

Applied Mathematics 202: Physical Mathematics II

FAS Course web page: <http://isites.harvard.edu/icb/icb.do?keyword=k87026> (Spring 2013)

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Feel free to write call or visit us with any questions.

1 Administrative

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Day & time: MWF 11-12

Location: see course web page

Sections: once a week, see FAS course web page for times and places.

1st meeting: Jan 28, 2013

Office hours: Eli: Please see course web page for times; 24 Oxford, museum building, 4th floor, room 456. TFs: please see course web page.

Textbooks: Page or section numbers from the relevant textbook for any given lecture are given in the detailed syllabus below. The main course textbook is

CP Carrier & Pearson, *Partial Differential Equations, theory & technique*

Also used at times,

Za Zauderer, *Partial differential equations of applied mathematics*, 3rd edition, Wiley.

Gr Greenberg, *Advanced Engineering Mathematics*, 2nd edition.

Gr2 Greenberg *Foundations of Applied Mathematics*

HW Haltiner and Williams, *Numerical prediction and dynamic meteorology*, 2nd edition, (Wiley, 1980).

OC Ockendon, Howison, Lacey & Movchan. *Applied partial differential equations*, (Oxford, 2003)

RM Richtmyer and Morton, *Difference methods for initial value problems*, (Interscience/ Wiley 1967)

Ze Zemyan, *The classical theory of integral equations*, Springer 2012.

Wh Whitham, *Linear and nonlinear waves*, 1974.

Ha Haberman, *Applied partial differential equations with Fourier series and boundary value problems*. 4th edition, 2003.

CG Cross and Greenside, *Pattern formation and dynamics in nonequilibrium systems*, Cambridge University Press New York, 2009.

Some additional ones,

Hi Hildebrand, *Advanced Calculus for Applications* (2nd Edition).

CH Courant & Hilbert, *Methods of Mathematical Physics*, vols. 1,2 (Wiley, 1989)

MF Morse & Feshbach, *Methods of theoretical physics*, vols. 1,2 (MGH, 1953)

Supplementary materials: Additional materials from several additional textbooks and other sources, including Matlab programs used in class, may be found [here](#). Follow links below for the specific source material for each lecture. **In order to access these materials from outside the Harvard campus, you'll need to use the VPN software which can be downloaded from the FAS software download site.**

Prerequisites: Applied Mathematics 105 (intro to ODEs and PDEs) or equivalent; also useful: Applied Mathematics 104 (complex analysis) or equivalent. *Note:* Applied Mathematics 201 and 202 are independent courses, and may be taken in any order.

Sections: Each TF will hold a weekly section and have weekly office hours. During the sections, the TFs will discuss and expand on the lecture material and solve additional problems.

Programming Skills: some of the demonstrations and homework assignments will be Matlab-based. Some previous programming exposure is assumed, although not necessarily in Matlab. Students are asked to download and install Matlab on their computers from the [FAS software download site](#).

Homework: homework will be assigned every nine to ten days, and will be due nine to ten days later in class. The homework assignments are essential for understanding the lecture material and introduce you to some important extensions. We strongly encourage you to discuss and work on homework problems with other students (and with the teaching staff, of course), but you must write your final answers in your own words. You should ensure that any written work you submit for evaluation reflects your own work and your own understanding of the topic.

Grading: Homework: 70%; midterm 15%; final 15%.

Readings: Students are encouraged to read from the sources pointed to by this extended syllabus, to obtain a broader perspective on the course material.

This document: <http://www.seas.harvard.edu/climate/eli/Courses/APM202/2013spring/detailed-syllabus-apm202.pdf>, available from within campus or via VPN.

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2 Outline

Theory and techniques for finding exact and approximate analytical solutions of partial differential equations: eigenfunction expansions, Green functions, variational calculus, transform techniques, perturbation methods, characteristics, selected nonlinear PDEs, introduction to numerical methods.

Note: Applied mathematics 201 and Applied mathematics 202 are independent of each other and may be taken at any order.

Prerequisites: Applied Mathematics 104 and Applied Mathematics 105 or equivalent.

3 Syllabus

Follow links to see the [source materials](#), including Matlab demo programs used for each lecture.

3.1 Introduction, overview

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Logistics, course requirements, textbooks, overview of the course, what to expect and what not to expect.

3.2 Separation of variables and basics

for diffusion, wave and Laplace equations. [downloads](#).

1. Fourier series and **Sturm-Liouville expansions**: S-L theorem (**Gr**§17.7.1 p 887-888 until but not including example 1; inner product definition eqn 14 p 890; theorem 17.7.1 p 891). Examples: Fourier series (example 1 p 888-889, eqns 2-9; then continuation in example 2, p 891-892, eqns 16-18); periodic and singular S-L (**Gr** p 906, eqns 2-5); Bessel (example 2 p 908-909, eqns 12-24); Legendre (example 2, p 910, eqns 25-28). Integrating factor to bring to S-L form ([notes](#))
2. **Diffusion**: **Motivation**, derivation of diffusion-advection eqn ([notes](#), section 2), scaling of diffusion-advection (same notes, section 3). Separation of variables and eigenfunction expansion for an inhomogeneous (forced) problem (**CP**§1.5, p 13-16), inhomogeneous end conditions (**CP**§1.7, p 17-18). Similarity solution ([notes](#)). [Time permitting:] Kelvin's wrong estimate of the age of the Earth (England et al, eqns 1-4); maximum principle (**CP**§1.9 p 19-20);
3. **Wave**: **Motivation** and derivation (**Gr**§19.1 p 1017-1019, eqns 2,5-9). Finite domain, separation of variables and S-L, using a 2d vibrating membrane example to keep it different from the 1d diffusion case above (**Gr**§19.3 p 1035-1039). Factoring into 1st order and D'Alembert's solution, e.g., for an infinite domain (**CP**§3.3 p 38-41), semi-infinite domain using the method of images (**CP**, problem 3.4.3 p 43). Using energy integral to demonstrate uniqueness (**CP**§3.11 p 52-53).
4. **Laplace** equation:
 - (a) **Motivation**, derivation ([notes](#), section 4).
 - (b) Separation of variables and S-L, for a 2d problem on a cylinder using non-Cartesian coordinates (**CP**§4.4, p 63-64 eqns 4.9-4.12);
 - (c) Average value principle derived from 4.12, and the resulting minimum and maximum principles (also, not essential: a more general discussion is given in **CP**§4.3).
 - (d) Integral constraints: consistency requirement with Neumann b.c. $\nabla^2 u = f(x, y)$. Mathematically: integrate equation over the domain; physically: prescribed heat source $f(x, y)$ plus prescribed heat flux into the domain must sum to zero for a steady state solution to the diffusion equation to be possible (**Gr** Exercise 17, p 1069).

- (e) Smoothing of discontinuities in boundary conditions (**CP**, problem 4.8.9 p 74, see also last paragraph starting on page 67 and [notes](#)).
- (f) Real and imaginary parts of an analytic function are harmonic; complex variable and conformal mapping (**CP**§4.7 p 68-71).
- (g) Some problem are non-separable due to eqn ($u_{xx} + u_{xy} + u_{yy} = 0$) or b.c.

3.3 Brief intro to numerics

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- (a) Motivation: On the need to solve numerically: (i) even very simple equations cannot be solved analytically (e.g., chaotic systems such as the [Lorenz equations](#)); (ii) a complicated analytic solution is not necessarily more insightful than a numerical one; in both cases one plots the solution as function of different parameters; (iii) a numerical solution is often the first step toward an analytic approximation, allowing to find which terms are dominant and which may be neglected.
- (b) Basics: first order one-sided ($O(\Delta)$) vs second order center difference ($O(\Delta^2)$) approximations (in space or time; **HW** p 109) as examples of the order (accuracy) of numerical schemes; first derivative in time (e.g., for diffusion equation) using first order Euler forward and improved Euler-Forward (**St** pp32-33).
- (c) Numerical stability: definition of convergence and stability (**HW**, p 122); stability analysis using the matrix method (**HW**, §5-5-1, pp 123-126)); Stability analysis using the Von Newman method (**HW**, §5-5-2, pp 127-129; Euler forward example in §5-6-1); [alternatively: **RM**, §1.2, 1.3 and 1.4, pp 4-12].
- (d) Implicit schemes and their stability advantage (semi-implicit scheme for advection equation **HW**, §5-6-3 p 132 and first half of p 133; [alternatively, implicit scheme for diffusion equation **RM**, §1.5, pp 16-18];
- (e) Stiff problems ([wikipedia](#), or a [local copy](#), highlighted definitions and examples of eqns 1-3, 10-15).
- (f) Preserving conservation laws of the continuous equations in the finite difference approximation, examples: advection and diffusion, advantage of writing the finite difference equations in flux form, and demonstrating staggered grids using the same example ([notes](#)).
- (g) Consistent formulation of finite-difference boundary conditions: prescribed flux/ value for diffusion equation, fixed vs stress-free end of a string for wave equation, location of end points on grid as function of type of boundary condition ([notes](#)).
- (h) Finite element methods (Burden and Faires, Numerical Analysis, 8th edition, §12.4 pp 721-733).

- (i) Spectral methods (Durrant, Numerical methods for wave equations in geophysical fluid dynamics, §4.2 p 176-184 or so).
- (j) Artificial numerical dispersion and dissipation (Durrant, Numerical methods for wave equations in geophysical fluid dynamics, §2.4.1, 2.4.2, 2.4.3)

3.4 Classification of 2nd order PDEs

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- (a) Intro: calculating the solution from Cauchy data (specified value and normal derivative) along the y axis, and when this might fail (CP§5.1 p 75-76).
- (b) More generally, trying to find a local solution based on Cauchy data on an arbitrary curve using a power method expansion, e.g., if characteristic is the y axis:

$$\phi = \phi(0, y) + x\phi_x(0, y) + \frac{x^2}{2!}\phi_{xx}(0, y) + \dots$$
; characteristics of 2nd order PDEs are lines along which this cannot be done; for other cases, this is possible according to the not so useful (see below) Cauchy-Kowalewski theorem. [Note: if curves $\xi(x, y)$, $\eta(x, y)$ are parallel at a point, the cross product of their gradients should vanish, so that $0 = \nabla\xi \times \nabla\eta = \xi_x\eta_y - \xi_y\eta_x = J(\xi, \eta)$]. (CP§5.2).
- (c) Case I: hyperbolic (wave, two real characteristics, $B^2 - AC > 0$): there are two cases (curves) for which the coefficient of $\phi_{\xi\xi}$ vanishes, so there are two curves $y(x)$ where Cauchy's data are insufficient. (CP§5.4, p 79-80, only until and including eqn 5.8). Example: for the standard wave equation, $\phi_{tt} - c^2\phi_{yy} = 0$ we have $A = 1$, $C = -c^2$, $B = D = E = F = G = 0$, so that $\pm\sqrt{B^2 - AC} = \pm c$. Comments: (1) the slope of the line $y(x)$ along which $\xi(x, y) = \text{const}$ is determined as follows,
 $0 = \frac{d}{dx}\text{const} = d\xi/dx = \partial_x\xi + \partial_y\xi\frac{dy}{dx}$, which implies $dy/dx = -\xi_x/\xi_y$. (2) Note the similarity of eqn 5.8 to the one derived in D'Alembert's solution, $\phi_{\eta\xi} = 0$ by using $\xi = x + ct$, $\eta = x - ct$ for the simple wave equation $\phi_{tt} = c^2\phi_{xx}$. (3) "Physical" interpretation: the two characteristics correspond to the trajectories of wave propagation in the (x, t) plane. Because the value of ϕ is effectively propagated along these curves, it cannot propagate off the curves in order to allow us to find the solution away from the curves. With any other curve on which Cauchy data are prescribed, these data can be carried off the curve by wave propagation to allow calculation of the solution there. (4) This is an important lesson on a consistent b.c. formulation for the wave equation and on what to avoid.
- (d) Case II: parabolic (diffusion, $B^2 - AC = 0$, one characteristic, CP§5.5, p 81): in the case of the standard 1d diffusion eqn $\phi_t = \kappa\phi_{xx}$ the characteristics in the (x, t) plane satisfy $dt/dx = -B/A = 0$ so that they are given by $t = \text{const}$ and are parallel to the x axis. Note that we cannot specify arbitrary Cauchy data in this case because the normal derivative is nothing by ϕ_t which is already given by ϕ_{xx} via the equation itself (determined from $\phi(x, t = c)$ along the characteristic). So in this case the characteristic

is a curve along which *arbitrary* Cauchy data *cannot* be specified rather than that they are *insufficient* for solving around the curve. While the classification indicates that we cannot solve the equation by a power series method with Cauchy data specified on the characteristic, we can still find a solution via time integration as long as the Cauchy data are consistently specified. Cauchy-Kowalewski theorem is clearly not so relevant in this case.

- (e) Case III: elliptic (Laplace, $B^2 - AC < 0$, no real characteristics): can always find a solution near a curve with specified Cauchy data via a power series expansion. Example: Laplace equation, $\phi_{xx} + \phi_{yy} = 0$, $A = 1$, $C = 1$, $B = D = E = F = G = 0$, $B^2 - AC = -1$. Physically, think steady diffusion, and note that information diffuses to the neighborhood of the curve, allowing the solution to be determined. However, one can come up with examples where the solution does not depend continuously on the Cauchy data (CP§5.10, p 90, middle paragraph), so that Cauchy-Kowalewski theorem is again not useful from practical point of view. Still, one can show that any elliptic equation may be locally transformed to the Laplace equation, providing some insight.
- (f) *Time permitting*: Characteristics as only possible location of discontinuities in second derivatives, as paths for signal propagation, as curves where Cauchy data cannot be specified arbitrarily. (CP§5.8).

3.5 1st order PDEs and characteristics

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- (a) **Motivation**: advection ([notes](#), section 2); traffic as an example of conservation laws ([Haberman](#), p 549, eqns 12.6.10 and 12.6.12, with $c(\rho) \equiv dq(\rho)/d\rho$); age distribution (population at age a and time t is equal to population at age $a - dt$ and time $t - dt$ minus those that died between $a - dt$ and a :
 $n(a, t) = n(a - dt, t - dt)(1 - \mu(a - dt)dt)$; this implies
 $[n(a, t) - n(a - dt, t - dt)]/dt = -\mu(a - dt)n(a - dt, t - dt)$; use
 $n(a - dt, t - dt) = n(a, t) - \partial_t n dt - \partial_a n dt$ to finally get $\frac{\partial n}{\partial t} + \frac{\partial n}{\partial a} = -\mu n$); factoring 2nd order wave PDE into first order PDEs.
- (b) **Linear** 1st order PDEs in two independent variables: solution using characteristics. Examples: (1) unidirectional wave equation **Za**, example 2.2 p68-69; (2) a slightly more advanced case (see section 1 of [notes](#), section 1, based on CP§6.1, eqns 6.6-6.10 p 93-94, plus problem 6.2.1, pp 93-94).
- (c) **Quasilinear, shocks**: quasilinear 1st order PDEs in two independent variables, characteristics; Examples: (1) equations (6.13-6.15) in CP§6.3p 97; (2) traffic problem, demonstrating, multivalued solutions and shock formation, shock conditions, velocity of shock propagation ([Haberman](#), §12.6.3-12.6.4, p 549-555). A complete example showing multivalued solution and the formation of a shock, see section 2 of [notes](#) and Matlab [program](#).

- (d) A bit of **theory**: characteristics here have the same meaning as with 2nd order PDEs: specifying the value of the function on characteristic curves does not allow us to solve near these curves (heuristically: because signal propagates along the curves rather than away from them. See details in **CP**§6.5 p 99-101). Implication: solvability and Jacobian of characteristic curves and curve along which initial values are specified (Jacobian vanishing means they are parallel and the problem is not well posed); *Time permitting*: extension to more independent variables (**CP**§6.7, eqns 6.18-end); envelopes of characteristics (**CP**§13.1).
- (e) **Nonlinear** 1st order PDEs, characteristics, Charpit's equations; example: Eikonal (Eiconal) equation ([notes](#) from Oxford course by Dr. Norbury; see also, although less transparent, **Za**§2.4 pp 102-111 or **OC**§8.2.1, §8.2.3 pp 360-368).

3.6 Transform methods

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used to reduce the order of the PDE or even convert it into an ODE. Fourier transforming the spatial dimension of a PDE often leads to a solvable ODE initial value problem in the time dimension; solving it and inverse Fourier transforming solves the original problem. Similarly, Laplace transforming a wave or diffusion equation leads to a boundary value problem, which can then be solved and inverse Laplace transformed.

- (a) **Fourier transform**: Fourier transform and inverse formula in n dimensions, ([proof](#)),

$$F(\mathbf{k}) = \frac{1}{(\sqrt{2\pi})^n} \int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} e^{i\mathbf{k}\cdot\mathbf{x}} f(\mathbf{x}) d\mathbf{x}; \quad f(\mathbf{x}) = \frac{1}{(\sqrt{2\pi})^n} \int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} e^{-i\mathbf{k}\cdot\mathbf{x}} F(\mathbf{k}) d\mathbf{k},$$

see also basic 1d definition and properties in **Za**§5.2, eqns 5.2.6-7, 5.2.10-11 p 256-257. Application to *diffusion* equation (**Za** example 5.2, p 261-262, eqns 5.2.26-5.2.39); *wave* equation, and derivation of D'Alembert's solution (**Za** example 5.3, p 264; is there a missing minus sign in front of one of the $G(\lambda)$ integrals in 5.2.46?); *Laplace* equation on a half-plane (**Za** example 5.4, eqns 5.2.50-5.2.58, p 265 to line 4 on p 266).

- (b) Higher dimensional Fourier transforms (**Za**§5.4, eqns 5.4.1-2, p 281). Example: 2d Modified Helmholtz equation (**Za** pp 287-288, eqns 5.4.26-5.4.36, skip details in eqns 5.4.32-5.4.35).
- (c) **Laplace transform**: Laplace transform and inverse transform,

$$F(s) = \int_0^{\infty} e^{-st} f(t) dt; \quad f(t) = \frac{1}{2\pi i} \int_{\gamma-i\infty}^{\gamma+i\infty} e^{st} F(s) ds.$$

Transform of time derivatives and other basic properties (**Za**§5.6, pp 297-299). Applications: *diffusion* equation in a semi-infinite domain, noting infinite propagation

speed of diffusing signal (CP§2.1, pp 24-25); *wave* equation (statement of problem in CP§3.3, eqn 3.5 on p 39; then solution method in CP§3.9, pp 50-51, with details given in the [notes](#); and the final solution is given by CP§3.3, eqn 3.7 on p 40).

(d) *Time permitting*: Fourier sine and cosine transforms; Hankel transform (Za§5.5).

3.7 Green's functions

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- (a) Motivation, using Green's function for nonhomogeneous problems, and/ or to satisfy initial and boundary conditions. Solving once for Green's function allows to easily solve many nonhomogeneous cases. We'll demonstrate several methods of solving for Green's function.
- (b) δ function reminder (viewed either as a generalized function defined only through its integrals when multiplying other functions: **Za**, p 438-441; or, alternatively, viewed as a limiting case of well behaved functions that tend to a delta function as a parameter goes to zero or infinity: **CP**, §2.5 p 30-33 for 1d case and p 141, eqns 9.5-9.8 for 3d case)
- (c) Laplace equation in a finite domain:
 - i. Construction of equation *and* boundary conditions for Green's function for Laplace equation using the divergence theorem; (section 1 in [notes](#); and then the somewhat more general case in **Za**§7.1 pp 410-412. Equivalently: **CP**§9.2, pp 142-143).
 - ii. Solving for the Green's function, **Method 1**: using eigenfunction expansion, useful for self-adjoint operators in bounded domains (first, theoretical derivation in **Za**§3 p 444 eqns 7.3.1-7.3.6 plus my notes that elaborate on the derivation of the eigenfunction expansion and show that the expansion indeed leads to a green's function; then example of a Laplace equation on a rectangle, **Za** example 7.6, eqns 7.3.26-7.3.41 pp 448-450); *Time permitting*: modification for Newman conditions (**Za** example 7.7, p 454-456);
 - iii. **Method 2**: finding an explicit solution for the Green's function using jump conditions at $x = \xi$. Start with a general derivation (**Za** eqns 7.3.7-7.3.12, pp 445-446); proceed with an example for an ODE (**Za** example 7.5, eqns 7.3.13-7.3.18, pp 446-447), and finish general discussion (**Za** eqn 7.3.1, p 447). Example: elliptic eqn on a rectangle again, this time using this alternative method (**Za** eqns 7.3.42-7.3.45, pp 450-451).
 - iv. **Method 3**: Finding a Green function solution g_1 with the right singularity at $x = \xi$, and adding a harmonic function p satisfying Laplace equation in interior and b.c. such that $g = g_1 + p$ satisfies the needed Green's function b.c. First, note that (in 3d!) $\Delta(1/r) = \delta(\vec{x} - \vec{\xi})$, [in 2d, the equivalent eqn is $\Delta \log r = \delta(\vec{x} - \vec{\xi})$] where

$r = |\vec{x} - \vec{\xi}|$ (CP p 141, first eqn and then 9.7-9.8). Next, definition of two components of Green's function, $1/r$ and p and an example in a sphere (CP§9.2 pp 142-144). This is based on Kelvin's inversion formula for a solution of Laplace eqn outside of a sphere in terms of a solution inside the sphere, briefly explained in CP question 7.2.5 on p 109); *Time permitting*: Modified Laplacian (CP§9.6, pp 152-154, uses modified Bessel functions K_0, I_0).

- (d) Diffusion equation in an unbounded domain. Start by deriving the eqn and b.c. for the Green's function using section 3 in these [notes](#). In order to solve for the Green's function, consider **Method 4**: using Fourier transform, useful in unbounded domains (Za§7.4, eqns 7.4.1-7.4.6, pp 462-463). *Time permitting*: see also [here](#) for solving for the Green's function of the wave equation using Fourier transform.
- (e) Wave equation: can use several of the previous methods, but consider an alternative, **Method 5**: using Laplace transform (CP§9.8, pp 156-157 eqns 9.37-9.40, with an example of a moving wave source; the actual derivation of the Green's function solution (9.38) is too brief, so see section 2 in [notes](#)). *Time permitting*: for an alternative approach using both Fourier and Laplace transforms, see eqns 18-37 on pp 3-5 of these [notes](#) from [here](#).

3.8 Variational methods

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- (a) Motivation: minimum area of soap films (derivation of problem using [notes](#)); equivalence of variational problems and PDEs (CP problem 10.2.7, p 166); data assimilation and weather prediction ([notes](#)); access to additional numerical methods.
- (b) Introductory example, calculus of variations, demonstrated first by differentiating with respect to epsilon and then using the δ notation (CP§10.1, pp 161-164).
- (c) A variational principle from squaring a given PDE: show explicitly CP problem 10.2.7, p 166 using my notes.
- (d) Natural boundary conditions (CP§10.3, p 167, eqns 10.4-10.7 plus the paragraph after this last equation).
- (e) Constraints and adjoint equations:
 - i. Reminder of Lagrange multipliers (CP§10.4, pp 168 and then text around eqn 10.12).
 - ii. An actual variational problem, posed at the beginning of the last paragraph ("we now extend...") On p 170, and then solved on p 171, eqn 10.14 to end of page.
 - iii. Note that when constraint is applied at each point, Lagrange multiplier becomes a function.

- iv. A time dependent example: calculating sensitivity efficiently using adjoint equations ([notes](#)).
- (f) Approximations: Rayleigh-Ritz method (**CP**§10.6, pp 174-177, until the end of the paragraph following eqn 10.23). A brief reminder: finite element (**CP**§10.8) is closely related to Rayleigh-Ritz method.

3.9 Perturbation methods

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- (a) Motivation.
- (b) Scaling, non-dimensionalization. Example 1: scaling estimate for maximum height of a thrown ball ([notes](#), “idea 2” on page 2). Example 2: forced pendulum: $m\ddot{x} + r\dot{x} + kx = F \sin \omega t$, use $x = Lx'$, $t = Tt'$, to get $\ddot{x}' + (T^2 r/Tm)\dot{x}' + (T^2 k/m)Lx' = (T^2 F/mL) \sin \omega Tt'$, now choose $T = \sqrt{m/k}$ (natural frequency), to find $\ddot{x}' + (r/\sqrt{mk})\dot{x}' + x' = (F/kL) \sin \omega \sqrt{m/kt}'$, choose again $L = F/k$, $\gamma = r/\sqrt{mk}$, define $\omega' = \omega/\sqrt{k/m}$ to finally get $\ddot{x}' + \gamma\dot{x}' + x' = \sin \omega't'$; note that this scaling predicts the amplitude L of the oscillations. Example 3: rotating shallow-water fluid dynamics ([notes](#) sections 1-2).
- (c) Regular perturbations: Example 1 (**CP**§8.1, pp 127-129; order: eqn 8.1 then 8.4, 8.5 and the following equations and b.c., then solution for $\phi^{(1)} = \psi^{(1)} - \psi^{(0)}$ from 8.2 and last eqn on p 127; then write $\psi^{(2)} = \phi^{(0)} + \phi^{(1)} + \phi^{(2)}$ from p 128 after eqn 8.3).
- (d) Singular perturbations and boundary layers: First, ODE reminder (**CP**§15.1, use these [notes](#), section 1). Then, Example 1: PDE case from (section 2 of [notes](#), based on **CP**§15.1). Example 2: quasi-geostrophy again, steady large-scale ocean circulation, with Gulf Stream as a boundary layer ([notes](#), section 5). Example 3: Boundary (initial) layer in a singular perturbation wave problem (**Za**, example 9.10, pp 606-610). Example 4: degeneracy of geostrophy and quasi-geostrophic shallow water vorticity equation ([notes](#) sections 3-4).
- (e) Boundary perturbations: when the boundary shape is close to that of a simpler object (e.g., circle) and the difference may be treated as a perturbation (**CP**§8.4). Another example: surface gravity waves, where the b.c is applied at an approximate boundary location rather than the accurate one (my hand-written notes, based on Knauss, introduction to physical oceanography, 2nd edition, 1996m pp 195-198).
- (f) A brief reminder of 1d bifurcations: saddle node and pitchfork.
- (g) Method of multiple scales: is again an approach to dealing with perturbation problems in which regular perturbation fails. This may happen for example in a time-dependent problem when the regular perturbation holds only for a short time due to the appearance of secular terms in the higher order perturbation terms which lead to a failure of the perturbation expansion at longer times.

- i. ODE example: a weakly nonlinear damped oscillator. (**Ha**§14.9.1, pp 696-699)
- ii. PDE example: a weakly unstable nonlinear diffusion equation. This is an example that occurs in the study of pattern formation (**Ha**§14.9.3, pp 703-705).

3.10 Integral equations

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- (a) Motivation and examples: random walks, radiative transfer ([notes](#)); Integral transforms are an example of an integral equation (e.g., Laplace transform $F(s) = \int_a^\infty e^{-st} f(t) dt$ is an inhomogeneous Fredholm integral eqn of the first kind for $f(t)$ in terms of the assumed known $F(s)$ with the symmetric kernel $K(x,t) = e^{-st}$); Conversion of 2nd order ODE to a Volterra integral equation of the second kind ([Shestopalov and Smirnov, 2002](#), section 4.1 including example 5, p 8-10, eqns 31-46).
- (b) Classification:
 - Fredholm integral equation of the first kind: $\varphi(z) = \int_a^b K(z, z_0)\psi(z_0)dz_0$,
 - and of the second kind: $\psi(z) = \varphi(z) + \lambda \int_a^b K(z, z_0)\psi(z_0)dz_0$,
 - Volterra of the first kind: $\varphi(z) = \int_a^z K(z, z_0)\psi(z_0)dz_0$,
 - and of the second kind: $\psi(z) = \varphi(z) + \int_a^z K(z, z_0)\psi(z_0)dz_0$.
 - Homogeneous ($\varphi = 0$) and non-homogeneous; Writing a Volterra equation in Fredholm form; Volterra equations for Green's function.
- (c) Fredholm second kind for separable Kernels: definition of problem (**Ze**§1, p 1); parallel with matrix eqn $\vec{\varphi} = \vec{f} + \lambda K\vec{\varphi}$; separable kernel example (**Ze**§1.2, p 4-11); summary combined Fredholm theorem (**Ze**§1.3.4 p 23-24). Discuss the condition for solvability when λ is an eigenvalue of the Kernel using a matrix example from my hand written notes.
- (d) Fredholm second kind for general kernels.
 - i. Method of successive substitution (**Ze**§2.2, p 33-34 to eqn 2.1); mention that this works only if $|K(x,t)| < M$ for all x,t in domain and $|\lambda|M(b-a) < 1$. Example ((a) on page 37?), make sure resolvent can be summed in close form.
 - ii. Method of successive approximation (**Ze**§2.3, p 37-39, to eqn 2.4; then theorem 2.3.1, p 41 until the expression for the resolvent kernel; note the different convergence condition obtained by this method although solution for resolvent is essentially the same).
 - iii. Example: **Ze**, p 42-43: example 1, and then example 2 (second approach, skipping the one based on the kernel being separable).

- (e) Briefly: Fredholm second kind, Hermitian Kernels. A Kernel is Hermitian if $K^*(x, t) \equiv \overline{K(t, x)} = K(x, t)$. E.g., $K = (x + t)$, $K = e^{i(x-t)}$ are Hermitian. Parallels with the matrix problem $\vec{\phi} = \vec{f} + \lambda K \vec{\phi}$ when K is symmetric, $K = K^T$ (use my notes); A Hermitian Kernel K has specific properties involving its eigenfunctions and eigenvalues, and both it and its resolvent can be expanded in terms of these and the integral equation be explicitly solved giving exactly the same expression as in the matrix problem (**Ze**§3, selected theorems and then Example 2, p 116-117).
- (f) Singular integral equations (infinite domain), consider only one simple but important example, of equations that can be solved using the convolution theorem and Fourier transform (**Ze**§7.2.2, p 256 until the third displayed equation on p 257).
- (g) Volterra equations: convolution type eqns can be solved using Laplace transform (**Ze**§4.1 p 152 and then **Ze**§4.3 p 167-168, only eqns 4.3, 4.5 and first displayed equation on p 168). Show example 1, p 168. Mention that successive approximation and substitution etc can also be used.

3.11 Nonlinear PDEs

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So far we deal with nonlinearities in the discussion of 1st order PDEs using the method of characteristics, as well as in the case of weakly nonlinear PDEs using the perturbation methods. We now consider two classes of higher order, strongly nonlinear PDEs as a brief introduction to the very rich area of nonlinear PDEs, one leading to solitons and the other to pattern formation.

3.11.1 Solitons

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- (a) Kortewegde Vries (KdV) eqn $\eta_t + c_0(1 + \frac{3}{2h_0}\eta)\eta_x + \gamma\eta_{xxx} = 0$ or $\eta_t + \eta_x + 6\eta\eta_x + \eta_{xxx} = 0$ (**Wh**, p 463, eqn 99);
- (b) Linear analysis with nonlinear term set to zero and dispersion relation ($\eta = e^{i(kx - \omega t)}$), so that $\omega = -k(1 + k^2)$, $c_{ph} = \omega/k = -(1 + k^2)$; so that linear wave propagation is to the left, short waves propagate faster);
- (c) Derivation of nonlinear propagating solutions (**Wh**§13.12, pp 467-468). Show nonlinear and linear single soliton solutions using Matlab program on course web page. Explanation: nonlinearity exactly balances dispersion.
- (d) Numerically only: elastic interaction of solutions, show two interacting solitons using same Matlab code (hence the name Solitons, indicating particle-like solutions). Note phase shift during interaction, easier to note for slower soliton.

- (e) (Time permitting:) infinite number of conservation laws, inverse scattering transform (OC§9.7, pp 417-426, or Wh§17).

3.11.2 Pattern formation

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- (a) Motivation: patterns in nature, pattern formation in Swift-Hohenberg model using Matlab code from [here](#), also posted [here](#) under course web page.
- (b) The Swift-Hohenberg equation in 1d and 2d. Potential dynamics of Swift-Hohenberg eqn (CG§5.1, p 179-182).
- (c) Linear stability analysis: while a uniform state leads to the global minimum value of the potential, it is unstable to small perturbations and the system then evolves to a different, local, minimum of the potential (CG§2.2, 2.3; Figs 2.7, 2.8, 2.9 in §2.5).
- (d) Complex amplitude, phase and translation symmetry, heuristically deduced nonlinear cubic form of amplitude equation (CG§4.1.1).
- (e) Nonlinear saturation, bifurcation theory, stripe states (CG§4.1.2, 4.1.3 pp 134-139).
- (f) Amplitude equation, derivation using multiple-scale perturbation theory (CG§A2.3.2 p 512-514).
- (g) Applications of amplitude equation:
 - i. effect of pattern-suppressing lateral boundaries, first a single boundary and then two (CG§6.4.1, pp 226-229).
 - ii. Eckhaus instability, (CG§6.4.2 p 230-233). Mention connection to Floquet theory: consider the linearized stability of a periodic orbit leading to the equation $\dot{\mathbf{x}} = A(t)\mathbf{x}$ where the matrix function $A(t+T) = A(t)$ is periodic and $\mathbf{x}(t)$ is the perturbation vector; Floquet theory tells us there is a solution of the form $\mathbf{x}(t) = \mathbf{p}(t)e^{\mu t}$ where $\mathbf{p}(t+T) = \mathbf{p}(t)$ is periodic; μ is also related to the eigenvalues of the linearized dynamics of a Poincare section of the periodic orbit (Strogatz).
 - iii. Existence of front solutions in a nonlinear diffusion equation and super-critical vs sub-critical pitchfork bifurcation (CG§8.3 p 296-299).
 - iv. (Time permitting:) Wavenumber selection (CG§8.3 p 296-308).
- (h) Mention briefly and show two figures of solution of Kuramoto-Sivashinsky eqn (CG§5.4 p 196-199).
- (i) (Time permitting:) Stability balloons, Zigzag instability of Swift-Hohenberg model (CG§4.2.1 p 139-147).
- (j) (Time permitting:) complex Ginzburg-Landau eqn (CG§5.5 p 196-199).

- (k) (Time permitting:) Nonlinear reaction-diffusion equations: fronts, linearized stability analysis via normal-mode eigenfunction expansion (Wikipedia; **CG**§5.6 and chapter 11).

3.12 More (Time permitting)

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- (a) Ray tracing solution of wave equations; WKB calculation of amplitude variations
- (b) Floquet theory
- (c) Similarity solutions, Lie groups (**OC**§6.5 p 262-271).
- (d) Barotropic instability, **CP** p 138, question 8.5.12).
- (e) Stochastic PDEs

3.13 Review

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