"Learning and Deterrence in Dynamic Research Contests: Evidence from Kaggle"

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Large-scale research contests, which "crowdsource" innovative solutions to well-posed problems, are becoming increasingly common. The Netflix Prize garnered much media attention almost a decade ago, and since then this model has sparked many new examples of large-scale research contests. Private companies have been formed which specialize in hosting similar contests to procure innovative products (almost exclusively software or standalone algorithms) on behalf of other firms. The federal government uses these contests as well: the 2011 COMPETES Act authorized the use of such contests to procure innovation for federal agencies, and the government runs similar contests on challenge.gov. In this project, I will develop a structural model of such contests and ask how the design—and in particular the design of the *information structure*—affects outcomes.

The main question I will study about competition design is whether opponents' progress should be revealed to competitors. The key tradeoff is between learning and deterrence. In most contests, there is uncertainty about the *return* to effort, and seeing opponents' successes can inform competitors of this return. However, as long as contestants have some information about their own progress, progress could be disclosed strategically to deter opponents from exerting effort. Whether the learning or the deterrence effect dominates would inform whether the information design should allow contestants to publicize progress.

The theoretical literature on learning in races with uncertainty can be traced back to Choi (1991). Most recently, Halac et al. (2016) and Bimpikis et al. (2016) specifically study information disclosure and prize structure in dynamic innovation contests, although they restrict to two-stage contests with binary outcomes. There is a small empirical literature on online innovation contests, studying the effect of competition (Boudreau et al., 2011; Gross, 2016), skill heterogeneity (Boudreau et al., 2016), and prize structure (Kireyev, 2016) on outcomes. I will study information disclosure specifically and will do so through the lens of a structural model to study broader design counterfactuals. This project builds on the theoretical literature and complements the empirical literature by analyzing a design question that has gone understudied; it also contributes to the literature in empirical industrial organization on the estimation of dynamic games with private states.

In this proposal, I first discuss the empirical setting. I then sketch a preliminary model for this setting. Next, I discuss the empirical strategy to both conduct descriptive analysis of the learning and deterrence effects and then estimate the primitives of the structural model. I conclude with a connection to my prior work on R&D contests as well as a discussion of potential avenues for future research.

Empirical Setting and Data. I have data from Kaggle, a company which serves as a platform to host prediction contests sponsored by various firms. Each firm posts a training set containing covariates and an outcome of interest. Contestants submit code that predicts the outcome, given covariates, and they receive a "public" score based on their accuracy on some fraction of a test set. Contestants can submit algorithms as frequently as they would like over the period during which the contest runs—usually three to six months). Each competitor's identity and most recent public score can be viewed by all competitors in the contest. At the end of the contest, the algorithms are given a "private" score based on the remainder of the test set, and the contestants with the highest scores win prespecified monetary prizes. The winning algorithms become the intellectual property of the firm that sponsors the contest.

I have access to the time path of scores—when each contestant submitted a new algorithm and

the public and private scores attained by the algorithm—for all contests run by Kaggle. Furthemore, contestants can be linked across contests, and I have some biographical information about many of the contestants (such as occupation).

Model. I model research in this setting as a continuous-time control problem in which a contestant can control the drift of a stochastic process at some cost.[1] This formulation captures salient features of R&D: effort is costly and higher effort tends to lead to better outcomes, but there is inherent randomness in the process. Exerting effort e_{it} over an interval dt costs contestant i $e_{it}\ dt$. By controlling this process, contestant i can control a "public" score process S_{it} satisfying $dS_{it} = \theta \cdot \gamma(e_{it})\ dt + \theta\sigma\ dZ_{it}$, where θ is an unknown contest-specific parameter that parameterizes the difficulty of the contest, $\gamma(\cdot)$ is the shape of the marginal return to effort, and σ parameterizes the stochasticity of research. Each contestant observes a noisy measure of their score at all times, with a process given by $d\hat{S}_{it} = \gamma(e_{it})\ dt + \sigma\ d\hat{Z}_{it}$, where dZ_{it} and $d\hat{Z}_{it}$ have correlation ρ.[2] When contestants submit, they learn their true scores. At a fixed time T, a prespecified monetary prize is awarded to the winner; contestants with higher scores are more likely to be selected as the winner.[3]

Contestants observe the history of all public scores of all their competitors, along with when they last submitted. Each contestant also observes the noisy signal of her score at all times. Based on this information, at each instant t, each contestant chooses effort and decides whether to submit her algorithm to (i) learn her true score S_{it} and (ii) reveal it to all competitors. Fixing a state,[4] each competitor i has a cutoff strategy for when to submit: i will submit if $\hat{S}_{it}$ is either sufficiently high or when $\hat{S}_{it}$ is sufficiently low. The former is to deter opponents from exerting effort by signaling that she is well ahead of the pack; the latter is to resolve uncertainty about one's own score and gauge the returns to exerting further effort.

Empirical Strategy. The first step in the empirical analysis will be to normalize the observed scores: increasing from 20% accuracy to 50% accuracy is likely much easier than moving from 50% accuracy to 80% accuracy. I propose to do this by leveraging the observation that there is usually a large "competitive fringe" of contestants who may be acting nonstrategically.[5] If these contestants are exerting constant effort, then there are distributional predictions on the observed scores. The transformation between the observed distribution and the predicted distribution can be used to normalize scores.

Upon normalization, I will first explore descriptive evidence of learning and deterrence. In particular, I will compute correlations between the size of the improvement in the best public score and observable measures of activity, such as future improvements in individual scores and the number of submissions. A large jump in the frontier is more likely to lead to deterrence effects—especially if it occurs later in the contest—and a smaller jump may lead to learning and encouragement effects.[6]

[1] This formulation has been used in other papers studying contests with continuous outputs (Seel and Strack, 2016).

[2] This noisy measure captures that contestants may have a sense of their score by testing the fit on the training set.

[3] The reason the contestant with the highest score is not automatically the winner is that awards are based on the private score. The benefit of this institutional detail from a modeling perspective is that it smooths out the payoff distribution.

[4] A state consists of scores and most recent submit times of all competitors. It also consists of beliefs over θ, which are actually common across competitors in this parameterization. Since θ does not enter the noisy signal, contestant update only on submits.

[5] These contestants may be distinguished on observable attributes, such as experience. However, this fringe is often distinguishable visually, so I am currently exploring clustering algorithms to identify them.

[6] Through the lens of the structural model, note that submissions and observed score improvements are not necessarily

I then turn to the estimation of the structural model, extending a procedure by Nekipelov (2007). I first restrict to a relatively small subset of players and consider the rest of them to be the "competitive fringe." Then, fixing an arbitrary contestant, I estimate the transition matrix of public states directly from the data using variation across contests;[7] given the high dimensionality, this step will require a good deal of smoothing. Then, for a candidate parameter vector—the drift function γ, the randomness σ, the accuracy of the noisy signal $\hat{S}$, and the prior on θ—I can simulate the contestant's best response to this transition matrix as a single-agent optimal control problem. This optimal response will lead to a distribution of realized score paths, which I can match to the observed score path using an indirect inference procedure.

Once the parameters are estimated, I can simulate the main counterfactuals of interest and study their effect on outcomes such as quality of the research produced and social surplus generated. First, I will shut down the leaderboard entirely (and let contestants observe S_{it} privately), which eliminates the learning and the deterrence effects. Second, I will study procurement outcomes when S_{it} is always public; this counterfactual eliminates the strategic nature of disclosure, which can enhance the learning effect and weaken deterrence.[8] Together, this analysis will allow for a quantification of learning and deterrence in an empirical setting and inform the design of large-scale innovation contests.

Relation to Previous Work and Future Directions. In my job market paper, I study R&D procurement contests in the context of the DOD Small Business Innovation Research program, in which firms compete with each other over a number of phases to develop an innovative product and win a contract to supply it to the DOD. I propose a new structural model of this setting, study how to identify and estimate the primitive, and then use this model to evaluate the effect of various methods to modulate competition in these research contests. The project discussed in this proposal complements my job market paper by continuing the agenda of analyzing R&D procurement through a structural lens, which is a promising direction to push both the literature on innovation and the one on empirical IO. However, this project also tackles a substantially different design consideration: my job market paper studies entry restrictions and other methods to directly modulate the intensity of competition, while the current proposal studies information disclosure. The two projects together highlight that R&D procurement mechanisms can take many different forms, and future work can analyze the underlying differences between these settings.[9]

In a different line of inquiry, it is interesting to note that performance in large-scale online contests are also sometimes used to evaluate candidates for employment. Studying the relationship between these contests and labor market outcomes can help understand this growing market in the economy.[10]

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directly tied to effort, which is the object of interest. Thus, these regressions are mostly descriptive.

[7] This step is similar to estimating the policy function in Bajari et al. (2007).

[8] The second counterfactual is computationally challenging, and I will have to explore methods to make the analysis more tractable.

[9] For instance, entry restrictions are, at least in popular discource, not a concern discussed in large-scale online contests. One rationale may be that such contests attract a large number of skilled contestants who compete for leisure but still produce valuable research. Studying the extent to which this is empirically validated, and whether entry restrictions can nevertheless improve outcomes significantly, is an avenue for future work.

[10] In principle, individual contestants can be linked to public professional accounts, such as LinkedIn, and thus contest-level results can be compared to labor market outcomes. Exploring strategies to causally identify the impact of such contests on outcomes is an interesting avenue for study.

References

Bimpikis, K., S. Ehsani, and M. Mostagir (2016): "Designing Dynamic Contests," Tech. rep., Stanford Graduate School of Business.

Boudreau, K. J., N. Lacetera, and K. R. Lakhani (2011): "Incentives and problem uncertainty in innovation contests: an empirical analysis," *Management Science*, 57, 843–863.

Boudreau, K. J., K. R. Lakhani, and M. E. Menietti (2016): "Performance responses to competition across skill-levels in rank order tournaments: field evidence and implications for tournament design," *RAND Journal of Economics*, 47, 140–165.

Choi, J. P. (1991): "Dynamic R&D competition under "hazard rate" uncertainty," *RAND Journal of Economics*, 22, 596–610.

Gross, D. P. (2016): "Creativity under fire: the effects of competition on creative production," Working paper, Harvard Business School.

Halac, M., N. Kartik, and Q. Liu (2016): "Contests for Experimentation," *Journal of Political Economy*, Forthcoming.

Kireyev, P. (2016): "Markets for ideas: prize structure, entry limits, and the design of ideation contests," Working paper 16-129, Harvard Business School.

Nekipelov, D. (2007): "Entry deterrence and learning prevention on eBay," Tech. rep., Duke University.

Seel, C. and P. Strack (2016): "Continuous time contests with private information," *Mathematics of Operations Research*, 41, 1093–1107.

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Angier B. Duke Memorial Scholarship	2008-12

PROFESSIONAL ACTIVITIES

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Presentations: Duke University IO/PF Lunch (Fall 2015)

PUBLICATIONS

"Regulating Bidder Participation in Auctions," ***RAND Journal of Economics*****, 45(4), 2014** (With James W. Roberts and Andrew Sweeting)
In the standard model of procurement auctions with endogenous and free entry, too many or too few suppliers may enter because their entry decisions are not coordinated. We show how an alternative "entry rights auction" mechanism, where an initial auction is used to allocate rights to participate in a second auction for the contract, may improve efficiency depending on how much information suppliers have about their costs when they decide whether to enter. In an empirical application, using data from highway procurement auctions in Oklahoma and Texas, we show that entry is moderately selective and predict that the entry rights auction mechanism would both increase efficiency and reduce procurement costs significantly.

"Selective Entry and Auction Design," ***International Journal of Industrial Organization,*** **43, 2015** (With Andrew Sweeting)
This article examines how different auction designs perform when entry is endogenous and selective, by which we mean that bidders with higher values are more likely to enter. In a model where potential bidders are symmetric, we show that three alternative designs can significantly outperform the "standard auction with simultaneous and free entry" when entry is selective. When bidders are asymmetric, we show that the level of bid preference that maximizes a seller's

revenues is significantly affected by the degree of selection. We also describe recent empirical and econometric work that shows that the degree of selection can be identified and estimated using standard types of auction data.

RESEARCH PAPERS

"An Empirical Model of R&D Procurement Contests: An Analysis of the DOD SBIR Program" (Job Market Paper)

This paper develops a new empirical model of a multistage R&D contest for a procurement contract and uses it to study the design of the Small Business Innovation Research program in the Department of Defense. Firms' incentives to innovate depend on the cost of research, the intensity of competition, and the rewards from securing the procurement contract. The cost of research, the distributions of project values and delivery costs, and the fraction of the surplus shared by the procurer are nonparametrically identified and can be tractably estimated using data on the procurement contract amount and the firms' R&D expenditures. Estimates suggest that there is fairly low variation in the values of projects developed by different firms and that most of the variation in the procurement contract is attributable to differences in delivery costs, which are drawn later in the research process. Further, the DOD currently provides high-powered incentives, sharing approximately three-quarters of the surplus from the innovation with the supplier. Increasing the number of competitors in later stages of the contest, lowering the share of the surplus firms receive in procurement, and mandating that firms share intellectual property would all increase total social surplus. However, since the DOD pays for research expenditures but only partially internalizes the gains from improved innovations, many socially beneficial design changes would actually reduce its profits from the contest. Together, these results suggest that at the estimated parameters, the DOD may have an incentive to skew the design of the contest significantly away from the socially optimal one.

"Imperfect Public Monitoring with a Fear of Signal Distortion," Revise and Resubmit, ***Journal of Economic Theory*** (With Lucas Manuelli and Ludwig Straub)

This paper proposes a model of signal distortion in a two-player game with imperfect public monitoring. Each player has the opportunity to distort the true public signal and is uncertain about the distortion technologies available to the other player. When players evaluate strategies according to their worst-case guarantees—i.e., are ambiguity-averse over certain distributions in the environment—perceived continuation payoffs endogenously lie on a positively sloped line. We then provide examples showing that, counterintuitively, identifying deviators can be harmful in enforcing a strategy profile and that signal distortion can sustain cooperation when it is impossible in standard settings. We finally extend our model to a repeated game and prove an anti-folk theorem, showing that payoffs under our equilibrium concept are under general conditions bounded away from efficiency.

"Rank-Based Elicitation Schemes for Relative Likelihoods of Events" (With Benjamin N. Roth)

This paper studies whether rank-based scoring rules, in which agents are asked to order events by their likelihoods, can elicit truthful rankings. Such

mechanisms are commonly used in the field since they only require agents to compare probabilities of similar events to each other rather than to numerical probabilities, which may be difficult for agents with low numeracy. We first show that commonly-used rank-based scoring rules need not elicit truthful rankings from agents who are not risk-neutral. We then provide a variation of a rank-based scoring rule that incentivizes agents to rank arbitrary sets of events truthfully, regardless of risk preferences. This scheme can elicit approximate *numerical* probabilities as well. We provide a simple implementation of this scheme using a series of questions that ask agents about the relative likelihoods of pairs of events. Finally, we conduct numerical experiments that show that this scheme elicits probabilities to high precision using relatively few questions.

RESEARCH IN PROGRESS

"An Empirical Model of Learning and Deterrence in Dynamic Research Contests"

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November 1, 2016

To whom it may concern:

It is a great pleasure to write a letter for Vivek Bhattacharya. Vivek is a star student working in industrial organization. Behind his unassuming nature, Vivek has an extraordinary command of theory and of structural econometric techniques, a mature sense for crafting models, a natural feel for economics, and a real dedication to his work. His job-market paper examining research contests run by the US Navy is a thoughtful, creative, and technically sophisticated paper that should immediately become a staple of graduate reading lists. I think he will one of the stars of this year's job market and every school – even those in the top five – should want to hire him.

In recent years there has been substantial interest in research contests both among theorists and among applied researchers in multiple fields. Most of this literature is theoretical and has highlighted design principles that may be important, e.g. that we may want to limit entry into contests so that each individual participant has a sufficient chance of winning to be incentivized to exert effort. On a general level Vivek's work is pushing this literature forward by showing how one might turn these models into something that could be estimated empirically. He's gone quite a distance from anything in the existing literature and I think his paper has a chance to be highly influential both in the contest literature and more broadly.

Vivek's job market paper is structural empirical analysis of multistage R&D contests run by the US Navy. In each contest the Navy describes an innovative product it would like to procure if it is feasible and can be built at a reasonable cost. In the first stage small-to-medium size firms submit proposals describing ideas for developing the product. The Navy awards research funding to those it regards as most promising. In the second stage the Navy reviews reports describing what firms were able to accomplish with their first-stage funding and offers larger grants to one or two firms to enable them to develop prototypes. In the third stage the Navy may enter into a large procurement contract with one of these firms. (Most of the time, however, the goal is sufficiently elusive so that no procurement occurs.)

There are many design choices in setting up such a contest including how many firms to let into each stage, how much funding to provide, how much surplus to leave with the winner of the final stage, etc. The optimal contest design depends on a number of features of the environment. The main goal of Vivek's paper is to develop techniques that can be used to estimate the relevant primitives and to apply these techniques in his dataset to provide insights on the merits of the Navy's current design relative to some alternatives.

The paper has a number of very nice features. First, Vivek shows really impressive maturity for applied modeling in developing a parsimonious model that rings true and incorporates features of the environment that seem most relevant to the contest design decision. He models the first stage as involving ex ante symmetric entrants exert effort in order to increase the probability that they will succeed in developing a design. If a firm is successful, the value to the Navy of the design is a random draw from a distribution known to the firms and the Navy. Second stage effort is then assumed to reduce the cost of producing the designed product. Again, these costs are stochastic.

In the third stage the Navy bargains with the firm that has developed the best product (v - c largest), with other firms with $v - c > 0$ serving as outside options that affect payoffs if they exist. It's a nicely thought out set of assumptions that yields a rich model which is still amenable to analysis.

A second very impressive feature of the paper is its discussion of the nonparametric identification and estimation of the model given the data we naturally observe: the number of firms chosen to receive funding in each of the three stages of each contest and the values of the research payment/procurement contract awarded to each. There are several ideas here. First, he notes that the second-period research funding will optimally be a monotone function of the value of each product to the Navy. As a result the distribution of the procurement contracts awarded to firms receiving any given level of research funding will have a support that varies the research funding with the upper bound of this support being the value to the Navy. Next, he notes that given any value of the bargaining parameter we can infer the distribution of cost realizations from the value of the product to the Navy and the distribution of contract amounts. Probabilities of success in the first-stage can be directly inferred from the data by looking at the number of firms advancing to stage two when then number of first-stage competitors is such that the Navy does not constrain the number advancing to the second stage. Finally, the bargaining parameter is itself identified if one assumes that first stage research funding is set at the firm-optimal amount. The paper develops an estimation methodology closely following on the identification argument and shows that the estimation is feasible given the available data. An important part of this argument is that he can allow both for the effects of observed covariates and of an unobserved project-specific shifter that affects the cost and valuation distributions.

Finally, the paper is very nice applied paper that yields a number of insights into the procurement contests it studies. A preliminary observation which provides an important cautionary note for anyone tempted to make naïve use of variation in contest designs that vary across contests is that the Navy's contest design choices are systematically related to primitives: the Navy is funding more firms on projects that are ex ante more promising. Controlling for this, he notes that there appears to be limited scope for firms to develop designs that yield very different values to the Navy – perhaps this results from the product descriptions being fairly specific. Costs are estimated to usually be much larger than values (which results in the Navy usually choosing to not fund any project) but he estimates that conditional on success the surplus generated is often substantial. Research effort is estimated to reduce costs, but the elasticity is not large. Estimates of the bargaining parameter indicate that the Navy is allowing winning firms to retain the majority of the surplus generated. Counterfactual simulations indicate that this decision is not inappropriate: the Navy is on the correct side of the effort-tax rate Laffer curve and is not far from what would be optimal under some conceptions of what the Navy might want to maximize.

My bottom line is that it's an outstanding and impressive paper. It should be published in a top general interest journal, it should be featured on many reading lists, and it could open up future research not just on the narrow topic given that many economic situations in which one or a limited number of firms will win have some contest-like features.

Vivek's job market paper is just one of a number of impressive research accomplishments. (And note that he is just in his fifth year in graduate school having come directly here after his undergraduate degree.) Vivek already has two published papers which he's written jointly with Andrew Sweeting (and in one case also with Jimmy Roberts) continuing relationships that started when he was an undergraduate. Their 2014 *RAND* paper on auctions with costly entry is

particularly impressive. It considers situations in which bidders who want to enter an auction, e.g. a procurement auction to choose that the firm that will be chosen to repave a road or repair a bridge, incur substantial costs of preparing their bids. It provides some theoretical results comparing a traditional auction with unregulated entry with an alternate mechanism in which the government uses a preliminary auction to choose a limited number of firms who will be allowed to bid and then only invites the winner of this initial round to provide full bids. It has some interesting results on the relative merits of the two mechanisms and then a nice empirical section examining a particular set of procurement contests (for bridge repairs in Texas and Oklahoma) which indicates that they indeed seem to constitute an environment where entry-rights auction would increase welfare. My understanding from Andrew is that Vivek played a big role in all aspects of the project.

Vivek has a second published paper (this one just with Andrew) on auctions with selective entry which is also very nicely done. I also very much like his working paper with a couple of his graduate school classmates which develops a very creative model of incentive provision and cooperation when agents are afraid that others may be able to manipulate the signals on which payments are to be based. The paper begins with a two-player single-period model in which the players' actions generate a random signal on which exogenously given payoffs are based, but each player may with some probability be presented with an opportunity to change the signal to another nature-selected signal. Players are uncertain about the distribution of opportunities and the order in which the opportunities are presented and are ambiguity averse. In the two period model, the main result of interest in a linearity theorem noting that there must be an alignment of payoffs across the players in any equilibrium. They then extend the model so that the exogenous payoffs of the initial static game are instead continuation payoffs from a longer game and provide a number of interesting and impressive observations about what is and is not possible and how it is affected by the uncertainty. I don't know how much theory Vivek will do going forward, but he is a first rate theorist who can do creative technically demanding work.

While I've spent a long time discussing the papers Vivek is an attractive candidate on many other dimensions. He's a very mature and very nice guy who will take any job he's asked to do very seriously. I was fortunate enough to have him as a TA in my graduate industrial organization class and took advantage both by having him do much more than I usually would ask a TA to do, including giving him a lot of latitude to put together problem sets and having him pick out and lead discussions of recent papers with students instead of just going over problem sets in the recitations. He is unassuming in presenting his own work and might benefit from more enthusiasm in his presentations, but my students really appreciated the mastery of the material and his caring for the students that comes through very clearly. He should do very well in teaching from day one regardless of where he ends up: he'd do well in a top Ph.D. program; undergraduates will like him; and he should do fine with MBA teaching. He is very thoughtful and will contribute a lot to the day-to-day life of any department.

Overall, I'd like to give Vivek my strongest recommendation. He'd be a great person to add to an existing group. He's also sufficiently mature, broad, and independent to take care of himself and help out students in a program that finds itself shorthanded in the field. He has a tremendous skill set, a very impressive job market paper, and is sufficiently dedicated that I can't imagine that he won't have a very successful career. He definitely belongs in a top five department or business school and I'll be surprised if doesn't end up on this year's *Review of Economic Studies* tour.

If you have any questions at all please feel free to contact me.

Sincerely,



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November 13, 2016

Dear Junior Faculty Recruiting Committee:

I am writing to recommend **VIVEK BHATTACHARYA** for a junior faculty position in your Department or School. I have known Vivek since he sat in on my second-year graduate industrial organization course in his third year (it was my first year teaching IO at MIT). Since then he has worked as a TA for me in that course, and I have come to be on his thesis committee.

Vivek is an industrial organization economist with a very strong set of empirical and theoretical skills, a very sharp and deep mind, and a good dose of creativity. To put things simply, I think that every top Economics Department and Business School should interview, and if they can, hire Vivek. He is in an equivalence class with other top students of mine over the years who have gotten offers at top 5 Economics Departments or Business Schools (such as Aviv Nevo, Ilan Kremer, Jakub Kastl, Ben Handel, and Kei Kawai). And he is in the small top group of students in this year's MIT class.

My advising of Vivek has largely centered around his job market paper, "An Empirical Model of R&D Procurement Contests: An Analysis of the DOD SBIR Program." I think this is a tremendously interesting and creative paper, that is unlike anything that I've seen before analyzing R&D empirically.

In it, Vivek studies the DoD's Small Business Procurement Program (SBIR). This program has a highly structured three phase procurement process that lends itself well to structural analysis. As well, a good deal of information is available on which firms entered these contests, which succeeded in moving on to the next phase, the research awards/spending at each stage, and the final procurement contract that resulted (if any).

Vivek constructs a theoretical model of this process, and brings it to this data to estimate the model's structural parameters. In the model, which is tightly motivated by the actual structure of these contests, firms first exert effort in Phase I to develop an idea that may generate value for the DoD. Then, if selected to continue to Phase II, they conduct research into lowering costs. Finally, in Phase III firms who competed in Phase II may bargain with the DoD over procurement of their products, at most one of which the DoD will buy. Vivek shows how the model is identified given his data (including a very nice discussion of how much of the model can be identified with very weak assumptions on how Phase II research levels are determined), and then uses the model to estimate its key parameters: the Phase I and II R&D technologies (specifically, the cost of achieving a Phase I success, the distribution of Phase I values, and the relation between realized costs and Phase II research expenditures), and the DoD's bargaining power in Phase III.

Using the estimated parameters, Vivek is able to examine welfare issues and the outcomes of various counterfactual contest designs. He first examines whether R&D efforts in the DoD's actual process are excessive or insufficient, and the welfare costs of this inefficiency. He finds that Phase II efforts are too low from a social perspective because of the hold-up problem caused by having to bargain with the DoD in Phase III. To my knowledge, this is the *first* estimate in the literature of the cost of hold up. Phase I research efforts, in contrast, are too high both because of a business stealing effect (each firm is trying to be chosen for Phase II) and the fact that the DoD ends up covering firms' research expenses – a factor that is very specific to this setting. Overall, the current design results in a significant reduction in welfare compared to the first best.

He then considers the effects of a number of counterfactuals. First, he examines whether welfare would be greater if the number of firms allowed in Phase I or Phase II were different (and also unpacks how much of these welfare changes are due to changes in R&D caused by the incentive effects of facing more or fewer rivals). Second, he studies how welfare would be affected by changes in the bargaining power of the DoD. Reductions in the DoD's bargaining power would reduce the hold up problem, thereby increasing Phase II efficiency, but worsen the over-investment in Phase I as the firms anticipate greater returns from success. Put together, the latter effect dominates, and some increase in DoD bargaining power would raise welfare. Third, he investigates how sharing of intellectual property (i.e., giving the best Phase I design to all Phase II firms) would affect welfare.

After doing all of this, he contrasts these results with the effects these changes would have on the DoD. While the DoD's objective is not entirely clear, Vivek shows convincingly that changes that would raise welfare often lower the DoD's payoff.

All together, I think this a terrific paper. It is creative, well-executed, and focuses on the tremendously important issue of R&D in a new way. At a broad level, it successfully delivers measures of the effects of hold up and competition on R&D incentives, while on a narrower level it offers specific proscriptions for the DoD's procurement process.

Vivek also has a number of other papers. Two are published papers done when he was an undergaduate at Duke that are joint with faculty members. Obviously, not many undergraduates end up being coauthors on projects of this sort. He also has a working paper on games with imperfect public monitoring that I am less familiar with. Its focus is on cases in which there is uncertainty about rivals' ability to distort the public signal and players are ambiguity averse. One interesting result from an IO perspective is that this can provide a reason why less transparency can make collusion easier (my colleague Alex Wolitzky has a recent paper showing this from a different perspective).

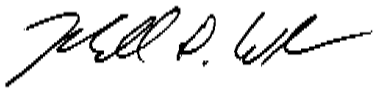
At a personal level, Vivek is a pleasure to interact with. He is thoughtful, kind, and public-spirited. He is also a terrific person to have in a seminar or reading group (he is a regular attendee at the structural reading group I have been running this term and regularly offers excellent insights on the papers we are

discussing). I have not seen him teach, but his seminars are very clear, so I think he would also do well in a business school environment.

In sum, I strongly urge you to interview Vivek, then fly him out, and then try to hire him.

I hope this is helpful.

Sincerely,



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November 3, 2016

Letter of Recommendation for Vivek Bhattacharya (CONFIDENTIAL)

To whom it may concern:

It is my pleasure to very strongly recommend Vivek Bhattacharya for a position as an assistant professor or researcher. All departments, business schools and policy schools, including the **very best**, should seriously consider his application.

Vivek has been working with me since he was a second-year student, first as a research assistant, and then on his thesis. To get to the bottom-line right away, in my opinion, he is amongst the best students graduating from MIT across all fields in the last few years, and the top student studying IO at MIT since I joined the department.

Vivek's job market paper studies the design of a multi-stage procurement contest for a new product. Like many other R&D settings, the contest involves research, development and production phases. Although research effort is socially valuable, duplication of effort by various firms within the contest is socially wasteful. The design of the contest in terms of the level of competition or the reward structure influences firms' incentives to exert effort at the various phases. There is a significant theoretical literature that studies various models of such contests, but empirical work that quantifies the value and cost of research, and firms' responses to incentives created by the design of the contest is essentially non-existent.

Vivek fills this gap by developing a new empirical model of procurement contests, showing that it is non-parametrically identified, proposing a new tractable estimation procedure and applying it to study the design of a Department of Defense procurement program. Aside from a very thorough analysis of this new empirical model, each of the steps requires significant technical and empirical innovation. The modelling exercise requires a command over the theoretical literature and ingenuity in mapping the theory to the data. His non-parametric identification argument is intuitive and combines ideas from the auctions literature and selection models. The estimation procedure is clever, and does not rely on a full solution brute-force approach. Collecting data on a new empirical setting and analyzing an important government program is in itself a contribution that requires initiative and entrepreneurship. Most of all, this effort pays of in a series of interesting design experiments, on the effects of competition and rewards structure on the social surplus generated by these contests.

Although the details are somewhat involved and tailored to the specific setting, the basic empirical approach should be adaptable to other procurement settings for new products. The key requirement is that the researcher has information on expenses incurred during the development phase and observes the final payments made to the winning firm. Vivek uses the expenses to learn about the value of the project, on the basis of the simple and intuitive assumption that firms with higher value ideas are more likely to expend effort to lower costs. This assumption also holds the key to how he is able to develop a tractable estimator for his model. He then embeds the probability of success and value of the contract amounts awarded into a selection model, where a contract is awarded only if the value of a firm's product exceeds the costs. These two intuitive and likely general features of the model are at the core of his empirical strategy for inferring research costs, and the distribution of values.

Vivek uses these estimates to study the optimal design of such procurement contests, and evaluates the procurer's incentives to distort the design of the contest. The differences between private and social incentives for innovation has important implications for economic growth, and there is little structural empirical work quantifying the incentive effects of competition and rewards to this end. This part of his paper demonstrates the ability of the model to answer a variety of economically relevant questions, and quantify several different economic forces. For example, it can be used to separately quantify business stealing effects, incentives for exerting more research effort, and holdup by the winning firm. These strengths of the model will make it a strong base for investigating related questions in other settings.

As in most ambitious projects that involve developing and estimating a new empirical model, Vivek had to carefully consider various alternative approaches and constantly weigh their pros and cons. Vivek persevered at improving every single aspect of the paper, and is still bothered by features that is less than 100% satisfactory. This desire to achieve the best possible product and a keen awareness of the limitations of his research will be a great asset during his career as an academic.

In addition to having a great job market paper, Vivek has been extremely productive ever since he was an undergraduate student. He has two published papers on auctions that he started working on while he was at Duke. His co-authors, Jimmy Roberts and Andrew Sweeting, tell me that, even as an undergraduate, Vivek wasn't the "typical" research assistant and instead make substantial intellectual contributions to the paper. Specifically, Andrew wrote to me saying, "From the very beginning, when he was a junior, Vivek was much more than a RA. He could take even the barest prototype of a procedure/idea and almost magically turn it into something that worked quickly, accurately and on a grand scale. What was more he was great at seeing the economic trade-offs involved, and understanding what was going to be true and what was not. This was probably clearest to me when we were revising the RAND paper, and the referees had identified that the formulation we'd initially used for the counterfactual would not necessarily have the monotonic bid functions that we'd been assuming. Even before we'd really discussed it,

Vivek had pretty much completely analyzed the problem and thought through the viability of possible solutions to it (we ended up going with the all-pay auction), and started thinking about how the changes could affect the counterfactual numbers. Simultaneously he was balancing lots of projects at MIT, and he has an amazing capacity to leap back into what he was doing 9 months or a year ago almost at a click of a button." I can attest to a similar experience while Vivek worked on one of my projects with Paulo Somaini.

In addition to his job market paper, Vivek has several other completed papers. I find it particularly impressive that two are theory papers, one of which is R&R at the Journal of Economic Theory. Yet two others are published IO papers that study entry models in auctions. This portfolio demonstrates his rather large skill set and exceptional productivity.

He is currently continuing his research agenda on contests for new products with a new project that studies a dynamic innovation contest in which a procurer provides regular feedback to firms on their products in the form of a score. An important question here is whether to make the score public, as it might motivate greater effort by some firms. However, it may also discourage other firms that are far behind, with possible equilibrium effects spilling over to the leaders. Public scores also have interesting effects on the leading firm. It may become complacent or work harder depending on whether or not the closest competitors are lagging far behind.

As you can tell, I think very highly of Vivek, and believe that he will be an invaluable asset for any department. In addition to his exceptional abilities, his humility and willingness to help others will make him a fantastic colleague and teacher.

Sincerely



Nikhil Agarwal