Comparative statics with adjustment costs and the Le Chatelier principle

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Motivation

Comparative statics: under what circumstances does a parameter shift 'increase' optima / equilibria?

Adjustment costs: key feature of many economic models, e.g.

- capital investment (e.g. Jorgenson, 1963; Hayashi, 1982; Cooper & Haltiwanger, 2006)
- sticky prices (e.g. Mankiw, 1985; Caplin & Spulber, 1987; Golosov & Lucas, 2007; Midrigan, 2011)
- trade in illiquid assets (e.g. Kyle, 1985; Back, 1992)
- wealthy hand-to-mouth (e.g. Kaplan & Violante, 2014; Berger & Vavra, 2015; Chetty & Szeidl, 2016)
- labour supply (e.g. Chetty, Friedman, Olsen & Pistaferri, 2011; Chetty, 2012)
- labour demand (e.g. Hamermesh, 1988; Bentolila & Bertola, 1990)

Motivation

Comparative statics: under what circumstances does a parameter shift 'increase' optima / equilibria?

Adjustment costs: key feature of many economic models.

This paper: comparative statics for adjustment-cost models.

Example: sticky-price models

Central plank of new Keynesian macro models: sticky prices.

Most important micro-foundation: adjustment ('menu') costs.
(e.g. Mankiw, 1985; Golosov & Lucas, 2007; Midrigan, 2011)

<u>Simplest model:</u> monopolist with constant marg. cost $c \geq 0$,

decr. demand curve $D(\cdot, \eta)$,

parameter η shifts $|\text{elasticity}|$.

Adjusting price by ϵ costs $C(\epsilon) \geq 0$.

Under what ass'ns on demand $D(\cdot, \eta)$ & adj. cost $C(\cdot)$ do

$$\text{supply shocks } (c \nearrow) \quad \Longrightarrow \quad \text{inflation?}$$

$$\text{demand-elasticity shocks } (\eta \searrow) \quad \Longrightarrow \quad \text{inflation?}$$

Overview

Basic setting: one-off parameter shift,
agent adjusts subject to cost.

Basic insight (Th'm 1): need only very weak
assumptions on cost.

Consequence (Th'm 2): new, greatly generalised
Le Chatelier principle.

Consequence (Th'ms 3–6): results extend to
infinite-horizon model.

Applications: factor demand, pricing, investment,
labour supply, saving.

Setting

Action $x \in L$, $\quad L \subseteq \mathbf{R}^n \quad$ (L a sublattice)

Objective $F(x, \theta)$ depends on parameter θ

($\in \Theta$, a partially ordered set)

At initial parameter $\underline{\theta}$, agent chose $\underline{x} \in \arg\max_{x \in L} F(x, \underline{\theta})$

Parameter $\nearrow$ to $\bar{\theta}$, $\quad$ agent adjusts $x \in L$

Adjusting by $\epsilon = x - \underline{x}$ costs $C(\epsilon) \geq 0$

Agent maximises $G(x, \bar{\theta}) \coloneqq F(x, \bar{\theta}) - C(x - \underline{x})$.

Cost assumptions

Cost $\quad C : \Delta L \to [0, \infty] \qquad$ where $\Delta L \coloneqq \{x - y : x, y \in L\} \subseteq \mathbf{R}^n$.

Assume little about C: $\quad C(0) < \infty \quad$ and

– for first result : $\quad C \;$ <u>minimally monotone</u>

– for other results: $\quad C \;$ <u>monotone</u>

Allows

– non-convex costs (even non-quasiconvex)

– some adjustments infeasible: $\quad C(\epsilon) = \infty$

– non-separability between dimensions (as in Midrigan (2011))

Minimal monotonicity

C is minimally monotone iff $C(\epsilon \wedge 0) \leq C(\epsilon) \geq C(\epsilon \vee 0) \quad \forall \epsilon.$

('$\wedge$' is entry-wise min; '$\vee$' is entry-wise max.)

Interpretation: cancelling all upward adjustments lowers cost; likewise for downward adjustments.

For 1D action $L \subseteq \mathbf{R}$,

C minimally monotone

$\iff$ C minimised at 0.

For additively separable $C(\epsilon) = \sum_{i=1}^{n} C_i(\epsilon_i)$,

C minimally monotone

$\iff$ each C_i minimised at 0.

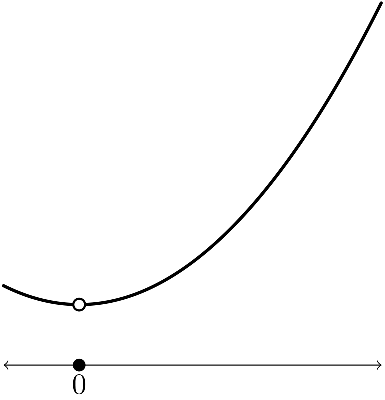
Minimal monotonicity: example

1D action $L \subseteq \mathbf{R}$

fixed cost $k > 0$

variable cost $a\epsilon^2$ $(a > 0)$

$$C(\epsilon) = \begin{cases} 0 & \text{for} \quad \epsilon = 0 \\ k + a\epsilon^2 & \text{for} \quad \epsilon \neq 0 \end{cases}$$



Minimal monotonicity: example

1D action $L \subseteq \mathbf{R}$

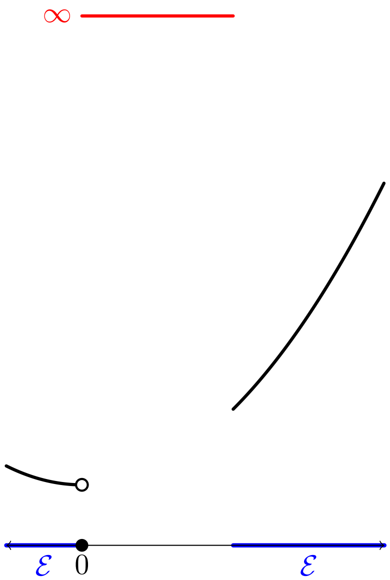
fixed cost $k > 0$

variable cost $a\epsilon^2 \quad (a > 0)$

constraint set $\mathcal{E} \quad (\ni 0)$

$$C(\epsilon) = \begin{cases} 0 & \text{for } \quad \epsilon = 0 \\ k + a\epsilon^2 & \text{for } 0 \neq \epsilon \in \mathcal{E} \\ \infty & \text{for } \quad \epsilon \notin \mathcal{E} \end{cases}$$

As in Field–Pande–Papp–Rigol 2013,
Bari–Malik–Meki–Quinn 2021



Review: costless adjustment

Basic result (see Milgrom & Shannon, 1994)**:** if $F(x,\theta)$ exhibits

(1) complementarity btw. action x & parameter θ

(2) complementarity btw. action dimensions $x = (x_1, \ldots, x_n)$

then $\bar{x} \geq \underline{x}$ for some $\bar{x} \in \arg\max_{x \in L} F(x, \bar{\theta})$ $\substack{\text{provided arg max} \\ \text{is not empty}}$.

Here

(1) means <u>single-crossing differences in (x,θ)</u>: for any $x' > x$,

$$F(x',\theta) \geq (>)\, F(x,\theta) \implies F(x',\theta') \geq (>)\, F(x,\theta') \quad \text{if } \theta < \theta'$$

(2) means <u>quasi-supermodularity in x</u>: for any $x, x' \in L$,

$$F(x,\theta) \geq (>)\, F(x \wedge x', \theta) \implies F(x \vee x', \theta) \geq (>)\, F(x', \theta) \quad \forall \theta$$

Review: ordinal vs. cardinal complementarity

SCD & QSM are

- ordinal: preserved by $\nearrow$ transformations
- not inherited by sums: sum of SCD (QSM) functions generally not SCD (QSM)

Cardinal sufficient conditions
that are (not ordinal, but) inherited by sums:

incr. differences in (x, θ): marginal return $F(x', \theta) - F(x, \theta)$
$\nearrow$ in θ (for $x' > x$)

supermodularity in x: marginal return

$F((x_i', x_j, x_{-ij}), \theta) - F((x_i, x_j, x_{-ij}), \theta)$

$\nearrow$ in x_j (for $x_i' > x_i$, $i \neq j$)

Comparative statics with costly adjustment

Recall: agent maximises $G(x, \bar{\theta}) \coloneqq F(x, \bar{\theta}) - C(x - \underline{x})$.

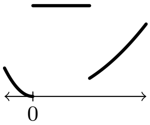
Theorem 1: if $F(x, \theta)$ exhibits

(1) complementarity btw. action x & parameter θ

(2) complementarity btw. action dimensions $x = (x_1, \dots, x_n)$

and cost C is minimally monotone,

then $\widehat{x} \geq \underline{x}$ for some $\widehat{x} \in \arg\max_{x \in L} G(x, \bar{\theta})$ $\substack{\text{provided arg max} \\ \text{is not empty}}$.

Costs need not even be single-dipped! E.g. $C =$ 

Only <u>ordinal</u> complementarity on F. (<u>Not</u> inherited by G!)

Proof of Theorem 1

Fix $x' \in \arg\max_{x \in L} G(x, \bar{\theta})$.

Clearly $\underline{x} \vee x' \geq \underline{x}$. Will show $\underline{x} \vee x' \in \arg\max_{x \in L} G(x, \bar{\theta})$.

Standard steps:

$$
\begin{aligned}
& & F(\underline{x}, \underline{\theta}) \geq F(\underline{x} \wedge x', \underline{\theta}) \quad & \text{by def'n of } \underline{x} \\
& \implies & F(\underline{x} \vee x', \underline{\theta}) \geq F(x', \underline{\theta}) \quad & \text{by QSM} \\
& \implies & F(\underline{x} \vee x', \bar{\theta}) \geq F(x', \bar{\theta}) \quad & \text{by SCD.}
\end{aligned}
$$

New step:

$$
\begin{aligned}
& C\big(\underline{x} \vee x' - \underline{x}\big) \\
&= C\big((x' - \underline{x}) \vee 0\big) \\
&\leq C\big(x' - \underline{x}\big) \qquad \text{by minimal monotonicity.}
\end{aligned}
$$

So

$$
\begin{aligned}
G(\underline{x} \vee x', \bar{\theta}) &= F(\underline{x} \vee x', \bar{\theta}) - C(\underline{x} \vee x' - \underline{x}) \\
&\geq F(x', \bar{\theta}) - C(x' - \underline{x}) = G(x', \bar{\theta}).
\end{aligned}
$$

QED

Monotonicity

Cost C is <u>monotone</u> iff for each adj. vector ϵ & each i,

$$C(\epsilon_1, \ldots, \epsilon_{i-1}, \epsilon_i', \epsilon_{i+1}, \ldots, \epsilon_n) \leq C(\epsilon) \quad \text{whenever } 0 \leq \epsilon_i' \leq \epsilon_i \text{ or } 0 \geq \epsilon_i' \geq \epsilon_i.$$

Interpretation: adjusting less lowers cost.

For $L \subseteq \mathbf{R}$, C monotone

$\iff$ C <u>single-dipped</u> & <u>minimised at 0</u>.

(i.e. $\searrow$ on $(-\infty, 0]$, $\nearrow$ on $[0, \infty)$)

For additively separable $C(\epsilon) = \sum_{i=1}^n C_i(\epsilon_i)$,

C monotone

$\iff$ each C_i single-dipped & minimised at 0.

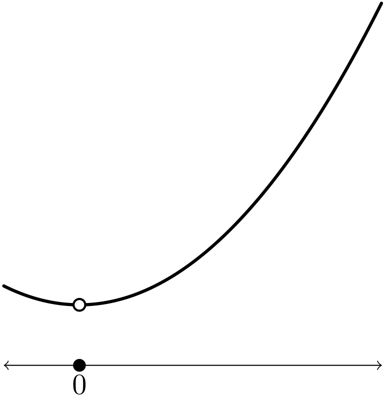
Example of monotonicity

1D action $L \subseteq \mathbf{R}$

fixed cost $k > 0$

variable cost $a\epsilon^2 \quad (a > 0)$

$$C(\epsilon) = \begin{cases} 0 & \text{for} \quad \epsilon = 0 \\ k + a\epsilon^2 & \text{for} \quad \epsilon \neq 0 \end{cases}$$



Example of monotonicity violation

1D action $L \subseteq \mathbf{R}$

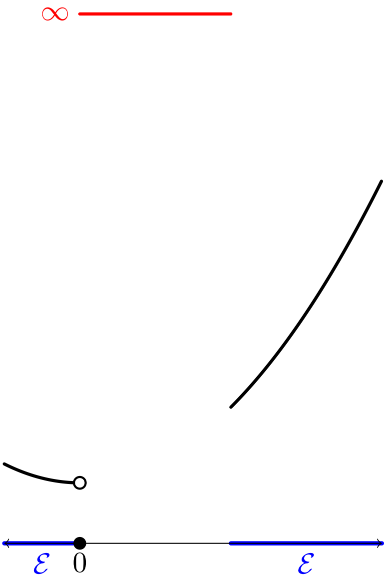
fixed cost $k > 0$

variable cost $a\epsilon^2$ $(a > 0)$

constraint set $\mathcal{E}$ $(\ni 0)$

$$C(\epsilon) = \begin{cases} 0 & \text{for} \quad \epsilon = 0 \\ k + a\epsilon^2 & \text{for } 0 \neq \epsilon \in \mathcal{E} \\ \infty & \text{for} \quad \epsilon \notin \mathcal{E} \end{cases}$$

As in Field–Pande–Papp–Rigol 2013,
Bari–Malik–Meki–Quinn 2021



Examples of monotonicity

– Additively separable: $C(\epsilon) = \sum_{i=1}^{n} C_i(\epsilon_i)$,

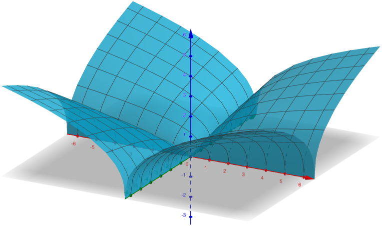
each C_i single-dipped & minimised at 0.

– Euclidean: $C(\epsilon) = \sqrt{\sum_{i=1}^{n} \epsilon_i^2}$.

– Cobb–Douglas: $C(\epsilon) = \prod_{i=1}^{n} |\epsilon_i|^{a_i}$

where $a_1, \ldots, a_n > 0$.

(not quasiconvex)



The Le Chatelier principle

Le Chatelier principle: $|\text{LR elasticity}| \geq |\text{SR elasticity}|$.

Usual story: only some dimensions of x adjustable in SR.

Formalisation (Milgrom & Roberts, 1996)**:** suppose $F(x, \theta)$ exhibits

(1) complementarity btw. action x & parameter θ

(2) complementarity btw. action dimensions $x = (x_1, \ldots, x_n)$.

Let $\bar{x} \in \arg\max_{x \in L} F(x, \bar{\theta})$ satisfy $\bar{x} \geq \underline{x}$.[1] (LR optimum.)

Then $\bar{x} \geq \widehat{x} \geq \underline{x}$ for some SR-optimal $\widehat{x}$.

[1]Such $\bar{x}$ exists by the 'basic result' (sl. 9), provided argmax nonempty.

General Le Chatelier principle

Different story: SR adjustment is <u>costly</u>.

Nests usual story as (very) special case: $C(\epsilon) = \sum_{i=1}^{n} C_i(\epsilon_i)$,

– some dimensions have $C_i \equiv 0$

– other dimensions have $C_i(\epsilon_i) = \infty$ for every $\epsilon_i \neq 0$.

Theorem 2: suppose $F(x, \theta)$ exhibits

(1) complementarity btw. action x & parameter θ

(2) complementarity btw. action dimensions $x = (x_1, \ldots, x_n)$

and cost C is monotone.

Let $\bar{x} \in \arg\max_{x \in L} F(x, \bar{\theta})$ satisfy $\bar{x} \geq \underline{x}$.[2] (LR optimum.)

Then $\bar{x} \geq \widehat{x} \geq \underline{x}$ for some $\widehat{x} \in \arg\max_{x \in L} G(x, \bar{\theta})$ provided arg max is not empty.

[2] Such $\bar{x}$ exists by the 'basic result' (sl. 9), provided argmax nonempty.

Proof of Theorem 2

By Theorem 1, may choose $x' \geq \underline{x}$ in $\arg\max_{x \in L} G(x, \bar{\theta})$.

Clearly $\bar{x} \geq \bar{x} \wedge x' \geq \underline{x}$. We show $\bar{x} \wedge x' \in \arg\max_{x \in L} G(x, \bar{\theta})$.

Standard step: $F(\bar{x} \vee x', \bar{\theta}) \leq F(\bar{x}, \bar{\theta})$ by def'n of $\bar{x}$

$\Longrightarrow$ $F(x', \bar{\theta}) \leq F(\bar{x} \wedge x', \bar{\theta})$ by QSM.

New step: $x' \geq \bar{x} \wedge x' \geq \underline{x}$ $\Longrightarrow$ $(x' - \underline{x}) \geq (\bar{x} \wedge x' - \underline{x}) \geq 0$

$\Longrightarrow$ $C(x' - \underline{x}) \geq C(\bar{x} \wedge x' - \underline{x})$ by monotonicity.

So
$$\begin{aligned} G(x', \bar{\theta}) &= F(x', \bar{\theta}) - C(x' - \underline{x}) \\ &\leq F(\bar{x} \wedge x', \bar{\theta}) - C(\bar{x} \wedge x' - \underline{x}) \\ &= G(\bar{x} \wedge x', \bar{\theta}). \end{aligned}$$

QED

Why not minimal monotonicity?

Minimal monotonicity is not enough for Le Chatelier. Example:

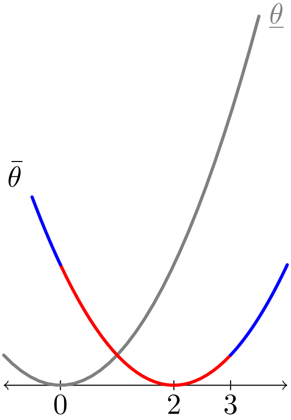
$$L = \mathbf{R} \qquad \begin{aligned} F(x,\underline{\theta}) &= -x^2 \\ F(x,\bar{\theta}) &= -(x-2)^2 \end{aligned} \qquad C(\epsilon) = \begin{cases} \infty & \text{if } 0 < \epsilon < 3 \\ 0 & \text{otherwise.} \end{cases}$$

C is minimally monotone,
not monotone.

Initial: $\underline{x} = 0 \in \arg\min_{x\in\mathbf{R}} x^2$

SR: $\widehat{x} = 3 \in \arg\min_{x\in\mathbf{R}\setminus(0,3)} (x-2)^2$

LR: $\bar{x} = 2 \in \arg\min_{x\in\mathbf{R}} (x-2)^2$



Application to factor demand

Inputs (k,ℓ), real input prices (r,w), production function f

Monotone adjustment cost

Profit $F(k,\ell,-w) = f(k,\ell) - rk - w\ell$

- supermodular in (k,ℓ): if f supermodular (complements)
- incr. diff. in $((k,\ell),-w)$: $\nabla_{(k,\ell)}F = \begin{pmatrix} f_k - r \\ f_\ell - w \end{pmatrix} \nearrow$ in $-w$

As $w \searrow$, both factor demands $\nearrow$ (Theorem 1)

In LR, both factor demands further $\nearrow$ (Theorem 2)

If instead f submodular (substitutes), ℓ demand $\nearrow$ but
k demand $\searrow$.

Application to pricing

Menu-cost model: monopolist with constant marg. cost $c \geq 0$,

decr. demand curve $D(\cdot, \eta)$,

parameter η shifts $|\text{elasticity}|$.

Adjusting price by ϵ costs $C(\epsilon) \geq 0$.

Profit $F(p, (c, -\eta)) = (p - c)D(p, \eta)$

- F QSM in p: automatic since p one-dimensional $(\in \mathbf{R})$
- $\ln F$ has incr. differences in $(p, (c, -\eta))$:

$$\frac{\mathrm{d}}{\mathrm{d}p} \ln F = \frac{1}{p-c} + \frac{D'(p,\eta)}{D(p,\eta)} = \frac{1}{p-c} - \frac{|\text{elasticity}(p,\eta)|}{p}$$

$\nearrow$ in c & $-\eta$

Dynamic adjustment

Agent chooses $x_t \in L$ in each period $t \in \mathbf{N}$

Period-t payoff: $F(x_t, \theta_t) - C_t(x_t - x_{t-1})$

Taken as given:

- initial choice $x_0 = \underline{x} \in \arg\max_{x \in L} F(x, \underline{\theta})$
- parameter path $(\theta_t)_{t=1}^{\infty}$
- cost path $(C_t)_{t=1}^{\infty}$

Agent forward-looking, discount rate $\delta \in (0, 1)$

Chooses path $(x_t)_{t=1}^{\infty}$ to max $\displaystyle\sum_{t=1}^{\infty} \delta^t [F(x_t, \theta_t) - C_t(x_t - x_{t-1})].$

Dynamic Le Chatelier principle

Theorem 3: suppose $F(x, \theta)$ exhibits

(1) complementarity btw. action x & parameter θ

(2) complementarity btw. action dimensions $x = (x_1, \ldots, x_n)$,

and that each cost C_t is monotone.

Fix $\bar{x} \in \arg\max_{x \in L} F(x, \bar{\theta})$ such that $\bar{x} \geq \underline{x}$.[3]

If $\underline{\theta} \leq \theta_t \leq \bar{\theta} \quad \forall t,$ then $\underline{x} \leq x_t \leq \bar{x} \quad \forall t$

for some solution $(x_t)_{t=1}^{\infty}$, provided a solution exists.

Proof: straightforward extension of Theorem 1+2 logic.

[3] Such $\bar{x}$ exists by the 'basic result' (sl. 9), provided argmax nonempty.

Strong dynamic Le Chatelier principle

Theorem 4: suppose $F(x, \theta)$ exhibits

(1) complementarity btw. action x & parameter θ

(2) cardinal complementarity btw. dimensions $x = (x_1, \ldots, x_n)$

(3) boundedness in x on each compact set $\subseteq L$, for each θ,

and that $C_t = C \quad \forall t$ for C monotone & additively separable.

Fix $\bar{x} \in \arg\max_{x \in L} F(x, \bar{\theta})$ such that $\bar{x} \geq \underline{x}$.[4]

If $\theta_t = \bar{\theta} \quad \forall t,$ then $\underline{x} \leq x_t \leq x_{t+1} \leq \bar{x} \quad \forall t$

for some solution $(x_t)_{t=1}^{\infty}$, provided a solution exists.

[4]Such $\bar{x}$ exists by the 'basic result' (sl. 9), provided argmax nonempty.

Sketch proof of Theorem 4

Can 'monotonise' any $(x_t)_{t=1}^{\infty}$ by replacing t^{th} entry

with cumulative max $\quad x_1 \vee x_2 \vee \cdots \vee x_{t-1} \vee x_t$.

<u>Claim:</u> monotonisation preserves optimality.

(Suffices since can then monotonise solution from Theorem 3.)

By boundedness & limit argument, suffices to show that

if $(x_t)_{t=1}^{\infty}$ optimal & $\quad x_1 \leq x_2 \leq \cdots \leq x_{k-1} \leq x_k$,

remains optimal if replace t^{th} entry by $\quad x_{t-1} \vee x_t \quad \forall t \geq k+1$.

Proved using supermodularity of $F(\cdot, \bar{\theta})$,
+ monotonicity & additive separability of C.

(argument: slide 28)

Application to pricing, continued

Assume cost C time-invariant,
demand $D(\cdot, \eta)$ upper semi-continuous.

Profit $F(p,(c,-\eta)) = (p-c)D(p,\eta)$

- $F(p,(c,-\eta))$ SM in p & C additively separable: automatic since p one-dimensional ($\in \mathbf{R}$)
- $F(p,(c,-\eta))$ bounded in p on each compact set $\subseteq \mathbf{R}_+$

Theorem 4:

- supply shock $(c \nearrow)$ $\Longrightarrow$ inflation at every horizon
- demand shock s.t. $\eta \searrow$ $\Longrightarrow$ inflation at every horizon

Thanks!

$$\nearrow$$

Sketch proof of Theorem 4: main step

$(x_t)_{t=1}^{\infty}$ optimal $\implies$ better than $(x_t \wedge x_{t+1})_{t=1}^{\infty}$:

$$\sum_{t=k}^{\infty} \delta^{t-k}\left[F(x_t,\bar\theta) - F(x_t \wedge x_{t+1},\bar\theta)\right]$$
$$-\sum_{t=k}^{\infty} \delta^{t-k}[C(x_t - x_{t-1}) - C(x_t \wedge x_{t+1} - x_{t-1} \wedge x_t)] \geq 0.$$

$F(\cdot,\bar\theta)$ supermodular:
$$F(x_t \vee x_{t+1},\bar\theta) - F(x_{t+1},\bar\theta)$$
$$\geq F(x_t,\bar\theta) - F(x_t \wedge x_{t+1},\bar\theta) \qquad \forall t \geq k$$

C monotone & additively separable: (argument omitted)

$$C(x_t \vee x_{t+1} - x_{t-1} \vee x_t) - C(x_{t+1} - x_t)$$
$$\leq C(x_t - x_{t-1}) - C(x_t \wedge x_{t+1} - x_{t-1} \wedge x_t) \qquad \forall t \geq k$$

So (changing variables,) $(x_{t-1} \vee x_t)_{t=1}^{\infty}$ better than $(x_t)_{t=1}^{\infty}$:

$$\sum_{t=k+1}^{\infty} \delta^{t-(k+1)}\left[F(x_{t-1} \vee x_t,\bar\theta) - F(x_t,\bar\theta)\right]$$
$$-\sum_{t=k+1}^{\infty} \delta^{t-(k+1)}[C(x_{t-1} \vee x_t - x_{t-2} \vee x_{t-1}) - C(x_t - x_{t-1})] \geq 0.$$

(back to slide 25)

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