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Manufacturing Doubt

Caroline Orset, Yann Bramoullé

Abstract: In their efforts to affect regulations, firms have developed specific strategies to exploit scientific uncertainty. They have manufactured doubt by hiring and funding dissenting scientists, by producing and publicizing favorable scientific findings and by generally concealing their involvement in biased research. We propose a new model to study the interplay between scientific uncertainty, firms' miscommunication and public policies. The government is benevolent but populist, and maximizes social welfare as perceived by citizens. The industry can produce costly reports showing that its activity is not harmful. Citizens are unaware of the industry's miscommunication. We first characterize the industry's optimal miscommunication policy. The industry notably ceases miscommunicating abruptly when scientists' belief reaches a critical threshold. We identify a natural condition under which miscommunication is stronger under a tax on emissions than under command and control. We then analyze research funding. A populist government may support research to enable firms to falsely reassure citizens. Establishing an independent research agency helps limit the welfare losses induced by populist policies.

Keywords: Environmental Policy Instruments; Populist Policies; Research Funding; Scientific Uncertainty.

1 Introduction

Many important government regulations have to be adopted under significant scientific uncertainty. In their efforts to affect regulations, firms have developed specific strategies to exploit this uncertainty. For instance, tobacco producers vigorously denied the adverse effects of active smoking in the 1950s and 1960s and of second-hand smoke exposure from the 1970s through the 1990s (Bero, 2013).[1] They spent large amounts of money on hiring and funding dissenting scientists, generating and publicizing favorable scientific findings, and shaping the public's perceptions through large-scale communication campaigns (Proctor, 2011). Throughout this time, the industry tried hard to conceal its involvement in biased research (Bero, 2013, p.157-158). The extent of this involvement only became known after the forced release of confidential corporate documents, as part of the 1998 tobacco master settlement agreement.[2] On climate change, special interest groups have long exploited scientific uncertainties to promote inaction (Hoggan & Littlemore, 2009). Communication strategies outlined in a leaked 1998 memo by the American Petroleum Institute are remarkably similar to those documented for tobacco (Cushman, 1998; and Walker, 1998). Objectives included "Identifying and establishing cooperative relationships with all major scientists whose research in this field supports our position" and "Providing grants for advocacy on climate science, as deemed appropriate." Oreskes & Conway (2010) document how, as announced in this memo, a handful of scientists were coopted by industrial lobbies. Concealing their industry ties and exploiting their scientific stature, they played an effective role in science-denying communication campaigns. On tobacco and climate change, firms have deliberately manufactured doubt in order to avoid, weaken or postpone regulations. These unscrupulous practices likely yield first-order welfare losses.[3] Economic analysis of this subject is still underdeveloped , however, and our analysis aims to fill this gap.

[1] For instance, a 1978 report prepared for the Tobacco Institute states that "The strategic and long-run antidote to the passive smoking issue is, as we see it, developing and widely publicizing clear-cut, credible medical reports that passive smoking is not harmful to the non-smoker's health." see Bero (2013, p.154).

[2] These documents can be consulted at https://www.industrydocumentslibrary.ucsf.edu/tobacco/.

[3] Proctor (2011) argues that early doubt manufactured by the tobacco industry on the link between smoking and cancer caused an excess 8000 billion smoked cigarettes and 8 million premature deaths.

In this paper, we propose a new model to study the interplay between scientific uncertainty, firms' miscommunication and public policies. We assume that firms' economic activity generates uncertain damage, and that this uncertainty can be reduced through scientific research. Firms can miscommunicate by producing favorable reports that resemble independent scientific evidence. Citizens are unaware of firms' miscommunication and do not distinguish between industry-generated information and scientific knowledge. The government is benevolent but populist: it maximizes social welfare as perceived by citizens. It regulates firms' activity either by imposing a maximal level of emissions or through a tax on emissions.

We analyze a sequential game with the following timing. First, either the government or an independent research agency decides how much research to finance. Scientists then run experiments and form their belief. Second, the industry miscommunicates. Scientific knowledge and the industry's communication determine the citizens' belief. Third, the government regulates firms' activity. We develop our analysis in two stages. For a given scientific belief, we characterize the industry's optimal miscommunication and its impact on citizens' beliefs, regulations and welfare. We study how these outcomes depend on the type of environmental regulation implemented. We then analyze how firms' miscommunication affects research funding under different institutions.

Our analysis yields novel insights. We first show that the industry's miscommunication effort is a non-monotonic and discontinuous function of scientific belief. As scientists become increasingly convinced that the activity is harmful, the industry first devotes more and more resources to falsely reassuring the citizens. This yields increasingly large welfare losses. When scientists' belief reaches a critical threshold, however, countering the scientific consensus becomes too costly and the industry abruptly ceases its miscommunication. This qualitative pattern is robust to the type of instrument used (command and control or tax on emissions).

This result sheds light on some documented tendencies. It is consistent with the large time lags typically observed between when scientists reach a consensus on the need for

regulation and when an effective public policy is implemented.[4] It can help explain people's persistent underestimation of the scientific consensus on climate change (Ding et al., 2011). Our finding helps explain sudden reversals in the official positions of special interest groups, as observed in the past on tobacco and recently on climate change. It also helps explain episodes of abrupt awakening to the dangers posed by some industrial activity.

We then look at the impact of the type of environmental regulation implemented. We identify a natural condition that leads to more industry miscommunication under a tax on emissions than under command and control. Since the industry's payoff is lower under a tax on emissions, due to the added fiscal burden relative to command and control, the industry has more to gain from influencing public opinion and regulation.

Next, we show that the wedge driven by the industry between scientists' and citizens' beliefs has important implications for research funding. We analyze different institutions' incentives to support research. Since a populist government cares about perceived welfare, its utility increases when citizens are falsely reassured. This may lead to a partial alignment of interests between the government and the industry. We find that a populist government may support research to allow the industry to miscommunicate more effectively. We show that a partial answer to this problem is to establish an independent funding agency, not unlike the current National Science Foundation and European Research Council. Interestingly, the independent agency may decide to provide more or less research funding than under the first-best. Either strategy may provide the best way to limit the damaging effects of firms' miscommunication. Our analysis thus provides a new rationale for the establishment of independent scientific agencies.

A key assumption is that citizens are unaware of the industry's involvement in biased research. This assumption is consistent with evidence of dissimulation of negative scientific findings by the tobacco industry and with the documented tendency of industry-funded scientists to conceal their funding sources (Bero, 2013; Proctor, 2011). The many scandals in the medical sector brought to light this concealment, leading to the adoption of disclosure

[4]See European Environment Agency (2013), which notably shows that 'false positives', where preventive actions undertaken due to early scientific warnings turn out to be unnecessary, are much less frequent than 'false negatives', where no action is taken despite early warnings that are confirmed ex-post.

rules by academic journals. These rules do not appear to be very effective, however, and corporate-funded ghostwriting is still suspected of being a major problem in biomedical research (Bero, Glantz & Hong, 2005; PLoS Medicine Editors, 2009; Thacker, 2014).[5] This may help explain why citizens hold incorrect beliefs on many important issues (Flynn, Nyhan & Reifler, 2016).

Our analysis contributes to several literatures. It first advances understanding of the political economy of scientific uncertainty. It contributes to a growing literature on indirect lobbying, where special interest groups try to affect voters' beliefs, see e.g. Laussel & van Ypersele (2012), and Petrova (2012). In Yu (2005), an industrial and an environmental lobby compete for political influence directly and through communication campaigns. However, scientific progress plays no role in his analysis. Baron (2005) and Shapiro (2016) model competition between special interests to seek political influence through the news media. They adopt a coarse representation of science where evidence is either uninformative or fully informative. By contrast, we consider a single lobby and voters who are not aware of the lobby's miscommunication.[6] We adopt a rich representation of science where evidence can accumulate and bring scientists progressively closer to the truth. This allows us to analyze how firms' miscommunication depends on the level of scientific uncertainty and how, in turn, this miscommunication affects research funding.

Second, our paper contributes to a literature studying the implications of the fact that citizens often hold incorrect beliefs. Researchers have long debated the normative consequences of citizens' misperceptions: should a benevolent government respect citizens' incorrect beliefs and assuage fears? Or should it use scarce resources where they are really needed, for instance, to save lives?[7] Salanié & Treich (2009) analyze optimal regulations for two types of governments, and we adopt some of their terminology. In this literature, citizens' and experts' beliefs are typically taken as given. By contrast, these beliefs are formed endogenously in our framework, and are affected by scientific progress and by

[5]Relatedly, Monsanto has recently been accused of ghostwriting scientific articles vouching for the safety of its Roundup herbicide, see Waldman, Stecker & Rosenblatt (2017).

[6]Some studies consider Bayesian voters who are fully aware of the lobbies' actions, see Baron (2005) and Stone (2011). However, their results and insights may not carry over to an economy with effective concealment and systematic misperceptions.

[7]See, in particular, Pollak (1998), Portney (1992), and Viscusi & Hamilton (1999).

industry miscommunication. This raises new questions, such as how misperceptions depend on the economy's fundamentals and the determination of scientific policies.

Third, a large and growing literature explores the effect of uncertainty on environmental outcomes. Most studies in this literature consider a benevolent social planner with no misperception.[8] Recently, researchers have started to study uncertainty in strategic contexts, such as free-riding between countries.[9] Here, we focus on a new channel through which uncertainty may affect the environment: citizens' misperceptions induced by firms' miscommunication in the presence of scientific uncertainty. We provide a systematic analysis of this channel and show that it may have a first-order impact on environmental and scientific outcomes.

Our paper also contributes to the literature on the choice of environmental policy instruments. We show that a tax on emissions (or a market for permits with permits auctioned) may lead to more miscommunication than command and control (or a market for permits with permits freely allocated).

The remainder of the paper is organized as follows. Section 2 introduces our model. We develop models of scientific progress and of belief formation, and characterize the industry's optimal miscommunication in Section 3. The level of research is endogenized in Section 4. We conclude in Section 5.

2 Model

We consider a society composed of four groups of agents: firms, scientists, citizens and the government. The firms' economic activity generates pollution, which may be harmful to health and to the environment. The government has to decide on the degree of regulation of this pollution. The impacts of the pollution and the extent of harm it might cause are uncertain. Scientists can do research to reduce this uncertainty. Both firms and scientists communicate about the economic activity's impacts. Citizens then form beliefs about these

[8] See, e.g., Gollier, Jullien & Treich (2000), Heal & Kriström (2002), Weitzman (2009) and studies based on integrated assessment models like Nordhaus (1994) and Stern (2007).

[9] As in Baker (2005), Boucher & Bramoullé (2010), Bramoullé & Treich (2009), Finus & Pintassilgo (2013) and Ulph (2004).

effects, and the government considers public opinion when adopting regulations.

Formally, firms' benefits from emitting emissions e are equal to $B(e) = be_0e - \frac{1}{2}be^2$ with $b, e_0 > 0$.[10] In the absence of regulation, benefits are maximized by emitting $e = e_0$, the "business as usual" level of pollution. The government regulates emissions, and can do so in different ways. Let $e^* \leq e_0$ be the target level of regulated emissions. Under command and control, the government directly imposes this maximal level. Alternatively, the government can tax emissions at rate t. Firms choose emissions to maximize $B(e) - te$, which yields $B'(e) = t$. The government then sets $t = B'(e^*) = b(e_0 - e^*)$. Firms' payoffs are equal to $B(e^*) = be_0e^* - \frac{1}{2}b(e^*)^2$ under command and control and to $B(e^*) - te^* = \frac{1}{2}b(e^*)^2$ under a tax on emissions. In either case, firms' payoffs decrease as e^* decreases, giving them an incentive to be as little regulated as possible.[11]

Emissions may generate damage. For simplicity, we assume that scientific uncertainty takes a binary form. Either pollution is indeed harmful, and overall damage is equal to $D(e) = d_0e + \frac{1}{2}de^2$ with $d_0, d \geq 0$. We further assume that $d_0 < be_0$. The marginal benefit from the first unit of emission exceeds its marginal damage. Or pollution is not harmful. Scientists believe that pollution is harmful with probability p. The expected social welfare is thus equal to:[12]

$$W(p, e) = B(e) - pD(e).$$

Say that a government is *technocratic* when it maximizes social welfare computed with up-to-date scientific knowledge. A technocratic government sets the emissions level to optimally balance social benefits and social costs. This means that $B'(e) = pD'(e)$, which

[10] Quadratic functional forms have been widely used in environmental economics (e.g. Nordhaus, 2015). They allow researchers to maintain tractability while capturing key economic features, such as the property that marginal abatement cost is increasing in abatement.

[11] The government could also regulate emissions through tradeable permits. Let r be the price on the market for permits. If permits are initially auctioned, firms' payoffs are equal to $B(e) - re$. If permits are initially freely allocated, firms' payoffs are equal to $B(e) - re + re^*$. In either case, this yields $B'(e) = r$ and hence $r = B'(e^*) = t$. Firms' payoffs under command and control and under freely allocated permits are then equal. They are also equal under a tax on emissions and under auctioned permits.

[12] Under a tax on emissions, we assume that tax revenues are redistributed in a lump-sum manner to citizens. Citizens' utility is then equal to $te - pD(e)$ and overall welfare is equal to $B(e) - pD(e)$, as under command and control.

yields:

$$e(p) = \frac{be_0 - pd_0}{b + pd}. \tag{1}$$

This corresponds to the first-best outcome, which can be equivalently reached through command and control or through a tax on emissions. Note that e is decreasing and convex in scientific belief p.[13]

Citizens' beliefs may differ from scientists' beliefs. Firms are organized in a communication lobby, which tries to affect public opinion on the effects of pollution.[14,15] Citizens' beliefs, q, then depend both on scientific beliefs and on the industry's miscommunication effort. Say that a government is *populist* when it maximizes social welfare as perceived by citizens: $W(q, e) = B(e) - qD(e)$. The level of regulation chosen by a populist government is then equal to $e(q)$. When citizens are less worried about the impacts of pollution than scientists, $q < p$ and $e(q) > e(p)$. A populist government then underregulates with respect to the first-best. This provides incentives for the industry to try to falsely reassure citizens on the effects of its activity.

We assume that the government is populist in Section 3. We consider an exogenous level of research and characterize the industry's optimal communication policy. In Section 4, we endogenize the level of research under various institutional arrangements.

3 Exogenous Science

In this section, we consider an exogenous level of research. We first develop a simple Bayesian model of scientific progress. We then build on it to model industry miscommunication and opinion formation. Finally, we characterize the industry's optimal commu-

[13]The assumption that $be_0 > d_0$ guarantees that $e(p) > 0$. By contrast if $be_0 \leq d_0$, $e(p) = 0$ if $p \geq be_0/d_0$. This introduces a kink in the optimal regulation, which complicates the analysis without affecting the insights obtained.

[14]For instance, in 1954 US tobacco companies formed the Tobacco Industry Research Committee, which later became the Council for Tobacco Research. "The industry stated publicly that it was forming the TIRC to fund independent scientific research to determine whether there was a link between smoking and lung cancer. However, internal documents from Brown & Williamson Tobacco Company have shown that the TIRC was actually formed for public relations purposes, to convince the public that the hazards of smoking had not been proven.", see Bero (2013, p.156).

[15]We abstract away from issues of formation and stability of the communication lobby and, more generally, from strategic interactions between firms in the industry.

nication policy. We contrast outcomes under command and control and under a tax on emissions.

3.1 Scientific and popular beliefs

Consider the following model of scientific progress. Scientists can do research to reduce their uncertainty on the effects of pollution. They have prior beliefs p_0 that pollution is harmful. They may run n experiments to learn about pollution's impact. Each experiment provides a noisy signal on the true state of the world, and there is a probability $\frac{1}{2} < P < 1$ of its findings being correct. Denote by k the number of experiments indicating that pollution is harmful. Applying Bayes' rule, we see that scientists' ex-post belief is equal to

$$p = \frac{p_0 \binom{n}{k} P^k (1-P)^{n-k}}{p_0 \binom{n}{k} P^k (1-P)^{n-k} + (1-p_0) \binom{n}{k} P^{n-k} (1-P)^k}.$$

Let $\alpha = P/(1-P) > 1$ denote the relative accuracy of experimental findings. This yields:

$$p(p_0, k, n) = \frac{p_0 \alpha^k}{p_0 \alpha^k + (1-p_0)\alpha^{n-k}}. \tag{2}$$

Note that $p \geq p_0 \Leftrightarrow k \geq n/2$. More generally, this formula embodies key features of Bayesian updating. For instance, if experiments are run in several stages the final belief does not depend on their ordering. Formally, $p(p(p_0, k_1, n_1), k_2, n_2) = p(p_0, k_1 + k_2, n_1 + n_2)$ for any $k_1 \leq n_1$ and $k_2 \leq n_2$.

Thus, scientists' belief is a discrete stochastic variable $\tilde{p}$, such that $\tilde{p} = p(p_0, k, n)$ with probability $p_0 \binom{n}{k} P^k (1-P)^{n-k} + (1-p_0) \binom{n}{k} P^{n-k} (1-P)^k$ for any integer k between 0 and n. We can check that the expectation of scientists' belief is equal to their prior: for any n, $E(\tilde{p}) = p_0$. As n increases, $\tilde{p}$ puts more and more probability mass on beliefs farther and farther away from p_0. As $n \to \infty$, we show in the Appendix that $\tilde{p}$ converges in probability towards the distribution $p_\infty = 0$ with probability $1 - p_0$ and 1 with probability p_0. As the number of experiments becomes arbitrarily large, scientific knowledge converges to the truth.

Citizens' beliefs may differ from scientists' beliefs. At cost c, the industry can produce

a report indicating that pollution is not harmful. Citizens are unaware of the industry's miscommunication and treat the information produced by the industry as independent scientific evidence.[16,17] Under this assumption, the citizens' belief is equal to

$$q = \frac{p_0 \alpha^k}{p_0 \alpha^k + (1 - p_0)\alpha^{n-k+m}}$$

where m denotes the industry's communication effort, i.e. the number of reports it has produced. In fact, q can be expressed as a function of scientists' belief p and of communication effort m:[18]

$$q(p, m) = \frac{p}{p + (1 - p)\alpha^m}. \tag{3}$$

We assume in what follows that m can take continuous values, $m \in \mathbb{R}_+$. This helps simplify computations and the expressions for the main results without affecting our main insights.

We next clarify how the citizens' belief varies with p and m. We compute q's various derivatives in the Appendix. We see, first, that $\partial q/\partial p > 0$ and $\partial^2 q/\partial p^2 > 0$. The marginal impact of scientists' belief on citizens' belief is positive and increasing. Then, observe that $\partial q/\partial m < 0$: q is decreasing in m from $q(p, 0) = p$ to $q(p, \infty) = 0$. Interestingly, its curvature may vary: $\partial^2 q/\partial m^2 < 0$ if $q > \frac{1}{2}$ and $\partial^2 q/\partial m^2 > 0$ if $q < \frac{1}{2}$. Two cases emerge. Suppose first that $p \leq \frac{1}{2}$. Then, q is convex in m. In that case, the marginal impact of industry's miscommunication on citizens' belief is decreasing in absolute value. By contrast if $p \geq \frac{1}{2}$, q is first concave in m for $q \geq \frac{1}{2}$, which happens for $m \leq \ln(p/(1-p))/\ln(\alpha)$, and convex when $m \geq \ln(p/(1-p))/\ln(\alpha)$ and $q \leq \frac{1}{2}$. Therefore, when scientists think that pollution is likely to be harmful, miscommunication initially has an increasing marginal impact, in absolute value, on citizens' belief. These increasing returns capture a well-

[16]By contrast, we assume that the government and the research agency are aware of the industry's miscommunication.

[17]Miscommunication costs are not included in the welfare computations. Proposition 1 below is robust to including them. Numerical simulations indicate that welfare effects may be further amplified when accounting for these costs.

[18]In the absence of miscommunication, citizens' belief is equal to scientists' belief. Thus, we abstract away from frictions and costs in knowledge dissemination and from the role played by various media (TV, press, internet) in this process. We discuss these issues further in the Conclusion.

known property of Bayesian updating: extra information has the largest effect when the agent is most uncertain. In addition, the impact of extra information decreases as the agent becomes more certain. We will see below that this feature plays an important role in determining the optimal communication policy.

3.2 Firms' optimal communication

We now derive our first main result. We characterize the industry's optimal communication policy, uncovering three domains. When p is low and scientists believe that pollution is unlikely to be harmful, the benefits from miscommunication are too low and the industry does not try to change the citizens' beliefs. When p takes intermediate values, and scientists are more uncertain about the effects of the pollution, the industry engages in miscommunication and targets a specific level of citizens' belief. As p increases, the target is unchanged and communication efforts first increase continuously. When p reaches a critical threshold, the costs of miscommunication become too high and the industry abruptly ceases its efforts. Optimal miscommunication is therefore non-monotonic and discontinuous in scientists' belief.

Formally, the industry's objective is to maximize its payoff with respect to m:
$\pi_c(m) = be_0e(q(p,m)) - \frac{1}{2}be(q(p,m))^2 - cm$ under command and control and
$\pi_t(m) = \frac{1}{2}be(q(p,m))^2 - cm$ under a tax on emissions. We provide an in-depth analysis of these payoff functions in the Appendix. Let m_c^* (m_t^*) be a solution to the problem of maximizing π_c (π_t) over $[0, +\infty[$.

Theorem 1 *Under command and control, there exists $\bar{c}_c > 0$ such that if $c \geq \bar{c}_c$, then $m_c^* = 0$. If $c < \bar{c}_c$, there exist a target popular belief q_c^* and a threshold scientific belief $p_c^* > q_c^*$ such that $m_c^* = 0$ if $p \leq q_c^*$ or $p \geq p_c^*$. If $q_c^* \leq p \leq p_c^*$, then $q(m_c^*, p) = q_c^*$ and*

$$m_c^* = \frac{1}{\ln(\alpha)}\left[\ln(\frac{p}{1-p}) - \ln(\frac{q_c^*}{1-q_c^*})\right].$$

Miscommunication under a tax on emissions has a similar shape, with thresholds $\bar{c}_t$, q_t^* and p_t^*.

We provide a sketch of the proof here. See the Appendix for details and for characterizations of the threshold values $\bar{c}_c$, q_c^*, p_c^* and $\bar{c}_t$, q_t^*, p_t^*.[19] We start by examining the second derivatives of the payoff function. Two cases emerge. On the one hand, if p is low enough, π_c is concave everywhere. Since the payoff becomes negative when m is large enough, the solution is then obtained by analyzing the sign of $\partial\pi_c/\partial m(0)$. We show that $\partial\pi_c/\partial m(0) < 0$ if $p < q_c^*$, which implies that $m_c^* = 0$ in that case. In contrast, $\partial\pi_c/\partial m(0) > 0$ if $p > q_c^*$ and m_c^* then solves $\partial\pi_c/\partial m(m_c^*) = 0$. We can express $\partial\pi_c/\partial m$ as a function of q, and this equation then defines the target belief q_c^*. On the other hand, if p is high enough, π_c is first convex and then concave. When p is high, the industry's payoff first displays increasing returns on communication effort. We show that in this case, the solution is either to reach the target q_c^* or to set $m_c^* = 0$. We compare the payoffs obtained from these two actions and show that there exists a critical threshold p_c^* above which q_c^* leads to less payoff than no communication.[20] This discontinuity in the solution is induced by the presence of convexities in payoffs. We then analyze properties of π_t, firms' payoff under a tax on emissions. We show that it displays similar qualitative features and leads to a solution with a similar shape.

We next analyze how the type of environmental regulation affects firms' miscommunication.

Theorem 2 *Suppose that* $be_0 \geq 2d_0 + de_0$. *Then,* $m_t^* \geq m_c^*$ *with a strict inequality if* $m_t^* > 0$.

This result means that if marginal damages at zero are not too high, firms always miscommunicate more under a tax on emissions than under command and control. This notably implies that $\bar{c}_c < \bar{c}_t$ and if $c < \min(\bar{c}_c, \bar{c}_t)$, $q_t^* < q_c^* < p_c^* < p_t^*$. Observe that with both instruments, firms obtain lower profits because of the lower level of emissions: $B(e) < B(e_0)$. Under a tax on emissions, firms face an additional fiscal burden and see

[19] For clarity, we sometimes omit subscripts in what follows. We may for instance write q^* when the argument applies both to q_c^* and q_t^*.

[20] At $p = p_c^*$, the industry is indifferent between playing $m_c^* = 0$ or reaching q_c^*. The problem of maximizing π_c has two solutions.

their profits further reduced by the amount of the tax paid to the government. This gives them an extra incentive to influence regulation relative to command and control.[21]

We illustrate Theorems 1 and 2 in Figure 1. Parameter values are set as follows: $d_0 = 9.9$, $d = 0.01$, $e_0 = 10$, $b = 2$, $c = 4.3$, and $P = 0.64$. From our characterizations in the Appendix, we compute the thresholds: $\bar{c}_c \approx 4.31$, $q_c^* \approx 0.21$, $p_c^* \approx 0.99$ and $\bar{c}_t \approx 11.27$, $q_t^* \approx 0.08$, $p_t^* \approx 0.99$.

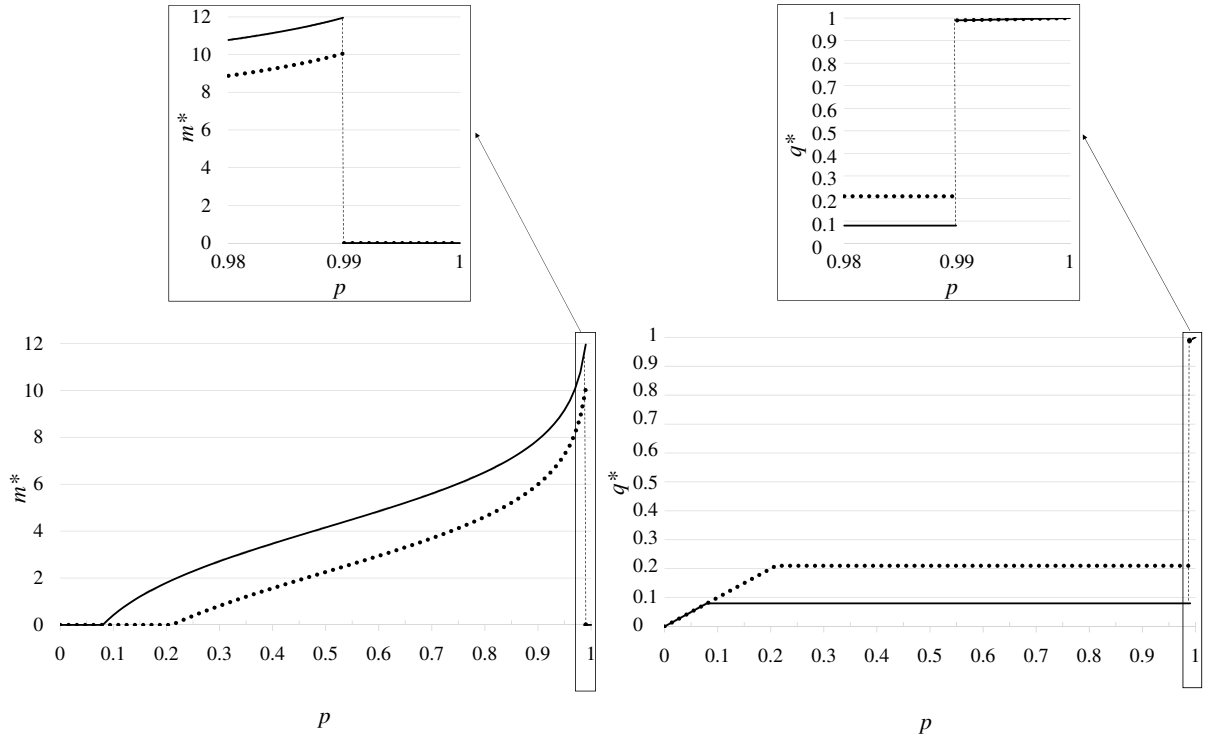


Figure 1: Firms' miscommunication and citizens' beliefs under tax on emissions (Solid line) and under command and control (Dotted line).

Here, the costs of miscommunication are quite low compared to the benefits, and effort is positive over a large range of scientific beliefs, under both types of regulation. We depict in Figure 1 how m^*, in the Left panel, and $q(m^*, p)$, in the Right panel, vary with p under

[21]The condition $be_0 \geq 2d_0 + de_0$ guarantees that $e(p) \geq (d_0 + de_0)/(b + d)$ and the first-best level of emissions is bounded from below. When this condition is not satisfied, emissions can get arbitrarily close to zero. The fiscal burden also gets arbitrarily close to zero and miscommunication incentives may be higher under command and control in some situations.

a tax on emissions and under command and control. Note that citizens' belief also varies discontinuously with p. It stays at the target level q^* as long as the industry engages in miscommunication and then jumps back to p when the industry ceases to miscommunicate.

The combination of citizens' industry-induced misperceptions and of populist policies can lead to significant welfare losses. Note that $W(p, e(q)) - W(p, e(p)) = -\frac{1}{2}(b+pd)[e(p) - e(q)]^2 < 0$. This loss increases in absolute value as q decreases and moves farther away from p. In Figure 2, we depict the ratio of the level of welfare under the populist policy over the first-best level of welfare (technocratic policy), $W(p, e(q))/W(p, e(p))$, for the same parameter values as in Figure 1.

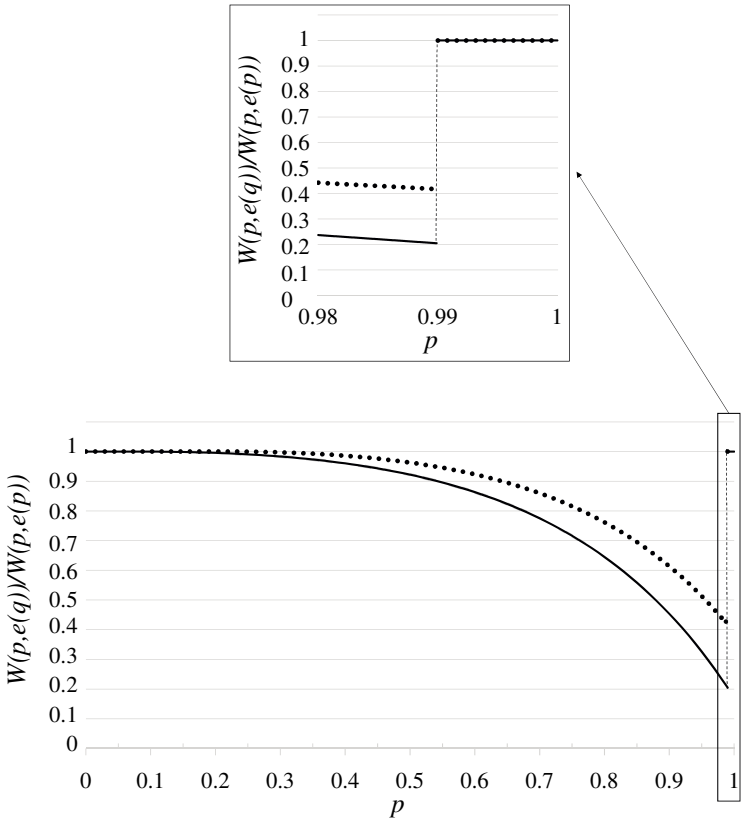


Figure 2: Welfare loss induced by firms' miscommunication under tax on emissions (Solid line) and under command and control (Dotted line).

We see that relative welfare loss first increases as scientific belief, and hence firms' miscommunication and the induced distortion in citizens' belief, increases. When scientific

belief becomes high enough, however, the industry stops miscommunicating and welfare jumps back to its first-best value. In addition, welfare losses are larger under a tax on emissions, due to the increased miscommunication.

From our characterization of firms' communication policy, we can further derive some potentially interesting comparative statics. Consider, for instance, the impact of the accuracy of experimental findings under command and control. An increase in α has two countervailing effects. On the one hand, scientists converge more quickly towards the truth when α is higher. The variance in scientific beliefs tends to be higher when α is higher and, in the absence of industry miscommunication, this applies to citizens' beliefs as well. On the other hand, we see that $\bar{c}_c$ is increasing in α and we show in the Appendix that q_c^* is decreasing while p_c^* is increasing in α. Because citizens do not differentiate between information provided by the industry and by scientists, *a higher α makes the industry's miscommunication more effective.*[22] Industry miscommunication thus emerges for higher values of communication costs and over a larger range of scientific beliefs. This runs counter to the first effect and tends to slow down the convergence of citizens' beliefs towards the truth.[23]

4 Endogenous Science

In this section, we analyze the level of research chosen in three different setups: when the government is technocratic; when the government is populist and decides on both research funding and environmental regulation; and when the government is populist but research funding is decided by an independent agency. Throughout the section, we analyze a sequential game with three steps. (1) First, the institution setting the research policy decides how many experiments n to finance. These experiments are then run and scientists form their belief p. (2) Second, the industry observes scientific belief and chooses a level of

[22]Similarly, the amount of communication needed to reach a fixed target of popular belief is lower when α is higher.

[23]This negative impact of experimental accuracy is reminiscent of findings in Edmond (2013). In a context of information manipulation and political regime change, the accuracy of signals received by citizens may actually help autocratic regimes stay in power.

miscommunication effort m. Citizens then form their belief q. (3) Third, the government regulates the industry's activity. Finally, benefits and costs are realized.

As in Stackelberg competition, the institution deciding scientific research funding takes its decision before the industry miscommunicates. We analyze the subgame perfect equilibria of this sequential game through backwards induction. (2) Conditional on scientists' realized belief p, the industry chooses its optimal level of miscommunication as described in Theorem 1. (1) The government or the research agency chooses the level of scientific research funding, rationally anticipating the industry's subsequent miscommunication.

4.1 Welfare

We first determine the welfare ranking of these three institutional arrangements. Recall, $W(p, e) = B(e) - pD(e)$ denotes welfare computed once research is done but before the state of the world is revealed. We now consider expected welfare computed *ex-ante*, before the results from research are known. Assume that each experiment costs C.[24] A technocratic government chooses the level of research funding by maximizing expected welfare:

$$W_{tech}(n) = E[W(\tilde{p}, e(\tilde{p}))|n] - Cn$$

and let W^*_{tech} denote its maximal value.

By contrast, a populist government maximizes expected *perceived* welfare, computed with potentially false popular beliefs:

$$\Pi_{pop}(n) = E[W(\tilde{q}, e(\tilde{q}))|n] - Cn$$

In general, $\Pi_{pop}(n)$ differs from the expected welfare computed with unbiased scientific belief $E[W(\tilde{p}, e(\tilde{q}))|n] - Cn$. Denote by W^*_{pop} the expected welfare induced by a populist choice of research funding level.[25]

[24]These costs may notably include opportunity costs of public funds. We introduce explicit budget considerations in Section 5.

[25]Since $q \leq p$, $\Pi_{pop}(n) \geq E[W(\tilde{p}, e(\tilde{q}))|n] - Cn$. Undue reassurance increases perceived welfare by decreasing perceived expectations of future harm.

Finally, consider an independent research agency deciding on the level of research funding before firms miscommunicate and the populist government regulates emissions. Assume that this agency is benevolent and computes welfare based on up-to-date scientific knowledge. It seeks to maximize

$$W_{indep}(n) = E[W(\tilde{p}, e(\tilde{q}))|n] - Cn.$$

and let W^*_{indep} denote its maximal value.

We show next that welfare can be unambiguously ranked across the three institutions.

Proposition 1 $W^*_{pop} \leq W^*_{indep} \leq W^*_{tech}$.

To see why Proposition 1 holds, note first that W^*_{tech} corresponds to the first-best - and hence highest - level of welfare attainable in the economy. Therefore, $W^*_{pop}, W^*_{indep} \leq W^*_{tech}$. Then, observe that the independent agency maximizes welfare under populist environmental regulation. Therefore, W^*_{indep} is the highest level of welfare attainable when $e = e(q)$, which implies that $W^*_{indep} \geq W^*_{pop}$. Populist policies thus entail welfare losses even when research funding is endogenous. Moreover, these losses are partially offset when research funding is controlled by a technocratic agency which is independent from the government.

4.2 Scientific policies

We now analyze the scientific policies adopted under the different institutions. The institutions' optimization problems involve non-convexities and discrete jumps, and we could not characterize scientific policies analytically. Our objective in this section is accordingly more modest: to illustrate the variety of potential outcomes and to explore the main forces at work.

Consider the technocratic benchmark first. The government anticipates that research will change the ex-post distribution of scientific beliefs. Since $W(p, e(p)) = B(e(p)) - pD(e(p))$ is convex in p,[26] $E[W(\tilde{p}, e(\tilde{p})]$ is higher when the distribution of scientific beliefs

[26]By the envelope theorem, the first derivative is equal to $-D(e(p))$. The second derivative is then equal to $-e'(p)D'(e(p)) \geq 0$.

$\tilde{p}$ is more dispersed. Expected welfare gross of the costs of experiments is highest when $n = \infty$ and scientists have converged to the truth: $\tilde{p} = 0$ with probability $1 - p_0$ and 1 with probability p_0. As n increases, scientists get increasingly closer to the truth. Extensive numerical simulations show that expected gross welfare generally increases at a decreasing rate in n.[27] In this case, the optimal level of research funding can be characterized by a standard marginal condition. It should be set at the level where the marginal gain from an additional experiment is approximately equal to its marginal cost C. To sum up, *a technocratic government trades the welfare benefits from uncertainty reduction against the research costs.* Note that this classic incentive also affects the decisions of a populist government and an independent agency. These two institutions are, in addition, affected by firms' miscommunication.

Next, consider a populist government. A key new motive appears in its objective function. Observe that $W(q, e(q))$ increases when q decreases. Perceived welfare is decreasing in actual citizens' belief that emissions are harmful. *A populist government would therefore like citizens to be falsely reassured.* This is precisely what doubt manufacturing does, and hence the interests of a populist government may be partly aligned with those of the industry.[28] Note, then, that doubt manufacturing only occurs when $\tilde{p}$ takes on moderate values. From Theorem 1, we know that $m^* = 0$ and $q = p$ if $p \leq q^*$ or $p \geq p^*$ while $m^* > 0$ and $q = q^*$ if $q^* < p < p^*$. A populist government may then choose an amount of research ensuring that scientific belief likely takes on moderate values. This, in turn, is partly determined by the position of the initial scientific belief p_0 with respect to the domain of effective miscommunication $[q^*, p^*]$. If $p_0 \in [q^*, p^*]$, public opinion is biased by industry's efforts even when there is very little research. Expected citizens' belief $E(\tilde{q})$ may then be increasing in n and a populist government may not want to support scientific activities. By contrast, if $p_0 < q^*$ or $p_0 > p^*$, $E(\tilde{q}) = p_0$ when $n = 0$. In that case $E(\tilde{q})$ is

[27] However, simulations also indicate that $E[W(\tilde{p}, e(\tilde{p})]$ may be non-monotonous and non-concave in n in some circumstances. For instance, when p_0 is close to 0 or 1 and α is close to 1, expected gross welfare is often initially convex in n.

[28] In the long-run, belief distortion is of course untenable and reality must eventually assert itself. Due to the electoral cycle, governments tend to have relatively short time horizons. They may well decide to assuage citizens' worries now, without caring about long-term consequences.

typically non-monotonic in n, reaching a minimum for some positive value n. This level of research allows the industry to most effectively miscommunicate in expectation, and hence may be preferred by a populist government.

Finally, consider an independent research agency which anticipates the actions of the industrial lobbies and their impact on environmental regulations. In contrast to a populist government, this independent agency tries to counter the negative impact of the industry's miscommunication. This may lead the agency to provide more or less research funding than a technocratic government.

We illustrate these effects in Figures 3 and 4. We depict in Figure 3 how scientific policies set by the three institutions vary with initial belief p_0, for the same parameters as in Figure 1 and for $C = 0.1$.

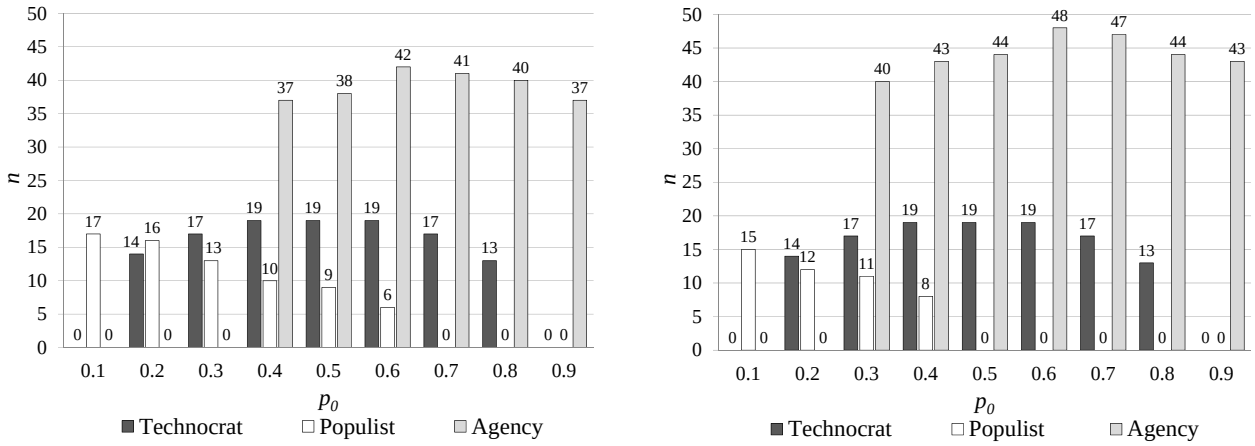


Figure 3: Research funding under three institutional arrangements. Command and control (on the left) and tax on emissions (on the right).

The left bars in dark grey correspond to the first-best levels of funding, in the absence of citizens' misperceptions. Support for research first increases and then decreases as p_0 increases. A technocratic government only cares about the direct benefits and costs of reducing scientific uncertainty. These benefits are highest when uncertainty is strongest. Here funding reaches a maximum at $p_0 = 0.5$, and research is not funded when initial scientific uncertainty is very low ($p_0 = 0.1$) or very high ($p_0 = 0.9$).

The middle bars in white depict the scientific policies chosen by a populist government.

When scientists have initial suspicions that harm is not unlikely, the government provides less funding for research than under the first-best. Too much research would decrease perceived welfare by reducing the ability of firms to reassure citizens. By contrast, when initial belief is low ($p_0 = 0.1$ or 0.2 under command and control; $p_0 = 0.1$ under a tax), *the populist government provides more support for research than in the first-best.* Remember that here $q_c^* \approx 0.21$ and $q_t^* \approx 0.08$. As n increases, a portion of the distribution of scientific beliefs shifts to the right of p_0, and may then fall into the miscommunication range. Firms can thus better miscommunicate, in expectation, for some intermediate value of n. This generates an extra incentive for a populist government to support research.

In addition, we see that populist support for research is stronger under command and control than under a tax on emissions. The reason, paradoxically, is that the miscommunication range is smaller under command and control: $[q_c^*, p_c^*] \subset [q_t^*, p_t^*]$. Reaching this range, and thus better reassuring citizens in expectations, therefore requires more research.

This intuition is confirmed by looking at the expected level of firms' miscommunication, $E(\tilde{m})$, and at the expected level of popular beliefs, $E(\tilde{q})$ in Figure 4.

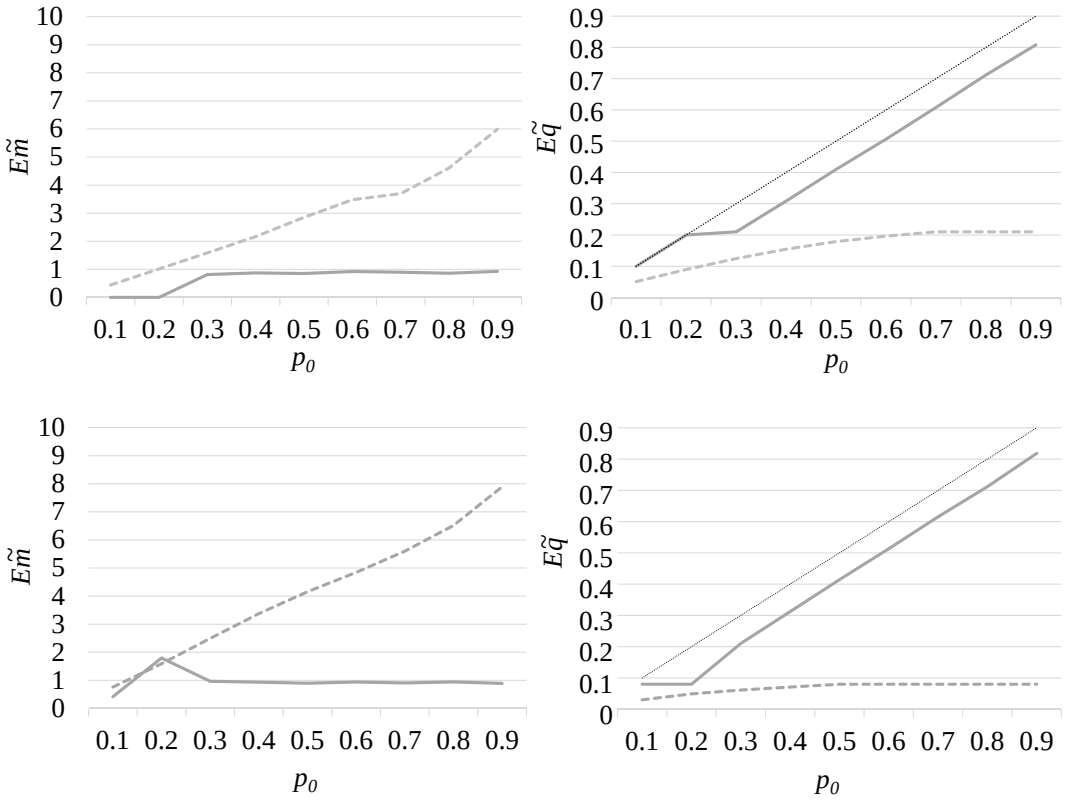


Figure 4: Expected firm's miscommunication and citizens' belief under populist policy (Dotted line) and agency policy (Solid line). Command and control (Above) and tax on emissions (Below).

We see that under a populist government, firms increase their communication effort continuously with scientists' initial belief.[29] This miscommunication is effective: citizens' belief lies significantly below correct belief represented by the 45-degree line in the Right panel.

Finally, the right bars in light grey in Figure 3 depict the scientific policies of an independent funding agency. We see that the agency essentially tries to limit the welfare losses induced by populist policies in two opposite ways. When initial beliefs are not too low, the agency provides much more funding than under the first-best. This is a strategy of *scientific overkill*: by doing lots of research, scientists necessarily get close to the truth

[29]If scientists are initially close enough to certainty, firms' communication essentially disappears in expectation. Thus, $E(\tilde{m})$ collapses when p_0 gets close to 1.

and firms then have little leeway to influence public opinion.[30] The benefits from shutting down firms' miscommunication outweigh the added research costs when the likelihood that the activity is harmful is not too low. In addition, scientific overkill starts for a lower level of scientific belief and leads to more research under a tax on emissions than under command and control. Because firms' incentives to miscommunicate are stronger under a tax on emissions, the agency must provide more research funding to counter firms' efforts. This is confirmed by looking at $E(\tilde{m})$ and $E(\tilde{q})$ in Figure 4. When p_0 is not too high, firms' expected communication is much lower than under a populist government. Moreover, $E(\tilde{m})$ stays more or less constant, leading to a widening gap in expected miscommunication under the two regimes as p_0 increases. Scientific overkill is effective at countering firms' miscommunication. We see in the Right panel of Figure 4 that in this range, expected citizens' belief, while biased, closely follows the correct beliefs.

By contrast, when initial belief is low, the agency provides no funding. This is a strategy of *deliberate ignorance*, since some research would yield lower welfare than no research. Indeed, firms' expected communication is generally lower than under a populist government, which provides more funding in this range. Relatedly, citizens' expected belief is less biased.

5 Conclusion

We provide one of the first analyses of the interactions between scientific uncertainty, firms' miscommunication and public policies. Characterizing firms' optimal miscommunication, we show that it can yield significant welfare losses and can have a strong impact on scientific research funding. Moreover, miscommunication may be reduced by regulating through command and control.

Our analysis relies on a number of simplifying assumptions. Relaxing them would provide potentially fruitful directions for future research. Since a populist government maximizes perceived welfare, firms do not have an incentive to engage in political lobbying here.

[30] That is, there is a low probability that scientists' belief p ends up in the range $[q^*, p^*]$ where firms affect public opinion.

Alternatively, the government could maximize a combination of welfare and transfers, as in Grossman & Helpman (1994). Firms would then try to affect regulation both directly through transfers and indirectly via public opinion, and exploring the interaction between direct and indirect lobbying could be interesting. We suspect that Theorem 1 would extend and that the sharp drop in communication effort would be accompanied by a sharp increase in political lobbying.[31]As in Yu (2005), it would also be natural to consider interactions between an industrial and an environmental lobby. Competition to affect public opinion would likely increase firms' communication effort and could lead them to abandon miscommunication for lower levels of scientific beliefs.

In our analysis, we assume that firms are organized in a communication lobby which tries to maximize the industry's payoff. In reality, firms within the industry may be tempted to free-ride and to benefit from the lobby's actions without paying their share of the communication costs. Introducing strategic interactions between firms would be an interesting direction for future research. We conjecture that these strategic interactions would generally reduce the effectiveness of the lobby and hence the extent of miscommunication.

Another assumption is that, in the absence of miscommunication, scientific knowledge disseminates widely and with no additional cost to citizens. In reality, knowledge diffusion may be imperfect and costly, and may depend on decisions by other agents such as journalists and media owners (Shapiro 2016). More generally, misperceptions may have a variety of causes, such as lack of Bayesian rationality.[32] It would be interesting to introduce these considerations in our framework. We suspect that miscommunication would be amplified in some instances and reduced in others. If there is poor diffusion of scientific knowledge, for instance, this likely reduces firms' incentives to produce biased research.

Finally, we have focused our representation of science on the key question of understanding the level of harm induced by the economic activity. In reality, science of course covers a wide variety of issues and questions. Another documented strategy of industrial

[31]In particular, this could shed new light on the debate on the regulation of political contributions. The introduction of a limit to contributions, for instance, could lead to an increase in miscommunication and, possibly, to a decrease in welfare. We thank Arnaud Dellis for drawing our attention to this implication.

[32]For example, agents may not properly account for the sources of the information they receive when forming their beliefs, as explored in the literature on persuasion bias (DeMarzo, Vayanos & Zwiebel 2003) and correlation neglect (Levy & Razin 2015).

lobbies has been to fund "distraction research", i.e., legitimate research that does not advance knowledge on this key question and distracts scientists and citizens' attention away from it.[33] Analyzing this elaborate strategy would require developing a richer model of science.

[33]See, in particular, chapter 16 in Proctor (2011).

APPENDIX

Proofs of statements in Section 3.1 We first prove that $\tilde{p}$ converges in probability to p_∞ as n tends to ∞. Let us first consider even values of n. Introduce $l = k - n/2$ and $\sigma = P(1-P)$. Since $\frac{1}{2} < P < 1$, $\sigma < \frac{1}{4}$. We have: $p(p_0, k, n) = \frac{p_0\alpha^l}{p_0\alpha^l + (1-p_0)\alpha^{-l}} = \hat{p}(p_0, l)$ with probability $x_{l,n} = \binom{n}{l+n/2}\sigma^{n/2}(p_0\alpha^l + (1-p_0)\alpha^{-l})$ for $l \in \{-\frac{n}{2}, -\frac{n}{2}+1, ..., -1, 0, 1, ..., \frac{n}{2}-1, \frac{n}{2}\}$. We show next that $x_{l,n} \to 0$ as $n \to \infty$. That is, keeping l constant, the probability attached to specific belief $\hat{p}(p_0, l)$ converges to 0 as the number of experiments n becomes arbitrarily large. To see why, note that:

$$\frac{x_{l,n+2}}{x_{l,n}} = \sigma \frac{(n+2)(n+1)}{(\frac{n}{2}+1+l)(\frac{n}{2}+1-l)}.$$

This implies that $\frac{x_{l,n+2}}{x_{l,n}} \to 4\sigma < 1$ as $n \to \infty$. Therefore there exists $K < 1$ such that $\frac{x_{l,n+2}}{x_{l,n}} \leq K < 1$ if n is large enough. This implies that $x_{l,n} \to 0$ as $n \to \infty$.

Next, consider $\hat{p}$ as a function of l. We see that $\hat{p}$ is increasing in l and that $\hat{p}(p_0, l) \to 0$ when $l \to -\infty$ and that $\hat{p}(p_0, l) \to 1$ when $l \to +\infty$. Take $\varepsilon > 0$. This implies that there exist two threshold values l_1 and l_2 such that:

$$\hat{p}(p_0, l) \in [\varepsilon, 1-\varepsilon] \Leftrightarrow l_1 \leq l \leq l_2.$$

Importantly, these values l_1 and l_2 do not depend on n. Take $\eta > 0$. Since for any l, $x_{l,n} \to 0$ as $n \to \infty$, there exists $\bar{n}$ such that $n \geq \bar{n} \Rightarrow \sum_{l=l_1}^{l_2} x_{l,n} \leq \eta$. This sum is precisely equal to the probability that belief will end up lying within $[\varepsilon, 1-\varepsilon]$. We showed that $\forall \varepsilon, \eta > 0, \exists \bar{n} : n \geq \bar{n} \Rightarrow \Pr(p(p_0, k, n) \in [\varepsilon, 1-\varepsilon]) \leq \eta$. Since $E(\tilde{p}) = p_0$, $\tilde{p}$ must converge in probability to p_∞. The proof for n odd runs along similar lines. QED.

Next, compute the derivatives of $q(p,m)$:

$$\begin{aligned}
\frac{\partial q}{\partial p} &= \frac{\alpha^m}{[p+(1-p)\alpha^m]^2} \\
\frac{\partial^2 q}{\partial p^2} &= \frac{-2\alpha^m(1-\alpha^m)}{[p+(1-p)\alpha^m]^3} \\
\frac{\partial q}{\partial m} &= -p(1-p)\ln(\alpha)\frac{\alpha^m}{[p+(1-p)\alpha^m]^2} \\
\frac{\partial^2 q}{\partial m^2} &= -p(1-p)[\ln(\alpha)]^2\alpha^m\frac{p-(1-p)\alpha^m}{[p+(1-p)\alpha^m]^3}
\end{aligned}$$

QED.

Proof of Theorem 1. We first obtain some useful formulas. By taking the derivative of (1), we get:

$$\frac{\partial e}{\partial q} = \frac{-b(d_0+de_0)}{(b+qd)^2}.$$

Then, observe that

$$\frac{q}{1-q} = \frac{p}{1-p}\alpha^{-m}.$$

Taking logs and differentiating with respect to m yields

$$\frac{\partial q}{\partial m} = -\ln(\alpha)q(1-q).$$

Differentiating again and substituting yields

$$\frac{\partial^2 q}{\partial m^2} = -\ln^2(\alpha)q(1-q)(2q-1).$$

We first consider payoff under command and control. We compute the first derivative of π_c with respect to m:

$$\begin{aligned}
\frac{\partial \pi_c}{\partial m} &= b(e_0-e(q))\frac{\partial e}{\partial q}\frac{\partial q}{\partial m} - c \\
\Leftrightarrow \frac{\partial \pi_c}{\partial m} &= \ln(\alpha)b^2(d_0+de_0)^2\frac{q^2(1-q)}{(b+qd)^3} - c.
\end{aligned}$$

Differentiating again and simplifying yields

$$\frac{\partial^2 \pi_c}{\partial m^2} = -\ln^2(\alpha)b^2(d_0+de_0)^2\frac{q^2(1-q)}{(b+qd)^4}[2b-(3b+d)q].$$

(1) Suppose first that $p < \frac{2b}{3b+d}$. Since $q \leq p$, $\frac{\partial^2 \pi_c}{\partial m^2} < 0$ and π_c is concave. Since $\frac{\partial \pi_c}{\partial m}(\infty) = -c$, either $\frac{\partial \pi_c}{\partial m}(0) \leq 0$ and the optimal effort is 0 or $\frac{\partial \pi_c}{\partial m}(0) > 0$ and the optimal effort is the unique $m_c^* > 0$ satisfying $\frac{\partial \pi_c}{\partial m}(m_c^*) = 0$. We have:

$$\frac{\partial \pi_c}{\partial m}(0) = \ln(\alpha) b^2 (d_0 + d e_0)^2 \frac{p^2(1-p)}{(b+pd)^3} - c.$$

To understand how $\frac{\partial \pi_c}{\partial m}(0)$ varies with p, study the function $f(p) = \frac{p^2(1-p)}{(b+pd)^3}$. We have:

$$f'(p) = \frac{p[2b - (3b+d)p]}{(b+pd)^4}.$$

This implies that $f' > 0$ if $p \in]0, \frac{2b}{3b+d}[$ and < 0 if $p \in]\frac{2b}{3b+d}, 1[$. Therefore, $f(0) = f(1) = 0$ and f is increasing over $[0, \frac{2b}{3b+d}]$, decreasing over $[\frac{2b}{3b+d}, 1]$ and reaches its maximum at $\frac{2b}{3b+d}$. Moreover, $f(\frac{2b}{3b+d}) = \frac{4}{27} \frac{1}{b(b+d)^2}$. Two subcases appear:

(1.1) If $c \geq \bar{c}_c = \frac{4}{27} \ln(\alpha) \frac{b(d_0 + d e_0)^2}{(b+d)^2}$, then $\frac{\partial \pi_c}{\partial m}(0) \leq 0$ and $m_c^* = 0$.

(1.2) If $c < \bar{c}_c$, then there is a unique $q_c^* \in [0, \frac{2b}{3b+d}]$ such that $\frac{\partial \pi_c}{\partial m}(m) = 0$. It satisfies:

$$\frac{q_c^{*2}(1-q_c^*)}{(b+qd)^3} = \frac{c}{\ln(\alpha) b^2 (d_0 + d e_0)^2}$$

Optimal communication is then such that $q = q_c^*$ which implies that

$$m_c^* = \frac{1}{\ln(\alpha)} [\ln(\frac{p}{1-p}) - \ln(\frac{q_c^*}{1-q_c^*})]$$

(2) Suppose, next, that $p > \frac{2b}{3b+d}$. Then π_c is a convex function of m for $q > \frac{2b}{3b+d}$ and a concave function for $q \leq \frac{2b}{3b+d}$. The marginal impact of an incremental unit of effort is increasing for $q > \frac{2b}{3b+d}$ and then decreasing when $q < \frac{2b}{3b+d}$. In particular, the optimal effort is such that $q \leq \frac{2b}{3b+d}$. We can see that the optimal effort is either 0 or $\hat{m}_c$ the unique m such that $\frac{\partial \pi_c}{\partial m}(\hat{m}_c) = 0$ and $q \leq \frac{2b}{3b+d}$. Compare the payoffs of these two effort levels:

$$\varphi(p) = \pi_c(0) - \pi_c(\hat{m}_c) = B(e(p)) - B(e(q_c^*)) + \frac{c}{\ln(\alpha)} [\ln(\frac{p}{1-p}) - \ln(\frac{q_c^*}{1-q_c^*})]$$

Study how φ varies with p. We have:

$$\begin{aligned} \frac{\partial \varphi}{\partial p} &= -\frac{b^2(d_0+de_0)^2}{(b+pd)^3}p + \frac{c}{\ln(\alpha)}(\frac{1}{p}+\frac{1}{1-p}) \\ \Leftrightarrow \frac{\partial \varphi}{\partial p} &= \frac{b^2(d_0+de_0)^2}{p(1-p)}[f(q_c^*)-f(p)]. \end{aligned}$$

Note that there is a unique $\bar{q}_c > \frac{2b}{3b+d}$ such that $f(\bar{q}_c) = f(q_c^*)$. From the derivative of function f, we know that $\frac{\partial \varphi}{\partial p}$ is > 0 over $]0, q_c^*[$, < 0 over $]q_c^*, \bar{q}_c[$ and > 0 over $]\bar{q}_c, 1[$. Therefore, φ is increasing over $[0, q_c^*]$, decreasing over $[q_c^*, \bar{q}_c]$ and increasing over $[\bar{q}_c, 1]$. Since $\varphi(q_c^*) = 0$ and $\varphi(1) = +\infty$, there is a unique level $p_c^* > \bar{q}_c > \frac{2b}{3b+d}$ such that $\varphi(p_c^*) = 0$ and $p < p_c^* \Rightarrow \pi_c(0) < \pi_c(\hat{m}_c)$ and $p > p_c^* \Rightarrow \pi_c(0) > \pi_c(\hat{m}_c)$.

Next, consider payoff under a tax on emissions. We have:

$$\begin{aligned} \frac{\partial \pi_t}{\partial m} &= be(q)\frac{\partial e}{\partial q}\frac{\partial q}{\partial m} - c \\ \Leftrightarrow \frac{\partial \pi_t}{\partial m} &= \ln(\alpha)b^2(d_0+de_0)\frac{q(1-q)(be_0-qd_0)}{(b+qd)^3} - c. \end{aligned}$$

Next, note that

$$\frac{\partial}{\partial q}\left[\frac{q(1-q)(be_0-qd_0)}{(b+qd)^3}\right] = \frac{h(q)}{(b+qd)^4}$$

with $h(q) = b^2e_0 - 2b(d_0+e_0(b+d))q + (d_0(3b+d)+dbe_0)q^2$. This implies that

$$\frac{\partial^2 \pi_t}{\partial m^2} = -\ln^2(\alpha)b^2(d_0+de_0)\frac{q(1-q)h(q)}{(b+qd)^4}.$$

Then, $h(0) = b^2e_0 > 0$ while $h(1) = (b+d)(d_0-be_0) < 0$. Since h is quadratic, there exists $\bar{p}_t \in]0,1[$ such that $h(\bar{p}_t) = 0$ and $h(q) > 0$ if $0 \leq q < \bar{p}_t$ and $h(q) < 0$ if $\bar{p}_t < q \leq 1$. Therefore, $\frac{\partial^2 \pi_t}{\partial m^2} < 0$ if $q \in]0, \bar{p}_t[$ and $\frac{\partial^2 \pi_t}{\partial m^2} > 0$ if $q \in]\bar{p}_t, 1[$. As under command and control, there are two cases.

(1) Suppose that $p < \bar{p}_t$. Then π_t is concave. Note that $\frac{\partial \pi_t}{\partial m}(\infty) = -c$ and

$$\begin{aligned} \frac{\partial \pi_t}{\partial m}(0) &= \ln(\alpha)b^2(d_0+de_0)\frac{p(1-p)(be_0-pd_0)}{(b+pd)^3} - c, \\ \frac{\partial^2 \pi_t}{\partial m \partial p}(0) &= \ln(\alpha)b^2(d_0+de_0)\frac{h(p)}{(b+pd)^4}. \end{aligned}$$

Therefore, $\frac{\partial \pi_t}{\partial m}(0)$ is increasing over $[0, \bar{p}_t]$ and decreasing over $[\bar{p}_t, 1]$, and $\frac{\partial \pi_t}{\partial m}(0)$ is maximum for $p = \bar{p}_t$. Introduce

$$\bar{c}_t = \ln(\alpha) b^2 (d_0 + d e_0) \frac{\bar{p}_t (1 - \bar{p}_t)(b e_0 - \bar{p}_t d_0)}{(b + \bar{p}_t d)^3}.$$

Then if $c \geq \bar{c}_t$, $\frac{\partial \pi_t}{\partial m}(0) \leq 0$ and $m_t^* = 0$. By contrast, if $c < \bar{c}_t$, then define $q_t^* < \bar{p}_t$ such that

$$\ln(\alpha) b^2 (d_0 + d e_0) \frac{q_t^* (1 - q_t^*)(b e_0 - q_t^* d_0)}{(b + q_t^* d)^3} = c.$$

If $p \leq q_t^*$, then $\frac{\partial \pi_t}{\partial m}(0) \leq 0$ and $m_t^* = 0$ while if $p > q_t^*$, then m_t^* is such that $q(m_t^*, p) = q_t^*$.

(2) Suppose that $p > \bar{p}_t$. Then π_t is a convex function of m for $q > \bar{p}_t$ and a concave function for $q \leq \bar{p}_t$. Therefore the optimal effort is either 0 or $\hat{m}_t$ such that $q(\hat{m}_t, p) = q_t^*$. Compare payoffs:

$$\psi(p) = \pi_t(0) - \pi_t(\hat{m}_t) = \frac{1}{2} b e(p)^2 - \frac{1}{2} b e(q_t^*)^2 + \frac{c}{\ln(\alpha)} [\ln(\frac{p}{1-p}) - \ln(\frac{q_t^*}{1 - q_t^*})]$$

with derivative

$$\begin{aligned} \frac{\partial \psi}{\partial p} &= b \frac{\partial e}{\partial p} e(p) + \frac{c}{\ln(\alpha)} (\frac{1}{p} + \frac{1}{1-p}) \\ \Leftrightarrow \frac{\partial \psi}{\partial p} &= -b^2 (d_0 + d e_0) \frac{(b e_0 - p d_0)}{(b + p d)^3} + \frac{c}{\ln(\alpha)} \frac{1}{p(1-p)}. \end{aligned}$$

Introduce $g(p) = \frac{p(1-p)(b e_0 - p d_0)}{(b + p d)^3}$. Note that by definition of q_t^*, $g(q_t^*) = c / [\ln(\alpha) b^2 (d_0 + d e_0)]$. This yields

$$\frac{\partial \psi}{\partial p} = \frac{b^2 (d_0 + d e_0)}{p(1-p)} [g(q_t^*) - g(p)].$$

Since $\partial g / \partial p = h(p) / [(b + p d)^4]$, g is increasing over $[0, \bar{p}_t]$ and decreasing over $[\bar{p}_t, 1]$. Therefore, there is a unique $\bar{q}_t > \bar{p}_t$ such that $g(\bar{q}_t) = g(q_t^*)$ and ψ is increasing over $[0, q_t^*]$, decreasing over $[q_t^*, \bar{q}_t]$ and increasing over $[\bar{q}_t, 1]$. Since $\psi(q_t^*) = 0$ and $\psi(1) = +\infty$, then there exists a unique $p_t^* > q_t^*$ such that $\psi(p_t^*) = 0$. Then $p < p_t^* \Rightarrow \pi_t(0) < \pi_t(\hat{m}_t)$ and $p > p_t^* \Rightarrow \pi_t(0) > \pi_t(\hat{m}_t)$. QED.

Proof of Theorem 2. Recall that we have: $\frac{\partial \pi_c}{\partial m} = \ln(\alpha) b^2 (d_0 + d e_0) \tilde{f}(q) - c$ while

$\frac{\partial \pi_t}{\partial m} = \ln(\alpha) b^2 (d_0 + de_0) g(q) - c$ with $\tilde{f}(q) = \frac{(d_0+de_0)q^2(1-q)}{(b+qd)^3}$ and $g(q) = \frac{q(1-q)(be_0-qd_0)}{(b+qd)^3}$. Then,

$$\frac{g(q)}{\tilde{f}(q)} = \frac{be_0 - qd_0}{(d_0 + de_0)q} \geq \frac{be_0 - d_0}{d_0 + de_0}$$

where the inequality comes from the fact that $g(q)/\tilde{f}(q)$ is decreasing with q. Therefore if $be_0 - d_0 \geq d_0 + de_0$, $g(q) > \tilde{f}(q)$ for any $q \in [0, 1[$ and hence

$$\frac{\partial \pi_t}{\partial m}(m) > \frac{\partial \pi_c}{\partial m}(m)$$

and the marginal impact of effort on payoff is always greater under a tax on emissions than under command and control. Integrate this inequality over $[0, m]$:

$$\pi_t(m) - \pi_t(0) > \pi_c(m) - \pi_c(0).$$

Therefore if 0 is the optimal choice under a tax on emissions, it must also be the optimal choice under command and control. This implies that $\bar{c}_c < \bar{c}_t$ and, if $c < \min(\bar{c}_c, \bar{c}_t)$, $q_t^* < q_c^* < p_c^* < p_t^*$. Moreover, m_t^* is equal to the highest m such that $\frac{\partial \pi_t}{\partial m}(m) = 0$ and $\frac{\partial \pi_t}{\partial m}$ is decreasing above m_t^*, and similarly for $\frac{\partial \pi_c}{\partial m}$. The inequality $\frac{\partial \pi_t}{\partial m} > \frac{\partial \pi_c}{\partial m}$ implies that this last crossing must happen at a larger value for π_t than for π_c. Therefore if $m_t^* > 0$, then $m_t^* > m_c^*$. QED.

Comparative statics. From the characterization of q_c^*, we can write:

$$q_c^*(c) = f^{-1}\left(\frac{c}{\ln(\alpha) b^2 (d_0 + de_0)^2}\right)$$

where f^{-1} is the inverse of f over the range $[0, \frac{2b}{3b+d}]$. Since f is increasing in that range, f^{-1} is also increasing. Since f only depends on d and b, this shows that q_c^* is increasing in c and decreasing in α, d_0 and e_0.

To study the comparative statics of p_c^*, introduce $\lambda(p, c) = B(e(p)) + \frac{c}{\ln(\alpha)} \ln(\frac{p}{1-p})$ such that $\varphi(p, c) = \lambda(p, c) - \lambda(q_c^*(c), c)$. Consider $c_1 < c_2$. Then

$$\lambda(p, c_2) - \lambda(p, c_1) = \frac{c_2 - c_1}{\ln(\alpha)} \ln(\frac{p}{1-p})$$

and this function is increasing in p. Since q_c^* is increasing in c, we have:

$q_c^*(c_2) > q_c^*(c_1)$. Moreover, $q_c^*(c_2) < \frac{2b}{3b+d}$ hence lies in the range where $\lambda(., c)$ is decreasing. Since $p_c^*(c_2) > q_c^*(c_2)$, $\lambda(p_c^*(c_2), c_2) - \lambda(p_c^*(c_2), c_1) > \lambda(q_c^*(c_2), c_2) - \lambda(q_c^*(c_2), c_1)$. This means that $\lambda(p_c^*(c_2), c_2) - \lambda(q_c^*(c_2), c_2) > \lambda(p_c^*(c_2), c_1) - \lambda(q_c^*(c_2), c_1)$. Since $\lambda(p_c^*(c_2), c_2) - \lambda(q_c^*(c_2), c_2) = \varphi(p_c^*(c_2), c_2) = 0$ and $\lambda(q_c^*(c_1), c_1) > \lambda(q_c^*(c_2), c_1)$, we have

$$\lambda(p_c^*(c_2), c_1) - \lambda(q_c^*(c_1), c_1) = \varphi(p_c^*(c_2), c_1) < 0$$

and hence $p_c^*(c_2) < p_c^*(c_1)$. Finally, note that an increase in α has the same impact as a decrease in c. QED.

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