Partial Differential Equations I

January 8, 2024

Homework

Assigned exercises and concept maps. Graded by completion.

Presentations

Assigned topics; responsible for giving a class.

Definition: Partial Differential Equation(s) (PDE)

An identity relating an uknown function, its partial derivatives and its variables.

$$F(D^k u, \dots, D^2 u, Du, u, x) = 0, \quad x \in U \subseteq \mathbb{R}^n$$

where U is an open subset of $\mathbb{R}^n$, $u : U \subset \mathbb{R}^n \to \mathbb{R}$, $Du = (\partial_{x_1} u_1, \dots, \partial_{x_n} u)$.
Then $F : \mathbb{R}^{n^k} \times \cdots \times \mathbb{R}^n \times \mathbb{R} \times \mathbb{R}^n \to \mathbb{R}$, where F is given.
$x = (x_1 \dots, x_n)$ is (are) the independent variable(s).
u is the unknown function or dependent variable.
k is the order of the PDE.

Goal

Given a PDE, we consider

- Existence
- Uniqueness
- Stability

Recall: Multiindex Notation

$\alpha = (\alpha_1, \dots, \alpha_n)$ a vector such that $\alpha_i \in \mathbb{Z}_{\geq 0}$.
Then we say that α is a multiindex with order $|\alpha| = \alpha_1 + \cdots + \alpha_n$.

Notation

$u : U \subseteq \mathbb{R}^n \to \mathbb{R}$, $\alpha = (\alpha_1, \dots, \alpha_n)$.
$u^\alpha := D^\alpha u = \partial_{x_n}^{\alpha_n} \cdots \partial_{x_1}^{\alpha_1} u$, where $\partial^0 u = u$.

Definition: Linear Partial Differential Equation

A linear PDE of order k is of the form

$$(*) \sum_{|\alpha| = k} a_\alpha(x) D^\alpha u = f(x)$$

Remark

This means that F is multilinear in the first $n^k + n^{k-1} + \cdots$ variables.

Definition: Homogeneous Linear Partial Differential Equation

A linear given by $(*)$ is homogeneous if $f(x) \equiv 0$.
Otherwise, it is non-homogeneous.

Example 1: Linear Transport Equation

$$\nabla u \cdot (1, b) = u_t + b \cdot Du = f(t, x)$$

This is a linear PDE of order 1 on $\mathbb{R} \times \mathbb{R}^n \equiv \mathbb{R}^{n+1}$ where (t, x) are independent variables and u is dependent.
Here, x is the spatial variable while t is time and Du represents the gradient.
$\nabla u = (\partial_t u, \nabla u)$, $b \cdot Du = \sum_{i=1}^n b_i \partial_{x_i} u$, $(b_1, \ldots, b_n) \in \mathbb{R}^n$ is fixed.

Example 2: Laplace Equation

$$\Delta u := \sum_{i=1}^{n} \partial_{x_i} u = 0$$

This is a linear, homogeneous PDE of order 2.

Example 3: Poisson Equation

$-\Delta u := f(u)$
This is a nonlinear PDE of order 2.
Consider $f(u) = u^2$.

Example 4: Heat Equation (Diffusion Equation)

$$u_t - \Delta u = 0$$

This is a linear, homogeneous PDE of order 2.

Example 5: Wave Equation

$$u_{tt} - \Delta u = 0$$

This is a linear, homogeneous PDE of order 2.

Transport Equation

$u : \mathbb{R}^n (0, \infty) \to \mathbb{R}$ given by

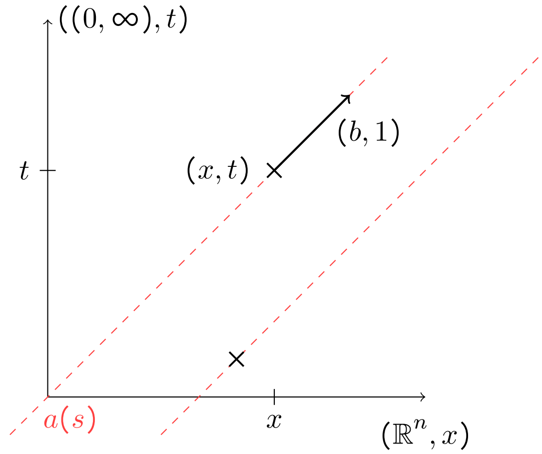
$$u_t + b \cdot Du = 0, \quad b \in \mathbb{R}^n$$

In order to get a solution, first assume that ther exists a “nice” (e.g. smooth, C^1, differentiable, etc.) solution.

Step 1

Notice that the PDE is equivalent to

$$\nabla u \cdot (b, 1) = 0$$



Step 2

Consider a curve on $\mathbb{R}^{n+1}$ with velocity $(1,b)$ which passes through (x,t). i.e.

$$\alpha(s) = (x+sb, t+s)$$

Notice $\alpha'(s) = (b,1)$.
Then, let us study u along the curve $\alpha(s)$.

$$z(s) := u(\alpha(s))$$

Taking the derivative with respect to s,

$$z'(s) := \frac{d}{ds}(u \circ \alpha(s)) = \nabla u|_{\alpha(s)} \cdot \alpha'(s) = \nabla u|_{\alpha(s)} \cdot (b,1) = 0$$

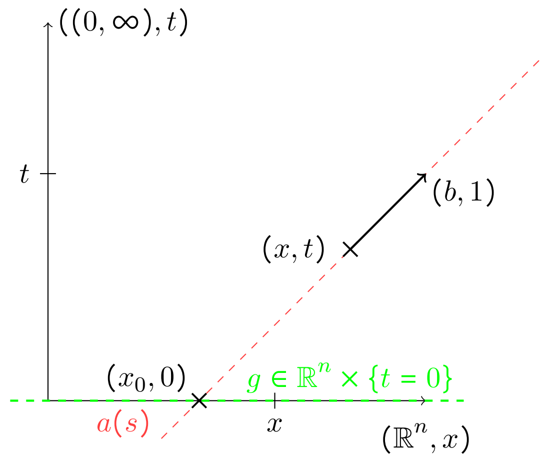
That is $z'(s) = 0$, $z(s)$ is constant, and u along $\alpha(s)$ is constant.

Conclusion

If we know some value of u along $\alpha(s)$, then we know all values along $\alpha(s)$.
If we have some value of u along every $\alpha(s)$, then we know u on $\mathbb{R}^n \times (0,\infty)$.

Transport Equation - Homogeneous Initial Value Problem

$$(*)\begin{cases} \nabla u \cdot (b,1) = 0, & \mathbb{R}^n \times (0,\infty) \\ u = g, & \mathbb{R}^n \times \{t=0\} \end{cases}$$



Here, $g : \mathbb{R}^n \to \mathbb{R}$ is given.
Consider (x,t); we want to find $(x_0, 0)$.
We know $\alpha(s) = (x+sb, t+s) = (x_0, 0)$, therefore

$$\begin{cases} x + sb = x_0 & (1) \\ t + s = 0 \implies s = -t & (2) \end{cases}$$

Then, by replacing (2) in (1),

$$x_0 = x - tb$$

Then from the conclusion

$$u(x,t) = u(x_0, 0) = g(x_0) = g(x - tb)$$

Therfore, $u(x,t) := g(x-tb)$ (♥).

Remark

1. If there exists a regular (differentiable or C^1) solution u for $*$, then u should look like ♥.

2. If g is (differentiable or C^1), then u defined by ♥ is a (differentiable or C^1) solution for my problem.

Homework

Show that ♥ satisfies $*$.

Transport Equation - Non-homogeneous Initial Value Problem

$$(*) \begin{cases} \nabla u \cdot (b, 1) = f(x,t), \quad \mathbb{R}^n \times (0, \infty) \\ u = g, \quad \mathbb{R}^n \times \{t = 0\} \end{cases}$$

Where $g : \mathbb{R}^n \to \mathbb{R}$ and $f : \mathbb{R}^n \times (0,\infty) \to \mathbb{R}$ are given.

Solution

Notice that the PDE is equivalent to

$$\nabla u \cdot (b, 1) = f(x,t)$$

Define the "characteristic curve"

$$\alpha(s) = (x + sb, t + s)$$

and

$$z(s) := u(\alpha(s))$$

Taking $\frac{d}{ds}$,

$$z'(s) = \nabla u|_{\alpha(s)} \cdot (b,1) = f(\alpha(s)) \implies z'(s) = f(x+sb, t+s)\ (c)$$

Notice that c is an ordinary differential equation. Integrating from $-t$ to 0.

$$\begin{aligned}\int_{-t}^{0} z'(s)\, ds &= \int_{-t}^{0} f(x+sb, t+s)\, ds \\ z(0) - z(-t) &= \int_{-t}^{0} f(x+sb, t+s)\, ds\end{aligned}$$

Notice that $z(0) = u(x,t)$ and $z(-t) = u(\alpha(-t)) = u(x-tb, 0)$.

$$u(x,t) = u(x-tb,0) + \int_{-t}^{0} f(x+sb, t+s)\, ds$$

Then

$$\begin{aligned}u(x,t) &= g(x-tb,0) + \int_{-t}^{0} f(x+sb,t+s)\, ds \\ &\underset{\bar{s}=s+t}{=} g(x-tb,0) + \int_{0}^{t} f(x+(\bar{s}-t)b, \bar{s})\, d\bar{s} \\ &= g(x-tb,0) + \int_{0}^{t} f(x+(s-t)b, s)\, ds\end{aligned}$$

Remark: Method of Characteristics

Try to vert the PDE into an ODE and solve using characteristic curves.

January 10, 2024

Definition: Harmonic Function

If $u \in C^2$ such that $\Delta u = 0$, then u is a harmonic function.

Laplace Equation

Consider $u : U \subseteq \mathbb{R}^n \to \mathbb{R}$ with U open, then the homogeneous (Laplace) form is given by

$$\Delta u = 0$$

and the non-homogeneous (Poisson) form is

$$-\Delta u = f$$

where $f : \mathbb{R}^n \to \mathbb{R}$ is given.

Remark / Exercise

The Laplace equation is invariant under translation and rotation.
That is, if $\Delta u(x) = 0$ and $v(x) = u(x-y)$, then $\Delta v = 0$.
Similarly, if $w(x) = u(O(x))$ then $\Delta w = 0$ where O is an orthogonal matrix.

Fundamental Solution of the Laplace Equation

Remark: since the Laplace equation is invariant under rotation, we can consider a function in terms of the radius $v(x) = v(|x|)$.
Recall $r = |x| = (x_1^2 + \cdots + x_n^2)^{1/2}$.
Because of this remark, assume that $u(x) = v(|x|) = v(r(x)) \quad (*)$ where $v : (0, \infty) \to \mathbb{R}$.
Therefore, we need

$$\frac{\partial r}{\partial x_i} = \frac{1}{2} \cdot \frac{2x_i}{(x_1^2 + \cdots + x_n^2)^{1/2}} = \frac{x_i}{r}$$

Replace $(*)$ in the PDE

$$\frac{\partial u}{\partial x_i} = \frac{\partial}{\partial x_i} v(r(x)) = v'(r(x)) \cdot \frac{\partial r}{\partial x_i} = v'(r(x)) \cdot \frac{x_i}{r}$$

and

$$\begin{aligned}\frac{\partial^2 u}{\partial x_i^2} = \frac{\partial}{\partial x_i}\left(v'(r(x)) \cdot \frac{x_i}{r}\right) \\ &= \frac{\partial}{\partial x_i}(v'(r(x))) \cdot \frac{x_i}{r} + v'(r(x)) \cdot \frac{\partial}{\partial x_i}\left(\frac{x_i}{r}\right) \\ &= v''(r(x)) \cdot \frac{x_i^2}{r^2} + v'(r(x))\left[\frac{1}{r} + x_i \frac{\partial}{\partial x_i}(r)\right] \\ &= v'' \frac{x_i^2}{r^2} + v'\left[\frac{1}{r} - \frac{x_i^2}{r^3}\right]\end{aligned}$$

Thenm, summing across i,

$$\Delta u = v'' + v'\left[\frac{n}{r} + \frac{1}{r}\right] = 0$$

Then the PDE is equivalent to

$$v''(r) + \frac{v'}{r}(n-1) = 0 \ (\square)$$

We need to find a solution for $\square$.

$$v''(r) = \frac{(1-n)v'}{r}$$

Assume, without loss of generality, that $v' \neq 0$ such that

$$\frac{v''(r)}{v'(r)} = \frac{1-n}{r} \implies (\log(|v'|))' = \frac{1-n}{r}$$

Then, integrating,

$$\log(|v'|) = (1-n)\log(r) + C = \log\left(r^{1-n}\right) + C$$

such that

$$|v'| = Cr^{1-n} \implies v' = Cr^{1-n} \implies v(r) = Cr^{1-n+1} + D = Cr^{2-n} + D$$

Definition: Fundamental Solution of the Laplace Equation

The function Φ given by

$$\Phi(x) = \begin{cases} -\frac{1}{2\pi}\log|x|, & n = 2 \\ \frac{1}{n(n-2)\alpha(n)} \cdot \frac{1}{|x|^{n-2}}, & n \geq 3 \end{cases}$$

where $\alpha(n)$ is the volume of the unit ball in $\mathbb{R}^n$ is called the fundamental solution.

Remark

Φ solves the Laplace equation away from 0.

Lemma: Estimates for the Fundamental Solution

- First Estimate
  $|D\Phi(x)| \leq \frac{C}{|x|^{n-1}}$, for $x \neq 0$.

  $$\frac{\partial \Phi}{\partial x_i} = C\frac{\partial}{\partial x_i}\left(|x|^{2-n}\right) = \frac{C(2-n)}{1-n}|x|^{2-n-1}\frac{\partial |x|}{\partial x_i} = |x|^{1-n} \cdot \frac{x_i}{|x|} = Cx_i|x|^{-n}$$

  Therefore

  $$|D\Phi(x)| \leq C|x||x|^{-n} \implies |D\Phi(x)| \leq C|X|^{1-n}$$

  - Exercise
    Compute for $n = 2$.

- Second Estimate
  $|D^2\Phi(x)| \leq \frac{C}{|x|^n}$, for $x \neq 0$.

  $$\begin{aligned} \frac{\partial^2}{\partial x_J \partial x_i}\Phi &= C\frac{\partial}{\partial x_J}\left(x_i|x|^{-n}\right) \\ &= C\left[\delta_{iJ}|x|^{-n} + x_i\frac{\partial}{\partial x_J}|x|^{-n}\right] \\ &= C\left[\delta_{iJ}|x|^{-n} + (-n)\cdot\frac{x_i|x|^{-n-1}x_J}{|x}\right] \\ &= C\left[\frac{\delta_{iJ}|x|}{|x|^n} + \frac{Cx_ix_J}{|x|^{n+1}}\right] \end{aligned}$$

  Then

  $$\left|\frac{\partial \Phi}{\partial x_i \partial x_J}\right| \leq \frac{C}{|x|^n} + \frac{C|x_i||x_J|}{|x|^{n+2}} \leq \frac{2C}{|x|^n} = \frac{C}{|x|^n}$$

  Then, we are done since

  $$|D^2\Phi(x)| = \sqrt{\sum_J \left(\frac{\partial \Phi}{\partial x_i \partial x_J}\right)}$$

Poisson Equation

Motivation

Suppose we have $\Phi(x)$, the fundamental solution.
Then for an arbitrary, fixed element $y \in \mathbb{R}^n$, then we have $x \to \Phi(x-y)$ harmonic for $x \neq y$.
Consider $f : \mathbb{R}^n \to \mathbb{R}$ such that $y \to f(y)$ then $x \to f(y)\Phi(x-y)$ is similarly harmonic for $x \neq y$.
Now, if given $\{y_1, \dots, y_m\}$ where $y_i \in \mathbb{R}^n$, then $x \to \sum_{i=1}^m f(y_i)\Phi(x-y_i)$ is harmonic $\forall x \neq \{y_1, \dots, y_m\}$.
Then, what happens if we consider

$$u(x) := \int_{\mathbb{R}^n} f(y)\Phi(x-y)\, dy \quad (\square_3)$$

Is u harmonic? No, since $\Delta\Phi(x-y)$ is not summable in $\mathbb{R}^n$ we may not pass the limit into the integral.
(to be covered later) However, since $\Delta\Phi(x-y)$ acts as δ_{xy} in distribution, this may solve the Poisson equation.

Remark / Exercise

Assume that $f \in C_C^2(\mathbb{R}^n)$ (i.e f is twice continuously differentiable with compact support on $\mathbb{R}^n$).
The function Φ is integrable near the singularity on compact sets.
Prove using spherical coordinates.
Therefore, u defined by $\square_3$ is well defined

$$|u| = \left|\int_{\mathbb{R}^n} f(y)\Phi(x-y)\, dy\right| = \left|\int_K \Phi(x-y)\, dy\right| < \infty$$

Theorem: Solving the Poisson Equation

If $f \in C_C^2(\mathbb{R}^n)$ and u is defined by $\square_3$, then

1. $u \in C^2(\mathbb{R}^n)$
2. $-\Delta u = f$, in $\mathbb{R}^n$

- Proof of 1
  Since Φ presents a problem at $x = y$ but f is well behaved, we will change variables such that $\overline{y} = x - y$, $y = x - \overline{y}$, and $\frac{dy}{d\overline{y}}(-1)I_{m\times m}$ and then redefine $\overline{y} = y$.

$$u(x) = \int_{\mathbb{R}^n} f(y)\Phi(x-y)\, dy = \int_{\mathbb{R}^n} f(x-\overline{y})\Phi(\overline{y})\, d\overline{y} = \int_{\mathbb{R}^n} f(x-y)\Phi(y)\, dy$$

  In short, we have sent the problem from Φ to f.
  Now, let us consider $e_i = (0, \dots, 1, \dots, 0)$.
  Then for $h > 0$,

$$\frac{u(x+he_i) - u(x)}{h} = \frac{1}{h}\int_{\mathbb{R}^n} \Phi(y)\left[f(x+he_i-y) - f(x-y)\right]\, dy$$

  Now, the limit as $h \to 0$

$$\begin{aligned} \lim_{h\to 0} \frac{u(x+he_i) - u(x)}{h} &= \lim_{h\to 0} \int_{\mathbb{R}^n} \overbrace{\Phi(y)\left[\frac{f(x+he_i-y) - f(x-y)}{h}\right]}^{H(h,y)}\, dy \\ &= \int_{\mathbb{R}^n} \Phi(y) \cdot \frac{\partial f(x-y)}{\partial x_i}\, dy \end{aligned}$$

To justify passing the limit into the integral, take an arbitrary sequence $h_m \xrightarrow{\to 0} 0$ and consider

$$f_m(y) := H(h_m, y)$$

We want to consider

$$\begin{aligned} |H(h_m, y)| &\leq \Phi(y)\left[\frac{f(x + h_m e_i - y) - f(x - y)}{h}\right] \\ &\leq \Phi(y) f'(c) \end{aligned}$$

Where c is along the curve between $f(x + h_m e_i - y)$ and $f(x - y)$ and chosen by mean value theorem.

– Exercise

$$|H(h_m, y)| \leq \Phi(y) ||f'||_{L^\infty} \chi_{B(x,R)}(y)$$

Note that

$$C \int_{\mathbb{R}^n} |\Phi(y)| \chi_{B(x,R)}(y)\, dy = \int_{B(x,R)} |\Phi(y)|\, dy < \infty$$

– Exercise

Using the fact that a continuous function is uniformly continuous on a compact set, show that $u \in C^2(\mathbb{R}^n)$.

Dominated Convergence Theorem

If $f_m(x)$ such that $f_m(x) \xrightarrow[\text{pointwise}]{m \to \infty} f(x)$, and $|f_m(x)| \leq g(x)$ for $g \in L^1$, then f is integrable and

$$\lim_{m \to \infty} \int f_m(x)\, dx = \int f(x)\, dx$$