Notes

Chapter 1

Section 1.1 contains the basic differential calculus on Banach spaces; the material can be found in any nonlinear functional analysis book, for instance, Schwartz [Scw], Nirenberg [Ni 1], Deimling [De], Zeidler [Zei], Berger [Ber 1] etc. The discussion on Nemytscki operator can be found in Vainberg [Va], but the proof is much simpler than that in the reference.

The presentations of the implicit function theorem and the inverse function theorem are standard. Interesting applications are scattered in the literature, for instance, Nirenberg [Ni 4], Kazdan [Ka], Chow, Hale [CH], Mawhin [Maw 3] etc. The continuity method is extensively used in the existence proof of differential equations. The global implicit function theorem is due to Hadamard [Ha], Caccioppoli [Cac 1]; extensions can be found in Browder [Bd 1] and Plastock [Pl]. However, the proof presented here is very different. The application of the continuity method to an a priori bound as a simpler proof for semi-linear elliptic equations with quadratic growth was given by Amann and Crandall [AC]; the result for quasi-linear elliptic equations can be found in Ladyzenskaya and Ural'zeva [LU].

The Lyapunov–Schmidt reduction is extensively used in nonlinear problems. The application to the study of bifurcation problems introduced here is due to Crandall and Rabinowitz [CR 1], [CR 2]. The references on bifurcation theory are recommended to Chow and Hale [CH].

Sections 1.3.3–1.3.4 provide examples on gluing, which is an important technique in symplectic geometry. The material here is taken from Floer and Weinstein [FW] and Oh [Oh]. Further references are Floer [Fl 1] [Fl 2], Hofer and Zehnder [HZ 2]. Parallel to the implicit function theorem method, a gluing technique via the variational method was developed by Sere [Se]; it has been applied to the homoclinic orbits in Hamiltonian systems, multi-bump solutions, and multi-peak solutions for elliptic differential equations, see also Coti Zelati and Rabinowitz [CR], Li [Li 1], Gui [Gu] etc. Section 1.3.5 is another important technique in applying the implicit function theorem. The notion of transversality is taken from differential geometry. Combining with the Sard theorem, it provides a method for proving various generic type results. The finite-dimensional form of the transversality theorem can be found in Guillemin and Podollak [GP]. The Sard–Smale theorem is taken from Smale [Sm 3]. The simplicity of eigenvalues of the Laplacian on generic domains is due to Uhlenbeck [Uh].

Section 1.4 is on the Nash–Moser technique. See Nash [Na 2] and Moser [Mos 1] [Mos 2]. KAM theory is due to Kolmogorov [Ko], Arnold [Ar 2] and Moser [Mo 3]. The presentation here can be found in Hormander [Hor 2]. Applications in differential geometry can be found in Hamilton [Ham]; a version setting up on Frechet spaces is given therein. Other versions can be found in Nirenberg [Ni 1], see also Zehnder [Ze]. For further reading on recent developments of KAM theory to partial differential equations, Bourgain [Bou], Kuksin [Kuk], Wayne [Way], and Poschel [Po] are recommended.

Chapter 2

The order method is very different from other methods in this book. In concrete problems, once the assumptions are met, the method is simple and powerful. Our discussions start with the Bourbaki–Kneser principle [Bo], [Kn], see also Tarski [Ta]. The Amann theorem [Am 1] is a version that is easy to apply. The sub- and super-solutions method is extensively applied in ODE and PDE whenever the maximum principle is applicable. However, the constructions of sub- and super-solutions require special knowledge and techniques. We are satisfied introducing the method by an example. The Caristi fixed-point theorem [Ca] is among a few fixed-point theorems without assuming the continuity of the nonlinear mappings, applications can be found in [Lie]. Also, an equivalent version of this theorem is the very important Ekeland variational principle [Ek 1]; various applications in different branches of analysis can be found in [Ek 1] and de Figueiredo [dF].

There are lots of books on convex analysis; in Sect. 2.2, we only present very briefly the necessary material for the sequel discussions. References can be found in Ekeland and Temam [ET], Aubin and Ekeland [AE] etc.

Fixed points for nonexpansive mappings have been studied by Browder [Bd 2], Goebel [GK], etc. The importance of this class of mappings is that one of the fixed points can be figured out by iteration methods. Many algorithms for finding feasible solutions for convex programming have been studied in recent years, see [B], [BB].

There are many ways to introduce the Schauder fixed-point theorem and related topics. We use the KKM theorem [KKM] and Ky Fan's inequality [FK 3] as the starting point. The Nash equilibrium [Na 3], the Von Neumann–Sion minimax theorem [VN] [Si], the Schauder fixed-point theorem [Sc], the Schauder–Techonoff theorem, the Ky Fan–Glicksberg theorem [FK 1], [FK 2], and the existence result of Hartman and Stampacchia on variational inequalitiy [HS] are direct consequences. The variational inequality [LS], [Bd 3], [Stm] is another direction in convex analysis with many applications in free boundary problems from mathematical physics, see Duvaut and Lions [DL], Kinderlehrer and Stampacchia [KS], Friedman [Fr] etc. However, the approach based on the fixed points of set-valued mappings is due to the author, see [Ch 1], [Ch 2].

The theory of monotone operators and pseudo-monotone operators attracted much attention in the 1960s and 70s. The works of Minty [Min], Browder [Bd 4], Hartman and Stampacchia [HS], H. Brezis [Br 1], etc. constitute the basic content of the theory. Again we use the version of the Ky Fan inequality due to Brezis, Nirenberg and Stampacchia [BNS] to derive the most important results on this topics. For applications to quasi-linear elliptic equations see Leray and Lions [LL], to boundary value problems in nonlinear partial differential equations see Lions [LJ 1], and to nonlinear semigroups of operators see Brezis [Br 1], Crandall and Ligget [CLi].

Chapter 3

The Brouwer degree is a topological invariant; roughly speaking, there are two approaches: algebraic (see for instance Spanier [Sp], Greenberg [GH]) and differential (Milnor [Mi 2]). The Leray–Schauder degree is its extension to compact vector fields [LS] on Banach space.

The analytic presentation can be found in many books and lecture notes, for instance: J. Schwartz [Scw], Nirenberg [Ni 1], Rabinowitz [Ra 2], Guillemin and Podollak [GP], Zeidler [Zei] etc. The materials of Sects. 3.1–3.4 are taken from these references. An application of the transversality theorem to the proof for the Borsuk–Ulam theorem and to the computation of S^1-invariant degree are due to Nirenberg [Ni 3].

Sections 3.5 and 3.6.3 are adapted from Rabinowitz [Ra 1], [Ra 2]. Section 3.6.2 is based on Dancer [Dan 1]. The material of Sects. 3.6.4 and 3.6.5 is taken from Amann [Am 2], Krasnosel'ski [Kr 2], de Figueiredo, Lions and Nussbaum [FLN], Chang [Ch 3], and Dancer [Dan 2]. The blowing up method in a priori estimates is a useful technique, see for instance, Gidas and Spruck [GS].

Section 7 contains various extensions of the Leray–Schauder degree; for α-set contraction mappings, see Darbo [Dar], Stuart and Toland [ST]; for condensing mappings, see Nussbaum [Nu], Sadovskii [Sa], set-valued mappings see Browder [Bd 5], Cellina [Ce], Ma [Ma], Chang [Ch 2]. There are other directions: Fredholm operators, see Elworthy and Tromba [ElT 1] [ElT 2], Nirenberg [Ni 4], Llyord [Ll], Fitzpatrick, Pejsachowicz and Rabier [FP], [FPR], [PR 1, PR 2]; coincidence degree theory, Mawhin [Maw 1], etc.

Chapter 4

Section 4.1 is an introduction to the calculus of variations. The derivations of the Euler–Lagrange equation, the Legendre–Hadamard condition and the Ljusternik theorem on constraint variational problems can be found in any standard textbook. For the dual variational principle, i.e., the Legendre–Fenchel transformation, see for instance, Arnold [Ar 1], Ekeland and Temam [ET] or Aubin and Ekeland [AE]. For the Hamiltonian systems, the second version of the dual variational principle, i.e., the Legendre transform to the Hamiltonian function of all variables if the latter is strictly convex, see Clarke and Ekeland [CE].

In Sect. 4.2, the direct method is a general principle in the calculus of variations. We introduce a few interesting examples showing how the principle works.

Harmonic maps were introduced by Eells and Sampson [ES] in representing homotopy classes of mappings between two manifolds. Here we only touch on the existence of a weak solution. For $m = 2$ the harmonic map with minimal energy is smooth, see Morrey [Mo 2]; for $m > 2$, Schoen and Uhlenbeck [ScU 1], [ScU 2] proved that the singularity has at most a codimension 3 finite Hausforff measure. A nonsmooth minimal energy harmonic map was given by Lin [Lin]. As to nonminimal energy harmonic maps, the smoothness for $m = 2$ was proved by Helein [Hel 1], and the existence of a nowhere continuous harmonic for $m = 3$ constructed by Riviere [Ri].

The example on constant mean curvature surface is taken from Hildebrandt [Hi 1]; a systematic introduction can be found in Struwe [St 2].

The prescribing scalar curvature problem can be found in Kazdan [Ka], Kazdan and Warner [KW 1], [KW 2]. The result for $\chi(M) = 0$ is due to Berger [Ber 2], that for real projective space P^2 is due to Moser [Mos 4]; however, we present an easy proof with the aid of Aubin's inequality [Au 3].

Section 4.3 is from Morrey [Mo 1] [Mo 2], Dacorogna [Dac], Acerbi and Fusco [AF], Marcellini [Mar], Muller [Mul 1] [Mul 2] Sverak [Sv 1] [Sv 2], Zhang [Zh 1] and Ball [Bal 1].

The relaxation method is from Buttazzo [Bu] and Dacorogna [Dac]. For the two-well problem, Zhang [Zh 2] has obtained an explicit expression of the quasi-convex envelope for the square distance function.

The Young measure was introduced by Young [Yo]; the presentation here is due to Ball [Bal 2], see also [Mul 1], Kinderlehrer and Pedregal [KP 1, KP 2]. In Chipot [Chi], there are examples on the computation of Young measures.

There are few books in dealing with the BV space, see for instance, Giusti [Gi], Evans and Gariepy [EG], Zimer [Zi], Ambrosio [Amb] etc. Section 4.5.1 is adapted from these books.

The Hardy space and BMO space are important parts in harmonic analysis, see Stein [Ste 1, Ste 2] and Stein–Weiss [SW]. They are applied to PDEs in compensated compactness (as seen in Sect. 4.5.2) and in regularity (for harmonic maps see Helein [Hel 2] Evans [Ev 2]. For the background material we recommend Brezis and Nirenberg [BN 3], and Semmes [Se] as references. The connection between Hardy space and the compensated compactness is revealed by Coifman, Lions, Meyer and Semmes [CLMS]. In the applications to the calculus of variations, the bitting theorem due to Chacon is required, see Brooks and Chacon [BC]. Compensated compactness is also an important tool in nonlinear analysis; we refer the reader to Tartar [Tar 1, Tar 2], DiPerna [Di] and Evans [Ev 2].

We briefly introduce the Γ-convergence in Sect. 4.6 by a result of Modica and Mortola [MM], see also Alberti [Al]. Readers who want to know more can read Dal Maso [D].

The Munford–Shah model [MS] in the segmentation of the image processing is an interesting subject; the existence proof was given by Ambrisio [Amb], De Giorgi and [DG 2], and De Giorgi and Ambrosio [GA]. More details can be found in Ambrosio Fusco and Pallara [AFP], Dal Maso, Morel and Solimini [DMS] and Morel and Solimini [MS]. As to the regularity of the edge curve, see Morel [Mor]. However, all of these results require deep knowledge on BV functions. A much simplified model presented here is from Nordström [No].

Concentration compactness [LP] in combination with blowing up analysis [SU] is one of the most important techniques in nonlinear problems without compactness. Since interesting concrete problems require more background knowledge, they are out of the scope of this book. We present in Sect. 4.7 just an introduction of the idea: The concentration phenomenon and the role of the bubble (or best constant). Two examples on semilinear elliptic equations are studied: The subcritical exponent on R^n, see Coti Zelati [CZ], and the critical exponent on bounded domain, see Brezis and Nirenberg [BN 1].

Section 4.8 is the preliminary of the minimax method. The Palais–Smale condition [PS] and the mountain pass lemma due to Ambrosetti and Rabinowitz [AR] are introduced in accordance with the Ekeland minimizing principle. The proof was given by Shi [Shi] and Aubin and Ekeland [AE]. Examples are taken from Mawhin [Maw 2] and Ambrosetti and Rabinowitz [AR].

Chapter 5

Section 5.1: The most recommended book in introducing Morse theory on compact manifolds is Milnor [Mi 1]. The classics are Morse [Mo] and Morse and Cairns [MC]. The extension to infinite-dimensional space can be found in Chang [Ch 4], [Ch 5]. See also Mawhin and Willem [MW].

The background material in this section can be found in Palais [Pa 1], Palais and Smale [PS], Rothe [Ro 1], [Ro 2], [Ro 3], Marino and Prodi [MP 1], [MP 2], Chang [Ch 7], [Ch 8], Wang [Wa 1], [Wa 2], Castro and Lazer [CaL].

The critical point theory has been extended to non-differentiable functionals, see Chang [Ch 6] for locally Lipschitzian functionals on Banach space, and Kartiel [Ka], Ioffe, Schwartzmann [IS], and Corvellec, De Giovanni, Marzocchi [CGM] for continuous functions on metric spaces.

Section 5.2: There are several books on minimax methods, see for instance Rabinowitz [Ra 4], Struwe [St 1], Ghoussoub [GH], and Willem [Wi] etc.

The background material can be found in Rabinowitz [Ra 4], [Ra 5], Palais [Pa 2], [Pa 3], Ni [Ni], Chang [Ch 5], Tian [Ti], Liu [Liu 1], [Liu 2], Viterbo [Vi 2], Solimini [So], Chang, Long and Zehnder [CYZ], Fournier and Willem [FoW].

The notion of category was discovered by Ljusternik and Schnirelmenn [LjS 1]. The genus was introduced by Krasnosel'ski in [Kr 1], while for general index theory see Fadell and Rabinowitz [Fr]. The geometric index for S^1 is taken from Benci [Be 1] and Nirenberg [Ni 3]; other extensions of the index theory can be found in Benci and Rabinowitz [BR 2].

Section 5.3: There are many papers on periodic solutions for Hamiltonian systems via variational methods. The results related to this section are Rabinowitz [Ra 3], Weinstein [We 1], [We 2], Viterbo [Vi 1], Hofer and Zehnder [HZ 2], Struwe [St 1]. Further development on the Weinstein conjecture can be found in Hofer and Viterbo [HV], Hofer [Ho 2] and Liu and Tian [LT 1].

The following books are recommended: Hofer and Zehnder [HZ 1], Ekeland [Ek 2], Mawhin and Willem [MW].

Other important topics on the periodic solutions include:

- For Arnold conjecture on the symplectic fixed points and Lagrangian intersections, see Conley and Zehnder [CZ 1], Floer [Fl 1], [Fl 2], [Fl 3], Liu and Tian, [LT 2], Fukaya Ono [FO].
- The number of the periodic orbits on compact convex hypersurface has been estimated by Long and Zhu [LZ].
- For the N-body problem, see Bahri and Rabinowitz [Br].

Section 5.4: The main result of this section is taken from Chang and Yang [CY 1], [CY 2], and Chang and Liu [CL 2]. See also Han [Han], Chen and Li [ChL 1], [ChL 2]. The related prescribing scalar curvature problem on S^n has received extensive attention. For $n = 3$ see Bahri and Coron [BC], and for high dimension, see Schoen and Zhang [SZ], Bahri [Bar 1], [Bar 2], Li [Li 1], and Chen and Lin [ChL].

Section 5.5: Conley's index theory was introduced by Conley [Co], in which isolating neighborhoods for isolated invariant sets are compact. The theory is completed by Conley and Zehnder [CZ 2], Salamon [Sal], Salamon and Zehnder [SZ]. There are many ways to extend the theory to infinite-dimensional spaces, see Rybakowski [Ry], Rybakowski and Zehnder [RZ], Benci [Be 2] etc. The relationship between the Conley theory and the Morse theory can be found in Chang and Ghoussoub [CG]. For further reading see Michaikov [Mic] and Smoller [Smo].

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