constraint (recall that $v = u'$)

$$u' \notin (-1,\ 1) \quad \text{at the optimal trajectory.} \tag{15}$$

The second regime in (14) is never optimal because it is realized inside of the forbidden interval. It is not clear how to satisfy both the Euler equations and Weierstrass test because the Euler equation does not have a freedom to change the trajectory to avoid the *forbidden interval*.

We can check that the stationary trajectory can be broken at any point. The Weierstrass-Erdman condition (**??**) (continuity of $\frac{\partial L}{\partial u'}$) must be satisfied at a point of the breakage. This condition permits switching between the first ($u' > 1/2$) and third ($u' < -1/2$) regimes in (13) when

$$\left[\frac{\partial L}{\partial u'}\right]_-^+ = 2\left(u'_{(1)} - 1\right) - 2\left(u'_{(3)} + 1\right) = 0$$

or when

$$u'_{(1)} = 1, \quad u'_{(3)} = -1$$

which means the switching from one end of the forbidden interval $(-1,1)$ to another.

Remark 3.1 Observe, that the easier verifiable Legendre condition $\frac{\partial^2 F}{\partial (u')^2} \geq 0$ gives a twice smaller forbidden region $|u'| \leq \frac{1}{2}$ and is not in the agreement with Weierstrass-Erdman condition. One should always use stronger conditions!

Minimizing sequence The minimizing sequence for problem (12) can be immediately constructed. Indeed, the infimum of (12) obviously is nonnegative, $\inf_u I(u) \geq 0$. Therefore, any sequence u^s with the property

$$\lim_{s\to\infty} I(u^s) = 0 \tag{16}$$

is a minimizing sequence.

Consider a set of functions $\tilde{u}^s(x)$ with the derivatives equal to ± 1 at each point,

$$\tilde{u}'(x) = \pm 1 \quad \forall x.$$

These functions belong to the boundary of the *forbidden interval* of the nonconvexity of $G(.,v)$; they make the second term in the Lagrangian (13) vanish, $G(\tilde{u}, \tilde{u}') = u^2$, and the problem becomes

$$I(\tilde{u}^s, (\tilde{u}^s)') = \min_{\tilde{u}} \int_0^1 (\tilde{u}^s)^2 dx. \tag{17}$$

The sequence $\tilde{u}^s$ oscillates near zero if the derivative $(\tilde{u}^s)'$ changes its sign on intervals of equal length. The cost $I(\tilde{u}^s)$ depends on the density of switching points and tends to zero when the number of these points increases (see **??**). Therefore, the minimizing sequence consists of the saw-tooth functions $\tilde{u}^s$; the heights of the teeth tend to zero and their number tends to infinity as $s \to \infty$.

Note that the minimizing sequence $\{\tilde{u}^s\}$ does not converge to any classical function. This minimizer $\tilde{u}^s(x)$ satisfies the contradictory requirements, namely, the derivative must keep the absolute value equal to one, but the function itself must be arbitrarily close to zero:

$$|(\tilde{u}^s)'| = 1 \quad \forall x \in [0,1], \qquad \max_{x\in[0,1]} \tilde{u}^s \to 0 \quad \text{as } s \to \infty. \tag{18}$$

The limiting curve u_0 has zero norm in $C_0[0,\ 1]$ but a finite norm in $C_1[0,\ 1]$.

Remark 3.2 Below, we consider this problem with arbitrary boundary values; the solution corresponds partly to the classical extremal (14), (15), and partly to the saw-tooth curve; in the last case u' belongs to the boundary of the forbidden interval $|u'| = 1$.

Regularization and relaxation We may apply regularization to discourage the solution to oscillate infinitely often. For example, we may penalize for the discontinuity of the u' adding the stabilizing term $\epsilon(u'')^2$ to the Lagrangian. Doing this, we pass to the problem

$$\min_u \int_0^1 (\epsilon^2 (u'')^2 + G(u, u'))dx$$

that corresponds to Euler equation:

$$\begin{array}{ll} \epsilon^2 u^{IV} - u'' + u = 0 & \text{if} \quad |u'| \geq \frac{1}{2} \\ \epsilon^2 u^{IV} + u'' + u = 0 & \text{if} \quad |u'| \leq \frac{1}{2}. \end{array} \tag{19}$$

The Weierstrass condition this time requires the convexity of the Lagrangian with respect to u''; this condition is satisfied.

One can see that the solution of equation (19) is oscillatory; the period of oscillations is of the order of $\epsilon \ll 1$: The solution still tends to an infinitely often oscillating distribution. When ϵ is positive but small, the solution has finite but large number of wiggles. The computation of such solutions is difficult and often unnecessary: It strongly depends on an artificial parameter ϵ, which is difficult to justify physically. Although formally the solution of regularized problem exists, the questions remain. The problem is still computationally difficult and the difficulty grows when $\epsilon \to 0$ because the finite frequency of the oscillation of the solution tends to infinity.

Below we describe the relaxation of a nonconvex variational problem. The idea of relaxation is in a sense opposite to regularization. Instead of penalization for fast oscillations, we admit oscillating functions as legitime minimizers enlarging set of minimizers. The main problem is to find an adequate description of infinitely often switching controls in terms of smooth functions. It turns out that the limits of oscillating minimizers allows for a parametrization and can be effectively described by a several smooth functions: the values of alternating limits for u' and the average time that minimizer spends on each limit. The relaxed problem has the following two basic properties:

- The relaxed problem has a classical solution.
- The infimum of the functional (the cost of the problem) in the initial problem coincides with the cost of the relaxed problem.

Here we will demonstrate two approaches to relaxation based on necessary and sufficient conditions. Each of them yields to the same construction but uses different arguments to achieve it. In the next chapters we will see similar procedures applied to variational problems with multiple integrals; sometimes they also yield the same construction, but generally they result in different relaxations.

3.2 Minimal Extension

We introduce the idea of relaxation of a variational problem. Consider the class of Lagrangians $\mathcal{N}F(x,y,z)$ that are smaller than $F(x,y,z)$ and satisfy the Weierstrass test $\mathcal{W}(\mathcal{N}F(x,y,z)) \geq 0$:

$$\begin{cases} \mathcal{N}F(x,y,z) - F(x,y,z) \leq 0, \\ \mathcal{W}(\mathcal{N}F(x,y,z)) \geq 0 \end{cases} \quad \forall\ x,y,z. \tag{20}$$

Let us take the maximum on $\mathcal{N}F(x,y,z)$ and call it $\mathcal{S}F$. Clearly, $\mathcal{S}F$ corresponds to turning one of these inequalities into an equality:

$$\begin{array}{llll} \mathcal{S}F(x,y,z) = F(x,y,z), & \mathcal{W}(\mathcal{S}F(x,y,z)) \geq 0 & \text{if} & z \notin \mathcal{Z}_{\text{f}}, \\ \mathcal{S}F(x,y,z) \leq F(x,y,z), & \mathcal{W}(\mathcal{S}F(x,y,z)) = 0 & \text{if} & z \in \mathcal{Z}_{\text{f}}. \end{array} \tag{21}$$

This variational inequality describes the extension of the Lagrangian of an unstable variational problem. Notice that

1. The first equality holds in the region of convexity of F and the extension coincides with F in that region.
2. In the region where F is not convex, the Weierstrass test of the extended Lagrangian is satisfied as an equality; this equality serves to determine the extension.

These conditions imply that $\mathcal{S}F$ is convex everywhere. Also, $\mathcal{S}F$ is the maximum over all convex functions that do not exceed F. Again, $\mathcal{S}F$ is equal to the convex envelope of F:

$$\mathcal{S}F(x, y, z) = \mathcal{C}_z F(x, y, z). \tag{22}$$

The cost of the problem remains the same because the convex envelope corresponds to a minimizing sequence of the original problem.

Remark 3.3 Note that the geometrical property of convexity never explicitly appears here. We simply satisfy the Weierstrass necessary condition everywhere. Hence, this relaxation procedure can be extended to more complicated multidimensional problems for which the Weierstrass condition and convexity do not coincide.

Recall that the derivative of the minimizer never takes values in the region $\mathcal{Z}_{\mathrm{f}}$ of nonconvexity of F. Therefore, a solution to a nonconvex problem stays the same if its Lagrangian $F(x, \boldsymbol{y}, \boldsymbol{z})$ is replaced by any Lagrangian $\mathcal{N}F(x, \boldsymbol{y}, \boldsymbol{z})$ that satisfies the restrictions

$$\begin{aligned} \mathcal{N}F(x, \boldsymbol{y}, \boldsymbol{z}) &= F(x, \boldsymbol{y}, \boldsymbol{z}) \quad \forall\ z \notin \mathcal{Z}_{\mathrm{f}}, \\ \mathcal{N}F(x, \boldsymbol{y}, \boldsymbol{z}) &> \mathcal{C}F(x, \boldsymbol{y}, \boldsymbol{z}) \ \forall\ z \in \mathcal{Z}_{\mathrm{f}}. \end{aligned} \tag{23}$$

Indeed, the two Lagrangians $F(x, \boldsymbol{y}, \boldsymbol{z})$ and $\mathcal{N}F(x, \boldsymbol{y}, \boldsymbol{z})$ coincide in the region of convexity of F. Therefore, the solutions to the variational problem also coincide in this region. Neither Lagrangian satisfies the Weierstrass test in the forbidden region of nonconvexity. Therefore, no minimizer can distinguish between these two problems: It never takes values in Z_{f}. The behavior of the Lagrangian in the forbidden region is simply of no importance. In this interval, the Lagrangian cannot be computed back from the minimizer.

Minimizing Sequences Let us prove that the considered extension preserves the value of the objective functional. Consider the extremal problem (10) of superlinear growth and the corresponding stationary solution $u(x)$ that may not satisfy the Weierstrass test. Let us perturb the trajectory u by a differentiable function $\omega(x)$ with the properties:

$$\max_x |\omega(x)| \le \varepsilon, \quad \omega(x_k) = 0 \ k = 1 \dots N \tag{24}$$

where the points x_k uniformly cover the interval (a, b). The perturbed trajectory wiggles around the stationary one, crossing it at N uniformly distributed points x_k; the derivative of the perturbation is not bounded.

The integral $J(u, \omega)$

$$J(u, \omega) = \int_0^1 F(x, u+\omega, u'+\omega')dx$$

on the perturbed trajectory is estimated as

$$J(u, \omega) = \int_0^1 F(x, u, u'+\omega')dx + o(\varepsilon).$$

because of the smallness of ω (see (24)). The derivative $\omega'(x) = v(x)$ is a new minimizer constrained by N conditions (see (24))

$$\int_{\frac{k}{N}}^{\frac{k+1}{N}} v(x)dx = 0, \quad k = 0, \dots N-1; \tag{25}$$

correspondingly, the variational problem can be rewritten as

$$J(u, \omega) = \sum_{k=1}^{N-1} \int_{\frac{k}{N}}^{\frac{k+1}{N}} F(x, u, u'+\omega')dx + o\left(\frac{1}{N}\right).$$

Perform minimization of a term of the above sum with respect of v, treating u as a fixed variable:

$$I_k(u) = \min_{v(x)} \int_{\frac{k}{N}}^{\frac{k+1}{N}} F(x, u, u'+v)dx \quad \text{subject to} \quad \int_{\frac{k}{N}}^{\frac{k+1}{N}} v(x)dx = 0$$

This is exactly the problem (**??**) of the convex envelope with respect to v.

By referring to the Carathéodory theorem (**??**) we conclude that the minimizer $v(x)$ is a piece-wise constant function in $(\frac{k}{N}, \frac{k+1}{N})$ that takes at most $n+1$ values $v_1, \dots v_{n+1}$ at each interval. These values are subject to the constraints (see (25))

$$m_i(x) \geq 0, \quad \sum_{i=1}^{n} m_i = 1, \quad \sum_{i=1}^{p} m_i \boldsymbol{v}_i = 0. \tag{26}$$

This minimum coincides with the convex envelope of the original Lagrangian with respect to its last argument (see (**??**)):

$$I_k = \min_{m_i, \boldsymbol{v}_i \in (26)} \frac{1}{N} \left(\sum_{i=1}^{p} m_i F(x, \boldsymbol{u}, u' + \boldsymbol{v}_i) \right) \tag{27}$$

Summing I_k and passing to the limit $N \to \infty$, we obtain the relaxed variational problem:

$$I = \min_{\boldsymbol{u}} \int_0^1 \mathcal{C}_{\boldsymbol{u}'} F\left(x, \boldsymbol{u}(x), \boldsymbol{u}'(x)\right) dx. \tag{28}$$

Note that $n+1$ constraints (26) leave the freedom to choose $2n+2$ inner parameters m_i and $\boldsymbol{v}_i$ to minimize the function $\sum_{i=1}^{p} m_i F(u, \boldsymbol{v}_i)$ and thus to

Average derivative	Pointwise derivatives	Optimal concentrations	Convex envelope $\mathcal{C}G(u,v)$
$v<-1$	$v_1^0=v_2^0=v$	$m_1^0=1,\ m_2^0=0$	$u^2+(v-1)^2$
$\vert v\vert<1$	$v_1^0=1, v_2^0=-1$	$m_1^0=m_2^0=\frac{1}{2}$	u^2
$v>1$	$v_1^0=v_2^0=v$	$m_1^0=0,\ m_2^0=1$	$u^2+(v+1)^2$

Table 1: Characteristics of an optimal solution in Example **??**.

minimize the cost of the variational problem (see (27)). If the Lagrangian is convex, $\boldsymbol{v}_i=0$ and the problem keeps its form: The wiggle trajectories do not minimize convex problems.

The cost of the reformulated (relaxed) problem (28) corresponds to the cost of the problem (10) on the minimizing sequence (**??**). Therefore, the cost of the relaxed problem is equal to the cost of the original problem (10). The extension of the Lagrangian that preserves the cost of the problem is called the *minimal extension.* The minimal extension enlarges the set of classical minimizers by including generalized curves in it.

3.3 Examples

Relaxation of nonconvex problem in Example ?? We revisit Example **??**. Let us solve this problem by building the convex envelope of the Lagrangian $G(u,v)$:

$$\begin{aligned} \mathcal{C}_v G(u,v) &= \min_{m_1,m_2}\min_{v_1,v_2}\left\{u^2+m_1(v_1-1)^2+m_2(v_2+1)^2\right\}, \\ v &= m_1v_1+m_2v_2, \quad m_1+m_2=1, \quad m_i\geq 0. \end{aligned} \tag{29}$$

The form of the minimum depends on the value of $v=u'$. The convex envelope $\mathcal{C}G(u,v)$ coincides with either $G(u,v)$ if $v\notin[0,\ 1]$ or $\mathcal{C}G(u,v)=u^2$ if $v\in[0,\ 1]$; see Example **??**. Optimal values $v_1^0,\ v_2^0,\ m_1^0\ m_2^0$ of the minimizers and the convex envelope $\mathcal{C}G$ are shown in Table 1. The relaxed form of the problem with zero boundary conditions

$$\min_u \int_0^1 \mathcal{C}G(u,\ u')dx, \quad u(0)=u(1)=0, \tag{30}$$

has an obvious solution,

$$u(x)=u'(x)=0, \tag{31}$$

that yields the minimal (zero) value of the functional. It corresponds to the constant optimal value m_{opt} of $m(x)$:

$$m_{\text{opt}}(x)=\frac{1}{2}\ \forall x\in[0,1]$$

.

The relaxed Lagrangian is minimized over four functions u, m_1, v_1, v_2 bounded by one equality, $u' = m_1 v_1 + (1-m_1)v_2$ and the inequalities $0 \le m \le 1$, while the original Lagrangian is minimized over one function u. In contrast to the initial problem, the relaxed one has a differentiable solution in terms of these four controls.

Inhomogeneous boundary conditions Let us slightly modify this example. Assume that boundary conditions are

$$u(0) = V \ (0 < V < 1), \quad u(1) = 0$$

In this case, an optimal trajectory of the relaxed problem consists of two parts,

$$u' < -1 \quad \text{if } x \in [0, x_0), \quad u = u' = 0 \quad \text{if } x \in [x_0, 1]$$

At the first part of the trajectory, the Euler equation $u'' - u = 0$ holds; the extremal is

$$u = \begin{cases} Ae^x + Be^{-x} & \text{if } x \in [0, x_0) \\ 0 & \text{if } x \in [x_0, 1] \end{cases}$$

Since the contribution of the second part of the trajectory is zero, the problem becomes

$$I = \min_{u, x_0} \int_O^{x_0} \mathcal{C}_v G(u, u') dx$$

To find unknown parameters A, B and x_0 we use the conditions

$$u(0) = V, \quad u(x_0) = 0, \quad u' = -1$$

The last condition expresses the optimality of x_0, it is obtained from the condition (see (**??**))

$$\mathcal{C}_v G(u, u')|_{x=x_0} = 0.$$

We compute

$$A + B = V, \quad Ae^{x_0} + Be^{-x_0} = 0, \quad Ae^x - Be^{-x} = 1$$

which leads to

$$u(x) = \begin{cases} \sinh(x - x_0) & \text{if } x < x_0, \\ 0 & \text{if } x > x_0, \end{cases}$$
$$x_0 = \sinh^{-1}(V)$$

The optimal trajectory of the relaxed problem decreases from V to zero and then stays equal zero. The optimal trajectory of the actual problem decays to zero and then become infinite oscillatory with zero average.

Relaxation of a two-wells Lagrangian We turn to a more general example of the relaxation of an ill-posed nonconvex variational problem. This example highlights more properties of relaxation. Consider the minimization problem

$$\min_{u(x)} \int_0^z F_p(x, u, u')dx, \quad u(0) = 0, \ u'(z) = 0 \tag{32}$$

with a Lagrangian

$$F_p = (u - \alpha x^2)^2 + F_n(u'), \tag{33}$$

where

$$F_n(v) = \min\{a\, v^2, \ b\, v^2 + 1\}, \quad 0 < a < b, \ \alpha > 0.$$

Note that the second term F_n of the Lagrangian F_p is a nonconvex function of u'.

The first term $(u - \alpha x^2)^2$ of the Lagrangian forces the minimizer u and its derivative u' to increase with x, until u' at some point reaches the interval of nonconvexity of $F_n(u')$, after which it starts oscillating by alternation of the values of the ends of this interval, because u' must vary outside of this forbidden interval at every instance. (see **??**)

To find the convex envelope $\mathcal{C}F$ we must transform $F_n(u')$ (in this example, the first term of F_p (see (33)) is independent of u' and it does not change after the convexification). The convex envelope $\mathcal{C}F_p$ is equal to

$$\mathcal{C}F_p = (u - \alpha x^2)^2 + \mathcal{C}F_n(u'). \tag{34}$$

The convex envelope $\mathcal{C}F_n(u')$ is computed in Example **??** (where we use the notation $v = u'$). The relaxed problem has the form

$$\min_u \int \mathcal{C}F_p(x, u, u')dx, \tag{35}$$

where

$$\mathcal{C}F_p(x, u, u') = \begin{cases} (u - \alpha x^2)^2 + a(u')^2 & \text{if} \ \ |u'| \le v_1, \\ (u - \alpha x^2)^2 + 2u'\sqrt{\frac{ab}{a-b}} - \frac{b}{a-b} & \text{if} \ \ v_1 \le |u'| \le v_2, \\ (u - \alpha x^2)^2 + b(u')^2 + 1 & \text{if} \ \ |u'| \ge v_2. \end{cases}$$

Note that the variables $u, \ v$ in the relaxed problem are the averages of the original variables; they coincide with those variables everywhere when $\mathcal{C}F = F$. The Euler equation of the relaxed problem is

$$\begin{aligned} au'' - (u - \alpha x^2) = 0 & \ \ \text{if} \ \ |u'| \le v_1, \\ (u - \alpha x^2) = 0 & \ \ \text{if} \ \ v_1 \le |u'| \le v_2, \\ bu'' - (u - \alpha x^2) = 0 & \ \ \text{if} \ \ |u'| \ge v_2. \end{aligned} \tag{36}$$

The Euler equation is integrated with the boundary conditions shown in (32). Notice that the Euler equation degenerates into an algebraic equation in the interval of convexification. The solution u and the variable $\frac{\partial}{\partial u'}\mathcal{C}F$ of the relaxed problem are both continuous everywhere.

Integrating the Euler equations, we sequentially meet the three regimes when both the minimizer and its derivative monotonically increase with x (see **??**). If the length z of the interval of integration is chosen sufficiently large, one can be sure that the optimal solution contains all three regimes; otherwise, the solution may degenerate into a two-zone solution if $u'(x) \leq v_2 \ \forall x$ or into a one-zone solution if $u'(x) \leq v_1 \ \forall x$ (in the last case the relaxation is not needed; the solution is a classical one).

Let us describe minimizing sequences that form the solution to the relaxed problem. Recall that the actual optimal solution is a generalized curve in the region of nonconvexity; this curve consists of infinitely often alternating parts with the derivatives v_1 and v_2 and the relative fractions $m(x)$ and $(1 - m(x))$:

$$v = \langle u'(x) \rangle = m(x) v_1 + (1 - m(x)) v_2, \quad u' \in [v_1, v_2], \tag{37}$$

where $\langle \ \rangle$ denotes the average, u is the solution to the original problem, and $\langle u \rangle$ is the solution to the homogenized (relaxed) problem.

The Euler equation degenerates in the second region into an algebraic one $\langle u \rangle = \alpha x^2$ because of the linear dependence of the Lagrangian on $\langle u \rangle'$ in this region. The first term of the Euler equation,

$$\frac{d}{dx} \frac{\partial F}{\partial \langle u \rangle'} \equiv 0 \quad \text{if} \ \ v_1 \leq | \langle u \rangle' | \leq v_2, \tag{38}$$

vanishes at the optimal solution.

The variable m of the generalized curve is nonzero in the second regime. This variable can be found by differentiation of the optimal solution:

$$(\langle u \rangle - \alpha x^2)' = 0 \quad \Longrightarrow \quad \langle u \rangle' = 2\alpha x. \tag{39}$$

This equality, together with (37), implies that

$$m = \begin{cases} 0 & \text{if} \ \ |u'| \leq v_1, \\ \frac{2\alpha}{v_1 - v_2} x - \frac{v_2}{v_1 - v_2} & \text{if} \ \ v_1 \leq |u'| \leq v_2, \\ 1 & \text{if} \ \ |u'| \geq v_2. \end{cases} \tag{40}$$

Variable m linearly increases within the second region (see **??**). Note that the derivative u' of the minimizing generalized curve at each point x lies on the boundaries v_1 or v_2 of the forbidden interval of nonconvexity of F; the average derivative varies only due to varying of the fraction $m(x)$ (see **??**).