An Empirical Model of R&D Procurement Contests

An Analysis of the DOD SBIR Program

Vivek Bhattacharya

Department of Economics, Northwestern University

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Motivation

Competition plays a nontrivial role in R&D-intensive markets

- Increased competition → incentives to exert effort → outcomes

Innovations often result from a **contest** for the rights to supply a product

- Research → prototyping / development → delivery

- **How do the extent of competition and the design of R&D contests affect procurement outcomes?**

✓ **Methdology:** Develop a model of R&D procurement contests

✓ **Application:** DOD Small Business Innovation Research Program

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Overview of Program, Model, and Counterfactuals

Phase I: Research — **Phase II: Development** — **Phase III: Delivery**

- Phase I: Research
  - effort → values
- Phase II: Development
  - effort → delivery costs
  - receive R&D contracts
  - limited number of spots
- Phase III: Delivery
  - Nash bargaining
  - capture portion of surplus

- **Solicitation:** fairly narrow topic specific to military applications
- **Phase I:** proof-of-concept to assess technical feasibility
- **Phase II:** commercial development to reduce delivery cost
- **Phase III:** delivery and acquisition

Estimate primitives and quantify inefficiencies

- Holdup + business stealing and reimbursement of research efforts

Consider simple design counterfactuals

- Number of competitors, surplus given in procurement, IP sharing

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Data

Navy SBIR contracts (2000–2012) from Federal Procurement Data System

- Number and identity of competitors at each stage
- R&D contract amount at each stage
- Phase III procurement amount (if observed)

Project-level characteristics from the Navy SBIR Program

- Contract duration, fiscal year, division of the Navy
- Text of solicitations and abstracts for winning proposals
- $\implies$ generate topics via Latent Dirichlet Allocation

Title	**Keywords**
aircraft	aircraft, control, unmanned vehicles, flight, operations
acoustics	acoustics, sonar, underwater, submarine, anti-submarine warfare
optics	optics, laser, fiber, infrared, wavelength

Descriptive Statistics

Fairly small competitions, with noticeable failure rates

- $\sim 83\%$ to Phase II, $\sim 11\%$ to Phase III
- Motivates identifying primitives governing stochastic nature of research

	0	1	2	3	4	≥ 5
# Phase I Comp	–	12.9%	41.8%	32.8%	8.9%	3.6%
# Phase II Comp	16.9%	61.1%	19.0%	2.3%	0.6%	0.2%
# Phase III Comp	91.2%	8.8%				

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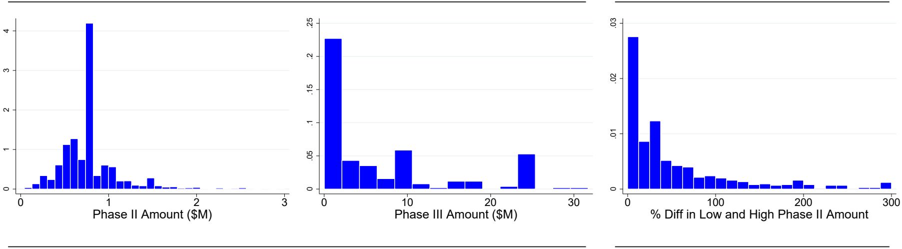
Variation both **across**- and **within**-contest in Phase II and III funding

- Phase I funding almost always $70-80K
- Variation indicative of **value** (higher funding $\implies$ increased success)



Across-Contest

Within-Contest

Model Primitives and Timing

Phase I: N_1 firms each exert effort p_i at a monetary cost $\psi(p_i)$

- Generate a success w.p. $p_i \longrightarrow$ draw a value $v_i \sim F$
- DOD sees successes and v_i and lets the top $\bar{N}_2$ enter Phase II

Phase II: N_2 firms enter with a draw of v_i

- Exert research effort $t_i \longrightarrow$ delivery cost $c_i \sim H(\cdot; t_i)$
- N_2 is public, but firms have beliefs F_{v_i} over opponents' values
- No selection into Phase II ($N_2 < \bar{N}_2$ or $\bar{N}_2 = N_1$) $\implies F_{v_i} = F$

Phase III: DOD sees $(v_i, c_i, s_i \equiv v_i - c_i)$ for all firms

- Pays firm with the largest surplus $c_i + \eta \cdot (v_i - c_i - \max\{s_{-i}, 0\})$
- ... as long as $v_i > c_i$

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Properties of the Equilibrium

Search for symmetric equilibrium p^* and $\{t^*_{N_2}(v)\}_{N_2 \leq \bar{N}_2}$

Phase II: For each N_2, a firm with type v solves

$$\arg\max_t \left\{ \int_{\underline{c}}^{v} \int_{-\infty}^{v-c} \underbrace{\eta \cdot (v - c - \max\{s, 0\})}_{\text{profits if win}} \underbrace{dG(s; v, t^*_{N_2}(\cdot), p^*)}_{\substack{v\text{'s beliefs over max}\\ \text{surplus of opponents}}} \underbrace{dH(c; t)}_{\text{cost}} - t \right\}$$

Phase I: Set $\psi'(p^*) =$ expected profits conditional on success

Key empirical assumption

- Phase II contract corresponds to the **firm-optimal** research amount
- $\implies$ Phase II award is **monotone** in value

Overview of Identification

Identification uses three features of the model

- **Monotonicity:** Higher $v \implies$ spend more on Phase II research
- **Transfer Rule + Positive Surplus**
  - Phase III transfer $T_3 = \eta v + (1 - \eta)c$ (roughly)
  - Observed **if and only if** some firm draws delivery cost $c <$ value v

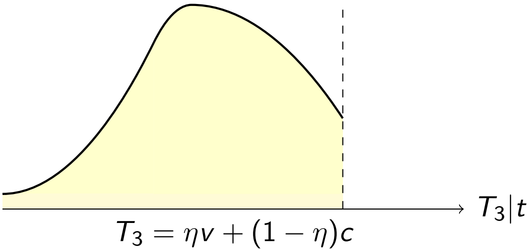
Identifying the bargaining parameter leverages equilibrium of the model

- **Optimality:** The firm's research budget is chosen optimally

Identification of Phase II Parameters

(Phase II research t, {Phase III contract T_3, fail}) $\longrightarrow$
value distribution F, delivery cost distribution $H(\cdot; t)$, bargaining power η

- Identification conditional on $(N_1, \bar{N}_2)$; consider $N_2 = 1$



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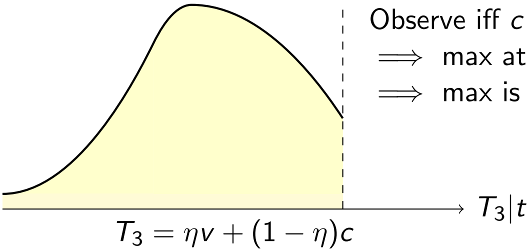

Observe iff $c \le v$
$\implies$ max at $c = v$
$\implies$ max is $T_3 = v$

Step 1: Values.

- $v(t)$ identified off the **support** of Phase III contracts for each t

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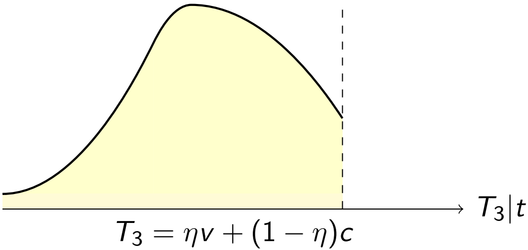

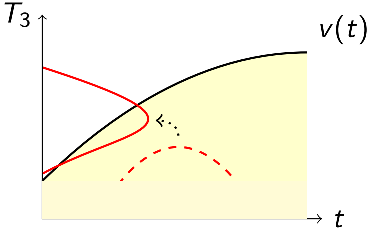

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- Value *distribution* F from transforming observed Phase II amounts

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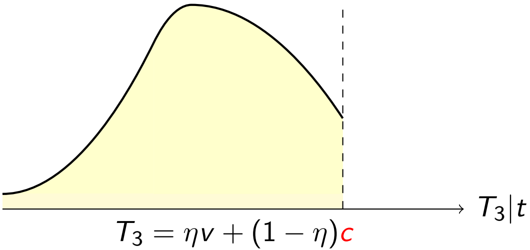

Step 2: Costs.

- Fixing η, delivery costs $H(\cdot;t)$ identified directly from $T_3|t$

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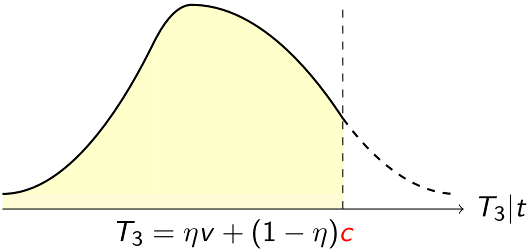

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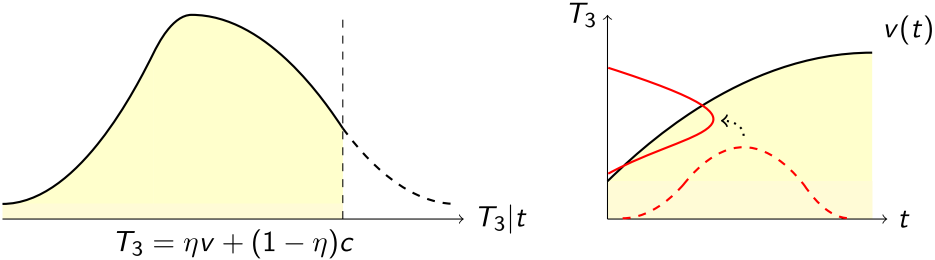

Steps 1 and 2 only used **monotonicity** + **positive surplus**

- No information about the optimality of research effort

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$$\eta \int_{\underline{c}}^{v(t)} (v(t) - c) \frac{dh}{dt}(c; t, \eta) \, dc = 1$$

Step 3: Bargaining Parameter.

- Recover η from firm's marginal benefit of research
- Identification from **ex-ante investment**, a hallmark of R&D

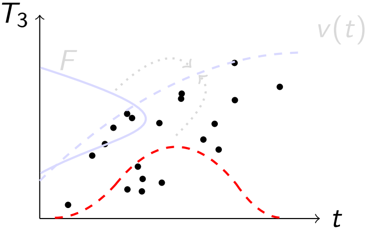
Towards an Estimation Procedure

Identification suggests a tractable method to estimate Phase II parameters

Fix η

- Pick candidate value distribution F and cost distributions $H(\cdot; t)$
- Compute $v(t)$ by matching quantiles of F and the observed Phase II efforts

Choose F and $H(\cdot; t)$ via MLE



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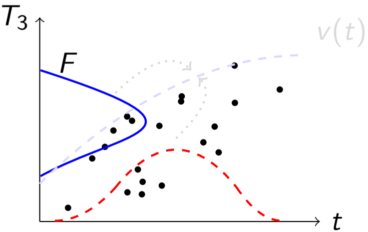

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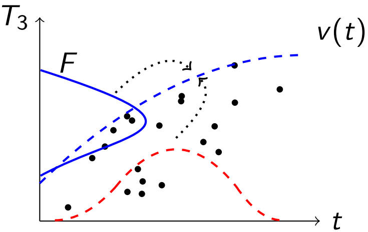

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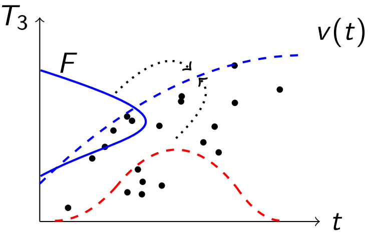

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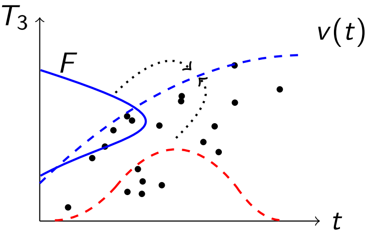

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Empirical Model and Estimation

Covariates X_j and **unobserved heterogeneity** θ_j scale values **all** costs proportionally

- $\implies$ equilibrium research efforts scale as well

Value distribution depends on N_1

- Reduced-form method of accounting for selection of N_1

Use the parametric form $\psi(p) = \alpha \cdot p^2/2$

- Avoid using Phase I amount as indicative of cost of research

Estimation proceeds by

(i) backing out the distribution of θ,

(ii) MLE conditional on η, and

(iii) matching FOCs

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Estimates

- DOD selects more competitors for contests that have higher values
- Rather small variation in values within contest ($\sim$ 12% of mean)
- Larger variation in the conditional cost distribution
- Firms receive about three-fourths of the (incremental) surplus
- Average Phase I research cost $\approx$ \$27,000

Values (\$M)	$N_1 = 1$	$N_1 = 2$	$N_1 = 3$	$N_1 = 4$
Mean	10.98	11.96	13.20	14.94
	(4.09)	(2.76)	(2.88)	(2.90)
95% Range	1.32	1.41	1.55	1.79
	(0.51)	(0.34)	(0.37)	(0.36)

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$\Pr(c < v)$		$\mathbb{E}[c \mid c < v]$		Quantiles (\$M)			
Value	Semi-Elas	Value	Elas	1%	5%	10%	Elas
0.071	0.012	6.85	-0.016	2.85	9.27	17.39	-0.161
(0.010)	(0.004)	(0.91)	(0.005)	(0.40)	(1.30)	(2.43)	(0.046)

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Firm Bargaining Parameter (η)	0.73
Phase I Marginal Cost (α)	0.208 $M

Is research under- or over-provided in R&D contests?

Phase I: Competing effects on R&D relative to social optimum

- **Holdup**: Only capture a portion $\eta < 1$ of surplus
- **Business Stealing**: Displace opponents from Phase II
- **Reimbursement**: Internalize Phase II expenditures will be refunded

Phase I R&D is excessive in this setting

- Small gain ($\sim 4\%$) with $N_1 = 1$ (no business stealing)
- ... but large ($\sim 22\%$) when $N_1 = 4$

Phase II: R&D efforts are less than socially optimal

- Receive $\underbrace{\text{a fraction}}_{\text{holdup}}$ of their $\underbrace{\text{marginal contribution}}_{\textbf{no}\text{ business stealing}}$ to social surplus

Optimal research efforts are 40–50% larger than equilibrium efforts

- Surplus can be improved by 5–10% $\longleftarrow$ **"cost of holdup"**

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- Receive $\underbrace{\text{a fraction}}_{\text{holdup}}$ of their $\underbrace{\text{marginal contribution}}_{\textbf{no}\text{ business stealing}}$ to social surplus

Optimal research efforts are 40–50% larger than equilibrium efforts

- Surplus can be improved by 5–10% $\longleftarrow$ **"cost of holdup"**

Early- and Late-Stage Competition

Total **change** from baseline ($N_1 = \bar{N}_2 = 1$), in millions of dollars

Social Surplus (Base = 0.144 \$M)

	$\bar{N}_2 = 1$	$\bar{N}_2 = 2$	$\bar{N}_2 = 3$	$\bar{N}_2 = 4$
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- **Low substitutability** between projects in Phase II
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Planner prefers to invite contestants in both stages

- Benefits: **direct effect** in Phase II and **incentive effect** in Phase I

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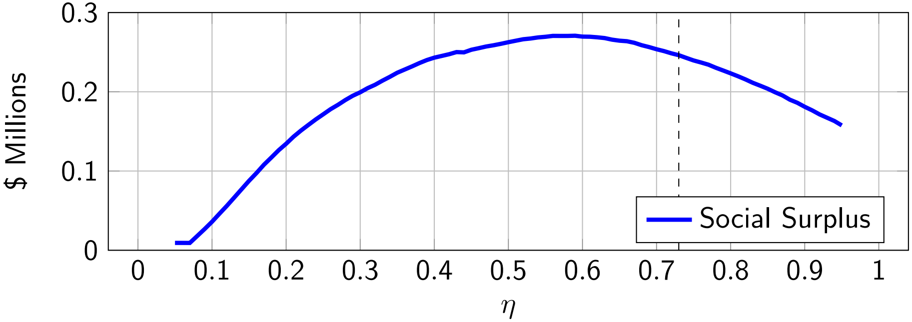
Intensity of Competition: The Effect of η

Increase $\eta \implies$ reduce holdup costs, but increase excessive Phase I effort



- Socially-optimal value of η is 0.5–0.6
- Holdup costs are low, so benefit to reducing other inefficiencies
- Net benefit is fairly small ($<10\%$)

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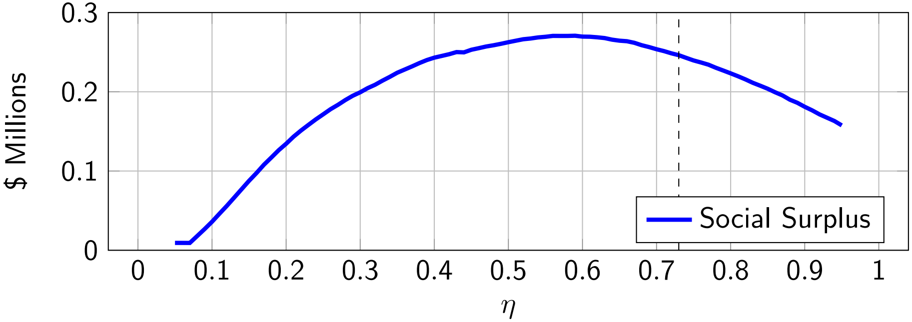

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Aside: η is on the Pareto frontier between DOD and firm profits ▸ Laffer Curve

Would the DOD prefer to make these changes?

Consider $N_1 = 4$, with $\bar{N}_2 = 2$ as a baseline

Social Surplus (\$M) $\longrightarrow$

0.243 — 0.521

Base — Opt

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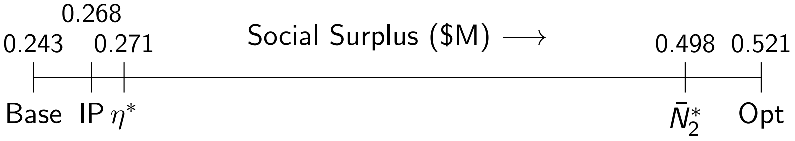

- IP sharing, reducing η, and increasing $\bar{N}_2$ all increase social surplus

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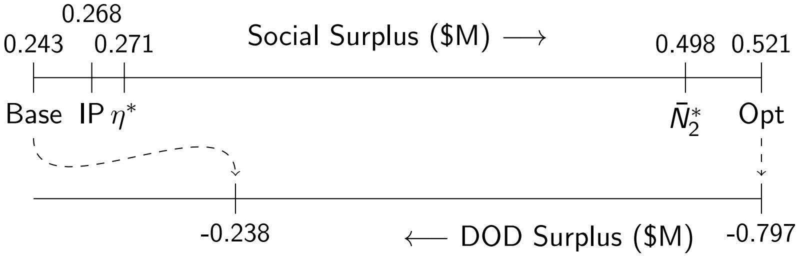

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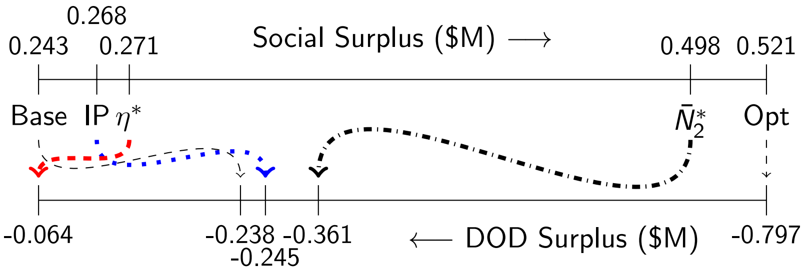


- IP sharing, reducing η, and increasing $\bar{N}_2$ all increase social surplus
- ... but most socially-optimal design changes are harmful for DOD
- DOD internalizes research costs but captures small portion of surplus

Most design changes benefit **either** planner **or** DOD

Conclusion

Developed a structural model of R&D contests

- ✓ Identified from research expenditures and procurement contracts
- ✓ Tractable estimation procedure applied to the DOD SBIR program

Increasing competition, reducing the share of the surplus given to the firms, and mandating that firms sharing IP can improve social outcomes

- Simple design changes can substantially improve social surplus
- But, usually detrimental to DOD profits

Future Work: Key aspects of the model apply to more general settings of multistage interactions

- FDA trials and product market competition; procurement of large construction projects; venture capital funding...

Monotonicity

We can write first term of the maximand as

$$\eta \int_{\underline{c}}^{v} \left[\int_0^{v-c} (v-c-s)\ dG(s) + (v-c)G(0) \right]\ dH(c;t)$$

$$= \eta \int_{\underline{c}}^{v} \left[-(v-c)G(0) + \int_0^{v-c} G(s)\ ds + (v-c)G(0) \right]\ dH(c;t)$$

$$= \left(\int_0^{v-c} G(s)\ ds \right) H(c,t) \Big|_{\underline{c}}^{v} + \int_{\underline{c}}^{v} G(v-c)H(c,t)\ dc = \int_{\underline{c}}^{v} G(v-c)H(c,t)\ dc.$$

The cross partial with respect to v and t is

$$G(0)\frac{\partial H(v,t)}{\partial t} + \int_{\underline{c}}^{v} g(v-c)\frac{\partial H(c,t)}{\partial t}\ dc,$$

and each term is positive.

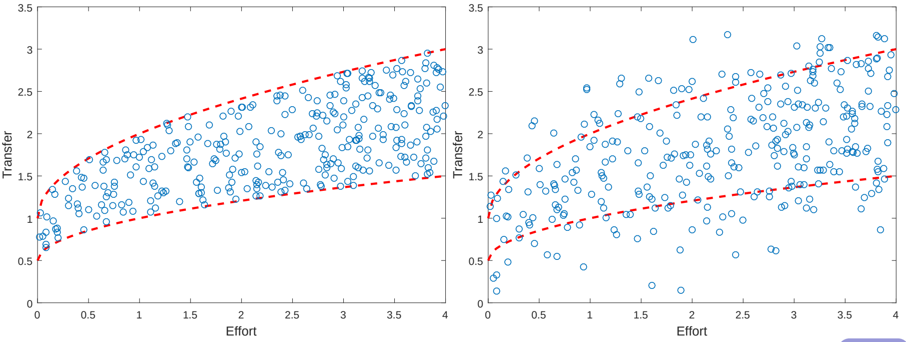
Back

Role of the Unobserved Heterogeneity θ

Economic Interpretation: Higher value projects may also have higher costs, so it introduces a correlation in the model not captured by X

- They also have **higher surplus**, so it affects research incentives

Statistical Interpretation: Justify especially high/low values of transfer



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	$\bar{N}_2 = 1$	$\bar{N}_2 = 2$	$\bar{N}_2 = 3$	$\bar{N}_2 = 4$
$N_1 = 2$	-0.023	-0.094		
$N_1 = 3$	-0.024	-0.134	-0.180	
$N_1 = 4$	-0.026	-0.135	-0.222	-0.258

$N_1 \uparrow$, $\bar{N}_2$ –

- Phase I R&D per-firm $\downarrow$, but only other benefit is added draws of value
- DOD only captures 1/4 of this benefit

$N_1 \uparrow$, $\bar{N}_2 \uparrow$

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- Social surplus and DOD profits change almost linearly

Planner prefers to invite contestants, DOD prefers to restrict entry

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Decomposing the Effect of Competition

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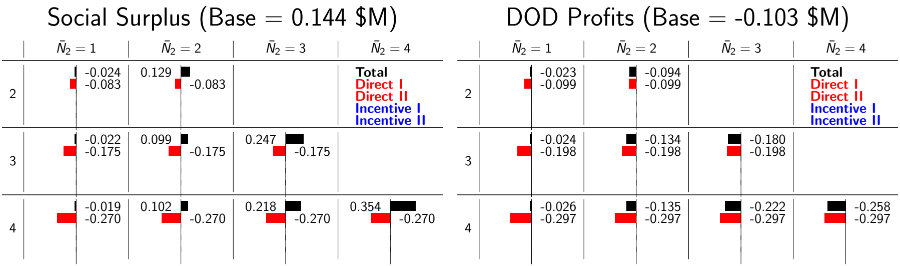
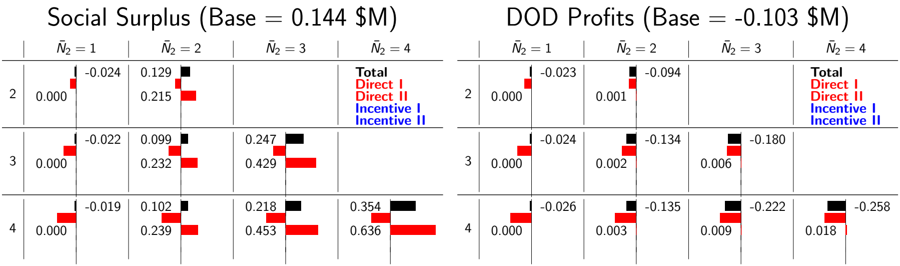


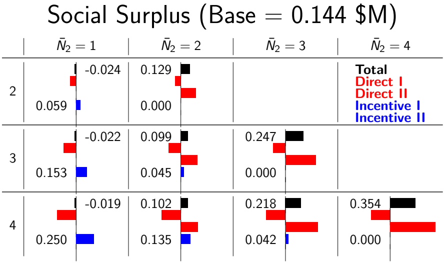
- **Direct effect of Phase I** < 0
- Benefit of added value draws in Phase I is low
- DOD only internalizes part of generated surplus $\longrightarrow$ larger in magnitude for DOD than social planner

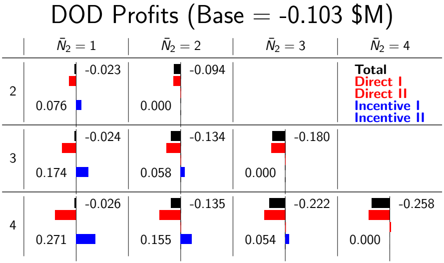
Decomposing the Effect of Competition



- **Direct effect of Phase II** > 0 for SS, ≈ 0 for DOD
- Additional chance at success is beneficial due to low substitutability
- ... but the DOD has to pay the full research costs
- **Key difference** between social planner and DOD

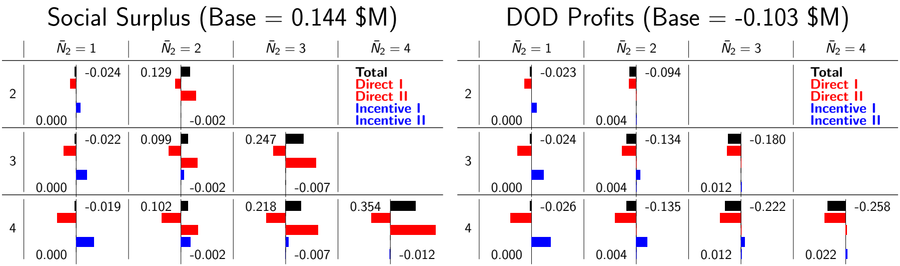
Decomposing the Effect of Competition





- **Incentive effect of Phase I** > 0
- Effort overprovided $\longrightarrow$ firms readjusting efforts downward is beneficial
- Slightly larger in magnitude for DOD

Decomposing the Effect of Competition



- **Incentive effect for Phase II** ≈ 0
- Competition is only relevant if both succeed, which is an unlikely event

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Intensity of Competition: The Effect of η

Increase $\eta \implies$

- more surplus created, but less to DOD $\longleftarrow$ **"DOD's Laffer Curve"**
- reduce holdup costs, but increase excessive Phase I effort

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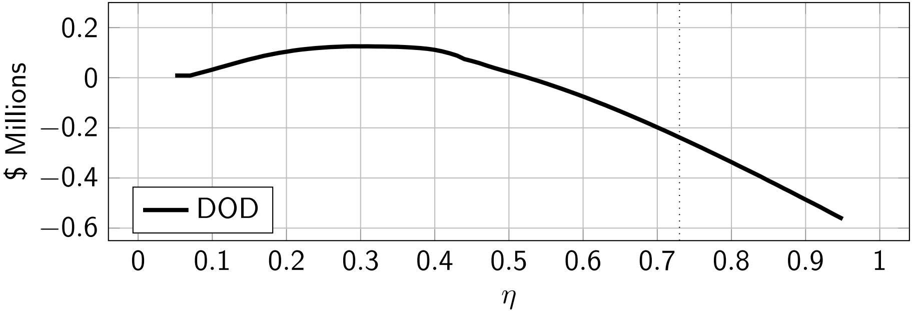

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- DOD profits (with research costs) can be improved significantly

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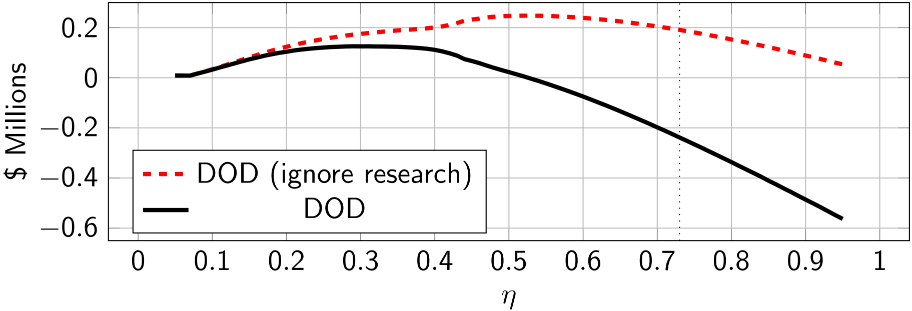

- $\eta \gtrsim 0.3$ is Pareto efficient
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- DOD profits without research costs are closer to optimal

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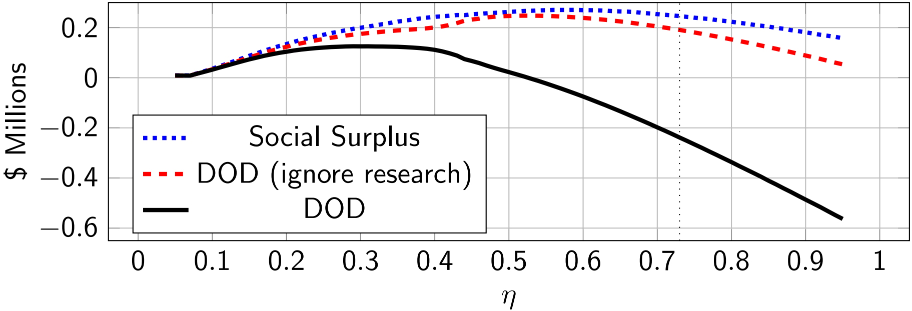

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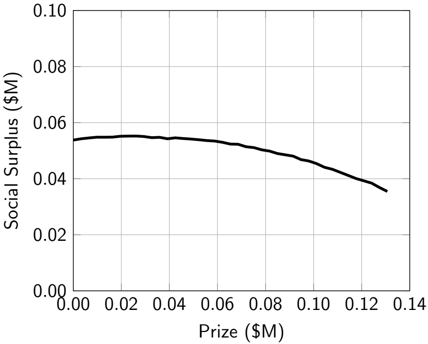
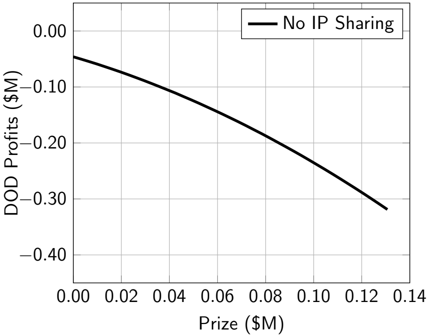
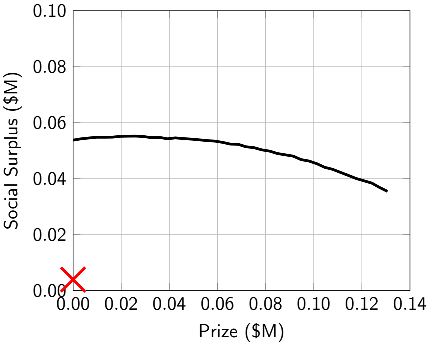
Decoupling Research and Delivery: DOD Profits





- Prizes can improve social surplus but reduce DOD profits
- … but small at most because Phase I research is often overprovided

Decoupling Research and Delivery: DOD Profits



- IP sharing w/o prizes → Phase I research ↓ → DOD profits ↑ and SS ↓
- **Free-rider problems** from IP sharing → research is underprovided → prizes are beneficial

▸ Back

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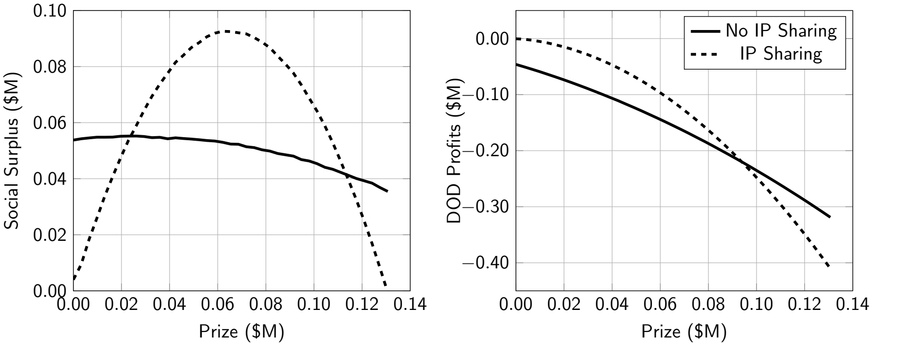

- IP sharing w/o prizes → Phase I research ↓ → DOD profits ↑ and SS ↓
- **Free-rider problems** from IP sharing → research is underprovided → prizes are beneficial
- Substantial social gains to (IP sharing + prizes) vs. baseline contest

Back

IP Sharing

No Sharing		$K=0$		K^*_{SS}		
N_1	N_2	SS	DOD	$\mathbb{E}[K(\cdot)]$	SS	DOD
2	2	0.054	-0.046	0.026	0.055	-0.083
3	2	0.111	-0.135	0.000	0.111	-0.135
3	3	0.139	-0.160	0.000	0.139	-0.160
4	2	0.246	-0.238	0.000	0.246	-0.238
4	3	0.362	-0.325	0.000	0.362	-0.325
4	4	0.498	-0.361	0.000	0.498	-0.361

IP Sharing		$K=0$		K^*_{SS}			K_{IC}		
N_1	N_2	SS	DOD	$\mathbb{E}[K(\cdot)]$	SS	DOD	$\mathbb{E}[K(\cdot)]$	SS	DOD
2	2	0.004	-0.000	0.062	0.093	-0.103	0.131	-0.001	-0.410
3	2	0.162	-0.130	0.000	0.162	-0.130	0.099	0.047	-0.469
3	3	0.013	-0.000	0.073	0.264	-0.103	0.083	0.185	-0.445
4	2	0.268	-0.245	0.000	0.268	-0.245	0.041	0.212	-0.407
4	3	0.400	-0.342	0.000	0.400	-0.342	0.002	0.396	-0.353
4	4	0.647	-0.294	0.001	0.650	-0.296	0.001	0.602	-0.345

- A few instances where IP sharing and prizes can improve DOD profits and social surplus

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