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?

 ✓ **Methodology:** 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
- 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
- \( \rightarrow \) generate topics via Latent Dirichlet Allocation

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<tr>
<th>Title</th>
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<tr>
<td>aircraft</td>
<td>aircraft, control, unmanned vehicles, flight, operations</td>
</tr>
<tr>
<td>acoustics</td>
<td>acoustics, sonar, underwater, submarine, anti-submarine warfare</td>
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<tr>
<td>optics</td>
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**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

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<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>( \geq 5 )</th>
</tr>
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<tr>
<td># Phase I Comp</td>
<td>−</td>
<td>12.9%</td>
<td>41.8%</td>
<td>32.8%</td>
<td>8.9%</td>
<td>3.6%</td>
</tr>
<tr>
<td># Phase II Comp</td>
<td>16.9%</td>
<td>61.1%</td>
<td>19.0%</td>
<td>2.3%</td>
<td>0.6%</td>
<td>0.2%</td>
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<td># Phase III Comp</td>
<td>91.2%</td>
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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)
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. $p_i$ → 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 $t_i$ → 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 $v_i > c_i$
Model Primitives and Timing

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Properties of the Equilibrium

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

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

$$\arg \max_{t} \left\{ \int_{v}^{v - c} \int_{-\infty}^{v} \eta \cdot (v - c - \max\{s, 0\}) \, dG(s; v, t_{N_2}^*(\cdot), p^*) \, dH(c; t) - t \right\}$$

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

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

Identifying the bargaining parameter leverages equilibrium of the model

- **Optimality**: The firm’s research budget is chosen optimally
Identification of Phase II Parameters

\[(\text{Phase II research } t, \{\text{Phase III contract } T_3, \text{ fail}\}) \rightarrow \text{value distribution } F, \text{ delivery cost distribution } H(\cdot; t), \text{ bargaining power } \eta\]

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

\[T_3 = \eta v + (1 - \eta) c\]
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(Phase II research \( t \), \{Phase III contract \( T_3 \), fail\} \( \rightarrow \) value distribution \( F \), delivery cost distribution \( H(\cdot; t) \), bargaining power \( \eta \)

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\[
T_3 = \eta v + (1 - \eta)c
\]

Observe iff \( c \leq v \)

\[\Rightarrow \text{max at } c = v\]

\[\Rightarrow \text{max is } T_3 = v\]

Step 1: Values.

- \( v(t) \) identified off the support of Phase III contracts for each \( t \)
Identification of Phase II Parameters

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\[
T_3 = \eta v + (1 - \eta)c \quad \Rightarrow \quad T_3|t
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Step 1: Values.

- \( v(t) \) identified off the support of Phase III contracts for each \( t \)
- Value distribution \( F \) from transforming observed Phase II amounts
Identification of Phase II Parameters

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value distribution $F$, delivery cost distribution $H(\cdot; t)$, bargaining power $\eta$

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Step 2: Costs.

- Fixing $\eta$, delivery costs $H(\cdot; t)$ identified directly from $T_3|t$
Identification of Phase II Parameters

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value distribution \( F \), delivery cost distribution \( H(\cdot; t) \), bargaining power \( \eta \)

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\[ T_3 = \eta v + (1 - \eta)c \]

\[ T_3 \mid t \]

Step 2: Costs.

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Steps 1 and 2 only used \textbf{monotonicity} + \textbf{positive surplus}

- No information about the optimality of research effort
Identification of Phase II Parameters

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

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

**Step 3: Bargaining Parameter.**

- Recover $\eta$ 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 $\eta$

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

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

- **Tractable**: Can parametrize primitives without solving the model
- **Conceptually Robust**: Only depends on monotonicity + pos surplus
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Empirical Model and Estimation

Covariates $X_j$ and **unobserved heterogeneity** $\theta_j$ scale values **all** costs proportionally

- 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 $\theta$,

(ii) MLE conditional on $\eta$, and

(iii) matching FOCs
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DOD selects more competitors for contests that have higher values

- Rather small variation in values within contest (≈ 12% of mean)
- Larger variation in the conditional cost distribution
- Firms receive about three-fourths of the (incremental) surplus
- Average Phase I research cost ≈ $27,000

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<th>Values ($M)</th>
<th>$N_1 = 1$</th>
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<td>11.96</td>
<td>13.20</td>
<td>14.94</td>
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<td></td>
<td>(4.09)</td>
<td>(2.76)</td>
<td>(2.88)</td>
<td>(2.90)</td>
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<td>95% Range</td>
<td>1.32</td>
<td>1.41</td>
<td>1.55</td>
<td>1.79</td>
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<td>(0.51)</td>
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<td>(0.37)</td>
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- Average Phase I research cost \( \approx \$27,000 \)

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

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\begin{align*}
\text{Firm Bargaining Parameter (}\eta\text{)} & \quad 0.73 \\
\text{Phase I Marginal Cost (}\alpha\text{)} & \quad 0.208 \text{ $M}
\end{align*}
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 a fraction of their marginal contribution to social surplus
  - **holdup**
  - **no business stealing**

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

- Surplus can be improved by 5–10% ← “cost of holdup”
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- Surplus can be improved by 5–10% ← “cost of holdup”
Early- and Late-Stage Competition

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

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\(N_1 \uparrow, \tilde{N}_2 \downarrow\)
- Phase I R&D per-firm \(\downarrow\), but only other benefit is added draws of value

\(N_1 \uparrow, \tilde{N}_2 \uparrow\)
- Low substitutability between projects in Phase II
- Social surplus changes almost linearly

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 $\eta$

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

- Socially-optimal value of $\eta$ 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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Aside: $\eta$ is on the Pareto frontier between DOD and firm profits
Would the DOD prefer to make these changes?

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

\[
\begin{align*}
0.243 & \quad \text{Social Surplus (}$M$$) \quad \rightarrow \quad 0.521 \\
\text{Base} & \quad \text{Opt}
\end{align*}
\]
Would the DOD prefer to make these changes?

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

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- IP sharing, reducing $\eta$, and increasing $\tilde{N}_2$ all increase social surplus.
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IP sharing, reducing $\eta$, and increasing $\bar{N}_2$ all increase social surplus.
Would the DOD prefer to make these changes?

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

- IP sharing, reducing $\eta$, and increasing $\tilde{N}_2$ 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

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

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

\[ = \left( \int_{0}^{v-c} G(s) \, ds \right) H(c, t) \bigg|_{c}^{v} + \int_{c}^{v} G(v - c)H(c, t) \, dc = \int_{c}^{v} G(v - c)H(c, t) \, dc. \]

The cross partial with respect to \( v \) and \( t \) is

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

and each term is positive.
Role of the Unobserved Heterogeneity $\theta$

**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
# Early- and Late-Stage Competition

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

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$N_1 \uparrow$, $\tilde{N}_2 \downarrow$

- Phase I R&D per-firm ↓, but only other benefit is added draws of value
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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 $\rightarrow$ larger in magnitude for DOD than social planner
Decomposing the Effect of Competition

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- **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

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- **Incentive effect of Phase I > 0**
- Effort overprovided \( \rightarrow \) firms readjusting efforts downward is beneficial
- Slightly larger in magnitude for DOD
Decomposing the Effect of Competition

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- **Incentive effect for Phase II** ≈ 0
- Competition is only relevant if both succeed, which is an unlikely event
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Increase $\eta \implies$
- more surplus created, but less to DOD $\leftarrow$ “DOD’s Laffer Curve”
- reduce holdup costs, but increase excessive Phase I effort
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$\eta \gtrsim 0.3$ is Pareto efficient

DOD profits (with research costs) can be improved significantly
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- reduce holdup costs, but increase excessive Phase I effort

$\eta \gtrsim 0.3$ is Pareto efficient

DOD profits (with research costs) can be improved significantly

DOD profits without research costs are closer to optimal
Intensity of Competition: The Effect of $\eta$

Increase $\eta \implies$

- more surplus created, but less to DOD
  
  “DOD’s Laffer Curve”

- reduce holdup costs, but increase excessive Phase I effort

$\eta$

$\text{Social Surplus}$

$\text{DOD (ignore research)}$

$\text{DOD}$

$\text{Millions}$

- Socially-optimal value of $\eta$ is 0.5–0.6
- Holdup costs are low, so benefit to reducing other inefficiencies
- Net benefit is fairly small ($< 10\%$)
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
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
- Substantial social gains to (IP sharing + prizes) vs. baseline contest
### IP Sharing

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<th>No Sharing</th>
<th>$K = 0$</th>
<th>$K_{SS}$</th>
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- A few instances where IP sharing and prizes can improve DOD profits and social surplus.