

MA 523: Homework, Midterms and Practice Problems Solutions

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1 Homework Solutions

These are my (corrected) solutions to Petrosyan's Math 523 homework for the fall semester of 2016.

1.1 Homework 1

PROBLEM 1.1.1 (TAYLOR'S FORMULA). Let $f: \mathbb{R}^n \rightarrow \mathbb{R}$ be smooth, $n \geq 2$. Prove that

$$f(x) = \sum_{|\alpha| \leq k} \frac{1}{\alpha!} D^\alpha f(0) x^\alpha + O(|x|^{k+1})$$

as $x \rightarrow 0$ for each $k = 1, 2, \dots$, assuming that you know this formula for $n = 1$.

Hint: Fix $x \in \mathbb{R}^n$ and consider the function of one variable $g(t) := f(tx)$. Prove that

$$\frac{d^m}{dt^m} g(t) = \sum_{|\alpha|=m} \frac{m!}{\alpha!} D^\alpha f(tx) x^\alpha,$$

by induction on m .

Solution. Taking the hint, apply Taylor's formula to the function $g(t) = f(tx)$,

$$g(t) = \sum_{k=0}^{\infty} \frac{g^{(k)}(0)}{k!} t^k$$

■

PROBLEM 1.1.2. Write down the characteristic equation for the PDE

$$u_t + b \cdot Du = f \tag{*}$$

on $\mathbb{R}^n \times (0, \infty)$, where $b \in \mathbb{R}^n$. Using the characteristic equation, solve (*) subject to the initial condition

$$u = g$$

on $\mathbb{R}^n \times \{t = 0\}$. Make sure the answer agrees with formula (5) in §2.1.2 of [E].

Solution.

■

PROBLEM 1.1.3. Solve using the characteristics:

- (a) $x_1^2 u_{x_1} + x_2^2 u_{x_2} = u^2$, $u = 1$ on the line $x_2 = 2x_1$.
- (b) $uu_{x_1} + u_{x_2} = 1$, $u(x_1, x_1) = \frac{x_1}{2}$.
- (c) $x_1 u_{x_1} + 2x_2 u_{x_2} + u_{x_3} = 3u$, $u(x_1, x_2, 0) = g(x_1, x_2)$.

Solution.

■

PROBLEM 1.1.4. For the equation

$$u = x_1 u_{x_1} + x_2 u_{x_2} + \frac{1}{2}(u_{x_1}^2 + u_{x_2}^2)$$

find a solution with $u(x_1, 0) = \frac{1-x_1^2}{2}$.

Solution.

■

1.2 Homework 2

PROBLEM 1.2.1. Verify assertion (36) in [E, §3.2.3], that when Γ is not flat near x^0 the noncharacteristic condition is

$$D_p F(p^0, z^0, x^0) \cdot \nu(x^0) \neq 0.$$

(Here $\nu(x^0)$ denotes the normal to the hypersurface Γ at x^0).

Solution. ■

PROBLEM 1.2.2. Show that the solution of the quasilinear PDE

$$u_t + a(u)u_x = 0$$

with initial conditions $u(x, 0) = g(x)$ is given implicitly by

$$u = g(x - a(u)t).$$

Show that the solution develops a shock (becomes singular) for some $t > 0$, unless $a(g(x))$ is a nondecreasing function of x .

Solution. ■

PROBLEM 1.2.3. Show that the function $u(x, t)$ defined for $t \geq 0$ by

$$u(x, t) = \begin{cases} -\frac{2}{3} \left(t + \sqrt{3x + t^2} \right) & \text{for } 4x + t^2 > 0 \\ 0 & \text{for } 4x + t^2 < 0 \end{cases}$$

is an (unbounded) entropy solution of the conservation law $u_t + \left(\frac{u^2}{2}\right)_x = 0$ (*inviscid Burgers' equation*).

Solution. ■

1.3 Homework 3

PROBLEM 1.3.1. Consider the initial value problem

$$\begin{cases} u_t = \sin u_x, \\ u(x, 0) = \frac{\pi}{4}x. \end{cases}$$

Verify that the assumptions of the Cauchy–Kovalevskaya theorem are satisfied and obtain the Taylor series of the solution about the origin.

Solution.

■

PROBLEM 1.3.2. Consider the Cauchy problem for $u(x, y)$

$$\begin{cases} u_y = a(x, y, u)u_x + b(x, y, u), \\ u(x, 0) = 0, \end{cases}$$

let a and b be analytic functions of their arguments. Assume that $D^\alpha a(0, 0, 0) \geq 0$ and $D^\alpha b(0, 0, 0) \geq 0$ for all α . (Remember by definition, if $\alpha = 0$ then $D^\alpha f = f$.)

- (a) Show that $D^\beta u(0, 0) \geq 0$ for all $|\beta| \leq 2$.
- (b) Prove that $D^\beta u(0, 0) \geq 0$ for all $\beta = (\beta_1, \beta_2)$. (*Hint:* Argue as in the proof of the Cauchy–Kovalevskaya theorem; i.e., use induction in β_2)

Solution.

■

PROBLEM 1.3.3. (Kovalevskaya’s example) show that the line $\{t = 0\}$ is characteristic for the heat equation $u_t = u_{xx}$. Show there does not exist an analytic solution u of the heat equation in $\mathbb{R} \times \mathbb{R}$, with $u = \frac{1}{1+x^2}$ on $\{t = 0\}$. (*Hint:* assume there is an analytic solution, compute its coefficients, and show instead that the resulting power series diverges in any neighborhood of $(0, 0)$.)

Solution.

■

1.4 Homework 4

PROBLEM 1.4.1 (LEGENDRE TRANSFORM). Let $u(x_1, x_2)$ be a solution of the quasilinear equation

$$a^{11}(Du)u_{x_1x_1} + 2a^{12}(Du)u_{x_1x_2} + a^{22}(Du)u_{x_2x_2} = 0$$

in some region of \mathbb{R}^2 , where we can invert the relations

$$p^1 = u_{x_1}(x_1, x_2), \quad p^2 = u_{x_2}(x_1, x_2)$$

to solve for

$$x^1 = x^1(p_1, p_2), \quad x^2 = x^2(p_1, p_2).$$

Define then

$$v(p) := \mathbf{x}(p) \cdot p - u(\mathbf{x}(p)),$$

where $\mathbf{x} = (x^1, x^2)$, $p = (p_1, p_2)$. Show that v satisfies the *linear* equation

$$a^{22}(p)v_{p_1p_2} - 2a^{12}(p)v_{p_1p_2} + a^{11}(p)v_{p_1p_2} = 0.$$

(Hint: See [Evans, 4.4.3b], prove the identities (29)).

Solution.

■

PROBLEM 1.4.2. Find the solution $u(x, t)$ of the one-dimensional wave equation

$$u_{tt} - u_{xx} = 0$$

in the quadrant $x > 0, t > 0$ for which

$$\begin{cases} u(x, 0) = f(x), & u_t(x, 0) = g(x), & \text{for } x > 0, \\ u_t(0, t) = \alpha u_x(0, t), & & \text{for } t > 0, \end{cases}$$

where $\alpha \neq -1$ is a given constant. Show that generally no solution exists when $\alpha = -1$. (Hint: Use a representation $u(x, t) = F(x - t) + G(x + t)$ for the solution.)

Solution.

■

PROBLEM 1.4.3. (a) Let u be a solution of the wave equation $u_{tt} - c^2 u_{xx} = 0$ for $0 < x < \pi, t > 0$ such that $u(0, t) = u(\pi, t) = 0$. Show that the *energy*

$$E(t) = \frac{1}{2} \int_0^\pi (u_t^2 + c^2 u_x^2) dx, \quad t > 0$$

is independent of t ; i.e., $\frac{d}{dt} E = 0$ for $t > 0$. Assume that u is C^2 up to the boundary.

(b) Express the energy E of the Fourier series solution

$$u(x, t) = \sum_{n=1}^{\infty} (a_n \cos(nct) + b_n \sin(nct)) \sin(nx)$$

in terms of coefficients a_n, b_n .

Solution.

■

1.5 Homework 5

PROBLEM 1.5.1. Prove that Laplace's equation $\Delta u = 0$ is rotation invariant; that is, if O is an orthogonal $n \times n$ matrix and we define $v(x) := u(Ox)$, $x \in \mathbb{R}^n$, then $\Delta v = 0$.

Solution. ■

PROBLEM 1.5.2. Let $n = 2$ and U be the halfplane $\{x_2 > 0\}$. Prove that

$$\sup_U u = \sup_{\partial U} u$$

for $u \in C^2(U) \cap C(\bar{U})$ which are harmonic in U under the additional assumption that u is bounded from above in \bar{U} . (The additional assumption is needed to exclude examples like $u = x_2$.)

[Hint: Take for $\varepsilon > 0$ the harmonic function

$$u(x_1, x_2) - \varepsilon \ln \sqrt{x_1^2 + (x_2 + 1)^2}.$$

Apply the maximum principle to a region $\{x_1^2 + (x_2 + 1)^2 < a^2, x_2 > 0\}$ with large a . Let $\varepsilon \rightarrow 0$.]

Solution. ■

PROBLEM 1.5.3. Let $U \subset \mathbb{R}^n$ be an open set. We say $v \in C^2(U)$ is subharmonic if

$$-\Delta v \leq 0 \quad \text{in } U.$$

(a) Let $\varphi: \mathbb{R}^m \rightarrow \mathbb{R}$ be smooth and convex. Assume u^1, \dots, u^m are harmonic in U and

$$v := \varphi(u_1, \dots, u_m).$$

Prove v is subharmonic.

[Hint: Convexity for a smooth function $\varphi(z)$ is equivalent to $\sum_{j,k=1}^m \varphi_{z_j, z_k}(z) \xi_j \xi_k \geq 0$ for any $\xi \in \mathbb{R}^m$.]

(b) Prove $v := |Du|^2$ is subharmonic, whenever u is harmonic. (Assume that harmonic functions are C^∞ .)

Solution. ■

1.6 Homework 6

PROBLEM 1.6.1. For $n = 2$ find Green's function for the quadrant $U := \{x_1, x_2 > 0\}$ by repeated reflection.

Solution. Taking the hit, set $x' := (x_1, -x_2)$, $x'' := (-x_1, x_2)$, $x''' := (-x_1, -x_2)$, and define

$$\varphi^x(y) := \Phi(y - x') + \Phi(y - x'') - \Phi(y - x'''). \quad (1)$$

We claim that φ^x , as defined above, solves

$$\begin{cases} \Delta \varphi^x = 0 & \text{in } U, \\ \varphi^x(y) = \Phi(y - x) & \text{on } \partial U. \end{cases}$$

It is clear that $\Delta \varphi^x = 0$ since it is built up from the fundamental solutions on \mathbb{R}^n (this follows from the linearity of the Laplace operator). To see that $\varphi^x(y) = \Phi(y - x)$ on ∂U , we do a case by case analysis.

Note that on $\{x_1 = 0\} \subset \partial U$, we have

$$\varphi^x(y_1, 0) = \Phi(-x_1, y_2 + x_2) + \Phi(-x_1, y_2 - x_2) - \Phi(x_1, y_2 + x_2),$$

where, since the fundamental solution is radial, we have $\Phi(-x_1, y_2 + x_2) = \Phi(x_1, y_2 + x_2)$, and hence the above equals

$$\begin{aligned} &= \Phi(-x_1, y_2 - x_2) \\ &= \Phi(y - x) \end{aligned}$$

and on $\{x_2 = 0\} \subset \partial U$, we have

$$\varphi^x(0, y_2) = \Phi(y_1 - x_1, x_2) + \Phi(y_1 + x_1, -x_2) - \Phi(y_1 + x_1, x_2)$$

where, again because Φ is radial, $\Phi(y_1 + x_1, -x_2) = \Phi(y_1 + x_1, x_2)$, thus the above equals

$$\begin{aligned} &= \Phi(y_1 - x_1, x_2) \\ &= \Phi(y - x). \end{aligned}$$

Thus, $\varphi^x(y) = \Phi(y - x)$ on ∂U .

Therefore, Green's function on U is

$$G(x, y) = \Phi(y - x) - \varphi^x(y) = \Phi(y - x) - \Phi(y - x') - \Phi(y - x'') + \Phi(y - x'''). \quad \blacksquare$$

PROBLEM 1.6.2. (Precise form of Harnack's inequality) Use Poisson's formula for the ball to prove

$$\frac{r^{n-2}(r - |x|)}{(r + |x|)^{n-1}} u(0) \leq u(x) \leq \frac{r^{n-2}(r + |x|)}{(r - |x|)^{n-1}} u(0)$$

whenever u is positive and harmonic in $B(0, r) = \{x \in \mathbb{R}^n : |x| < r\}$.

Solution. Recall Poisson's formula for the ball

$$u(x) = \frac{r^2 - |x|^2}{n\alpha_n r} \int_{\partial B(0,r)} \frac{g(y)}{|x-y|^n} dS(y), \quad (2)$$

where $x \in B(0, r)$ and u solves the boundary-value problem

$$\begin{cases} \Delta u = 0 & \text{in } B(0, r), \\ u = g & \text{on } \partial B(0, r). \end{cases}$$

For fixed $x \in B(0, r)$, write

$$u(x) = r^{n-2}(r + |x|)(r - |x|) \left[\frac{1}{n\alpha_n r^{n-1}} \int_{\partial B(0,r)} \frac{g(y)}{|x-y|^n} dS(y) \right].$$

Now, since $r + |x| \geq |x - y| \geq r - |x|$ for all $y \in \partial B(0, r)$, we have

$$\frac{r^{n-2}(r - |x|)}{(r + |x|)^{n-1}} \int_{\partial B(0,r)} g(y) dS(y) \leq u(x) \leq \frac{r^{n-2}(r + |x|)}{(r - |x|)^{n-1}} \int_{\partial B(0,r)} g(y) dS(y). \quad (3)$$

Since $u = g$ on the boundary $\partial B(0, r)$, by applying the mean-value property on (3) we have

$$\frac{r^{n-2}(r - |x|)}{(r + |x|)^{n-1}} u(0) \leq u(x) \leq \frac{r^{n-2}(r + |x|)}{(r - |x|)^{n-1}} u(0),$$

as desired. ■

PROBLEM 1.6.3. Let $P_k(x)$ and $P_m(x)$ be homogeneous harmonic polynomials in \mathbb{R}^n of degrees k and m respectively; i.e.,

$$\begin{cases} P_k(\lambda x) = \lambda^k P_k(x), & P_m(\lambda x) = \lambda^m P_m(x) & \text{for every } x \in \mathbb{R}^n, \lambda > 0, \\ \Delta P_k = 0, & \Delta P_m = 0 & \text{in } \mathbb{R}^n. \end{cases}$$

(a) Show that

$$\begin{cases} \frac{\partial P_k}{\partial \nu} = k P_k(x), & \frac{\partial P_m}{\partial \nu} = m P_m(x) & \text{on } \partial B(0, 1), \end{cases}$$

where $B(0, 1) = \{x \in \mathbb{R}^n : |x| < 1\}$ and ν is the outward normal on $\partial B(0, 1)$.

(b) Use (a) and Green's formula to prove that

$$\int_{\partial B(0,1)} P_k(x) P_m(x) d\sigma = 0, \quad \text{if } k \neq m.$$

Solution. For part (a), let

$$P_k(x) = \sum_{|\alpha|=k} a_\alpha x^\alpha.$$

Then, since $v = (x_1, \dots, x_n)$, the derivative along v is given by

$$\begin{aligned} \frac{\partial P_k(x)}{\partial v} &= \sum_{i=1}^n (P_k)_{x_i} x_i \\ &= \sum_{i=1}^n \left(\sum_{|\alpha|=k} a_\alpha x^\alpha \right)_{x_i} x_i \\ &= \sum_{i=1}^n \left(\sum_{j=1}^m a_\alpha x_1^{\alpha_1^j} \dots x^{\alpha_i^j} \dots x^{\alpha_n^j} \right)_{x_i} x_i \end{aligned}$$

where $\sum_{i=1}^n \alpha_i^j = k$ and $1 \leq j \leq \binom{n+k-1}{n} =: m$ (by the stars and bars theorem)

$$\begin{aligned} &= \sum_{i=1}^n \sum_{j=1}^m \left(\alpha_i^j a_\alpha x_1^{\alpha_1^j} \dots x^{\alpha_i^j-1} \dots x^{\alpha_n^j} \right) x_i \\ &= \sum_{i=1}^n \sum_{j=1}^m \alpha_i^j a_\alpha x_1^{\alpha_1^j} \dots x^{\alpha_i^j} \dots x^{\alpha_n^j} \\ &= \sum_{i=1}^n \sum_{j=1}^m \alpha_i^j a_\alpha x^\alpha \end{aligned}$$

switching the order of summation, we have

$$\begin{aligned} &= \sum_{j=1}^m \sum_{i=1}^n \alpha_i^j a_\alpha x^\alpha \\ &= \sum_{j=1}^m k a_\alpha x^\alpha \\ &= k \sum_{j=1}^m a_\alpha x^\alpha \\ &= k P_k(x). \end{aligned}$$

This argument, of course, applies to every $k \in \mathbb{N}$.

For part (b), by Green's theorem, we have

$$\begin{aligned} \int_{B(0,r)} P_k(x) \Delta P_m(x) - (\Delta P_k(x)) P_m(x) dx &= \int_{\partial B(0,r)} P_k(x) \frac{\partial}{\partial \nu} P_m(x) - \frac{\partial}{\partial \nu} P_k(x) P_m(x) dS(x) \\ &= \int_{\partial B(0,r)} (m-k) P_k(x) P_m(x) dS(x), \end{aligned}$$

where the left-hand side is equal to zero since both ΔP_k and ΔP_m are zero. Since $m \neq k$, it must be the case that

$$\int_{\partial B(0,r)} P_k(x) P_m(x) dS(x) = 0.$$

■

PROBLEM 1.6.4. Solve the Dirichlet problem for the Laplace equation in \mathbb{R}^2

$$\begin{cases} \Delta u = 0 & \text{in } 1 < |x| < 2, \\ u = x_1 & \text{on } |x| = 1, \\ u = 1 + x_1 x_2 & \text{on } |x| = 2. \end{cases}$$

(Hint: Use Laurent series.)

Solution. ■

PROBLEM 1.6.5. Let Ω be a bounded domain with a C^1 boundary, $g \in C^2(\partial\Omega)$ and $f \in C(\bar{\Omega})$. Consider the so called *Neumann problem*

$$\begin{cases} -\Delta u = f & \text{in } \Omega, \\ \frac{\partial u}{\partial \nu} = g & \text{on } \partial\Omega, \end{cases} \quad (*)$$

where ν is the outer normal on $\partial\Omega$. Show that the solution of $(*)$ in $C^2(\Omega) \cap C^1(\bar{\Omega})$ is unique up to a constant; i.e., if u_1 and u_2 are both solutions of $(*)$, then $u_2 = u_1 + \text{const.}$ in Ω .

(Hint: Look at the proof of the uniqueness for the Dirichlet problem by Energy methods [E, 2.2.5a].)

Solution. ■

PROBLEM 1.6.6. Write down an explicit formula for a solution of

$$\begin{cases} u_t - \Delta u + cu = f & \text{in } \mathbb{R}^n \times (0, \infty), \\ u = g & \text{on } \mathbb{R}^n \times \{t = 0\}, \end{cases}$$

where $c \in \mathbb{R}$.

(Hint: Rewrite the problem in terms of $v(x, t) := e^{ct} u(x, t)$.)

Solution. ■

2 Exams

2.1 Midterm Practice Problems

PROBLEM 2.1.1. Solve $u_{x_1}^2 + x_2 u_{x_2} = u$ with initial conditions $u(x_1, 1) = \frac{x_1^2}{4} + 1$.

Solution. By inspection, we may suspect that $v(x_1, x_2) = \frac{x_1^2}{4} + x_2$ is a solution to the PDE. It certainly satisfies the boundary condition. A routine calculation shows that v is in fact a solution to the PDE. Lucky guess!

More formally, let us solve this problem using the method of characteristics. First, write

$$F(p, z, x) = (p^1(s))^2 + x^2(s)p^2(s) - z(s) = 0.$$

Then, the characteristic ODEs are

$$\begin{cases} (\dot{p}^1(s), \dot{p}^2(s)) = -(0, p^2(s)) + (p^1(s), p^2(s)) \\ \quad = (p^1(s), 0), \\ \dot{z}(s) = (2p^1(s), x^2(s)) \cdot (p^1(s), p^2(s)) \\ \quad = 2p^1(s)^2 + x^2(s)p^2(s), \\ (\dot{x}^1(s), \dot{x}^2(s)) = (2p^1(s), x^2(s)). \end{cases}$$

Now, for $(x^1(0), x^2(0)) = (x^0, 1)$, integrating the characteristics, we get

$$\begin{cases} (p^1(s), p^2(s)) = (p_0^1 e^s, p_0^2), \\ (x^1(s), x^2(s)) = (2p_0^1 e^s + x_0^1, x_0^2 e^s), \\ z(s) = \frac{(x^0)^2}{4} e^{2s} + p_0^2 e^s + z^0 \end{cases}$$

Using the initial condition and the PDE, we find that

$$\begin{aligned} p_0^1 &= \frac{x^0}{2}, & p_0^2 &= \frac{(x^0)^2}{4} + 1 - \frac{(x^0)^2}{4} = 1, \\ x_0^1 &= 0, & x_0^2 &= 1 \\ z^0 &= 0, \end{aligned}$$

and consequently

$$\begin{cases} (x^1(s), x^2(s)) = (x^0 e^s, e^s), \\ z(s) = \frac{(x^0)^2}{4} e^{2s} + e^s \end{cases}$$

so, rewriting z in terms of (x^1, x^2) , we have

$$\begin{aligned} z(s) &= \frac{(x^0)^2}{4} e^{2s} + e^s \\ &= \frac{(x^1(s))^2}{4} + x^2(s), \end{aligned}$$

so the solution in terms of (x_1, x_2) , is

$$u(x_1, x_2) = \frac{x_1^2}{4} + x_2,$$

just as we suspected. ■

PROBLEM 2.1.2. Find the maximal $t_0 > 0$ for which the (classical) solution of the Cauchy problem

$$\begin{cases} uu_x + u_t = 0, \\ u(x, 0) = e^{-\frac{x^2}{2}}, \end{cases}$$

exists in $\mathbb{R} \times [0, t)$; i.e., the first time $t = t_0$ when the shock develops.

Solution. First, let us find a solution to the PDE using the method of characteristics. Write

$$F(p, z, x) = z(s)p^1(s) + p^2(s).$$

Then, the characteristic ODEs are

$$\begin{cases} (p^1(s), p^2(s)) = -(0, 0) - p^1(p^1(s), p^2(s)) \\ \quad = (-p^1(s)^2, -p^1(s)p^2(s)), \\ \dot{z}(s) = (z(s), 1) \cdot (p^1(s), p^2(s)) \\ \quad = z(s)p^1(s) + p^2(s) \\ \quad = 0, \\ (\dot{x}(s), \dot{t}(s)) = (z(s), 1). \end{cases}$$

Thus, integrating the characteristic ODEs from $(x^0, 0)$, we have

$$\begin{cases} \dot{z}(s) = z^0, \\ (x(s), t(s)) = (z^0 s + x^0, s); \end{cases}$$

since the PDE is quasilinear, we disregard (p^1, p^2) .

Applying the boundary conditions, we see that

$$z^0 = u(x^0, 0) = e^{-\frac{(x^0)^2}{2}}.$$

Here's where it gets tricky. After a little struggling, we see that there is really no way to solve for z in terms of $(x(s), t(s))$. However, we can solve for the projected characteristics:

$$(x(t, y), t) = (e^{-\frac{y^2}{2}} t + y, t);$$

and this is really all that matters for us to find the time t_0 when the shock develops, i.e., the time when the projected characteristic fails to be injective.

A little calculation shows that this happens precisely when $t = e^{-\frac{1}{2}}$. ■

PROBLEM 2.1.3. If ρ_0 denotes the maximum density of cars on a highway (i.e., under bumper-to-bumper conditions), then a reasonable model for traffic density ρ is given by

$$\begin{cases} \rho_t + (F(\rho))_x = 0, \\ F(\rho) = c\rho\left(1 - \frac{\rho}{\rho_0}\right), \end{cases}$$

where $c > 0$ is a constant (free speed of highway). Suppose the initial density is

$$\rho(x, 0) = \begin{cases} \frac{1}{2}\rho_0 & \text{if } x < 0, \\ \rho_0 & \text{if } x > 0. \end{cases}$$

Find the shock curve and describe the weak solution. (Interpret your result for the traffic flow.)

Solution. First, note that

$$\begin{aligned} (F(\rho))_x &= F'(\rho)\rho_x \\ &= \left[-c\frac{\rho}{\rho_0} + c\left(1 - \frac{\rho}{\rho_0}\right) \right] \rho_x \\ &= \left(c - \frac{2c\rho}{\rho_0} \right) \rho_x. \end{aligned}$$

Let us find a solution to the PDE using the method of characteristics. Write

$$G(p, z, x) = p^2(s) + F'(z(s))p^1(s).$$

Then, the characteristic ODEs are

$$\begin{cases} (\dot{p}^1(s), \dot{p}^2(s)) = (-F''(z(s))p^1(s), -F''(z(s))p^2(s)), \\ \dot{z}(s) = F'(z(s))p^1(s) + p^2(s) \\ \quad = 0, \\ (\dot{x}^1(s), \dot{x}^2(s)) = (F'(z(s)), 1). \end{cases}$$

Now, integrating the characteristics, we have

$$\begin{cases} z(s) = z^0, \\ (x^1(s), x^2(s)) = (F'(z^0)s + x^0, s). \end{cases}$$

We have two cases to consider, $x^0 < 0$ or $x^0 > 0$. For $x^0 < 0$, $z^0 = \frac{\rho_0}{2}$ and the projected characteristics look like

$$\begin{aligned} \left(F'\left(\frac{\rho_0}{2}\right)t + x^0, t \right) &= \left(\left[c - \frac{2c(\frac{\rho_0}{2})}{\rho_0} \right] t + x^0, t \right) \\ &= (0 \cdot t + x^0, t) \\ &= (x^0, t) \end{aligned}$$

(where we have replaced s with the more appropriate t). Whereas for $x^0 > 0$, we have

$$\begin{aligned}\left(F'(\rho_0)t + x^0, t\right) &= \left(\left[c - \frac{2c\rho_0}{\rho_0}\right]t + x^0, t\right) \\ &= (-ct + x^0, t).\end{aligned}$$

These characteristics intersect precisely when

$$t = \frac{x_1^0 - x_2^0}{c},$$

where $x_1^0 > 0$, $x_2^0 < 0$. ■

PROBLEM 2.1.4. Find the characteristics of the second order equation

$$u_{xx} - (2 \cos x)u_{xy} - (3 + \sin^2 x)u_{yy} - yu_y = 0,$$

and transform it to the canonical form.

Solution. First, writing the PDE in the form

$$Au_{xx} + 2Bu_{xy} + Cu_{yy} + 2Du_x + 2Eu_y + Fu = 0,$$

we see that $A = 1$, $B = -\cos x$, $C = -3 \sin^2 x$, and $E = -\frac{y}{2}$. We solve for the characteristic curve by find a solution to the ODEs

$$\begin{aligned}\frac{dy}{dx} &= \frac{B \pm \sqrt{B^2 - AC}}{A} \\ &= -\cos x \pm \sqrt{\cos^2 x + 3 + \sin^2 x} \\ &= -\cos x \pm 2.\end{aligned}$$

The solutions give us the following ODEs

$$\begin{cases} y = -\sin x + 2x + \xi(x, y), \\ y = -\sin x - 2x + \eta(x, y). \end{cases}$$

Integrating these equations, we have

$$\begin{cases} \xi(x, y) = y + \sin x - 2x, \\ \eta(x, y) = y + \sin x + 2x. \end{cases}$$

These are the characteristic strips for the PDE.

To put this PDE in canonical form, we first compute the following partial derivatives

$$\begin{aligned}u_x &= u_\xi \xi_x + u_\eta \eta_x, \\ u_y &= u_\xi \xi_y + u_\eta \eta_y, \\ u_{xx} &= u_\xi \xi_{xx} + u_\eta \eta_{xx} + (u_{\xi\xi} \xi_x + u_{\xi\eta} \eta_x) \xi_x + (u_{\xi\eta} \xi_x + u_{\eta\eta} \eta_x) \eta_x \\ &= u_{\xi\xi} (\xi_x)^2 + u_{\eta\eta} (\eta_x)^2 + 2u_{\xi\eta} \xi_x \eta_x + u_{\xi\xi} \xi_{xx} + u_{\eta\eta} \eta_{xx},\end{aligned}$$

exploiting symmetry, we can find u_{yy} by replacing x with y above

$$u_{yy} = u_{\xi\xi}(\xi_y)^2 + u_{\eta\eta}(\eta_y)^2 + 2u_{\xi\eta}\xi_y\eta_y + u_{\xi\xi\xi_y} + u_{\eta\eta\eta_y},$$

the last thing we need to figure out is the mixed partial

$$\begin{aligned} u_{xy} &= u_{\xi\xi\xi_y} + u_{\eta\eta\eta_y} + (u_{\xi\xi\xi_y} + u_{\xi\eta\eta_y})\xi_x + (u_{\xi\eta\xi_y} + u_{\eta\eta\eta_y})\eta_x \\ &= u_{\xi\xi\xi\xi_y} + u_{\eta\eta\eta\eta_y} + u_{\xi\eta}(\xi_x\eta_y + \xi_y\eta_x) + u_{\xi\xi\xi_y} + u_{\eta\eta\eta_y}. \end{aligned}$$

Now find the partials $\xi_x, \eta_x, \xi_y, \eta_y, \xi_{xy}, \dots$, etc.

$$\begin{aligned} \xi_x &= \cos x - 2, & \eta_x &= \cos x + 2, \\ \xi_{xx} &= -\sin x, & \eta_{xx} &= -\sin x, \\ \xi_{xy} &= 0, & \eta_{xy} &= 0, \\ \xi_y &= 1, & \eta_y &= 1, \\ \xi_{yy} &= 0, & \eta_{yy} &= 0. \end{aligned}$$

Thus,

$$\left\{ \begin{aligned} u_x &= (\cos x - 2)u_{\xi} + (\cos x + 2)u_{\eta}, \\ u_y &= u_{\xi} + u_{\eta}, \\ u_{xx} &= (\cos x - 2)^2 u_{\xi\xi} + (\cos x + 2)^2 u_{\eta\eta} \\ &\quad + 2(\cos x + 2)(\cos x - 2)u_{\xi\eta} - (\sin x)u_{\xi} - (\sin x)u_{\eta} \\ &= (\cos^2 x - 4\cos x + 4)u_{\xi\xi} + (\cos^2 x + 4\cos x + 4)u_{\eta\eta} \\ &\quad + 2(\cos^2 x - 4)u_{\xi\eta} - (\sin x)u_{\xi} - (\sin x)u_{\eta} \\ u_{yy} &= u_{\xi\xi} + u_{\eta\eta} + 2u_{\xi\eta}, \\ u_{xy} &= (\cos x - 2)u_{\xi\xi} + (\cos x + 2)u_{\eta\eta} + 2(\cos x)u_{\xi\eta}, \end{aligned} \right.$$

so the canonical form is

$$\begin{aligned} 0 &= u_{xx} - (2\cos x)u_{xy} - (3\sin^2 x)u_{yy} - yu_y \\ &= \xi^2 u_{\xi\xi} + \eta^2 u_{\eta\eta} \\ &\quad + 2\xi\eta u_{\xi\eta} - (\sin x)u_{\xi} - (\sin x)u_{\eta} \\ &\quad - (2\cos x)((\cos x - 2)u_{\xi\xi} + (\cos x + 2)u_{\eta\eta} + 2(\cos x)u_{\xi\eta}) \\ &\quad - (3\sin^2 x)(u_{\xi\xi} + u_{\eta\eta} + 2u_{\xi\eta}) \\ &\quad - y(u_{\xi} + u_{\eta}) \end{aligned}$$

Who cares. ■

PROBLEM 2.1.5. Let $Lu := u_{xx} - 4u_{yy} + \sin(y + 2x)u_x = 0$.

- Consider the level curve $\Gamma = \{(x, y) : \varphi(x, y) = C\}$ where $|D\varphi| \neq 0$ on Γ . Define what it means for Γ to be characteristic with respect to L at a point $(x_0, y_0) \in \Gamma$.
- Find the points at which the curve $x^2 + y^2 = 5$ is characteristic.

- (c) Is it true that every smooth simple closed curve Γ in \mathbb{R}^2 has at least one point at which it is characteristic with respect to L ?

Solution. ■

PROBLEM 2.1.6. Consider the second order equation

$$Lu := u_{xx} - 2xu_{xy} + x^2u_{yy} - 2u_y = 0.$$

- (a) Find the characteristic curves of $Lu = 0$. What is the type of this equation?
 (b) Find the points on the line $\Gamma := \{(x, y) \in \mathbb{R}^2 : x + y = 1\}$ at which Γ is characteristic with respect to $Lu = 0$.

Solution. ■

PROBLEM 2.1.7. Solve the initial boundary value problem for the equation $u_{tt} = u_{xx}$ in $\{x > 0, t > 0\}$ satisfying

$$\begin{cases} u(x, 0) = \sin^2 x, & u_t(x, 0) = \sin x, \\ u(0, t) = 0. \end{cases}$$

Solution. ■

PROBLEM 2.1.8. Consider the initial/boundary value problem

$$\begin{cases} u_{tt} - u_{xx} = 0 & \text{for } 0 < x < \pi, t > 0, \\ u(x, 0) = x, & u_t(x, 0) = 0 \quad \text{for } 0 < x < \pi, \\ u_x(0, t) = 0, & u_x(\pi, t) = 0 \quad \text{for } t > 0. \end{cases}$$

- (a) Find a weak solution of the problem.
 (b) Is the solution unique? Continuous? C^1 ?

Solution. ■

PROBLEM 2.1.9. Let B_1^+ denote the open half-ball $\{x \in \mathbb{R}^n : |x| < 1, x_n > 0\}$. Assume $u \in C(\bar{B}_1^+)$ is harmonic in B_1^+ with $u = 0$ on $\partial B_1^+ \cap \{x_n = 0\}$. Set

$$v(x) := \begin{cases} u(x) & \text{if } x_n \geq 0, \\ -u(x_1, \dots, x_{n-1}, -x_n) & \text{if } x_n < 0, \end{cases}$$

for $x \in B_1$. Prove v is harmonic in B_1 .

Hint: It will be enough to prove that $\int_B \nabla v \nabla \eta \, dx = 0$ for any test function $\eta \in C_0^\infty(B_1)$. Split $\int_{B_1} = \int_{B_1^+} + \int_{B_1^-}$ and apply the integration by parts formula to each of $\int_{B_1^\pm}$.

Solution. ■

PROBLEM 2.1.10. Let u and v be harmonic functions in the unit ball $B_1 \subset \mathbb{R}^n$. What can you conclude about u and v if

- (a) $D^\alpha u(0) = D^\alpha v(0)$ for every multiindex α ?
- (b) $u(x) \leq v(x)$ for every $x \in B_1$ and $u(0) = v(0)$?

Justify your answer in each case.

Solution. ■

PROBLEM 2.1.11. Let Φ be the fundamental solution of the Laplace equation in \mathbb{R}^n and $f \in C_0^\infty(\mathbb{R}^n)$. Then the convolution

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

is a solution to the Poisson equation $-\Delta u = f$ in \mathbb{R}^n . Show that if f is radial, i.e., $f(y) = f(|y|)$, and supported in $B_R := \{|x| < R\}$, then

$$u(x) = c\Phi(x)$$

for any $x \in \mathbb{R}^n \setminus B_R$, where

$$c = \int_{\mathbb{R}^n} f(y) dy.$$

[Hint: Use polar (spherical) coordinates and apply the mean value property for harmonic functions.]

Solution. ■

3 Qualifying Exams

3.1 Qualifying Exam, August '04

PROBLEM 3.1.1. Consider the initial value problem

$$\begin{cases} a(x, y)u_x + b(x, y)u_y = -u, \\ u = f \end{cases} \quad \text{on } S^1 = \{x^2 + y^2 = 1\},$$

where a and b satisfy

$$a(x, y) + b(x, y)y > 0$$

for any $x, y \in \mathbb{R}^n \setminus \{(0, 0)\}$.

- (a) Show that the initial value problem has a unique solution in a neighborhood of S^1 . Assume that a , b , and f are smooth.
- (b) Show that the solution of the initial value problem actually exists in $\mathbb{R}^2 \setminus \{(0, 0)\}$.

Solution.

■

PROBLEM 3.1.2. Let $u \in C^2(\mathbb{R} \times [0, \infty))$ be a solution of the initial value problem for the one-dimensional wave equation

$$\begin{cases} u_{tt} - u_{xx} = 0 & \text{on } \mathbb{R} \times (0, \infty), \\ u = f, \quad u_t = g & \text{in } \mathbb{R} \times \{0\}, \end{cases}$$

where f and g have compact support. Define the kinetic energy by

$$K(t) = \frac{1}{2} \int_{-\infty}^{\infty} u_t^2(x, t) dx,$$

and the potential energy by

$$P(t) = \frac{1}{2} \int_{-\infty}^{\infty} u_x^2(x, t) dx.$$

Show that

- (a) $K(t) + P(t)$ is constant in t ,
- (b) $K(t) = P(t)$ for all large enough times t .

Solution.

■

PROBLEM 3.1.3. Use Kirchhoff's formula and Duhamel's principle to obtain an integral representation of the solution of the following Cauchy problem

$$\begin{cases} u_{tt} - \Delta u = e^{-t}g(x) & \text{for } x \in \mathbb{R}^3, t > 0, \\ u(x, 0) = u_t(x, 0) = 0 & \text{for } x \in \mathbb{R}^3. \end{cases}$$

Verify that the integral representation reduces to the obvious solution $u = e^{-t} + t - 1$ when $g(x) = 1$.

Solution. ■

PROBLEM 3.1.4. Let Ω be a bounded open set in \mathbb{R}^n and $g \in C_0^\infty(\Omega)$. Consider the solutions of the initial boundary value problem

$$\begin{cases} \Delta u - u_t = 0 & \text{for } x \in \Omega, t > 0, \\ u(x, 0) = g(x) & \text{for } x \in \Omega, \\ u(x, t) = 0 & \text{for } x \in \partial\Omega, t \geq 0, \end{cases}$$

and the Cauchy problem

$$\begin{cases} \Delta v - v_t = 0 & \text{for } x \in \mathbb{R}^n, t > 0, \\ v(x, 0) = |g(x)| & \text{for } x \in \mathbb{R}^n, \end{cases}$$

where we put $g = 0$ outside Ω .

(a) Show that

$$-v(x, t) \leq u(x, t) \leq v(x, t)$$

for any $x \in \Omega, t > 0$.

(b) Use (a) to conclude that

$$\lim_{t \rightarrow \infty} u(x, t) = 0,$$

for any $x \in \Omega$.

Solution. ■

PROBLEM 3.1.5. Let $P_k(x)$ and $P_m(x)$ be homogeneous harmonic polynomials in \mathbb{R}^n of degrees k and m respectively; i.e.,

$$P_k(\lambda x) = \lambda^k P_k(x), \quad P_m(\lambda x) = \lambda^m P_m(x),$$

for any $x \in \mathbb{R}^n, \lambda > 0$,

$$\Delta P_k = 0, \quad \Delta P_m = 0$$

in \mathbb{R}^n .

(a) Show that

$$\frac{\partial P_k(x)}{\partial \nu} = k P_k(x), \quad \frac{\partial P_m(x)}{\partial \nu} = m P_m(x)$$

on ∂B_1 , where $B_1 = \{ |x| < 1 \}$ and ν is the outward normal on ∂B_1 .

(b) Use (a) and Green's second identity to prove that

$$\int_{\partial B_1} P_k(x) P_m(x) dS = 0,$$

if $k \neq m$.

Solution. ■

3.2 Qualifying Exam, August '05

PROBLEM 3.2.1.

- (a) Find a solution of the Cauchy problem

$$\begin{cases} yu_x + xu_y = xy, \\ u = 1 \end{cases} \quad \text{on } S^1 = \{x^2 + y^2 = 1\}.$$

- (b) Is the solution unique in a neighborhood of the point $(1, 0)$? Justify your answer.

Solution. The solution to the first part is

$$u(x, y) = \frac{x^2 + y^2}{4} + \frac{3}{4}.$$

■

PROBLEM 3.2.2. Consider the second order PDE in $\{x > 0, y > 0\} \subset \mathbb{R}^2$

$$x^2 u_{xx} - y^2 u_{yy} = 0.$$

- (a) Classify the equation and reduce it to the canonical form.
 (b) Show that the general solution of the equation is given by the formula

$$u(x, y) = F(x, y) + \sqrt{xy}G\left(\frac{x}{y}\right).$$

Solution.

■

PROBLEM 3.2.3. Let Φ be the fundamental solution of the Laplace equation in \mathbb{R}^3 and $f \in C_0^\infty(\mathbb{R}^n)$. Then the convolution

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

is a solution of the Poisson equation $-\Delta u = f$ in \mathbb{R}^n . Show that if f is radial (i.e., $f(y) = f(|y|)$) and supported in $B_R = \{|x| < R\}$, then

$$u(x) = c\Phi(x),$$

for any $x \in \mathbb{R}^n \setminus B_R$, where

$$c = \int_{\mathbb{R}^n} f(y) dy.$$

[Hint: Use spherical (polar) coordinates and the mean value property.]

Solution.

■

PROBLEM 3.2.4. Consider the so-called 2-dimensional wave equation with dissipation

$$\begin{cases} u_{tt} - \Delta u + \alpha u_t = 0 & \text{in } \mathbb{R}^2 \times (0, \infty), \\ u(x, 0) = g(x), \quad u_t(x, 0) = h(x) & \text{for } x \in \mathbb{R}^2, \end{cases}$$

where $g, h \in C_0^\infty(\mathbb{R}^2)$ and $\alpha \geq 0$ is a constant.

- (a) Show that for an appropriate choice of constant λ and μ the function

$$v(x_1, x_2, x_3, t) := e^{\lambda t + \mu x_3} u(x_1, x_2, t)$$

solves the 3-dimensional wave equation $v_{tt} - \Delta v = 0$.

- (b) Use (a) to prove the following domain of dependence result: for any point $(x_0, t_0) \in \mathbb{R}^2 \times (0, \infty)$ the value $u(x_0, t_0)$ is uniquely determined by values of g and h in $\overline{B_{t_0}(x_0)} := \{ |x - x_0| \leq t_0 \}$. (You may use the corresponding result for the wave equation without proof.)

Solution. ■

PROBLEM 3.2.5. Let $u(x, t)$ be a bounded solution of the heat equation $u_t = u_{xx}$ in $\mathbb{R} \times (0, \infty)$ with the initial condition

$$u(x, 0) = u_0(x)$$

for $x \in \mathbb{R}$, where $u_0 \in C^\infty$ is 2π -periodic, i.e., $u_0(x + 2\pi) = u_0(x)$. Show that

$$\lim_{t \rightarrow \infty} u(x, t) = a_0,$$

uniformly in $x \in \mathbb{R}$, where

$$a_0 := \frac{1}{2\pi} \int_0^{2\pi} u_0(x) dx.$$

Solution. ■

3.3 Qualifying Exam, January '14

PROBLEM 3.3.1. Consider the first order equation in \mathbb{R}^2

$$x_2 u_{x_1} + x_1 u_{x_2} = 0.$$

- (a) Find the characteristic curves of the equation.
- (b) Consider the Cauchy problem for this equation prescribed on the line $x_1 = 1$:

$$u(1, x_2) = f(x_2).$$

Find a necessary condition on f so that the problem is solvable in a neighborhood of the point $(1, 0)$.

Solution. ■

PROBLEM 3.3.2. Let u be a continuous bounded solution of the initial value problem for the Laplace equation

$$\begin{cases} \Delta u = 0 & \text{in } \{x_n > 0\}, \\ u(x', 0) = g(x') & \text{for } x' \in \mathbb{R}^{n-1}, \end{cases}$$

where g is a continuous function with compact support in \mathbb{R}^{n-1} . Here $n \geq 2$. Prove that

$$u(x) \longrightarrow 0, \quad \text{as } |x| \longrightarrow \infty,$$

for $x \in \{x_n > 0\}$.

Solution. ■

PROBLEM 3.3.3. Let u be a bounded solution of the heat equation

$$\Delta u - u_t = 0 \quad \text{in } \mathbb{R} \times (0, \infty),$$

with the initial conditions $u(x, 0) = g(x)$, where g is a bounded continuous function on \mathbb{R} satisfying the Hölder condition

$$|g(x) - g(y)| \leq M|x - y|^\alpha, \quad x, y \in \mathbb{R}$$

with a constant $\alpha \in (0, 1]$. Show that

$$\begin{aligned} |u(x, t) - u(y, t)| &\leq M|x - y|^\alpha, & x, y \in \mathbb{R}, t > 0, \\ |u(x, t) - u(x, s)| &\leq C_\alpha M|t - s|^{\frac{\alpha}{2}}, & x \in \mathbb{R}, t, s > 0. \end{aligned}$$

[Hint: For the last inequality, in the representation formula of $u(x, t)$ as a convolution with the heat kernel $\Phi(y, t)$, make a change of variables $z = \frac{y}{\sqrt{t}}$ and use that $|\sqrt{t} - \sqrt{s}| \leq \sqrt{|t - s|}$.]

Solution. ■

PROBLEM 3.3.4. Let u be a positive harmonic function in the unit ball B_1 in \mathbb{R}^n . Show that

$$|D(\ln u)| \leq M \quad \text{in } B_{\frac{1}{2}}$$

for a constant M depending only on the dimension n .

[Hint: Use the interior derivative estimate $|Du(x)| \leq (\frac{C_n}{r}) \sup_{B_r(x)} |u|$ for $B_r(x) \subset B_1$ as well as the Harnack inequality for harmonic functions.]

Solution.

■

PROBLEM 3.3.5. Let u be a C^2 solution of the initial value problem

$$\begin{cases} u_{tt} - \Delta u = |x|^k & \text{in } \mathbb{R}^n \times (0, \infty), \\ u = 0, \quad u_t = 0 & \text{on } \mathbb{R}^n \times \{0\}. \end{cases}$$

for some $k \geq 0$. Prove that there exists a function $\varphi(r)$ such that

$$u(x, t) = t^{k+2} \varphi\left(\frac{|x|}{t}\right).$$

[Hint: As one of the steps show that u is $(k+2)$ -homogeneous in (x, t) variables, i.e., $u(\lambda x, \lambda t) = \lambda^{k+2} u(x, t)$ for any $\lambda > 0$.]

Solution.

■