Economic Coordination, Bundled Goods, and the Impact of Complementarities

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Abstract. The allocation of a set of resources to a set of agents is studied. The agents may express preferences for complementary use of goods. It is assumed that the agents are self-interested. A procedure to compute fair, competitive prices is suggested. The prices may be used to elicit honest preference. This allows to solve the allocation problem optimally in most cases. Finally, the applicability of the approach is discussed.

1 Introduction

The efficient allocation of resources is still a problem of significant practical relevance. The "virtualisation" of processes and companies; the increasing importance of integration along supply-chains[1]; company mergers resulting in distributed and often loosely coupled units–all call for efficient and controllable mechanisms to coordinate the interests of the participating agents. An important source of coordination requirements is the allocation of resources. Although related through a contractual framework, the agents in the examples above can be considered as being self-interested. Offering an incentive for the agents to participate in the allocation mechanism is an important goal. This may require that the mechanism be fair, transparent and that the result satisfies the agents with respect to their short-, mid-, and long-term goals. Ideally, the mechanism should also allow to fully exploit the potential of the resources, i.e. the allocation should be optimal with respect to a goal commonly acknowledged among the participating agent.

It is tempting to apply economic coordination mechanisms to tackle these allocation problems. Considering this has a long tradition in economics and a not-so-long history in computer science/AI, compare Section 4.

* This work is closely related to a cooperation with Prof. Adelsberger, U Essen. I also gained much insight from discussions with P. Wurman (some time ago), U of Ann Arbor and R. Krukis, Zeda GmbH. Thank you! Nevertheless, all errors are my own–and there will be some because the paper documents ongoing work.

[1] for both, tangible and intangible goods.

Unfortunately, most of the more realistic problems exhibit nasty properties, as for example the presence of complementarities. This type of allocation problems is not exceedingly well studied.

This paper suggests a procedure allowing to compute an allocation of goods to agents that is (mostly) optimal with respect to efficient use. Furthermore, it is fair and transparent and each participating agent will be satisfied with the result of the allocation. This is accomplished by introducing prices for allocated goods respectively combinations of allocated goods (bundles).

The paper will proceed as follows. We will briefly discuss the prerequisites of developing a coordination mechanisms for resources with complementary use. We will present a model of the allocation problem and an allocation mechanism solving it. We will discuss alternative pricing strategies. The final section will relate the suggestions made in this paper to recent research and it will discuss the opportunities and drawbacks of the proposed approach.

2 Developing an Economic Coordination Mechanism

The problem we want to solve can be described as follows: A *set of goods*, G, will be offered to a *set of agents*, A. Each agent has certain preferences for individual goods and for combinations of goods (*bundles*). We will assume that each agent is able to express his preference order in terms of a common and meaningful currency. Furthermore, the valued preferences are complete, i.e. there exist a valuation of each agent for each individual good and each bundle.

Let $G = \{g_k\}, k = 1, \cdots, M$ be a set of individual or "atomic" goods. The elements of G can be combined to a set B of $2^M - 1$ different bundles (excluding the empty bundle, $\emptyset$). Please, note that B includes "bundles" containing only one good. We can define an index mapping of the natural numbers between 1 and $2^M - 1$ to the bundles allowing us to uniquely identify each bundle.

Traditionally, the valuation of agent i for bundle j is given as h_{ij}.

To allow the easy identification of goods and agents, we will alternatively index the goods with characters (A,B, ...) and bundles with concatenations of characters (AB).

Each agent is able to express a number of relations between preferred goods:

Agent/Type	A	B	AB	Explanation
1	3	2	5	"Classical" additive valuation of a bundle
2	0	0	5	"Strictly synergetic" valuation of a bundle
3	3	2	7	"Synergetic" valuation of a bundle
4	3	2	4	Sub-additive valuation of a bundle
5	3	2	1	Negative synergistic effect of bundling
6	3	2	3	Potentially "exclusive" valuation of goods

Table 1. Examples for possible preference structures

The most commonly studied allocation problems are those in which the preference structure of each agent is limited to type 1 in which the consumption of goods is mutually independent. We will allow every type of preference structure with exception of type 5, that is we will assume that *free disposal* is always possible. This excludes negative valuations and guarantees that the valuation for a bundle is always at least as high as the maximum valuation for any of the sub-bundles.

The main goal of the design of a mechanism is to develop an instrument having at least the potential to be applicable in real-world settings. We assume that the agents are participating voluntarily and that a certain form of cooperation seems to promise an advantage to every agent. This may be valid for a number of consecutive allocations. We therefore assume that the success of a co-operation depends on the on-going commitment of the still widely autonomous participants. We will use a price-based mechanism to achieve this commitment. The coordination mechanism should have the following properties:

- **Optimal Allocation**: The resources should be utilised most efficiently[2], i.e. given a certain way to aggregate the utility of the participating agents, the chosen allocation should maximise this aggregated utility.
- **Individual Satisfaction with the Prices**: Given a set of prices for the bundles "on offer", each agent should want to buy the bundle that is assigned to it. This is the case if the surplus it obtains is as least as high as the surplus it may obtain from buying any of the other bundles on offer.
- **Fairness**: The mechanism ensures that the price an agents has to pay for a bundle reflects the utility of its competitors. This is especially relevant if the further use of the buyer's surplus affects the outcome of subsequent allocations.
- **Transparency**: The process of price determination and the following allocation should be comprehensible and observable. Ideally, the prices should allow the presentation of the bundles to be sold in a shop-like environment where agents may buy the bundles anonymously and the optimal allocation is established without further control or enforcement. Alternatively, the goods may be observably distributed to the "optimal" agents[3].

We will later see that the "local" goals price-satisfaction, transparency, and fairness and the "global" goal optimality are sometimes antagonistic. Keeping this in mind, we will now discuss a price-based allocation mechanism.

3 The Model

So far, we have formalised the agents, the bundles, and the agent's valuations for the bundles. The assumption are: Valuations are non-negative; the valuation

[2] This is the economic notion of efficiency.

[3] The shop solution requires the prices to be discriminating, i.e. only the "optimal" agent should want to buy its bundle. For the distribution solution, prices that leave agents not receiving a certain good in a state of indifference are sufficient. Prices in the shop solution need to be a small Δ higher than prices for the distribution solution.

for each bundle is at least as high as the maximum of the valuations of any sub-bundle.

We will assume for now that *the true valuations of all agents are known.* Each agent is able to pay a price for bundles up to his valuation. Our goal now is to determine a price vector supporting a solution with the wanted properties.

Prior to discussing this, we will formalise the properties (as far as this seems to be reasonable).

Optimality

An allocation is an assignment of bundles to agents. We assume that the bundling of individual goods does not imply a physical combination of the individual goods or any other implicit adding of value. Thus, we could as well study allocations of individual goods to agents.

An allocation l is a mapping of the goods G to the set of agents, A, and the null agent, $\perp$. Allocating a good to the null agent characterises the situation in which a good is not assigned to any agent in A.

The inverse relation $l^{-1} : A \cup \perp \longrightarrow B$ determines the bundle assigned to an agent. $l^{-1}(i)$ is defined as the bundle $b \in B$ with $b = \{g_j | l(g_j) = a_i\}$. l^{-1} can easily be extended to include the assignment of an empty bundle, $\emptyset$, to agents not receiving a good in l. We assume that l^{-1} has this property. To abbreviate the notation, we will write $b(i)$ instead of $l^{-1}(i)$. A bundle b is called an *assigned* bundle if and only if $\exists a_i \in A$ with $b(i) = b$. This excludes sub-bundles of an assigned bundle from being an assigned bundle.

The value of an assignment l will be written as $V(l)$. We define the value to be the sum of the individual valuations. It could as well be defined differently (e.g. weighted sum, product, etc.), though the sum is the most common and "natural" aggregation. Because "empty" bundles are assigned, we have to define the following: $h_{i\emptyset} = 0 \ \forall a_i \in A \cup \perp$ and $h_{\perp j} = 0 \ \forall g_j \in G \cup \emptyset$. This allows to define the value as

$$V(l) = \sum_{a_i \in A} h_{ib(i)} \quad (1)$$

Please note that precisely one bundle is assigned to each agent. Furthermore, each assigned non-empty bundle is free from an overlap with any other assigned bundle.

An allocation is optimal if there doesn't exist another possible allocation with a higher value. The set of all possible allocations, L, can be determined from enumerating all possible ways to allocate the individual goods in G to $A \cup \perp$. As the sets are finite, at least one optimal allocation l^* always exists and can be computed in finite time.[4] V^* will denote the maximum value for a given problem and it is defined as $V^* = V(l^*)$.

[4] A brief discussion of the complexity follows in the last section.

Individual Price Satisfaction

It is not so easy to define this property as clear cut as optimality. As we will see below, prices may or may not exist for certain goods or bundles. We will leave out some details of the formalisation.

Let l be an allocation. Let $B_v \subseteq B$ be the set of bundles for which prices are given. v is a mapping from B_v to non-negative real numbers, it determines the prices. We define an agent to be satisfied with the prices if his indidual surplus is as least as high as every other *possible* surplus. If $b(i)$ is in B_v, his individual surplus is given as

$$s_i = h_{ib(i)} - v(b(i)) \tag{2}$$

Otherwise, the surplus is undefined.

Price satisfaction may be defined as follows: An agent i is *satisfied with a price mapping* v with respect to an allocation l iff

$$s_i \geq h_{ib} - v_{ib}^{\mathcal{E}} \qquad \forall\, b \,\in\, B_v^{\mathcal{E}} \tag{3}$$

To be precise, the *extension* $\mathcal{E}$ of a price mapping has to be considered. An extension price of a bundle is set to be the minimal sum of extension prices of the sub-bundles in any possible partition of the bundle[5].

Fairness and Transparency

Fairness and Transparency can only be formalised in a much broader system-theoretic approach including formalisations of information flows, information accessibility, goal hierarchies, goal development, en-counting rules, etc. While we consider this to be a worthwhile tool for analysis, this is beyond the scope of this paper.

3.1 The Determination of Prices

For which subset of B prices will be computed? In principle, there are 3 obvious "target" sets.

1. The set of bundles containing only one good. This is equivalent to pricing the *individual goods* only.
2. Prices for all *possible bundles.*
3. Prices for all *assigned bundles.*

We will now study all three cases.

[5] Speaking of extensions enables us to augment incomplete price mappings and to define contradiction-free price mappings. Further details and a complete definition can be found in a report obtainable from the author.

Prices for Individual Goods

It is well known that it might be impossible to derive prices with the wanted properties for problems involving complementarities if only individual goods are considered (compare [4]). The following (2 agents, 2 goods)-example demonstrates this:

	A	B	AB
Agent 1	0	0	3
Agent 2	2	2	2

The optimal solution is to assign both goods to agent 1. However, the price of each individual good must exceed 2 to exclude agent 2 from the allocation–which in turn would prevent agent 1 from buying both goods because its valuation is below 4.

Prices for Bundles

Both remaining alternatives make use of the following consideration. The optimal allocation, as defined above, assigns *at most one bundle* of goods to each agent (or exactly one if the empty bundle is also considered). If we would know beforehand which bundles are "packaged" from individual goods for distribution to agents, the remaining problem is that of assigning at most one "pre-packed" bundle to each agent. This resembles the well-studied *assignment problem.* If we know the true preferences of the agents, an optimal allocation l^* can be computed. This allocation directly gives the set B^{l^*} of bundles to be assigned.

We can now feed this set of bundles into a procedure developed by Leonard [3] to determine a set of prices for this bundles. Leonard uses the dual problem to a simple formulation of the assignment problem to determine prices for the goods which obey the individual price satisfaction condition[6] and support the optimal allocation:

$$\begin{aligned} \text{Minimise} \quad & \sum_i s_i + \sum_j v_j \\ \text{subject to} \quad & s_i + v_j \geq h_{ij} \quad \forall i, j. \\ & s_i, v_j \geq 0 \quad i, j. \end{aligned} \tag{4}$$

Here, the bundles in B^{l^*} are indexed with j. v_j determines the price for bundle j. s_i gives the individual surplus of agent i, i.e. if good j is assigned to agent i, s_i is equal to $h_{ij} - v_j$. Thus, the first condition is a handy reformulation of the condition for individual price satisfaction, i.e. each agent receives the bundle that maximises its surplus at given prices.

Leonard shows with a nice argumentation that there is *always a set of minimal shadow prices*, $\underline{v}$ for which each price does not depend on the values that the individual to whom good j is assigned to, reports. $\underline{v}$ are in fact Grooves-Clark prices–they provide a set of incentive compatible market-clearing prices.

[6] When consideration is restricted to preferences for assigned bundles only.

Incentive compatibility refers to the fact that the mechanism of the price determination gives an incentive to report the preferences honestly.

To compute this set of prices, the model has to be extended.

$$\begin{aligned}
\text{Minimise} \quad & \sum_j v_j \\
\text{subject to} \quad & s_i + v_j \geq h_{ij} \quad \forall i, j. \\
& s_i, v_j \geq 0 \quad \forall i, j. \\
& \sum_i s_i + \sum_j v_j = V^*.
\end{aligned} \tag{5}$$

Please, note that the set $\underline{v}$ is minimal in the sense that it leaves the maximum consumer surplus in the hands of the buying agents (the set maximising the auctioneer's surplus wouldn't be incentive compatible). Further details can be found in [3].

As Leonard noted, his procedure (which he calls a "multiple auction procedure") can only be used if each individual's preferences are either completely *independent* or *exclusive*. Restricting the set of considered preferences to those for bundles that are actually allocated in the optimal solution ensures that this condition is met.

Unfortunately, this restriction is too strict. The following example will demonstrate the problem: Consider an auction for the bundles A and B. 3 agents are interested in buying the goods offered. Their preferences are (- stands for 0):

	A	**B**	AB
Agent 1	**5**	-	5
Agent 2	-	**3**	3
Agent 3	-	-	4

The best allocation would be to assign bundle A to agent 1 and bundle B to agent 2, optimising the allocation with a combined valuation of 8. If we would restrict the set of preferences as we did before, only the following preferences would be considered:

	A	B
Agent 1	5	-
Agent 2	-	3
Agent 3	-	-

The resulting price vector would simply be (v_A/0,v_B/0). This neglects individual preferences that are relevant: agent 3 would still "know" that its valuation for an assignment of AB is 4. Consequently, agent 3 would not want to accept the assignment–it would be able and wanting to buy the bundles A and B at the quoted prices.

How can this situation be handled? One solution is to *force* the agents to accept any announced assignment. This has a number of drawbacks:

1. The prices *do not reflect the competition* for the goods. An especially nasty problem is that the prices set *wrong signals* for future allocations. If bundles

are sold too cheap, as in the example above, the surplus of the agents receiving the bundles is higher than it should be. This potentially weakens the position of its competitor in subsequent allocations and prevents the mechanism to serve the purpose of supporting a "correct" formation of mid- or long-term equilibria.
2. Agent 3 in the example above is not price-satisfied. The extension price $v^{\mathcal{E}}_{AB}$ for bundle AB would be $v_a + v_B = 0$, violating the price-satisfaction condition.
3. Agent 3 perceives the allocation as being unfair because agent 3 is not allowed to purchase the bundles A and B.
4. If an agency is needed to enforce the allocation, it is pretty hard to justify the use of a price-based mechanism that pretends to be "fair". Question 1: If the agency has enough power to enforce a solution with a contradictory price set, couldn't it force the agents to report their valuations truly without a price mechanism (by law, auditing, etc.)? Question 2: If the agency has this kind of power, shouldn't a monopoly analysis be the right instrument (studying price differentiation etc.)?

A second possibility here is to determine additionally prices for all unallocated bundles, see [9].[7] We would like to call such prices "control" prices. Their primary purpose is to fulfil the price-satisfaction condition[8]. In the example above, this can be achieved by setting a price for the bundle AB at 4 or higher. However, this technical trick still requires to explain to the agent why it is not allowed to buy both bundles A and B separately at the quoted prices $v_a = 0$, $v_b = 0$. Also, the effect of competition is captured correctly[9]. As a consequence, pricing all bundles in this way does still exhibit the drawbacks 1,3, and 4 given above.

Further on, only prices for allocated bundles are considered.

To reflect the competition correctly, it is necessary to additionally consider agent 3's preferences for good AB when the prices are determined.

	A	**B**	AB
Agent 1	**5**	-	5
Agent 2	-	**3**	3
Agent 3	-	-	4

We need to find the minimal set of prices additionally satisfying the following condition: $v_A + v_B \geq h_{3AB}$.

This would exclude agent 3 from the allocation. Intuitively, the condition reflects the fact that the prices of the allocated goods should be set in a way that

[7] The price for an unallocated bundle b can simply be set to $v_b = \max_i[h_{ib} - s_i]$, or arbitrarily higher. This prevents all agents from preferring bundle b.

[8] However, the extension of the price mapping may not be contradiction-free, that is, the extended price does not equal the given price

[9] This makes it somewhat misleading to call the prices "competitive equilibrium prices" as in [9]. Using the term "Competitive equilibrium" implies that the prices truly and completely reflect competition. This gives the agents the rationale to participate in the mechanism, to accept the prices and to not behave strategically.

they support the optimal allocation no matter how an agent valuing a combination of the offered goods tries to distribute its budget to buy this combination.

This can be generalised as follows: To determine the prices for each assigned bundle, all valuations of combinations of sub-bundles have to be considered. The LP model has to be extended accordingly: Let B^{l^*} be the set of bundles assigned to agents in the optimal solution l^*. Let $S_{B^{l^*}}$ be the set of all possible subsets of B^{l^*} with more than one element. Furthermore,we define $\oplus$ as a join-operator, glueing together two or more bundles, e.g. $\oplus(A, B, CD) = ABCD$.

$$\begin{aligned} \text{Minimise} \quad & \sum_j v_j \qquad (6) \\ \text{subject to} \quad & s_i + v_j \geq h_{ij} \ \forall i, j. \\ & \sum_i s_i + \sum_j v_j = V^*. \\ & s_i + \sum_{j \in s} v_j \geq h_{i \oplus(s)} \ \forall s \in S_{B^{l^*}},\ i \in I. \\ & s_i, v_j \geq 0 \ \forall i, j. \end{aligned}$$

The determined set gives the minimal set of prices supporting the optimal allocation, reflecting the competition, and keeping all agents price-satisfied.

This is pretty much what we were looking for. Unfortunately, the LP may not be solvable under certain circumstances:

	A	**B**	AB
Agent 1	**5**	5	5
Agent 2	-	**3**	3
Agent 3	-	-	7

Here, the prices for the bundles A and B are limited to 3, keeping the sum of prices below the required 7.[10]

The following procedure may solve the problem:

In the example above, the auctioneer would decide to sell the bundle AB instead of selling each bundle/good separately. He would inform agent 1 and 2 that *forming a coalition* and *jointly bidding* may allow them to buy the bundle AB. If the agents decide to bid jointly, bundle AB will be sold for a minimal price of 7. Agents 1 and 2 will split the bundle AB and negotiate each individual's share of the price. Each agent resp. each agent coalition will be price-satisfied, the final allocation is optimal, the price reflects the competition correctly and the procedure is transparent and fair.

However, if the agents decide not to collaborate, the bundle AB will be sold for a price of 5. Still, all agents are price-satisfied. The procedure is still fair and transparent, but the allocation is not optimal any more. As the loss of optimality

[10] The optimal solution is to assign bundle A to agent 1 and bundle B to agent 2. Thus the price for bundle B may not exceed 3. This, in turn, limits the price for bundle A to 3 as well, otherwise agent 1 would want to buy bundle B!

is the consequence of a conscious decision of some of the participating agents, this seems to be acceptable. If the overall constituents of the problem are considered, the notion of optimality should be extended to include fairness, price-satisfaction and transparency. Given this, even the not perfectly efficient solution is optimal.

The overall procedure works as follows:

1. Ask for all preferences.
2. Optimally solve the allocation problem and determine the bundles to sell.
3. Try to solve (6) to compute prices. If this is possible, distribute the goods to the agents according to the optimal allocation–done. Otherwise, decide about a reasonable aggregate bundling, inform the affected agents about possible coalitions and await their answers. Transform (6) with respect to the aggregate bundling. Iterate step 3.

4 Discussion

The suggested procedure may be used to establish an allocation of goods to agents in the presence of complementary preferences. The procedure is transparent and fair, the computed prices are competitive. However, there are potential drawbacks:

Complexity: The allowed structure of preference orders can easily be used to formulate, e.g. production scheduling problems. The underlying problem may thus be NP hard. Determining the optimal allocation may require an enormous effort (combinatorial explosion). Once the allocation is known, the prices for the allocated bundles can be determined in polynomial time (not demonstrated in this paper). This leaves room for applying heuristics to determine a "reasonable" solution to the allocation problem. We call this "auction selection" because, from all possible allocations and the corresponding "auctions", only one or a few are heuristically picked for price determination. It is as well possible to try to integrate price determination and allocation procedure to an iterative auction procedure that is based on successive revelation of preferences. We do, however, not expect this to be very fruitful because of the potentially non-convex structure of the preference structures which will prevent intermediate prices from being a very useful behavioural signal.

Incentive compatibility: A price-based mechanism is especially useful if it allows to elicit honest preferences of the participating agents, making strategic behaviour obsolete. This result is easy to establish if the computed price for a bundle does not depend on the valuation of the agent receiving the bundle, see Leonard or Vickrey. It seems, as if the construction of the mechanism has this property (at least for most cases), however, this remains to be proven.

Coalition Formation: The procedure supports the formation of coalition whenever this is beneficial for the overall result of the mechanism. The agents may as well use coalition formation in other situations. It may occur in situations where agents expect to improve the likelihood of receiving a bundle if acting jointly. This does not lead to problems if the agents announce their joint valuation prior to the allocation. However, it might be problematic if the agents form a coalition after the prices are announced. In this case, the joint surplus may exceed the price that was determined for a bundle[11]. This can either be ruled out (which seems to be reasonable) or the price determination procedure may be adjusted accordingly. This would require the additional condition that the price for a bundle must be set so that the potential surplus for each coalition from buying this bundle does not exceed the aggregated surplus of the agents in the coaling for the optimal allocation. This is possible, because otherwise a contradiction to the optimality of the allocation can be constructed.

Other forms of collusion may occur as well, as in similar situations with second-price auctions.

Further Aspects (briefly mentioned): For specific application areas, such as production scheduling, it may be very difficult to obtain *valued* preferences. The auctioneer should be a trust-worthy institution and the goal of the auctioneer (maximising "common" or "individual" benefit) should be clearly set. The seller side has to be carefully analysed. The impact of competing auctioneers needs to be addressed. Etc.

Related Work

The suggestions made in this paper a related to a number of active research areas, we will give only some brief pointers.

The problem of complementarities led to a number of research activities in economics and AI. An early approach to solve problems with complementarities is described in [8]. Wellman et al. discuss the problems of trying to apply Walrasian-like economic coordination models of competitive equilibrium in a non-convex domain.

A recent report of Tuomas Sandholm [7] suggests an efficient algorithm for winner determination in a setting that is closely related to a generalisation of the problem setting laid out here. The solution, however, is based on a (domain-independent) bidding-based procedure that is implemented as an IDA*-like search, while in our case a combination of (domain-specific) allocation algorithm and a subsequent price-determination procedure is suggested. The goal of the auctioneer might be different too. We assume that the auctioneer tries to establish incentive compatible prices (which does not necessarily maximise the seller's surplus), while Sandholm studies the maximisation of the auctioneer's revenue. Sandholm's report gives pointer to further relevant literature.

A comprehensive account of market-based coordination mechanisms along with instructing application examples can be found in [10]. In the broader context of coordination mechanism (without requiring the use of a meaningful "currency"

[11] Example: Announced price for bundle AB is 6. AB should be assigned to agent 3 with valuation 9. Agent 1's preference for A is 6, agent 2's preference for B is 2. Joint valuation: 8.

as a medium of coordination), much information and numerous pointers can be found in [6].

Previous work on economically motivated coordination mechanism in application areas, e.g. in a manufacturing context, is numerous. Mostly, the suggested models are either applied in a simplified context [2] or difficult to interpret in terms of economic analysis [1, 5], or both. However, the approaches often suggest interesting heuristic approaches and thus may be useful to heuristically obtain a solution for the allocation or price determination problem.

Conclusion

This paper offers an approach to practically relevant allocation problems. Studying heuristic modifications and analysing the property of incentive compatibility are important steps for future research. If an applicational context is considered, economic coordination mechanisms may offer interesting new possibilities to explore the opportunities of localised decision making, flexible organisational structures, etc. However, designing a specific mechanism is still a hard task, especially because some of the nice properties of the "optimal" procedure, such as allocation efficiency and incentive compatibility, may not survive the obviously necessary application of heuristics. Nevertheless, this kind of economic coordination mechanism widens the design space for coordination mechanism and, hence, may open up new possibilities worthwhile to study.

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