Partial Differential Equations - Class Notes

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1 Chapter 1

Sidenotes

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What is a PDE?
A PDE is an equation which contains partial derivatives of an unknown function and we want to find that unknown function.
Example: $F(t, x, y, z, u, \frac{\partial u}{\partial t}, \frac{\partial u}{\partial x}, \frac{\partial u}{\partial y}, \frac{\partial u}{\partial z}, \frac{\partial^2 u}{\partial t^2}, \frac{\partial^2 u}{\partial x \partial y}, \ldots) = 0$.
Note, the first partial derivatives are considered 1^{st} ordered partials whereas the second ordered partials are considered 2^{nd} ordered partials.
The variables that are not u are considered independent variables and u is considered a dependent variable.
What PDEs do we study?
Generally, we restrict our attention to equations that model some phenomenom from physics, engineering, economics, geology, ... etc. We can use physical intuition to help guide the math.
Classification of PDEs

1. Order of PDE: Highest derivative.
   Example: $\frac{\partial^3 u}{\partial x^3} - \sin(y)u^7 = 3$ is a third order PDE.
   Example: $(\frac{\partial y}{\partial t})^5 - \frac{\partial^2 y}{\partial x \partial t} = e^x$ is a second order PDE.
2. Number of independent variables.
   Example: $\frac{du}{dt} = \frac{\partial^2 u}{\partial x^2}$ has two independent variables: t, x.
   This is the $1-D$ heat equation.
   Example: $\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} = \Delta u$ has 4 independent variables.
   This is the $3-D$ heat equation. Δu is Laplacian of u.
   Notation
   $\Delta u = \nabla^2 u = \nabla \cdot \nabla u = (\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}) \cdot (\frac{\partial u}{\partial x}, \frac{\partial u}{\partial y}, \frac{\partial u}{\partial z}) = \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}$
   $\Delta u = 0$ is considered Laplace's equation.
3. Linear vs non-linear
   A linear PDE is any equation of the form $L[u(x)] = f(x)$ where $f(x)$ is a known function is a linear partial differential operator.

Definition: A differential operator is any rule that takes a function as its input and returns an expression that involves the derivatives of that function.
Example:

$$\begin{aligned}
u(x,t) \qquad & v(x,t) && (1)\\
O[u] &= \frac{\partial^2 u}{\partial x^2} + \sin x + \pi - 7e^{tu} && (2)\\
O[u+3v] &= \frac{\partial^2}{\partial x^2}(u+3v) + \sin x + \pi - 7e^{tu+3tv} && (3)\\
&= \frac{\partial^2 u}{\partial x^2} + 3\frac{\partial^2 v}{\partial x^2} + \sin x + \pi - 7e^{tu+3tv} && (4)
\end{aligned}$$

Definition: A linear operator, L, is an operator that has the property:

$$L[au + bv] = aL[u] + bL[v] \tag{5}$$

Where a and b are constants.
Theorem: If u and v are vectors and L is linear, then L can be represented by a matrix.
Theorem: If L is linear ordinary operator, it must take the form:

$$L[u] = f_0(x)u + f_1(x)u' + f_2(x)u'' + \ldots + f_n(x)u^{(n)} \tag{6}$$

Where the f_i's are known functions.
Definition: A linear ODE is any ODE of the form where $f(x)$ is known is the following:

$$L[u] = f(x) \tag{7}$$

If $f(x) = 0$, then the equation is homogeneous. Otherwise, the equation is non-homogeneous.
Ex: $(u')^2 = 0 \Rightarrow u' = 0 \rightarrow$ linear, homogeneous.
Theorem: If L is a linear partial differential operator, it must take the form (x is a vector with n unknowns)

$$L[u(x)] = f_0(x)u + \sum_{i=1}^{n} f_i(x)\frac{\partial u}{\partial x_i} + \sum_{i=1}^{n}\sum_{j=1}^{n} f_{ij}(x)\frac{\partial^2 u}{\partial x_i \partial x_j} + \ldots \tag{8}$$

Definition: A linear PDE is any PDE of the form

$$L[u(x)] = f(x) \tag{9}$$

If $f(x) = 0$, the equation is homogeneous, else it is non-homogeneous.
Ex: $u_t = 4u_x$ - Linear, homogeneous.