Mechanism Design for Task Delegation to Agents with Private Ordering Preferences

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Abstract—A principal selects a group of agents to execute a collection of tasks according to a specified order. Agents, however, have their own individual ordering preferences according to which they wish to execute the tasks. There is information asymmetry since each of these ordering preferences is private knowledge for the individual agent. The private nature of the priorities of the individual agents (adverse selection) leads to the effort expended by the agents to change from the initial preferred priority to the realized one to also be hidden as well (moral hazard). We design a mechanism for selecting agents and incentivizing the selected agents to realize a priority sequence for executing the tasks that achieves socially optimal performance in the system, i.e., maximizes collective utility of the agents and the principal. Our proposed mechanism consists of two parts. First the principal runs an auction to select some agents to allocate the tasks, based on the ordering preference they bid. Each task is allocated to one agent. Then, the principal rewards the agents according to the realized order with which the tasks were performed. We show that the proposed mechanism is individually rational and incentive compatible. Further, it is also socially optimal under linear cost of ordering preference modification by the agents.

I. INTRODUCTION

When you ask people to perform tasks for you, they often prefer to perform them in an order that is different than you would prefer. Is there a way to jointly choose and incentivize people to behave in the order you would prefer? This is the problem considered herein.

Consider a setting in which a system operator hires some agents selected from several possible agents to execute a group of tasks. The operator has a quality of service (QoS) constraint that implies a desired order in which the tasks should be executed. The agents, however, may prioritize task execution in a different order depending on their own private preferences; executing tasks in a different order than preferred may impose a cost on the agents. Such misalignment of the preferred order of execution among the principal and the agents, especially with information asymmetry, creates performance inefficiency from the principal’s viewpoint. Minimizing this inefficiency requires the principal to devise an appropriate mechanism to select the agents and incentivize them to shift their preferred priority order for executing the tasks.

Such a mechanism design problem arises in many situations. For instance, in a cloud computing application, users request a Cloud Computing Service Provider (CCSP) to perform a job. The CCSP then allocates the tasks among the servers. If tasks come in at a high rate and the number of servers is limited, the tasks may form a task queue [2]–[4]. In this case, the CCSP may have a preferred order in which the tasks are executed based on QoS guarantees it has promised to the users. However, if the servers are independent entities providing service for a fee, they may follow a different order of performing the tasks. This misalignment can cause the CCSP to violate the QoS guarantees it has promised, and hence, degrade system performance. Thus, the CCSP may wish to incentivize the servers to follow the requested order.

As another instance, employees of an organization may perform tasks (such as responding to emails in technical support) that are assigned to them in a different order than the one that is desired by the organization. Since the rate at which humans can respond to emails is limited, emails pile up [5], [6]. People generally do not respond to emails in the received order, but act on them based on their priorities [7]–[10] which may be based on factors that are both intrinsic (e.g., interest, curiosity, or information gaps) and extrinsic (e.g., incentives provided by the organization). Thus, the organization must incentivize employees to respond to tasks according to the order preferred by the organization [11].

In this paper, we design a contract through which the principal (the system operator) asks the agents about their private priorities and incentivizes them to shift their priorities in a way that is individually rational for the agent and socially optimal. Specifically, since the agents incur a cost to change their order from their private preferences, the principal must provide enough incentives so rational agents will shift their order to align with the principal. We consider two task allocation scenarios: (i) indivisible array of tasks for which only one agent is selected to perform all tasks, and (ii) divisible array of tasks which can be allocated to multiple agents. We treat the former as a static (single stage) contract design problem and the latter as a dynamic (multiple stage) contract design problem.

Note that for divisible arrays of tasks, the priority sequence of each agent can vary depending on the allocation history. That is, the priority of an agent for a task in the future may change if the agent receives a task at the current stage.

The primary challenge in the design of the contract arises from the hidden nature of the priorities of the agents who are...
free to misreport them. Thus, a simple compensation scheme based on self-reported priority will not be sufficient as the agents can misreport their private priorities. The private nature of the agents’ priorities further implies the cost they incur to change from their preferred order to the realized one is also hidden. That is, there is both hidden information and hidden action for the principal. These difficulties are often referred to as adverse selection and moral hazard, respectively (Chapter 14C and 14B), (13), (14). Further, the principal can only observe the order realized by agents selected for performing the tasks. Thus, she does not have a way to verify preferences for the other agents. This adds to the complexity of the problem. Our goal is to design a contract which resolves these issues and incentivizes the agents to incur sufficient cost to realize an order that optimizes social welfare.

The setting we consider proceeds as follows: Agent selection by the principal, task performance by the agent, and compensation to the agent. We assume that for each task, first, the principal selects the agent to whom to allocate the task using the priorities self-reported by the agents. Next, the agent performs the task with a realized order, incurring a cost for any deviation from preferred order. Finally, the principal compensates the selected agent using the realized order so as to achieve social optimality.

Our solution relies on formulating as a two-step contract design problem for each task: (i) task allocation by the principal to select the right agents to perform the tasks, and then (ii) compensation to the agents to execute the tasks in a desired order. We propose a VCG-based mechanism for the first step in which the agents announce their private priorities to the principal and the principal selects the agent to whom to assign tasks. The payment structure in the second step limits misreporting by the agents at the first step. In the second step, we design a compensation scheme based on the observed order realized by the selected agent and the initially declared priority orders by the agents. In this two-step design, the agents bid (possibly falsified) priorities in the first step and the selected agent optimizes the realized order to perform tasks in the second step. The principal designs the auction in the first step and the compensation in the second step.

The model considered herein is inspired by (15), which presents a queueing-theoretic study of task allocation. However, unlike (15), we do not consider the realized order as a given and fixed function of the priority of the principal and interests of the agent, but as a design parameter for the agent to maximize his own utility. Although there is a vast literature on multi-agent task scheduling literature (see, e.g., (11), (16–19)), prior work does not consider either information asymmetry between the agents and the principal or the design of incentives. To the best of our knowledge, this paper is the first work to adopt a game-theoretic approach to analyzing priority misalignments between task senders and task receivers with both moral hazard as well as adverse selection.

VCG mechanisms have long been used for incentive design in the case of hidden information in principal-agent problems (Chapter 23), (20) Chapter 5). In particular, VCG mechanisms are used to incentivize agents to reveal their true private information and to guarantee the efficient (socially optimal) outcome in dominant strategies (21)–(24). The VCG mechanism deals with adverse selection only, not moral hazard. Thus, a VCG-based mechanism is effective only for the first step of our problem when we select the agents (based on their declared private information) to perform the tasks under adverse selection, but not for the second step when hidden effort is also present. How VCG may interact with the second step of compensating hidden effort is, a priori unclear. Further, notice the notion of social welfare that VCG maximizes is only the sum of utilities of the agents. Here as part of the social welfare, we also include utility of the principal, which is a function of hidden effort.

Our main contribution is a game-theoretic approach to the problem of task allocation and priority realization when there is information asymmetry and possibility of misreporting private information by the agents. Since there is both hidden information and action, it differs from pure adverse selection or pure moral hazard. We propose a VCG-based mechanism followed by an incentivization method for the problem. We show that under the proposed scheme, agents act truthfully in reporting their preferred order as a dominant strategy. Moreover, the principal can achieve the socially optimal outcome and guarantee individual rationality and incentive compatibility, through the proposed mechanism.

The rest of the paper is organized as follows. Section II presents the problem statement and some preliminaries. Section III proposes and analyzes our incentive mechanism for the task delegation problem. Section IV concludes by presenting potential directions for future work.

II. Model

Consider a group of $I+1$ decision makers. Decision maker 0 is the principal, who is interested in a sequence of tasks being performed in a particular order. Decision makers $i = 1, \ldots, I$ are agents with their own private priorities for performing the tasks $\{t\}$. The principal must incentivize the agents to perform the tasks in the desired order.

The principal seeks to delegate $K$ tasks, denoted $t_k = t_1, \ldots, t_K$, to the self-interested agents. We suppose all decision makers have an associated preference order for executing tasks. Let $X = [x_1, \ldots, x_K] \in \mathbb{Z}^+$ represent the priority (order) based on which the principal desires the tasks to be executed where $x_k$ is the priority for executing the $k$th task. Formally, if the principal desires task $t_k$ to be performed in $m$th priority order, we set $x_k = m$. For example, if the principal would like task $t_3$ to be performed first, we set $x_3 = 1$. We call $X$ the priority of the principal. Similarly, let $Y_i = [y_{i1}, \ldots, y_{iK}] \in \mathbb{Z}^+$ represent the priority of $i$th agent to perform the tasks, where $y_{ik}$ is the priority of the $i$th agent for fulfilling the task $t_k$. Formally, if agent $i$ prefers to perform task $t_k$ in order (time) $m$, $y_{ik} = m$. We call $Y_i$ the priority of the $i$th agent. The vector $X$ is public knowledge whereas the vector $Y_i$ is private knowledge to the $i$th agent. The principal wishes agents to prioritize tasks according to $X$. Agent $i$, on the other hand, has his own set of

1 We will henceforth use she/her for the principal, and he/his for agents.
2 $\mathbb{Z}^+$ is the set of positive integers.
interests and naturally prioritizes tasks according to $Y$, if not incentivized otherwise.

The principal selects the agents and incentivizes them to execute the tasks in an order as close to $X$ as possible. Given the incentive, if the $i$th agent is selected to execute task $t_k$, let $z_{ik}$ be the realized order of execution for task $t_k$. Similarly, $Z = [z_{11}, \ldots, z_{ik}]$ represents the realized order for all tasks. Further, denote by $h(y_{ik}, z_{ik})$ the cost for agent $i$ to change his performance from $y_{ik}$ to $z_{ik}$. That is, when an agent with priority $y_{ik}$ is selected and he performs the tasks with order $z_{ik}$, he incurs the cost $h(y_{ik}, z_{ik})$. In the following we illustrate the definition through an example.

**Example 1.** Consider a setting as described above with 4 tasks and one agent. We assume the priority of the principal is $X = [1, 2, 3, 4]$, i.e., she prefers task $t_1$ to be performed first, task $t_2$ second, task $t_3$ third, and task $t_4$ last. Further, we assume the agent would prefer to perform task $t_2$ first, then task $t_1$, then task $t_4$, and finally task $t_3$. Thus, we can write $Y$ as $Y = [2, 1, 4, 3]$. Without any incentive, the agent follows his own priority $Y$ to perform the tasks, i.e., $Z = Y$. Suppose that the principal offers an incentive to the agent to change his priority to better align with hers. If the incentive is provided by the principal to the agent, suppose the agent performs the tasks with the following realized order $Z = [1, 2, 4, 3]$. In the presence of a (proper) incentive, the realized order $Z$ better matches the priority of principal $X$ compared to the initial priority $Y$.

If agent $i$ is selected to perform task $t_k$, the order in which the task was actually executed $z_{ik}$ is observed by the principal. Note that the priority modification by the agent $i$ enhances the performance of the organization and leads to profit $S(x_k, z_{ik})$ for the principal. Contrarily, if $i$ is not selected, neither $Y_i$ nor $Z_i$ is observable for that agent, since the agent is not assigned any task to realize the priority $Z_i$.

Since the principal does not have access to the priorities of the agents’ $Y_i$ values, these variables are not contractible. In fact, if the principal asks about the $Y_i$ vectors, the agents can misreport them as $Y_i'$ to try and exploit the incentive mechanism for more benefit, where $Y_i' = [y_{i1}', \ldots, y_{ik}']$ and $y_{ik}'$ is the reported priority of the $i$th agent to fulfill task $t_k$.

For simplicity, we define the misalignment between various priorities for task $t_k$ as a scalar, which is the absolute value of their difference, cf. Spearman’s footrule that has strong robustness properties with respect to any notion of distance among rankings and is equivalent to the other popular notion of distance, Kendall’s tau [25].

**Definition 1.** Let the misalignments between the various priority for task $t_k$ be

$$
\theta_{ik} = |x_k - y_{ik}|, \quad \theta'_{ik} = |x_k - y'_{ik}|, \quad \gamma_{ik} = |x_k - z_{ik}|,
$$

where $\theta_{ik}$ and $\gamma_{ik}$ denote the initial priority misalignment and the realized priority misalignment between the agent $i$ and the principal respectively. Further, $\theta'_{ik}$ is the priority misalignment declared by the agent initially.

**Assumption 1.** We assume that the cost $h(y_{ik}, z_{ik})$ is a function of the misalignments $|x_k - y_{ik}|$ and $|x_k - z_{ik}|$. Further the profit $S(x_k, z_{ik})$ is a function of the misalignment $|x_k - z_{ik}|$.

In the sequel, we abuse notation and denote the cost as $h(\theta_{ik}, \gamma_{ik})$ and the profit of the principal as $S(\gamma_{ik})$.

**Assumption 2.** We assume that for a given $\gamma_{ik}$, $h(\theta_{ik}, \gamma_{ik})$ is an increasing function of $\theta_{ik}$, so agent $i$ incurs a higher cost when modifying a larger initial misalignment with the principal. Further, we assume $S(\cdot)$ is a decreasing function, so the principal’s profit decreases as the realized misalignment increases.

Again, let us emphasize that we assume $\theta_{ik}$ is private information for agent $i$ and thus can be misreported as $\theta'_{ik}$, whereas $\gamma_{ik}$ is observable to the principal.

The timeline of the problem is as follows. Suppose that at each step one task is allocated to an agent for execution, i.e., task $t_k$ is allocated at time/stage $k$. For each task $t_k$, the principal first receives the (possibly false) reported misalignment $\theta'_{ik}, \ldots, \theta'_{ik}$ of all agents and she chooses an agent $w_{ik}$ based on an as yet undetermined mechanism. The principal then observes the realized misalignment of the agent $\gamma_{i, k}$ and pays every agent $i$ an amount equal to $P_{ik}(\theta'_{ik}, \ldots, \theta'_{ik}, \gamma_{ik})$. The mechanism to choose the agent as well as the payment are committed ex ante.

The utilities of the various decision makers are as follows. Suppose agent $w_{ik}$ is selected to execute task $t_k$. Then, the utility $U_{ik}$ of the $i$th agent at stage $k$ is:

$$
U_{ik} = \begin{cases}
    P_{ik}(\theta'_{ik}, \ldots, \theta'_{ik}, \gamma_{ik}) - h(\theta_{ik}, \gamma_{ik}), & i = w_{ik} \\
    P_{ik}(\theta'_{ik}, \ldots, \theta'_{ik}, \gamma_{ik}), & i \neq w_{ik},
\end{cases}
$$

The utility of the principal at stage $k$ is:

$$
V_k = S(\gamma_{ik}) - \sum_{i=1}^{I} P_{ik}(\theta'_{ik}, \ldots, \theta'_{ik}, \gamma_{ik}).
$$

and the total utility of the agent and the principal over all the stages (tasks) is $U_i = \sum_{k=1}^{K} U_{ik}$ and $V = \sum_{k=1}^{K} V_k$, where $K$ is the number of tasks.

We are interested, in particular, in mechanisms that are socially optimal (efficient). An incentive mechanism is socially optimal if the decision makers choose to realize an outcome that maximizes the social welfare:

$$
\Pi = V + \sum_{i=1}^{I} U_i.
$$

The problem faced by each agent $i$ is to optimize the choice of reported misalignment $\theta' = \{\theta'_{ik}, \ldots, \theta'_{ik}\}$ instead of $\theta = \{\theta_{1k}, \ldots, \theta_{ik}\}$, and if chosen to perform the task $t_k$, the choice of realized priority $\gamma_{ik}$, to maximize his utility (subject to the principal’s choices). The problem faced by the principal is to choose the agent $w_{ik}$ for each task $t_k$ to execute the task and to design the payment $P_{ik}$ to optimize the social welfare (subject to the choices of the agents). Thus, the design problem is:

$$
\mathcal{P}_1: \begin{cases}
    \{w_{ik}, P_{ik}\} = \arg \max_{\theta_i'} \Pi \\
    \text{subject to } \theta'^{*} = \arg \max_{i} U_i, \forall i \\
    \gamma_{ik} = \arg \max_{i} U_i, \quad i = w_{ik}.
\end{cases}
$$

additional constraints
We consider the following two additional constraints in $\mathcal{P}_1$.

(i) **Individual Rationality (IR):** This participation constraint implies that under the incentive mechanism

\[ V \geq 0, \quad U_{ik} \geq 0 \text{ for all } i,k. \]

Informally, the principal and the agents, acting rationally, prefer to participate in the proposed contract rather than opting out. This constraint limits the space of contracts by, e.g., precluding contracts based only on penalties.

(ii) **Incentive Compatibility (IC):** A payment or a contract is incentive compatible if agents submit their hidden information truthfully if asked. Specifically, this constraint implies that the utility of an agent does not increase if they report $\theta'_i \neq \theta_i$; i.e., for any $i$:

\[ U_i(\theta_1, \ldots, \theta_{i-1}, \theta'_i, \theta_{i+1}, \ldots, \theta_I) \leq U_i(\theta_1, \ldots, \theta_{i-1}, \theta_i, \theta_{i+1}, \ldots, \theta_I). \]

We make the following two further assumptions.

**Assumption 3.** If agent $i$ is selected, the realized misalignment by the agent is always less than or equal to the initial misalignment, i.e., $\gamma_k \leq \theta_k$. That is, the agent does not gain any benefit by increasing his misalignment with the principal.

Given this assumption, the principal can restrict the falsification by the agents in reporting their priorities through an appropriate payment function. Note that $\theta_i$ is not observable to the principal even if agent $i$ is selected to execute the tasks. Thus, the principal must instead rely on $\theta'_i$ for the payment scheme. However, the principal may pay an agent only if $\gamma \leq \theta'_i$ to restrict falsification by the agent. We assume such a payment scheme is used and the agents behave as follows.

**Assumption 4.** Agent $i$, if selected for task $t_k$, chooses $\gamma_{ik}$ and $\theta'_{ik}$ such that $\gamma_{ik} \leq \theta'_{ik}$.

Going forward, we consider two specific scenarios.

(i) **Indivisible array of tasks:** All tasks must be executed by one agent. In this case, the principal optimally chooses one agent to execute the array of tasks $[t_1, \ldots, t_K]$ and then compensates the agent for any misalignment cost incurred. This implies a single-stage game.

(ii) **Divisible array of tasks:** Tasks can be allocated to multiple agents over multiple stages. In each stage $k$, the principal chooses an agent to perform task $t_k$, then compensates the agent for any priority modification. Within the divisible array setting, we consider two possibilities: either agents’ private priorities are fixed or they dynamically become more aligned with the principal as they perform tasks for her.

The choice of the agent(s) to execute tasks is challenging since the payment function is committed *ex ante*.

### III. MAIN RESULTS

We propose a mechanism in which, for each task, first an agent is selected to execute the task through an auction mechanism and then payments are made according to the reported and realized priorities.

#### A. Central difficulties

The hidden nature of the preferred priorities and the cost creates hidden information (adverse selection) in the first stage and hidden action (moral hazard) in the second stage. Requiring individual rationality and incentive compatibility significantly constrains the design of each of these steps. For instance, at the first stage, an auction which asks the agents to report their priorities and chooses the agents with the least reported priority misalignment will not be incentive compatible since it provides an opportunity for the agents to announce a priority close to that of the principal to be selected.

Similarly, consider a payment scheme in which the agent $w_k$ that is selected to execute the task $t_k$ which depends merely on the reported misalignment $\theta'_w$ regardless of the realized priority $z_{w,k}$ (or equivalently $\gamma_w$) and ignores the effort cost. Given $\theta_{w,k}$, this payment limits the range of realized priority such that

\[ h(\theta_{w,k}, \gamma_{w,k}) \leq P(\theta'_{w,k}). \]

There is no *a priori* guarantee that the resulting priority $z_{w,k}$ (or equivalently $\gamma_{w,k}$) will be socially optimal. On the other hand, a payment that is merely a function of the realized priority $\gamma_{w,k}$ and ignores the self-reported priorities may also be too restrictive. In particular, individual rationality will once again constrain $z_{w,k}$ (or equivalently $\gamma_{w,k}$) so that given $\theta_{w,k}$,

\[ h(\theta_{w,k}, \gamma_{w,k}) \leq P(\gamma_{w,k}). \]

Finally, we note that even if the payment depends on both $\theta'_w$ and $\gamma_w$ to account for the effort cost properly and satisfy individual rationality, the payment must still be carefully designed to ensure incentive compatibility. Thus, a payment function $P(\theta_{w,k}, \gamma_{w,k})$ that depends on the level of effort cost that the agent claims that he incurred for priority modification provides the opportunity for the agents to behave strategically. For instance, under such a payment, a strategic agent may choose not to exert any effort and choose

\[ \gamma_{w,k} = \theta_{w,k}, \quad \theta'_{w,k} = \max_{\theta'} P(\theta', \gamma_{w,k}). \]

Thus, this payment is not incentive compatible since although the strategic agent does not change his priority, he obtains a non-zero payment.

To illustrate the concept, Sec. [III-B](#) starts with an indivisible array of tasks, which considers task delegation to single agent. Sec. [III-C](#) then considers task delegation with multiple agents.

#### B. Mechanism for indivisible array of tasks

We design a mechanism which has desired properties of individual rationality, incentive compatibility, and under further assumptions, social optimality. This mechanism first selects an agent to execute the tasks and then compensates him. Note that not all tasks are allocated in one stage and a single agent is chosen to perform $[t_1, \ldots, t_K]$. Thus, for notational ease, we drop the subscripts $k$ corresponding to each individual task.

The value of $\theta_i$, $\theta'_i$, and $\gamma_i$ then are:

\[ \theta_i = \sum_{k=1}^{K} \theta_{ik}, \quad \theta'_i = \sum_{k=1}^{K} \theta'_{ik}, \quad \gamma_i = \sum_{k=1}^{K} \gamma_{ik}. \]
Fig. 1 demonstrates the timeline of the problem as follows:

1. **Agents submit their preference vectors** $Y_i$’s (equivalently, the variables $\theta_i$’s). However, they can misreport the vectors as $Y_i'$’s (equivalently as $\theta_i'$’s).
2. The principal chooses an agent as the winner of the auction. Assume that agent $w$ is the winner and must execute tasks in the next step.
3. Agent $w$ performs the task with a realized order $Z_w$, choosing the variable $\gamma_w$ and incurring the corresponding cost $h(\theta_w, \gamma_w)$.
4. Agent $w$ receives a payment.

We now present our proposed mechanism $\mathcal{M}$.

(i) **Allocation:** The principal chooses the agent $w$ to execute all the tasks such that $w = \arg\min\{\theta_i'\}_{i=1}^M$.

(ii) **Payment:** The payment to agent $w$ is chosen as a function of $\gamma_w$ and the second lowest bid

$$\bar{\theta} = \min\{\theta'_1, \ldots, \theta'_{w-1}, \theta'_w, \ldots, \theta'_M\}.$$

Specifically, we consider a payment $P_w(\bar{\theta}, \gamma_w)$ to agent $w$ which satisfies two properties:

$$\begin{align*}
\forall \gamma_w, & \text{ if } \theta_w \geq \bar{\theta}, \text{ we have } P_w(\bar{\theta}, \gamma_w) \leq h(\theta_w, \gamma_w), \quad (4) \\
\exists \gamma_w & \text{ s.t. if } \theta_w < \bar{\theta}, \text{ we have } P_w(\bar{\theta}, \gamma_w) > h(\theta_w, \gamma_w). \quad (5)
\end{align*}$$

All other agents $i \neq w$ are not paid.

Remark 1. Notice the conditions in (4) and (5) are essential for inducing incentive compatibility. An example of a payment scheme which satisfies this condition for the cost function $h(\theta_w, \gamma_w) = \theta_w - \gamma_w$ is of the form $P_w(\bar{\theta}, \gamma_w) = \bar{\theta} - \gamma_w$.

Under mechanism $\mathcal{M}$, the utilities of the agents are:

$$U_i = \begin{cases} 
P_i(\bar{\theta}, \gamma_w) - h(\theta_i, \gamma_i), & i = w \\ 0, & i \neq w, \end{cases}$$

while the principal’s utility and social welfare are:

$$V = S(\gamma_w) - P_w(\bar{\theta}, \gamma_w), \quad \Pi = S(\gamma_w) - h(\theta_w, \gamma_w). \quad (7)$$

Indeed, mechanism $\mathcal{M}$ is incentive compatible and individually rational.

**Theorem 1.** Consider problem $\mathcal{P}_1$. Mechanism $\mathcal{M}$ is incentive compatible, i.e., every agent $i$ reports $\theta_i' = \theta_i$. Further, it satisfies the individual rationality constraint.

Proof. See Appendix.

Remark 2. The proposed mechanism resembles the celebrated VCG mechanism in the way it selects $w$ and in the structure of the proposed payment. However, beyond the fact that the payment depends on the additional parameter $\gamma_w$, note that the standard solution of offering a payment of the form $S(\gamma_w) - \Pi^*$, where $\Pi^*$ denotes the value of the social welfare under the socially optimal outcome, will not result in the agent $w$ realizing the socially optimal outcome in our case. This payment violates (4) and (5) and therefore violates incentive compatibility.

Although social optimality is difficult to achieve for a general form of the cost, it can be achieved for the case of linear cost, i.e., when $h(\theta_i, \gamma) = \theta_i - \gamma$.

**Theorem 2.** Consider problem $\mathcal{P}_1$ with mechanism $\mathcal{M}$. If the cost is linear and the payment is of the form $P_w = \bar{\theta} - \gamma_w$, then $\mathcal{M}$ solves $\mathcal{P}_1$. Specifically, the mechanism realizes the socially optimal outcome as well as truth-telling by the agents and individual rationality.

Proof. See Appendix.

C. **Mechanism for divisible array of task**

Consider task allocation with a divisible array of tasks to be allocated to multiple agents. We design a task delegation mechanism that has the desired properties of individual rationality, incentive compatibility, and social optimality by generalizing the one-winner mechanism in Sec. III-B for indivisible array of tasks. First, tasks are allocated to the agents, through an auction for each task, run by the principal. After task allocation to the agents, the agents perform the tasks with certain realized order and then are compensated by the principal for misalignment. Recall the timeline of the problem:

1. **Agents are asked to submit their preferred priority for task $t_k$, i.e., $\theta_{ik}$. However, they can misreport the value as $\theta_{ik}'$.**
2. The principal chooses an agent as the winner of the auction based on the proposed mechanism. Assume that the agent with index $w_k$ is the winner of task $t_k$ and must execute task $t_k$.
3. **Agent $w_k$ performs the task with a realized order by choosing $\gamma_{wk}$ and incurring the corresponding cost $h(\theta_{wk}, \gamma_{wk})$.**
4. The agents receive a payment based on the proposed mechanism.

We consider two scenarios for which we discuss the design of allocation and incentive mechanism:

(i) **Fixed private information:** Private information $\theta_{ik}$ for realizing $\gamma_{ik}$ for each task $t_k$ does not depend on task allocation history, i.e., the private information $\theta_{ik}$ for each task $t_k$ and each agent $i$ is fixed (ex ante) regardless of whether the agent has been allocated another task or not.

(ii) **Dynamic private information:** Private information of the agent $i$, $\theta_{ik}$, for each task depends on the history of...
for each task. The proof is similar to proof of Theorem 2, repeated.

1) Fixed private information: In this case, private information of agent \( i \), \( \theta_i \), is independent of allocation history. Thus, the proposed mechanism in this case is the repeated (as many times as the number of tasks) version of the mechanism in Sec. III-B. This yields mechanism \( \mathcal{A}_1 \).

(i) Allocation: For task \( t_k \), the principal chooses the agent \( w_k \) to execute the task \( t_k \) such that \( w_k = \arg\min_i \{ \theta_i \}_{i=1}^t \).

(ii) Payment: The payment to agent \( w_k \) is chosen as a function of \( \gamma_{w_k} \) and the second lowest bid

\[
\hat{\theta}_{w_k} = \min\{ \theta'_1, \ldots, \theta'_{(w-1)k}, \theta'_{(w+1)k}, \ldots, \theta'_t \}.
\]

Specifically, we consider a payment \( P_{w_k}(\hat{\theta}_{w_k}, \gamma_{w_k}) \) to agent \( w_k \) which satisfies two properties for each task \( t_k \):

\[
\forall \gamma_{w_k}, \text{ if } \theta_{w_k} \geq \hat{\theta}_{w_k}, \text{ then } P_{w_k}(\hat{\theta}_{w_k}, \gamma_{w_k}) \leq h(\theta_{w_k}, \gamma_{w_k}),
\]

\[
\exists \gamma_{w_k} \text{ s.t if } \theta_{w_k} < \hat{\theta}_{w_k}, \text{ then } P_{w_k}(\hat{\theta}_{w_k}, \gamma_{w_k}) > h(\theta_{w_k}, \gamma_{w_k}).
\]

All other agents \( i \neq w_k \) are not paid.

Under mechanism \( \mathcal{A}_1 \), the utilities of the agents are:

\[
U_{ik} = \begin{cases} 
P_{ik}(\hat{\theta}_{ik}, \gamma_{ik}) - h(\theta_{ik}, \gamma_{ik}), & i = w_k, \\
0, & i \neq w_k,
\end{cases}
\]

and the total utility of the agent over all stages (tasks) is \( U_i = \sum_k U_{ik} \), where \( K \) is the number of tasks.

**Theorem 3.** Mechanism \( \mathcal{A}_1 \) is incentive compatible and it satisfies the individual rationality constraint.

**Proof.** The proof is similar to proof of Theorem 1 repeated for each task \( t_k \).

**Theorem 4.** If the effort cost is linear and the payment is chosen to be of the form \( P_{w_k} = \hat{\theta}_{w_k} - \gamma_{w_k} \), then mechanism \( \mathcal{A}_1 \) solves \( \mathcal{P}_1 \) and the mechanism realizes the socially optimal outcome as well as truth-telling by the agents and individual rationality.

**Proof.** The proof is similar to proof of Theorem 2 repeated for each task \( t_k \).

Here, the strategy chosen by the agents for each task \( t_k \), i.e., reporting \( \theta'_k \), is independent of the strategy chosen for other tasks. Further, whether reporting \( \theta'_k \) occurs a priori or at each stage makes no difference and we can achieve incentive compatibility for this framework.

2) Dynamic private information: In this case, agent \( i \)’s private information, \( \theta_i \), depends on the history of task allocation. Hence, the fact that the agent receives a task in the past can change his priority misalignment for future tasks. In particular, we assume a Markov property for \( \theta_i \) so \( \theta_k \) depends on whether task \( t_{k-1} \) has been allocated to the agent.

**Assumption 5.** We assume that if agent \( i \) wins the task at time \( k-1 \), his priority misalignment for task \( k \) is \( \hat{\theta}_k \). Otherwise, his priority misalignment is \( \hat{\theta}_k \), i.e.,

\[
\theta_k = \begin{cases} 
\hat{\theta}_k, & \text{if allocated task } t_{k-1}, \\
\hat{\theta}_k, & \text{otherwise},
\end{cases}
\]

where \( \hat{\theta}_k < \hat{\theta}_k \).

The general case in which the priority misalignment for task \( t_k \) depends on entire allocation history increases the problem complexity significantly and is left for future work.

For the sake of simplicity in the following we proceed with the linear effort cost.

**Assumption 6.** We assume effort cost to be linear, i.e., given \( \theta_k \) and \( \gamma_k \) the effort cost is \( h(\theta_k, \gamma_k) = \theta_k - \gamma_k \).

Note that unlike the fixed private information setting where misreporting of private information by the agents at a given stage did not change utilities of future stages, here the strategy chosen by the agents at the first stage affects utilities of further stages. To illustrate, we start with two tasks and two agents, explaining why we can not use the previous mechanism in the dynamic private information setting.

**Example 2.** Consider two tasks for two agents and suppose we follow mechanism \( \mathcal{A}_1 \). Let us assume the allocation is such that agent 1 receives the task in the second stage. In this case at the first stage even if \( \theta_{11} > \theta_{12} \), agent 1 can still claim that \( \theta_{11} < \theta_{12} \) and receive the task in the first stage since he might earn more benefit in stage 2 after receiving the task in the first stage. Thus, under mechanism \( \mathcal{A}_1 \), the agent will not be truthful in reporting his private information in the first stage if the utility he gains in the second stage is more than his loss \( \theta_{11} - \theta_{12} \) in the first stage, i.e., he falsifies \( \theta_{11} \) if

\[
\theta_{11} - \theta_{11} + \theta_{12} - \theta_{12} < \theta_{12} - \theta_{12}.
\]

Thus, mechanism \( \mathcal{A}_1 \) will not achieve incentive compatibility for the case of dynamic private information.

We now design mechanism \( \mathcal{A}_2 \) for the dynamic private information setting.

(i) Allocation: The principal chooses the agent \( w_k \) to execute the task \( t_k \) such that

\[
\begin{align*}
\theta'_{w_k} + \theta'_{w_k+1} &< \hat{\theta}_{w_k} + \theta'_{w_k+1}, & w_k \text{ allocated } t_{k+1}, \\
\theta'_{w_k} &< \hat{\theta}_{w_k}, & w_k \text{ not allocated } t_{k+1},
\end{align*}
\]

where \( \hat{\theta}_{w_k} \) represents the second lowest bid, i.e.,

\[
\hat{\theta}_{w_k} = \min\{ \theta'_1, \ldots, \theta'_{(w-1)k}, \theta'_{(w+1)k}, \ldots, \theta'_t \}.
\]

(ii) Payment: The payment to agent \( w_k \) is:

\[
P_{w_k} = \begin{cases} 
\hat{\theta}_{w_k} - \hat{\theta}_{w_k+1} + \hat{\theta}_{w_k+1}, & w_k \text{ allocated } t_{k+1}, \\
\hat{\theta}_{w_k}, & w_k \text{ not allocated } t_{k+1}.
\end{cases}
\]

All other agents \( i \neq w_k \) are not paid.

*Note that the principal chooses the agent at last stage \( w_K \) to execute the task \( t_k \) such that \( w_K = \arg\min_i \{ \theta'_i \}_{i=1}^t \).
**Theorem 5.** Consider problem $\mathcal{P}_1$ with mechanism $\mathcal{M}_2$. Under Assumption 6, mechanism $\mathcal{M}_2$ solves problem $\mathcal{P}_1$. Specifically, the mechanism realizes the socially optimal outcome as well as truth-telling by the agents and individual rationality.

\[ \text{Proof.} \] See Appendix.

**D. Discussion**

Mechanism design is challenging primarily since our problem exhibits both hidden information and hidden effort on the part of the agents without any recourse to verification. The combination of adverse selection and moral hazard creates a possibility of rich strategic behavior by the agents. Hence we needed to design both an auction and a compensation scheme.

If the problem were of either auction design or compensation design alone, standard mechanisms would have sufficed. Specifically, for auction design under adverse selection, incentive compatibility, individual rationality, and social optimality can be achieved by the VCG mechanism. Similarly, for compensation design to counteract pure moral hazard, social optimality and individual rationality can be realized through the standard contract of the form discussed in Remark 2.

However, in our problem, strategic agents can exploit information asymmetry to degrade the efficiency of the outcome under either of the standard solutions for auction design or compensation for moral hazard alone. Standard approaches cannot achieve both incentive compatibility and social optimality, similar in spirit to the so-called price of anarchy that captures the inefficiency in a system due to selfish/strategic behavior of agents.

The surprising result in Theorem 2 is that for linear effort cost, we realize all three properties of individual rationality, incentive compatibility, and social optimality even in this challenging setting. That this is possible was not \textit{a priori} obvious, and it would be interesting to identify further properties, such as budget balance, that may be achievable.

Impossibility results such as [26, 27] may seem contradictory to the goal of obtaining an efficient, individually rational, budget-balanced mechanism. It should be noted, however, that we are restricting attention to a specific class of valuation functions that are different from those studied there; hence, the existing impossibility results may not hold. Studying the existence of such behavior is left for future study.

**IV. Conclusion**

We studied the problem of contract design between a system operator and a group of agents that each have a preferred order with the one that is socially optimal. The principal selects agent(s) to execute the tasks and to compensate him to minimize the misalignment of the realized order with the one that is socially optimal. The problem features both moral hazard and adverse selection. We proposed a two-stage mechanism including a VCG-like mechanism for task allocation followed by a compensation mechanism. We showed that the mechanism is individually rational, incentive compatible, and for linear costs, socially optimal.

Future work will consider more general nonlinear cost functions; this is challenging since mechanisms may not necessarily be socially optimal and the agents might realize a suboptimal order of tasks. Other directions include considering the possibility of designing a mechanism that is also budget balanced in addition to being individually rational, incentive compatible, and socially optimal.

**APPENDIX**

**A. Proof of Theorem 1**

Given an arbitrary agent $i$, its hidden priority $\theta_i$, and the reported priority misalignment of the other players, we need to show that utility of agent $i$ is maximized by setting $\tilde{\theta}_i = \theta_i$. Note also that $\tilde{\theta}$ denotes the lowest misalignment reported by other agents. If $\theta_i > \tilde{\theta}$, then agent $i$ loses and receives utility $0$. If $\theta_i \leq \tilde{\theta}$, then agent $i$ wins the tasks and receives utility $P_i(\tilde{\theta}, \gamma) - h(\theta_i, \gamma)$ for performance of the task.

We consider two cases. First, if $\theta_i > \tilde{\theta}$, the highest utility that agent $i$ can gain for any value of $\gamma$ is:

$$\max\{0, P_i(\theta, \gamma) - h(\theta_i, \gamma)\}.$$

According to (4) and (5):

$$\max\{0, P_i(\tilde{\theta}, \gamma) - h(\theta_i, \gamma)\} = 0.$$

Thus, agent $i$ achieves this utility by bidding his priority truthfully (and losing the auction). Second, if $\theta_i \leq \tilde{\theta}$, the highest utility that agent $i$ can gain according to our mechanism is:

$$\max\{0, P_i(\theta, \gamma) - h(\theta_i, \gamma)\} = P_i(\tilde{\theta}, \gamma) - h(\theta_i, \gamma),$$

and agent $i$ achieves this utility by bidding his priority truthfully and winning the auction. Note that the utility of the agent for each case is always non-negative and therefore the mechanism satisfies individual rationality.

**B. Proof of Theorem 2**

First notice that according to Assumption 3 we can write the effort cost as $h(\theta_i, \gamma) = \theta_i - \gamma$.

We first prove that the proposed mechanism design induces truth-telling as a dominant strategy, i.e., it is incentive compatible. Similar to the proof of Theorem 1 we consider two cases. First, if $\theta_i > \tilde{\theta}$, the highest utility that agent $i$ can get is

$$\max\{0, P_i(\theta, \gamma) - h(\theta_i, \gamma)\}.$$

Given $P_i(\theta, \gamma) = \theta - \gamma$ and $h(\theta_i, \gamma) = \theta_i - \gamma$, the highest utility that agent $i$ can get if $\theta_i > \tilde{\theta}$ is

$$\max\{0, \theta_i - \gamma - (\theta_i - \gamma)\} = 0$$

and agent $i$ gains this utility by bidding truthfully and losing the auction. Second, if $\theta_i \leq \tilde{\theta}$, the highest utility that agent $i$ can get is

$$\max\{0, \theta - \gamma - (\theta_i - \gamma)\} = \tilde{\theta} - \theta_i.$$
and agent $i$ gains this utility by bidding his priority truthfully and winning the auction. Note that another approach to check incentive compatibility of $P_i$ is to see that $P_i$ satisfies (4) and (5).

To prove social optimality, we must check both task allocation by the principal as well as the fact that the selected agent realizes $\gamma^*$. First, for agent selection, note that the socially optimal outcome is obtained as

$$\arg \max S(\gamma^* - (\theta_w - \gamma^*)) .$$

Thus, for a given $\gamma^*$, agent $w$ must be chosen with minimum $\theta_w$, as chosen by the mechanism. Next, we show that the agents realizes $\gamma^*$ through this payment. The socially optimal outcome is obtained as

$$\gamma^*_w = \arg \max S(\gamma^*_w) - h(\theta_w, \gamma^*_w) .$$

On the other hand, given (11) and (12), the utilities of the agents are:

$$U_i(\theta, \tilde{\theta}) = \begin{cases} \tilde{\theta} - \theta_i, & i = w \\ 0, & i \neq w, \end{cases}$$

(13)

which do not depend on the values of $\gamma$. Thus, the agent is indifferent among his realized priorities and so the agents realize the socially optimal outcome $\gamma^*_w$.

Note that the utility of the agent in (13) for each case is always non-negative and therefore the proposed mechanism satisfies individual rationality. □

C. Proof of Theorem 3

We start with the truth-telling property. We prove that under mechanism $M_2$, each agent $i$ at each time $k$ receives the true value of the private information, i.e., $\theta^*_k = \theta_k$. We begin with the last stage $K$. If $\theta^*_k \leq \tilde{\theta}_k$, the highest utility agent $i$ can achieve is $\tilde{\theta}_k - \theta^*_k$, achieved by bidding his priority truthfully. If $\theta^*_k > \tilde{\theta}_k$, the highest utility agent $i$ can achieve is

$$\max \{ \tilde{\theta}_k - \theta^*_k, 0 \} = 0,$$

achieved by bidding his priority truthfully. Thus, agent $i$ is always truthful in reporting valuation for last stage $K$. Consider the penultimate stage $K-1$. Depending on the task allocation at stage $K$ and the value of $\theta^*_k$ and $\tilde{\theta}_k$, we consider four cases.

- If agent $i$ does not receive the task at $K$ and $\theta^*_{k-1} \leq \tilde{\theta}_{k-1}$, the highest utility agent $i$ can achieve is

$$\tilde{\theta}_{k-1} - \theta^*_k,$$

which can be achieved when bidding his priority truthfully.

- If agent $i$ receives the task at $K$ and $\theta^*_{k-1} + \tilde{\theta}_{k-1} \leq \tilde{\theta}_{k-1} + \tilde{\theta}_k$, the highest utility agent $i$ can achieve

$$\tilde{\theta}_{k-1} - \tilde{\theta}_k + \tilde{\theta}_k - \theta^*_k,$$

which can be achieved by bidding his priority truthfully.

- If agent $i$ does not receive the task at $K$ and $\theta^*_{k-1} > \tilde{\theta}_{k-1}$, the highest utility agent $i$ can achieve is

$$\max \{ \tilde{\theta}_{k-1} - \theta^*_{k-1}, 0 \} = 0,$$

which can be achieved by bidding his priority truthfully.

- If agent $i$ receives the task at $K$ and $\theta^*_{k-1} + \tilde{\theta}_{k-1} > \tilde{\theta}_{k-1} + \tilde{\theta}_k$, the highest utility agent $i$ can achieve is

$$\max \{ \tilde{\theta}_{k-1} - \tilde{\theta}_k + \tilde{\theta}_k - \theta^*_{k-1}, 0 \} = 0,$$

which can be achieved by bidding his priority truthfully. Thus, the agent $i$ is truthful in reporting his private information for stage $K-1$. Using backward induction, it follows that agent $i$ is always truthful in reporting valuation for any stage $k$, i.e., $\theta^*_k = \theta_k$. Note that the utility of each agent for stage $K$ is always non-negative and therefore the mechanism $M_2$ satisfies individual rationality for the agents.

Next, we prove social optimality of mechanism $M_2$. For the mechanism to be socially optimal note that both agent selection and compensation to the agents must be optimal. First note that the allocation that maximizes the social welfare is as follows: We start with the task allocation at last stage $K$ and then penultimate stage $K-1$ for a given realized priority misalignment $\gamma$. 

- If agent $i$ receives the tasks at stages $K-1$ and $K$, social welfare at stage $K-1$ looking forward is:

$$S - (\theta^*_{k-1} - \gamma) + S - (\tilde{\theta}_k - \gamma).$$

- If agent $i$ receives task at stage $K$ but not $K$, social welfare at stage $K-1$ looking forward is:

$$S - (\theta^*_{k-1} - \gamma) + S - (\tilde{\theta}_k - \gamma).$$

- If agent $i$ receives the task at stage $K-1$ but not $K$, social welfare at stage $K-1$ looking forward is:

$$S - (\theta^*_{k-1} - \gamma) + S - (\tilde{\theta}_k - \gamma).$$

Given different cases, to maximize social welfare, agent $i$ receives task at stage $K-1$ if

$$\begin{cases} \theta^*_{k-1} + \tilde{\theta}_k < \tilde{\theta}_{k-1} + \tilde{\theta}_k \quad & \text{if agent } i \text{ receives task } t_k \\
\theta^*_{k-1} < \tilde{\theta}_{k-1} \quad & \text{if agent } i \text{ does not receive } t_k \end{cases}$$

and agent $i$ receives task at stage $K$ if

$$\begin{cases} \tilde{\theta}_k < \tilde{\theta}_k \quad & \text{if agent } i \text{ receives task } t_{K-1} \\
\theta^*_k < \tilde{\theta}_k \quad & \text{if agent } i \text{ does not receive task } t_{K-1}. \end{cases}$$

i.e., $\theta^*_k < \tilde{\theta}_k$ regardless of the allocation at stage $K-1$. Using backward induction, the optimal allocation at each stage $k$ is when the principal chooses the agent $w_k$ to execute the task $t_k$ such that

$$\begin{cases} \theta^*_{w_k} + \tilde{\theta}_{w_k} < \tilde{\theta}_{w_k} + \tilde{\theta}_{w_k} \quad & w_k \text{ is allocated } t_{k+1} \\
\theta^*_{w_k} < \tilde{\theta}_{w_k} \quad & w_k \text{ is not allocated } t_{k+1} \end{cases}$$

Further, given that the agents are truthful in reporting their private information, the socially optimal mechanism is:

$$\begin{cases} \theta^*_{w_k} + \tilde{\theta}_{w_k} < \tilde{\theta}_{w_k} + \tilde{\theta}_{w_k} \quad & w_k \text{ is allocated } t_{k+1} \\
\theta^*_{w_k} < \tilde{\theta}_{w_k} \quad & w_k \text{ is not allocated } t_{k+1}. \end{cases}$$
So far we found the optimal allocation for maximizing social welfare. Now we find optimal order realization by agent $i$. First note that given the linear cost, social welfare at stage $k$ is:

$$S(\gamma_{wk}) - h(\theta_{wk}, \gamma_{wk}) = S(\gamma_{wk}) + \gamma_{wk} - \theta_{wk}$$

and the socially optimal outcome at each stage $k$ is obtained as

$$\gamma_{wk} = \arg\max S(\gamma_{wk}) + \gamma_{wk} - \theta_{wk}.$$ 

Next, we show that agent $w_k$ realizes $\gamma_{wk}$ through the mechanism.

To this end, note that the utility of agent $i$ at stage $k$ is:

$$U_i = \begin{cases} 
\hat{\theta}_{ik} - \tilde{\theta}_{ik}, & i = w_k, \text{ at stage } k - 1 \\
\hat{\theta}_{ik} - \theta_{ik}, & i = w_k, \text{ not at stage } k - 1 \\
0, & i \neq w_k,
\end{cases}$$

which does not depend on the value of $\gamma_i$. Thus, the agent is indifferent among his realized priorities and we conclude the agents realize the socially optimal outcome $\gamma_{wk}$.

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