

Promoting Intellectual Discovery: Patents vs. Markets

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Running title: Markets Promote Intellectual Discovery

Abstract

Because they provide exclusive property rights, patents are generally considered to be a superior way to promote intellectual discovery. Here we propose a new compensation scheme, where everyone holds shares in the components of potential discoveries and can trade those shares in an anonymous market. In it, incentives to invent are indirect, through changes in share prices. In a series of experiments, we used the knapsack problem (KP) as a typical representation of intellectual discovery problems, where the challenge is to find the right combination of a number of components ('items'). We found that our 'markets system' performed better than the patent system: not only did subjects find the right solution in the markets system whenever they did in the patent system; more subjects also reported the right solution. Our findings challenge the universal superiority of the patent system.

1 Introduction

In a patenting system, only the first to discover the solution to a problem receives a prize, in the form of exclusive property rights to the fruits from the discovery. Patents originated in the 15th century in Venice (*1*) and have since become an important way to compensate inventors. Patents are generally viewed as a superior way to promote intellectual discovery because they provide strong incentives to invest in effort, the cost of which can be recuperated from the earnings generated by applications of the discovery.

The patent system has recently been criticized on various grounds. First, there is the obvious fairness issue: only the winner is compensated for her effort. Second, ownership may become

fragmented, which inhibits further discovery if such requires input from and coordination between the owners of prior inventions [see (2)]. Third, intellectual-property rights defy precise definition, and hence, their scope will be subject to constant costly challenge [e.g., (3)]. Finally, patents imply monopoly rights and exploitation of monopoly rights leads to sub-optimal production, even no production whatsoever (4); the distortion becomes even more pronounced when the monopoly right covers downstream licensing (5)].

Here we propose an alternative, markets-based system to organize compensation of intellectual discovery. The key feature is to introduce markets for all the items that can potentially become crucial components of or inputs to implementations of a future discovery. Everyone can then own shares of these items, and these shares can be traded in an anonymous market prior to discovery. This way, agents who posit that a certain item is more likely to be part of a new discovery are induced to invest in it, while selling shares in items that show less potential. Notice that incentives are indirect: discoverers are compensated when they are the first to realize which items can solve an outstanding problem; compensation is in the form of share price increases; indeed, one can expect the value of items in useful discoveries to increase, while items not part of them will become cheaper. Moreover, even if an agent believes that others are already very close to a certain discovery, he will still have an incentive to exert effort in discovery, as he might discover a part that no other agent has discovered yet, and thus obtain rents in the market for some item. Also, there are not only incentives to invent: once they have taken their positions in the relevant items, inventors have a strong incentive to reveal their discovery, in order for share prices to adjust in their favor as soon as possible. This should speed up development of applications based on new discoveries.

A simple example is in order. Concrete is made of several elements, such as gypsum, lime, water, etc. The Romans realized at one point that the addition of volcanic ash made concrete far more durable and waterproof (6). In a patent system, the person who first discovered (and filed a patent) to add volcanic ash to concrete would be given monopoly rights to sell ash-based concrete. In the proposed markets-based system, all agents who discover that volcanic ash was a useful additive to concrete should take positions in securities whose value would increase with the price of volcanic ash. After announcement of the discovery (which the inventors would rush to make), the demand for volcanic ash would increase as use of the new additive becomes widespread, and hence, the price of volcanic ash increases. The inventors are compensated indirectly for their

discovery, through an increase in the value of their shareholding.

In a series of experiments, we compared the performance of a patent-like ‘prize system’ against that of the proposed ‘markets system.’ In our experiments, we used the knapsack problem (KP) as a typical representation of intellectual discovery problems. In the KP the challenge is to find the optimal combination of a number of components (‘items’). Specifically (see fig. 1a), subjects were asked to fill containers with at most ten to twelve items; containers had a weight constraint, which means that generally not all items fitted; items had different values; the goal was to maximize total value of items that could fit.

Instances of KP may be notoriously difficult: while many approximate solution algorithms exist, the only generally effective way to guarantee that one has the correct solution is to enumerate all possible solutions and compare [see (7) and (8)]. Indeed, KP is an example of an ‘NP-complete’ problem. Nevertheless, specific instances of KP may be solved with heuristics not requiring the enumeration of all possible solutions. A family of such heuristics is the Sahni-scheme [see (9)]. In our experiment we use instances of KP that can be solved with a range of complexities of algorithms in this family. However, it is not *a priori* known which algorithm is appropriate for any given problem.

At the heart of KP is the task to devise the right combination of a potentially large number of inputs; in this sense, we think that it aptly represents intellectual discovery. In the economics literature (10), (11), intellectual discovery is generally modeled as an exercise of information aggregation, in which disparate pieces of information (‘signals’) need to be put together.¹ Information-aggregation problems thus merely involve taking weighted averages of a number of signals. KP is far more difficult: to be sure that one has found the right solutions to a KP (or that one has been using the right heuristic), a list of all possible outcomes is required. In KP, this list is large, and includes outcomes that may not have been obvious *a priori*. We think that this feature of KP is also at the heart of intellectual discovery, which often involves original and surprising ways of ‘putting things together.’

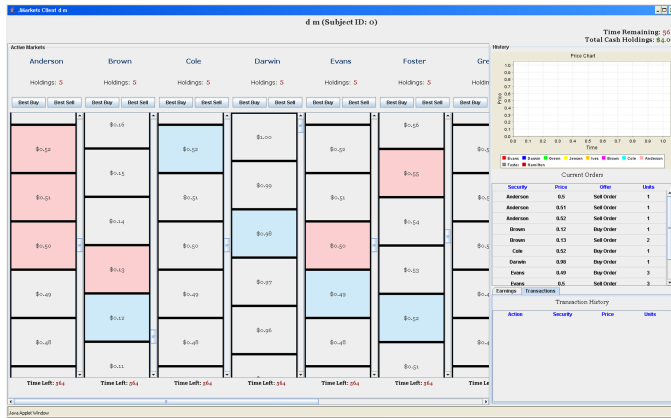
In our experiment, we used eight instances (variations) of the KP. The instances varied in

¹This includes Hirshleifer (12), who argues that intellectual discovery concerns discovery of the most likely future states of nature; agents profit from it by investing in those combinations of factors of production that generate most profitable production in the states of nature considered to be most likely. In Hirshleifer’s view, the best input combinations for each state of nature are *known*; they need not be discovered. In our view, it is precisely this best combination of inputs that needs to be found.

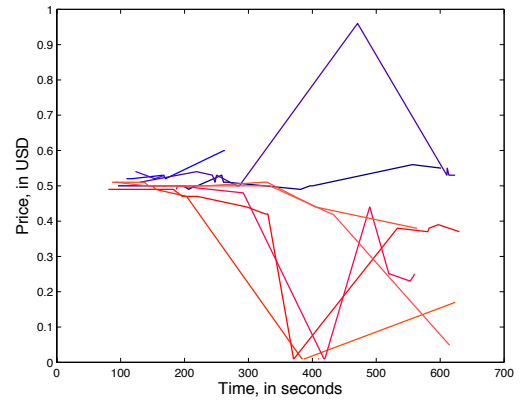
Weight limit: 1500

	A	B	C	D	E	F	G	H	I	J
Values	37	72	106	32	45	71	23	44	85	62
Weights	50	820	700	46	220	530	107	180	435	360
Solution										

(a)



(b)



(c)

Figure 1: (a) Presentation of KP instance IV, as seen by experiment participants. The first row lists the values of the items and the second one their weights; the third row is left blank for subjects to enter their suggested solution. The weight limit of the container is indicated on top of the table. The goal is to find the combination of the items that maximizes total value and is feasible (i.e., fits within the weight limit of the container). Objects are indivisible. (b) Snapshot of the trading interface in the markets treatment; shown is the *jMarkets* (web site: jmarkets.ssel.caltech.edu) interface used in the robustness check experiments. Each column on the left hand side provides price levels at which orders to buy (indicated in blue) and orders to sell (in red) can be entered. Orders are entered by a simple click of the mouse. Trades take place automatically when an order to buy (sell) is entered at a price above (below) the best available sell (buy) order. Subjects can see their current holdings above the columns. A list of the subject's current standing orders is provided to the right; above it is a chart with past transaction prices; below it is a summary of earnings in past trading rounds. (c) Evolution of transaction prices during one experimental period (KP instance V under the markets treatment, run during session 11/12/2006). Lines in blue connect trade prices for each of the securities that represent positions in 'IN' items (items that are part of the optimal solution); lines in red connect trade prices of securities corresponding to 'OUT' items. While initially equal, trade prices of 'IN' securities tend to increase, while those of 'OUT' securities tend to decrease.

degree of difficulty, as measured by an index based on the Sahni's heuristics. One of the goals of the study was to determine whether the patent (prize) system dominated the markets-based system for a range of difficulties, or whether it dominated uniformly. In our prize system, we rewarded the first subject to discover the optimal solution with USD (U.S. dollar) 66. While we imposed a time constraint (420s), it was binding in only one instance (no one found the right solution within the allowed time). To best reflect real-world patent systems, discovery was immediately and publicly announced. The nature of the solution was not revealed, however, and subjects could continue work on the KP instance at hand. After time elapsed, subjects handed in their suggested solutions. However, only the person who first discovered the right solution was compensated.

In the markets system, subjects were given an equal number of shares in each of the items of the KP instance at hand, as well as cash. They could trade these shares in an anonymous, electronic exchange platform during a pre-set amount of time (840s). The allowed time was double that of the prize system, to compensate for the fact that subjects needed to perform two tasks: to solve the KP, and to trade (to exploit the knowledge they gained from solving the KP). The platform was organized as a continuous double-sided open book (see fig. 1b), like most purely electronic stock markets in the world. The accumulation of orders generated the first transactions after about 100s. Thereafter, trading remained brisk in virtually all markets; see fig. 1c. After markets closed, each share in an item that was in the optimal solution paid a liquidating dividend of USD1; shares corresponding to items not in the optimal solution expired worthless.

In the markets system, we paid on average a total of USD66 in dividends per instance. This amount was the same as we paid to the single subject who discovered the right solution in the prize system. It was distributed across subjects depending on the number of shares of each item they were holding at the close of the markets. We also collected subjects' suggested solutions after markets closed; we did not compensate for correctness of these suggestions.

In each experiment, subjects solved four instances of the knapsack problem under the prize system, and four instances under the markets system. We repeated the experiment four times, so that each instance was solved twice under both systems. The experiments had the approval of the Caltech Institute Review Board for the protection of human subjects.

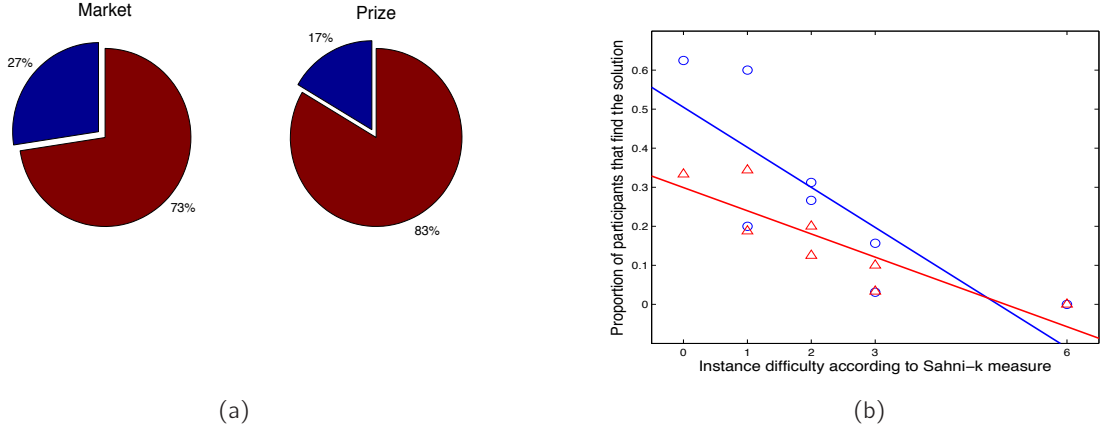


Figure 2: (a) Overall proportion of subjects that report the correct solution (in blue) and the incorrect one (in red) for the Markets (left hand side) and Prize (right hand side) treatments. The proportions are significantly different across treatments ($p < 0.05$). (b) Proportion of participants who report the correct solution of each instance of KP against its Sahni-k difficulty. Blue circles indicate the market treatment, red triangles represent the prize treatment. Linear fits for the two treatments are the blue line for market ($R^2 = 0.6433$), and the red line for prize ($R^2 = 0.737$). Slopes of both lines are significant ($p = 0.0083$, and $p = 0.0032$, respectively).

2 Results

We found that at least one subject discovered the correct solution under the markets system whenever this was the case under the prize system. In at least one sense the markets system actually performed better: a significantly higher fraction of subjects reported the correct solution under the markets system than under the prize system (see fig. 2a).

This difference became insignificant, however, when we altered the prize system in two ways: (i) unlike in real-world patent systems, discovery of the correct solution was not immediately announced, but only after allowed time elapsed, (ii) the allowed time was doubled to match the length of trading in the markets session (where subjects needed to trade in addition to solving the knapsack problem at hand). See Supplementary Online Material (SOM) for details. Nevertheless, the prize system never became dominant.

Based on the Sahni-k approximate solution scheme for the KP (9), we constructed an index of the difficulty of our instances (see SOM for details). Fig. 2b plots the average fraction of subjects that reported the correct solution for each instance against instance difficulty. Under both

the prize and markets systems, the average fraction is significantly decreasing. The difference in slopes is insignificant. It must be noted that the number of subjects that reported the correct solution was also contrasted with a measure of difficulty that can be associated with the exact solution algorithm - enumeration of all possible solutions ($n \log_2 c$, where n is the number of items, and c is the weight limit of the instance). No relation was found with this alternative measure of difficulty.

Trading in the markets system was heavy. See SOM for details. Fig. 3a displays estimated densities of the transaction prices of the shares of items that were part of the optimal knapsack ('IN') and of items that were not part of it ('OUT'). The histogram of the former is to the right of the latter, suggesting that prices of shares of IN items tend to be higher than shares of OUT items. The average transaction price for IN items is significantly higher than that for OUT items ($p < 0.01$).

In the markets system, subjects started with equal number of shares in each of the items (namely, five). At the end of trading, holdings were dispersed. Fig. 3b contrasts the frequency of average final holdings of shares of IN and OUT securities. It is this dispersion that indirectly compensates for correctly solving the KP: those who figured out the right solution buy more 'IN' securities and sell 'OUT' securities and, as a result, will eventually be paid higher total dividends.

Final holdings less than initial holdings overall occur more frequently for 'OUT' securities than for 'IN' securities, suggesting that many subjects successfully reduced their holdings of 'OUT' securities. But total frequencies for a security category ('IN', 'OUT') have to add up to 100%. Higher frequencies of low final holdings of 'OUT' securities are offset by (i) lower frequency of final holdings equal to initial endowments, and (ii) higher frequencies of extremely high final holdings. As such, the right tail of the histogram for 'OUT' securities is longer than that for the 'IN' securities. Final holdings of 'OUT' securities are therefore more dispersed than those of 'IN' securities.

3 Discussion

Despite the absence of direct incentives to find solutions to our knapsack problems, the experimental results indicate that our markets system performs equally well as a patent-like prize system. In the markets system, incentives are provided through positions in securities that represent the

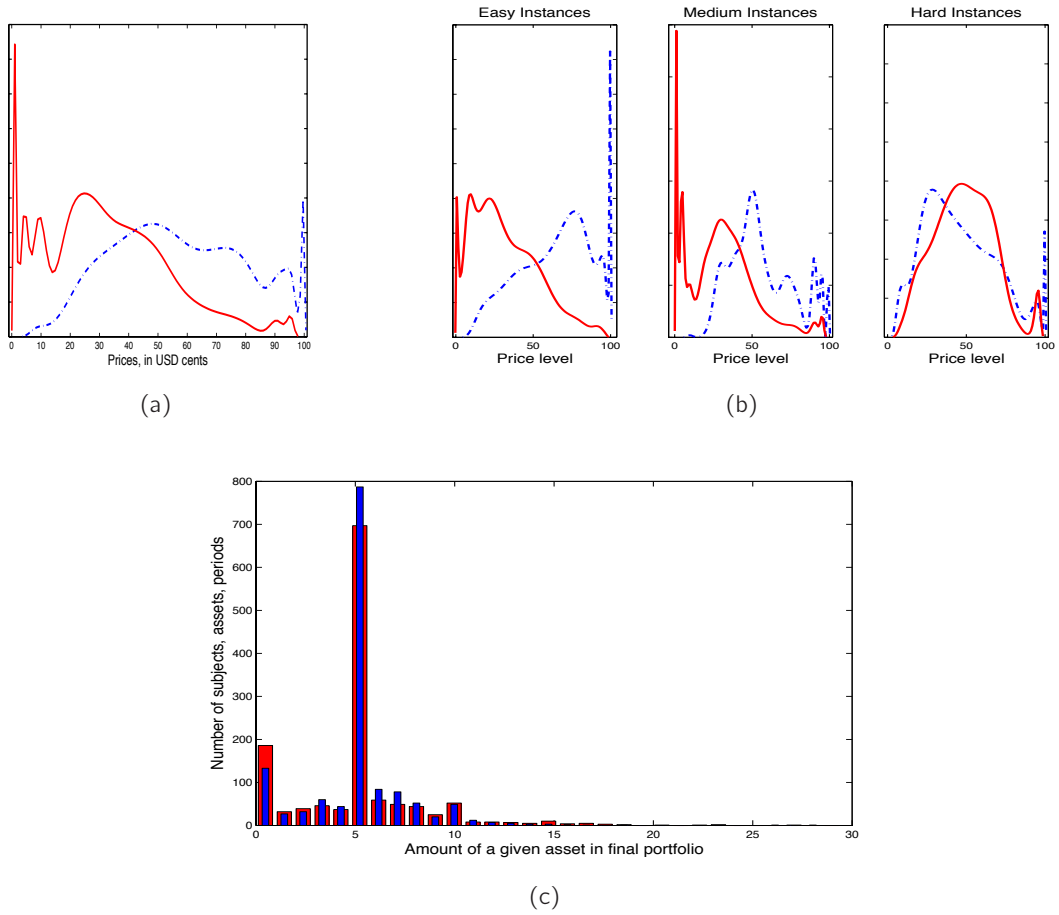


Figure 3: (a) Empirical densities of transaction prices (estimated using kernel smoothing with a gaussian kernel and imposing boundaries at 0 and 100). Density for 'IN' securities is in blue; that for 'OUT' securities in red. The former is to the right of the latter, indicating that prices of 'IN' securities tend to be above those of 'OUT' securities. (b) Same information stratified by Sahni-k difficulty level. (c) Histogram of final holdings of securities for all subjects, periods, and securities. Securities are grouped into 'IN' (blue histogram) and 'OUT' (red). The number of cases where holdings are less than or equal to five (the initial endowment) is higher for 'OUT' than for 'IN' securities, offset by a longer tail of the distribution to the right.

items used as components of potential solutions. If a subject is convinced that certain items are part of the correct answer, she will invest in those, while divesting other items. Although our experimental setup did not verify this, one can presume that our markets system provides strong incentives for early revelation of the optimal solution: once a subject has taken the desired market positions, she should announce her solution as soon as possible in order to gain from the immediate price reactions (prices of IN items will increase, while those of OUT items decrease), rather than waiting for the final dividends.

Our results suggest that our markets system performs equally well as the prize system, challenging the universal superiority of the latter. In one respect, the markets system actually did better: more subjects reported the right solution to the knapsack problems. The prize system improved only in our alternative treatment where, unlike in a true patent system, we did not announce the winner once she had handed in the optimal solution. Dispersion of knowledge of the correct solution is an important property when the process of discovery itself (the experience of finding the solution oneself) is needed to facilitate future discovery.

Performance of the markets system decreased with problem difficulty. However, we did not find a range of difficulty for which the patent system became superior. Indeed, performance of the patent system decreased with problem difficulty at a rate that was insignificantly different from that of the markets system.

Inspection of final securities holdings suggests how the markets system provides incentives to discover. While holdings were always the same for everyone before trading, after trading, holdings became dispersed. Dispersion of holdings of 'OUT' securities actually became extreme. Effort put into finding the right solution was therefore compensated through trading: subjects increased their positions in items which they thought may be part of the optimal solution, while decreasing positions in the other items.

The success of our markets system relies on agents' willingness to trade; without trading, those who make progress towards finding the optimal solution cannot exploit their acquired knowledge. If agents were able to instantaneously compute the optimal solution, the willingness to trade would be puzzling: when an agent sees an offer to buy an extra share in a particular item, why would she accept the offer? For the buyer may have figured out that the item is in the optimal solution! This puzzle is analogous to the one commonly observed in markets experiments with information aggregation and first documented in (13). However, in information aggregation

experiments this puzzle is even more extreme, as all knowledge is objective: an agent who trades on superior information knows that she has superior information. In our setting, agents never know whether they have the optimal solution (since they would need much more time to check all possible solutions). So, agents must be trading because they *are confident* that they are closer to resolving the problem than others. This overconfidence might be an explanation for emergence of trade in our setting. Overconfidence bias is well known in other environments: more than 50% of subjects usually think they are better than the median (14). Further research should shed light on the causes of trade, on which the success of our markets system depends.

Item prices partly revealed the correct solution. Presumably, this helped diffuse discovery, helping others in the marketplace to find the optimal solution. This diffusion property of markets has been observed in other contexts as well: markets can help agents overcome cognitive biases (15), (16), (17), (18). Our setting is obviously not one of cognitive biases (even if we may be exploiting one, namely, overconfidence); by the very nature of NP hard problems, our setting is one of cognitive limitations.

Our markets system involves two tasks: discovery (of the best solution) and trading (in items that could potentially be in the best solution). In contrast, the patent system involves only one task: discovery. In our experiments, we accommodated the differential in effort by allowing more time in the markets setting. Alternatively, one could envisage delegating the task of trading in the markets system to a second person with comparatively higher expertise in financial markets trading. We refrained from doing so, to avoid confounding of our results of individual decision making with group effort. Indeed, teamwork in itself is known to alleviate cognitive limitations (19), (20), (21).

Notice that our markets were defined in terms of the items that could potentially be part of the optimal solution. Significantly, we did not define securities in terms of potential optimal solutions. Because the KP is NP-complete, by definition too many markets would have been needed – it does not seem plausible that one would find the time to trade in *all* the markets. Besides, we use the KP because we think that it captures the essence of difficult intellectual discovery. An important aspect of intellectual discovery is that it is hard to envisage beforehand the scope of potential solutions. That is, one has a hard time imagining the nature of the optimal solution before finding the optimal solution in the first place.

Our markets system avoids many of the problems associated with a patent system. Among others, it is fairer, in the sense that all who spend effort to discover the best solution are potentially

compensated, not just the first one to announce the solution. This feature in our view provides better incentives to expend effort during the process of discovery. Moreover, future discovery does not require coordination among owners of fragmented intellectual property of past discoveries because past discoveries are in the public domain. Also, in our markets system, there is no problem of defining the scope of property rights to discoveries, again because intellectual property is public. But perhaps the most important advantage of the proposed markets system is that discoverers are not given monopoly rights, thus avoiding sub-optimal production of the fruits of the discovery. Indeed, optimal exploitation of monopoly rights implies reduced production, and hence, diminishes social welfare.

The patent system dates from 15th century Venice, Italy. Organized financial markets were first set up around the same time, in Antwerp, Flanders (present-day Belgium) (22). Intellectual discovery, however, has since almost exclusively been incentivized through patents. Despite their phenomenal growth, the role of financial markets has remained restricted to allocation and re-allocation of risky and/or time-dependent cash flows. We propose that these markets could be designed to play a crucial role in incentivizing innovation and discovery as well.

For our proposal to work, it is important that new markets can quickly be made available. Until recently, setting up new markets required time. Modern technology, however, has enabled quick design, ready deployment, and low-cost management of the anonymous, two-way markets we used in our experiments. The software we developed for our experiments (jMarkets), in fact, allowed us to set up and launch markets online in a matter of hours.

In summary, our experimental findings suggest that the patent system is not a universally superior way to incentivize intellectual discovery. We proposed a markets system that we found to work equally well, and in one respect, better. Our markets system avoids many of the problems associated with a patent system. Its main feature is that everyone shares in the fruits of intellectual discovery, because everyone starts with shares in the components of potential discoveries; still, all those who actually spent the time to find the best solution have the potential to earn more.

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