

WHAT'S WRONG WITH SCIENCE ?

Modeling the collective discovery processes with the Nobel Game

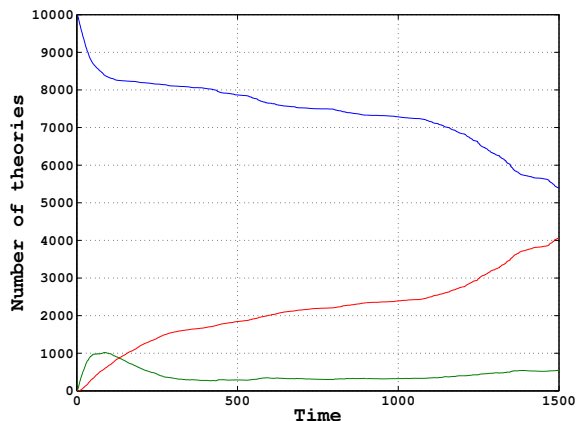
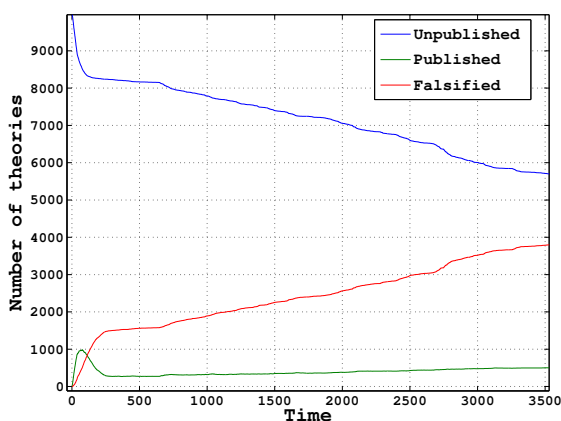
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APPENDICES

A1 Case-studies 1 and 2

TABLE S1 – Summary of the parameters used for case-studies 1 and 2.

Description	Values
Number of agents	$N_a = 1,000$
Number of theories	$N_T = 10,000$
Payoffs for a publication	$P = 1$ (case1) ; $P = 100$ (case2)
Payoffs for a refutation	$R = 10$
Loss for being refuted	$L = 10$
Proportion of Type II theories	$p = 0.9$
Bernoulli parameter for type II theories	$q = 0.98$

FIGURE S1 – Evolution of the number of CK theories (published), \overline{CK} (unpublished) and the set of falsified theories for case-study 1 (left, $P = 1$) and case-study 2 (right, $P = 100$).

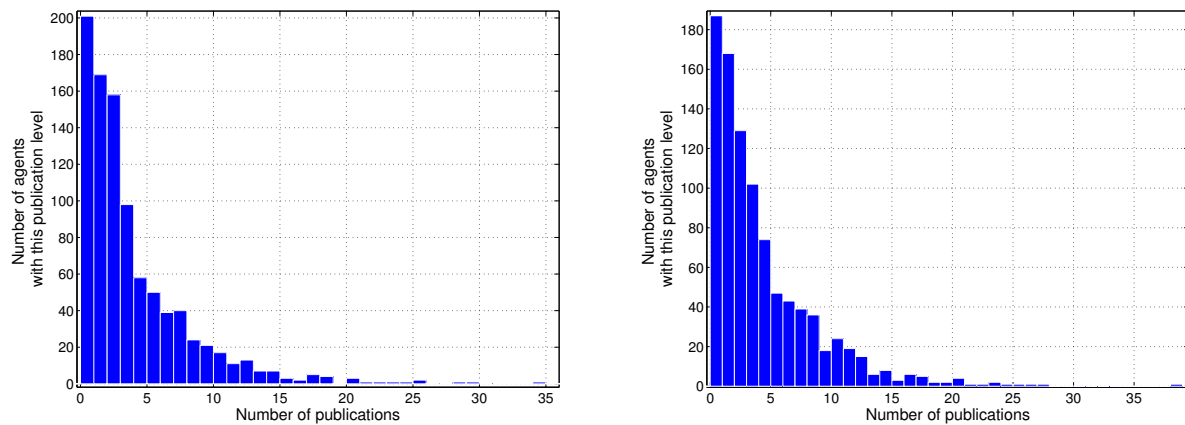


FIGURE S2 – Histogram of the number of publications per author for case-study 1 (left, $P = 1$) and case-study 2 (right, $P = 100$) for $A = 0.5$.

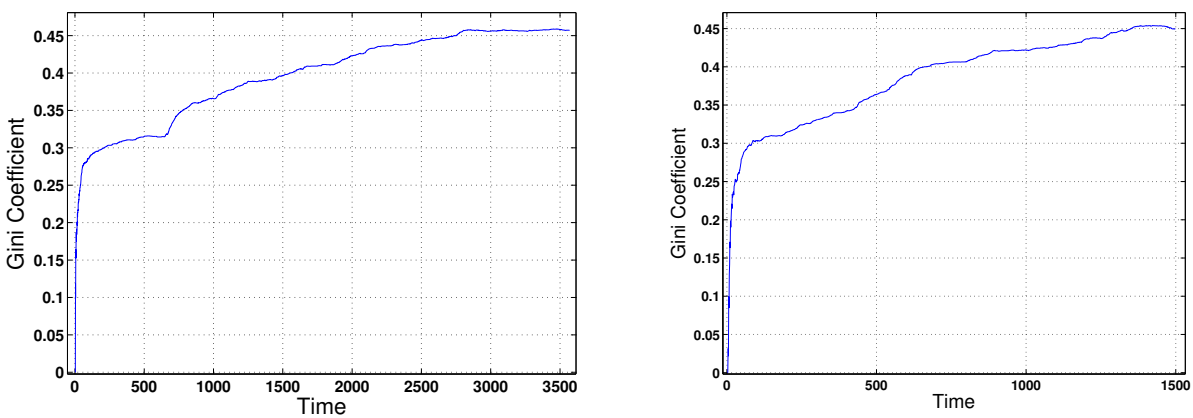


FIGURE S3 – Evolution of the Gini index of the number of publications per author for case-study 1 (left, $P = 1$) and case-study 2 (right, $P = 100$) until $A = 0.6$.

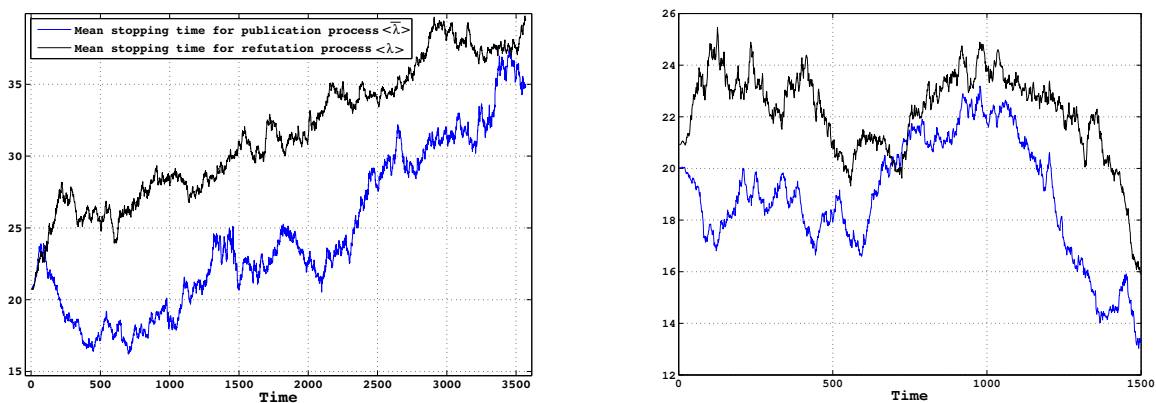


FIGURE S4 – Evolution of the stopping times for publication and refutation for case-study 1 (left, $P = 1$) and case-study 2 (right, $P = 100$) until $A = 0.5$.

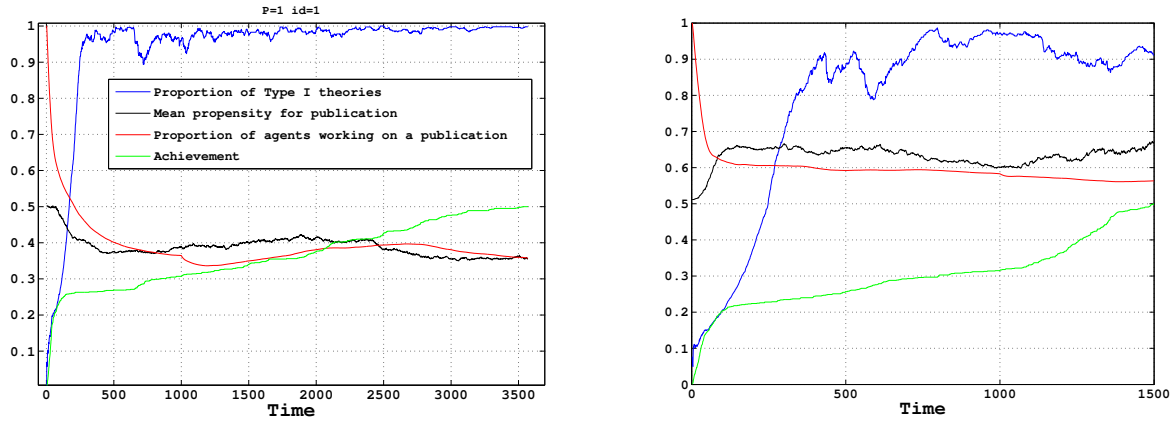


FIGURE S5 – Evolution of the proportion of type I theories, achievement and propensity for publication for case-study 1 (left, $P = 1$) and case-study 2 (right, $P = 100$) until $A = 0.5$. Note the significant differences in terms of type I theory dynamics and propensity for publication between the two cases.

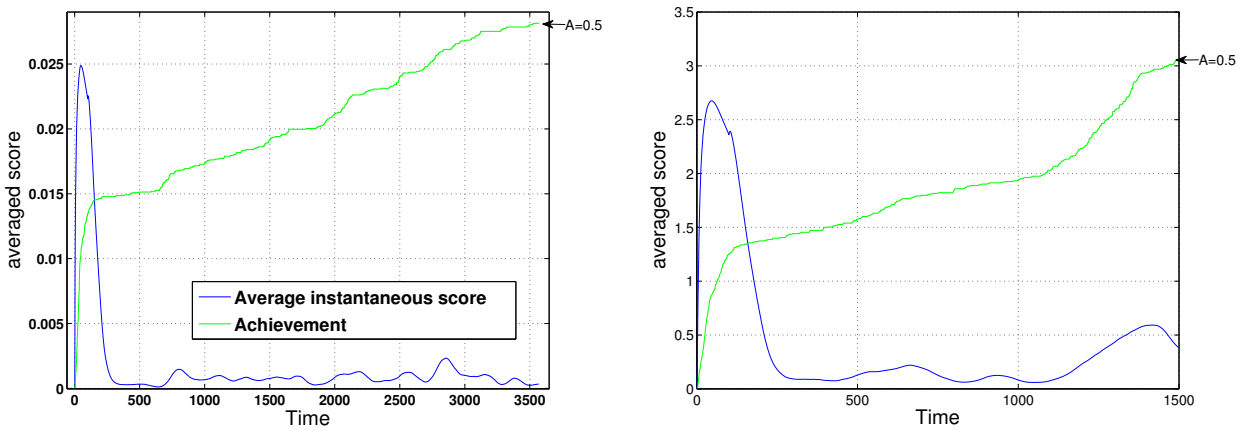


FIGURE S6 – Evolution of the proportion of instantaneous scores $\langle g_i^t \rangle_{i \in \mathcal{P}}$ for case-study 1 (left) and case-study 2 (right). For each point, scores are averaged over the population and the 100 last periods highlight the trends. Note that there are similarities between the two case-studies at the early stages of the discovery process although the later stages are different. For information, the achievement is also plotted, but the curve has been normalized for clarity, the last point corresponding to an achievement of $A = 0.5$.

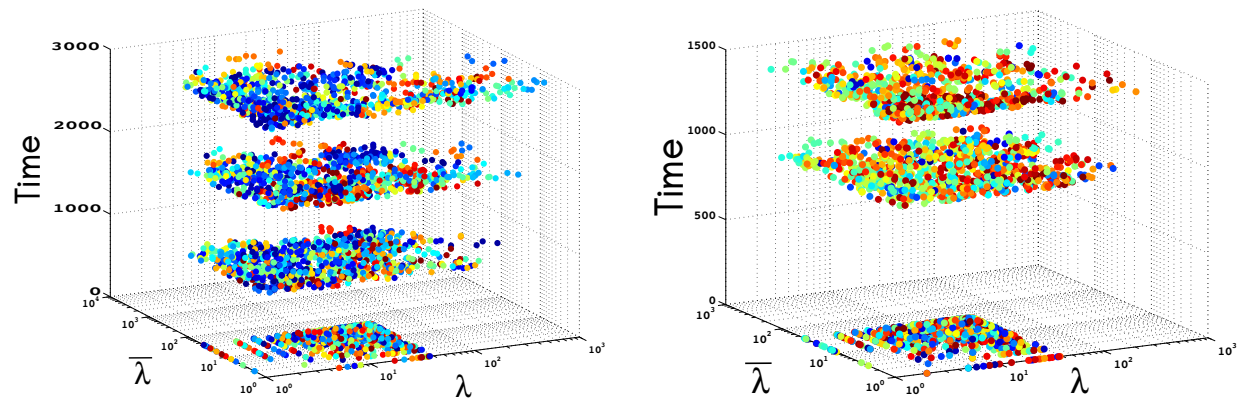


FIGURE S7 – Evolution of the agent's strategies in the 3D log coordinate $(\bar{\lambda}, \lambda, \text{Time})$ for case-study 1 (left) and case-study 2 (right) until $A = 0.5$. The color maps the values of ν : warm colors for high propensity for publication ($\nu > 0.5$), cold colors for low propensity for publication ($\nu < 0.5$). $\bar{\lambda}$ and λ are plotted on a log scale.

A2 Sensitivity analysis

A2.1 Sensitivity analysis 1 : abundance with weak separation

TABLE S2 – Summary of the parameters used for sensitivity analysis (*SA1*)

Description	Values
Number of agents	$N_a = 100$
Number of theories	$N_T = 3000$
Payoff for a publication	$P = 1, 5, 10, 20, 50, 100$
Payoff for a refutation	$R = 10$
Loss for being refuted	$L = 10$
Proportion of Type II theories	$p = 0.9$
Bernoulli parameter for type II theories	$q = 0.98$
Number of independent simulations per points	100

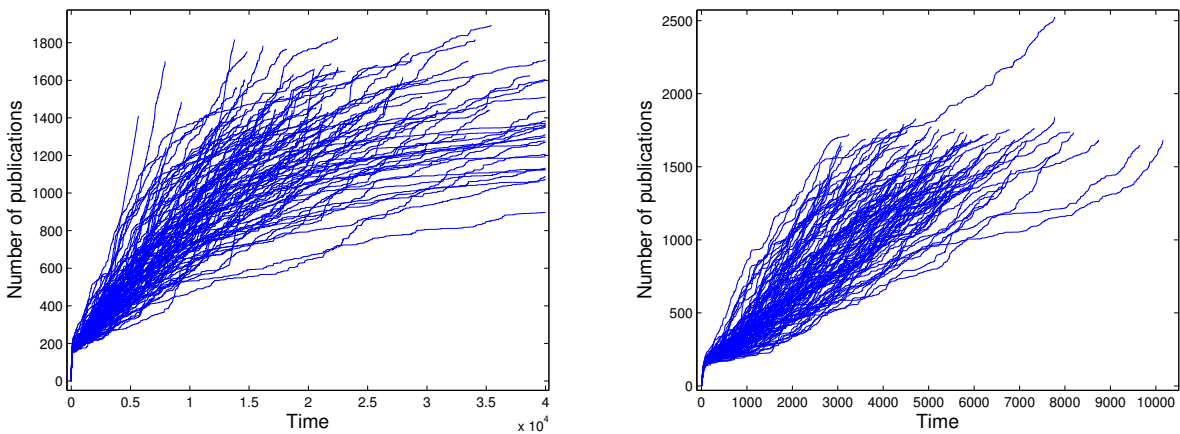


FIGURE S8 – Plot of the number of publications for sensitivity analysis *SA1* for $P = 1$ (left) and $P = 100$ (right). The number of publications is the sum of the published theories and falsified theories.

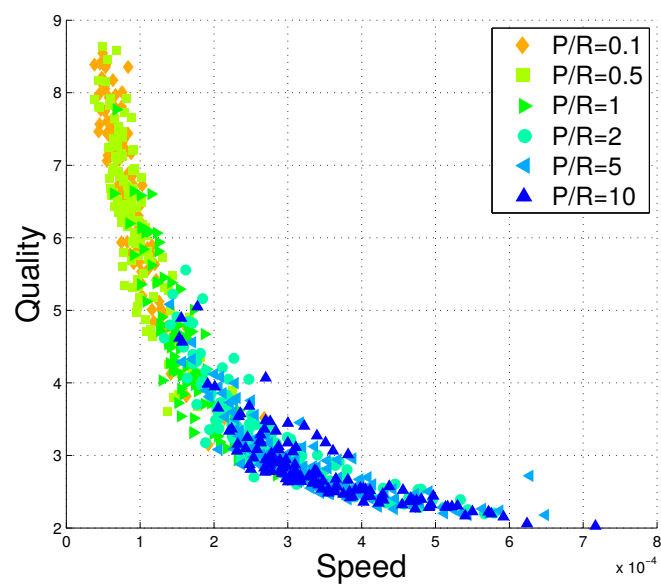


FIGURE S9 – **Speed-quality scatter plot for SA1 at $A = 0.5$.** Each point corresponds to the output of a simulation at $A = 0.5$. For each value of publication payoffs P , 100 simulations are plotted. We can observe the clear trade-off between speed and quality of the scientific discovery process, influenced by P . However, the same science policy $\{P, R, L\}$ can result in very different outputs.

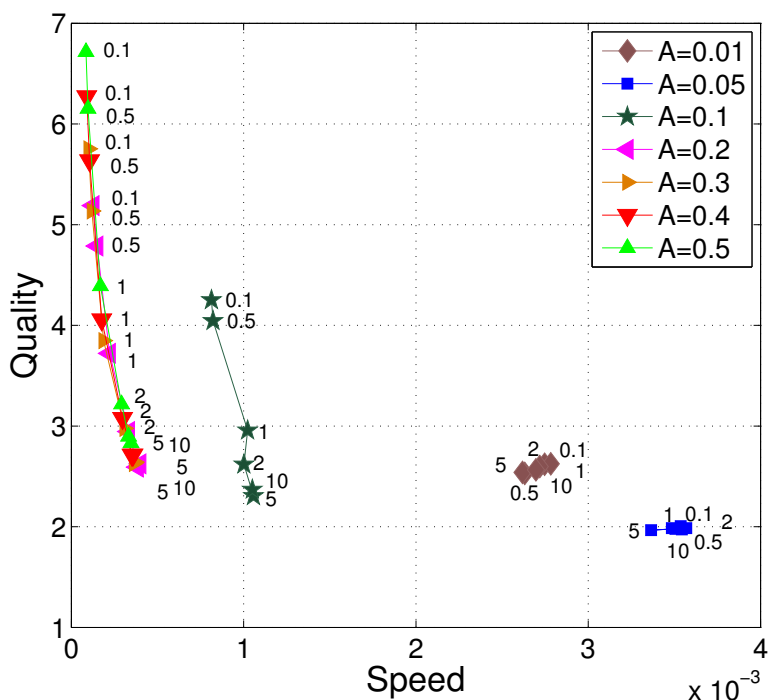


FIGURE S10 – **Average speed-quality diagram for SA1.** Influence of the incentives for publication (P) on the speed and the quality of the discovery process for different degrees of achievement A . The ratios P/R are indicated next to the markers. The population size is $N_a = 100$. Each data point is an average of 100 simulations. Only the incentives for publication P vary in the science policy, R and L being constant at 10. Except for emerging fields ($A < 0.1$), there is a clear trade-off between the speed and the quality of the discovery process, with a rapid decrease in quality as soon as the incentive to publish increases. Confidence intervals for speed and quality averages are given in supplementary figure S11.

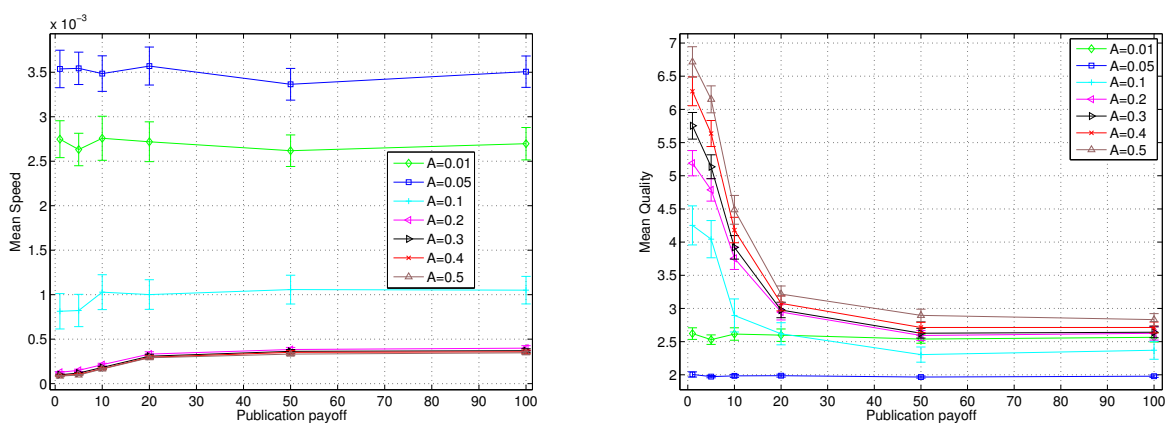


FIGURE S11 – Influence of the incentives for publication (P) on the average speed and quality of the discovery process for different degrees of achievement A . The size of the population is $N_a = 100$. Each data point is an average of 100 simulations. Only the incentive for publication P varies in the scientific policy, R and L are kept constant at 10. There is a clear trade-off between quality and speed with a rapid decrease in quality as soon as the incentive to publish increases. Error bars represent 95% confidence intervals.

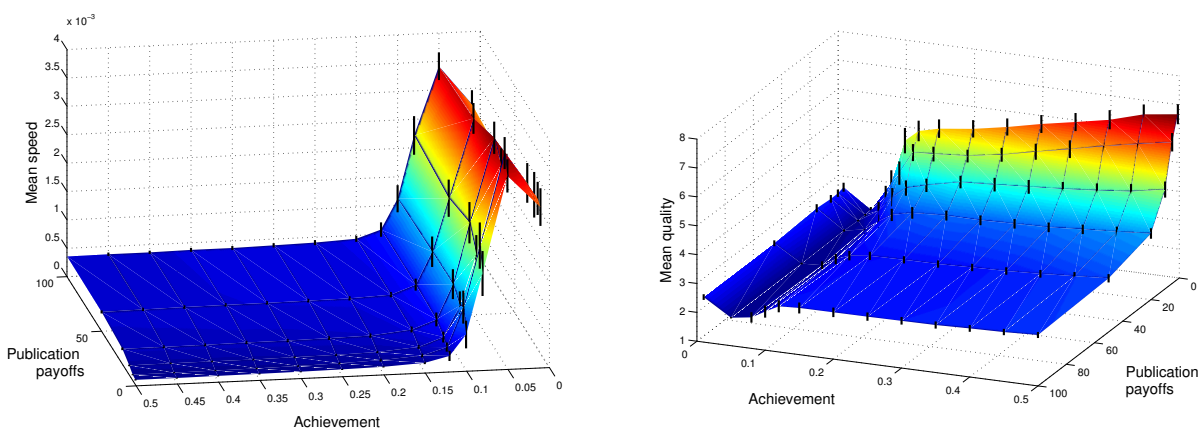


FIGURE S12 – Evolution of the average speed and quality in function of the publication payoffs P for $SA1$. Each data point is an average of 100 simulations. Only the incentives for publication P vary in the scientific policy, R and L being kept constant at 10. Error bars represent 95% confidence intervals.

A2.2 Sensitivity analysis 2 : easy science (abundance and separation)

TABLE S3 – Summary of the parameters used for sensitivity analysis 2 (SA2).

Description	Values
Number of agents	$N_a = 100$
Number of theories	$N_T = 3000$
Payoff for a publication	$P = 1, 5, 10, 20, 50, 100$
Payoff for a refutation	$R = 10$
Loss for being refuted	$L = 10$
Proportion of Type II theories	$p = 0.9$
Bernoulli parameter for type II theories	$q = 0.95$
Number of independent simulations per points	100

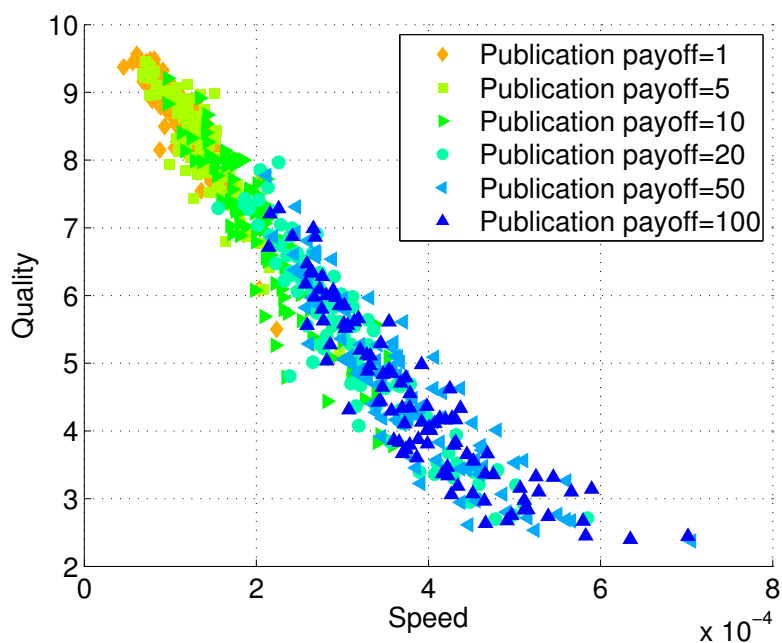


FIGURE S13 – **Speed-quality scatter plot for SA2 at $A = 0.5$.** Each point corresponds to the output of a simulation at $A = 0.5$. For each value of publication payoff P , 100 simulations were plotted. We observe the clear trade-off between speed and quality of the scientific discovery process, influenced by P . However, the same scientific policy $\{P, R, L\}$ can result in very different outputs.

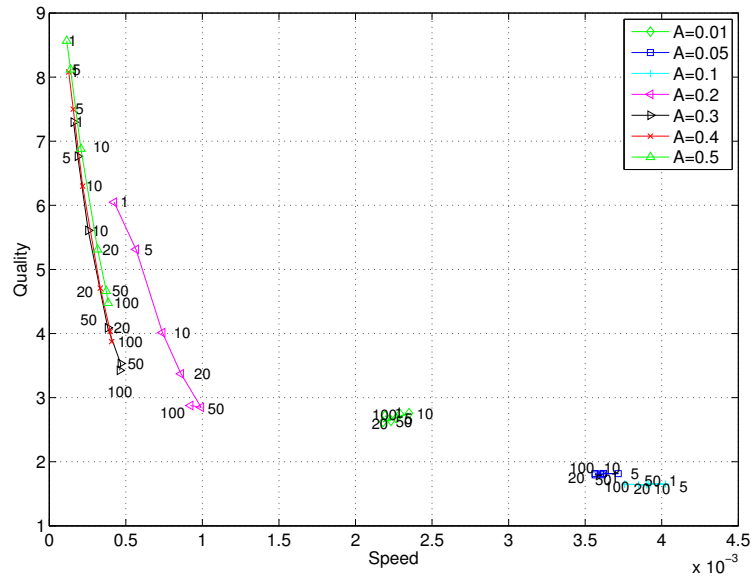


FIGURE S14 – **Speed-quality diagram for SA2.** Influence of the incentives for publication (P) on the average speed and average quality of the discovery process for different degrees of achievement A . Payoffs are the numbers indicated next to the dots. The population size is $N_a = 100$. Each data point is an average over 100 simulations. Only the incentives for publication P vary in the science policy, R and L being kept constant at 10. There is a clear trade-off between quality and speed with a rapid decrease in quality as soon as the incentive to publish increases. Confidence intervals for speed and qualities averages are given in figure S15.

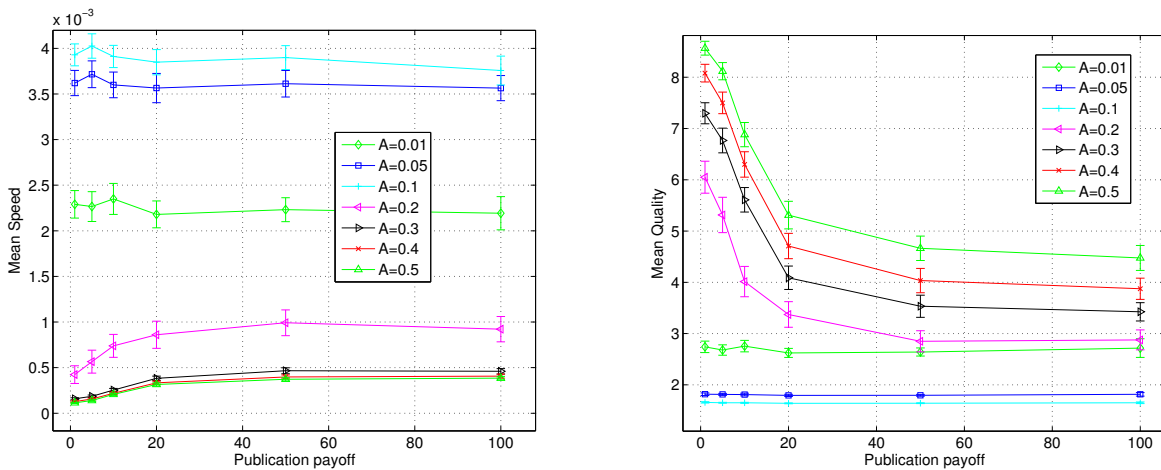


FIGURE S15 – Evolution of the average speed and quality as a function of the publication payoffs P for SA2. Each data point is an average of 100 simulations. Only the incentive for publication P varies in the scientific policy, R and L being kept constant at 10. Error bars represent 95% confidence intervals.

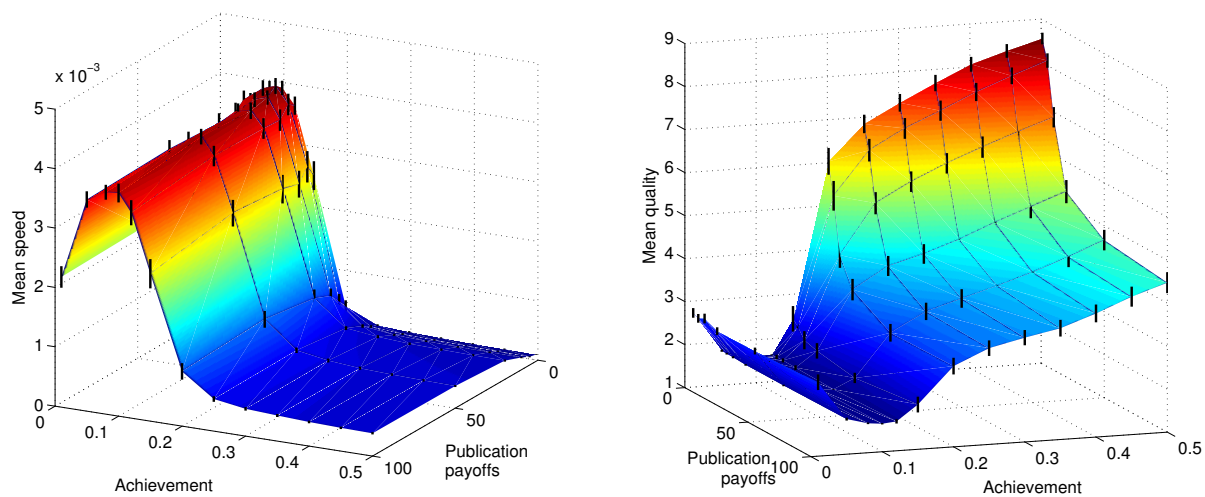


FIGURE S16 – Influence of the incentives for publication (P) on the average speed and quality of the discovery process for different degrees of achievement A for $SA2$. The size of the population is $N_a = 100$. Each data point is an average of 100 simulations. Only the incentive for publication P varies in the scientific policy, R and L being kept constant at 10. Error bars represent 95% confidence intervals.

A2.3 Sensitivity analysis 3 : separation without abundance

TABLE S4 – Summary of the parameters used for sensitivity analysis 3 (SA3).

Description	Values
Number of agents	$N_a = 100$
Number of theories	$N_T = 3000$
Payoff for a publication	$P = 1, 5, 10, 20, 50, 100$
Payoff for a refutation	$R = 10$
Loss for being refuted	$L = 10$
Proportion of Type II theories	$p = 0.99$
Bernoulli parameter for type II theories	$q = 0.95$
Number of independent simulations per points	100

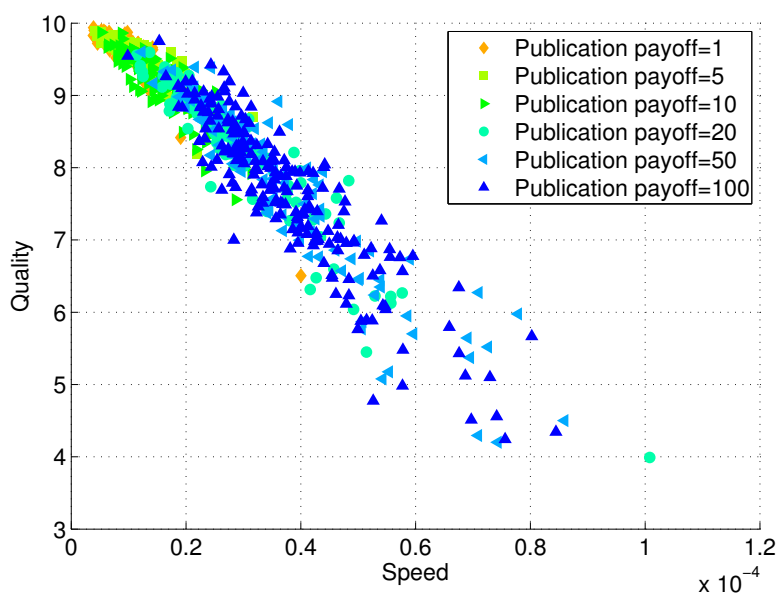


FIGURE S17 – **Speed-quality scatter plot for SA3 at $A = 0.5$.** Each point corresponds to the output of a simulation at $A = 0.5$. For each value of publication payoff P , 100 simulations are plotted. We can observe the clear trade-off between speed and quality of the scientific discovery process, influenced by P . However, the same scientific policy $\{P, R, L\}$ can result in very different outputs.

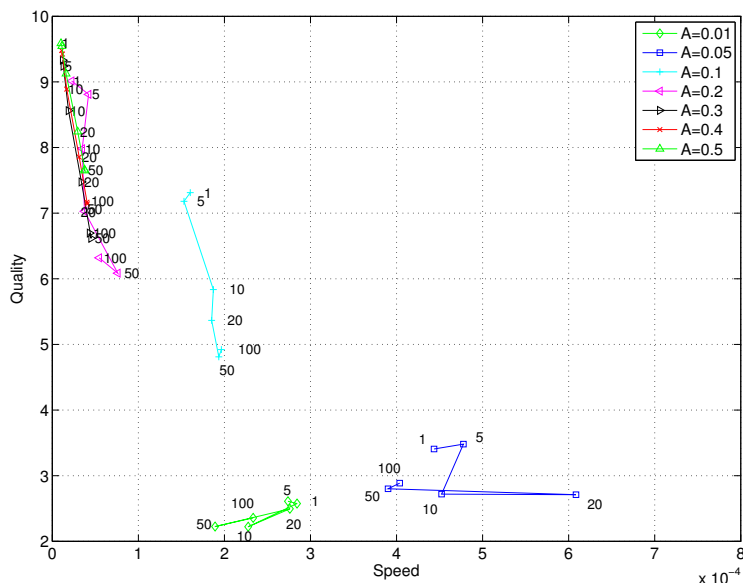


FIGURE S18 – **Speed-quality diagram for SA3.** Influence of the incentives for publication (P) on the average speed and quality of the discovery process for different degrees of achievement A . Payoffs are the numbers indicated next to the dots. The population size is $N_a = 100$. Each data point is an average of 100 simulations. Only the incentive for publication P varies in the scientific policy, R and L being kept constant at 10. There is a clear trade-off between quality and speed with a rapid decrease in quality as soon as the incentive to publish increases. Confidence intervals for speed and quality averages are given in figure S19.

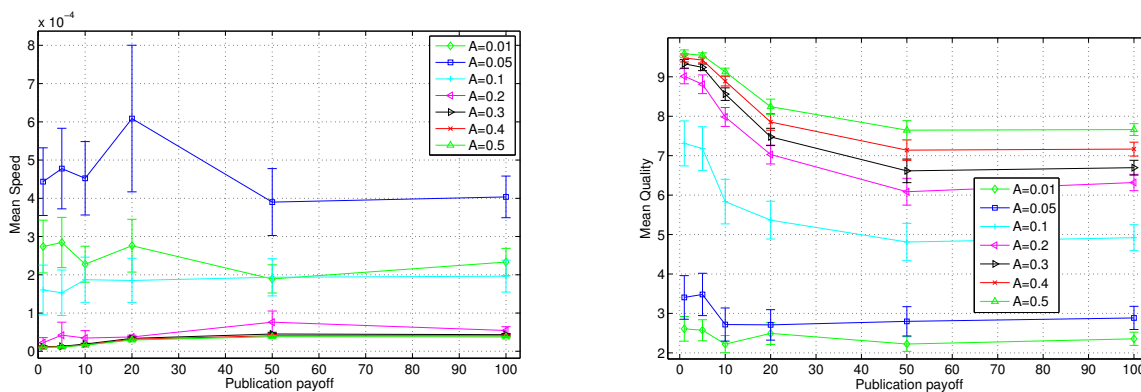


FIGURE S19 – Evolution of the average speed and quality in function of the publication payoffs P for SA3. Each data point is an average of 100 simulations. Only the incentive for publication P varies in the science policy, R and L being kept constant at 10. Error bars represent 95% confidence intervals.

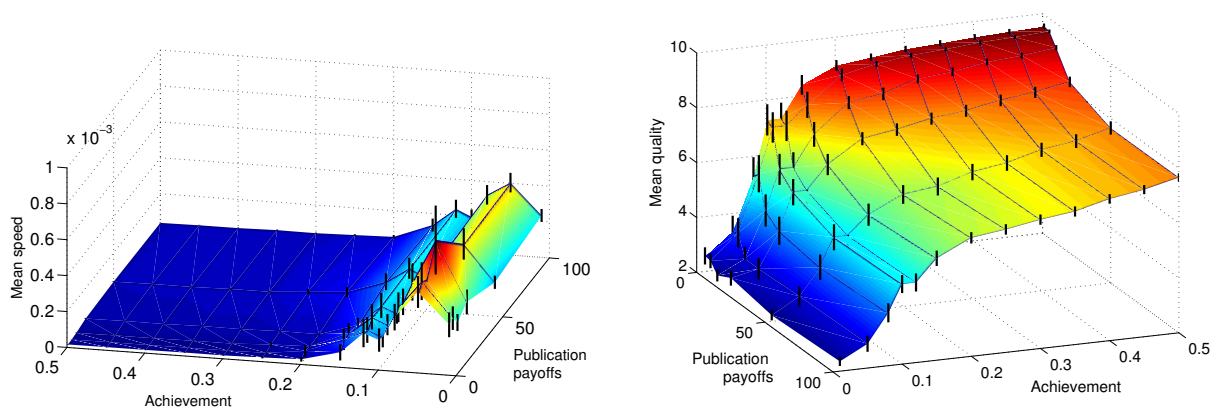


FIGURE S20 – Influence of the incentives for publication (P) on the average speed and quality of the discovery process for different degrees of achievement A for $SA3$. The size of the population is $N_a = 100$. Each data point is an average of 100 simulations. Only the incentives for publication P vary in the scientific policy, R and L are being constant at 10. Error bars represent 95% confidence intervals.

A2.4 Sensitivity analysis 4 : weak separation and low abundance

TABLE S5 – Summary of the parameters used for sensitivity analysis 4 (SA3).

Description	Values
Number of agents	$N_a = 100$
Number of theories	$N_T = 3000$
Payoff for a publication	$P = 1, 5, 10, 20, 50, 100$
Payoff for a refutation	$R = 10$
Loss for being refuted	$L = 10$
Proportion of Type II theories	$p = 0.99$
Bernoulli parameter for type II theories	$q = 0.98$
Number of independent simulations per points	100

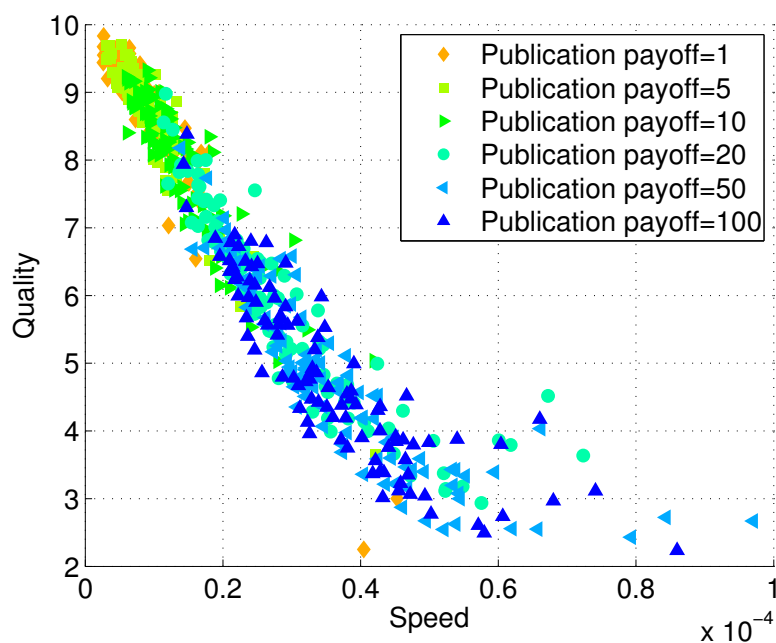


FIGURE S21 – **Speed-quality scatter plot for SA4 at $A = 0.5$.** Each point corresponds to the output of a simulation at $A = 0.5$. For each value of publication payoff P , 100 simulations are plotted. We can observe the clear trade-off between speed and quality of the scientific discovery process, influenced by P . However, the same scientific policy $\{P, R, L\}$ can result in very different outputs.

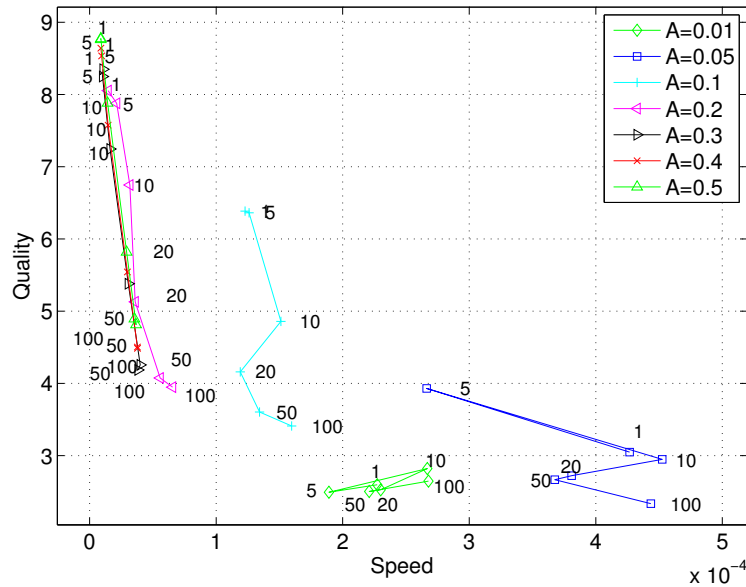


FIGURE S22 – **Speed-quality diagram for SA4.** Influence of the incentives for publication (P) on the average speed and quality of the discovery process for different degrees of achievement A . Payoffs are the numbers indicated next to the dots. The population size is $N_a = 100$. Each data point is an average of 100 simulations. Only the incentives for publication P vary in the scientific policy, R and L being kept constant at 10. There is a clear trade-off between quality and speed with a rapid decrease in quality as soon as the incentive to publish increases. Confidence intervals for speed and qualities averages are given in figure S23.

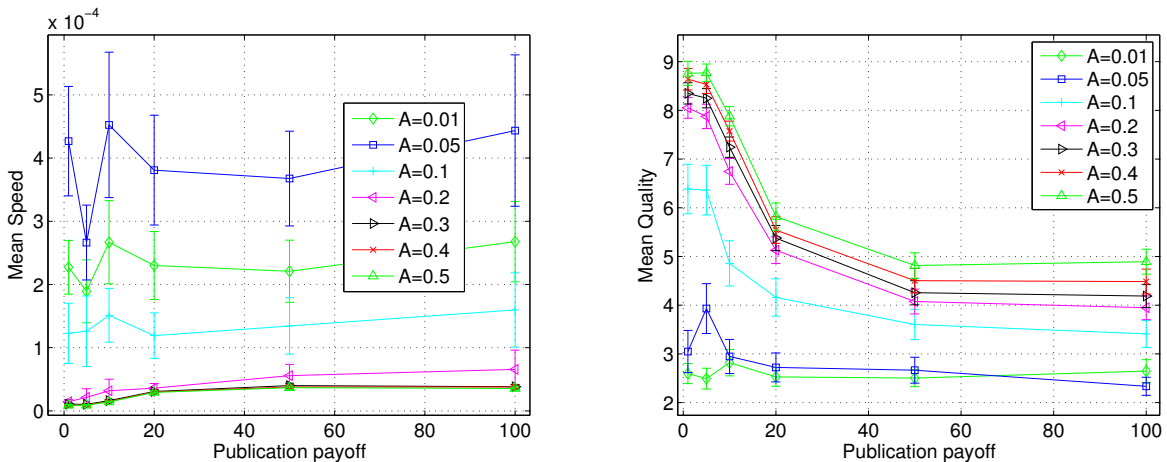


FIGURE S23 – Evolution of the average speed and quality as a function of the publication payoffs P for SA4. Each data point is an average of 100 simulations. Only the incentive for publication P varies in the science policy, R and L being kept constant at 10. Error bars represent 95% confidence intervals.

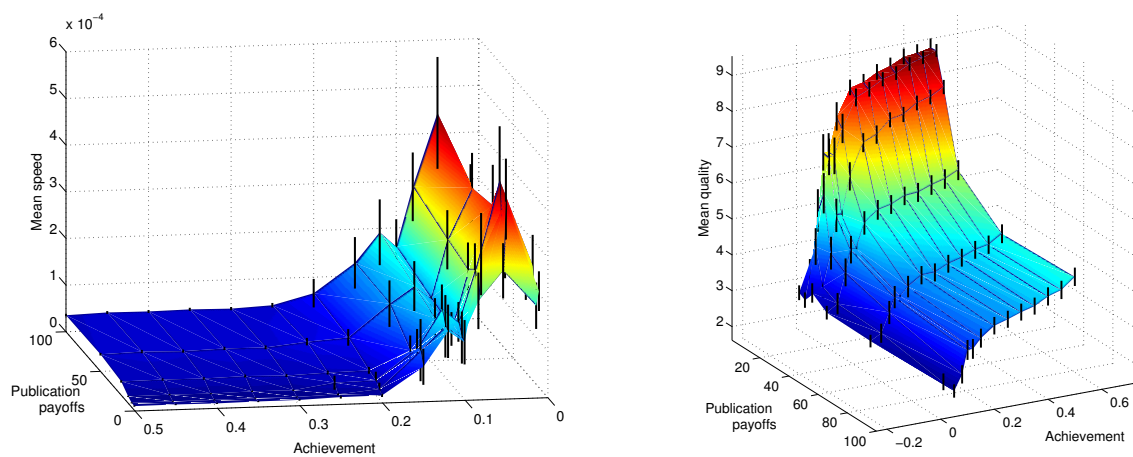


FIGURE S24 – Influence of the incentives for publication (P) on the average speed and quality of the discovery process for different degrees of achievement A for $SA4$. The size of the population is $N_a = 100$. Each data point is an average of 100 simulations. Only the incentive for publication P varies in the scientific policy, R and L being kept constant at 10. Error bars represent 95% confidence intervals.

A2.5 Pseudo-code

TABLE S6 – Summary of the parameters used for the reported sensitivity analyses.

<i>Parameters</i>	Description
N_a	Number of agents
N_T	Number of theories
P	Payoff for a publication
R	Payoff for a refutation
L	Loss for being refuted
p	Proportion of Type II theories
q	Bernoulli parameter for type II theories
Γ	Parameters for the small world network
e	Error rate of agents when copying other's strategies

A2.5.1 Description of a research process

Research process - private activity of agents i with strategy $(\bar{\lambda}_i, \lambda_i, \nu_i)$

1. Choice between refutation and publication

- if there are no published theories, i picks-up a theory φ at random in \overline{CK} and starts a publication process,
- if the agents obtains negative results for all theories in \overline{CK} , i picks-up a theory φ at random in CK and starts a refutation process,
- otherwise, draw a random variable r in $[0, 1]$; if $r < \nu_i$, i picks-up a theory φ at random in \overline{CK} and starts a publication process, else i picks-up a theory φ at random in CK and starts a refutation process.

2. **For a publication process** : test φ until time $\bar{\lambda}_i$. In the case of a negative result before $\bar{\lambda}_i$, stop the publication process, record the negative result for φ ; otherwise, stop after $\bar{\lambda}_i$ positive results and publish φ (φ moves to the CK set of published theories);

3. **For a refutation process** : test φ until time λ_i . In the case of a negative result before λ_i , stop the publication process, falsify publicly φ (φ moves to the set of falsified theories); otherwise, stop the refutation process after λ_i positive results;

A2.5.2 Initialization

- generate a population φ of N_a agents with strategies $(\bar{\lambda}_i, \lambda_i, \nu_i)_{i \in \varphi}$ uniformly distributed in ¹⁴ $[0, 40] \times [0, 40] \times [0, 1]$.
- generate N_T theories with p theories of parameter q and $(1 - p)$ theories of parameter 1.
- generate Γ as a small world network with parameter $\rho = 0.1$ and $n = 6$.

14. The upper limits for $\bar{\lambda}_i$ and λ_i is arbitrary in absence of intrinsic time constant in the model, like for example and average life expectancy of the agents. It has been chosen according to experimental observations of Nobel game players (cf. [Chavalarias et al.(2006)Chavalarias, Charron, Gardelle, and Bourgine]).

- each agent makes three research cycles according to [A2.5.1](#) and obtains associated payoffs without updating their initial strategy. Since at initialization all agents have a null score and no experience, these few research cycles guarantee that the agents have an estimation of the payoffs associated with his strategy before comparing himself to others. As soon as the three cycles are done, the agent moves to [A2.5.3](#).

A2.5.3 Simulation

For each time period :

- Each agent does one test on the theory of its current research process,
- Publication scores of publication processes ending at that period are recorded. If several agents publish the same theory, they share the payoff.
- Refutation scores of refutation processes ending at that period are recorded. If several agents refute the same theory, they share the payoffs,
- If some agents have negative results for just-published theories, they falsify and get the associated payoffs. If several agents falsify the same theory, they share the payoffs. Refutation scores are recorded,
- Scores are updated for agents that have been falsified,
- Agents are ranked according to their total payoffs since the beginning of the simulation, and engage in an imitation process with a probability proportional to their rank at the population level. If they are already the best, they stick to their strategy,
- Agents that engage in an imitation process copy, with some errors, the strategy of the best neighbor in their neighborhood in Γ . If an agent has several “best” neighbors, he copies one of them picked at random.

A2.6 Supplementary tables

TABLE S7 – Differences in speed and quality for the two extreme values of P in $SA1$ at $A = 0.5$. All values of parameters are the same for both cases, except P . Values are averages of 100 independent simulations. It is noteworthy that the proportion of false results for high publication incentives is not as extreme as the fears reported in section 1.1

Name	$SA1 ; P = 1$	$SA1 ; P = 100$
Avg. time at $A = 0.5$	19,905	4,035
Speed of the discovery process	$5.82 * 10^{-5}$	$4 * 10^{-4}$
Quality of the discovery process	7.12	2.32
Mean total number of publications	1,376	1,377
Mean total number of accepted publications (in CK)	151	161
Nb of Type I theories in CK	150	150

TABLE S8 – **Nine cases of ambulance chasing.** Data about the number of citations are provided by Backović (2016). Extra measurements on the nine cases of ambulance chasing were made to gain insight into the community size and activity. Citations and the total number of authors of these papers were extracted from the Web of Science, as well as the total number of citing papers in Google Scholars. Note that three of the nine results that triggered these ambulance chasing event have been refuted.

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Supp. Reference	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]
Statute	Refuted	OK	Refuted	OK	OK	OK	OK	OK	Refuted
Nb of Arxiv citations	272	135	133	200	293	364	461	1,271	1,054
WoS citations	19	10	104	N/A	130	249	397	1,171	674
Nb of WoS Authors	3,609	28	3,479	N/A	3,609	9,082	6,540	1,985	2,998
Google Citations	436	82	221	N/A	447	575	628	1,942	1,208

A2.7 Supplementary references

1. The OPERA Collaboration, Adam, T, Agafonova, N, Aleksandrov, A, Altinok, O, Sanchez, P. A, Anokhina, A, Aoki, S, Ariga, A, Ariga, T, Autiero, D, Badertscher, A, Dhahbi, A. B, Bertolin, A, Bozza, C, Brugiére, T, Brugnera, R, Brunet, F, Brunetti, G, Buontempo, S, Carlus, B, Cavanna, F, Cazes, A, Chaussard, L, Chernyavsky, M, Chiarella, V, Chukanov, A, Colosimo, G, Crespi, M, D’Ambrosio, N, De Lellis, G, De Serio, M, Declais, Y, Sanchez, P. d. A, Di Capua, F, Di Crescenzo, A, Di Ferdinando, D, Di Marco, N, Dmitrievsky, S, Dracos, M, Duchesneau, D, Dusini, S, Dzhatdoev, T, Ebert, J, Efthymiopoulos, I, Egorov, O, Ereditato, A, Esposito, L. S, Favier, J, Ferber, T, Fini, R. A, Fukuda, T, Garfagnini, A, Giacomelli, G, Giorgini, M, Giovannozzi, M, Girerd, C, Goldberg, J, Gollnitz, C, Golubkov, D, Goncharova, L,

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