

CMSC 3540 I: The Interplay of Learning and Game Theory (Autumn 2022)

Pricing of Information

Instructor: Haifeng Xu



Outline

- Bayesian Persuasion and Information Selling
- Sell to a Single Decision Maker
- Sell to Multiple Decision Makers

Motivation: Selling Information

- Car/house inspections



- Financial advices



- Credit report



- Consumer data



Motivation: Selling Information

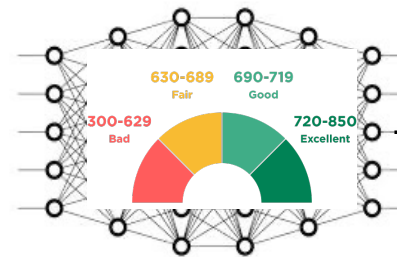
- Car/house inspections



- Financial advices



- Credit report



→ Prob. of default

- Consumer data



→ Prob. of purchase/conversion

Persuasion vs Information Selling

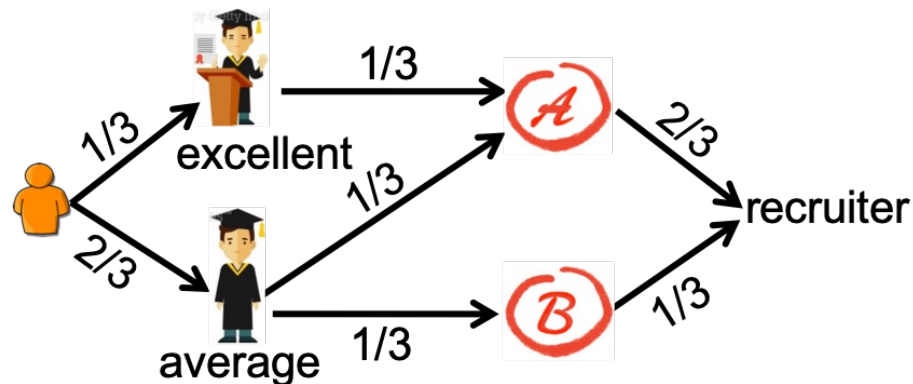
- In persuasion, we selectively reveal information to induce actions that we like



When selling information, we reveal information for a profit

Recap: Model of Bayesian Persuasion

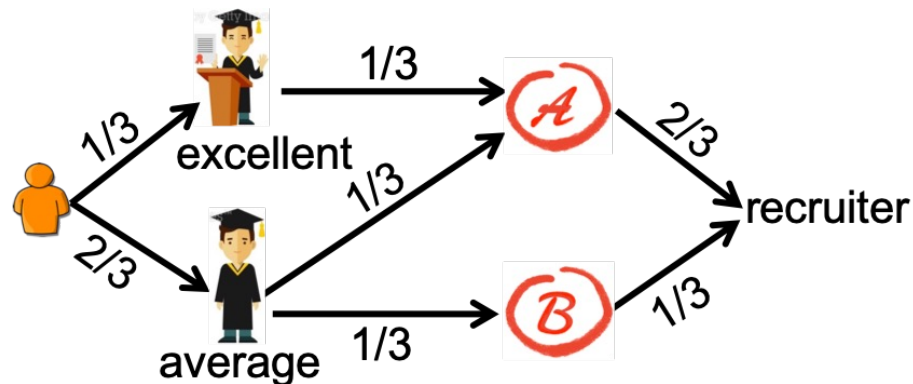
- Two players: persuader (**Sender, she**), decision maker (**Receiver he**)
 - Example: advisor = sender, recruiter = receiver
- Receiver looks to take an action $i \in [n] = \{1, 2, \dots, n\}$
 - Receiver utility $r(i, \theta)$ $\theta \in \Theta$ is a random **state of nature**
 - Sender utility $s(i, \theta)$
- Both players know $\theta \sim \text{prior dist. } \mu$, but Sender has an **informational advantage** – she can observe realization of θ
- Sender reveal partial information via a signaling scheme



(Simplified) Model of Selling Information

seller

- Two players: ~~persuader~~ (Sender, she), decision maker (Receiver he)
 - Example: advisor = sender, recruiter = receiver
- Receiver looks to take an action $i \in [n] = \{1, 2, \dots, n\}$
 - Receiver utility $r(i, \theta)$ $\theta \in \Theta$ is a random state of nature
 - Sender utility ~~$s(i, \theta)$~~ — payment from the receiver
- Both players know $\theta \sim \text{prior dist. } \mu$, but Sender has an informational advantage – she can observe realization of θ
- Sender reveal partial information via a signaling scheme



How to Sell Information Optimally?

➤ For any signaling scheme, seller knows how much it improves buyer's expected utility

- The value of any signaling scheme is known

1. Receiver utility under **no information**: $\max_i \sum_{\theta \in \Theta} r(i, \theta) \cdot \mu(\theta)$

2. Receiver utility under **any π** : $\sum_{\sigma} \Pr(\sigma) \cdot R(\sigma)$

$$\text{where } R(\sigma) = \max_{i \in [n]} \left[\sum_{\theta \in \Theta} r(i, \theta) \cdot \frac{\pi(\sigma, \theta) \cdot \mu(\theta)}{\Pr(\sigma)} \right]$$

➤ How to maximize revenue?

- Reveal full information helps the buyer the most. Why?
- So OPT is to charge him following amount and **then** reveal θ directly

$$\text{Payment} = \sum_{\theta \in \Theta} \mu(\theta) \cdot \left[\max_i u(i, \theta) \right] - \max_i \sum_{\theta \in \Theta} \mu(\theta) \cdot u(i, \theta)$$



Buyer expected utility if learns θ precisely

How to Sell Information Optimally?

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➤ How to maximize revenue?

- Reveal full information helps the buyer the most. Why?
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$$\text{Payment} = \sum_{\theta \in \Theta} \mu(\theta) \cdot \left[\max_i u(i, \theta) \right] - \max_i \sum_{\theta \in \Theta} \mu(\theta) \cdot u(i, \theta)$$

Q: Are we done?

No – in pricing problems, we typically do not know how much buyer values our “product”

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- Bayesian Persuasion and Information Selling
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(True) Model of Selling Information

- Sender = seller, Receiver = buyer who is a decision maker
- Buyer takes an action $i \in [n] = \{1, \dots, n\}$
- Buyer has a utility function $u(i, \theta; t)$ where
 - $\theta \sim \text{dist. } \mu$ is a random state of nature
 - $t \sim \text{dist. } f$ captures buyer's (private) utility type

Remarks:

- u, μ, f are public knowledge
- Assume θ, t are independent
- Seller observes θ but does not know buyer's type t
- Buyer knows his own type t but does not know θ

Key Challenge

The class of mechanisms is too broad

- The mechanism will: (1) elicit private info from buyer; (2) reveal info based on realized θ ; (3) charge buyer
- May interact with buyer for many rounds
- Buyer may misreport his private type t

Key Challenge

The class of mechanisms is too broad

. . . but, at the end of the day, the buyer of type t is charged some amount x_t in expectation and learns a posterior belief about θ

Theorem (Revelation Principle). Any information selling mechanism is “equivalent” to a **direct and truthful revelation mechanism**:

1. Ask buyer to report type t
2. Charge buyer x_t and reveal info to buyer via signaling scheme π_t that use n signals (as action recommendations)

Moreover, the mechanism is incentive compatible (IC) – it is the buyer’s best interest to truthfully report t

- Optimal mechanism reduces to computing an IC menu $\{x_t, \pi_t\}_t$
- Proof omitted here

The Optimal Mechanism

The Consulting Mechanism [CXZ, SODA'20]

1. Elicit buyer type t
2. Charge buyer x_t
3. Observe realized state θ and recommend action i to the buyer with probability $\pi_t(\sigma_i, \theta)$

- Will be incentive compatible – reporting true t is optimal
- The recommended action is guaranteed to be the optimal action for buyer t given his information
- $\{x_t, \pi_t\}_t$ is public knowledge, and computed by LP

Theorem. Consulting mechanism with $\{x_t, \pi_t\}_t$ computed by the following program is the optimal mechanism.

Computing the Optimal Mechanism

Optimal $\{x_t, \pi_t\}_t$ can be computed by a convex program

- Variables: $\pi_t(\sigma_i, \theta)$ = prob of sending σ_i conditioned on θ for each t
- Variable x_t is the payment from buyer type t

Expected revenue

$$\max \quad \sum_t f(t) \cdot x_t$$

$$\begin{aligned} \text{s.t.} \quad & \sum_i \left[\sum_{\theta} \mu(\theta) \pi_t(\sigma_i, \theta) u(i, \theta; t) \right] - x_t \\ & \geq \sum_i \max_j \left[\sum_{\theta} \mu(\theta) \pi_{t'}(\sigma_i, \theta) u(j, \theta; t) \right] - x_{t'}, && \text{for } t' \neq t \\ & \sum_i \left[\sum_{\theta} \mu(\theta) \pi_t(\sigma_i, \theta) u(i, \theta; t) \right] - x_t \geq \max_i \sum_{\theta} \mu(\theta) u(i, \theta; t), && \text{for } t \\ & \sum_{\theta} \mu(\theta) \pi_t(\sigma_i, \theta) u(i, \theta; t) \geq \sum_{\theta} \mu(\theta) \pi_t(\sigma_i, \theta) u(j, \theta; t), && \text{for } i \neq j, t \\ & \sum_i \pi_t(\sigma_i, \theta) = 1, && \text{for } \theta, t \\ & \pi_t(\sigma_i, \theta) \geq 0, && \text{for } t, \sigma_i, \theta \end{aligned}$$

Computing the Optimal Mechanism

Optimal $\{x_t, \pi_t\}_t$ can be computed by a convex program

- Variables: $\pi_t(\sigma_i, \theta)$ = prob of sending σ_i conditioned on θ for each t
- Variable x_t is the payment from buyer type t

Truthfully reporting true t is optimal

$$\max \sum_t f(t) \cdot x_t$$

$$\text{s.t. } \begin{cases} \sum_i \left[\sum_{\theta} \mu(\theta) \pi_t(\sigma_i, \theta) u(i, \theta; t) \right] - x_t \\ \geq \sum_i \max_j \left[\sum_{\theta} \mu(\theta) \pi_{t'}(\sigma_i, \theta) u(j, \theta; t) \right] - x_{t'}, & \text{for } t' \neq t \\ \sum_i \left[\sum_{\theta} \mu(\theta) \pi_t(\sigma_i, \theta) u(i, \theta; t) \right] - x_t \geq \max_i \sum_{\theta} \mu(\theta) u(i, \theta; t), & \text{for } t \\ \sum_{\theta} \mu(\theta) \pi_t(\sigma_i, \theta) u(i, \theta; t) \geq \sum_{\theta} \mu(\theta) \pi_t(\sigma_i, \theta) u(j, \theta; t), & \text{for } i \neq j, t \\ \sum_i \pi_t(\sigma_i, \theta) = 1, & \text{for } \theta, t \\ \pi_t(\sigma_i, \theta) \geq 0, & \text{for } t, \sigma_i, \theta \end{cases}$$

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- Variable x_t is the payment from buyer type t

Participation is no worse than not

$$\max \quad \sum_t f(t) \cdot x_t$$

$$\text{s.t.} \quad \sum_i \left[\sum_{\theta} \mu(\theta) \pi_t(\sigma_i, \theta) u(i, \theta; t) \right] - x_t \geq \sum_i \max_j \left[\sum_{\theta} \mu(\theta) \pi_{t'}(\sigma_i, \theta) u(j, \theta; t) \right] - x_{t'}, \quad \text{for } t' \neq t$$

$$\sum_i \left[\sum_{\theta} \mu(\theta) \pi_t(\sigma_i, \theta) u(i, \theta; t) \right] - x_t \geq \max_i \sum_{\theta} \mu(\theta) u(i, \theta; t), \quad \text{for } t$$

$$\sum_{\theta} \mu(\theta) \pi_t(\sigma_i, \theta) u(i, \theta; t) \geq \sum_{\theta} \mu(\theta) \pi_t(\sigma_i, \theta) u(j, \theta; t), \quad \text{for } i \neq j, t$$

$$\sum_i \pi_t(\sigma_i, \theta) = 1, \quad \text{for } \theta, t$$

$$\pi_t(\sigma_i, \theta) \geq 0, \quad \text{for } t, \sigma_i, \theta$$

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- Variable x_t is the payment from buyer type t

$$\begin{aligned}
 \max \quad & \sum_t f(t) \cdot x_t \\
 \text{s.t.} \quad & \sum_i \left[\sum_{\theta} \mu(\theta) \pi_t(\sigma_i, \theta) u(i, \theta; t) \right] - x_t \\
 & \geq \sum_i \max_j \left[\sum_{\theta} \mu(\theta) \pi_{t'}(\sigma_i, \theta) u(j, \theta; t) \right] - x_{t'}, \quad \text{for } t' \neq t \\
 & \sum_i \left[\sum_{\theta} \mu(\theta) \pi_t(\sigma_i, \theta) u(i, \theta; t) \right] - x_t \geq \max_i \sum_{\theta} \mu(\theta) u(i, \theta; t), \quad \text{for } t \\
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 \end{aligned}$$

Similar to constraints in persuasion

Computing the Optimal Mechanism

Optimal $\{x_t, \pi_t\}_t$ can be computed by a convex program

- Variables: $\pi_t(\sigma_i, \theta)$ = prob of sending σ_i conditioned on θ for each t
- Variable x_t is the payment from buyer type t

- A convex function of variables
- Can be converted to an LP

$$\begin{aligned}
 \max \quad & \sum_t f(t) \cdot x_t \\
 \text{s.t.} \quad & \sum_i \left[\sum_{\theta} \mu(\theta) \pi_t(\sigma_i, \theta) u(i, \theta; t) \right] - x_t \\
 & \geq \sum_i \max_j \left[\sum_{\theta} \mu(\theta) \pi_{t'}(\sigma_i, \theta) u(j, \theta; t) \right] - x_{t'}, \quad \text{for } t' \neq t \\
 & \sum_i \left[\sum_{\theta} \mu(\theta) \pi_t(\sigma_i, \theta) u(i, \theta; t) \right] - x_t \geq \max_i \sum_{\theta} \mu(\theta) u(i, \theta; t), \quad \text{for } t \\
 & \sum_{\theta} \mu(\theta) \pi_t(\sigma_i, \theta) u(i, \theta; t) \geq \sum_{\theta} \mu(\theta) \pi_t(\sigma_i, \theta) u(j, \theta; t), \quad \text{for } i \neq j, t \\
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 & \pi_t(\sigma_i, \theta) \geq 0, \quad \text{for } t, \sigma_i, \theta
 \end{aligned}$$

Practical Mechanisms?

What the mechanism is like?

- Generally, the optimal solution to the previous LP has no structure neither any interpretation
- Nevertheless, closed-form optimal solution is possible for more structured problems

Recall Model of Selling Information

- Sender = seller, Receiver = buyer who is a decision maker
- Buyer takes an action $i \in [n] = \{1, \dots, n\}$
- Buyer has a utility function $u(i, q; t)$ where
 - $q \sim \text{dist. } \mu$ is a random state of nature
 - $t \sim \text{dist. } f$ captures buyer's (private) utility type

Remarks:

- u, μ, f are public knowledge
- Assume q, t are independent

Selling Information to a Binary DM

- Sender = seller, Receiver = buyer who is a decision maker
- Buyer takes an action $i \in \{0,1\}$: an **active action 1** and a **passive action 0**
 - Active action: approve loan, buy a car, invest stock X, etc.
- Buyer has a utility function $u(i, q; t)$ where $\begin{cases} u(0, q; t) \equiv 0 \\ u(1, q; t) = v(q, t) \end{cases}$
 - $q \sim \text{dist. } \mu$ is a random state of nature
 - $t \sim \text{dist. } f$ captures buyer's (private) utility type
- Further assume $v(q, t)$ is linear and non-decreasing in t

Remarks:

- u, μ, f are public knowledge
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 - $t \sim \text{dist. } f$ captures buyer's (private) utility type
- Further assume $v(q, t)$ is linear and non-decreasing in t

That is: $v(q, t) = v_1(q)[t + \rho(q)]$ for some $v_1(q) \geq 0$

Can generalize to convex $v(q, t)$

Selling Information to a Binary DM

- Sender = seller, Receiver = buyer who is a decision maker
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 - Active action: approve loan, buy a car, invest stock X, etc.
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- Further assume $v(q, t)$ is linear and non-decreasing in t

That is: $v(q, t) = v_1(q)[t + \rho(q)]$ for some $v_1(q) \geq 0$

What is the optimal mechanism for this more structured problem?

An Example



- Buyer is a loan company; action is to approve a loan or not
 - If not approving (action 0), payoff is 0
 - If approving (action 1), payoff is

$$v(q, t) = (1 - q) \times t - 2 \longrightarrow \text{operation cost}$$

$q \in [0, 1]$ Revenue

default probability

Threshold experiments turn out to suffice

Recall $v(q, t) = v_1(q)[t + \rho(q)]$
(q is the state unknown to buyer)

Def. π_t is a threshold experiment if π_t simply **reveals** $\rho(q) \geq \theta(t)$ **or not** for some buyer-type-dependent threshold $\theta(t)$

➤ Threshold is on $\rho(q)$

Virtual Value Functions

- Recall virtual value function in [Myerson'81]: $\phi(t) = t - \frac{1-F(t)}{f(t)}$

Def. **Lower** virtual value function: $\underline{\phi}(t) = t - \frac{1-F(t)}{f(t)}$

Virtual Value Functions

➤ Recall virtual value function in [Myerson'81]: $\phi(t) = t - \frac{1-F(t)}{f(t)}$

Def. **Lower** virtual value function: $\underline{\phi}(t) = t - \frac{1-F(t)}{f(t)}$

Upper virtual value function: $\bar{\phi}(t) = t + \frac{F(t)}{f(t)}$

Mixed virtual value function: $\phi_c(t) = c\underline{\phi}(t) + (1-c)\bar{\phi}(t)$

Note: “upper” or “lower” is due to

$$\underline{\phi}(t) \leq t \leq \bar{\phi}(t)$$

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Def. **Lower** virtual value function: $\underline{\phi}(t) = t - \frac{1-F(t)}{f(t)}$

Upper virtual value function: $\bar{\phi}(t) = t + \frac{F(t)}{f(t)}$

Mixed virtual value function: $\phi_c(t) = c\underline{\phi}(t) + (1-c)\bar{\phi}(t)$

- Will assume the virtual value function $\phi(t)$ is monotone (weakly) increasing in t (known as the **regularity** assumption)
- Not crucial, since if not monotone, there is an “ironing” procedure to make it monotone

The Optimal Mechanism

Depend on two problem-related constants:

$$V_L = \max\{v(t_1), 0\} + \int_{t_1}^{t_2} \int_{q:\rho(q) \geq -\underline{\phi}^+(x)} \mu(q)v_1(q) dqdx,$$

$$V_H = \max\{v(t_1), 0\} + \int_{t_1}^{t_2} \int_{q:\rho(q) \geq -\overline{\phi}^+(x)} \mu(q)v_1(q) dqdx,$$

Note: $V_L < V_H$

The Optimal Mechanism

Theorem.

1. If $\bar{v}(t_2) \leq V_L$, the mechanism with threshold experiments $\theta^*(t) = -\underline{\phi}^+(t)$ and following payment function represents an optimal mechanism:

$$p^*(t) = \int_{q \in Q} \pi^*(q, x) \mu(q) v(q, t) dq - \int_{t_1}^t \int_{q \in Q} \pi^*(q, x) \mu(q) v_1(q) dq dx$$

The Optimal Mechanism

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1. If $\bar{v}(t_2) \leq V_L$, the mechanism with threshold experiments $\theta^*(t) = -\underline{\phi}^+(t)$ and following payment function represents an optimal mechanism:

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2. If $\bar{v}(t_2) \geq V_H$, the mechanism with threshold experiments $\theta^*(t) = -\bar{\phi}^+(t)$ and following payment function represents an optimal mechanism:

$$p^*(t) = \int_{q \in Q} \pi^*(q, t) \mu(q) (q, t) dq + \int_t^{t_2} \int_{q \in Q} \pi^*(q, x) \mu(q) v_1(q) dq dx - \bar{v}(t_2)$$

The Optimal Mechanism

Theorem (cont'd).

3. If $V_L \leq \bar{v}(t_2) \leq V_H$, the mechanism with threshold experiments $\theta^*(t) = -\phi_c^+(t)$ and following payment function represents an optimal mechanism:

$$p^*(t) = \int_{q \in Q} \pi^*(q, t) \mu(q) v(q, t) dq - \int_{t_1}^t \int_{q \in Q} \pi^*(q, x) \mu(q) v_1(q) dq dx$$

where **constant c** is chosen such that

$$\int_{t_1}^{t_2} \int_{q: \rho(q) \geq \phi_c^+(x)} \mu(q) v_1(q) dq dx = \bar{v}(t_2)$$

This is the technically more involved part to prove (see [LSX, EC'21])

Remarks

- Threshold mechanisms are common in real life
 - House/car inspections, stock recommendations: information seller only need to reveal it “passed” or “deserves a buy” or not
- Optimal mechanism has **personalized** thresholds and payments, tailored to accommodate different level of risk each buyer type can take
 - Different from optimal pricing of physical goods



Remarks

What if seller is restricted to sell the same information to every buyer? How will revenue change?

- Revenue can be arbitrarily worse
- $1/e$ -approximation of optimal revenue if the *value of full information* as a function of t is “heavy tail”

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Challenges

- For single decision maker, more information always helps
 - Recall in persuasion, receiver always benefits from signaling scheme
- A fundamental challenge for selling to multiple buyers is that information does not necessarily help them

Example: More Information Hurts Buyers

- Insurance industry: *insurance company* and *customer*
 - Both are potential information buyers
- Two types of customers: **Healthy** and **Unhealthy**
 - Publicly know, $\Pr(\text{Healthy}) = 0.9$
- Seller is an information holder, who knows whether any customer is healthy or not

		Insurance company	
		Sell	Not Sell
customer	Buy	(-10, 10)	(-0, 0)
	Not Buy	(0, 0)	(0, 0)

Healthy customer

		Insurance company	
		Sell	Not Sell
customer	Buy	(-10, -50)	(-110, 0)
	Not Buy	(-111, 0)	(-111, 0)

Unhealthy customer

Example: More Information Hurts Buyers

		Insurance company	
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Healthy customer, prob = 0.9

		Insurance company	
		Sell	Not Sell
customer	Buy	(-10, -50)	(-110, 0)
	Not Buy	(-111, 0)	(-111, 0)

Unhealthy customer

Q: What happens without seller's information ?

- Customer and insurance company will look at expectation
 - Dominant strategy equilibrium is (Buy, Sell)

	Sell	Not Sell
Buy	(-10, 4)	(-11, 0)
Not Buy	(-11.1, 0)	(-11.1, 0)

Example: More Information Hurts Buyers

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		Sell	Not Sell
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Unhealthy customer

Q: What if seller tells (even only) customer her health status ?

- If Healthy, customer will not buy → utility (0,0) for both
- If Unhealthy, customer will buy → Will not sell, utility (-110,0)
- Customer's reaction reveals his healthy status
- In expectation (-11, 0), and no insurance was sold ever

Recall previous utilities (-10,4)

Example: More Information Hurts Buyers

		Insurance company	
customer		Sell	Not Sell
	Buy	(-10, 10)	(-0, 0)
	Not Buy	(0, 0)	(0, 0)

Healthy customer, prob = 0.9

		Insurance company	
customer		Sell	Not Sell
	Buy	(-10, -50)	(-110, 0)
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Unhealthy customer

Q: What if seller tells (even only) customer her health status ?

Lessons Learned

- Existence of insurance is due to ignorance to our health condition
- Such ignorance benefits both us and insurance companies

Thank You

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