# The Rational Expectations Objection to Austrian Business Cycle Theory: Prisoner's Dilemma or Noisy Signal?

Robert P. Murphy*

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ABSTRACT

The most common mainstream objection to the canonical version of the Austrian (or more specifically, Mises-Hayek) theory of the trade cycle relies on rational expectations: Why are businesspeople fooled time and again by the government's manipulation of the interest rate? Carilli and Dempster (2001) have argued that ABCT need not rely on any misperception at all, and that the malinvestments made during the boom period are due to unfortunate incentives. I reject this approach, and instead argue that the original Misesian story is largely correct: Businesspeople really *are* "tricked" by distortions in the price system, leading to erroneous (and regrettable) investments. I conclude with some brief empirical evidence to support my view.

* Visiting Assistant Professor of Economics, Hillsdale College, Hillsdale, MI. Robert.Murphy@hillsdale.edu. I would like to thank Jeffrey Miron and Mark Erickson for help with the empirical evidence, and the Ludwig von Mises Institute for financial support.

## INTRODUCTION

The Mises-Hayek theory of the trade cycle, or what is now commonly referred to as Austrian business cycle theory (ABCT), relied on the central bank artificially lowering the rate of interest below the "natural" rate, i.e. the rate consistent with the supply of various capital goods and the consumers' intertemporal preferences. Because of the rate reduction, Mises and Hayek argued that entrepreneurs were in a sense fooled into acting as if there had been a genuine increase in savings, and hence expanded their long-term projects. Yet because the rate reduction was the result of purely monetary (not real) factors, all of these new projects could not be fulfilled, and at some point the "bust" had to occur.

The standard mainstream objection to ABCT is that it (apparently) relies on the recurrent stupidity of businesspeople.[1] Richard Wagner (2000) is typical:

> The primary line of informed criticism of traditional Austrian cycle theory is that it ignores some elementary requirements of rationality in economic life and modeling….This situation might have had plausibility when Austrian cycle theory was initially formulated. The collection of economic statistics was primitive. Central banks were committed to exchanging their notes for specie. There was no developed community of financial observers and Fed watchers.
>
> Throughout the postwar period, however, we have become ever increasingly removed from that earlier time. Statistics, observers, and pundits are everywhere. A cycle theory that depends on the inability of people to distinguish, in the aggregate, between an increase in personal saving and an increase in central bank holdings of government debt must rightfully be dismissed on the grounds that it fails to incorporate any reasonable requirement of individual rationality in economic action. The aggregate data are widely and readily available. Austrian cycle theory is animated by a clustering of entrepreneurial error, and in the canonical statements that error would seem to reside in the inability of entrepreneurs to distinguish an increase in saving from an increase in central bank holdings of government debt. (Wagner 2000, qtd. in Block 2001, pp. 64-65)

[1] Besides Wagner (2000), Tullock (1987) also raises the rational expectations objection.

Several Austrians have attempted to answer this common mainstream objection. Perhaps the single most famous answer is provided in the (award-winning) Carilli-Dempster (2001) article, "Expectations in Austrian Business Cycle Theory: An Application of the Prisoner's Dilemma." Carilli and Dempster argue that the boom-bust occurs because the government's intervention sets up incentives similar to those of a prisoner's dilemma: Even though actors maintain their *individual* rationality, they make decisions such that the *collective* outcome is far from optimal.

In this paper I reject the Carilli-Dempster defense of ABCT. In the first place, I find their specific arguments unpersuasive; they have not convinced me that the unsustainable boom really *is* a prisoner's dilemma. More generally, I believe that entrepreneurs really *can* be "fooled" by the central bank's machinations, even if their expectations are perfectly rational in the neoclassical sense. As I hope to show, the way to meet the rational expectations objection is *not* to recast the situation as a prisoner's dilemma, but rather to focus on the role of market prices in fostering coordination.

## CRITIQUE OF CARILLI-DEMPSTER

[I have removed the critique of C-D because it is not necessary for my own proposed solution to the rational expectations objection.—RPM, May 2009]

## THE BOOM CHARACTERIZED BY ERRORS

Because of the above difficulties, I reject the C&D approach. That is, I do not feel that the unsustainable boom is (primarily) the result of a "commons problem," but rather—as in the original Mises-Hayek stories—I theorize that it is fundamentally an increase in entrepreneurial errors that lead to any given boom.

In one sense, I believe my rival interpretation is obviously correct: *Even if* the C&D story of altered incentives were perfectly true, they would still need to give some account of the quality of entrepreneurial forecasting. After all, if entrepreneurs could perfectly anticipate all future economic conditions, then there couldn't possibly be a recession.[2] (Depending on the government's actions, there could be *misery*; for example, the government could execute anyone caught hiring workers, and this would certainly hamper economic growth. But the point is, there would never be any processes that had to be *abandoned* midstream, as there are in a recession.) Therefore, I believe my approach—explaining how government intervention in the credit market reduces the quality of entrepreneurial forecasting—is more fundamental. There certainly are many aspects of an unsustainable boom that resemble a prisoner's dilemma, but to focus on them is to overlook the more essential cause.

To make my position clearer, consider Walter Block's (2001) analogy in his comment on Richard Wagner's (2000) rational expectations objection to ABCT:

> Expectations are a big part of the ABC story, but they by no means exhaust it. There is also the fact that by artificially lowering the market or loan rate of interest below that of the originary or real rate, not only are expectations pushed out of whack, but entrepreneurs are in effect *bribed* into making otherwise unwarranted investments in the higher orders of the structure of production. This is a very crucial point, completely ignored by Wagner…
>
> Let us consider an analogy, far removed from the ABC. Suppose that the proportion of peas to carrots that will satisfy consumer demand is 1:1. The government, however, decrees that the appropriate proportion is 2:1, and begins to subsidize pea production. Third premise of the syllogism: Sophisticated (but not all) investors know that this policy cannot last, that there will be political or other repercussions, and eventually the government will have to pull in its horns and cease its mischievous attempt to reallocate resources. The question is, will this suffice to set up a peas-and-carrots cycle…? (Block 2001, pp. 66-67, italics original)

Notice that Block needs to rely on *some* ignorance; if all investors perfectly forecast the government's moves, then no one would be caught with unwanted peas. And even in the

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[2] This argument is admittedly a bit unfair. Given that there is *some* uncertainty and hence possibility of error, all C&D need to do is show that the government causes the banks and firms to optimize with a higher degree of risk—and indeed this is what C&D claim to do. (In my critique, we have explained why I feel they have failed in their specific arguments.) In the text above, I am simply trying to drive home the point that the boom is characterized by a cluster of errors, and that if these errors can be explained, no further explanation is needed.

more realistic case of a spectrum of investor knowledge, we would expect that, over time, the farmers and speculators who could not anticipate the government's shifting policies would go out of business. In the end, the explanation of periodic booms and busts in the pea market would *not* be due to the subsidies per se, but rather to the *additional* uncertainty that the government's fickle policies brought about. After all, if the subsidies were permanent, there would be no recurring cycles. The issue is thus not one of bribery, but one of extra uncertainty.

Beyond these problems, there is another flaw with the prisoner's dilemma (or more generally, argument from incentives) approach: It forces the Austrian to declare that *every* government credit expansion should cause a boom (and then bust). But is this position consistent with, say, the Japanese experience of the 1990s? For a different example, does it not conflict with the general free marketeer explanation of (a) the initial success of Keynesian policies and (b) their long-run unsustainability? The laissez-faire advocate generally endorses the "policy ineffectiveness theorem" in macro, which states that government interventions (in certain areas) can only affect real outcomes to the extent that they are unanticipated. I believe that one of these areas is the credit market.

*A return to the spirit of Mises-Hayek*

My own story of the business cycle is, at first glance, quite simple, and entirely consistent with Hayek's (1937) view of the coordinating function of prices: The various market rates of interest are the most important prices for achieving intertemporal coordination, i.e. for achieving compatibility between consumers' savings and consumption decisions, and firms' investment and production decisions. To the extent that the government tinkers with these prices, it necessarily hampers their coordinating function. In effect, the government introduces an additional source of "noise" in the signals being conveyed to actors in the economy. It is then not surprising that the entrepreneurs who rely on such signals periodically experience clusters of mistakes.

*Previous stories too unrealistic*

The story I have told above is quite orthodox; as yet I have not departed from the standard ABCT. Because of this, the standard rational expectations critic would find it just as unappealing as the stories of Mises and Hayek. The contribution I propose is *not* to abandon the element of entrepreneurial mistakes, but rather to render the Mises-Hayek stories more realistic.

In the first place, no entrepreneur ever needs to worry about the "natural" rate of interest; he must instead make his decisions on the basis of expected *actual* prices.[3] Similarly, no entrepreneur needs to speculate about a change in consumers' "rate of time preference," or about the "supply of capital goods." No, the individual entrepreneur is concerned only with a very small set of market prices, namely, the prices of the inputs she will need for her projects, and the prices for which these products will sell. That's the whole *point* of relying on the market rates of interest and other prices—it eliminates the need for any individual to speculate about aggregates that are far too complex for any single mind to comprehend.

The second major problem with standard expositions of ABCT is that they assume—at least in their description of the boom—an initial free market state, and then analyze the impact of a one-shot intervention. If *this* were really what happened, then yes, it would be surprising if rational businesspeople continually fell for the ruse. However, in reality the government (in each major country) has implemented a permanent intervention in the credit market by the creation of a central bank (or a centralized system of banks). Actors in these economies have no idea what the free market rate of interest would be in the absence of such interference; even if the Fed *raises* rates, the new rate could still be below the "natural rate" of canonical ABCT.

[3] Of course, it is possible that he relies on economic theory and, because of his knowledge of concepts such as the natural rate of interest, is better able to forecast market rates. I reject this possibility, though, because I don't believe there is any such thing as "the" natural rate of interest (Murphy 2004).

Once we revise the traditional stories to incorporate these more realistic aspects, the typical rational expectations objection is no longer applicable. As I shall demonstrate in the next subsection, even agents with RE will be more likely to commit a critical number of errors over time, if we add noise to the signal on which they rely for guidance. Yes, the agents will take into account this extra noise when making their decisions, but they cannot completely offset it. Finally, given certain choices of parameters, the increase in signal noise can make the difference between a good chance of zero "recessions" (as defined in the model) and a good chance of several recessions, over a certain time period.

*A simple model*

In this subsection I formalize my ideas with a simple model. It should go without saying that I do not intend this as an adequate description of the boom-bust cycle; I am merely trying to convince the mainstream reader that a noisier price signal can lead to clusters of errors, even if we assume rational expectations.

Suppose our imaginary economy consists of $N$ entrepreneurs (or agents), each of whom must decide in each period $t$ (from $t$=1 to $t$=$T$) whether to invest or not, in a particular project specific to each person. Further suppose that in every period, it is either profitable or not to make the investment in a given project. (We may assume that Nature determines this at the outset, according to a specific probability distribution.) This objective knowledge is not known by anyone in the model, but each entrepreneur knows Nature's original probability distribution, and additionally has a "signal" concerning the profitability (or lack thereof) of his or her particular project at each time $t$. For example, entrepreneur #4 might get a signal at time $t$=18 that his project (in that period!) is profitable.[4] Unfortunately, the signal is noisy; although it conveys *some* information to the entrepreneur, it is entirely possible that the signal will indicate profitability (or not) when in actual fact Nature has assigned the opposite for the project at that particular time. Specifically, we shall assume that if the project is in fact profitable, then the signal will

[4] To avoid confusion: Each project has a duration of only one period. Every period an agent must decide whether to invest in a *new* project, and to help in this decision the agent receives a (noisy) signal concerning that particular project's profitability.

indicate "profitable" with probability $p$, and will indicate "unprofitable" with probability $(1-p)$; if the project is unprofitable, the signal will be "unprofitable" with probability $p$ and "profitable" with probability $(1-p)$.[5] The agent is completely rational and thus uses Bayes' Law to form the correct expectation about the profitability of his project at each time $t$, based on his knowledge of Nature's original probabilities and his observed signal. Finally, assume that the agent wishes to maximize the expected (undiscounted) sum of payoffs from $t=1$ to $t=T$, where the payoff in each period is 0 if he chooses no investment, $L<0$ if he invests when the project is unprofitable in that period, and $G>0$ if he invests when the project is profitable.

I now wish to draw some conclusions from the above model. But first, I need to adopt a working definition of an unsustainable boom: I define it as any period in which a critical number $k$ (or more) of agents chooses to invest in an unprofitable project. (If this happens in any period $t$, then there is a "recession" in period $t+1$.)

With the above framework, it is easy to compute the *ex ante* probability that, over the entire history of $T$ periods, there will be at least $R$ recessions. My insight is nothing more than the fact that this probability will often be *greater* as the signal noise is increased. That is, if we first calculate the probability assuming $p=p_1$, and then recalculate assuming $p=p_2$, where $0.5 < p_2 < p_1$, the overall probability of $R$ (or more) recessions occurring will (normally) be higher in the second case.[6]

Consider the following numerical illustration: Set $G=1$, $L=-1$, $N=25$, $T=50$, $k=3$, $p_1=0.99$, and $p_2=0.91$. Finally, suppose that Nature makes projects profitable with probability 0.5, regardless of the agent or the time period. With these parameters, there is a probability of 0.9851 that there will be *zero* recessions in the fifty periods when the better signal (i.e. the signal with 99 percent accuracy) is available to the agents.

[5] Notice that if $p=0.5$, the signal is pure noise; it conveys no information about the profitability of the project.

[6] In extreme cases, the increase in signal noise can actually reduce the expected number of recessions, for the trivial reason that the agents may refrain from all investment. Thus, if the signal becomes so poor that agents no longer invest at all, then the expected number of recessions will drop to zero.

However, when the signal quality is reduced to 91 percent, there is a probability of 0.8900 that there will be *at least three* recessions during the same interval.[7]

Another qualitative result, in any such comparative statics experiment, is that the expected proportion of “seized opportunities” (i.e. any time that an entrepreneur chooses to invest in a profitable project) to total opportunities (i.e. the total number of profitable investments as determined by Nature) will possibly be lower (and never higher) with the noisier signal. Intuitively, the noisier signal makes the entrepreneur more conservative; he is more likely to pass on projects that are in truth profitable when he is less confident in the accuracy of his signal.

To illustrate this second feature of the model, consider the following numerical example: Suppose that Nature makes all projects in odd-numbered time periods profitable with probability 0.75, while she makes all projects in even-numbered time periods profitable with probability 0.5. Further suppose that $L$=-2 while $G$=1. Finally, suppose that $p_1$=0.7 while $p_2$=0.65. With these parameter values, entrepreneurs will always invest when the clearer signal (i.e. the signal associated with $p_1$) indicates “profitable” (and they will refrain from investing when the clearer signal indicates “unprofitable”). On the other hand, when entrepreneurs receive a noisier signal (i.e. the one associated with $p_2$), they will only invest after a “profitable” signal in *odd*-numbered time periods. That is, even when the entrepreneurs receive a “profitable” signal in even-numbered time periods, they will not invest, because the noisier signal cannot overcome their fear of losing 2 from a bad investment (as opposed to gaining 1 from a good investment).[8] Note that a relatively minor reduction in signal accuracy—in this numerical example, from 70 percent to 65 percent—can make a huge difference in the number of unexploited investment opportunities.

*The real world*

[7] Consult the appendix for a derivation of this result.
[8] Consult the appendix for a derivation of this result.

The relevance of this simplistic model to my verbal explanation should be clear. Even with perfectly rational agents, a noisier signal (concerning the "fundamentals" of a given project) can lead to both (a) a greater likelihood of clusters of mistakes and (b) slower economic growth (i.e. a lower proportion of seized opportunities). I believe these theoretical results are consistent with the history of central banking, at least in the US: There is a greater chance of recession and growth is more sluggish, relative to the free market outcome.

Before leaving this section, I should address one concern that is undoubtedly troubling the typical Austrian reader: Does my analysis imply that recessions are *not* necessarily the fault of governments per se, but could occur on an unhampered market (albeit with lower probability)? Why yes, this *is* my claim. But is this so controversial? After all, there is nothing in praxeology to rule out clusters of errors. As Hayek (1937) points out, the actual degree of coordination is not a matter of pure theory, but involves the empirical facts of the transmission of knowledge through the price system. I claim that the differences between high growth, sluggish growth, and recession are not qualitative, but matters of degree, of the relative number of successful entrepreneurial forecasts. As such, it is certainly *conceivable* that a critical number of forecasts can be mistaken, even under pure laissez-faire. My model shows, however, that with appropriate parameters, the probability of this occurring (in any specified length of time) can be quite low,[9] while the introduction of more noise can cause the chance of recession to spike quite sharply.

## EMPIRICAL SUPPORT

[9] To make my model more realistic, we could make the underlying profitability, as well as the investment decision, a continuous range of values, rather than a binary yes/no. This would then allow us to evaluate entrepreneurial decisions not simply as good or bad, but as (say) very good and disastrous. In this framework, we could show that the more accurate signal almost never leads to a large number of disastrous decisions in any given time period, which probably captures the feeling of most Austrians regarding the free market.

This paper is intended as a theoretical contribution, rather than an econometric exercise. Nonetheless, I have a few remarks on the econometric evidence for (or against) my approach.

Milton Friedman's discussion of the Fed in *Capitalism & Freedom* is consistent with the view presented here:

> The establishment of the Federal Reserve System was the most notable change in United States monetary institutions since at least the Civil War National Banking Act. For the first time since the expiration of the charter of the Second Bank of the United States in 1836, it established a separate official body charged with explicit responsibility for monetary conditions, and supposedly clothed with adequate power to achieve monetary stability…It is therefore instructive to compare experience as a whole before and after its establishment—say, from just after the Civil War to 1914 and from 1914 to date, to take two periods of equal length.
>
> The second period was clearly the more unstable economically, whether instability is measured by the fluctuations in the stock of money, in prices, or in output. Partly, the greater instability reflects the effect of two world wars during the second period…But even if the war and immediate postwar years are omitted, and we consider only the peacetime years from, say, 1920 through 1939, and 1947 to date, the result is the same. (Friedman 1971 [1962], p. 44)

A more modern treatment can be found in the work of Gregory Mankiw and Jeffrey Miron. For example, in Mankiw and Miron (1986), the authors find that "prior to the founding of the Federal Reserve System in 1915, the spread between long rates and short rates has substantial predictive power for the path of interest rates; after 1915, however, the spread contains much less predictive power" (p. 211). In particular, the authors find that the short-term interest rate is a random walk (actually, a martingale) after the founding of the Fed, but not before. They attribute this to the Fed's announced (and believed) goal of stabilization; at any given time the expected short-term interest rate next period is the *current* short-term rate. However, before the Fed, there were predictable movements in the short-term rate, and so often next period's expected short rate was not simply this period's.

Although quotations from their paper would seem to lend support to my thesis, the work of Mankiw and Miron is actually inconclusive in this regard. When they state that changes in the interest rate were more predictable before the founding of the Fed, this by itself doesn't imply that investors were actually more *confident* about the value of interest rates for any future date. For example, suppose that before the founding of the Fed, the interest rate of $r_{t+1}$ is given by $r_t + \Phi(0.1 - r_t) + e_{t+1}$, where $e_{t+1}$ is an error term with mean zero, and $0 < \Phi < 1$. Further, suppose that *after* the founding of the Fed, the interest rate moves according to the process $r_{t+1} = r_t + u_{t+1}$, where $u_{t+1}$ is also an error term with mean zero. Under these assumptions, the interest rate would be mean-reverting before the founding of the Fed—although it would bounce around due to shocks of a certain persistence, the interest rate would always move back toward 10 percent. On the other hand, in the second process the interest rate would be a random walk; after jumping from, say, 8 percent to 12 percent, investors would have no reason to expect it to sink in the following period. Even so, without knowing the *variances* of the error terms, we cannot say in which environment investors will make better forecasts. This is why the conclusions of Mankiw and Miron are actually of little value for the theoretical claims in this paper.

## CONCLUSION

The most common mainstream objection to ABCT is that it (allegedly) cannot be reconciled with rational expectations on the part of investors and entrepreneurs. In an understandable attempt to sidestep this objection, Carilli and Dempster (2001) (as well as other Austrians less explicitly) recast ABCT in a manner that is completely dependent on altered incentives, rather than forecasting errors, to generate the unsustainable boom. I reject the Carilli and Dempster approach, both because I find their particular exposition unpersuasive and, more important, because it abandons the essence of the original Mises-Hayek stories, namely that the central bank's manipulations of the interest rate can mislead entrepreneurs into making unsound investments. Once we remember that the entrepreneur must forecast an entire array of future prices, it is not surprising that he or she, even if perfectly rational in the neoclassical sense, will make more mistakes when the most important intertemporal prices (i.e. market interest rates) are influenced not only by "fundamentals" but also by the changing whims of central bankers.

I do not deny that there are many aspects of government credit expansion that resemble a prisoner's dilemma (or more accurately, a tragedy of the commons). In particular, I do not deny that an important feature of any such expansion is the forced redistribution of property titles.[10] However, redistribution as such does *not* lead to the boom-bust cycle, except insofar as it introduces additional uncertainty and causes entrepreneurs to make mistakes that they would not have otherwise committed.

The aspect of my approach that will undoubtedly worry most Austrians is the implication that it is not any particular reduction in the interest rate, but rather the intervention of the government as such, that causes an unsustainable boom. That is, my approach allows for the fact that the market may indeed fail to be "tricked" by a particular rate cut, whereas most Austrians (at least in certain contexts) argue that the boom-bust is a necessary consequence of the issuance of fiduciary media. To this, all I can reply is that I do *not* believe the market always "takes the bait" of lower rates. There are plenty of episodes where, e.g., the Fed cuts rates and is disappointed in the results, and must cut them again in an effort to stimulate the economy. My formal model easily handles such cases; even with a lower $p_2$, there are plenty of time periods in which the rational agents do not commit more than the critical number $k$ of unsound investments. All I can say in my model (and this is my view of the real world, too) is that the lower $p_2$ will make it more likely that *sometimes* a cluster of errors will occur, and that *then* there will follow a recession. Having said this, I should reiterate that the primary purpose of my formal model is to convince the skeptical mainstream reader; I do not offer it as a substitute for verbal analysis.

It is my hope that this paper will cause Austrians to think twice before abandoning the Mises-Hayek reliance on genuine ("sheer") entrepreneurial errors. It is possible to

[10] Dan Mahoney (private email discussion list) believes this to be the essential point of fiat money expansion, while the possible effects on knowledge transmission are incidental.

reconcile ABCT with mainstream rational expectations, *without* invoking a story of altered incentives such as Carilli and Dempster have done. The market price system conveys information to individual actors, as Hayek taught. When the government interferes with such signals, the decisions of entrepreneurs are necessarily worse.

## APPENDIX

In this appendix I elaborate on the numerical examples from the text. In the first example, I set $G$=1, $L$=-1, $N$=25, $T$=50, $k$=3, $p_1$=0.99, and $p_2$=0.91. I also stipulated that Nature made projects profitable with probability 0.5, regardless of the agent or the time period. With the first signal accuracy (i.e. 99 percent), the probability of *no* recession in a given time period is the probability that *two or fewer* agents invest in an unprofitable project (in the previous time period).

Because of the symmetry of the parameters, if there were no signal (or if the signal were complete noise) then an agent would be indifferent between investing or not in any time period. This is because the expected payoff from investment in any period would be (0.5)(1) + (0.5)(-1) = 0, which is the payoff from not investing. Therefore, we intuitively see that when the signal *does* convey information (i.e. when $p_i > 0.5$), the agent will always heed it. In other words, with these parameter choices the agent will always invest when the signal is "profitable" and will refrain from investing when the signal indicates "unprofitable."

It is now easy to calculate the probability that any given agent will make an unprofitable investment in a given time period: this is simply the probability that the project *is in fact* unprofitable, *and* that the agent receives an erroneous signal. The relevant probability is thus (0.5)(1-$p_i$), where $i$=1,2. Once we know this number, it is easy to calculate the probability that *at least k* agents will make such erroneous investments, and we can also easily compute the probability that such an unsustainable boom will occur $R$ times in the 50 time periods.

When using $p_1$=0.99, there is a (0.5)(1-.99) = .005 probability that an agent will make a bad investment in a given period. There is thus a $(.005)^2 * (.995)^{23} * (25*24)/2 = 0.0067$ probability that exactly two agents (out of all twenty-five) will do so, in a given time period. Likewise, there is a $(.005) * (.995)^{24} * (25) = 0.1108$ probability that exactly one agent (out of all twenty-five) will do so, and a $(.995)^{25} = 0.8822$ probability that zero agents will do so. The overall probability of no recession in a given time period is thus 0.0067 + 0.1108 + 0.8822 = 0.9997 (because a recession only occurs when at least $k$=3 agents make erroneous investments). Finally, the probability of zero recessions over the course of fifty time periods is $(.9997)^{50}$ = 0.9851, as I claimed in the text above.

Consider what happens when the signal accuracy is reduced to $p_2$=0.91. Now there is a (0.5)(1-.91) = .045 probability that an agent will make a bad investment in a given period. There is thus a $(.045)^2 * (.955)^{23} * (25*24)/2$ = 0.2107 probability that exactly two agents (out of all twenty-five) will do so, in a given time period. Likewise, there is a (.045) * $(.955)^{24}$ * (25) = 0.3726 probability that exactly one agent (out of all twenty-five) will do so, and a $(.955)^{25}$ = 0.3163 probability that zero agents will do so. The overall probability of no recession in a given time period is thus 0.2107 + 0.3726 + 0.3163 = 0.8996. Therefore, the probability of zero recessions in fifty time periods is $(.8996)^{50}$ = 0.0050, while the probability of one recession in fifty time periods is (.1004) * $(.8996)^{49}$ * (50) = 0.0281, and the probability of two recessions is $(.1004)^2 * (.8996)^{48} * (50*49)/2$ = 0.0769. We now can compute the probability of *two or fewer* recessions in the fifty time periods, which is simply 0.0050 + 0.0281 + 0.0769 = 0.1100. Finally, the probability of *at least three* recessions in fifty periods is 1 – 0.1100 = 0.8900, as I stated in the text above.

In the second numerical example, I altered the parameters so that $L$=-2, $G$=1, $p_1$=0.7, and $p_2$=0.65. I also stipulated that Nature makes all projects in odd-numbered time periods profitable with probability 0.75, while she makes all projects in even-numbered time periods profitable with probability 0.5. In order to understand the effects of signal accuracy on the willingness of agents to invest, we need to compute the expected payoff from investment as a function both of the time period (odd or even) and the signal received ("profitable" or "unprofitable").

In an odd-numbered time period when the signal is "profitable," the probability that the project is actually profitable is:

$$\frac{\frac{3}{4}p}{\frac{3}{4}p + \frac{1}{4}(1-p)}$$

This follows from Bayes' Law: The numerator is the probability of receiving a signal of "profitable" in an odd-numbered time period when the project is profitable; these are independent events and so it is simply ¾ (Nature's *ex ante* probability of a good project in an odd-numbered time period) times the probability of an accurate signal, which we above denote simply as $p$. (We are omitting subscripts so that it will be easier to plug in the different values of $p_1$ and $p_2$ once we have derived our final formulas.) The denominator represents the probability of seeing a signal of "profitable" in an odd-numbered time period, *regardless* of the project's actual desirability. The first term represents what we have already computed, i.e. the probability of seeing "profitable" when the signal is accurate. The remaining term, ¼ (1-$p$), is the probability of Nature making the project undesirable *and* the signal erroneously reporting "profitable"—an event that occurs with probability (1-$p$) anytime the project is in fact unprofitable.

In the same way, we can compute the probability that the project is profitable in an odd-numbered period if the signal is "unprofitable." It is:

$$\frac{\frac{3}{4}(1-p)}{\frac{3}{4}(1-p) + \frac{1}{4}p}$$

Now consider the probability that the project is profitable if we are in an even-numbered time period, and the signal is "profitable":

$$\frac{\frac{1}{2}p}{\frac{1}{2}p + \frac{1}{2}(1-p)}$$

(Note that this expression is also the probability that the project is unprofitable in an even-numbered time period, given a signal of "unprofitable.")

Using the expressions for all (eight) such contingencies, we can derive the expected payoffs from investing in any period, based on whether the time period is even or odd, and what the signal indicates. (The expected payoff from investment is the gain, 1, times the probability of a sound investment, plus the loss, -2, times the probability that the project is actually unprofitable.) The four possibilities are:

Period odd, Signal "profitable" $\rightarrow$

$$\frac{\tfrac{3}{4}p}{\tfrac{3}{4}p + \tfrac{1}{4}(1-p)} - \frac{\tfrac{1}{2}(1-p)}{\tfrac{3}{4}p + \tfrac{1}{4}(1-p)} = \frac{(5/4)\,p - \tfrac{1}{2}}{\tfrac{3}{4}p + \tfrac{1}{4}(1-p)}$$

Period odd, Signal "un-profitable" $\rightarrow$

$$\frac{\tfrac{3}{4}(1-p)}{\tfrac{3}{4}(1-p) + \tfrac{1}{4}p} - \frac{\tfrac{1}{2}p}{\tfrac{1}{4}p + \tfrac{3}{4}(1-p)} = \frac{\tfrac{3}{4} - (5/4)\,p}{\tfrac{1}{4}p + \tfrac{3}{4}(1-p)}$$

Period even, Signal "profitable" $\rightarrow$

$$\frac{\tfrac{1}{2}p}{\tfrac{1}{2}p + \tfrac{1}{2}(1-p)} - \frac{1-p}{\tfrac{1}{2}(1-p) + \tfrac{1}{2}p} = \frac{(3/2)\,p - 1}{\tfrac{1}{2}p + \tfrac{1}{2}(1-p)}$$

Period even, Signal "un-profitable" $\rightarrow$

$$\frac{\tfrac{1}{2}(1-p)}{\tfrac{1}{2}p + \tfrac{1}{2}(1-p)} - \frac{p}{\tfrac{1}{2}p + \tfrac{1}{2}(1-p)} = \frac{\tfrac{1}{2} - (3/2)\,p}{\tfrac{1}{2}p + \tfrac{1}{2}(1-p)}$$

Now that we've derived these general formulas, we can plug in the values of $p_1$=0.7 and $p_2$=0.65 to see how the lower signal strength makes the agents seize fewer profitable opportunities. With $p_1$=0.7 and a signal of "profitable," the expected payoff from investment is greater than zero for both even- and odd-numbered time periods. (To make sure the reader is using the formula properly: the expected payoff from investment in an odd time period with a signal of "profitable" is .375 / [.525 + .075] = 0.625.) On the other hand, the expected payoff from investing in even- and odd-numbered periods when the signal is "unprofitable" is negative. Because the payoff from no investment is zero, the agent will always heed the advice of the signal; i.e. it is better to invest when the signal indicates "profitable," and it is better to refrain from investing whenever the signal indicates "unprofitable."

This is *not* the case when the signal accuracy declines to $p_2$=0.65. In this case, investment has a positive expected payoff *only* in odd-numbered time periods when the agent receives a signal "profitable." In particular, in an even-numbered time period even with a signal of "profitable," the expected payoff is -.025 / (.325 + .175) = -.05 < 0.

Thus we see that the slight reduction in signal accuracy will cause the agents to *never* invest in even-numbered time periods. The expected proportion of seized profit opportunities will thus be much lower under this scenario, compared to the situation with a signal accuracy of 0.7.

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