

Ec 181:  
Convex Analysis and Economic Theory

KC Border

AY 2019–2020

Woe to the author who always wants to teach!  
The secret of being a bore is to tell everything.

—Voltaire, *De la Nature de l'Homme* (1737)

# Topics

<b>0 Vector spaces</b>	
0.1 Basic notation . . . . .	0–1
0.2 Some geometry of vector spaces . . . . .	0–3
0.3 Linear functions . . . . .	0–7
0.4 Aside: The Summation Principle . . . . .	0–8
References . . . . .	0–9
<b>1 Convex sets and functions</b>	
1.1 Convex sets . . . . .	1–1
1.2 Convex functions . . . . .	1–4
1.3 Related concepts . . . . .	1–6
1.4 Complements . . . . .	1–7
References . . . . .	1–9
<b>2 Convex hulls</b>	
2.1 The convex hull of a set . . . . .	2–1
2.2 The closed convex hull of a set . . . . .	2–3
2.3 Digression: Basic nonnegative linear combinations . . . . .	2–3
2.4 Carathéodory’s Theorem . . . . .	2–5
2.5 Shapley–Folkman Theorem I . . . . .	2–6
2.6 Extreme points, faces, and extreme rays . . . . .	2–8
References . . . . .	2–12
<b>3 Cones</b>	
3.1 Cones . . . . .	3–1
3.2 Dual cones . . . . .	3–3
3.3 A word on terminology . . . . .	3–4
References . . . . .	3–4
<b>4 Digression: Hulls</b>	
4.1 Some special classes of sets . . . . .	4–1
4.2 Affine subspaces . . . . .	4–2
4.3 Hulls . . . . .	4–5
<b>5 Topological properties of convex sets</b>	
5.1 Interior and closure of convex sets . . . . .	5–1
5.2 Internal points, affine hulls, and relative interiors . . . . .	5–4
5.3 Topological properties of convex hulls . . . . .	5–7
References . . . . .	5–7
<b>6 Convex functions I</b>	
6.1 Elementary properties of convex functions . . . . .	6–1
6.2 Extrema of convex and concave functions . . . . .	6–8
6.3 Continuity of convex functions . . . . .	6–9
References . . . . .	6–13

**7 Quasiconvex Functions I**

7.1	Level sets of functions . . . . .	7–1
7.2	Quasiconvexity and quasiconcavity . . . . .	7–1
7.3	Quasi-conXXXity and extrema . . . . .	7–3
7.4	Explicit quasiconXXXity and nonextremization . . . . .	7–4
	References . . . . .	7–6

**8 Separation theorems**

8.1	Hyperplanes and half spaces . . . . .	8–1
8.2	Separating convex sets with hyperplanes . . . . .	8–1
8.3	Strong separating hyperplane theorem . . . . .	8–5
8.4	Supporting hyperplanes . . . . .	8–7
8.5	More separating hyperplane theorems . . . . .	8–10
	References . . . . .	8–11

**9 Support Functions**

9.1	Support functions . . . . .	9–1
9.2	Sublinear functions . . . . .	9–4
9.3	Gauge functions . . . . .	9–5
9.4	Gauge functions and support functions . . . . .	9–7
	References . . . . .	9–9

**10 Constrained optima and Lagrangean saddlepoints**

10.1	An alternative . . . . .	10–1
10.2	Saddlepoints . . . . .	10–2
10.3	Lagrangeans . . . . .	10–2
10.4	Lagrangean Saddlepoints and Minimization . . . . .	10–8
10.5	Decentralization and Lagrange Multipliers . . . . .	10–9
	References . . . . .	10–12

**11 Models of economies and equilibria**

11.1	Models of economies . . . . .	11–1
11.2	The production possibility set: I . . . . .	11–4
11.3	The production possibility set: II . . . . .	11–5
11.4	Efficiency . . . . .	11–5
11.5	Models of equilibrium . . . . .	11–5
11.6	Properties for utilities . . . . .	11–8
11.7	Utility maximization and expenditure minimization . . . . .	11–8
	References . . . . .	11–11

**12 Welfare and the Core of an Economy**

12.1	The First Welfare Theorem . . . . .	12–1
12.2	The Second Welfare Theorem . . . . .	12–2
12.3	Digression: Drawing the Scitovsky set . . . . .	12–5
12.4	Saddlepoints and the Second Welfare Theorem . . . . .	12–5
12.5	Core of a pure exchange economy . . . . .	12–8
12.6	Core of a replica economy . . . . .	12–9
12.7	Edgeworth equilibria . . . . .	12–11
12.8	Approximate equilibria . . . . .	12–12
12.9	Complements . . . . .	12–12
	References . . . . .	12–12

**13 Convex and concave functions**

13.1	Talking convex analysis . . . . .	13–1
13.2	Hyperplanes in $X \times \mathbf{R}$ and affine functions on $X$ . . . . .	13–4
13.3	Lower semicontinuous convex functions . . . . .	13–4
13.4	Appendix: Semicontinuous functions . . . . .	13–9
13.5*	Appendix: Closed functions revisited . . . . .	13–11
	References . . . . .	13–14

**14 Subgradients**

14.1	Subgradients . . . . .	14–1
14.2	Jensen’s Inequality . . . . .	14–8
	References . . . . .	14–9

**15 Subgradients and Directional Derivatives**

15.1	Directional derivatives and the subdifferential . . . . .	15–1
15.2	Supergradient of a support function . . . . .	15–5
	References . . . . .	15–6

**16 Fenchel conjugates**

16.1	Conjugate functions . . . . .	16–1
16.2	Support functions are conjugates of indicator functions . . . . .	16–8
16.3	Conjugate of an affine function . . . . .	16–8
16.4	Fenchel’s Duality Theorem . . . . .	16–9
16.5	Infimal convolution . . . . .	16–11
16.6	Fenchel’s Duality Theorem redux . . . . .	16–12
16.7	The calculus of sub/superdifferentials . . . . .	16–14
	References . . . . .	16–16

**17 Monotone mappings**

17.1	The subdifferential correspondence . . . . .	17–1
17.2	Monotone and cyclically monotone mappings . . . . .	17–1
17.3	Cyclic monotonicity characterizes subdifferentials . . . . .	17–2
17.4	Monotonicity vs. cyclic monotonicity . . . . .	17–6
17.5	Monotonicity and second derivatives . . . . .	17–7
	References . . . . .	17–9

**18 Differentiability**

18.1	Differentiable functions . . . . .	18–1
18.2	Differentiability of convex functions on $\mathbf{R}^m$ . . . . .	18–6
18.3	Differentiability and the single subgradient . . . . .	18–9
18.4	Convex functions on finite dimensional spaces . . . . .	18–10
	References . . . . .	18–12

**19 Extreme sets**

19.1	Extreme points of convex sets . . . . .	19–1
	References . . . . .	19–4

**20 When are Sums Closed?**

20.1	Is a sum of closed sets closed? . . . . .	20–1
20.2	Asymptotic cones . . . . .	20–1
20.3	When a sum of closed sets is closed . . . . .	20–4
20.4	When is an intersection of closed sets bounded? . . . . .	20–5
	References . . . . .	20–6

**21 Closed Functions**

21.1*	Closed convex functions . . . . .	21–1
21.2*	The difference between closedness and semicontinuity . . . . .	21–2
21.3	The closure of a function . . . . .	21–3
21.4	Closed sublinear functions . . . . .	21–4
	References . . . . .	21–5

**22 Introduction to posets and lattices**

22.1	Partially ordered sets . . . . .	22–1
22.2	Zorn's Lemma . . . . .	22–2
22.3	Lattices . . . . .	22–3
22.4	Lattice homomorphisms . . . . .	22–5
22.5	The lattice $\mathcal{K}$ of compact convex sets . . . . .	22–5
22.6	The lattice $\mathcal{S}$ of continuous sublinear functions . . . . .	22–5
22.7	The lattice isomorphism of $\mathcal{K}$ and $\mathcal{S}$ . . . . .	22–6
22.8	Aside: More on profit functions . . . . .	22–6
22.9	Aside: Support functionals and the Hausdorff metric . . . . .	22–8
22.10	Aside: the Hausdorff metric . . . . .	22–8
22.11	Aside: Strassen's integrability theorem . . . . .	22–9
	References . . . . .	22–9

**23 Separation and the Hahn–Banach theorem**

23.1	Other approaches to separation theorems . . . . .	23–1
23.2	Extension of linear functionals . . . . .	23–1
23.3	The Hahn–Banach Extension Theorem . . . . .	23–2
23.4	Another Separating Hyperplane Theorem . . . . .	23–5
23.5	Extension and Separation . . . . .	23–5
23.6	Other equivalent propositions . . . . .	23–6
23.7*	Digression: Quotient spaces . . . . .	23–9
23.8*	Digression: Complementary subspaces . . . . .	23–10
	References . . . . .	23–11

**24 Convexity and incentive design**

24.1	Proper scoring rules . . . . .	24–1
24.2	Private information and trade . . . . .	24–4
	References . . . . .	24–9

**25 Inequalities and alternatives**

25.1	Solutions of systems of equalities . . . . .	25–1
25.2	Nonnegative solutions of systems of equalities . . . . .	25–5
25.3	Solutions of systems of inequalities . . . . .	25–6
25.4	Tucker’s Theorem . . . . .	25–13
25.5	The Gauss–Jordan method . . . . .	25–15
25.6	A different look at the Gauss–Jordan method . . . . .	25–16
25.7	<i>Tableaux</i> and the replacement operation . . . . .	25–19
25.8	More on <i>tableaux</i> . . . . .	25–22
25.9	The Fredholm Alternative revisited . . . . .	25–23
25.10	Farkas’ Lemma Revisited . . . . .	25–25
25.11	Application to saddlepoint theorems . . . . .	25–27
	References . . . . .	25–27

**26 Polyhedra and polytopes**

26.1	Solution sets, polyhedra, and polytopes . . . . .	26–1
26.2	Finitely generated cones . . . . .	26–1
26.3	Finitely generated cones and alternatives . . . . .	26–7
26.4	Polytopes . . . . .	26–8
26.5	Extreme rays of finitely generated convex cones . . . . .	26–11
26.6	How many extreme rays can a dual cone have? . . . . .	26–13
26.7	Fourier–Motzkin elimination . . . . .	26–16
26.8	The Double Description Method . . . . .	26–18
	References . . . . .	26–21

**27 The uses of alternatives in economic theory**

27.1	Revealed preference and utility maximization . . . . .	27–1
27.2	Subjective probability . . . . .	27–2
27.3	Subjective probability and betting . . . . .	27–8
27.4	No-arbitrage and Arrow–Debreu prices . . . . .	27–10
27.5	Statistical inference—the game . . . . .	27–12
27.6	Dynamic asset pricing . . . . .	27–14
27.7	Stochastic dominance and expected utility . . . . .	27–20
27.8	Harsanyi’s utilitarianism theorem . . . . .	27–22
27.9	Core of a TU game . . . . .	27–23
27.10	Reduced form auctions . . . . .	27–24
27.11	Simple rationality . . . . .	27–28
27.12	Stochastic rationality . . . . .	27–28
27.13	Concave rationality . . . . .	27–28
27.14	Dynamic Bayesian updating . . . . .	27–28
27.15	Representative voting . . . . .	27–28
27.16	Probabilities with given marginals . . . . .	27–29
	References . . . . .	27–29

**28 Linear Programming: Theory**

28.1	Primal and dual linear programs . . . . .	28–1
28.2	The primal is the dual of the dual . . . . .	28–3
28.3	Lagrangeans for linear programs . . . . .	28–3
28.4	The saddlepoint theorem for linear programs . . . . .	28–4
28.5	Other formulations . . . . .	28–8
28.6	Basic optimal solutions . . . . .	28–14
28.7	Basic feasible solutions are vertices . . . . .	28–15
28.8	Linear equations as LPs . . . . .	28–17
	References . . . . .	28–18

**29 The Simplex Method**

29.1	The simplex method . . . . .	29–2
29.2	How many steps until the Simplex Algorithm stops? . . . . .	29–9
29.3	The stopping conditions . . . . .	29–9
29.4	Phase 1: Finding a starting point . . . . .	29–12
29.5	A worked example . . . . .	29–14
29.6	The simplex algorithm solves the dual program too . . . . .	29–18
29.7	Degeneracy, cycling, and the lexicographic simplex algorithm	29–20
29.8	The simplex algorithm and vertexes . . . . .	29–25
29.9	The Simplex Algorithm jumps to an adjacent vertex . . . . .	29–34
29.10	The Simplex Algorithm is a steepest ascent method . . . . .	29–37
29.11	Why is it called the Simplex Algorithm? . . . . .	29–37
29.12	More worked examples . . . . .	29–37
	References . . . . .	29–46

**30 Introduction to graphs**

References . . . . .	30–1
----------------------	------

**A Mathematical background**

A.1 Extended real numbers . . . . .	A–1
A.2 Infimum and supremum . . . . .	A–1
A.3 Sets associated with functions . . . . .	A–2
A.4 Metric spaces . . . . .	A–3
A.5 Complete metric spaces . . . . .	A–3
A.6 Distance functions . . . . .	A–4
A.7 Topological spaces . . . . .	A–5
A.8 Semicontinuity . . . . .	A–9
A.9 Weierstrass's Theorem . . . . .	A–11
A.10 Compactness in metric spaces . . . . .	A–11
A.11 Topological vector spaces . . . . .	A–12
A.12 Continuity of the coordinate map . . . . .	A–12
A.13 $\mathbf{R}^m$ is a Hilbert space . . . . .	A–13
A.14 Parallelogram Law . . . . .	A–15
A.15 Metric projection in a Hilbert space . . . . .	A–15
References . . . . .	A–16

**Index**