Viability of a Privacy-differentiated Market for Free Online Services

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Arizona State University

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Joint work with Chong Huang (ASU)

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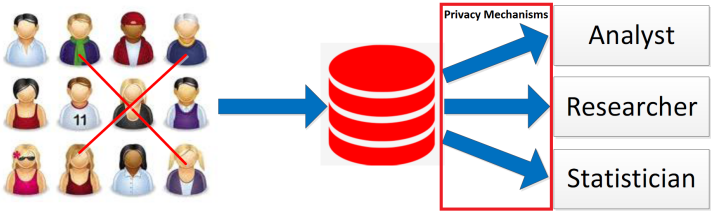
  - Differential privacy
  - Information-theoretic privacy



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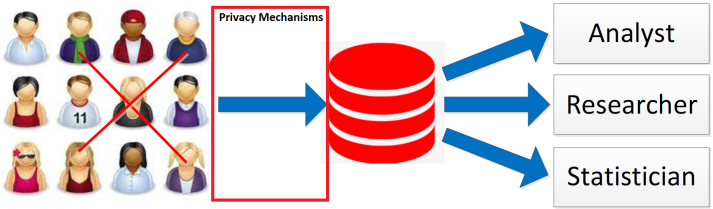

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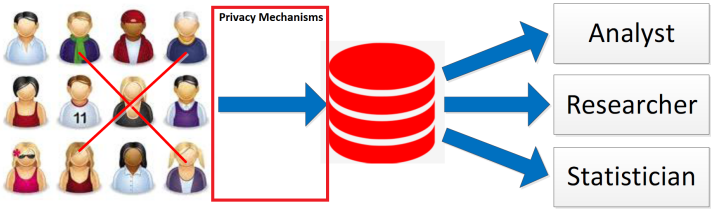

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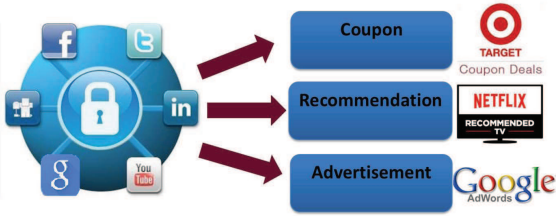

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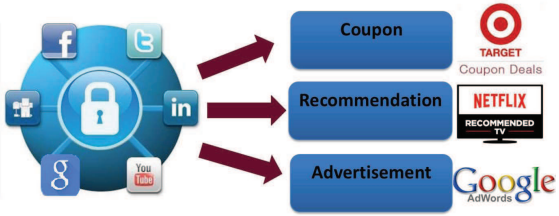
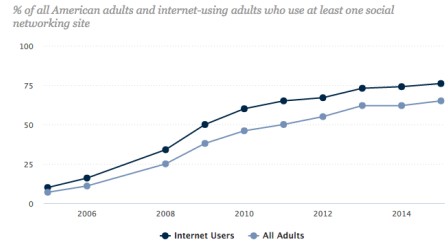
  - Need models to study privacy-sensitive consumer-service provider interactions



Introduction

- Dramatic increase in online interactions between online service providers (SPs) and consumers



- Often times online services are offered for free

Motivation

- Consumers enjoy free services

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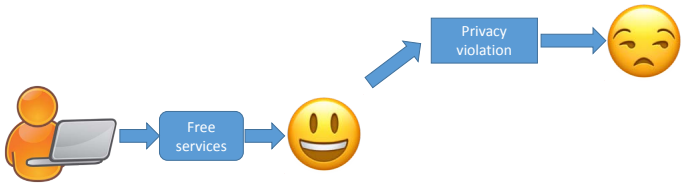
- Consumers enjoy free services until they begin encountering privacy violations on a daily/frequent basis



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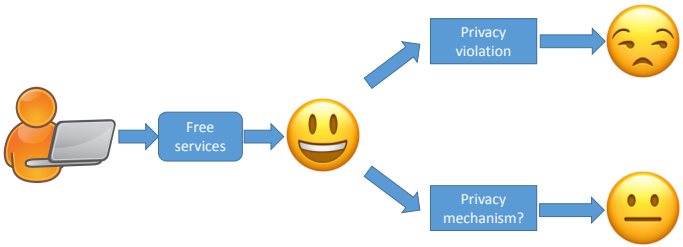

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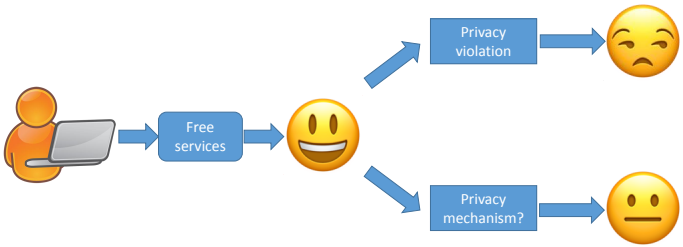

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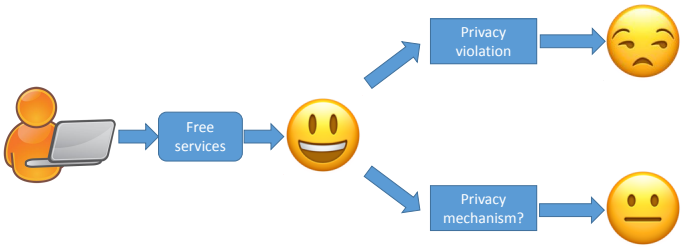
  - Consumers may not have a choice



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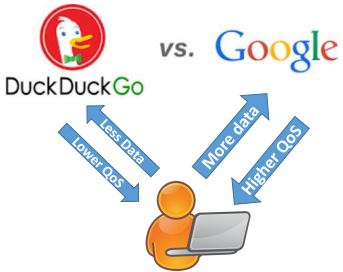
- No free lunch – better privacy protection may result in lower quality of service (QoS)



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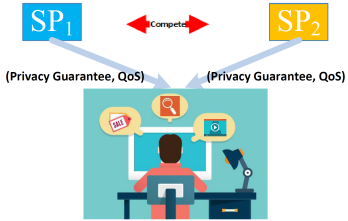

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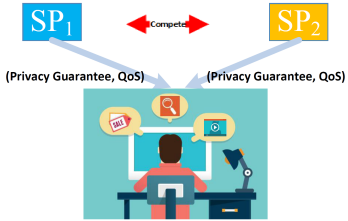

Related Work

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  - Effects of varying degrees of privacy protection on industry profits, consumer welfare and total welfare in competition
- Chellappa and Shivendu, 2010
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- Jentzsch, Preibusch, and Harasser, 2012
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Market segmentation of free services allowing for a wide range of privacy sensitivities has not yet been studied

Our Approach

Model the interaction between SPs and consumers as a non-cooperative game

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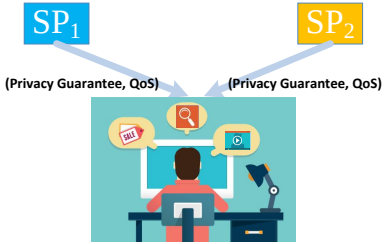
Modify Hotelling model to analyze market segmentation

System Model



- SPs offer free services differentiated by QoS and privacy risks

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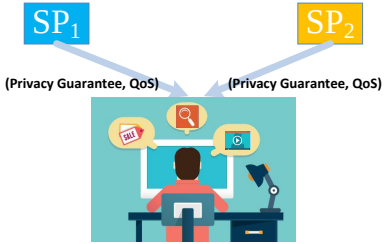

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- Assumption of quantifiable privacy risks and QoS

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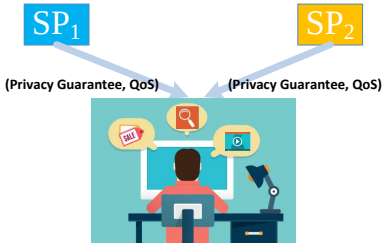

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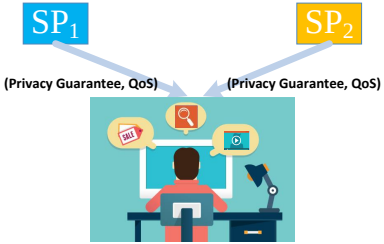

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- SPs can generate revenue by using the data obtained from their consumers
- Consumers choose the SP that optimally satisfies their privacy and QoS choices

Two-SP Model

- Two rational (profit maximization) SPs: SP_1 (e.g., Duckduckgo) and SP_2 (e.g., Google)

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	SP_1	SP_2
QoS offered	v_1	v_2
Privacy risk guarantee	ε_1	ε_2

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vs. Google

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- Assume $\varepsilon_1 \leq \varepsilon_2, \implies v_2 \geq v_1$
  - Otherwise SP_2's strategy is strictly dominated

Two-SP Model: Cost and Revenue

Total Cost to SP_i	Cost of providing services with QoS	Cost of exploiting private data
$C(v_i, \varepsilon_i) = C_{\mathrm{QoS}}(v_i) + C_P(\varepsilon_i)$	$C_{\mathrm{QoS}}(v_i)$	$C_P(\varepsilon_i)$

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Total Revenue of SP_i	Revenue from using consumer's private information	Revenue independent of consumer's private information
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How to model consumer-SP interaction?

- Modified Hotelling model

Modified Hotelling: Consumer Privacy Preferences and Retailers Risks

Hotelling model has been used to study market segmentation in a variety of contexts

DuckDuckGo vs. Google

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v_1	$\leq$	v_2
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- Map consumer privacy preference and SP risk offered from arbitrary range ($[0, \bar{\varepsilon}]$) to $[0, 1]$

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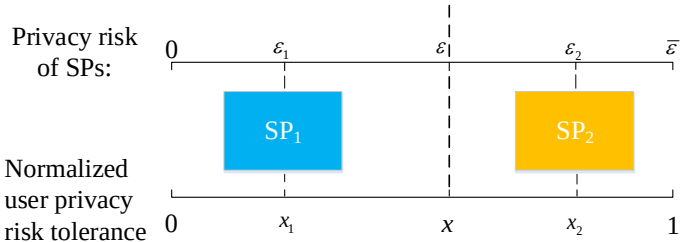

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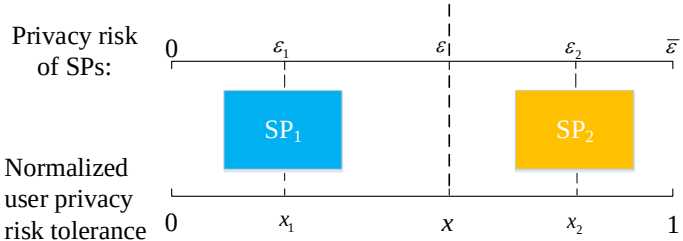
- Heterogeneous privacy preference of consumers: random variable $E \in [0, \bar{\varepsilon}]$ with CDF $F_E(\varepsilon)$



Modifying Hotelling Model For Consumer-Retailer Interaction

- Price captured by QoS

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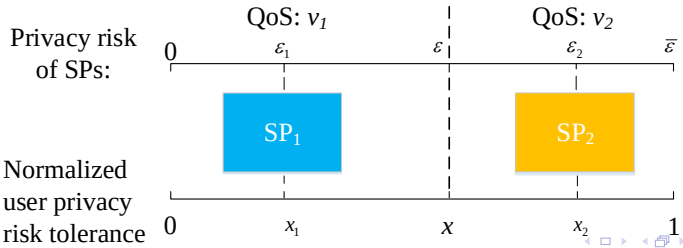

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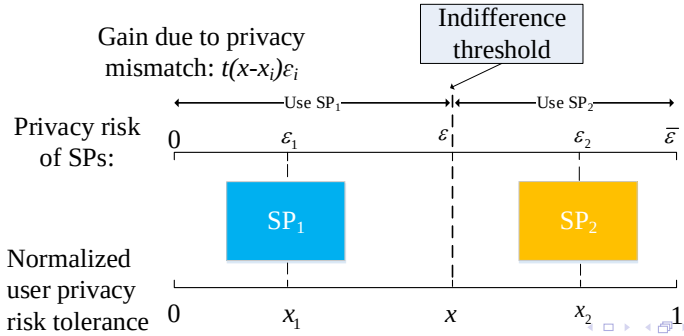
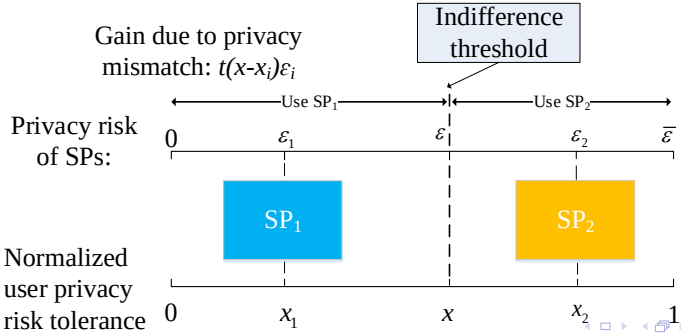


Modifying Hotelling Model For Consumer-Retailer Interaction

- Price captured by QoS
- Mismatch in preferences is no longer symmetric
- Consumer perceived privacy gain: $t(x - x_i)\varepsilon_i$ (t: consumer's valuation of privacy; factor mapping privacy mismatch to QoS)
  - Offered privacy risk $<$ consumer's preference $\implies$ positive utility (extra privacy protection)
  - Offered privacy risk $>$ consumer's preference $\implies$ negative utility (privacy violation)



Consumer Utility and SP Profit

Utility of consumer located at x for choosing SP_i: $u_i(x) = v_i + t(x - x_i)\varepsilon_i$

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Profit of SP_i: $\pi_i(v_i; \varepsilon_i; v_{-i}; \varepsilon_{-i}) = [R(\varepsilon_i) - C(v_i; \varepsilon_i)]n_i(v_i; \varepsilon_i; v_{-i}; \varepsilon_{-i})$

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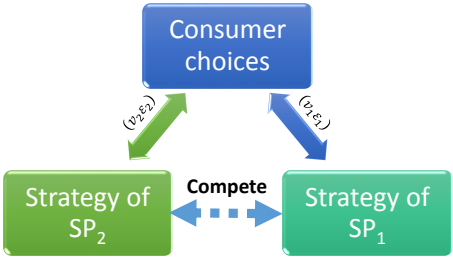
- *Assumption 1:* The services provided by both SPs have non-negative QoS
- *Assumption 2:* The model parameters are chosen such that they ensure the market is completely covered by SP_1 and SP_2

Two-SP Non-cooperative Sequential Game

- SPs market segmentation is a two player non-cooperative sequential game

Two-SP Non-cooperative Sequential Game



- Actions of each SP: (QoS, Privacy risk)

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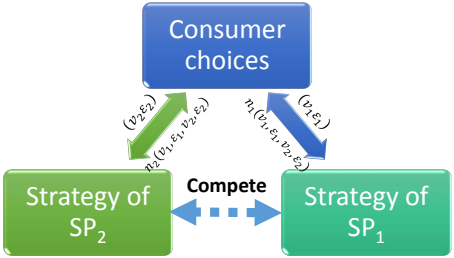

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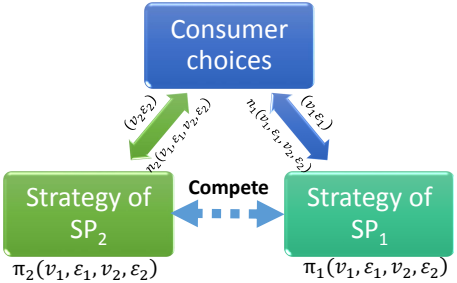

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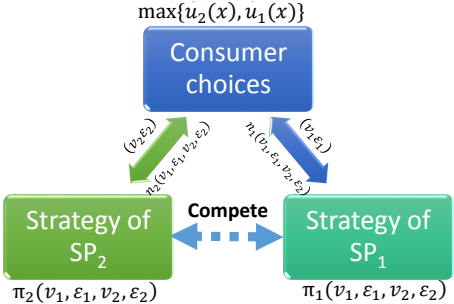

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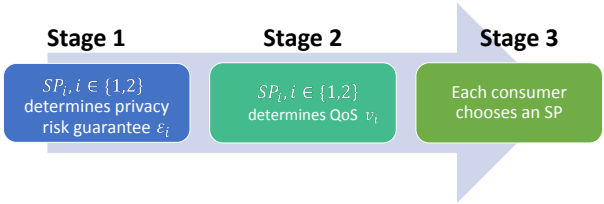

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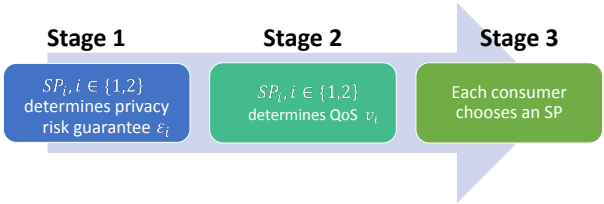

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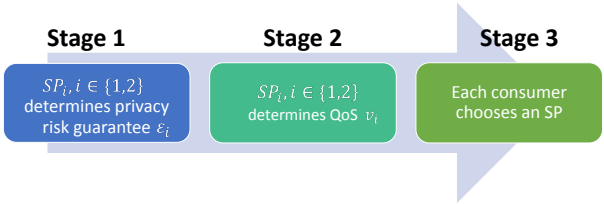

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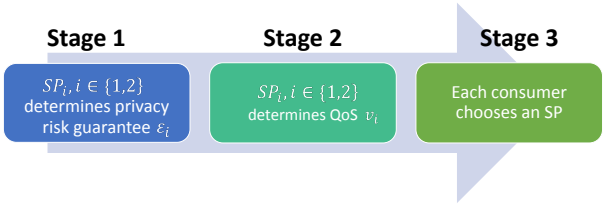

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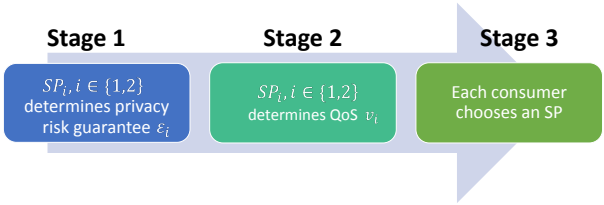

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Theorem 1

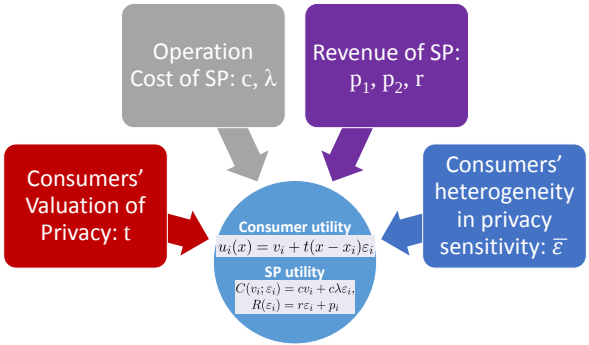
There is no SPNE in which both SPs offer the same privacy risk.

Two-SP Market With Linear Cost and Revenue Functions

- Linear cost and revenue model for each $SP_i, i \in \{1, 2\}$:

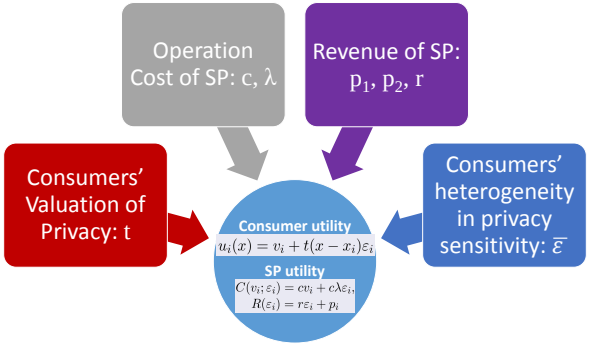
$$C(v_i; \varepsilon_i) = cv_i + c\lambda\varepsilon_i,$$
$$R(\varepsilon_i) = r\varepsilon_i + p_i$$

- Utility of consumer located at x for choosing SP_i: $u_i(x) = v_i + t(x - x_i)\varepsilon_i$



Consumers with Uniformly Distributed Privacy Risk Preference

- Consumers uniformly distributed over $[0, \bar{\varepsilon}]$



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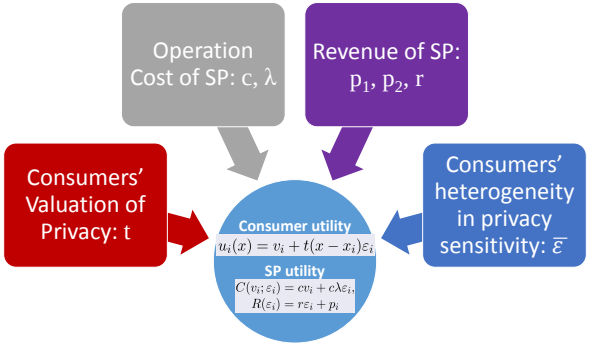

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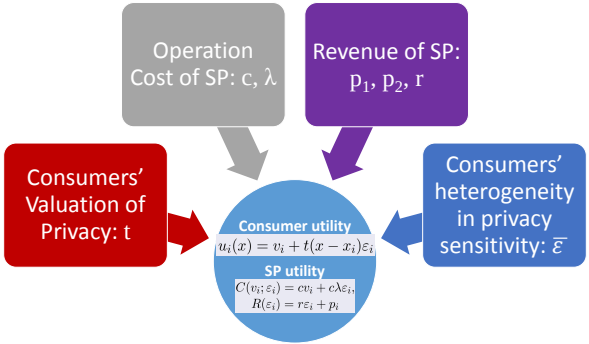

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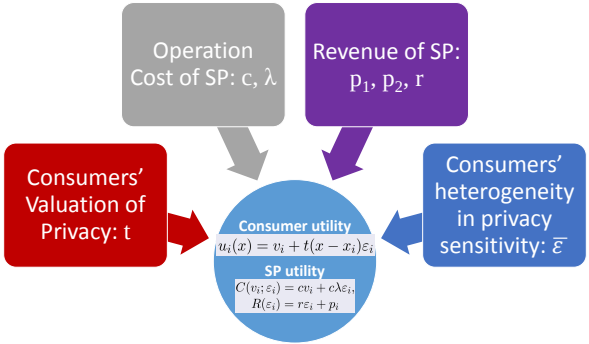

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Theorem 2

There exists an SPNE for the two-SP non-cooperative game if the model parameters $\{c, \alpha, t, \bar{\varepsilon}, p_1, p_2\}$ facilitate a competitive market.

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There exists an SPNE for the two-SP non-cooperative game if the model parameters $\{c, \alpha, t, \bar{\varepsilon}, p_1, p_2\}$ facilitate a competitive market.

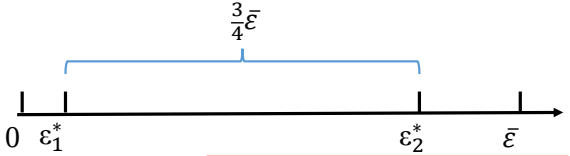
$$-1 \leq \frac{16(p_2 - p_1)}{9ct\bar{\varepsilon}} \leq 1,$$

$$\frac{4\alpha - 3t}{3t} \leq \frac{16(p_2 - p_1)}{9ct\bar{\varepsilon}} \leq \frac{4\alpha - t}{3t},$$

$$(12c\alpha\bar{\varepsilon})^2 - (15ct\bar{\varepsilon})^2 + 288ct\bar{\varepsilon}(p_2 + p_1) \geq [16(p_2 - p_1)]^2$$

Closed Form Solution of the SPNE

- Equilibrium privacy risk strategies:



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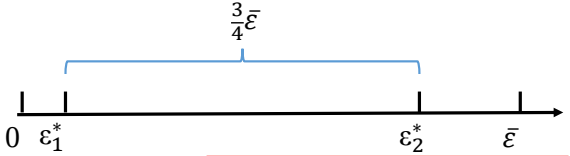
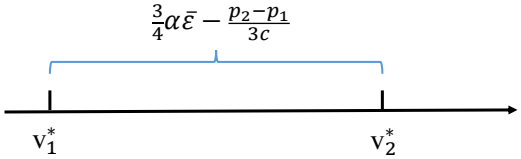


$$\varepsilon_2^* = \frac{12\bar{\varepsilon}c\alpha+15ct\bar{\varepsilon}-16(p_2-p_1)}{24tc}$$

- Equilibrium QoS strategies:



$$v_2^* = \frac{6(2\alpha+t)c\alpha\bar{\varepsilon}+9(\alpha-t)ct\bar{\varepsilon}+8(t-2\alpha)p_2+16(\alpha+t)p_1}{24tc}$$

Market Share of Each SP at Equilibrium

- p_i: SP_i's revenue independent of consumers' private data

c	Operation cost factor in units of cost/QoS
p_i	Revenue of SP_i independent of consumers' private data
t	Consumer's valuation of privacy
$\overline{\varepsilon}$	Consumer's heterogeneity in privacy sensitivity

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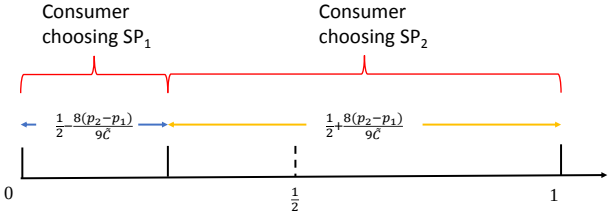

SP_1		SP_2
v_1	$\leq$	v_2
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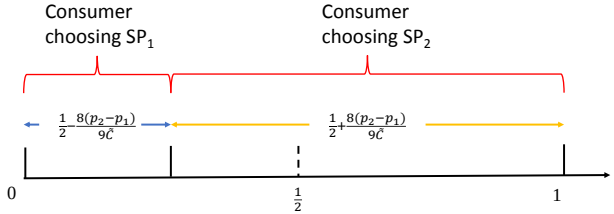

- As $\frac{p_2 - p_1}{\tilde{C}}$ increases, the market share of SP_1 decreases while SP_2s market share increases

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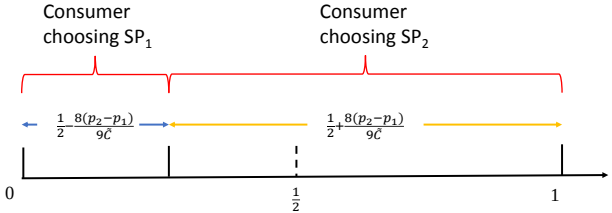

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- The SP with a larger non-private revenue gains more market share

DuckDuckGo vs. Google

SP_1		SP_2
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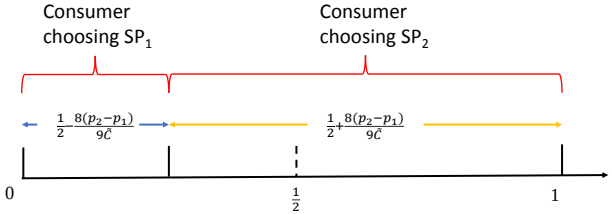

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SP_1		SP_2
v_1	≤	v_2
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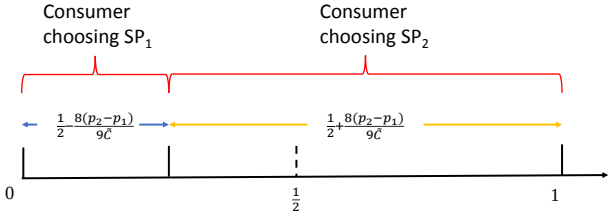

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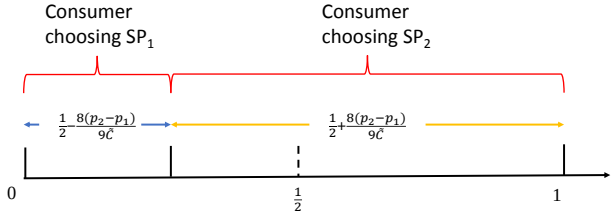

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  - Cost of offering per unit QoS c ⇑

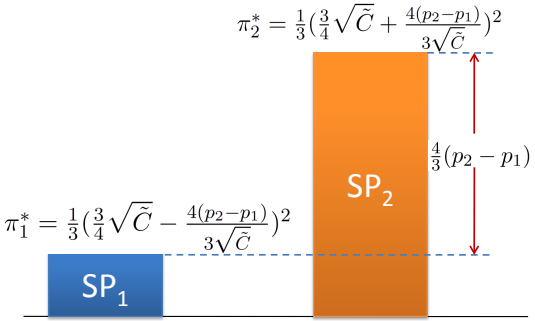
Profit for Each SP

DuckDuckGo vs. Google

SP_1		SP_2
v_1	$\leq$	v_2
ε_1	$\leq$	ε_2

$$C(v_i;\varepsilon_i) = cv_i + c\lambda\varepsilon_i$$
$$R(\varepsilon_i) = r\varepsilon_i + p_i$$

Total Profit



Profit for Each SP

- Both SPs will make more profits at the SPNE with a larger $\tilde{C}$

SP_1		SP_2
v_1	$\leq$	v_2
ε_1	$\leq$	ε_2

$$C(v_i;\varepsilon_i) = cv_i + c\lambda\varepsilon_i$$
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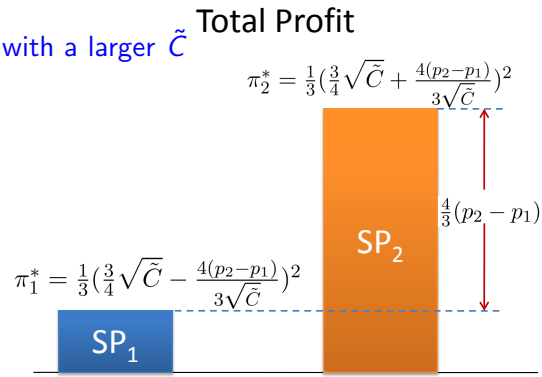

Profit for Each SP

- Both SPs will make more profits at the SPNE with a larger $\tilde{C}$
  - Higher revenue from exploiting private data ($\bar{\varepsilon} \Uparrow$)
  - Lower cost for offering low QoS and low privacy risk ($t \Uparrow$)
  - Offer high privacy risk to increase profit ($c \Uparrow$)

SP_1		SP_2
v_1	$\leq$	v_2
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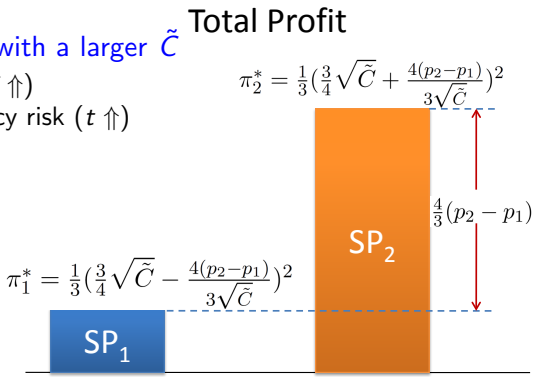

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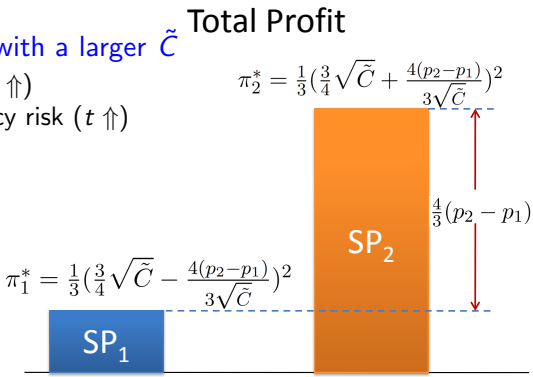


- Increase in difference of privacy independent revenue
  $\Longrightarrow$ increases in difference of profit between two SPs

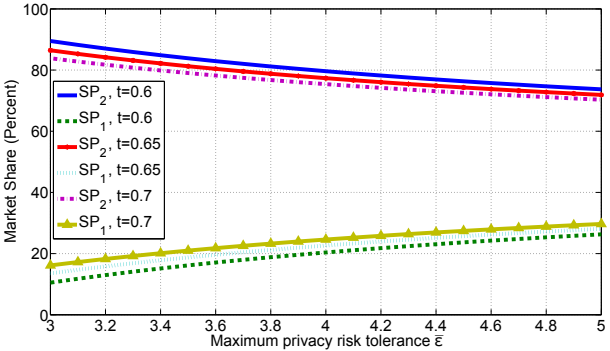
Illustration of Results (Market Share)

Parameter	c	λ	r	p_1	p_2
Value	0.5	0.75	0.7	0.4	0.8

vs. Google

SP_1		SP_2
v_1	$\leq$	v_2
ε_1	$\leq$	ε_2

Illustration of Results (Market Share)



DuckDuckGo vs. Google

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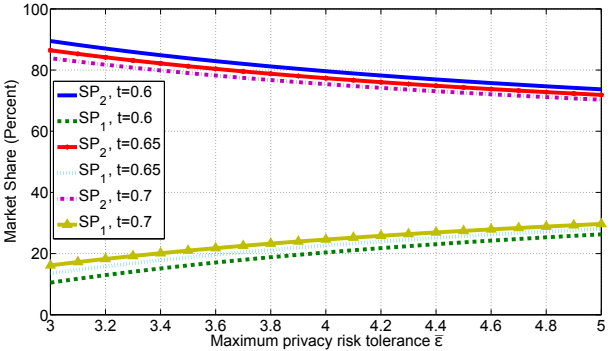

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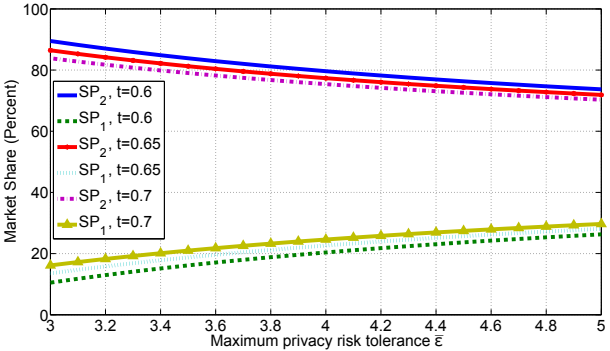

DuckDuckGo vs. Google

SP_1		SP_2
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ε_1	$\leq$	ε_2

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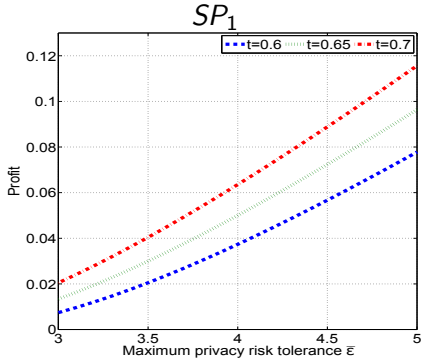
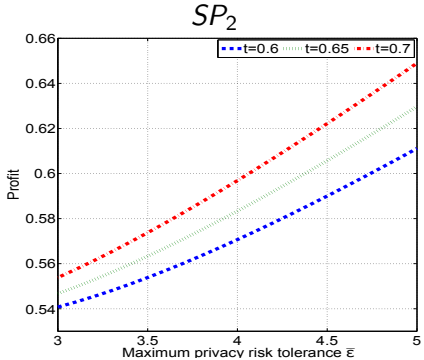
- As $\bar{\varepsilon}$ decreases, SP_2 offers high QoS and high privacy risk, thus its market share increases

Illustration of Results (SP Profit)





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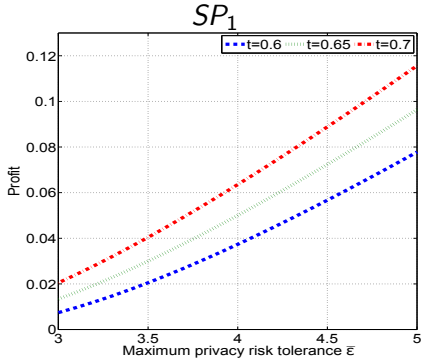

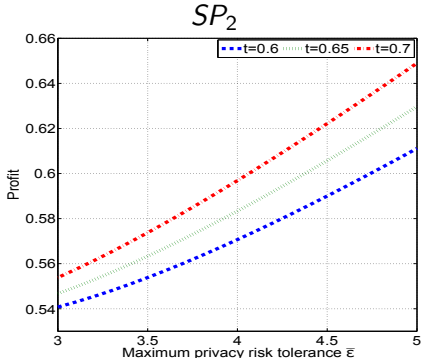

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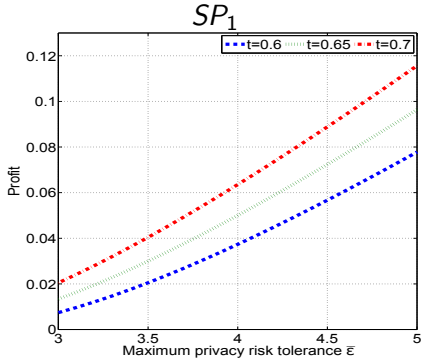

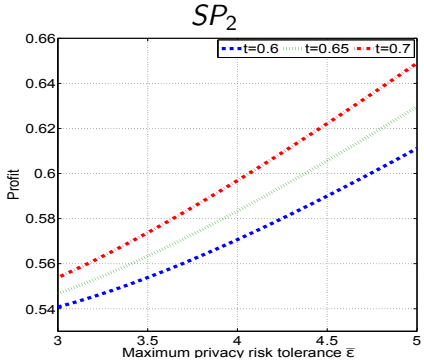

vs. Google

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- Increasing t: SPs offer lower risk & lower QoS (Cost reduction more than revenue reduction) $\Longrightarrow$ higher profit for SPs

Concluding Remarks

- Market segmentation for privacy differentiated “free” services is studied

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- Market segmentation for privacy differentiated "free" services is studied
- Investigated influences of consumers' valuation and heterogeneity in privacy preference on market share and SP profit
  - High valuation of privacy by consumers "softens" competition
  - Offering privacy aware services can still be profitable

Thank you!