

Economic Sciences Association (Asia-Pacific)

# The Effect of Price Signals on Effort and Productivity in a 'Hard' Task

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## Steam Engines in Cornwall (Nuvolari, 2004)

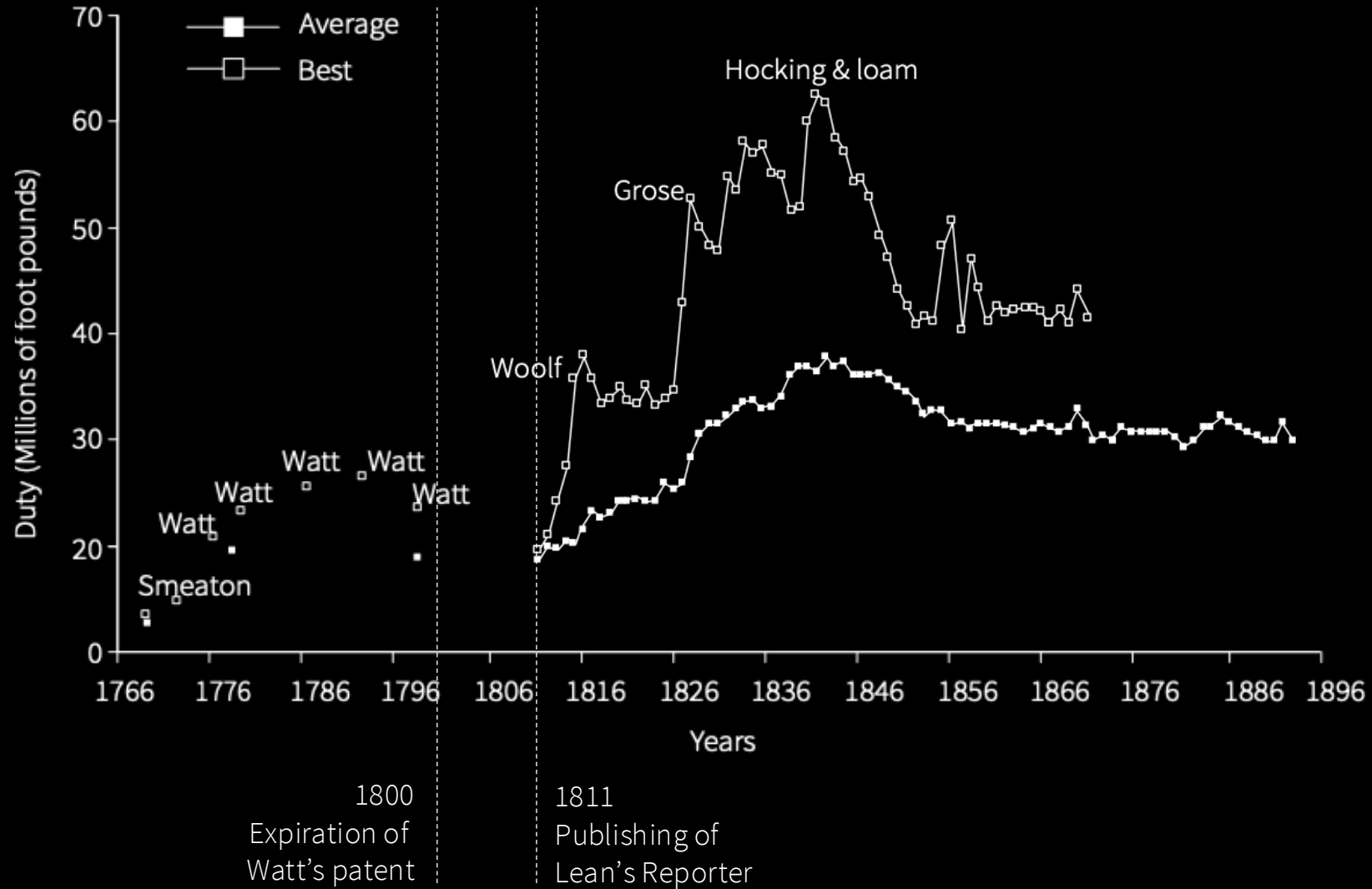
Improvements to the steam engine occurred at an unprecedented rate during the Industrial Revolution (1760-1840)

A disproportionately high number of these improvements originated in Cornwall.

Most of these improvements were not patented.

Historians attribute this to a collaborative culture of 'collective innovation'.

# Steam Engines in Cornwall (Nuvolari, 2004)



## Steam Engines in Cornwall (Nuvolari, 2004)

Why was Cornwall so successful?

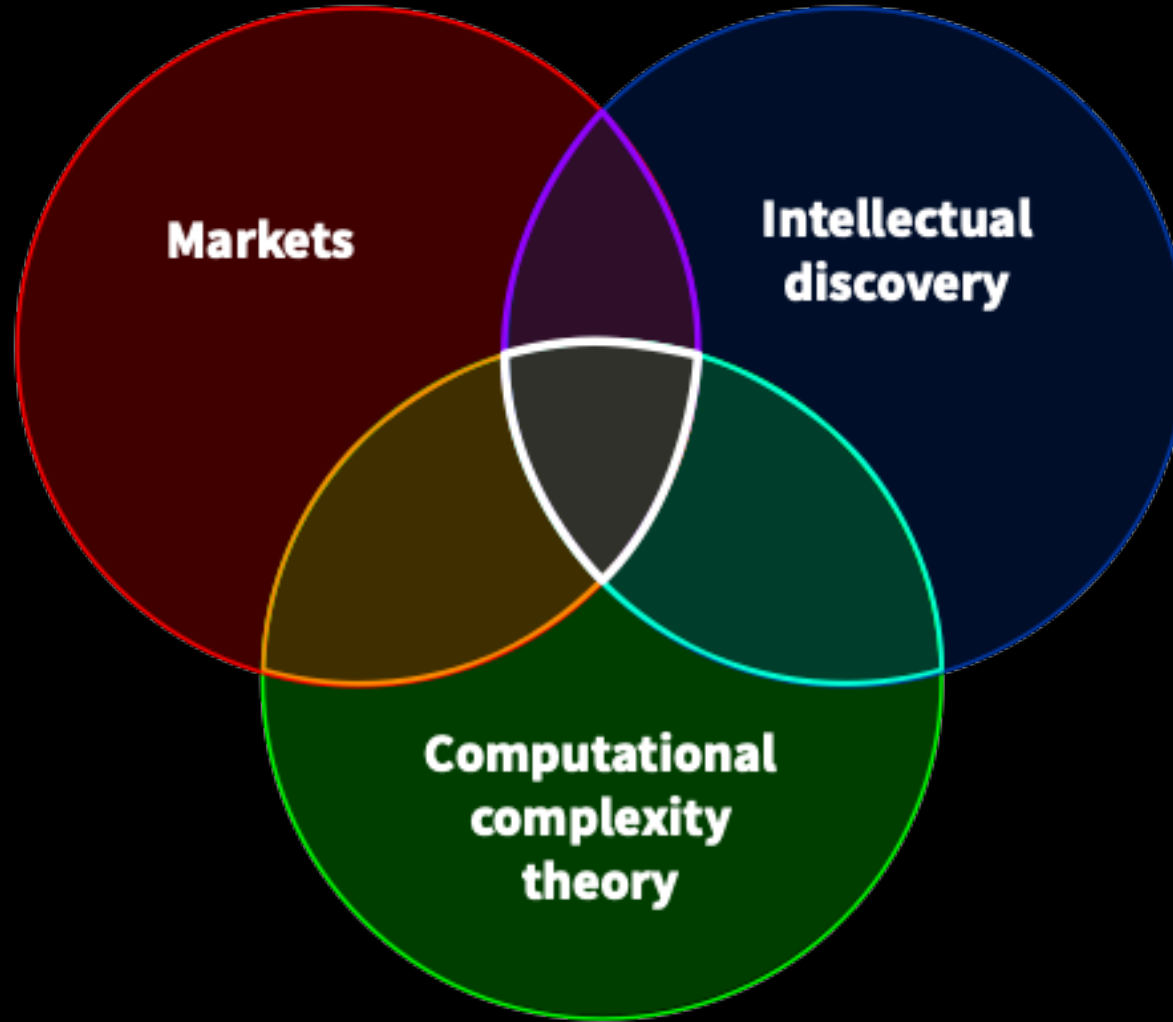
1. Lean's reporter: Mechanism to share information
2. Cost-book system: Incentive to share information

Miners often held shares in many different mines, as opposed to a single mine.

Interested in overall profitability of the region, rather than the profits of a single mine.

- ↑ average aggregate performance of the steam engine
- ↑ overall profitability of the district.

General theory



RE and market efficiency

Muth (1961); Grossman (1976); Fama (1970); Grossman & Stiglitz (1980)

Market-based incentives

Nuvolari (2004); Meloso, et al. (2009)

Collective intelligence

Hayek (1945); Bossaerts, et al., (2025);

Combinatorial problems

Papadimitriou & Steiglitz (1982); Pisinger (1998)

NP-hardness

Arora & Barak (2009)

Discovering new ideas is essential for growth  
Schumpeter (1911)

Ideas are free to use, but costly to find  
Romer (1990); Romer (1993)

Existing institutions have well-known shortcomings  
Fritz (1958); Usher (1964); Hall, et al., (2012)

**Contribution**

Markets as a mechanism for intellectual discovery

Disentangling the effects of incentives and price signals

## Operationalising intellectual discovery

Mirror the (combinatorial) nature of discovery in the real world

Romer (1990); Romer (1993)

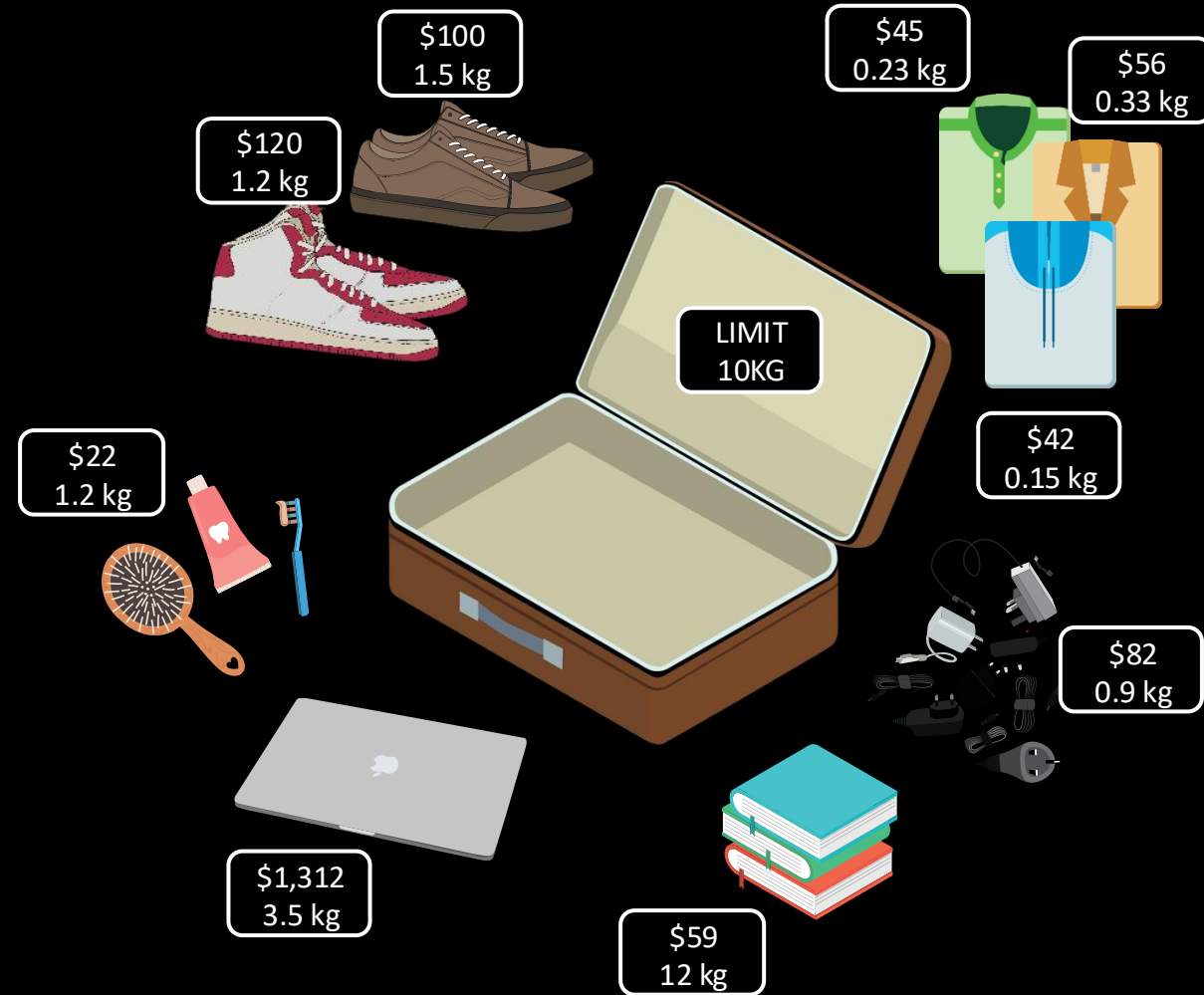
Canonical, with a well-defined optimum

Pisinger (1998)

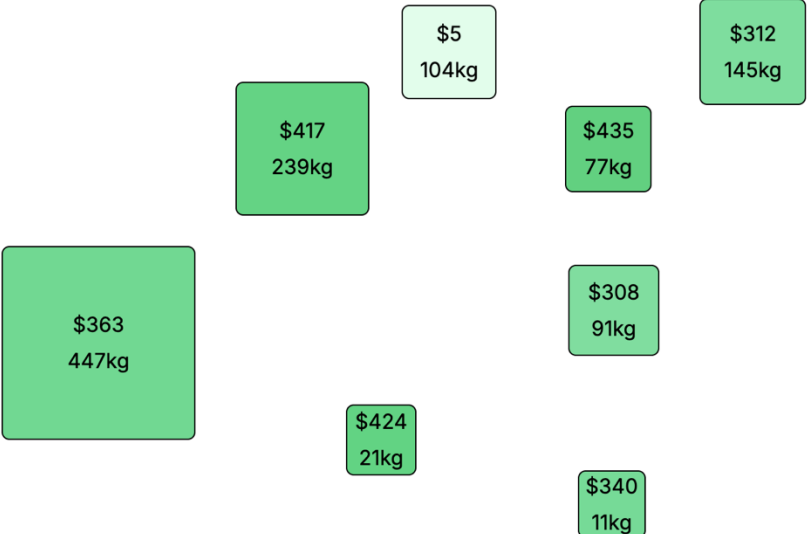
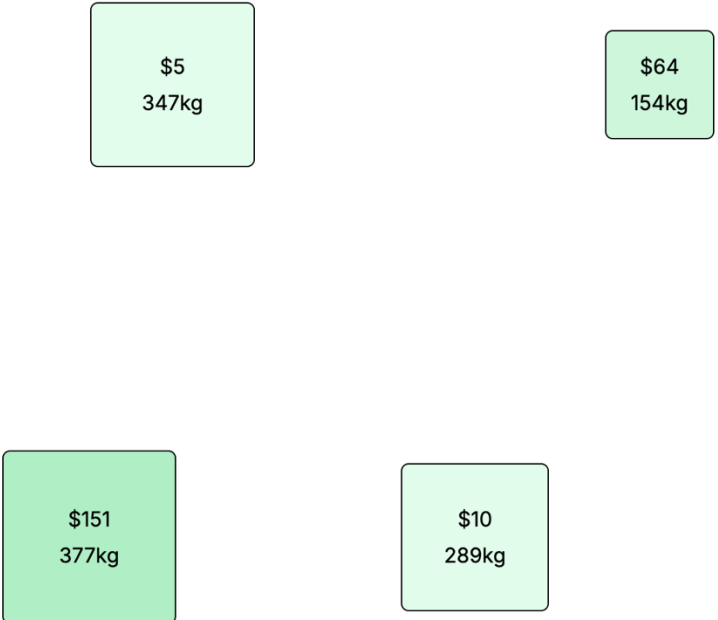
Allows us to precisely vary difficulty

Franco (2026, in prep.)

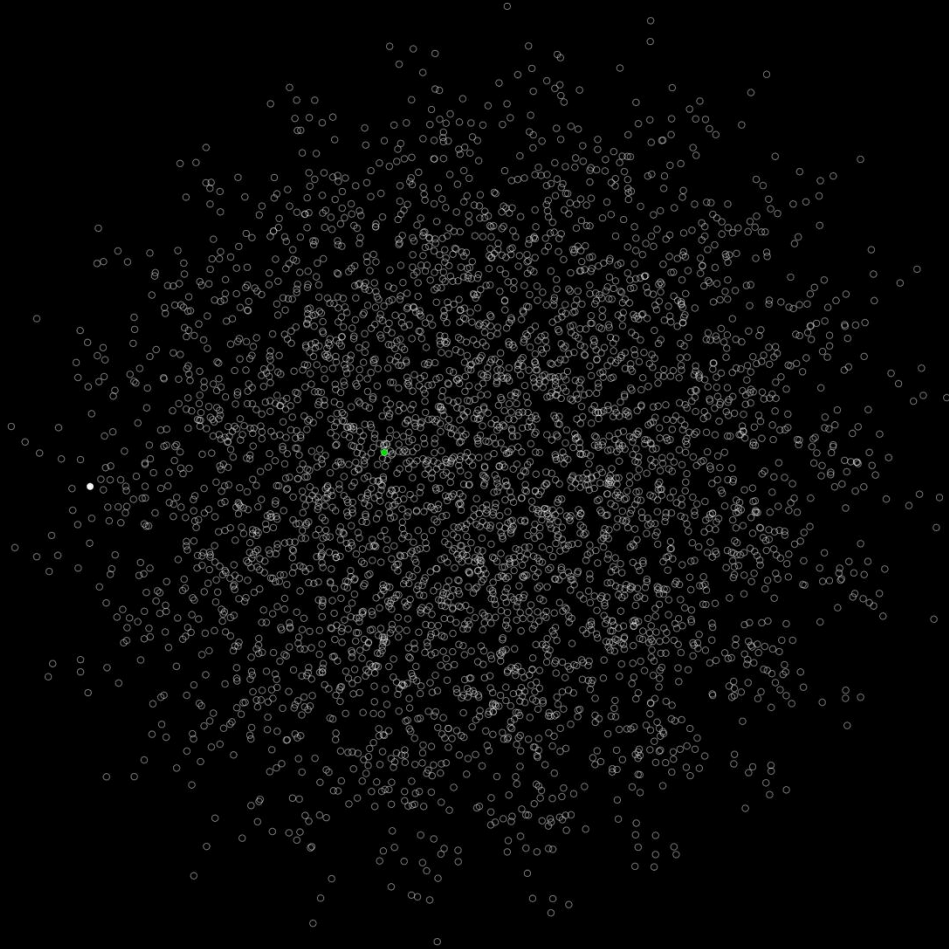
Our solution: **Knapsack Problem**



# A real instance

Knapsack	Out of knapsack
 <p>Items in Knapsack:</p> <ul style="list-style-type: none"><li>\$363 (447kg)</li><li>\$417 (239kg)</li><li>\$5 (104kg)</li><li>\$435 (77kg)</li><li>\$312 (145kg)</li><li>\$424 (21kg)</li><li>\$308 (91kg)</li><li>\$340 (11kg)</li></ul>	 <p>Items out of Knapsack:</p> <ul style="list-style-type: none"><li>\$5 (347kg)</li><li>\$64 (154kg)</li><li>\$151 (377kg)</li><li>\$10 (289kg)</li></ul>
<p>WEIGHT: <b>1135</b></p> <p>CAPACITY: <b>1151</b></p> <p>VALUE: <b>2604</b></p> <p><a href="#">Submit</a></p>	

## Approximation



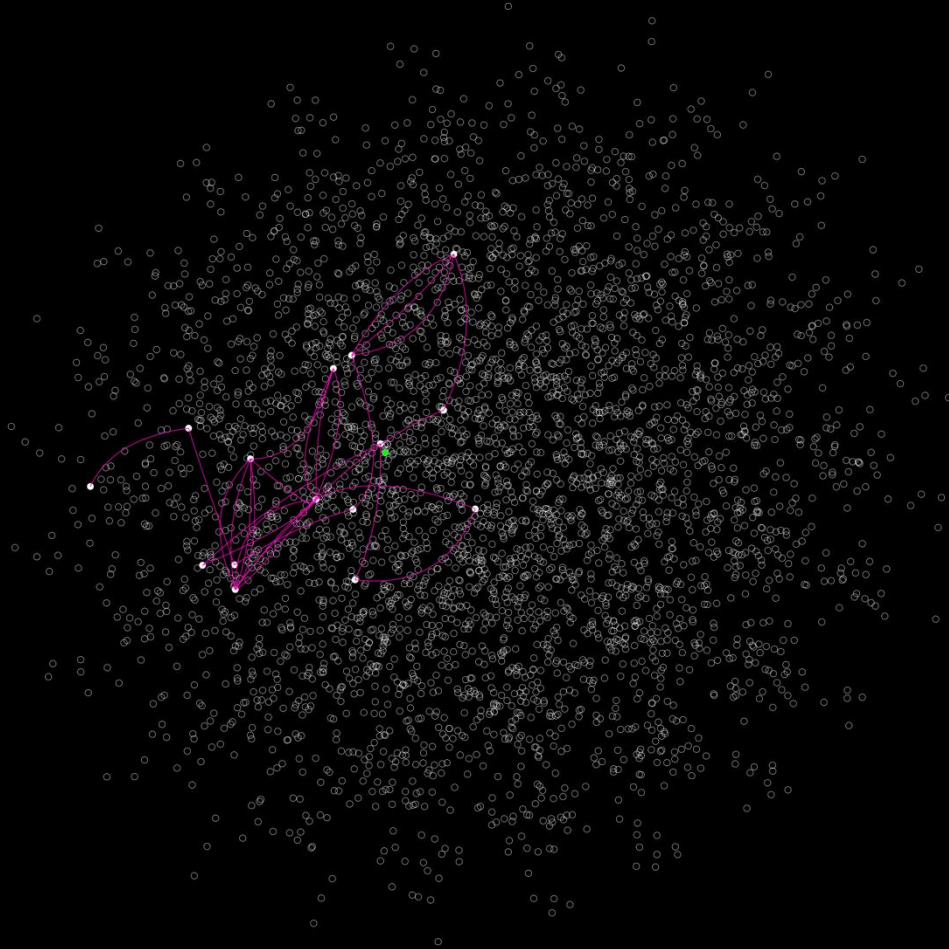
**Problem:** The total solution space is too vast to exhaustively explore.

**Compromise:** Individuals try to strike a balance between:

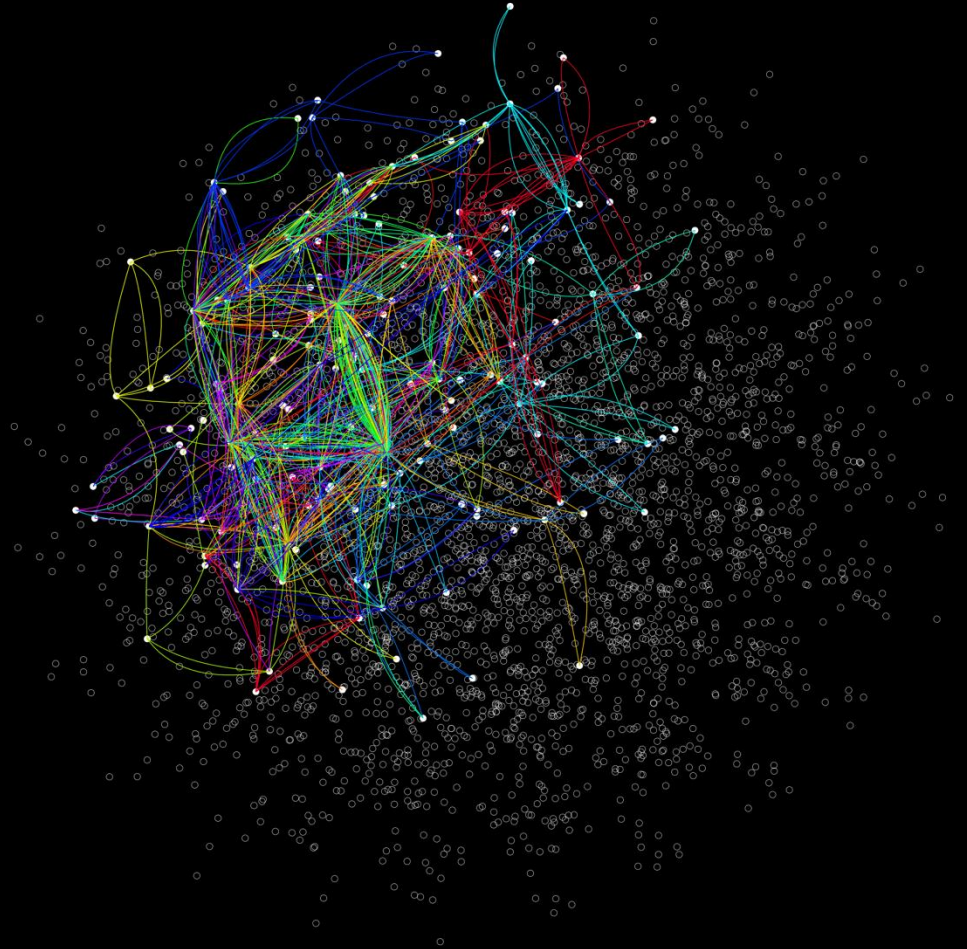
- **Solution quality** – the resulting solution should be within  $\epsilon$  of the optimum.
- **Frugality** – computational cost should be minimised.

**Result:** Search over constrained subset of total solution space.

## Collective problem-solving



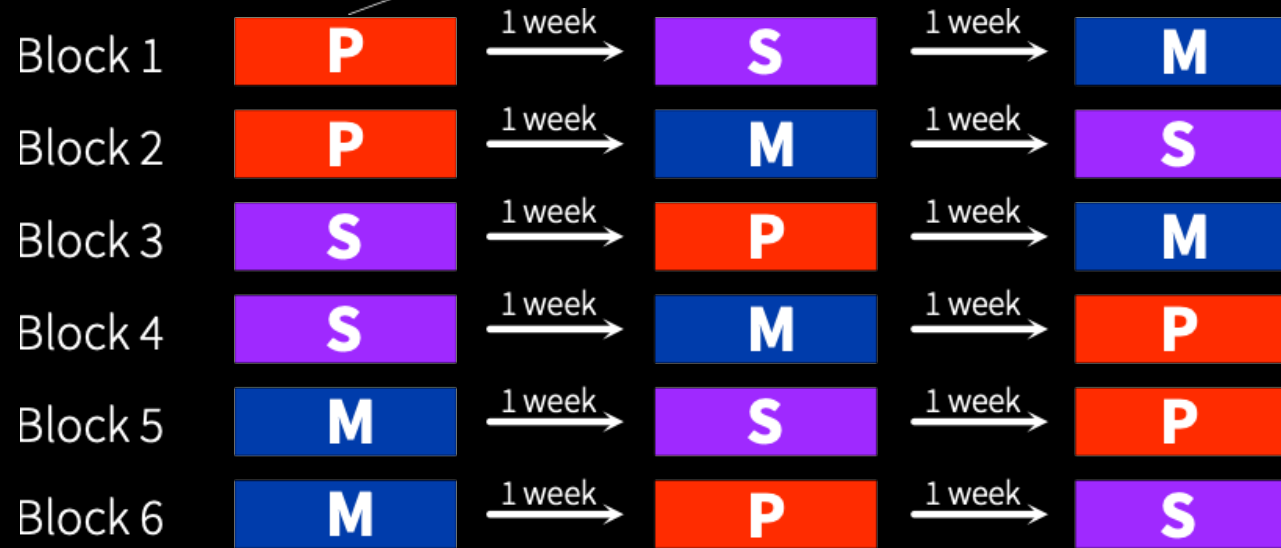
**A single individual** explores a small subset of the solution space.



**A group of individuals** collectively explore a large portion of the solution space.

# Experimental design

5 easy KP instances + 5 KP hard instances



 Prop. payments     Signal     Market







# Market treatment

Problem

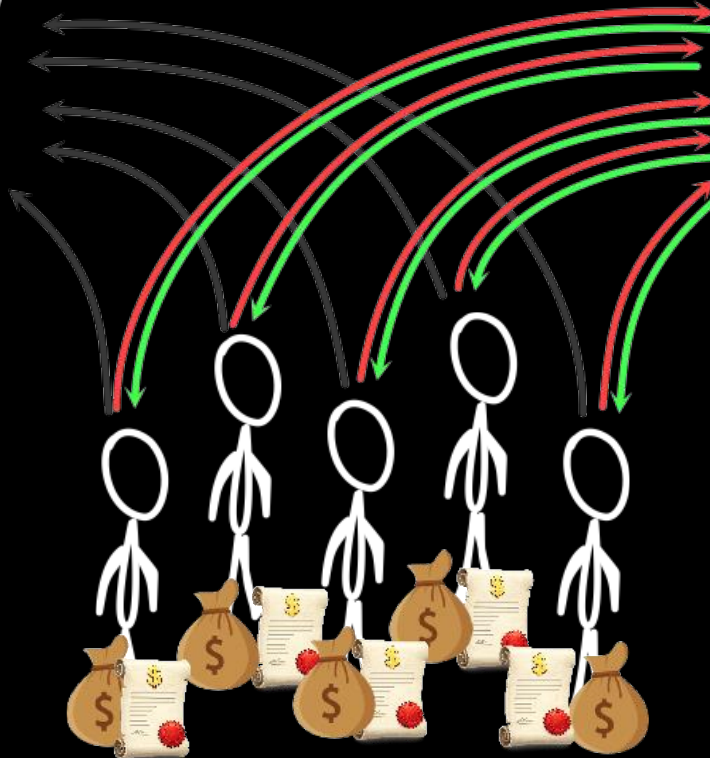


$$\pi = \max\{sol_i, \dots, sol_n\}$$



Contract

Market



People

Profit comes from:

- **Buying** stocks at prices below the final best solution; and
- **Selling** stocks at prices above the final best solution.

# Trading interface

×
FLEX-E-MARKETS beta

1395

SETTLED AVAILABLE

CASH \$10,000.00 \$10,000.00

STOCK 8 8

> STOCK <

ORDER BOOK			TRADE HISTORY	
UNITS	PRICE	MINE		
1	\$1,635.00		1	\$1,621.00 ↘ 12:12:15.653649
1	\$1,630.00		1	\$1,601.00 ↗ 12:11:40.076285
1	\$1,629.00		1	\$1,600.00 ↗ 12:11:33.408663
5	\$1,628.00		1	\$1,599.00 ↗ 12:11:32.055053
1	\$1,625.00		1	\$1,599.00 ↗ 12:11:31.449416
1	\$1,624.00		1	\$1,578.00 ↘ 12:11:29.961996
1	\$1,623.00		1	\$1,600.00 ↗ 12:11:29.591124
7	\$1,622.00		1	\$1,579.00 ↗ 12:11:23.832215
<i>spread</i> \$5.00 $\frac{\$}{\$}$			1	\$1,579.00 ↘ 12:11:20.677043
1	\$1,617.00		1	\$1,579.00 ↘ 12:11:19.880675
1	\$1,616.00		1	\$1,600.00 ↘ 12:11:19.860863
1	\$1,602.00		1	\$1,601.00 ↗ 12:11:18.852256
1	\$1,601.00		1	\$1,600.00 ↗ 12:11:09.014648
1	\$1,601.00		1	\$1,598.00 ↗ 12:11:01.493633
1	\$1,600.00		1	\$1,598.00 ↗ 12:10:58.571631
1	\$1,457.00		2	\$1,579.00 ↗ 12:10:44.022596
1	\$1,421.00		1	\$1,578.00 ↗ 12:10:40.072490
2	\$1,331.00		1	\$1,599.00 ↗ 12:10:03.885024

STOCK

BUY
SELL

UNITS 
●

1

−
+

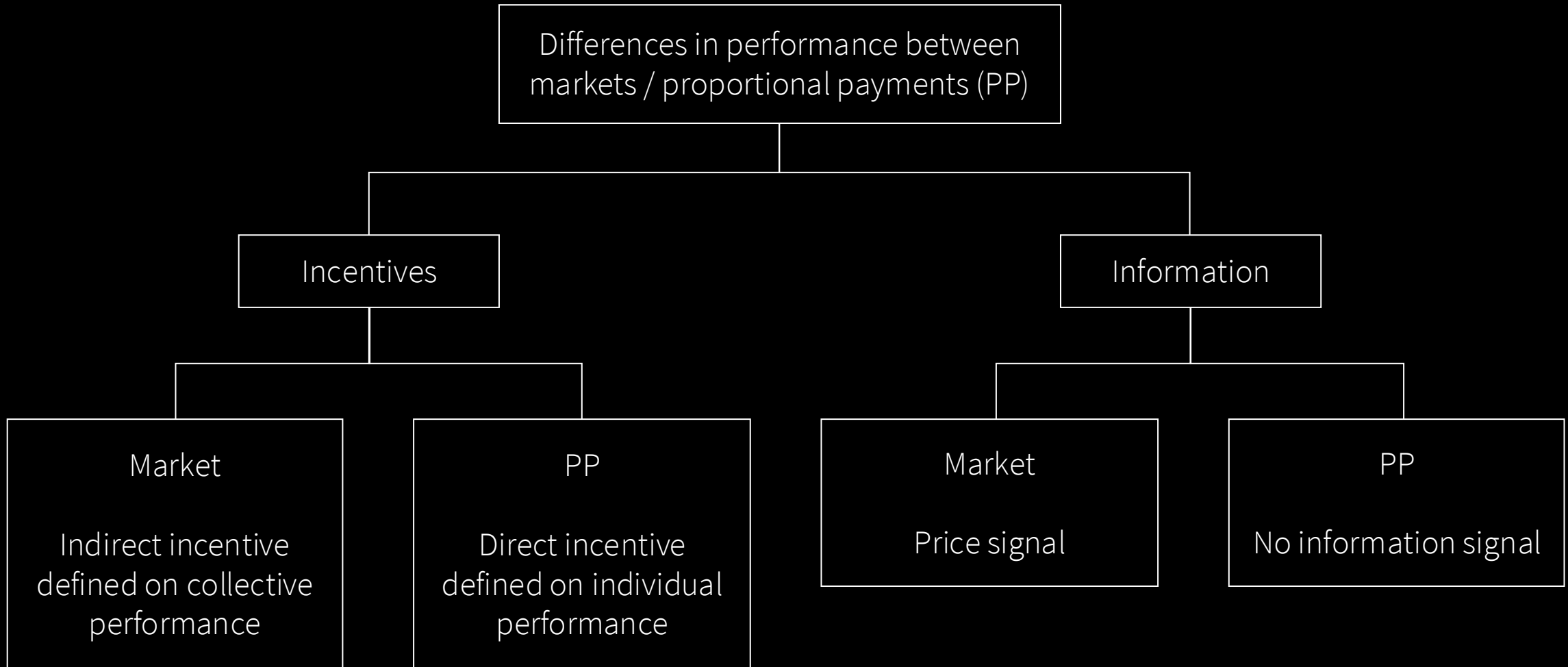
PRICE 
●

\$1.00

−
+

PLACE BUY ORDER

# Disentangling performance



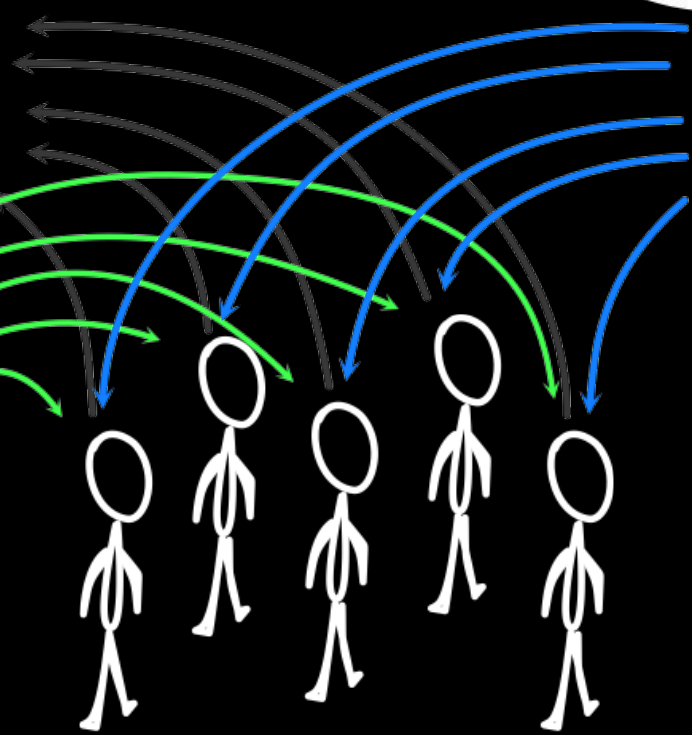


Proportional payments + signal treatment

Problem



Pot of money



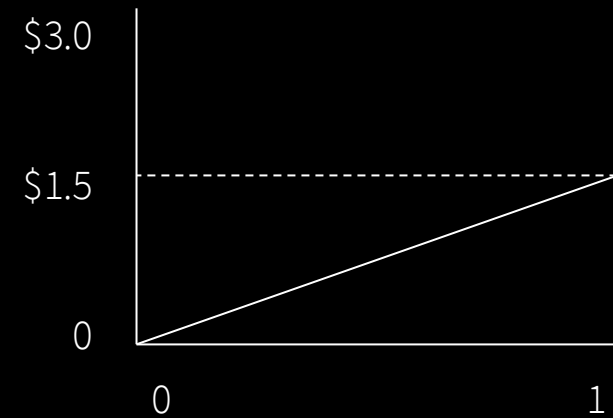
People

Oracle

The optimal value is \$1,999

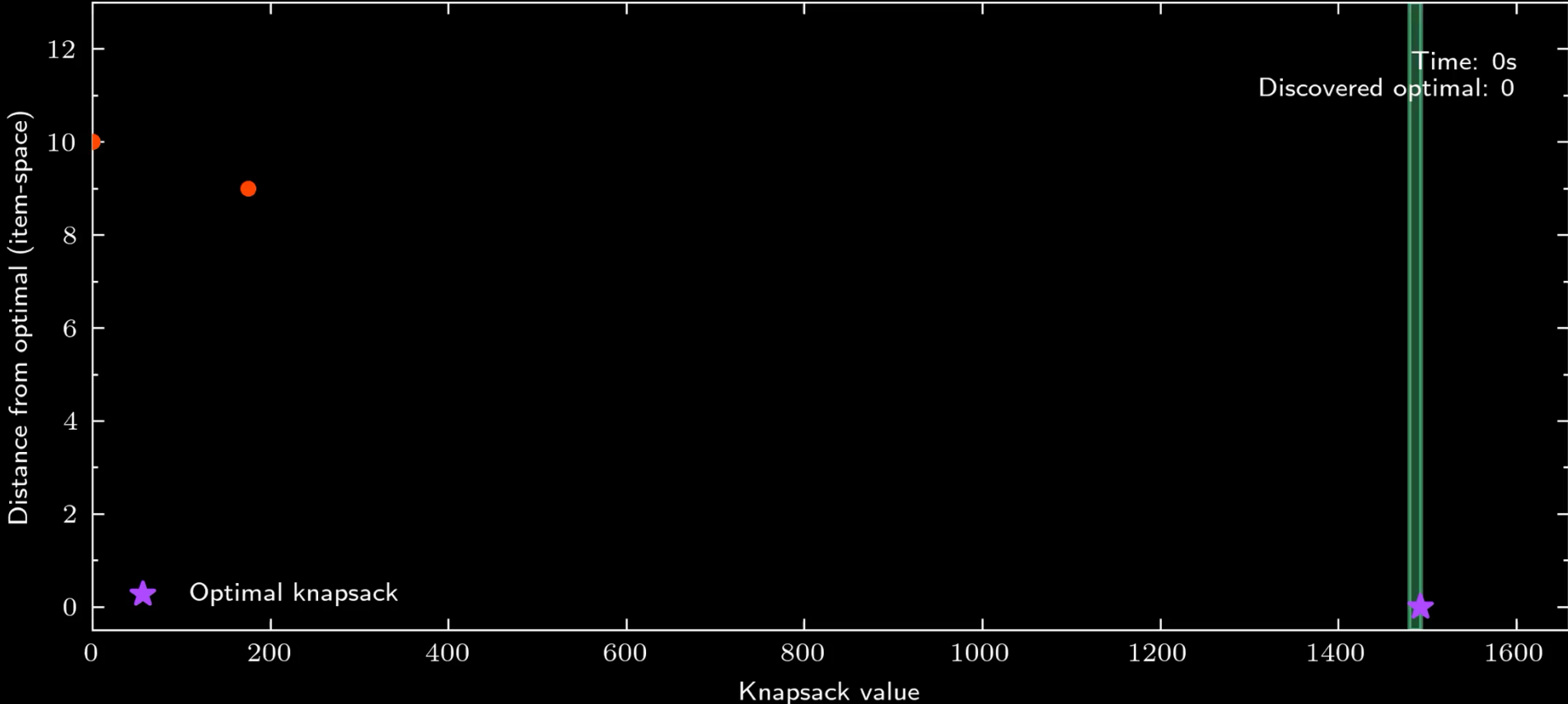


The Matrix, 1999



Submitted value / optimal value

# Market condition

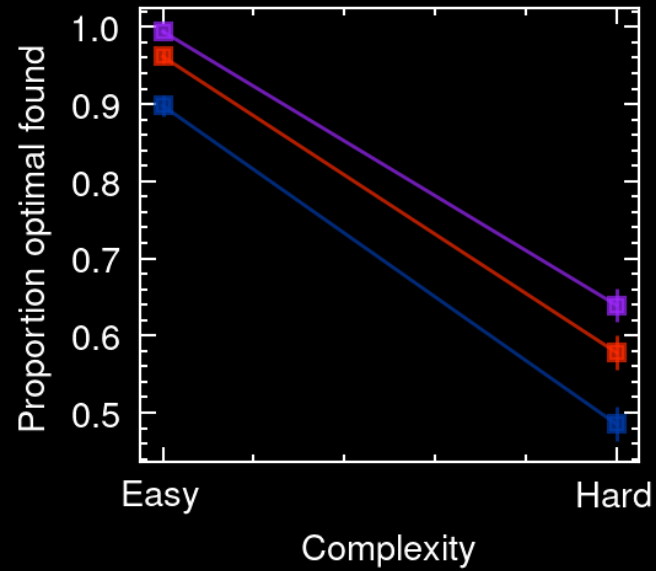


## Outcome measures

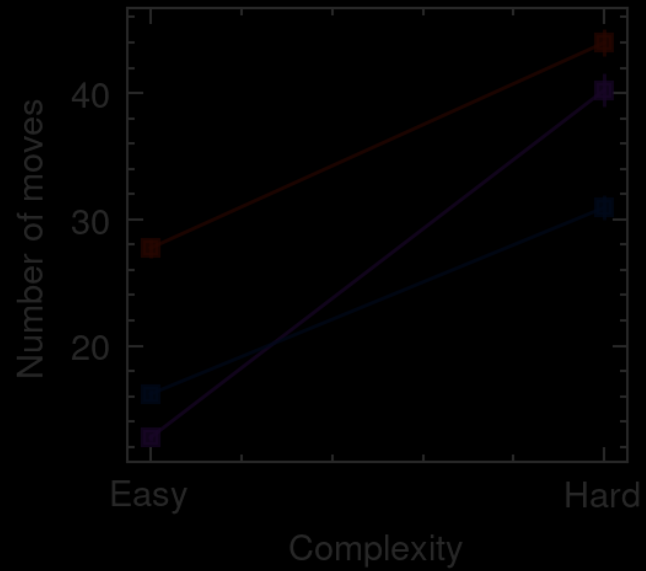
- 1. Quality**  
Probability optimal solution attained
- 2. Effort**  
Number of 'item moves'
- 3. Productivity**  
Submitted value / number of moves
- 4. Price efficiency**  
How well do prices aggregate knowledge?

# Quality, effort, productivity

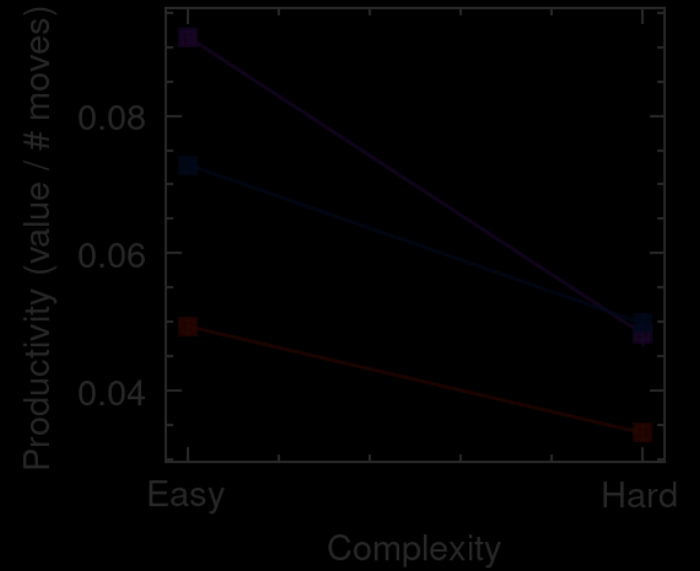
## A



## B



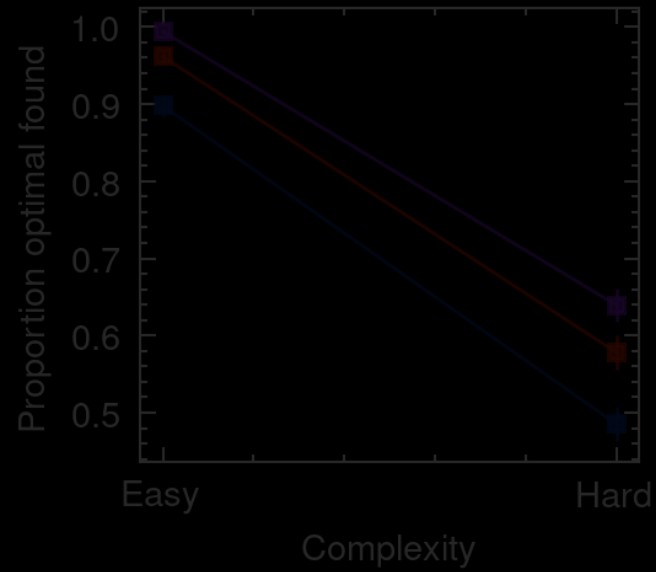
## C



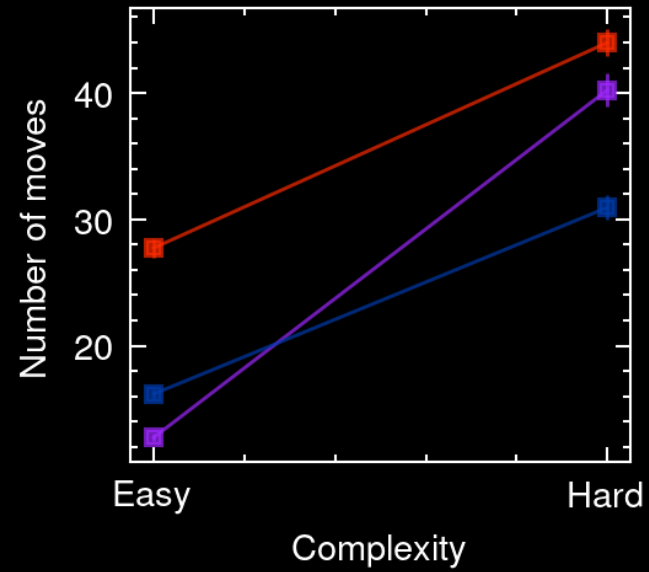
Prop. payments    Signal    Market

# Quality, effort, productivity

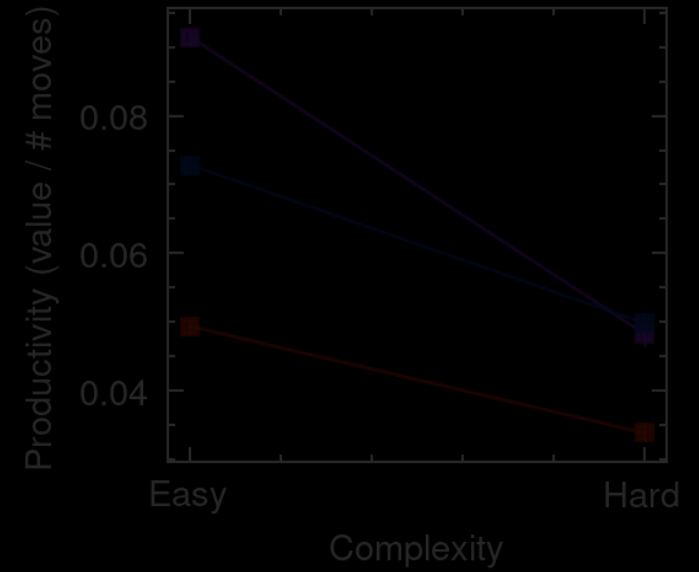
## A



## B



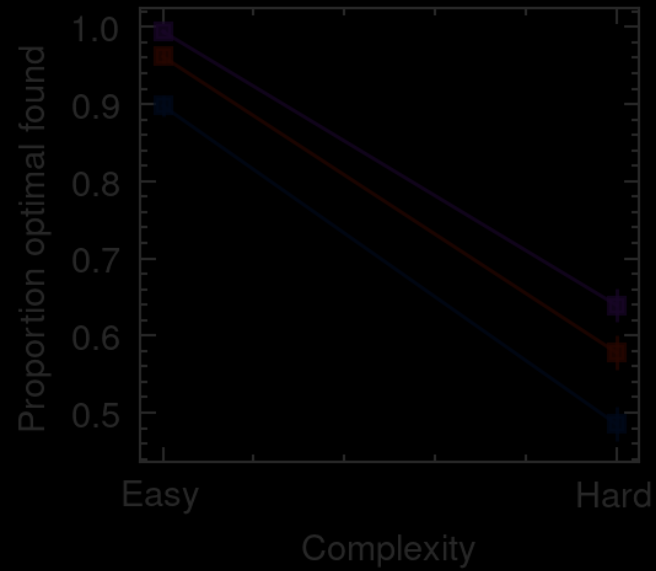
## C



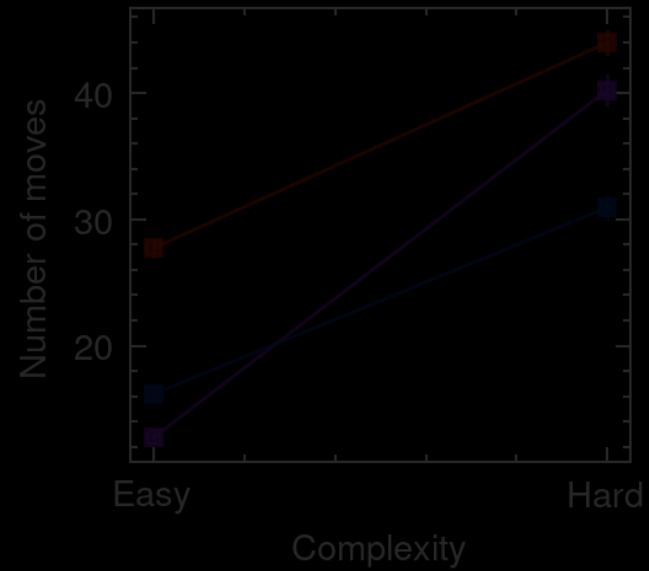
Prop. payments    Signal    Market

# Quality, effort, productivity

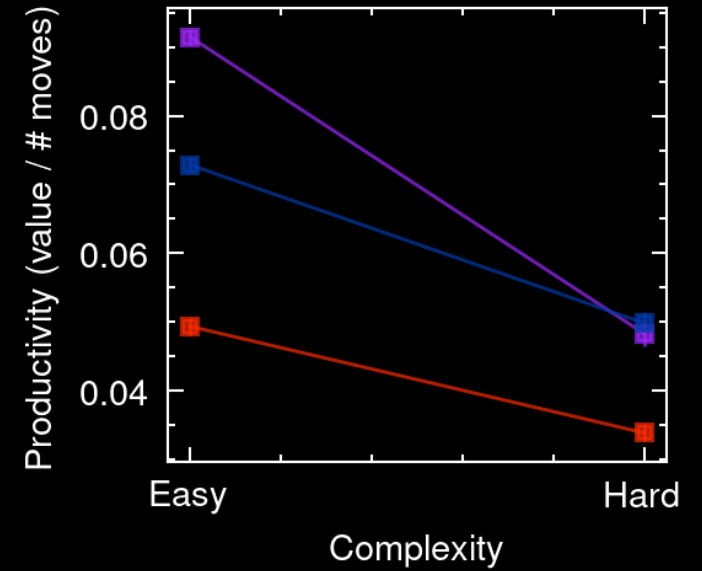
## A



## B



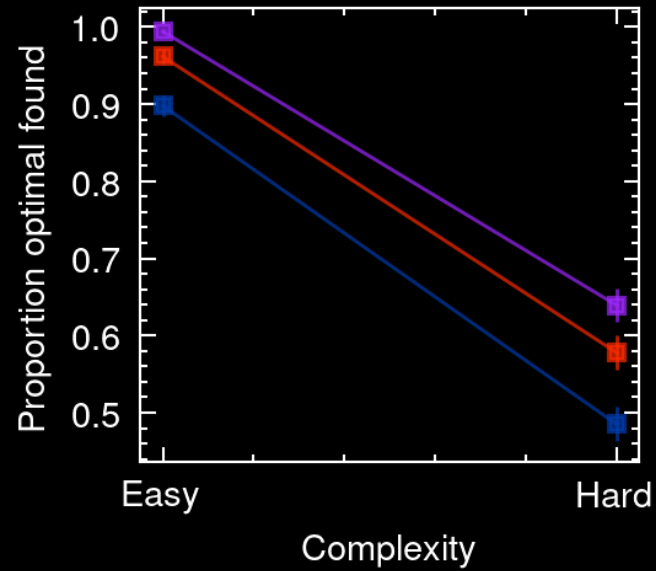
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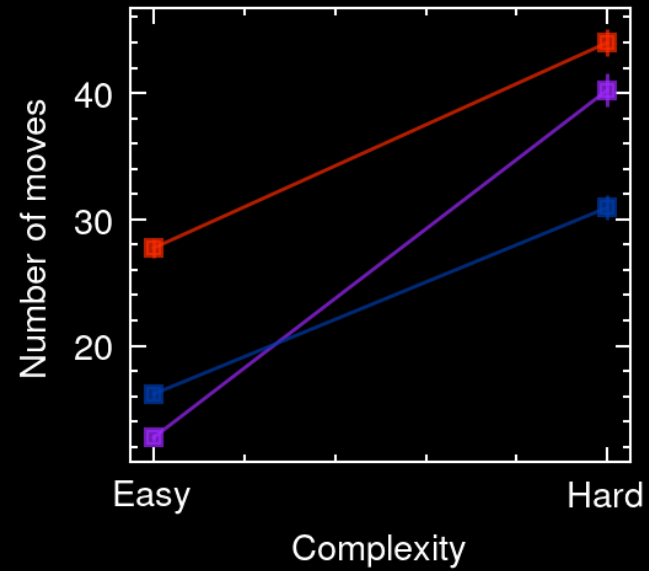
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# Quality, effort, productivity

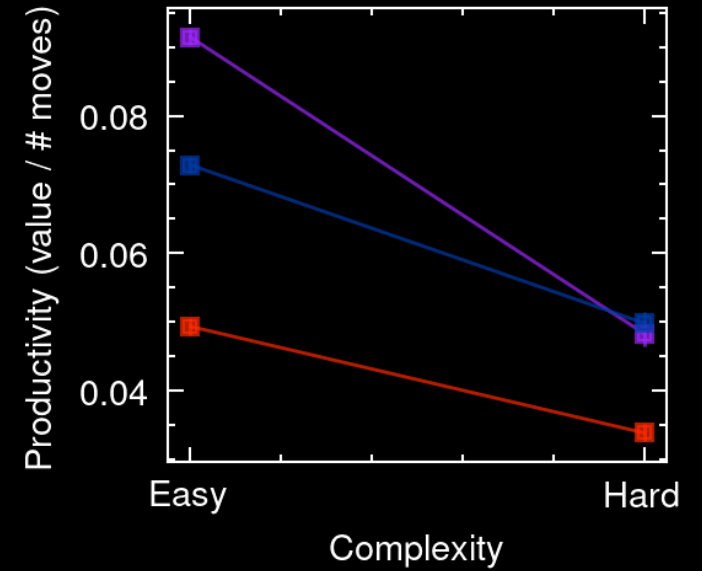
## A



## B



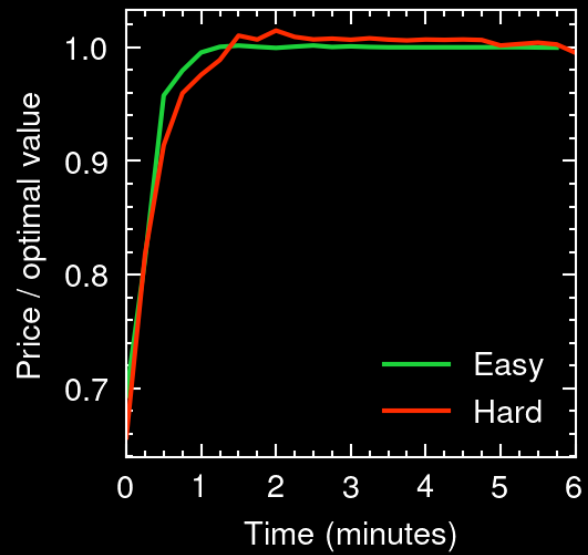
## C



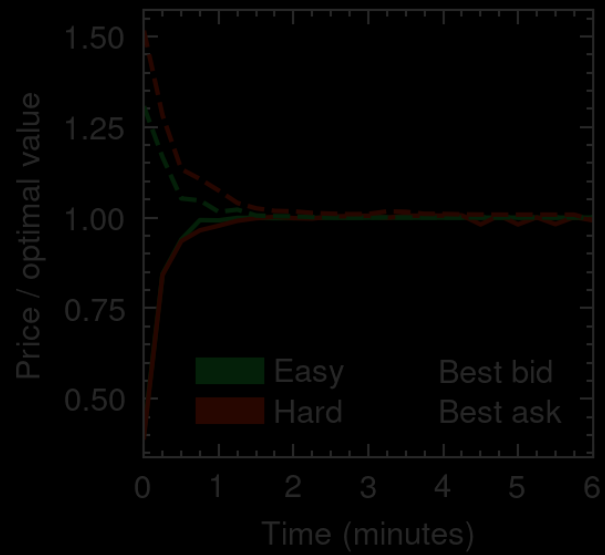
Prop. payments    Signal    Market

# Price efficiency and returns

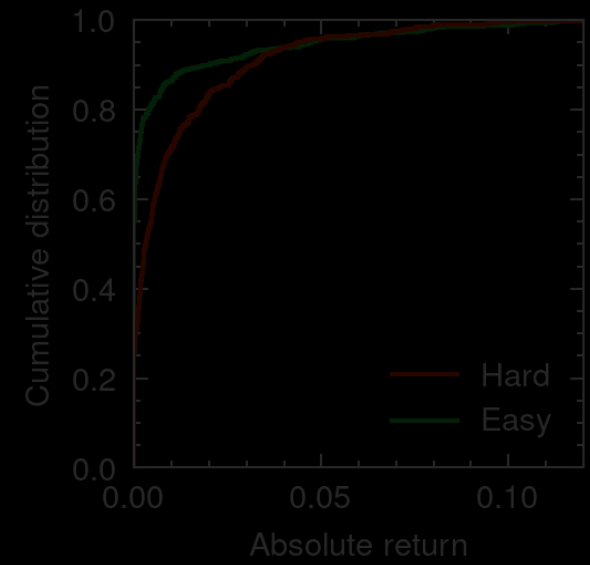
## A



## B

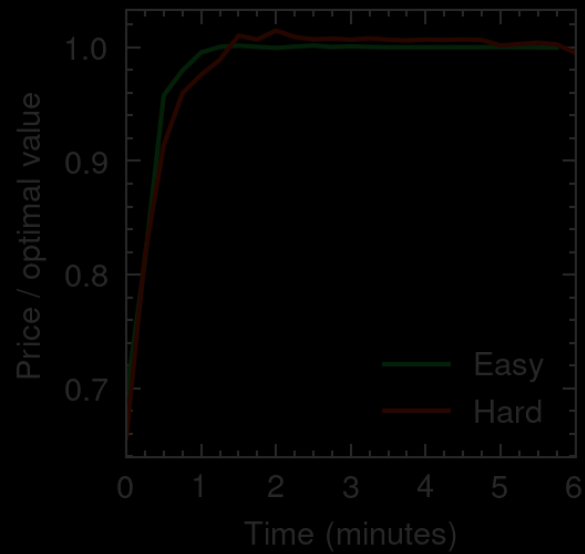


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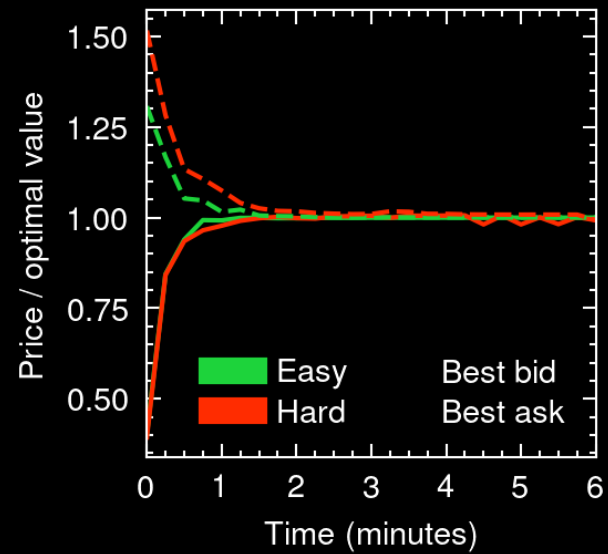


# Price efficiency and returns

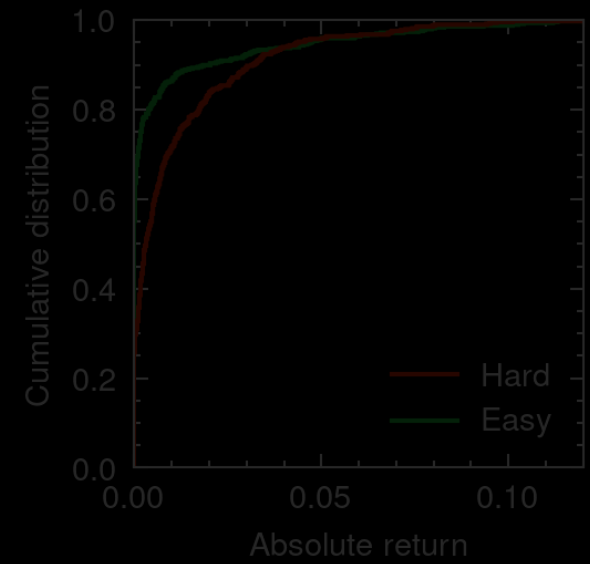
## A



## B

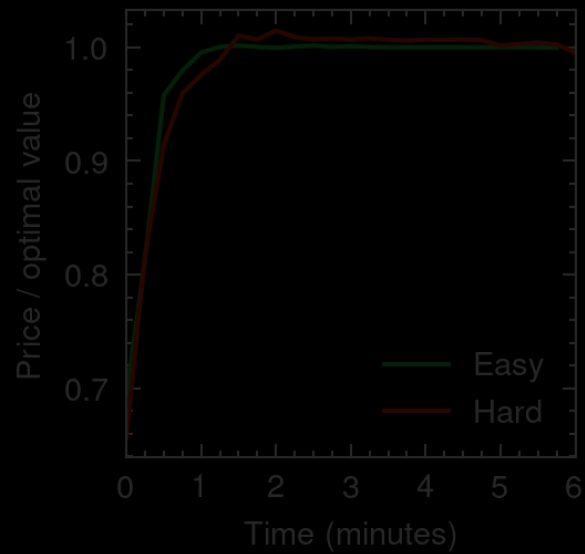


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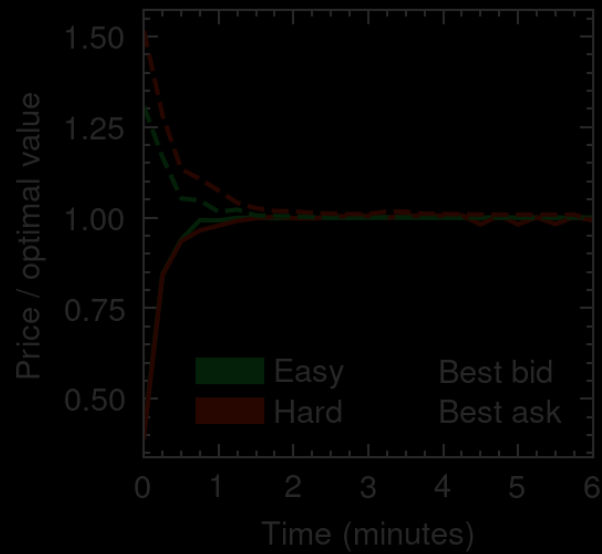


# Price efficiency and returns

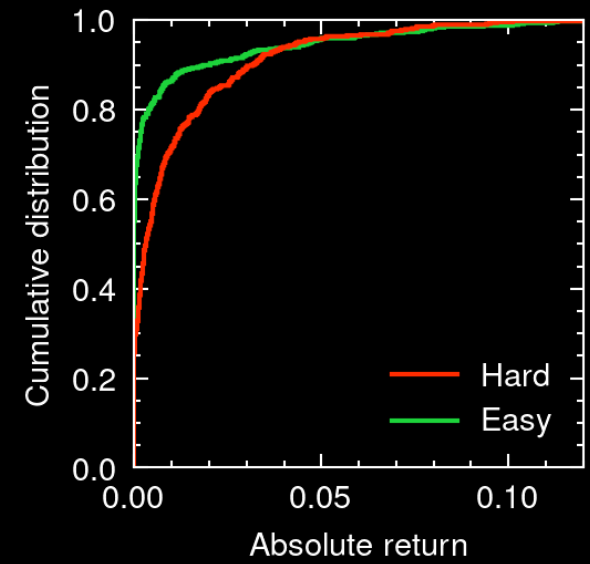
## A



## B

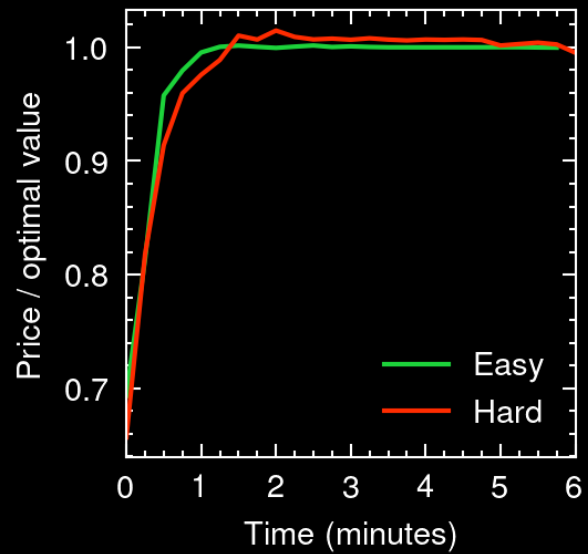


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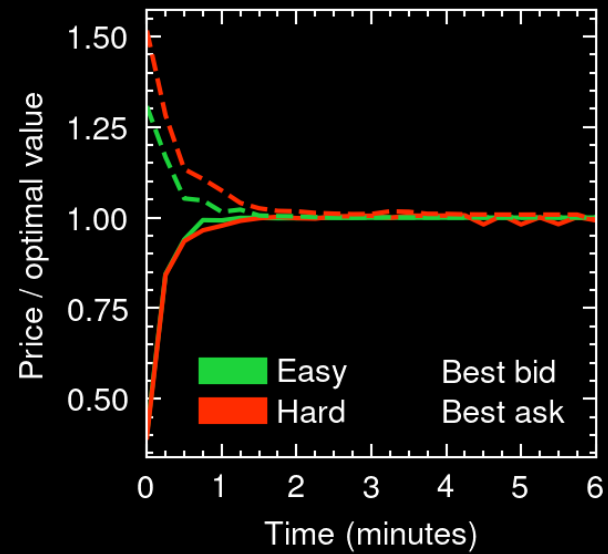


# Price efficiency and returns

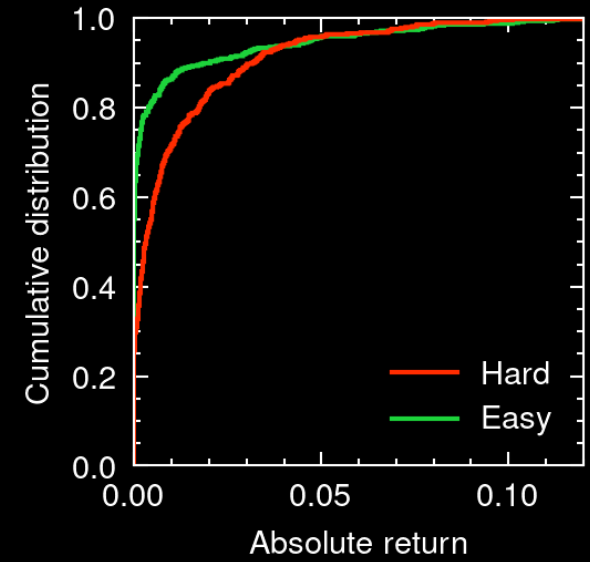
## A



## B



## C



## Summary

### **1. Complexity matters**

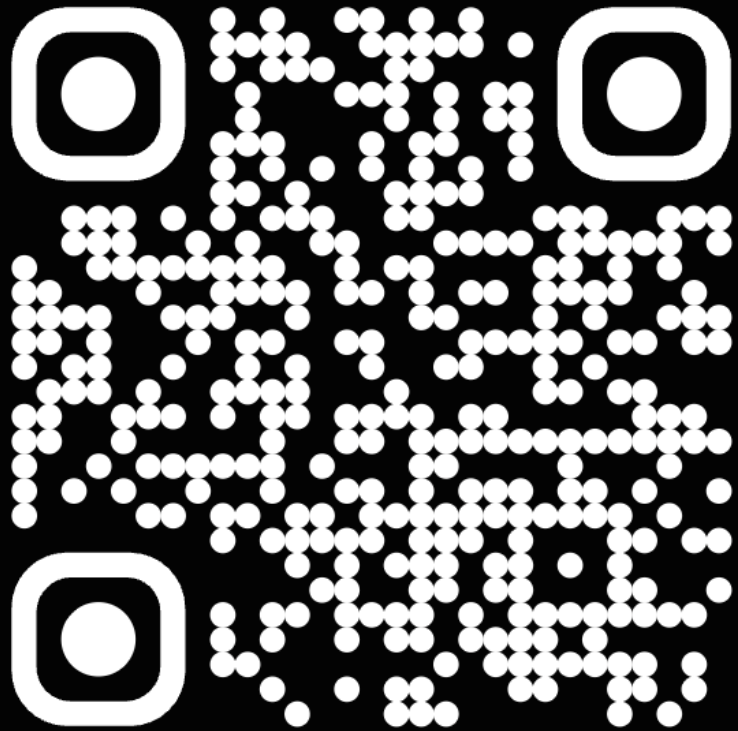
Higher problems reduce performance but markets and signals can mitigate this.

### **2. Markets enable coordination**

Groups explore larger portions of the solution space, trading shares information and reduces redundant effort.

### **3. Market efficiency degrades with complexity**

Prices are less efficient when it is computationally difficult to estimate fundamental



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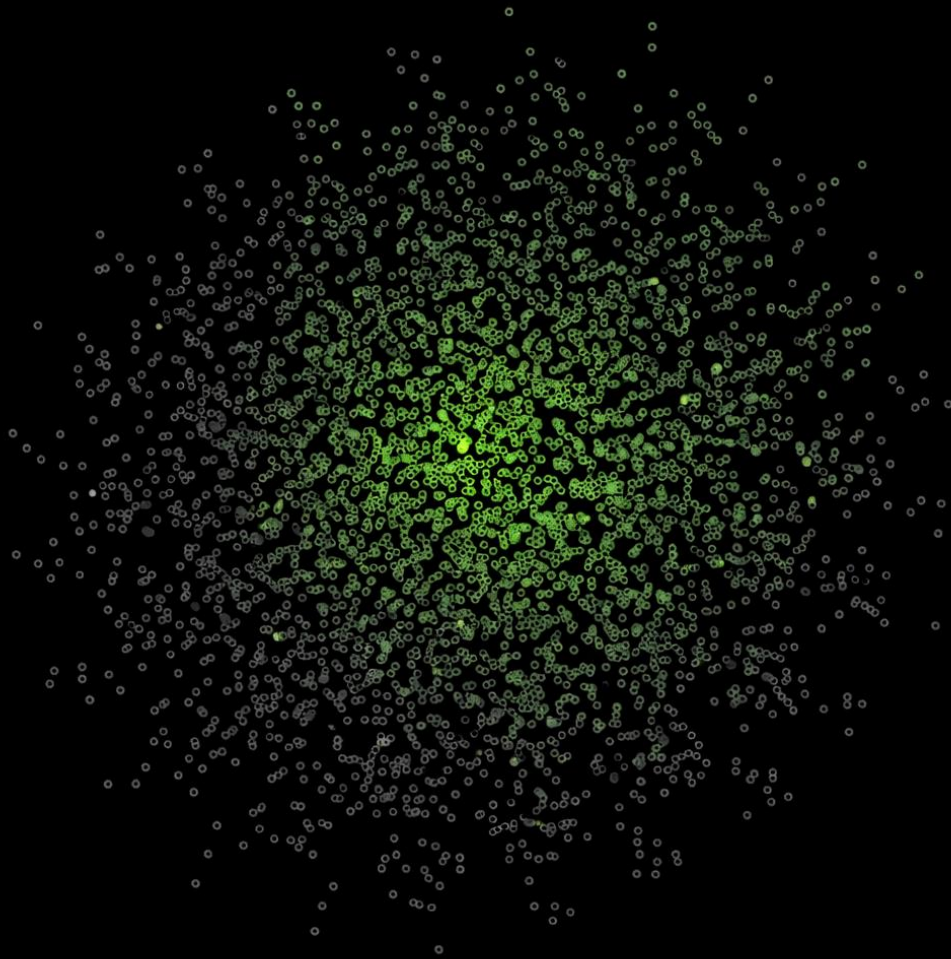
Peter Bossaerts  
LIPNE Laboratory  
Department of Economics  
University and Cambridge



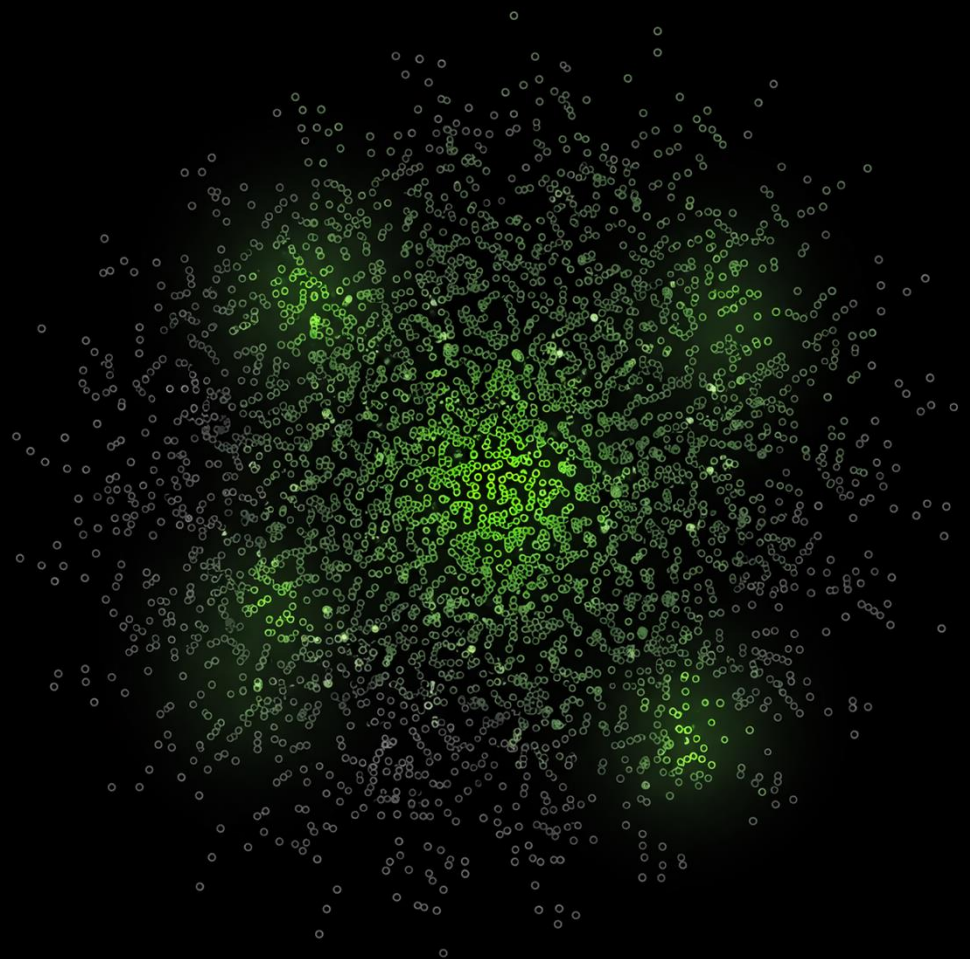
## References

1. Schumpeter, J. A. (1911). *The Theory of Economic Development: An Inquiry into Profits, Capital, Credit, Interest, and the Business Cycle*. Harvard University Press.
2. Hayek, F. A. (1945). The use of knowledge in society. *The American Economic Review* 35(4), 519–530.
3. Machlup, Fritz. *An economic review of the patent system*. No. 15. US Government Printing Office, 1958.
4. Usher, Dan. "The welfare economics of invention." *Economica* 31.123 (1964): 279-287.
5. Hall, Bronwyn H., and Dietmar Harhoff. "Recent research on the economics of patents." *Annu. Rev. Econ.* 4.1 (2012): 541-565.
6. Bossaerts, Peter, et al. "Resource allocation, computational complexity, and market design." *Journal of Behavioral and Experimental Finance* 42 (2024): 100906.

# Modulating complexity



**Smooth** landscape = **easy** instance

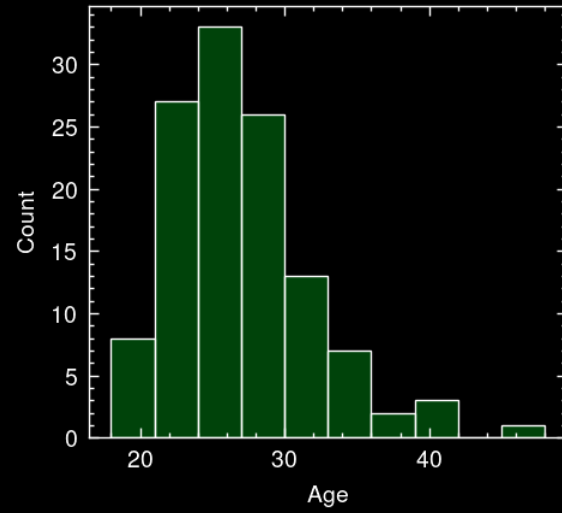


**Rugged** landscape = **hard** instance

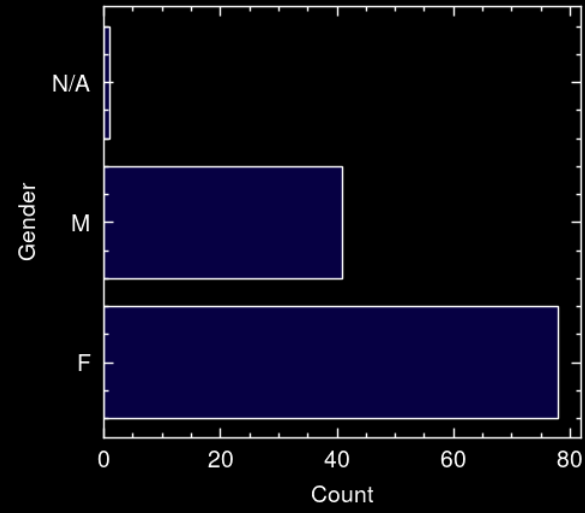


# Demographics

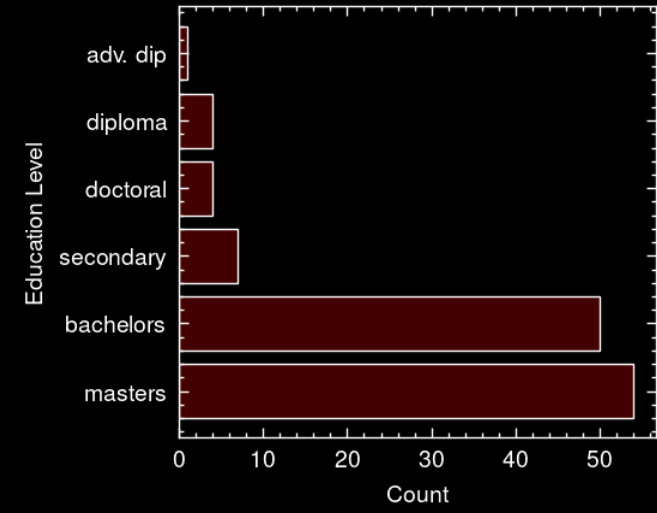
A



B

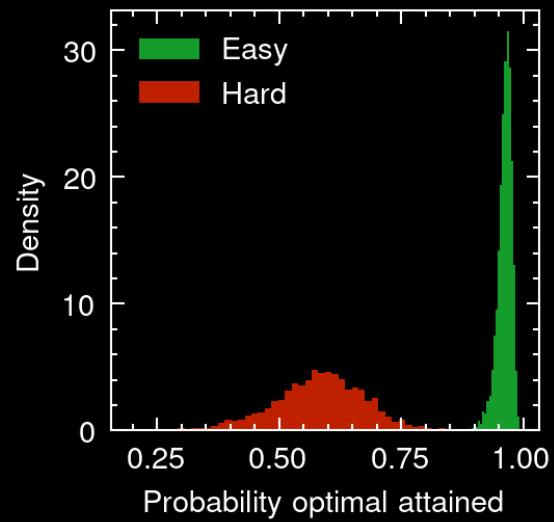


C

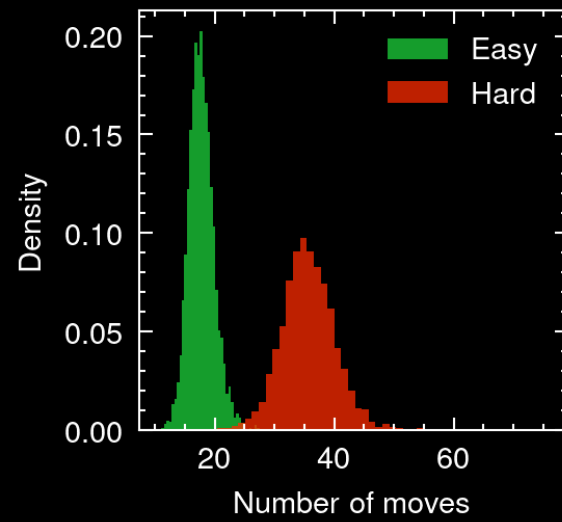


# Effectiveness of complexity manipulation

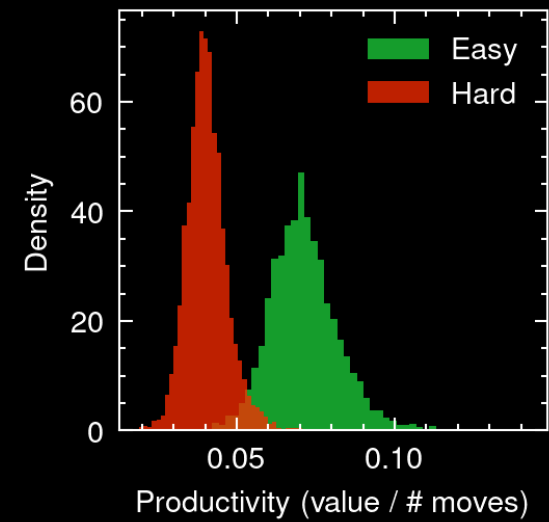
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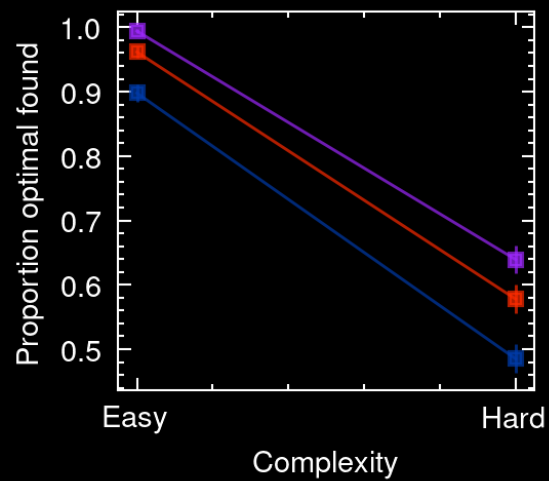
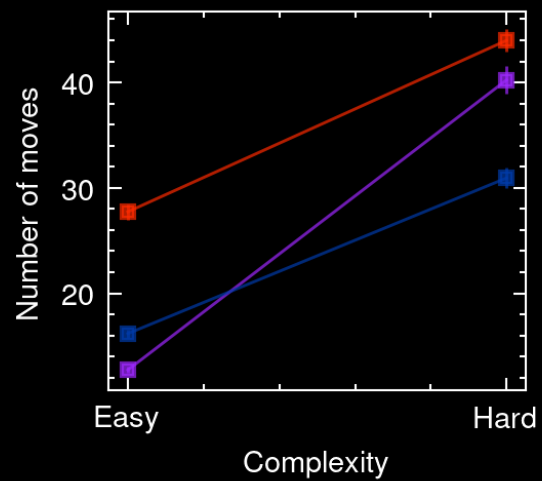
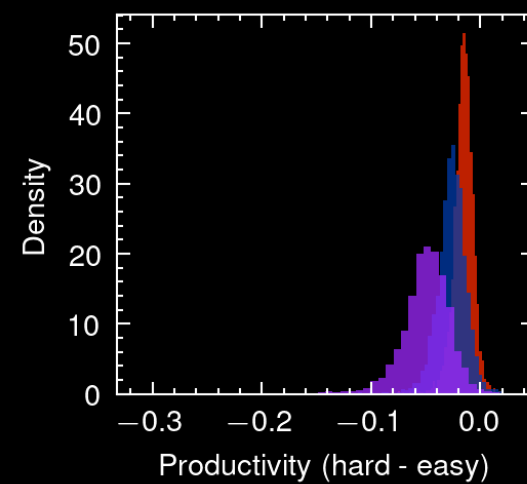
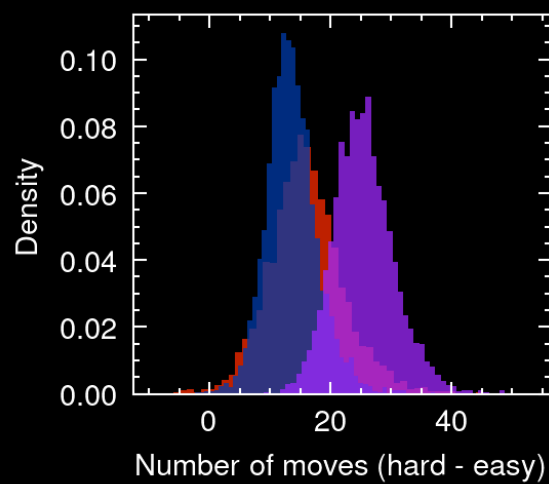
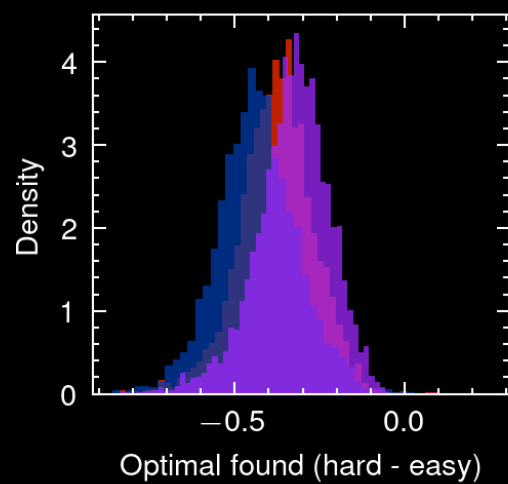
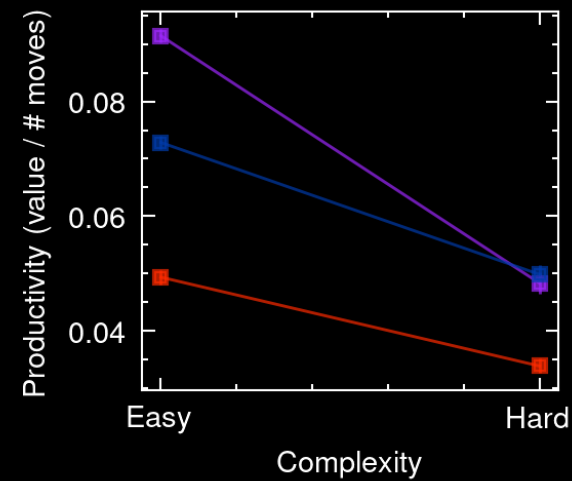


## B



## C

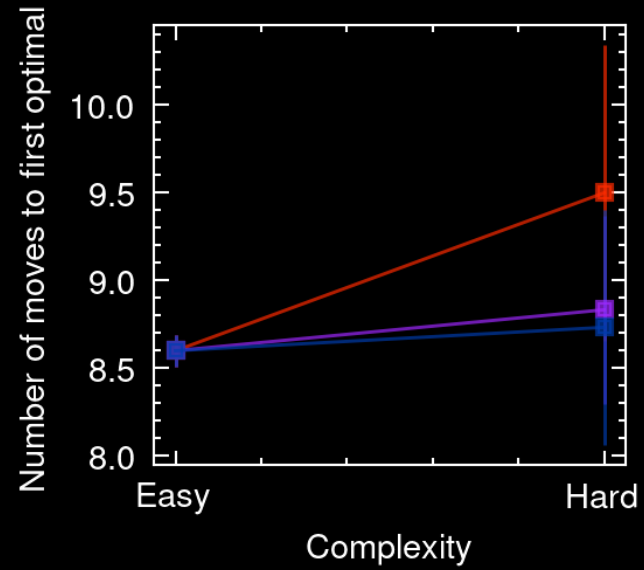


**A****B****C**

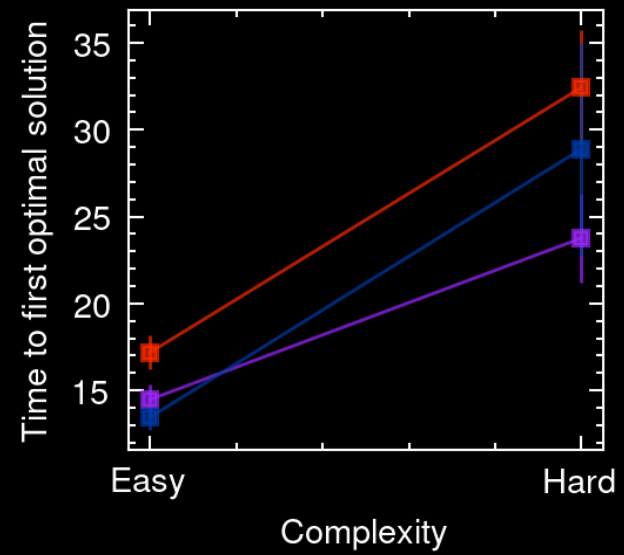
■ Prop. payments    
 ■ Signal    
 ■ Market

# Speed of discovery

## A



## B



Prop. payments    Signal    Market