

# A Proxy Contract Based Approach to the First-Order Approach in Agency Models

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Principal's canonical problem ( $\mathbf{x}$  is the multi-dimensional signal):

$$\max_{a, s(\cdot)} \int (\pi(\mathbf{x}) - s(\mathbf{x})) f(\mathbf{x}|a) d\mathbf{x} \quad \text{s.t.}$$

$$(i) \text{ (PC)} \quad U(s(\cdot), a) \geq \bar{U}$$

$$(ii) \text{ (IC)} \quad a \in \arg \max_{a'} \int u(s(\mathbf{x})) f(\mathbf{x}|a') d\mathbf{x} - a'$$

$$(iii) \text{ (LL)} \quad s(\mathbf{x}) \geq \underline{s}$$

**Note:** the limited-liability (LL)  $s(\mathbf{x}) \geq \underline{s}$  for the solution existence (e.g., Mirrlees (1975)): especially when

$$\frac{f_a}{f}(\mathbf{x}|a) \rightarrow -\infty, \quad \text{when } \mathbf{x} \rightarrow \underline{x} \quad (1)$$

Principal's canonical problem ( $\mathbf{x}$  is the multi-dimensional signal):

$$\max_{a, s(\cdot)} \int (\pi(\mathbf{x}) - s(\mathbf{x})) f(\mathbf{x}|a) d\mathbf{x} \quad \text{s.t.}$$

$$(i) \text{ (PC)} \quad U(s(\cdot), a) \geq \bar{U}$$

$$(ii)' \text{ (IC)-relaxed} \quad U_a(s(\cdot), a) = \int u(s(\mathbf{x})) f_a(\mathbf{x}|a) d\mathbf{x} - 1 = 0$$

$$(iii) \text{ (LL)} \quad s(\mathbf{x}) \geq \underline{s}$$

**Note:** the limited-liability (LL)  $s(\mathbf{x}) \geq \underline{s}$  for the solution existence (e.g., [Mirrlees \(1975\)](#)): especially when

$$\frac{f_a}{f}(\mathbf{x}|a) \rightarrow -\infty, \quad \text{when } \mathbf{x} \rightarrow \underline{\mathbf{x}} \quad (2)$$

Optimal contract  $(s^o(x), a^o)$  based on the first-order approach:

$$\frac{1}{u'(s^o(x))} = \begin{cases} \lambda + \mu \frac{f_a(x|a^o)}{f(x|a^o)}, & \text{if } s^o(x) \geq \underline{s}, \\ \frac{1}{u'(\underline{s})}, & \text{otherwise,} \end{cases}$$

with  $\lambda \geq 0$  and  $\mu > 0$

- Existence and uniqueness: Jewitt, Kadan, and Swinkels (2008)

If the agent's value function  $U(s^o(\cdot), a)$ ,

$$U(s^o(\cdot), a) = \int u(s^o(x))f(x|a)dx - a$$

is 'concave' in  $a$ , then the first-order approach is valid (e.g., Mirrlees (1975))

The previous literature since Mirrlees (1975): 'sufficient' conditions for  $U(s^o(\cdot), a)$  to be 'concave' in  $a$

## Question (Focus of the literature)

How can we make  $U(s^o(\cdot), a)$  concave in  $a$ ?

**Strategy 1:** put conditions on  $f(x|a)$ , the technology, only:

- ① One-signal (i.e.,  $x$  is scalar): **Mirrlees (1975)** and **Rogerson (1985)**: **MLRP** (monotone likelihood ratio property) and **CDFC** (convexity of the distribution function condition)
- ② Multi-signal extension of **CDFC**: **Sinclair-Desgagné (1994)**, **GCDFC**: generalized CDFC), **Conlon (2009)**, **CISP**: concave increasing set property), and **Jung and Kim (2015)**, **CDFCL**: convexity of the distribution function condition for the likelihood ratio)
- ③ Too restricted (e.g., normal, gamma distributions excluded)

## Question (Focus of the literature)

How can we make  $U(s^\circ(\cdot), a)$  concave in  $a$ ?

**Strategy 2:** put conditions on both  $u(s)$  and  $f(\mathbf{x}|a)$ :

① Theorem 1 in Jewitt (1988):

$$w(z) \equiv u\left(u'^{-1}\left(\frac{1}{z}\right)\right) \text{ is concave in } z > 0 \quad (3)$$

or Proposition 7 in Jung and Kim (2015):

$$U(s^\circ(\mathbf{x}), a^\circ) \equiv r(q) \text{ is concave in } q \equiv \frac{f_a}{f}(\mathbf{x}|a^\circ) \quad (4)$$

→ (3) and (4) are equivalent

② Problem: Cannot be used when the agent's limited liability  $s(\mathbf{x}) \geq \underline{s}$  binds:

$$U(s^\circ(\mathbf{x}), a^\circ) \text{ becomes convex in } q \equiv \frac{f_a}{f}(\mathbf{x}|a^\circ)$$

around  $\mathbf{x}$  where  $s(\mathbf{x}) \geq \underline{s}$  binds

# Examples show the existing conditions are not enough

## Example (Poisson distribution: (LL) not binding)

- ① The agent's utility is  $u(s) = \frac{1}{r} s^r$ , with  $r > \frac{1}{2}$
- ② The single-dimensional signal  $x$ , which is non-negative integer, follows

$$f(x|a) = \frac{[h(a)]^x}{\Gamma(x+1)} e^{-h(a)}. \quad (5)$$

which is the Poisson distribution with mean  $h(a)$  that is increasing in  $a$

Issue with  $r > \frac{1}{2}$ :

- $U(s^o(\mathbf{x}), a^o) \equiv r(q)$  becomes convex in  $q$ , not satisfying **Jewitt (1988)** and **Jung and Kim (2015)**
- Our Proposition 2 justifies the first-order approach in this case if  $h(a)$  becomes concave 'enough'
- **Jewitt (1988)** and **Jung and Kim (2015)** imposes  $h(a)$  is concave

**Trade-off:**  $h(a)$  should be more strictly concave, but  $r > \frac{1}{2}$  allowed

## Example (Exponential distribution: (LL) not binding)

- ① The agent's utility is  $u(s) = \frac{1}{r} s^r$ , with  $r < 0$
- ② The single-dimensional signal  $x$ , which is non-negative, follows

$$f(x|a) = \frac{1}{h(a)} e^{-\frac{x}{h(a)}}, \quad (6)$$

which is the exponential distribution with mean  $h(a)$  that is increasing in  $a$

- ③  $h(a)$  is convex to some degree (not too much) in  $a$

Issue with  $h(a)$ :

- Jewitt (1988) and Jung and Kim (2015) imposes  $h(\cdot)$  is concave
- Our Proposition 3 justifies the first-order approach in this case if

$$U(s^o(\mathbf{x}), a^o) \equiv r(q) \text{ becomes concave 'enough'}$$

**Trade-off:**  $r(q)$  should be more strictly concave, but convex  $h(a)$  allowed



## Example (Normal distribution: (LL) binding)

- ① The agent's utility is  $u(s) = \frac{1}{r} s^r$ , with  $r < 1$
- ② The single-dimensional signal  $x \sim N(h(a), \sigma^2)$ , i.e.,

$$f(x|a) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-h(a))^2}{2\sigma^2}}$$

which is a normal distribution with mean  $h(a)$  that is increasing in  $a$

- ③ In this case, (LL)  $s(x) \geq \underline{s}$  must be imposed

### Issue with normal distribution:

- The previous literature cannot justify the first-order approach in this simple example
- $U(s^o(\mathbf{x}), a^o) \equiv r(q)$  becomes convex at points where (LL) binds, not satisfying [Jewitt \(1988\)](#) and [Jung and Kim \(2015\)](#): even if  $r < \frac{1}{2}$

### Example (Normal distribution: (LL) binding)

- ④ The agent's utility is  $u(s) = \frac{1}{r} s^r$ , with  $r < 1$
- ② The single-dimensional signal  $x \sim N(h(a), \sigma^2)$ , i.e.,

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which is a normal distribution with mean  $h(a)$  that is increasing in  $a$

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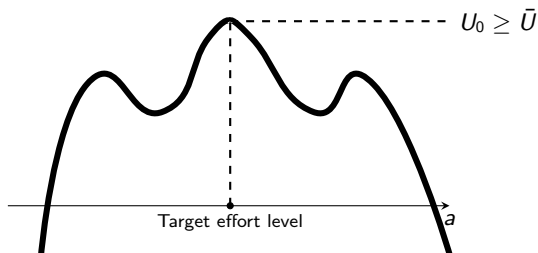
#### Issue with normal distribution:

- Our Proposition 4 justifies the first-order approach in this case if  $h(a)$  becomes concave 'enough', regardless of  $r < 1$
- Jewitt (1988) and Jung and Kim (2015) imposes  $h(a)$  is concave

**Trade-off:**  $h(a)$  should be more strictly concave, but (LL) allowed

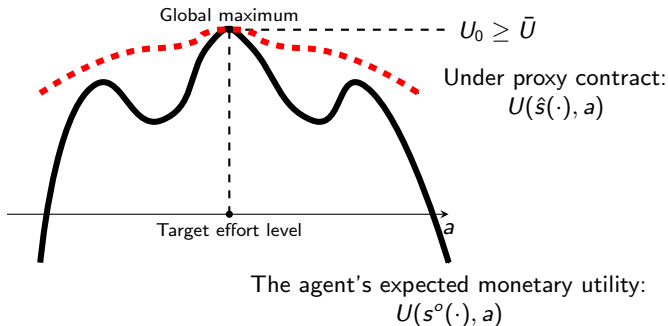
## Big Question (Possibly Non-Concave Expected Monetary Utility of the Agent)

Why should the agent's expected monetary utility  $U(s^o(\cdot), a)$  be concave in  $a$ ?



The agent's expected monetary utility obtained from the first-order approach

**Figure:** Possibly Non-Concave Expected Monetary Utility of the Agent



### Our approach:

- ① Finding a proxy function  $\hat{s}(x)$  where the proxy value  $U(\hat{s}(\cdot), a)$  is maximized at  $a = a^o$ , the same target action level
- ② Proving  $U(s^o(\cdot), a) \leq U(\hat{s}(\cdot), a)$ ,  $\forall a$ , justifying the first-order approach

**Key idea:** double-crossing property between  $s^o(\cdot)$  and  $\hat{s}(\cdot)$  in  $q$ -space

# Fundamental Lemma

À la Jung and Kim (2015), define the likelihood ratio

$$\tilde{q} \equiv Q_{a^o}(\tilde{\mathbf{x}}) \equiv \frac{f_a(\tilde{\mathbf{x}}|a^o)}{f(\tilde{\mathbf{x}}|a^o)}$$

The optimal contract  $s^o(x)$  in  $q$ -space becomes:

$$s^o(x) \equiv w(q) \equiv (u')^{-1} \left( \frac{1}{\lambda + \mu q} \right)$$

The agent's indirect utility given  $s^o(\cdot)$

$$u(s^o(\mathbf{x})) \equiv r(q) = \begin{cases} u(w(q)) \equiv \bar{r}(q), & \text{when } q \geq q_c \\ u(\underline{s}), & \text{when } q < q_c \end{cases}$$

- Threshold  $q_c$  solves  $u'(\underline{s})^{-1} = \lambda + \mu q_c > 0$ :
- $q \leq q_c$ : the limited liability binds

Distribution function for  $q$  given  $a$  (possibly different from  $a^o$ )

$$G(q|a) \equiv \Pr [Q_{a^o}(\tilde{\mathbf{x}}) \leq q|a], \quad dG(q|a) = g(q|a)dq$$

Define  $U^o \geq \bar{U}$  at the optimum:

$$U^o = U(s^o(\mathbf{x}), \mathbf{a}^o) = \int u(s^o(\mathbf{x})) f(\mathbf{x}|\mathbf{a}^o) d\mathbf{x} - \mathbf{a}^o \quad (7)$$

Lemma (How to construct a proxy contract  $\hat{s}(\cdot)$ )

(1a)  $f(\mathbf{x}|a)$  satisfies that  $\frac{g(q|a)}{g(q|\mathbf{a}^o)}$  is convex in  $q = \frac{f_a(\mathbf{x}|\mathbf{a}^o)}{f(\mathbf{x}|\mathbf{a}^o)}$  for all  $a$

(2a) (Double-crossing)  $\exists$  a contract  $\hat{s}(\mathbf{x})$  satisfying

$$(i) \text{ Same (PC) } U(\hat{s}(\cdot), \mathbf{a}^o) = \int u(\hat{s}(\mathbf{x})) f(\mathbf{x}|\mathbf{a}^o) d\mathbf{x} - \mathbf{a}^o = U^o \quad (8)$$

$$(ii) \text{ Same (IC) } \mathbf{a}^o \in \arg \max_{a'} \int u(\hat{s}(\mathbf{x})) f(\mathbf{x}|a') d\mathbf{x} - a' \quad (9)$$

such that  $\hat{r}(q) \equiv u(\hat{s}(\mathbf{x}))$  double-crosses  $r(q) \equiv u(s^o(\mathbf{x}))$  from above in  $q$ -space

then using the first-order approach is justified

**(1a)** and **(2a)** jointly imply:

$$U(s^\circ(\cdot), a) - U(\hat{s}(\cdot), a) = \int (r(q) - \hat{r}(q)) g(q|a) dq \leq 0, \quad \forall a$$

**Why?:** we know that  $U(s^\circ(\cdot), a^\circ) = U(\hat{s}(\cdot), a^\circ)$  when  $a = a^\circ$

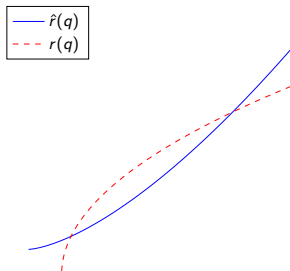


Figure:  $r(q)$  and  $\hat{r}(q)$ : double-crossing

For example, when  $a \uparrow$  from  $a^0$ :

- $G(q|a)$  shifts toward higher  $q$ , where  $r(q) - \hat{r}(q)$  becomes more negative
- **(1a)** condition operationalizes this intuition



(1a) and (2a) jointly imply:

$$U(s^o(\cdot), a) - U(\hat{s}(\cdot), a) = \int (r(q) - \hat{r}(q)) g(q|a) dq \leq 0, \quad \forall a$$

**But:** it might be the following case

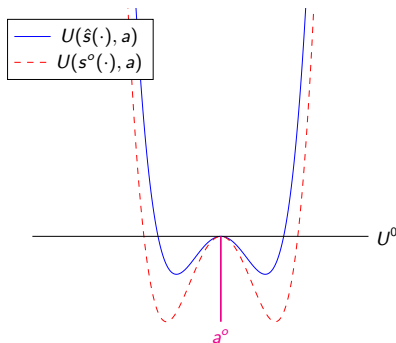
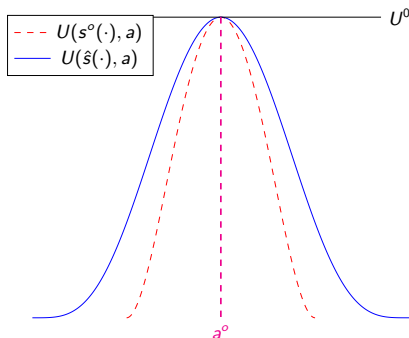


Figure: First-order approach not justified?

(2a) makes sure that  $U(\hat{s}(\cdot), a)$  is maximized at  $a = a^o$ , therefore:



**Figure:** First-Order Approach Justified

So  $U(s^o(\cdot), a)$  must be maximized at  $a = a^o$

- The first-order approach (FOA) justified

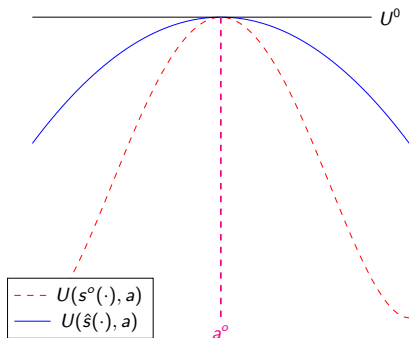


Figure: First-Order Approach Justified

So  $U(s^o(\cdot), a)$  must be maximized at  $a = a^o$

- The first-order approach (FOA) justified

# When the Limited Liability (LL) Not Binds

## Proposition (Proposition 1)

Given that the likelihood ratio,  $\tilde{q} \equiv \frac{f_a(\tilde{\mathbf{x}}|\mathbf{a}^o)}{f(\tilde{\mathbf{x}}|\mathbf{a}^o)}$ , is bounded below,<sup>a</sup> given  $\mathbf{a}^o$ ,

(1a)  $\frac{g(q|a)}{g(q|\mathbf{a}^o)}$  is convex in  $q \equiv \frac{f_a(\tilde{\mathbf{x}}|\mathbf{a}^o)}{f(\tilde{\mathbf{x}}|\mathbf{a}^o)}$  for all  $a$

(2b)  $m(a) \equiv \int qg(q|a)dq$  is concave in  $a$

(3b)  $r(q)$  is concave in  $q$

then the first-order approach is justified

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<sup>a</sup>We assume  $\underline{s}$  is small enough, so (LL) does not bind at optimum

**Note:** Now  $\bar{r}(q) = r(q)$  due to the nonbinding (LL)

- (2b) and (3b) are from **Jewitt (1988)** and **Jung and Kim (2015)**
- Find  $\hat{s}(\mathbf{x})$  such that  $u(\hat{s}(\mathbf{x})) \equiv \hat{r}(q)$  becomes linear in  $q$

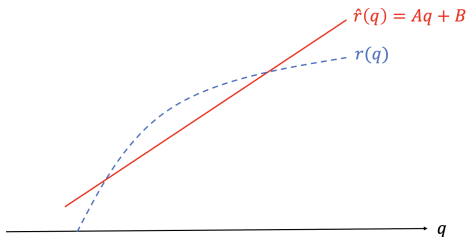


Figure: When the Agent's Limited Liability Constraint Does Not Bind

**Simplest case:** our proxy contract  $\hat{r}(q)$  is **linear** in  $q$

- (2b) makes sure under  $\hat{r}(q)$ , the agent will choose  $a = a^o$
- With (1a) and (3b), we apply the lemma above (double-crossing)

## Violating **(3b)**: what if $\bar{r}(q)$ becomes convex in $q$ ?

Define the moment generating function (MGF) of  $g(q|a)$ :

$$M(a; t) \equiv \int e^{tq} g(q|a) dq$$

### Proposition (Proposition 2)

Given that  $u(s) > 0$  for all  $s$  and  $\tilde{q} \equiv \frac{f_a(\tilde{\mathbf{x}}|\mathbf{a}^o)}{f(\tilde{\mathbf{x}}|\mathbf{a}^o)}$ , is bounded below, given  $\mathbf{a}^o$ ,

**(1a)**  $\frac{g(q|a)}{g(q|\mathbf{a}^o)}$  is convex in  $q \equiv \frac{f_a(\tilde{\mathbf{x}}|\mathbf{a}^o)}{f(\tilde{\mathbf{x}}|\mathbf{a}^o)}$  for all  $a$

**(2b')**  $\phi(a; t, \bar{U}) \equiv \frac{M_a(a; t)}{M(a; t)} \times [\bar{U} + a]$  is decreasing in  $a$  for any given  $t > 0$

**(3b')**  $\ln r(q)$  is concave in  $q$

then the first-order approach is justified

**(3b')**:  $\ln \bar{r}(q)$ , not  $\bar{r}(q)$ , is concave so  $\bar{r}(q)$  can be convex ( $\rightarrow$  weaker)

- We prove **(2b')** is a bit stronger than (implies) **(2b)** instead
- In this case, our proxy contract  $\hat{r}(q)$  is exponential in  $q$

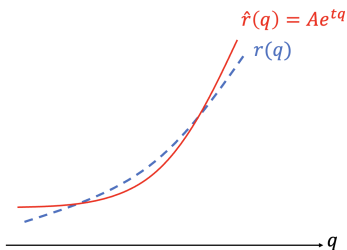


Figure: Double-Crossing:  $\hat{r}(q)$  and  $\bar{r}(q)$

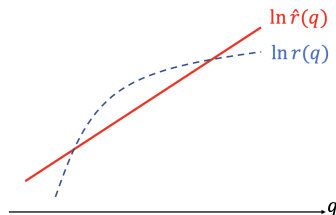


Figure:  $\ln \hat{r}(q)$  and  $\ln \bar{r}(q)$

**Double-crossing:** proxy contract  $\hat{r}(q)$  is **exponential** in  $q$  so  $\ln \hat{r}(q)$  is **linear**

- (2b') makes sure under  $\hat{r}(q)$ , the agent will choose  $a = a^o$
- (1a) and (3b') allow us to apply the lemma above (double-crossing)



## Example (Poisson distribution: (LL) not binding)

- ① The agent's utility is  $u(s) = \frac{1}{r} s^r$ , with  $r > \frac{1}{2}$
- ② The single-dimensional signal  $x$ , which is non-negative integer, follows

$$f(x|a) = \frac{[h(a)]^x}{\Gamma(x+1)} e^{-h(a)}. \quad (10)$$

which is the Poisson distribution with mean  $h(a)$  that is increasing in  $a$

Even with  $r > \frac{1}{2}$ :

- Our Proposition 2 justifies the first-order approach in this case if

$$\frac{h''(a)}{h'(a)} \leq -\frac{1}{U+a} < 0. \quad (11)$$

- Jewitt (1988) and Jung and Kim (2015) imposes  $h(a)$  is concave

**Trade-off:**  $h(a)$  should be more strictly concave, but  $r > \frac{1}{2}$  allowed

## Proposition (Proposition 3)

Given that  $u(s) < 0$  for all  $s$  and  $\tilde{q} \equiv \frac{f_a(\tilde{x}|\mathbf{a}^o)}{f(\tilde{x}|\mathbf{a}^o)}$ , is bounded below,<sup>a</sup> given  $\mathbf{a}^o$ ,

(1a)  $\frac{g(q|a)}{g(q|\mathbf{a}^o)}$  is convex in  $q \equiv \frac{f_a(\tilde{x}|\mathbf{a}^o)}{f(\tilde{x}|\mathbf{a}^o)}$  for all  $a$

(2b'')  $\phi(a; t, \bar{U}) \equiv \frac{M_a(a; t)}{M(a; t)} \times [\bar{U} + a]$  is decreasing in  $a$  for any given  $t < 0$

(3b'')  $-\ln[-r(q)]$  is concave in  $q$

then the first-order approach is justified

<sup>a</sup>We assume  $\underline{s}$  is small enough, so (LL) does not bind at optimum

(3b''):  $-\ln[-\bar{r}(q)]$ , not  $\bar{r}(q)$ , is concave so  $\bar{r}(q)$  is *more* concave ( $\rightarrow$  stronger)

- We prove (2b'') is a bit weaker than (implied by) (2b) instead
- In this case, our proxy contract  $\hat{r}(q)$  is negative exponential (concave) in  $q$

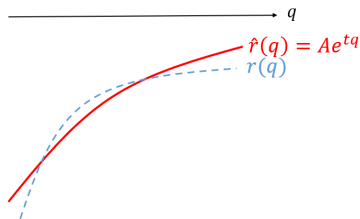


Figure: Double-Crossing:  $\hat{r}(q)$  and  $\bar{r}(q)$

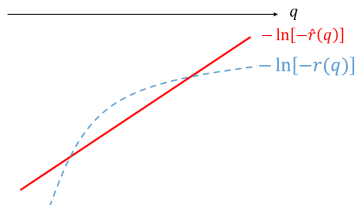


Figure:  $\ln \hat{r}(q)$  and  $\ln \bar{r}(q)$

**Double-crossing:** proxy contract  $\hat{r}(q)$  is **more concave** in  $q$  so  $\ln \hat{r}(q)$  is **linear**

- (2b'') makes sure under  $\hat{r}(q)$ , the agent will choose  $a = a^o$
- (1a) and (3b'') allow us to apply the lemma above (double-crossing)

## Example (Exponential distribution: (LL) not binding)

- ① The agent's utility is  $u(s) = \frac{1}{r}s^r$ , with  $r < 0$
- ② The single-dimensional signal  $x$ , which is non-negative, follows

$$f(x|a) = \frac{1}{h(a)} e^{-\frac{x}{h(a)}}, \quad (12)$$

which is the exponential distribution with mean  $h(a)$  that is increasing in  $a$

- ③  $h(a)$  is convex to some degree (not too much) in  $a$

- Our Proposition 3 justifies the first-order approach in this case if

$$\frac{h''(a)}{h'(a)} \leq -\underbrace{\frac{1}{\bar{U} + a}}_{>0}, \quad \forall a \in (0, \bar{a}], \quad (13)$$

if  $h(a) + h'(a)[\bar{U} + a] < 0$  for  $\forall a \in (0, \bar{a}]$

**Trade-off:**  $r(q)$  should be more strictly concave, but convex  $h(a)$  allowed

# When the Limited Liability (LL) Binds

## Finding a proxy contract when (LL) binds for $q \leq q_c$

Define the moment generating function (MGF) of  $g(q|a)$ :

$$M(a; t) \equiv \int e^{tq} g(q|a) dq$$

### Proposition (Proposition 4)

Given that the likelihood ratio,  $\tilde{q} \equiv \frac{f_a(\tilde{\mathbf{x}}|a^\circ)}{f(\tilde{\mathbf{x}}|a^\circ)}$ , is unbounded below, given  $a^\circ$ ,

(1a)  $\frac{g(q|a)}{g(q|a^\circ)}$  is convex in  $q = \frac{f_a(\mathbf{x}|a^\circ)}{f(\mathbf{x}|a^\circ)}$  for all  $a$

(2c)  $\phi(a; t, \bar{U} - u(\underline{s})) \equiv \frac{M_a(a; t)}{M(a; t)} \times [\bar{U} - u(\underline{s}) + a]$  is decreasing in  $a$  for any given  $t > 0$

(3c)  $\ln[\bar{r}(q) - u(\underline{s})]$  is concave in  $q$  for all  $q > q_c$ , where  $q_c$  solves  $\bar{r}(q_c) = u(\underline{s})$   
then the first-order approach is justified

(3c):  $\ln[\bar{r}(q) - u(\underline{s})]$ , not  $\bar{r}(q)$ , is concave so  $\bar{r}(q)$  can be convex ( $\rightarrow$  weaker)

- (2c): (2b') with  $\bar{U} - u(\underline{s})$

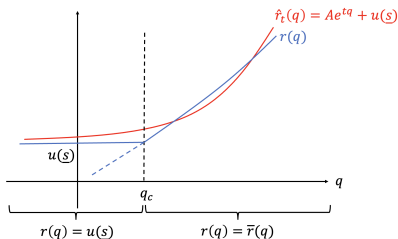


Figure: Double-Crossing:  $\hat{r}(q)$  and  $\bar{r}(q)$

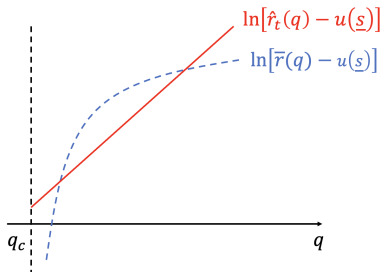


Figure:  $\ln \hat{r}(q)$  and  $\ln \bar{r}(q)$

**Double-crossing:** proxy contract  $\hat{r}(q)$  is **affine-exponential** in  $q$

- (2c) makes sure under  $\hat{r}(q)$ , the agent will choose  $a = a^\circ$
- (1a) and (3c) allow us to apply the lemma above (double-crossing)

## Example (Normal distribution: (LL) binding)

- ① The agent's utility is  $u(s) = \frac{1}{r}s^r$ , with  $r < 1$
- ② The single-dimensional signal  $x \sim N(h(a), \sigma^2)$ , i.e.,

$$f(x|a) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-h(a))^2}{2\sigma^2}}$$

which is a normal distribution with mean  $h(a)$  that is increasing in  $a$

- ③ In this case, (LL)  $s(x) \geq \underline{s}$  must be imposed

- Our Proposition 4 justifies the first-order approach if

$$\frac{h''(a)}{h'(a)} \leq -\frac{1}{\bar{U} - u(\underline{s}) + a} < 0, \quad \forall a, \quad (14)$$



To compare with Jung and Kim (2015)'s conditions (1J-1) and (1J-2):

- We introduce the total positivity of degree 3 ( $\text{TP}_3$ ) (Karlin (1968))
- Our (1a) condition is equivalent to  $(\text{TP}_3)$  under MLRP
- Thus, Proposition 1 implies Jung and Kim (2015)

$$((\text{TP}_3), (1J - 2)) \xleftarrow[\text{Given MLRP}]{\text{Lemma 5}} ((1a), (2b)) \xrightarrow{\text{Implies}} ((1J - 1), (1J - 2))$$

Figure: Relation Diagram between Conditions

**Still**, Our Propositions 2, 3, 4 extend the first-order approach's applicability