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COORDINATION, DUPLICATION OF EFFORTS, AND THE ROLE OF PUBLIC INFORMATION IN R&D

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This note provides a simple example that additional information made available to competing researchers in an R&D laboratory might decrease the overall probability of discovery, i.e. harm social welfare. If agents have only vague prior information on which project is more likely to succeed, the probability that the discovery is made is higher than in the case when the agents are provided with some noisy public signal. Thus, a laboratory principal might strategically choose to withheld some information from the subordinate researchers. If one researcher in a laboratory chooses a research portfolio first, she might strategically opt for some inferior projects in order to avoid excessive competition by other fellow researchers.

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В работе рассматриваются стратегические аспекты раскрытия информации в исследовательском коллективе. В некоторых ситуациях дополнительная информация может привести к неэффективному дублированию усилий нескольких исследователей; в этом случае у руководителя коллектива возникают стимулы к скрытию информации, даже если она помогает увеличить вероятность совершения открытия. Если сотрудники выбирают себе проекты последовательно, желание избежать конкуренции может привести к выбору заведомо менее перспективных направлений исследования.

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1 Introduction[1]

How should a principal researcher provide information to her subordinates? Should a regulator force revelation of information for R&D rivals? Is that a possible that the full disclosure of all available information lead to inefficiency? More precisely, when a principal needs to find a specific solution, is he better-off providing his uninformed lieutenants with all the available (and relevant) information? This note gives a simple example of a situation, where the presence of public information diminishes the social welfare as compared to the case where agents rely on their (common) prior only.

The stylized example runs as follows. There are several agents, either researchers within a laboratory or firms competing in an R&D contest, that seek for a treasure, which is equally valuable for each of the agents. For the principal and the society as a whole it does not matter which particular agent finds the diamond. The decision each agent has to make is where he is going to search for the treasure, and the area he can search is exogenously bounded (alternatively, there is a cost of searching each piece). If the treasure is located in the area searched by some agent, he necessarily finds it. If two or more agents find the treasure, they share it equally. If agents know that it is equally probable to find the treasure in any point, their search areas would never intersect provided that the forest is large enough. Now, suppose that there is a principal that receives a noisy signal about the location of the treasure. What happens if he communicates this information to the agents? The search areas will necessarily intersect around the area of the most probable location. Then the total area searched diminishes as compared with the case of no information, and thus the treasure is found with a smaller probability.

Though the R&D literature is vast, the literature on duplication of efforts is considerably smaller (see Chatterjee and Evans, 2004, for a selective review), and issues related both to optimal allocation of efforts within teams and to public information revelation remain largely unexplored. While specific details about allocation of efforts inside research laboratories are rarely available, a lot more could be said about inter-industry competition. Chatterjee and Evans (2004) provide a number of real-world examples, where duplication of efforts lead to competitors losing their profits because of almost-simultaneous discoveries. Most famous examples include the Lockheed and Boeing race to developing a four-engine turbojet in 1950s, Lockheed and Douglas competition for the first of a wide-bodied three-engined jet airliner in 1960s which ended up in a draw bringing losses to both parties, and parallel inventions in by Casio and Texas Instruments of the first electronic microcalculator in 1970s.

A specific feature of our model is that competitors do not have any private information. While private information plays an important role in R&D (Hopenhayn and Squintani,

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2004, Fershtman and Rubinstein, 1997), we show that some welfare effects may be obtained with public information only. There are both theoretical and empirical argument that public information might be harmful for efficiency as it might be detrimental to private information (e.g., Morris and Shin, 2002). E.g., in information cascade (herding) literature, where new information might discourage agents to undertake some socially valuable actions (Banerjee, 1992, Birchandani, Hirshleifer, and Welch, 1992). Our perspective is different: with herding, agents learn from each other's (or their predecessors) behavior, while in our model a certain action by one agent only discourages others to do the same. Indeed, the fact that some agents search in a specific area makes this area less attractive for any other agent. Also, there is no private information to ignore: in our model, public information is bad for social welfare without making any impact on agents private information. This provides intuition contrary to that of Morris and Shin (2002), where in the absence of private information more precise public information is always social-welfare enhancing.

Our first result mirrors that of Bhattacharya and Mookherjee (1986), in which each of the firms has access to two research projects (in our setup, there is infinitely many "projects"), each of which is a single draw from a random variable which depends on each firm's choice. As in this model, in our paper the social optimum and the non-cooperative solutions coincide when the degree of specialization is at maximum: the search areas of agents do not intersect. However, in contrast to Bhattacharya and Mookherjee (1986), the inefficiency due to duplication of efforts does not require risk aversion neither on society's, nor on firms' part. In a similar setup, Dasgupta and Maskin (1987) conclude that when firms are as far away from each other as possible, the social optimum might be achieved, while too much correlation brings up social inefficiency. Thus, firms might opt for a more risky project than the social planner world (see also Klette and de Meza, 1986). In Fershtman and Rubinstein (1997), two players face several boxes, one and only one of which contains a prize, but the focus of the paper is different as players do not observe search efforts of each other.

The rest of the paper is organized as follows. Section 2 contains the setup, while Section 3 contains the analysis of the case when there are two competitors. Section 4 lists some more general results and discusses robustness. Section 5 concludes.

2 Setup

The total area is a continuum $[0,1]$. The treasure might be found at any point $\theta \in [0,1]$ with equal probability (i.e. the distribution is uniform). Knowing this, each of N identical agents chooses some area (collection of points) $A_i \subset [0,1]$. For the sake of simplicity, we start by assuming that sets A_i are finite sums of (connected) open intervals; thus, they are Lebesgue-measurable; $|A|$ denotes the Lebesgue measure of set A. The agent i's utility is equal to $\frac{1}{\#\{j|\theta\in A_j\}}$, with $1>0$, if $\widehat{\theta} \in A_i$ i.e. the true location of the treasure is in i's search area, and

0 otherwise. The social welfare is equal to 1 if the treasure is found, and 0 otherwise: in an R&D context, the identity of researcher that made the breakthrough is irrelevant for social efficiency.

There is a cost $c(\cdot)$ associated with the search process. We start with considering a one-step cost function: for each agent i, $c(A_i) = 0$ if the search area has Lebesgue measure $|A_i| \leq \frac{1}{N}$, and $c(A_i) = \infty$, if $|A_i| > \frac{1}{N}$. In the robustness discussion, we consider the linear cost function: the total cost born by i is $c(A_i) = c|A_i|$, where $c > 0$. Finally, we prove some results for a general cost function $c(|A_i|)$.

We are interested in Nash equilibria, so each agents chooses A_i to maximize his expected utility taking others' choices as given. First, we describe what happens if agents have no additional information; that is, the only information they use is their prior knowledge that the treasure is distributed uniformly. Then we turn to the situation, where agents are provided with some additional information about the location of the treasure. Specifically, we assume that there is a coin flipped with probability of heads equal to $\widehat{\theta}$ (the true location of the treasure), and the result of the coin flip is announced to the agents. This provides agents with valuable information: e.g., if heads, their posterior probability density function is equal to

$$p(\theta|Heads) = 2\theta.(*) \tag{1}$$

When $N = 2$, we say that the interval $(0, 1)$ can be divided into a finite number of $0-, 1-, ..., k-$intervals, searched by $0, 1, ..., k$ players, respectively. Whenever we use the (A_i, A_j) notation, we assume that $i \neq j$, and denote $\widetilde{A}_i = A_i \setminus A_{12}$.

3 Analysis

We start with analyzing the situation when the two competing researchers do not have any information besides their priors. If there is an intersection $A_i \cap A_j$ such that $|A_i \cap A_j| > 0$, then there is some uncovered area B of the total length at least $|A_i \cap A_j|$. Agent i's expected utility strictly increases if he chooses to search B instead of $A_i \cap A_j$,which implies that $|A_i \cap A_j| = 0$ in any equilibrium. An immediate corollary is that the treasure is found with probability 1 as the search areas cover the whole forest. Formally, we have the following trivial proposition.

(i) Any partition of $[0, 1]$ such that each of search areas A_i has total length $\frac{1}{2}$ and sets A_i do not intersect is a Nash equilibrium. Any Nash equilibrium has these properties.

(ii) In any Nash equilibrium, the treasure is found with probability 1. The social welfare, measured as the expected total value of the treasure to its finders is equal to 1.

Since *ex ante* probabilities of Tails and Heads are equal, we concentrate on the case when the coin flip is Heads. With this *ex post* information available to the agents, the gain from searching a 2−interval (a, b) is

$$\int_a^b 2\theta d\,(\theta/2) = (b-a)\frac{b+a}{2},$$

i.e. the length of the interval (a, b) multiplied by the coordinate of its center. The similar gain from searching a 1−interval is twice this amount. So it is better to switch from 1−interval $(a, a+d)$ to 2−interval $(b, b+d)$ if the center of the former interval is at least twice as far from 0 than the center of the latter interval. Similarly, a player would switch from a 2−interval to a 0−interval if there is the inverse relation between the centers.

Any equilibrium $\pi = (A_1, A_2)$ must be of the form $A_{12} = (a, 1)$, $A_1 \cup A_2 = (1-a, 1)$. Indeed, if there is a 2−interval left to a 1−interval covered by player 1, then player 2 will better switch to the right interval. Now, strategy profile $\pi = (A_1, A_2)$ is a Nash equilibrium if and only if for any $0 < x, y < 1$ and $\varepsilon > 0$, the following two conditions hold. First,

$$If 2x \leq y,\ then (x-\varepsilon, x) \subset \widetilde{A}_i\ yieldsthat (y-\varepsilon, y) \subset A_i = \widetilde{A}_i \cup A_{12}.I \tag{2}$$

Indeed, if $2x \leq y$, then for the centers of these intervals we have $2(x-\varepsilon/2) < (y-\varepsilon/2)$. If $(y-\varepsilon, y) \subset \widetilde{A}_j$ then player i will benefit from switching from a 1-interval with center x to a 2−interval with center y.

The second equilibrium condition is that

$$If 2x \geq y,\ then (y, y+\varepsilon) \subset A_{12}\ yieldsthat (x, x+\varepsilon) \subset A_1 \cup A_2.II \tag{3}$$

Indeed, $2(x+\varepsilon/2) > (y+\varepsilon/2)$. Therefore, if an interval with center x is empty, then player 1 would benefit from switching from a 2−interval with center y interval to a 1-interval with center x. Conversely, if strategy profile π satisfies the two conditions, then π is an equilibrium.

Next, for any equilibrium $\pi = (A_1, A_2)$ with $A_{12} = (a, 1)$, a cannot be less than $\frac{2}{3}$. The $\frac{2}{3}$ threshold is a solution to the condition $x = 2(1-x)$, which equates the marginal utilities of searching an additional 1−interval to the left of $1-a$ or 2−interval. If $a < 2/3$, then $1-a > 1/3$ and we obtain a contradiction with (II) for $x = 1/3$, $y = 2/3$ and sufficiently small $\varepsilon > 0$.

If $a = 2/3$, then $1-a = 1/3$ and any partition of interval $(1/2, 2/3)$ into sets B_1 and B_2 such that $|B_1| = |B_1| = \frac{1}{6}$ produces a strategy π with $A_i = A_{12} \cup B_i, i = 1, 2$, and $A_{12} = (\frac{1}{3}, \frac{2}{3})$. It is easy to see that such a strategy satisfies conditions (I) and (II).

If $a > 2/3$ then $1-a < \frac{1}{3} < a/2$ and for sufficiently small $\varepsilon > 0$, there is an interval $(a-\varepsilon, a) \subset \widetilde{A}_i$ for $i = 1$ or 2. Let $i = 1$. We claim that then $(1-a, a/2) \subset \widetilde{A}_1$. Otherwise there is an interval $(x-\varepsilon, x) \in \widetilde{A}_2$ with $x \leq a/2$. Then $2x \leq a$ and by (I), for interval $(a-\varepsilon, a) \subset A_2$, which contradicts our assumption that $(a-\varepsilon, a) \subset \widetilde{A}_1$.

Now, let us show that inclusion $(1-a, a/2) \subset \widetilde{A}_1$ implies that $(2-2a, a) \subset \widetilde{A}_1$. This follows from (I) for $x \in (1-a, a/2)$ and $y \geq 2x$. Thus

$$\widetilde{A}_1 = (1-a, a/2) \cup B_1 \cup (2-2a, a),$$

where $B_1 \subset B(a) = (a/2, 2-2a)$, and $\widetilde{A}_2 = B_2$, where $B_1 \cup B_2 = B(a)$. Since $|A_2| = 1/2 = 1 - a + |B_2|$ and $|B_2| \leq |B(a)|$, we obtain a lower bound on $|B(a)|$, namely that

$$|B(a)| = 2 - 2a - a/2 \geq 1/2 - (1-a)$$

or $a \leq 5/7$. Thus any equilibrium is (non-uniquely) characterized by a, $2/3 \leq a \leq 5/7$. In particular, this implies that $3/14 \leq |B(a)| \leq 1/3$.

Now note that for such a any partition of $B(a) = B_1 \cup B_2$ such that $|B_2| = a - 1/2$ and $|B_1| = |B(a)| - |B_2| = 5/2 - 7a/2$ satisfies all conditions of the claim and thus defines an equilibrium described in Proposition 3.

With additional information revealed, there is no Nash equilibrium where agents cover the whole area, i.e. some of the search areas necessarily intersect. Consequently, in any equilibrium, the treasure is found with the probability less than 1, and the social welfare is strictly less than 1. Of course, a larger intersection area implies less social efficiency.

The following Proposition formally summarizes the above discussion.

Suppose that a public signal $(*)$ is available. Then a*ny equilibrium is of the following form:* $A_{12} = (a, 1)$, $\widetilde{A}_i = (1-a, a/2) \cup B_1 \cup (2-2a, a)$, $A_j^0 = B_2$, *where* $2/3 \leq a \leq 5/7$, *and* (B_1, B_2) *is any partition of the interval* $B(a) = (a/2, 2-2a)$ *such that* $|B_2| = a - 1/2$, $|B_1| = 5/2 - 7a/2$. *For such* a, $1 - a \leq \frac{1}{3} \leq a/2 < \frac{1}{2} < 2 - 2a \leq \frac{2}{3}a < 1$, *where the equality is possible if and only if* $a = \frac{2}{3}$.In any such equilibrium, the probability that the treasure is found is equal to $1-a$ and the social welfare is $1-a$.

3.0.1 The Strategic Advantage

Above, we assumed that the agents choose their search areas simultaneously. In practice, it is often not the case: one of the players might have the first-mover advantage. If player 1 has a possibility to choose the search area before the other player makes his choice, player 1 can exploit his advantage by choosing the equilibrium that provides him with the the highest expected utility. (It is straightforward that any equilibrium in the sequence game is an equilibrium of the simultaneous-move game.) As above, we analyze the situation when it is publicly revealed that the public signal is Heads.

Given the general description of equilibria in Proposition 3, player 1 chooses parameter a, which defines the following combination of intervals: the 2−interval $(a, 1)$, and two single intervals: $\left(1-a, \frac{a}{2}\right)$ and $\left(\frac{3}{2}a - \frac{1}{2}, a\right)$. Therefore, given a, the maximum utility of player 1 (i.e. the one that corresponds to the optimal choice in the 1−interval zone) is as follows.

$$u_A = \frac{1}{4}\left(-10a^2 + 14a - 3\right),$$

which is maximized by choosing $a = \frac{7}{10}$.

There are two "strategic preemption" effects: the first is the familiar first-mover advantage. Player 1 takes interval $\left(\frac{3}{2}a - \frac{1}{2}, a\right)$. The second one is less familiar: to avoid excessive competition, player 1 strategically chooses to pursue $\left(1 - a, \frac{a}{2}\right)$ rather than $\left(\frac{1}{2}, a\right)$.Otherwise, player 1 would have forced player 2 to intersect too much – bringing down both players' payoffs and social efficiency.

3.0.2 Many agents

With $N \geq 3$ players searching, one might potentially have $0-$, $1-$, $2-$, and so on, k-intervals, $k = 1, 2, ..., N$ and, conditional on the Heads coin flip, any interval where k players are searching will be to the left of an interval where more than k players search. If $J \subset \{1, 2, ..., N\}$, then denote $A_J = \cap_{i \in J} A_i$ and $\widetilde{A}_J = A_J \cap_{j \notin J} \overline{A}_j$, where $\overline{A}$ is a complement of A in $[0, 1]$. Now the above claim can be generalized as follows.

The assumption that $|A_i| = \frac{1}{N}$ implies that $a_2 - a_1 + 2(a_3 - a_2) + 3(a_4 - a_3) + ...N(1 - a_N) = 1$ or

$$a_1 + a_2 + ... + a_N = N - 1. \tag{4}$$

Extending the proof of Proposition 3 to the case $N \geq 3$, one can establish the following proposition.

A strategy profile $\pi = (A_1, A_2, ..., A_N), N \geq 2$ *is an equilibrium if and only if there are points* $0 < a_1 \leq a_2 \leq .. \leq a_{N-1} \leq a_N \leq 1 = a_{N+1}$ *such that* $(a_k, a_{k+1}) = \cup_J \widetilde{A}_J$ *with* $|J| = k, k = 1, 2, ..., N,$ *and for any* $0 < x, y < 1,$ *integers* k *and* m, $1 \leq k < m \leq N$ *and* $\varepsilon > 0$ *the following conditions hold*

(Ia) if $mx \leq ky$ *then* $(x - \varepsilon, x) \subset \widetilde{A}_K$ *with* $|K| = k$ *implies that* $(y - \varepsilon, y) \subset \widetilde{A}_M$ *for* M such that $K \subset M$ or $|M| \geq m$.

(IIa) if $mx \geq ky$ *then* $(y, y + \varepsilon) \subset \widetilde{A}_M$, $|M| = m$ *implies that* $(x, x + \varepsilon) \subset \widetilde{A}_K$ such that $|J| \geq k$.

This Proposition allows to show that, for our particular assumption about the information structure (the posterior distribution function), $3-$ and higher-order intervals are impossible when $N \geq 3$, i.e. $a_k = 1$ for $k = 3, ..., N$. If $a_N < 1$ then condition (Ia) applied to $y = a_N, m = N$,and $x = a_k, k = 1, 2, ..., N - 1$, and sufficiently small ε, yields that

$$a_1 \leq \frac{a_N}{N}, a_2 \leq \frac{2a_N}{N}, a_{N-1} \leq \frac{(N-1)a_N}{N}. \tag{5}$$

Combining (3) and (4) we obtain that

$$N - 1 = \sum_{i=1}^{N} a_i \leq a_N(1 + 2 + ... + N)/N = a_N(N + 1)/2,$$

which in turn yields that $a_N \geq 2(N-1)/(N+1)$. This is impossible when $N \geq 3$ and $a_N < 1$. Therefore $a_N = 1$. Similarly, all $a_i = 1$ for $i \geq 3$.

3.0.3 Robustness

It is tempting to think that the main result above (disclosure of relevant public information might decrease social welfare) is due to some exotic assumptions. However, the results seem to be pretty robust. Instead of being a finite sum of open intervals, one might require that each A_i is Lebesgue-measurable. Furthermore, the search areas might be not only multi-dimensional, but probably infinite-dimensional. For the length requirement, which does not allow agents in the model to search more than $1/N$, a general setup would assume some cost of search, increasing with the area. In these terms, the assumption made means that the cost is 0 if the length of search area A_i is smaller than $1/N$, and ∞ otherwise. Within a more general setup, it becomes possible that even when without additional information search areas of different agents might intersect, but social efficiency is still decreasing with public information for a generic set of parameters. There is also nothing special in the noisy signal structure (the current one is taken for expositional simplicity).

Still, the one-step cost function assumption ($c(A_i) = 0$ if $|A_i| \leq \frac{1}{N}$, and $c(A_i) = \infty$ if $|A_i| > \frac{1}{N}$) is responsible for the multiplicity of equilibria in Proposition 1. With the linear cost function, $c(A_i) = c|A_i|$, the intersection zone $(a, 1]$ is defined uniquely. In this case, each agent compares marginal cost of searching an additional area, c, with the probability of finding a diamond. For any $k \geq 0$, define $M_k = \{\theta | kc \leq f(\theta) < (k+1)c\}$. Now the above discussion can be summarized as follows. As above, we describe the equilibrium strategies conditional on the event that the coin flip is Heads. The other case is fully symmetric.

Let $f(\theta) = p(\theta|Heads)$ be any p.d.f., and $c(A_i) = c|A_i|$, $i \in N$.

(i) There is a unique Nash equilibrium.

(ii) If $N = 2$, then the intersection of two agents' search areas is defined as $\{\theta | f(\theta) \geq 2c\}$ and the area $\{\theta | c < f(\theta) < 2c\}$ is searched by one of the two agents.

(iii) For any N, $M_k = \{\theta | kc \leq f(\theta) < (k+1)c\}$ is the area searched by exactly k agents, $1 \leq k \leq N-1$. The area $\{\theta | f(\theta) \geq Nc\}$ is searched by all N agents.

As in the case of one-step cost function, now suppose that agents make their choice in turn, with no restriction on how big his preferred search area is. Again, the equilibrium structure allows for less variation. In the unique equilibrium, the first player to make choice opts for the area $[0,1] \backslash M_0$, the second chooses $[0,1] \backslash (M_1 \cup M_0)$, the k^{th} chooses $[0,1] \backslash (M_1 \cup M_0 \cup ... \cup M_k)$.

4 Conclusion

In this paper, we developed a theory of searching a treasure in a forest. If agents have only vague prior information about the location of the treasure, the probability that the treasure will be found is higher than in the case when the agents are provided with some noisy (but informative) public signal about the location. One possible explanation is that for social welfare, it is the vagueness of priors that matters, while public information forces agents to coordinate (though they dislike coordination). One possible implication is that a principal (e.g., in an R&D context) might strategically choose to withheld some information from agents he sends to find the treasure.

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Notes