Useful Economic Theory and Mathematics

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All models are wrong, but some are useful.

Contents

Chapter 1 Stochastic Dominance

Based on

- MIT 14.123 S15 Stochastic Dominance Lecture Notes
- Princeton ECO317 Economics of Uncertainty Fall Term 2007 Notes for lectures 4. Stochastic Dominance
- Jensen, M. K. (2018). Distributional comparative statics. *The Review of Economic Studies*, 85(1), 581-610.

1.1 General Definitions

Definition 1.1 (Jensen (2018), Defnition 1)

Let F and G be two distributions on the same measurable space. Let u be a function for which the following expression is well-defined,

$$\int u(x)dF \geq \int u(x)dG \tag{1.1}$$

Then:

- F **first-order stochastically dominates** G if 1.1 holds for any increasing function u.
- F is a **mean-preserving spread** of G if 1.1 holds for any convex function u.
- F is a **mean-preserving contraction** of G if 1.1 holds for any concave function u.
- F **second-order stochastically dominates** G if 1.1 holds for any concave and increasing function u.
- F **dominates** G **in the convex-increasing order** if 1.1 holds for any convex and increasing function u.

♣

Note *F is a **mean-preserving contraction** of $G \Leftrightarrow G$ is a **mean-preserving spread** of F.*

Definition 1.2 (MPS and MPC)

We define the following notations of sets.

- MPS(f) is the set of all **mean-preserving spread** of f;
- MPC(f) is the set of all **mean-preserving contraction** of f;

♣

1.2 First-order Stochastic Dominance

1.2.1 Two Equivalent Definitions

Definition 1.3 (First-order Stochastic Dominance)

For any lotteries F and G, F **first-order stochastically dominates** G if and only if the decision maker weakly prefers F to G under every weakly increasing utility function u, i.e.,

$$\int u(x)dF \geq \int u(x)dG$$

♣

Definition 1.4 (First-order Stochastic Dominance)

For any lotteries F and G, F **first-order stochastically dominates** G if and only if

$$F(x) \leq G(x), \forall x$$

♣

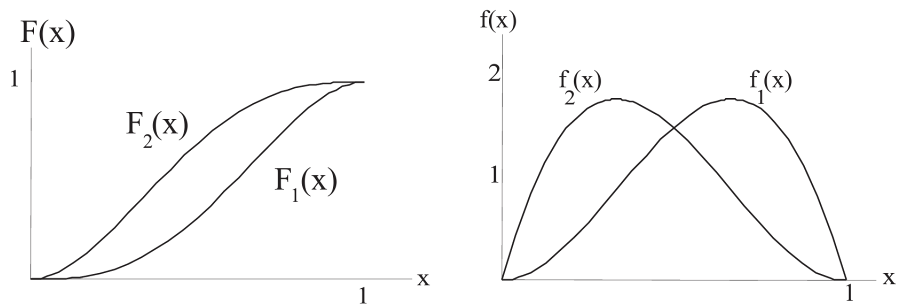

Figure 1.1: F_1 is FOSD over F_2: CDF and density comparison

1.3 Second-order Stochastic Dominance

1.3.1 Definition in terms of final goals

Definition 1.5 (Second-order Stochastic Dominance)

For any lotteries F and G, F **second-order stochastically dominates** G if and only if the decision maker weakly prefers F to G under every weakly **increasing concave** utility function u, i.e.,

$$\int u(x)dF \geq \int u(x)dG$$

♣

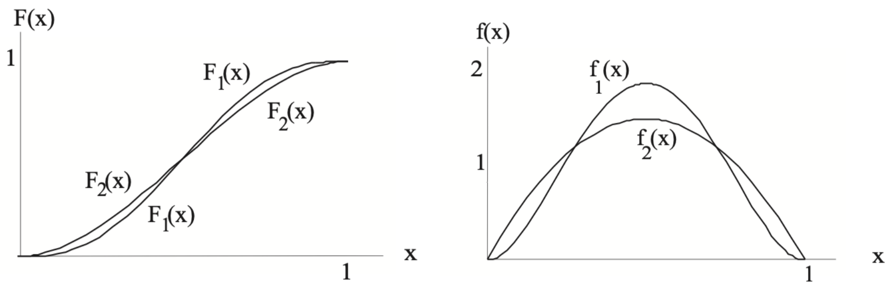

Figure 1.2: F_1 is SOSD over F_2: CDF and density comparison

1.3.2 Mean-Preserving Spread/Contraction

Definition 1.6 (Mean-Preserving Spread)

Let x_F and x_G be the random variables associated with lotteries F and G. Then G is a **mean-preserving spread** of F if and only if

$$x_G \stackrel{d}{=} x_F + \varepsilon$$

for some random variable ε such that $\mathbb{E}(\varepsilon \mid x_F) = 0 \; \forall x_F$. ♣

The "$\stackrel{d}{=}$" means "is equal in distribution to" (that is, "has the same distribution as").

Note *Given G is a **mean-preserving spread** of F, G has larger variance than F.*

Example 1.1 $F(198) = \frac{1}{2}, F(202) = \frac{1}{2}$ and $G(100) = \frac{1}{100}, G(200) = \frac{98}{100}, G(300) = \frac{1}{100}$. Then

$$x_G \stackrel{d}{=} x_F + \varepsilon$$

where the distribution of ε can be solved by

$$\begin{cases} G(300) = F(198)P(\varepsilon = 102|x_F = 198) + F(202)P(\varepsilon = 98|x_F = 202) \\ G(200) = F(198)P(\varepsilon = 2|x_F = 198) + F(202)P(\varepsilon = -2|x_F = 202) \\ G(100) = F(198)P(\varepsilon = -98|x_F = 198) + F(202)P(\varepsilon = -102|x_F = 202) \end{cases}$$

1.3.3 For Same Mean Distributions, Second-order Stochastic Dominance is equivalent to Mean-Preserving Spread

Theorem 1.1 (Second-order Stochastic Dominance Equivalence)

Given $\int x dF = \int x dG$ (same mean). The following are equivalent.

1. *F second-order stochastically dominates G: $\int u(x)dF \geq \int u(x)dG$ for every weakly increasing concave utility function u.*
2. *F is a mean-preserving contraction of G (G is a mean-preserving spread of F).*
3. *For every $t \geq 0$, $\int_a^t G(x)dx \geq \int_a^t F(x)dx$.* ♡

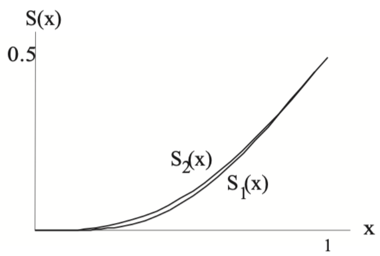

Figure 1.3: F_1 is SOSD over F_2, $S(t) : \int_a^t F_2(x)dx \geq \int_a^t F_1(x)dx$

Corollary 1.1 (Euqivalent Definitions of MPC and MPS)

F is a mean-preserving contraction of G (or G is a mean-preserving spread of F) if and only if

(1). $\int xdF = \int xdG$

(2). $\int_a^t G(x)dx \geq \int_a^t F(x)dx, \forall t$

♡

Corollary 1.2 (MPC(f) **and** MPS(f) **are convex and compact)**

MPC(f) *and* MPS(f) *are* ***convex*** *and* ***compact***.

♡

Chapter 2 Tools for Comparative Statics

Consider the function $f : (0, 2\pi) \times \mathbb{R} \to \mathbb{R}$ s.t.

$$f(x, a) = \sin x + a$$

Let $X = (0, 2\pi)$ and let $f_a(x) = f(x, a) = \sin x + a$ denote the perturbed function for fixed a.

2.1 Regular and Critical Points and Values

2.1.1 Rank of Derivatives $\text{Rank}df_x = \text{Rank}Df(x)$

Suppose $X \subseteq \mathbb{R}^n$ is open. Suppose $f : X \to \mathbb{R}^m$ is differentiable at $x \in X$, and let $W = \{e_1, ..., e_n\}$ denote the standard basis of $\mathbb{R}^n$. Then $df_x \in L(\mathbb{R}^n, \mathbb{R}^m)$, and

$$\begin{aligned}
\text{Rank}df_x &= \dim \text{Im}(df_x) \\
&= \dim \text{span}\{df_x(e_1), ..., df_x(e_n)\} \\
&= \dim \text{span}\{Df(x)e_1, ..., Df(x)e_n\} \\
&= \dim \text{span}\{\text{column 1 of } Df(x), ..., \text{column n of } Df(x)\} \\
&= \text{Rank}Df(x)
\end{aligned}$$

Thus,

$$\text{Rank}df_x \leq \min\{m, n\}$$

df_x has **full rank** if $\text{Rank}df_x = \min\{m, n\}$, that is, is df_x has the maximum possible rank.

2.1.2 Regular and Critical Points and Values

Definition 2.1 (Regular and Critical Points and Values)

Suppose $X \subseteq \mathbb{R}^n$ is open. Suppose $f : X \to \mathbb{R}^m$ is differentiable at $x \in X$.

1. x is a **regular point** of f if $\text{Rank}df_x = \min\{m, n\}$.
2. x is a **critical point** of f if $\text{Rank}df_x < \min\{m, n\}$.
3. y is a **critical value** of f if there exists $x \in f^{-1}(y)$ such that x is a critical point of f.
4. y is a **regular value** of f if y is not a critical value of f.

♣

Note *Notice that if $y \notin f(X)$, so $f^{-1}(y) = \emptyset$, then y is automatically a regular value of f.*

Example 2.1 Suppose $f(x,y) = (\sin x, \cos y)$, $Df(x,y) = \begin{bmatrix} \cos x & 0 \\ 0 & -\sin y \end{bmatrix}$. Critical point: $\{(\frac{k\pi}{2}, \mathbb{R}) : k \in 2\mathbb{Z}+1\} \cup \{(\mathbb{R}, k\pi) : k \in \mathbb{Z}\}$; Critical values: $\{(x,y) : x = 1$ or $x = -1$ or $y = 1$ or $y = -1\}$

2.2 Inverse and Implicit Function Theorem

2.2.1 Inverse Function Theorem

Using Taylor's theorem to approximate

$$f(x) = f(x_0) + Df(x_0)(x - x_0) + o(x - x_0)$$

The requirement of "regular point" is necessary for the $Df(x_0)$ being invertible.

Theorem 2.1 (Inverse Function Theorem)

Suppose $X \subseteq \mathbb{R}^n$ is open. Suppose $f : X \to \mathbb{R}^n$ is C^1 on X, and $x_0 \in X$. If $\det Df(x_0) \neq 0$ (i.e., x_0 is a regular point of f), then there are open neighborhoods U of x_0 and V of $f(x_0)$ s.t.

$$f : U \to V \text{ is bijective (on-to-on and onto)}$$

$$\exists\, f^{-1} : V \to U \text{ is } C^1$$

$$Df^{-1}(f(x_0)) = [Df(x_0)]^{-1}$$

$$(\text{In } \mathbb{R},\ (f^{-1})'(f(x_0)) = (f'(x_0))^{-1})$$

If in addition $f \in C^k$, then $f^{-1} \in C^k$. ♡

2.2.2 Implicit Function Theorem

Using Taylor's theorem to approximate

$$f(x,a) = f(x_0,a_0) + Df(x_0,a_0)(x - x_0) + Df(x_0,a_0)(a - a_0) + \text{remainder}$$

The requirement of "regular point" is necessary for the $Df(x_0,a_0)$ being invertible.

We want to know how the function $x^*(a)$ changes with keeping $f(x^*,a) = 0$.

Theorem 2.2 (Implicit Function Theorem)

Suppose $X \subseteq \mathbb{R}^n$ and $A \subseteq \mathbb{R}^p$ are open and $f : X \times A \to \mathbb{R}^n$ is C^1. Suppose $f(x_0,a_0) = 0$ and $\det(D_x f(x_0,a_0)) \neq 0$, i.e. x_0 is a regular point of $f(\cdot, a_0)$. Then there are open neighborhoods U of x_0 ($U \subseteq X$) and W of a_0 such that

$$\forall a \in W,\ \exists! x \in U \text{ s.t. } f(x,a) = 0$$

For each $a \in W$ *let* $g(a)$ *be that unique* x*. Then* $g : W \to U$ *is* C^1 *and*

$$Dg(a_0) = -[D_x f(x_0, a_0)]^{-1}[D_a f(x_0, a_0)]$$

If in addition $f \in C^k$*, then* $g \in C^k$*.*

2.2.3 Prove Implicit Function Theorem Given Inverse Function Theorem

Proof 2.1

1. *Firstly, we prove "g is differentiable": The "change of a" incurs the value change:*

$$\begin{aligned} f(x_0, a_0 + h) &= f(x_0, a_0) + D_a f(x_0, a_0)h + o(h) \\ &= D_a f(x_0, a_0)h + o(h) \end{aligned}$$

Find a Δx *such that the new* x *can let the value go back to* 0*, i.e.,* $f(x_0 + \Delta x, a_0 + h) = 0$*. That is,*

$$g(a_0 + h) = x_0 + \Delta x$$

To prove "g is differentiable", we want to prove "$\exists T \in L(A, X)$ *s.t.* $\Delta x = T(h) + o(h)$*"*

$$\begin{aligned} 0 &= f(x_0 + \Delta x, a_0 + h) \\ &= f(x_0, a_0) + D_x f(x_0, a_0 + h)\Delta x + D_a f(x_0, a_0)h + o(\Delta x) + o(h) \\ &= D_x f(x_0, a_0 + h)\Delta x + D_a f(x_0, a_0)h + o(\Delta x) + o(h) \end{aligned}$$

$$D_x f(x_0, a_0 + h)\Delta x = -D_a f(x_0, a_0)h + o(\Delta x) + o(h)$$

Because f *is* C^1 *and the determinant is a continuous function of the entries of the matrix,* $\det D_x f(x_0, a_0 + h) \neq 0$ *for* h *sufficiently small, so*

$$\Delta x = -[D_x f(x_0, a_0 + h)]^{-1} D_a f(x_0, a_0)h + o(\Delta x) + o(h)$$

$$\text{Since } f \in C^1, \Delta x = -[D_x f(x_0, a_0) + o(1)]^{-1} D_a f(x_0, a_0)h + o(\Delta x) + o(h)$$

$$\text{Since } f \in C^1, \Delta x = -[D_x f(x_0, a_0)]^{-1} D_a f(x_0, a_0)h + o(\Delta x) + o(h)$$

Hence, "g is differentiable" is proved and the derivative of g *is* $Dg(a_0) = -[D_x f(x_0, a_0)]^{-1}[D_a f(x_0, a_0)]$*.*

2. *Secondly, given the "g is differentiable", we can also compute the derivative by*

$$Df(g(a), a)(a_0) = 0$$

$$D_x f(x_0, a_0) Dg(a_0) + D_a f(x_0, a_0) = 0$$

$$Dg(a_0) = -[D_x f(x_0, a_0)]^{-1} D_a f(x_0, a_0)$$

Example 2.2 $f : \mathbb{R}^3 \to \mathbb{R}^2$, $f((3,-1,2)) = (0,0)$, $Df(3,-1,2) = \begin{bmatrix} 1 & 2 & 1 \\ 1 & -1 & 1 \end{bmatrix}$. Then, let $(x_0, a_0) = (3,-1,2)$, where $x_0 = 3$ and $a_0 = (-1,2)$. Or, we can let $(x_0, a_0) = (3,-1,2)$, where $x_0 = (3,-1)$ and $a_0 = 2$.

2.2.4 Prove Inverse Function Theorem Given Implicit Function Theorem

Proof 2.2 (Prove Inverse Function Theorem Given Implicit Function Theorem)

Define $F : X \times \mathbb{R}^n$ s.t. $F(x,y) = y - f(x)$. Let $y_0 = f(x_0)$.

$$D_x F(x,y) = -Df(x),\ D_y F(x,y) = I_{n\times n}$$

According to the implicit function theorem, there are open sets $U \subseteq X$ and $V \subseteq \mathbb{R}^n$ such that $x_0 \in U$, $y_0 \in V$ and a function $g : V \to U$ differentiable at y_0 such that $F(g(y), y) = 0$ for all $y \in V$. So, $0 = F(g(y), y) = y - f(g(y))$, we have $f(g(y)) = y$, that is $g = f^{-1}$. $f : U \to V$ is bijective because it has inverse $g : V \to U$.

By the implicit function theorem, $g(y)$ is differentiable and

$$Df^{-1}(y_0) = Dg(y_0) = -[D_x F(x_0, y_0)]^{-1}[D_y F(x_0, y_0)] = [Df(x_0)]^{-1}$$

where $y_0 = f(x_0)$.

By the implicit function theorem, the $g = f^{-1}$ is C^k if f is C^k.

All in all, the inverse function theorem is proved.

2.2.5 Example: Using Implicit Function Theorem

$x^2 + y^2 = c$. Define $g(x,y) = x^2 + y^2 - c$. The optimal solution of y given x is represented by $y^*(x)$. By the implicit function theorem,

$$\frac{\partial y^*}{\partial x} = -\frac{\frac{\partial g}{\partial x}\big|_{x,y^*}}{\frac{\partial g}{\partial y}\big|_{x,y^*}}$$

Example 2.3 Let us consider a firm that produces a good y; it uses two inputs x_1 and x_2. The firm sells the output and acquires the inputs in competitive markets: The market price of y is p, and the cost of each unit of x_1 and x_2 are w_1 and w_2 respectively. Its technology is given by $f : \mathbb{R}^2_+ \to \mathbb{R}_+$, where $f(x_1, x_2) = x_1^a x_2^b$, $a + b < 1$. Its profits take the form

$$\pi(x_1, x_2; p, w_1, w_2) = p x_1^a x_2^b - w_1 x_1 - w_2 x_2$$

The firm selects x_1 and x_2 in order to maximize profits. **We aim to know how its choice of x_1 and x_2 is affected by a change in w_1.**

Assuming an interior solution, the first-order conditions of this optimization problem are

$$\frac{\partial \pi}{\partial x_1}(x_1^*, x_2^*; p, w_1, w_2) = pa(x_1^*)^{a-1}(x_2^*)^b - w_1 = 0$$
$$\frac{\partial \pi}{\partial x_2}(x_1^*, x_2^*; p, w_1, w_2) = pb(x_1^*)^{a}(x_2^*)^{b-1} - w_2 = 0$$

for some $(x_1, x_2) = (x_1^*, x_2^*)$.

Let us define

$$F(x_1^*, x_2^*; p, w_1, w_2) = \begin{bmatrix} pa(x_1^*)^{a-1}(x_2^*)^b - w_1 \\ pb(x_1^*)^{a}(x_2^*)^{b-1} - w_1 \end{bmatrix}$$

Jacobian matrices are

$$D_{(x_1,x_2)}F(x_1^*, x_2^*; p, w_1, w_2) = \begin{bmatrix} pa(a-1)(x_1^*)^{a-2}(x_2^*)^b & pab(x_1^*)^{a-1}(x_2^*)^{b-1} \\ pab(x_1^*)^{a-1}(x_2^*)^{b-1} & pb(b-1)(x_1^*)^{a}(x_2^*)^{b-2} \end{bmatrix}$$

$$D_{w_1}F(x_1^*, x_2^*; p, w_1, w_2) = \begin{bmatrix} -1 \\ 0 \end{bmatrix}$$

By the implicit function theorem, we can get

$$\begin{aligned} \begin{bmatrix} \frac{\partial x_1^*}{\partial w_1} \\ \frac{\partial x_2^*}{\partial w_1} \end{bmatrix} &= -[D_{(x_1,x_2)}F(x_1^*, x_2^*; p, w_1, w_2)]^{-1}[D_{w_1}F(x_1^*, x_2^*; p, w_1, w_2)] \\ &= [D_{(x_1,x_2)}F(x_1^*, x_2^*; p, w_1, w_2)]^{-1}\begin{bmatrix} 1 \\ 0 \end{bmatrix} \end{aligned}$$

2.2.6 Corollary: $a \to \{x \in X : f(x,a) = 0\}$ is lhc

Corollary 2.1

Suppose $X \subseteq \mathbb{R}^n$ and $A \subseteq \mathbb{R}^p$ are open and $f : X \times A \to \mathbb{R}^n$ is C^1. If 0 is a regular value of $f(\cdot, a_0)$, then the correspondence

$$a \to \{x \in X : f(x,a) = 0\}$$

is ***lower hemicontinuous*** *at a_0.*

♡

2.3 Transversality and Genericity

2.3.1 Lebesgue Measure Zero

Definition 2.2 (Lebesgue Measure Zero)

Suppose $A \subseteq \mathbb{R}^n$. A has **Lebesgue measure zero** if for every $\varepsilon > 0$ there is a countable collection of rectangles $I_1, I_2, ...$ such that

$$\sum_{k=1}^{\infty} \text{Vol}(I_k) < \varepsilon \text{ and } A \subseteq \cup_{k=1}^{\infty} I_k$$

Here by a rectangle we mean $I_k = \times_{j=1}^{n}(a_j^k, b_j^k) = \{x \in \mathbb{R}^n : x_j \in (a_j^k, b_j^k), \forall j\}$ for some $a_j^k < b_j^k \in \mathbb{R}$, and

$$\text{Vol}(I_k) = \prod_{j=1}^{n} |b_j^k - a_j^k|$$

♣

Example 2.4

1. "Lower-dimensional" sets have Lebesgue measure zero. For example, $A = \{x \in \mathbb{R}^2 : x_2 = 0\}$
2. Any **finite** set has Lebesgue measure zero in $\mathbb{R}^n$.
3. **Finite Union** of sets that have Lebesgue measure zero has Lebesgue measure zero: If A_n has Lebesgue measure zero $\forall n$ then $\cup_{n \in N} A_n$ has Lebesgue measure zero.
4. Every **countable** set (e.g. $\mathbb{Q}$) has Lebesgue measure zero.
5. No open set in $\mathbb{R}^n$ has Lebesgue measure zero.

2.3.2 Sard's Theorem

Theorem 2.3 (Sard's Theorem)

Let $X \subseteq \mathbb{R}^n$ be open, and $f : X \to \mathbb{R}^m$ be C^r with $r \geq 1 + max\{0, n - m\}$. Then the set of all critical values of f has Lebesgue measure zero.

♡

2.3.3 Transversality Theorem

Theorem 2.4 (Transversality Theorem)

Let $X \subseteq \mathbb{R}^n$ and $A \subseteq \mathbb{R}^p$ be open, and $f : X \times A \to \mathbb{R}^m$ be C^r with $r \geq 1 + max\{0, n - m\}$. Suppose that 0 is a regular value of f (that is all (x, a) such that $f(x, a) = 0$ are regular points). Then,

1. *$\exists A_0 \subseteq A$ such that $A \backslash A_0$ has Lebesgue measure zero.*
2. *$\forall a \in A_0$, 0 is a regular value of $f_a = f(\cdot, a)$.*

♡

Example 2.5 $f : \mathbb{R}^4 \to \mathbb{R}^3$ s.t. $f(x, y, z, w) = (g(x) + y, z^3 + 1, w + x + y^2)$

Chapter 3 Fixed Point Theorem

3.1 Contraction Mapping Theorem (@ Lec 05 of ECON 204)

3.1.1 Contraction: Lipschitz continuous with constant < 1

Definition 3.1

Let (X, d) be a nonempty complete metric space. An operator is a function $T : X \to X$. An operator T is a **contraction of modulus** β if $\beta < 1$ and

$$d(T(x), T(y)) \leq \beta d(x, y), \forall x, y \in X$$

♣

A contraction shrinks distances by a *uniform* factor $\beta < 1$.

3.1.2 Theorem: Contraction $\Rightarrow$ Uniformly Continuous

Theorem 3.1 (Contraction $\Rightarrow$ Uniformly Continuous)

Every contraction is uniformly continuous.

♡

Proof 3.1

Let $\delta = \frac{\varepsilon}{\beta}$.

3.1.3 Blackwell's Sufficient Conditions for Contraction

Let X be a set, and let $B(X)$ be the set of all bounded functions from X to $\mathbb{R}$. Then $(B(X), \|\cdot\|_\infty)$ is a normed vector space.

(Notice that below we use shorthand notation that identifies a constant function with its constant value in $\mathbb{R}$, that is, we write interchangeably $a \in \mathbb{R}$ and $a : X \to \mathbb{R}$ to denote the function such that $a(x) = a, \forall x \in X$.)

Theorem 3.2 (Blackwell's Sufficient Conditions)

Consider $B(X)$ *with the sup norm* $\|\cdot\|_\infty$. *Let* $T : B(X) \to B(X)$ *be an operator satisfying*

1. *(monotonicity)* $f(x) \leq g(x), \forall x \in X \Rightarrow (Tf)(x) \leq (Tg)(x), \forall x \in X$
2. *(discounting)* $\exists \beta \in (0, 1)$ *such that for every* $a \geq 0$ *and* $x \in X$,

$$(T(f + a))(x) \leq (Tf)(x) + \beta a$$

Then T *is a contraction with modulus* β.

♡

Proof 3.2

Fix $f, g \in B(X)$. By the definition of the sup norm,

$$f(x) \leq g(x) + \|f - g\|_\infty \forall x \in X$$

Then

$$(Tf)(x) \leq (T(g + \|f - g\|_\infty))(x) \leq (Tg)(x) + \beta\|f - g\|_\infty \quad \forall x \in X$$

where the first inequality above follows from monotonicity, and the second from discounting. Thus

$$(Tf)(x) - (Tg)(x) \leq \beta\|f - g\|_\infty \quad \forall x \in X$$

Reversing the roles of f and g above gives

$$(Tg)(x) - (Tf)(x) \leq \beta\|f - g\|_\infty \quad \forall x \in X$$

Thus

$$\|T(f) - T(g)\|_\infty \leq \beta\|f - g\|_\infty$$

Thus T is a contraction with modulus β

3.2 Fixed Point Theorem (@ Lec 05 of ECON 204)

3.2.1 Fixed Point

Definition 3.2 (Fixed Point)

A **fixed point** of an operator T is element $x^* \in X$ such that $T(x^*) = x^*$. ♣

Definition 3.3 (Fixed Point of Function)

Let X be a nonempty set and $f : X \to X$. A point $x^* \in X$ is a **fixed point** of f if $f(x^*) = x^*$. ♣

Example 3.1 Let $X = \mathbb{R}$ and $f : \mathbb{R} \to \mathbb{R}$

1. $f(x) = 2x$ has fixed point: $x = 0$.
2. $f(x) = x$ has fixed points: $x \in \mathbb{R}$.
3. $f(x) = x + 1$ doesn't have fixed points.

3.2.2 ★ Contraction Mapping Theorem: contraction ⇒ exist unique fixed point

Theorem 3.3 (Contraction Mapping Theorem)

Let (X, d) be a nonempty complete metric space and $T : X \to X$ a contraction with modulus $\beta < 1$. Then

1. *T has a unique fixed point x^*.*
2. *For every $x_0 \in X$, the sequence defined by*

$$\begin{aligned} x_1 &= T(x_0) \\ x_2 &= T(x_1) = T(T(x_0)) = T^2(x_0) \\ &\vdots \\ x_{n+1} &= T(x_n) = T^{n+1}(x_0) \end{aligned}$$

converges to x^*.

♡

Note that the theorem asserts both the **existence** and **uniqueness** of the fixed point, as well as giving an **algorithm** to find the fixed point of a contraction.

Proof 3.3

Define the sequence $\{x_n\}$ as above. Then,

$$\begin{aligned} d(x_{n+1}, x_n) &= d(T(x_n), T(x_{n-1})) \\ &\leq \beta d(x_n, x_{n-1}) \\ &\leq \beta^n d(x_1, x_0) \end{aligned}$$

Then for any $n > m$,

$$\begin{aligned} d(x_n, x_m) &\leq d(x_1, x_0) \sum_{i=m}^{n-1} \beta^i \\ &< d(x_1, x_0) \sum_{i=m}^{\infty} \beta^i \\ &= \frac{\beta^m}{1-\beta} d(x_1, x_0) \to 0 \text{ as } m \to \infty \end{aligned}$$

Fixed $\varepsilon > 0$, we can choose $N(\varepsilon)$ such that $\forall n, m > N(\varepsilon)$,

$$d(x_n, x_m) < \frac{\beta^m}{1-\beta} d(x_1, x_0) < \varepsilon$$

Therefore, $\{x_n\}$ is Cauchy. Since (X, d) is complete, $x_n \to x^*$ for some $x^* \in X$.

Next we show that x^* is a fixed point of T.

$$\begin{aligned}
T(x^*) &= T\left(\lim_{n\to\infty} x_n\right) \\
&= \lim_{n\to\infty} T(x_n) \text{ since } T \text{ is continuous} \\
&= \lim_{n\to\infty} x_{n+1} \\
&= x^*
\end{aligned}$$

so x^* is a fixed point of T.

Finally, we show that there is at most one fixed point. Suppose x^* and y^* are both fixed points of T, so $T(x^*) = x^*$ and $T(y^*) = y^*$. Then

$$\begin{aligned}
d(x^*, y^*) &= d(T(x^*), T(y^*)) \\
&\leq \beta d(x^*, y^*) \\
\Rightarrow (1-\beta)d(x^*, y^*) &\leq 0 \\
\Rightarrow d(x^*, y^*) &\leq 0
\end{aligned}$$

So $d(x^*, y^*) = 0$, which implies $x^* = y^*$.

3.2.3 Conditions for Fixed Point's Continuous Dependence on Parameters

Theorem 3.4 (Continuous Dependence on Parameters)

Let (X, d) and (Ω, ρ) be two metric spaces and $T : X \times \Omega \to X$. For each parameter $\omega \in \Omega$ let $T_\omega : X \to X$ be defined by $T_\omega(x) = T(x, \omega)$.

Suppose (1). (X, d) is complete, (2). T is continuous in ω (that is $T(x, \cdot) : \Omega \to X$ is continuous for each $x \in X$), and (3). $\exists \beta < 1$ such that T_ω is a contraction of modulus β $\forall \omega \in \Omega$.

Then the fixed point function (about parameter ω) $x^* : \Omega \to X$ defined by $x^*(\omega) = T_\omega(x^*(\omega))$ is continuous. ♡

3.3 Brouwer's Fixed Point Theorem (@ Lec 13 of ECON 204)

3.3.1 Simple One: One-dimension

Theorem 3.5

Let $X = [a, b]$ for $a, b \in \mathbb{R}$ with $a < b$ and let $f : X \to X$ be continuous. Then f has a fixed point. ♡

Proof 3.4

Easily proved by Intermediate Value Theorem.

3.3.2 ★ Brouwer's Fixed Point Theorem: continuous function has fixed point over compact, convex set

Theorem 3.6 (Brouwer's Fixed Point Theorem)

*Let $X \subseteq \mathbb{R}^n$ be nonempty, **compact**, and **convex**, and let $f : X \to X$ be continuous. Then f has a fixed point.*

♡

Proof 3.5

Consider the case when the set X is the unit ball in $\mathbb{R}^n$.

Using a fact that "Let B be the unit ball in $\mathbb{R}^n$. Then there is no continuous function $h : B \to \partial B$ such that $h(x_0) = x_0$ for every $x_0 \in \partial B$", which is intuitive but hard to prove. (See *J. Franklin, Methods of Mathematical Economics*, for an elementary (but long) proof.)

Then prove by contradiction: suppose f has no fixed points in B. That is, $\forall x \in B$, $x \neq f(x)$. Since x and its image $f(x)$ are distinct points in B for every x, we can carry out the following construction. For each $x \in B$, construct the line segment originating at $f(x)$ and going through x. Let $g(x)$ denote the intersection of this line segment with ∂B. This construction gives a continuous function $g : B \to \partial B$. Furthermore, notice that if $x_0 \in \partial B$, then $x_0 = g(x_0)$. Then, g gives $g(x) = x, \forall x \in \partial B$. Since there are no such functions by the fact above, we have a contradiction.

Chapter 4 Correspondence: $\Psi : X \to 2^Y$ (@ Lec 07 of ECON 204)

Definition 4.1 (Correspondence)

A **correspondence** $\Psi : X \to 2^Y$ from X to Y is a function from X to 2^Y, that is, $\Psi(x) \subseteq Y$ for every $x \in X$. (2^Y is the set of all subsets of Y) ♣

Example 4.1 Let $u : \mathbb{R}^n_+ \to \mathbb{R}$ be a continuous utility function, $y > 0$ and $p \in \mathbb{R}^n_{++}$, that is, $p_i > 0$ for each i. Define $\Psi : \mathbb{R}^n_{++} \times \mathbb{R}_{++} \to 2^{\mathbb{R}^n_+}$ by

$$\Psi(p, y) = \operatorname{argmax} u(x)$$

$$\text{s.t. } x \geq 0$$

$$p \cdot x \leq y$$

Ψ is the demand correspondence associated with the utility function u; typically $\Psi(p, y)$ is multi-valued.

4.1 Continuity of Correspondences

4.1.1 Upper/Lower Hemicontinuous

Let $X \subseteq \mathbb{E}^n$, $Y \subseteq \mathbb{E}^m$, and $\Psi : X \to 2^Y$.

Definition 4.2 (Upper Hemicontinuous)

Ψ is **upper hemicontinuous** (uhc) at $x_0 \in X$ if, for every open set V with $\Psi(x_0) \subseteq V$, there is an open set U with $x_0 \in U$ s.t.

$$x \in U \Rightarrow \Psi(x) \subseteq V$$

♣

Upper hemicontinuity reflects the requirement that Ψ doesn't "jump down/implode in the limit" at x_0. *(A set to "jump down" at the limit x_0: It should mean the set suddenly gets smaller – it "implodes in the limit" – that is, there is a sequence $x_n \to x_0$ and points $y_n \in \Psi(x_n)$ that are far from every point of $\Psi(x_0)$ as $n \to \infty$.)*

Definition 4.3 (Lower Hemicontinuous)

Ψ is **lower hemicontinuous** (lhc) at $x_0 \in X$ if, for every open set V with $\Psi(x_0) \cap V \neq \emptyset$, there is an open set U with $x_0 \in U$ s.t.

$$x \in U \Rightarrow \Psi(x) \cap V \neq \emptyset$$

♣

Lower hemicontinuity reflects the requirement that Ψ doesn't "jump up/explode in the limit" at x_0. *(A set to "jump up" at the limit x_0: It should mean that the set suddenly gets bigger – it "explodes in the limit" – that is,* *there is a sequence $x_n \to x_0$ and a point $y_0 \in \Psi(x_0)$ that is far from every point of $\Psi(x_n)$ as $n \to \infty$.)*

Definition 4.4 (Continuous Correspondence)

Ψ is **continuous** at $x_0 \in X$ if it is both **uhc** and **lhc** at x_0. ♣

Proposition 4.1

Ψ is upper hemicontinuous (respectively lower hemicontinuous, continuous) if it is uhc (respectively lhc, continuous) at every $x \in X$. ♠

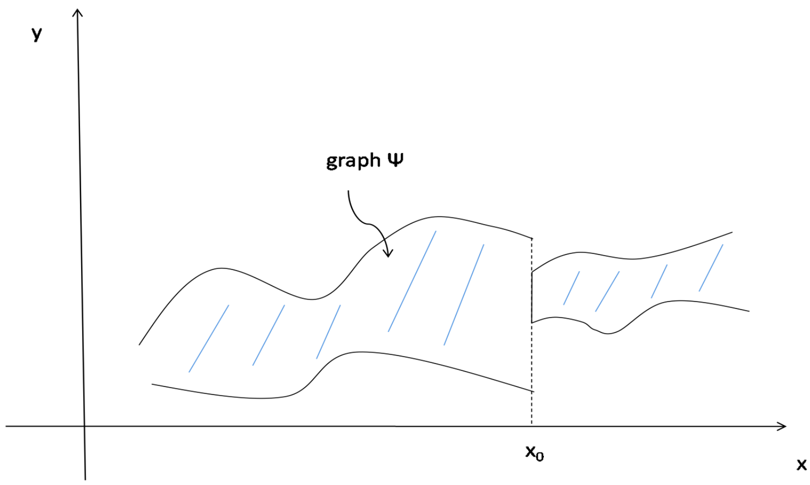

Figure 4.1: The correspondence Ψ "implodes in the limit" at x_0. Ψ is not upper hemicontinuous at x_0.

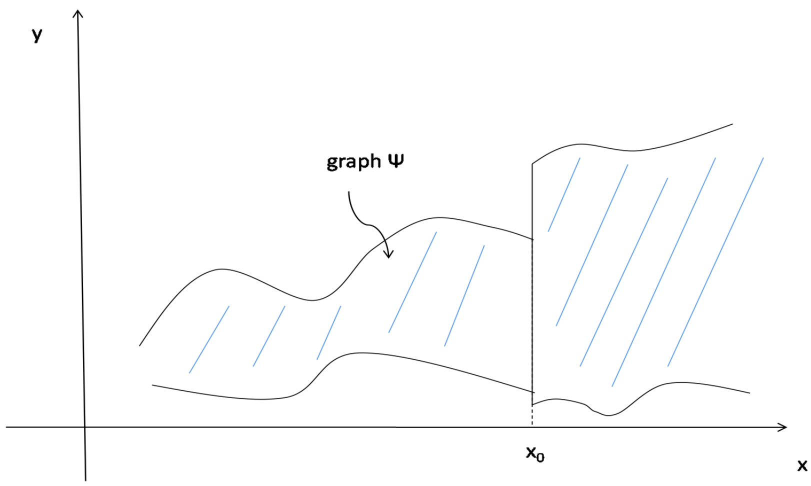

Figure 4.2: The correspondence Ψ "explodes in the limit" at x_0. Ψ is not lower hemicontinuous at x_0.

4.1.2 Theorem: $\Psi(x) = \{f(x)\}$ is uhc $\Leftrightarrow$ f is continuous

Theorem 4.1 **($\Psi(x) = \{f(x)\}$ is uhc $\Leftrightarrow$ f is continuous)**

*Let $X \subseteq \mathbb{E}^n$, $Y \subseteq \mathbb{E}^m$ and $f : X \to Y$. Let $\Psi : X \to 2^Y$ be defined by $\Psi(x) = \{f(x)\}$ for all $x \in X$. Then Ψ is **uhc** if and only if f is **continuous**.* ♡

4.1.3 Berge's Maximum Theorem: the set of maximizers is uhc with non-empty compact values

Theorem 4.2 (Berge's Maximum Theorem)

Let $X \subseteq \mathbb{R}^n$ and $Y \subseteq \mathbb{R}^m$. Consider the function $f : X \times Y \to \mathbb{R}$ and the correspondence $\Gamma : Y \to 2^X$. Define $v(y) = \max_{x\in\Gamma(y)} f(x, y)$ and the set of maximizers

$$\Omega(y) = \underset{x\in\Gamma(y)}{\operatorname{argmax}} f(x, y) = \{x : f(x, y) = v(y)\}$$

Suppose f and Γ are continuous, and that Γ has non-empty compact values. Then, v is continuous and Ω is uhc with non-empty compact values. ♡

4.2 Graph of Correspondence

An alternative notion of continuity looks instead at properties of the graph of the correspondence.

Definition 4.5 (Graph of Correspondence)

The **graph** of a correspondence $\Psi : X \to 2^Y$ is the set

$$\text{graph}\Psi = \{(x, y) \in X \times Y : y \in \Psi(x)\}$$ ♣

4.2.1 Closed Graph

By the definition of continuous function $f : \mathbb{R}^n \to \mathbb{R}$, each convergent sequence $\{(x_n, y_n)\}$ in graph f converges to a point (x, y) in graph f, that is, graph f is closed.

Definition 4.6 (Closed Graph)

Let $X \subseteq \mathbb{E}^n$, $Y \subseteq \mathbb{E}^m$. A correspondence $\Psi : X \to 2^Y$ has closed graph if its graph is a closed subset of $X \times Y$, that is, if for any sequences $\{x_n\} \subseteq X$ and $\{y_n\} \subseteq Y$ such that $x_n \to x \in X$, $y_n \to y \in Y$ and $y_n \in \Psi(x_n)$ for each n, then $y \in \Psi(x)$. ♣

Example 4.2 Consider the correspondence $\Psi(x) = \begin{cases} \{\frac{1}{x}\}, & \text{if } x \in (0, 1] \\ \{0\}, & \text{if } x = 0 \end{cases}$ ("implode in the limit")

Let $V = (-0.1, 0.1)$. Then $\Psi(0) = \{0\} \subseteq V$, but no matter how close x is to 0, $\Psi(x) = \{\frac{1}{x}\} \nsubseteq V$, so Ψ is not uhc at 0. However, note that Ψ has closed graph.

4.3 Closed-valued, Compact-valued, and Convex-valued Correspondences

Definition 4.7 (Closed-valued, Compact-valued, and Convex-valued Correspondences)

Given a correspondence $\Psi : X \to 2^Y$,

1. Ψ is **closed-valued** if $\Psi(x)$ is a closed subset of Y for all x;
2. Ψ is **compact-valued** if $\Psi(x)$ is compact for all x.
3. Ψ is **convex-valued** if $\Psi(x)$ is convex for all x.

♣

4.3.1 Closed-valued, uhc and Closed Graph

For closed-valued correspondences these concepts can be more tightly connected. A closed-valued and upper hemicontinuous correspondence must have closed graph. For a closed-valued correspondence with a compact range, upper hemicontinuity is equivalent to closed graph.

Theorem 4.3

Let $X \subseteq \mathbb{E}^n$, $Y \subseteq \mathbb{E}^m$, and $\Psi : X \to 2^Y$.

1. *Ψ is **closed-valued** and **uhc** $\Rightarrow$ Ψ has **closed graph**.*
2. *Ψ is **closed-valued** and **uhc** $\Leftarrow$ Ψ has **closed graph**. (If Y is **compact**)*

♡

Theorem 4.4

*Let $X \subseteq \mathbb{E}^n$, $Y \subseteq \mathbb{E}^m$, and $\Psi : X \to 2^Y$. If Ψ has **closed graph** and there is an **open set** W with $x_0 \in W$ and a **compact set** Z such that $x \in W \cap X \Rightarrow \Psi(x) \subseteq Z$, then Ψ is **uhc** at x_0.*

♡

4.3.2 Theorem: compact-valued, uhs correspondence of compact set is compact

Theorem 4.5

Let X be a compact set and $\Psi : X \to 2^X$ be a non-empty, compact-valued upper-hemicontinuous correspondence. If $C \subseteq X$ is compact, then $\Psi(C)$ is compact.

♡

Proof 4.1

Given the compact-valued Ψ, we can have an open cover of $\Psi(C)$, $\{U_\lambda : \lambda \in \Lambda\}$. So $\forall x \in C$, there exists $U_{l(x)}, l(x) \in \Lambda$ such that $U_{l(x)}$ is an open cover of $\Psi(x)$.

Consider a $c \in C$. Since Ψ is uhs and $\Psi(c) \subseteq U_{l(c)}$, there exists open set V_c s.t. $c \in V_c$ and $\Psi(x) \subseteq U_{l(c)}, \forall x \in V_c \cap C$.

$\{V_c : c \in C\}$ is an open cover of C. Because C is compact, there is a finite subcover $\{V_{c_i} : i = 1, ..., m\}, m \in \mathbb{N}$, where $\{c_i : i = 1, ..., m\} \subseteq C$.

Because $\Psi(x) \subseteq U_{l(c_i)}, \forall x \in V_{c_i} \cap C$ and $\{V_{c_i} : i = 1, ..., m\}, m \in \mathbb{N}$ is a open cover for C, we can infer $\{U_{l(c_i)} : i = 1, ..., m\}$ is a finite subcover of $\{U_{l(c)} : c \in C\}$ for $\Psi(C)$. Hence, $\Psi(C)$ is compact.

4.4 Fixed Points for Correspondences (@ Lec 13 of ECON 204)

4.4.1 Definition

Definition 4.8 (Fixed Points for Correspondences)

Let X be nonempty and $\psi : X \to 2^X$ be a correspondence. A point $x^* \in X$ is a fixed point of ψ if $x^* \in \psi(x^*)$.

Note *We only need x^* to be in $\psi(x^*)$, not $\{x^*\} = \psi(x^*)$. That is, ψ need not be single-valued at x^*. So x^* can be a fixed point of ψ but there may be other elements of $\psi(x^*)$ different from x^*.*

4.4.2 Kakutani's Fixed Point Theorem: uhs, compact, convex values correspondence has a fixed point over compact convex set

Theorem 4.6 (Kakutani's Fixed Point Theorem)

*Let $X \subseteq \mathbb{R}^n$ be a non-empty, **compact**, **convex** set and $\psi : X \to 2^X$ be an **upper hemi-continuous** correspondence with non-empty, **compact**, **convex** values. Then ψ has a fixed point in X.*

4.4.3 Theorem: $\exists$ compact set $C = \cap_{i=0}^{\infty} \Psi^i(X)$ s.t. $\Psi(C) = C$

Theorem 4.7

Let (X, d) be a compact metric space and let $\Psi(x) : X \to 2^X$ be a upper-hemicontinuous, compact-valued correspondence, such that $\Psi(x)$ is non-empty for every $x \in X$. There exists a compact non-empty subset $C \subseteq X$, such that $\Psi(C) \equiv \cup_{x \in C} \Psi(x) = C$.

Proof 4.2

Let's construct a sequence $\{C_n\}$ such that $C_0 = X$, $C_1 = \Psi(C_0)$, ..., $C_n = \Psi(C_{n-1})$, ... We claim that $C = \cap_{i=0}^{\infty} C_i$ is a non-empty compact set and satisfies $\Psi(C) = C$.

1. *Because we can infer $\Psi(X_1) \subseteq \Psi(X_2)$ if $X_1 \subseteq X_2$, $X = C_0 \supseteq C_1 \Rightarrow C_1 = \Psi(C_0) \supseteq C_2 = \Psi(C_1)$,...., so $C_0 \supseteq C_1 \supseteq \cdots C_n \supseteq \cdots$. Hence, C is not empty.*

2. *Because X is compact, by the theorem 4.5, we can infer C_n is compact for all n. Then, C_n is closed for all n, so C is closed. Because C is a closed set of compact set X, C is compact.*
3. $C \subseteq C_n, \forall n \Rightarrow \Psi(C) \subseteq \Psi(C_n), \forall n \Rightarrow \Psi(C) \subseteq C$
4. *Assume $C \subseteq \Psi(C)$ doesn't hold, that is $\exists y \in C$ s.t. $y \notin \Psi(C)$. Because $y \in C$ and $C_0 \supseteq C_1 \supseteq \cdots C_n \supseteq \cdots$, there exists $k \in C_n$ for all n s.t. $y \in \Psi(k)$. $k \in \cap_{i=1}^{\infty} C_i = C$, so $\Psi(k) \subseteq \Psi(C)$, which contradicts to $y \notin \Psi(C)$. Hence, $C \subseteq \Psi(C)$.*

All in all the claim "$C = \cap_{i=0}^{\infty} C_i$ is a non-empty compact set and satisfies $\Psi(C) = C$" is proved.

Chapter 5 Bayesian Persuasion: Extreme Points and Majorization

Based on

- Kleiner, A., Moldovanu, B., & Strack, P. (2021). Extreme points and majorization: Economic applications. *Econometrica*, 89(4), 1557-1593.
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5.1 Extreme Points

5.1.1 Extreme Points of Convex Set

Definition 5.1 (Extreme Points)

An **extreme point** of a convex set A is a point $x \in A$ that cannot be represented as a convex combination of points in A. ♣

5.1.2 Krein-Milman Theorem: Existence of Extreme Points

Theorem 5.1 (Krein-Milman Theorem)

Every non-empty ***compact convex*** *subset of a Hausdorff locally convex topological vector space (for example, a normed space) is the closed, convex hull of its extreme points.*

In particular, this set has extreme points. ♡

5.1.3 Bauer's Maximum Principle: Usefulness of Extreme Points for Optimization

Theorem 5.2 (Bauer's Maximum Principle)

Any function that is ***convex and continuous****, and defined on a set that is* ***convex and compact****, attains its maximum at some extreme point of that set.* ♡

5.2 Majorization

5.2.1 Majorization and Weak Majorization

Definition 5.2 (Majorization of Non-decreasing Functions)

Consider right-continuous functions that map the unit interval $[0, 1]$ into the real numbers. For two non-decreasing functions $f, g \in L^1$, we say that f **majorizes** g, denoted by $g \prec f$, if the following two conditions hold:

$$\int_x^1 g(s)ds \leq \int_x^1 f(s)ds, \forall x \in [0, 1] \qquad \text{(Condition 1)}$$

$$\int_0^1 g(s)ds = \int_0^1 f(s)ds \qquad \text{(Condition 2)}$$

♣

Definition 5.3 (Weak Majorization)

f **weakly majorizes** g, denoted by $g \prec_w f$, if Condition 1 holds (not necessarily Condition 2). ♣

5.2.2 How to work for non-monotonic functions? – Non-Decreasing Rearrangement

Note How this work with non-monotonic functions?

Suppose f, g are non-monotonic, we compare their non-decreasing rearrangements f^*, g^*.

Definition 5.4 (Rearrangement)

Given a function f, let $m(x)$ denote the Lebesgue measure of the set $\{s \in [0, 1] : f(s) \leq x\}$, that is $m(x) = \int_{s\in\{s\in[0,1]:f(s)\leq x\}} 1ds$ (the "length" of the set). The non-decreasing rearrangement of f, f^*, is defined by

$$f^*(t) = \inf\{x \in \mathbb{R} : m(x) \geq t\}, \; t \in [0, 1]$$

♣

5.2.3 Theorem: F majorizes $G \Leftrightarrow G$ is a mean-preserving spread of F

Based on

- Shaked, M., & Shanthikumar, J. G. (2007). *Stochastic orders*. New York, NY: Springer New York.

Definition 5.5 (Generalized Inverse)

Suppose G is defined on the interval $[0, 1]$, we can define the **generalized inverse**

$$G^{-1}(x) = \sup\{s : G(s) \leq x\}, x \in [0, 1]$$

♣

Let X_F and X_G be now random variables with distributions F and G, defined on the interval $[0, 1]$.

Theorem 5.3 (Shaked & Shanthikumar (2007), Section 3.A)

$$G \prec F \Leftrightarrow F^{-1} \prec G^{-1} \Leftrightarrow X_G \leq_{ssd} X_F \text{ and } \mathbb{E}[X_G] = \mathbb{E}[X_F]$$

where $\leq_{ssd}$ denotes the standard second-order stochastic dominance.

Based on Theorem 1.1 and the Condition 2 of Majorization, we can conclude

Corollary 5.1 (Majorization $\Leftrightarrow$ Mean-preserving Contraction)

F majorizes $G \Leftrightarrow F$ is a mean-preserving contraction of G (G is a mean-preserving spread of F)

That is, we can construct random variables X_F, X_G, jointly distributed on some probability space, such that $X_F \sim F$, $X_G \sim G$ and such that $X_F = \mathbb{E}[X_G \mid X_F]$.

5.3 Capture Extreme Points in Economic Applications

Let L^1 denote the real-valued and integrable functions defined on $[0, 1]$.

In this section, we focus on **non-decreasing (weakly increasing) functions**, for example, a cumulative distribution function in Bayesian persuasion, or an incentive-compatible allocation in mechanism design.

5.3.1 Definitions of $\mathcal{MPS}(f)$, $\mathcal{MPS}_w(f)$, $\mathcal{MPC}(f)$

Based on Corollary 5.1, we can define following sets

Definition 5.6

1. The set of non-decreasing functions that are majorized by f is denoted by

$$\begin{aligned}\mathcal{MPS}(f) &= \text{MPS}(f) \cap \{g \in L^1 \mid g \text{ is non-decreasing}\} \\ &= \{g \in L^1 \mid g \text{ is non-decreasing and } g \prec f\}\end{aligned}$$

2. The set of non-negative, non-decreasing functions that are weakly majorized by f is denoted by

$$\mathcal{MPS}_w(f) = \{g \in L^1 \mid g \text{ is non-negative, non-decreasing and } g \preceq f\}$$

3. The set of non-decreasing functions that majorize f and satisfy $f(0) \leq g \leq f(1)$ is denoted by

$$\begin{aligned}\mathcal{MPC}(f) &= \text{MPC}(f) \cap \{g \in L^1 \mid g \text{ is non-decreasing and } f(0) \leq g \leq f(1)\} \\ &= \{g \in L^1 \mid g \text{ is non-decreasing and } g \succ f \text{ and } f(0) \leq g \leq f(1)\}\end{aligned}$$

where $f(0) \leq g \leq f(1)$ is used to ensure compactness.

5.3.2 Proposition: $\mathcal{MPS}(f)$, $\mathcal{MPS}_w(f)$, $\mathcal{MPC}(f)$ have extreme points and any element is a combination of extreme points

Following two propositions are the Proposition 1 of the Kleiner et al. (2021).

Proposition 5.1 (Non-decreasing $f \Rightarrow \mathcal{MPS}(f)$, $\mathcal{MPS}_w(f)$, and $\mathcal{MPC}(f)$ have extreme points)

Suppose $f \in L^1$ is non-decreasing. Then $\mathcal{MPS}(f)$, $\mathcal{MPS}_w(f)$, and $\mathcal{MPC}(f)$ are convex and compact in the norm topology $\Rightarrow$ (by Krein-Milman Theorem 5.1) they all have non-empty set of extreme points. ♠

Note *We use* ext$A$ *to denote the set of extreme points of set A.*

Proposition 5.2 (Non-decreasing $f \Rightarrow$ any distribution is a combination of extreme points)

Suppose $f \in L^1$ is non-decreasing. For any $g \in \mathcal{MPS}(f)$, $\exists$ a probability measure λ_g over ext$\mathcal{MPS}(f)$ *such that*

$$g = \int_{\text{ext}\mathcal{MPS}(f)} h \, d\lambda_g(h)$$

(also hold for any $g \in \mathcal{MPS}_w(f)$ and $g \in \mathcal{MPC}(f)$). ♠

5.3.3 Extreme Points in $\mathcal{MPS}(f)$

Theorem 5.4 (Form of Extreme Points in MPS(f): Kleiner et al. (2021), Theorem 1)

*Let f be non-decreasing. Then g is an **extreme point** in $\mathcal{MPS}(f)$ <u>if and only if</u> there exists a collection of disjoint intervals $\{[\underline{x}_i, \overline{x}_i)\}_{i \in I}$ such that*

$$g(x) = \begin{cases} f(x), & \text{if } x \notin \cup_{i\in I}[\underline{x}_i, \overline{x}_i) \\ \frac{\int_{\underline{x}_i}^{\overline{x}_i} f(s)ds}{\overline{x}_i - \underline{x}_i}, & \text{if } x \in [\underline{x}_i, \overline{x}_i) \end{cases}$$

♡

g is an extreme point of $\mathcal{MPS}(f)$ implies either that $g(x) = f(x)$ or that g is constant at x.

Definition 5.7 (Exposed Element)

An element x of a convex set A is **exposed** if there exists a continuous linear functional that attains its maximum on A uniquely at x. ♣

Note *Every exposed point is extreme, but the converse is not true in general.*

Corollary 5.2 (Kleiner et al. (2021), Corollary 1)

Every extreme point of $\mathcal{MPS}(f)$ is exposed. ♡

5.3.4 Extreme Points in $\mathcal{MPS}_w(f)$

For a set $A \subseteq [0,1]$, we use $\mathbf{1}_A(x)$ denote the indicator function of set A: it equals to 1 if $x \in A$ and 0 otherwise.

Corollary 5.3 (Kleiner et al. (2021), Corollary 2)

Suppose that f is non-decreasing and non-negative. A function g is an extreme point of $\mathcal{MPS}_w(f)$ if and only if there is $\theta \in [0,1]$ such that g is an extreme point of $\mathcal{MPS}(f)$ and $g(x) = 0, \forall x \in [0,\theta)$. ♡

5.3.5 Extreme Points in $\mathcal{MPC}(f)$

Theorem 5.5 (Kleiner et al. (2021), Theorem 2)

Let f be non-decreasing and continuous. Then $g \in \mathcal{MPC}(f)$ is an extreme point of $\mathcal{MPC}(f)$ if and only if there exists a collection of intervals $[\underline{x}_i, \bar{x}_i)$, (potentially empty) sub-intervals $\left[\underline{y}_i, \bar{y}_i\right) \subseteq [\underline{x}_i, \bar{x}_i)$, and numbers v_i indexed by $i \in I$ such that for all $x \in [0,1]$,

$$g(x) = \begin{cases} f(x) & \text{if } x \notin \bigcup_{i\in I} [\underline{x}_i, \bar{x}_i) \\ f(\underline{x}_i) & \text{if } x \in \left[\underline{x}_i, \underline{y}_i\right) \\ v_i & \text{if } x \in \left[\underline{y}_i, \bar{y}_i\right) \\ f(\bar{x}_i) & \text{if } x \in [\bar{y}_i, \bar{x}_i) \end{cases} \tag{5.1}$$

Moreover, a function g as defined in (5.1) is in $\mathcal{MPC}(f)$ if the following three conditions are satisfied:

$$\left(\bar{y}_i - \underline{y}_i\right) v_i = \int_{\underline{x}_i}^{\bar{x}_i} f(s)\mathrm{d}s - f(\underline{x}_i)\left(\underline{y}_i - \underline{x}_i\right) - f(\bar{x}_i)(\bar{x}_i - \bar{y}_i) \tag{5.2}$$

$$f(\underline{x}_i)(\bar{y}_i - \underline{x}_i) + f(\bar{x}_i)(\bar{x}_i - \bar{y}_i) \leq \int_{\underline{x}_i}^{\bar{x}_i} f(s)\mathrm{d}s \leq f(\underline{x}_i)\left(\underline{y}_i - \underline{x}_i\right) + f(\bar{x}_i)\left(\bar{x}_i - \underline{y}_i\right) \tag{5.3}$$

If $v_i \in \left(f\left(\underline{y}_i\right), f(\bar{y}_i)\right)$, then for an arbitrary point m_i satisfying $f(m_i) = v_i$ it must hold that

$$\int_{m_i}^{\bar{x}_i} f(s)\mathrm{d}s \leq v_i(\bar{y}_i - m_i) + f(\bar{x}_i)(\bar{x}_i - \bar{y}_i) \tag{5.4}$$

♡

Condition (5.2) in the theorem ensures that g and f have the same integrals for each sub-interval $[\underline{x}_i, \bar{x}_i)$, analogously to the condition imposed in Theorem 5.3.3. Condition (5.3) ensures that $v_i \in (f(\underline{x}_i), f(\bar{x}_i))$, ensuring that g is non-decreasing. If f crosses g in the interval $\left[\underline{y}_i, \bar{y}_i\right]$, then there is $m_i \in \left[\underline{y}_i, \bar{y}_i\right]$ such that $f(m_i) = v_i$. In this case, Condition (5.4) ensures that $\int_s^{\bar{x}_i} f(t)\mathrm{d}t \leq \int_s^{\bar{x}_i} g(t)\mathrm{d}t$ for all $s \in [\underline{x}_i, \bar{x}_i)$ and thus that $f \prec g$. If $v_i \notin \left(f\left(\underline{y}_i\right), f(\bar{y}_i)\right)$, Condition (5.3) is enough to ensure that $f \prec g$ and thus Condition (5.4) is not necessary.

Chapter 6 Bayesian Persuasion: Bi-Pooling

Based on

- ★ Arieli, I., Babichenko, Y., Smorodinsky, R., & Yamashita, T. (2023). Optimal persuasion via bi-pooling. *Theoretical Economics*, 18(1), 15-36.
- Gentzkow, Matthew and Emir Kamenica (2016), "A Rothschild-Stiglitz approach to Bayesian persuasion." *American Economic Review*, 106, 597-601.
- Kolotilin, Anton (2018), "Optimal information disclosure: A linear programming ap-proach." *Theoretical Economics*, 13, 607-635.

6.1 Persuation Model

Consider a persuation model where the state space is the interval $[0, 1]$ with a common prior $F \in \Delta([0, 1])$ that has full support (i.e., $[0, 1]$ is the smallest closed set that has probability one). The sender knows the realized state and the receiver is uninformed.

1. Singaling: Prior to the realization of the state, the sender commits to a **signaling policy**

$$\pi : [0, 1] \to \Delta(S)$$

   where S is an arbitrary measurable space. Once the state $\omega \in [0, 1]$ is realized, the sender sends a signal $s \in S$ to the receiver based on the committed signaling policy, i.e., $s \sim \pi(\omega)$. Without loss of generality, we may assume that $S = [0, 1]$, and that the posterior mean of the state, given signal s, is s itself.

   Hence, the distribution of the posterior mean s given the signal policy π, denoted by $F_\pi \in \Delta([0, 1])$ is a *mean-preserving contraction* of F.

   It is also easy to note that for any $G \in \text{MPC}(F)$, there exists a signaling policy π (may not be unique) that makes $F_\pi = G$ (e.g., Gentzkow and Kamenica(2016), Kolotilin (2018)).

2. Persuation problem: The sender's indirect utility is denoted by $u : [0, 1] \to \mathbb{R}$, where $u(x)$ is the sender's expected utility in case the receiver's posterior mean is x. u is assume to be upper semicontinuous. (F, u) is referred as a **persuation problem**. The sender's problem takes the form:

$$\max_{G \in \text{MPC}(F)} \mathbb{E}_{x \sim G}[u(x)]$$

6.2 Bi-Pooling

6.2.1 Bi-pooling Distribution

Note *For a distribution $H \in \Delta([0,1])$ and a measurable set $C \subseteq [0,1]$ we denote by $H|_C$ the distribution of $h \sim H$ conditional on the event that $h \in C$.*

Definition 6.1 (Bi-pooling Distribution (Arieli et al. (2023), Definition 1))

A distribution $G \in \mathrm{MPC}(F)$ is called a **bi-pooling distribution** (with respect to F) if there exists a collection of pairwise disjoint open intervals $\{(\underline{y}_i, \overline{y}_i)\}_{i \in A}$ such that

- For every $i \in A$,

$$G((\underline{y}_i, \overline{y}_i)) = F((\underline{y}_i, \overline{y}_i))$$

  where $G((\underline{y}_i, \overline{y}_i)) = G(\overline{y}_i) - G(\underline{y}_i) = \int_{\underline{y}_i}^{\overline{y}_i} g(x)dx$, $F((\underline{y}_i, \overline{y}_i)) = F(\overline{y}_i) - F(\underline{y}_i) = \int_{\underline{y}_i}^{\overline{y}_i} f(x)dx$.

- The remaining intervals are the same:

$$G|_{[0,1]\setminus \cup_{i\in A}(\underline{y}_i, \overline{y}_i)} = F|_{[0,1]\setminus \cup_{i\in A}(\underline{y}_i, \overline{y}_i)}$$

- For every $i \in A$,

$$|\mathrm{supp}(G|_{(\underline{y}_i, \overline{y}_i)})| \leq 2$$

  which means there are at most two different values of G over $(\underline{y}_i, \overline{y}_i)$. If $|\mathrm{supp}(G|_{(\underline{y}_i, \overline{y}_i)})| = 2$, we call $(\underline{y}_i, \overline{y}_i)$ a **bi-pooling interval**; If $|\mathrm{supp}(G|_{(\underline{y}_i, \overline{y}_i)})| = 1$, we call $(\underline{y}_i, \overline{y}_i)$ a **pooling interval**. In the case where all intervals are pooling intervals, we say that G is a **pooling distribution** (with respect to F).

♣

Example 6.1 Consider the persuasion problem (F, u), where $F = U[0,1]$ is the uniform distribution over $[0,1]$ and $u : [0,1] \to \mathbb{R}$ is an arbitrary function satisfying $u(\frac{1}{3}) = u(\frac{2}{3}) = 0$ and $u(x) < 0, \forall x \notin \{\frac{1}{3}, \frac{2}{3}\}$. Consider using a binary signal space $S = \{s_1, s_2\}$, where s_1 is sent with probability 1 over the interval $(\frac{1}{12}, \frac{7}{12})$ and s_2 is sent with probability 1 over the interval $[0, \frac{1}{12}] \cup [\frac{7}{12}, 1]$. This policy is a bi-pooling policy for the singleton collection $\{[0,1]\}$.

6.3 Applying Bi-pooling Distributions to Persuasion Problems

6.3.1 It works for all

Theorem 6.1 (Arieli et al. (2023), Theorem 1)

Every persuasion problem (F, u) admits an optimal bi-pooling distribution. ♡

Proposition 6.1 (Arieli et al. (2023), Proposition 1)

The set of extreme points of $\mathrm{MPC}(F)$ *is precisely the set of bi-pooling distributions.* ♠

Theorem 6.2 (Arieli et al. (2023), Theorem 2)

For every bi-pooling distribution $G \in \mathrm{MPC}(F)$ there exists a continuous utility function u for which G is the unique optimal solution of $\max_{G \in \mathrm{MPC}(F)} \mathbb{E}_{x \sim G}[u(x)]$. That is, every extreme point of $\mathrm{MPC}(F)$ *is exposed.* ♡

6.3.2 How it works

Definition 6.2 (Bi-pooling Policy (Arieli et al. (2023), Definition 3))

A signaling policy π is called a **bi-pooling policy** if there exists a collection of pairwise disjoint intervals $\{(\underline{y}_i, \overline{y}_i)\}_{i \in A}$ such that

- for every state $\omega \in (\underline{y}_i, \overline{y}_i)$ we have $\mathrm{supp}(\pi(\omega)) \subseteq \{\underline{z}_i, \overline{z}_i\}$ (either $\pi(\omega) = \overline{z}_i$ or $\pi(\omega) = \underline{z}_i$) for some $\underline{z}_i \leq \overline{z}_i$ and $\underline{z}_i, \overline{z}_i \in [\underline{y}_i, \overline{y}_i]$;
- for every $\omega \notin \cup_{i \in A}(\underline{y}_i, \overline{y}_i)$, the policy sends the signal $\pi(\omega) = \omega$ (i.e., it reveals the state).

In the case where $\underline{z}_i = \overline{z}_i$ for all $i \in A$, we refer to π as a **pooling policy**. ♣

Definition 6.3 (Monotonic Signaling Policy (Arieli et al. (2023), Definition 4))

A (possibly mixed) signaling policy, $\pi : [0, 1] \to \Delta([0, 1])$, is **monotonic** if

$\pi(x)$ first-order stochastically dominates $\pi(y)$ for every $x \geq y$. ♣

Proposition 6.2 (Arieli et al. (2023), Proposition 2)

Every persuasion problem admits an optimal (mixed) monotonic signaling policy. ♠

Lemma 6.1 (Arieli et al. (2023), Lemma 3)

A persuasion problem (F, u) admits an optimal pure monotonic signaling policy if and only if it admits an optimal pooling policy. ♡

Definition 6.4 (Double-Interval Nested Structure)

A pure signaling policy: for each bi-pooling interval $(\underline{y}_i, \overline{y}_i)$, we can find a sub-interval $(\underline{w}_i, \overline{w}_i) \subseteq (\underline{y}_i, \overline{y}_i)$ such that π is constant over the interval $(\underline{w}_i, \overline{w}_i)$ as well as over its complement $(\underline{y}_i, \overline{y}_i) \backslash (\underline{w}_i, \overline{w}_i)$. ♣

Corollary 6.1 (Arieli et al. (2023), Corollary 2)

Every persuasion problem (F, u) has an optimal bi-pooling policy that has a double-interval nested structure. ♡

Chapter 7 Optimization Methods

7.1 Generalized Neyman-Pearson Lemma

Based on

- Chernoff, H., & Scheffe, H. (1952). A generalization of the Neyman-Pearson fundamental lemma. *The Annals of Mathematical Statistics*, 213-225.
- Dantzig, G. B., & Wald, A. (1951). On the fundamental lemma of Neyman and Pearson. *The Annals of Mathematical Statistics*, 22(1), 87-93.

Given

- $n+m$ real integrable functions $g_1, ..., g_n, f_1, ..., f_m$ of a point x in a Euclidean space X;
- a real function $\phi : \mathbb{R}^n \to \mathbb{R}$ of n;
- and m constants $c_1, ..., c_m$.

The problem considered is about the existence, necessary conditions, and sufficient conditions of

$$
\begin{gathered}
S_0 = \arg\max_{S \subset X} \phi\left(\int_S g_1 dx, ..., \int_S g_n dx\right) \\
\text{s.t. } \int_S f_i dx = c_i, i = 1, ..., m
\end{gathered}
$$

Notations: $y_j(S) \triangleq \int_S f_j dx, j = 1, ..., m$ and $z_i(S) \triangleq \int_S g_i dx, i = 1, ..., n$.

7.1.1 The Neyman-Pearson Lemma

The Neyman-Pearson lemma refers to the case $n = 1, \phi(z_1) = z_1$, X is 1-dimensional Euclidean space.

$$
\begin{gathered}
\max_{S \subset X} \int_S g(x) dx \\
\text{s.t. } \int_S f_i(x) dx = c_i, i = 1, ..., m
\end{gathered}
\tag{S1}
$$

Chapter 8 Politics Models

8.1 Voting Model: Implicit Function Theroem

Consider an incumbent I and a citizen/voter v.

- I picks $x_1 \in \mathbb{R}$;
- v observes $u_1 = -x_1^2 + \epsilon$, where $\epsilon \sim f$ and f is uninormal of 0, symmetric, continuous, and differentiable. $f'(z)$ is positive for $z < 0$, negative for $z > 0$, and zero for $z = 0$.
- v re-elects or not
- (new) I chooses x_2
- ...

8.1.1 Case 1

Incumbents have $\alpha \in (0, 1)$ probability to be "good" type who picks $x_1 = x_2 = 0$ and $1 - \alpha$ probability to be "bad" type who picks $\hat{x} = x_1 = x_2 > 0$.

Bayesian posterior beliefs are

$$\Pr(\text{good} \mid u_1) = \frac{\alpha f(u_1)}{\alpha f(u_1) + (1 - \alpha) f(u_1 + \hat{x}^2)}$$

where $\Pr(\text{good} \mid u_1) \geq \alpha \Leftrightarrow f(u_1) \geq f(u_1 + \hat{x}^2)$.

By our assumption about f, $f(u_1) \geq f(u_1 + \hat{x}^2)$ means u_1 is closer to zero than $u_1 + \hat{x}^2 \Rightarrow u_1^2 \leq (u_1 + \hat{x}^2)^2 = u_1^2 + 2u_1\hat{x}^2 + \hat{x}^4$, that is, $u_1 > -\frac{\hat{x}^2}{2}$.

8.1.2 Case 2: Moral Hazard Version

All incumbents are "bad": ideal policy is 1. Assume voters re-elect if and only if $u_1 \geq k$, where k is endogenous. Based on this rule, the probability of an incumbent being re-elected is

$$\Pr(\text{re-elect}|x_1) = \Pr(-x_1^2 + \epsilon \geq k) = 1 - F(k + x_1^2)$$

Suppose the utility of the incumbent is

$$U_I(x_1, x_2) = w - (1 - x_1)^2 + \delta(w - (1 - x_2)^2)\mathbf{1}_{\text{re-elect}}$$

Specifically, the expected utility with $u_2 = 1$ is

$$U_I(x_1, x_2 = 1) = w - (1 - x_1)^2 + \delta w \left[1 - F(k + x_1^2)\right]$$

Then, x_1^* should solve

$$\frac{\partial U_I}{\partial x_1} = 2(1-x_1) - 2\delta w x_1 f(k+x_1^2) = 0$$
$$\Rightarrow f(k+x_1^2) = -\frac{1}{\delta w} + \frac{1}{x_1}\frac{1}{\delta w}$$

Apply Implicit Function Theorem

Let $g(k,x) = f(k+x_1^2) + \frac{1}{\delta w} - \frac{1}{x_1}\frac{1}{\delta w}$.

The goal of the voter is to find the k that minimizes x_1^*. By the implicit function theorem

$$\frac{\partial x_1^*}{\partial k} = -\frac{\frac{\partial g}{\partial k}\big|_{x_1^*}}{\frac{\partial g}{\partial x}\big|_{x_1^*}}$$

As $\frac{\partial g}{\partial k} = f'(k+x_1^2)$ and $\frac{\partial g}{\partial x} = 2x_1 f'(k+x_1^2) + \frac{1}{x_1^2}\frac{1}{\delta w}$, we can conclude the optimal k satisfies $k = -x_1^{*2}$. Then, $f(0) = -\frac{1}{\delta w} + \frac{1}{x_1^*}\frac{1}{\delta w} \Rightarrow$

$$x_1^* = \frac{1}{1+\delta w f(0)},\ k^* = -\left(\frac{1}{1+\delta w f(0)}\right)^2$$

8.1.3 Case 3

Suppose the incumbent has probability α being "good" with $y_I = 0$ and probability $1-\alpha$ being "bad" with $y_I = 1$. He chooses $x_2 = y_I$ at stage 2.

Given the strategy x_g and x_b Bayesian posterior beliefs are

$$\Pr(\text{good} \mid u_1) = \frac{\alpha f(x_g^2 + u_1)}{\alpha f(x_g^2+u_1) + (1-\alpha) f(x_b^2+u_1)}$$

Hence, $\Pr(\text{good} \mid u_1) \geq \alpha$ if and only if $f(x_g^2+u_1) \geq f(x_b^2+u_1)$.

The voter's strategy is also represented by "re-elect" iff $u_1 \geq k$. At the critical point $u_1 = k$,

$$f(x_g^2+k) = f(x_b^2+k) \Rightarrow k = -\frac{x_g^2+x_b^2}{2}$$

Suppose the expected utility (constructed based on avoiding deviations from the incumbent's true type) of the incumbent is

$$\mathbb{E}U_I(x_1, x_2 = y_I) = w - (x_1 - y_I)^2 + \delta w\left(1 - F(k+x_1^2)\right)$$

Obviously, $x_1^* = 0$ for good incumbent. (i.e., $x_g = 0$). Then, $k = -\frac{x_b^2}{2}$, and

$$\mathbb{E}U_b(x_1) = w - (x_1-1)^2 + \delta w\left(1 - F(k+x_1^2)\right)$$

which has derivative

$$-2(x_1-1) - 2\delta w x_1 f(k+x_1^2)$$

So, the optimal x_1^* of "bad" type should satisfy

$$f(k+x_1^2) + \frac{1}{\delta w} - \frac{1}{\delta w x_1} = 0$$

Consider the $x_1 = \sqrt{-2k}$ (by what we induced, $k = -\frac{x_b^2}{2}$), the optimal k should be solved by

$$\begin{aligned} H(k) &= f(-k) + \frac{1}{\delta w} - \frac{1}{\delta w\sqrt{-2k}} \\ &= f(k) + \frac{1}{\delta w} - \frac{1}{\delta w\sqrt{-2k}} = 0 \end{aligned}$$

By our assumption about f, $f(k) = f(-k)$.

Also, by the implicit function theorem, we can analyze how the w affects k

$$\frac{\partial k}{\partial w} = -\frac{\frac{\partial H}{\partial w}\big|_{k^*}}{\frac{\partial H}{\partial k}\big|_{k^*}}$$

8.2 Two Period Accountability Model: Normal-Normal Learning

8.2.1 Normal-Normal Learning

Suppose θ has a prior $N(\mu_\theta, \sigma_\theta^2)$. We observe $s = \theta + \varepsilon$, where $\varepsilon \sim N(0, \sigma_\varepsilon^2)$.

Proposition 8.1 (Normal-Normal Learning)

The posterior beliefs about θ given s is also normal with mean $\mu_1 = \lambda\mu_\theta + (1-\lambda)s$ and variance $\lambda\sigma_\theta^2$,

$$\theta \mid s \sim N(\lambda\mu_\theta + (1-\lambda)s, \lambda\sigma_\theta^2)$$

where $\lambda = \frac{\sigma_\theta^{-2}}{\sigma_\theta^{-2}+\sigma_\varepsilon^{-2}} = \frac{\sigma_\varepsilon^2}{\sigma_\varepsilon^2+\sigma_\theta^2}$ is the precision weight.

8.2.2 Two Period Accountability Model

1. Nature chooses $\theta \in \mathbb{R}$, which follows distribution $N(\mu_\theta, \sigma_\theta^2)$.
2. Incumbent takes the first action $a_1 \geq 0$.
3. All observe $y_1 = \theta + a_1 + \epsilon_1$, where $\epsilon_1 \sim N(0, \sigma_\epsilon^2)$.
4. Citizens choose $s_1 \in \mathbb{R}$.
5. Incumbent takes the second action $a_2 \geq 0$.
6. Citizens observe a_1 and $y_2 = \theta + a_2 + \epsilon_2$.
7. Citizens choose $s_2 \in \mathbb{R}$.

The utility of the incumbent is

$$U_I = s_1 - ka_1^2 + s_2 - ka_2^2, k > 0$$

and the utility of the citizens is

$$U_C = y_1 - (s_1 - \theta)^2 + y_2 - (s_2 - \theta)^2$$

1. **Period 1 Belief:** Given y_1 and the conjecture $\tilde{a}_1$, we have

$$y_1 - \tilde{a}_1 = \theta + \epsilon_1$$

Based on the normal-Normal learning (8.1), the posterior belief about θ is

$$N(\underbrace{\lambda_1\mu_\theta + (1-\lambda_1)(y_1 - \tilde{a}_1)}_{\bar{\mu}_\theta}, \underbrace{\lambda_1\sigma_\theta^2}_{\bar{\sigma}_\theta^2})$$

where $\lambda_1 = \frac{\sigma_\varepsilon^2}{\sigma_\varepsilon^2+\sigma_\theta^2}$

2. **Period 2 Belief:** Given y_2, a_1 (substitute $\tilde{a}_1$ in $\bar{\mu}_\theta$ and $\bar{\sigma}_\theta^2$), and the conjecture $\tilde{a}_2$, we have

$$y_2 - \tilde{a}_2 = \theta + \epsilon_2$$

Based on the normal-Normal learning (8.1), the posterior belief about θ is

$$N(\underbrace{\lambda_2\bar{\mu}_\theta + (1-\lambda_2)(y_2 - \tilde{a}_2)}_{\bar{\bar{\mu}}_\theta}, \underbrace{\lambda_2\bar{\sigma}_\theta^2}_{\bar{\bar{\sigma}}_\theta^2})$$

where $\lambda_1 = \frac{\sigma_\varepsilon^2}{\sigma_\varepsilon^2+\bar{\sigma}_\theta^2}$

The optimal $s_2^* = \bar{\bar{\mu}}_\theta$. Then,

$$\begin{aligned}
U_{I,2} &= s_2^* - ka_2^2 \\
&= \lambda_2\bar{\mu}_\theta + (1-\lambda_2)(y_2 - \tilde{a}_2) - ka_2^2 \\
&= \lambda_2\bar{\mu}_\theta + (1-\lambda_2)(\theta + a_2 + \epsilon_2 - \tilde{a}_2) - ka_2^2 \\
\frac{\partial U_{I,2}}{\partial a_2} &= 1 - \lambda_2 - 2ka_2 \\
a_2^* &= \frac{1-\lambda_2}{2k}
\end{aligned}$$

Similarly,

$$a_1^* = \frac{1-\lambda_2}{2k} > \frac{1-\lambda_2}{2k}$$

8.3 Motivated Beliefs

1. The objective probability distribution is $\Pi = (\pi_1, \pi_2, ..., \pi_n)$;
2. The motivated belief $\Pi' = (\pi_1', \pi_2', ..., \pi_n')$ maximizes

$$f(\Pi') = \underbrace{-\alpha D_{KL}\left(\Pi' \| \Pi\right)}_{\text{accuracy}} + \underbrace{v(\Pi')}_{\text{directional}}$$

$$\text{s.t. } g(\Pi') = 1 - \sum_{i=1}^{n} \pi_i' = 0$$

where $D_{KL}\left(\Pi' \| \Pi\right) \triangleq \sum_{i=1}^{n} \pi_i' \log\left(\frac{\pi_i'}{\pi_i}\right)$ is the KL-divergence.

The Lagrangian is

$$
\begin{aligned}
L(\Pi') &= f(\Pi') - \lambda g(\Pi') \\
&= -\alpha D_{KL}\left(\Pi' \| \Pi\right) + v(\Pi') - \lambda(1 - \sum_{i=1}^{n} \pi_i') \\
\frac{\partial L(\Pi')}{\partial \pi_i'} &= -\alpha \left(1 + \log\left(\frac{\pi_i'}{\pi_i}\right)\right) + \frac{\partial v(\Pi')}{\partial \pi_i'} + \lambda = 0
\end{aligned}
$$

Let $v(\Pi') = \sum_{i=1}^{n} v_i \pi_i'$, then we have

$$\pi_i' = e^{\frac{\lambda}{\alpha}-1} e^{\frac{v_i}{\alpha}} \pi_i$$

By the constraint $1 - \sum_{i=1}^{n} \pi_i' = 0$, $e^{\frac{\lambda}{\alpha}-1} = \frac{1}{\sum_{j=1}^{n} e^{\frac{v_j}{\alpha}} \pi_j}$. Then,

$$\pi_i' = \frac{e^{\frac{v_i}{\alpha}} \pi_i}{\sum_{i=j}^{n} e^{\frac{v_j}{\alpha}} \pi_j}$$

8.3.1 Quadratic Motives

Suppose there is a $\theta \sim N(\mu, \sigma^2)$, the real density is

$$f(\theta) \propto e^{-\frac{1}{2}\left(\frac{\theta-\mu}{\sigma}\right)^2}$$

The motivated density is

$$
\begin{aligned}
\tilde{f}(\theta) &= \underset{f'(\theta)}{\operatorname{argmax}} -D_{KL}\left(f' \| f\right) + \int_{\theta} v(\theta) f'(\theta) d\theta \\
\Rightarrow \tilde{f}(\theta) &= \frac{f(\theta) e^{v(\theta)}}{\int_{\theta'} f(\theta') e^{v(\theta')} d\theta'} \propto f(\theta) e^{v(\theta)}
\end{aligned}
$$

where $\int_{\theta'} f(\theta') e^{v(\theta')} d\theta'$ is assumed to be finite.

We take any quadratic $v(\theta) = v_0 + v_1\theta + v_2\theta^2$. Then,

$$\tilde{f}(\theta) \propto e^{-\frac{1}{2}\left(\frac{\theta-\mu}{\sigma}\right)^2 + v_0 + v_1\theta + v_2\theta^2} = k e^{-\frac{1}{2}\left(\frac{\theta-\mu_d}{\sigma_d}\right)^2}$$

where $\mu_d = \frac{v_1 + \sigma^{-2}\mu}{\sigma^{-2} - 2v_2}$, $\sigma_d = \left(\sigma^{-2} - 2v_2\right)^{-\frac{1}{2}}$, and k is a constant that is not a function of θ.

8.3.2 Accountability Model with Motivated Reasoning

There is an incumbent (with $\theta_I \sim N(\mu_I = 0, \sigma_\theta^2)$), finite set of voters and a (non-strategic) challenger (with θ_C).

The incumbent takes action $e \geq 0$. Public signal is $s = \theta_I + e + \epsilon$, where $\epsilon \sim N(0, \sigma_\epsilon^2)$. Voters decide whether to retain the incumbent after observing s.

$$
\begin{aligned}
U_I(e, R) &= R - c(e) \\
U_j(R) &= s + a_j + R(\theta_I + a_j + v_I) + (1 - R)(\theta_C + v_C)
\end{aligned}
$$

$R = 1$ if the incumbent stays at $t = 2$, $R = 0$ otherwise.

v_I, v_C are candidate-specific utility shocks common to all voters ($v_I - v_C$ has mean 0 and variance σ_v^2).

a_j is the affinity of voter j to the incumbent.

Motivated Reasoning: (a simpler version), the voter is maximizing $\log f_{\theta|s}(\tilde{\theta}_I|s) + \delta v(a_j, \tilde{\theta}_I)$.

Assumptions: weakly concave in $\tilde{\theta}_I$ and $\frac{\partial^2 v(a_j,\tilde{\theta}_I)}{\partial a_j \partial \tilde{\theta}_I} \geq 0$.

A more general version:

$$\tilde{f}(\theta) = \underset{f'(\theta)}{\operatorname{argmax}} -D_{KL}\left(f' \| f\right) + \delta \int_\theta v(\theta) f'(\theta) d\theta$$

$$\Rightarrow \tilde{f}(\theta) = \frac{f(\theta)e^{\delta v(\theta)}}{\int_{\theta'} f(\theta')e^{\delta v(\theta')}d\theta'} \propto f(\theta)e^{\delta v(\theta)}$$

Example 8.1 Spatial Bias: $v(a_j, \theta_I) = -(a_j - \theta_I)^2$.

$\tilde{\mu}_I = \frac{1}{1+2\delta\sigma_\theta^2}\mu_I + \frac{2\delta\sigma_\theta^2}{1+2\delta\sigma_\theta^2}a_j$ and the variance is $\tilde{\sigma}_\theta^2 = \left(\sigma_\theta^2 + 2\delta\right)^{-1} < \sigma_\theta^2$.

Given the conjecture $\hat{e}$, the posterior belief of mean upon receiving s is $\lambda\tilde{\mu}_I + (1-\lambda)(s - \hat{e})$.

A voter votes to re-elect if and only if: $\tilde{\mu}_I(s, a_j, \delta, \hat{e}) + a_j + v_I \geq \mu_C + v_C$

8.4 Stochastic Game

A "stochastic game" consist of:

1. A set of states K;
2. A set of players N;
3. Action for player i: $A_i(k)$ ($k \in K$);
4. "Period Payoffs": $u_i(A, k)$;
5. Law of motion: $\Pr(k_{t+1} \mid k_t, a_t)$, where a_t is the action taken at t. ("Markov")
6. Discount Rate δ;
7. Utility for the entire game is given by
$$U_i = \sum_{t=1}^{\infty} \delta^{t-1} u_i(a_t, k_t)$$
8. History: $h_t \triangleq (a_1, k_1, ..., a_t, k_t)$ and the set of possible history is H_t.

Definition 8.1 (Markovian Strategy)

A **strategy** for i is a mapping $\sigma_i : H_t \times K \to \Delta A_i(k)$ for all t.

A **Markovian strategy** is a mapping $\sigma_i : K \to \Delta A_i(k)$.

♣

Game starting at t is a subgame; A strategy profile σ^* is a SPNE if all players play BR, starting at each t.

Definition 8.2 (Markov Perfect Equilibrium)

A σ^* is a **Markov Perfect Equilibrium (MPE)** iff it is a SPNE satisfying Markovian. ♣

8.4.1 Prison Dilemma as a stochastic game

Consider PD (Prison Dilemma) as a stochastic game,

1. $K = \{PD\}$;
2. $A_i(PD) = \{0, 1\}$, $u_i(a, PD) = 1 - a_{i,t} + 2a_{-i,t}$;
3. $\Pr(PD|PD, a_t) = 1$

Markov Strategy is defined by $\sigma_i = \Pr(a_{i,t} = 1) \in [0, 1]$.

In any MPE, the Markov Strategy at t should maximize U_i starting at t',

$$\begin{aligned}\sigma_i &= \operatorname*{argmax}_{\sigma_i' \in [0,1]} \delta^{t'}(1 - \sigma_i' + 2\sigma_{-i}) + \sum_{t=t'+1}^{\infty} \delta^{t-1}(1 - \sigma_i + 2\sigma_{-i}) \\ &= 0\end{aligned}$$

This a SPNE and MPE.

8.4.2 Revised Prison Dilemma

1. $K = \{PD, WPD\}$;
2. $A_i(PD) = \{0, 1\}$, $u_i(a, PD) = 1 - a_{i,t} + 2a_{-i,t}$;
3. $A_i(WPD) = \{0, 1\}$, $u_i(a, WPD) = u_i(a, PD) - x$, where $x \in \mathbb{R}_+$;
4. $\Pr(k_{t+1} = WPD \mid k_t = WPD) = 1$;
5. $\Pr(k_{t+1} = WPD \mid k_t = PD, (1, 1)) = 0$;
6. $\Pr(k_{t+1} = WPD \mid k_t = PD, \{(0, 1), (1, 0), (0, 0)\}) = q, q \in [0, 1]$.

Markov Strategy is defined by $\sigma_i(k_t)$. Obviously, $\sigma_i^*(WPD) = 0$ in any MPE.

"Value function" $v(PD, \sigma)$ represents the net present value of starting a period in state PD given σ. The most desirable situation that both players choose 1:

$$v(PD, \sigma^*) = 2 + \delta v(PD, \sigma^*) \Rightarrow v(PD, \sigma^*) = \frac{2}{1 - \delta}$$

Check one-period devotion from changing 1 to 0 at this stage:

$$\begin{aligned}v'(PD, \sigma^*) &= 3 + \delta\left[qv(WPD, \sigma^*) + (1 - q)v(PD, \sigma^*)\right] \\ &= 3 + \delta\left[q\frac{1 - x}{1 - \delta} + (1 - q)\frac{2}{1 - \delta}\right]\end{aligned}$$

This deviation is not profitable if

$$v'(PD, \sigma^*) \leq v(PD, \sigma^*)$$
$$\text{i.e. } q \geq \frac{1-\delta}{(1+x)\delta}$$

8.4.3 Dynamic Commitment Problem

1. $K = \{l, h, w_C, w_R\}$;
2. $N = \{C, R\}$;
3. In state $k \in \{l, h\}$:

   R makes an offer $x_k \leq 1$;

   C accepts (R and C get period payoffs $(1 - x_k, x_k)$ and $\Pr(k_{t+1} = h) = q$, $\Pr(k_{t+1} = l) = 1 - q$) or rejects (R and C get period payoffs $((1 - p_k)(1 - f), p_k(1 - f))$ and $\Pr(k_{t+1} = w_C) = p_k$, $\Pr(k_{t+1} = w_R) = 1 - p_k$), where $f \in (0, 1)$ and $0 < p_l < p_h < 1$.
4. If enter w_C (R and C get period payoffs $(0, 1 - f)$); If enter w_R (R and C get period payoffs $(1 - f, 0)$); Game over.

MPE

If offer accepted in l and h, x_k:

$$v_C(l; p) = x_k + \delta \left(q v_C(h; p) + (1 - q) v_C(l; p)\right)$$
$$= v_C(h; p) = x_k + \delta \left(q v_C(h; p) + (1 - q) v_C(l; p)\right)$$

If offer rejected, $\frac{p_k(1-f)}{1-\delta}$.

In equilibrium $\frac{p_k(1-f)}{1-\delta} = v_C(l; p) = v_C(h; p)$, then we have

$$x_k = (p_k - \delta \bar{p}) \frac{1 - f}{1 - \delta}, \text{ where } \bar{p} = q p_h + (1 - q) p_l$$