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How Little We Know: Big Gaps in Psychology and Economics

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A rule about variability is *reducing expectation of reward increases variation of the form of rewarded actions*. This rule helps animals learn what to do at a food source, something that is rarely studied. Almost all instrumental learning experiments start later in the learning-how-to-forage process. They start after the animal has learned where to find food and how to find it. Because of the exclusions (no study of learning where, no study of learning how), we know almost nothing about those two sorts of learning. The study of human learning by psychologists has a similar gap. Motivation to contact new material (curiosity) is not studied. Walking may increase curiosity, some evidence suggests. In economics, likewise, research is almost all about how people use economically-valuable knowledge. The creation and spread of that knowledge are rarely studied.

Several years ago, my colleagues and I proposed a rule: *Reducing expectation of reward increases variation in the form of rewarded actions* (Gharib, Derby, & Roberts, 2001). It was based on experiments in which reducing a rat's expectation of reward increased variation in how long it pressed a bar for food.

The rule was a new idea about what controls variability, but it also revealed the limits of what animal learning experiments study. By varying how they press a bar, rats learn the best way to press a bar. They learn what to do to get food. Almost all instrumental learning experiments begin – that is, the main data collection begins -- after this has been learned. At the start of a rat bar-pressing experiment, for example, the rat is trained to press a bar for food. Then the main experiment begins. It is easier to study learning *after* rats have learned where to go and what to do, but after a while, perhaps after several thousand experiments, it would be more profitable to study learning *before* rats have learned where to go and what to do.

Once you realize that we study only the final steps in foraging, it is easy to see that something similar happens in human learning and economics: only the last step is studied. Human learning experiments by psychologists (the sort of studies published in *Journal of Experimental Psychology: Learning Memory and Cognition*) are about how people learn material given to them. I have not seen a single study in that journal or similar journals about what causes people to seek information. It is like ignoring hunger when studying weight control. Likewise, almost all economic research is about the use of economically-valuable knowledge. Almost none of it is about how that knowledge originated or was transmitted.

This paper is about these gaps. They are gaps in science (what is studied) not just gaps in knowledge.

Control of Variation by Reward Expectation

My awareness of these gaps began with a puzzling result. In graduate school, I studied how rats measure time using the peak procedure, a discrete-trial version of a fixed-interval schedule (Catania, 1970;

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Roberts, 1981). Peak procedure trials are separated by intervals of darkness and silence. A trial begins with signal (light or sound) onset. There are two types of trials: food trials and empty trials. Both begin the same way – at first, a rat cannot tell them apart. On food trials, the first bar press more than 40 seconds after the start of the trial produces food and ends the trial (the light or sound goes off). On empty trials, the first bar press more than 40 seconds after the start of the trial does *not* produce food nor end the trial. The trial simply continues and ends a long time (e.g., 3 minutes) after it began, without any food. Food and empty trials are randomly mixed.

The function in the upper panel of Figure 1 (actual data) shows rate versus time during a peak procedure trial. Rate increased until the time that food was sometimes given. After that – on empty trials -- rate declined symmetrically to a low but non-zero level. In graduate school, I studied how various events changed this function (Roberts, 1981).

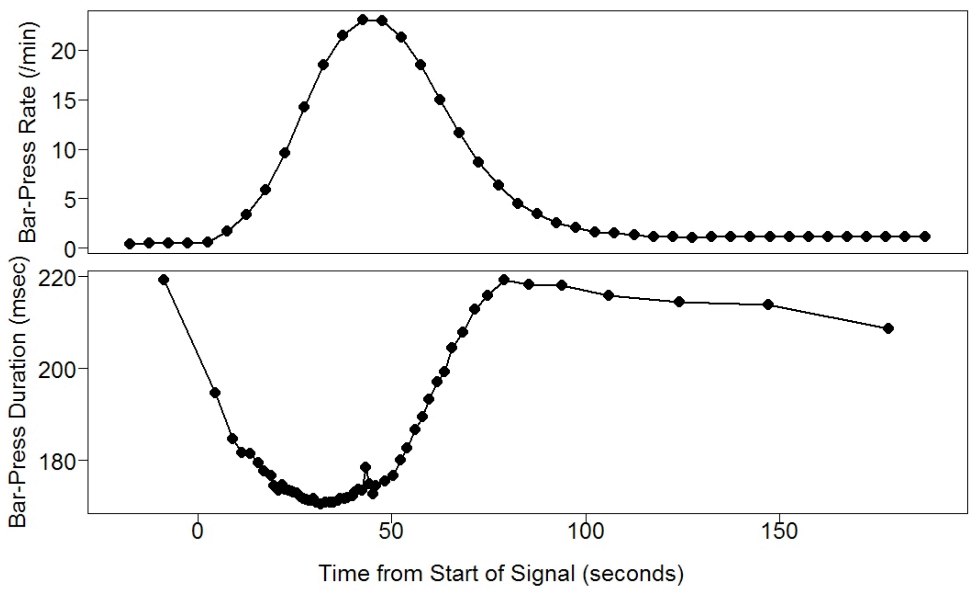

Figure 1. Bar-press rate (upper panel) and duration (lower panel) as a function of time from the start of the signal of a peak-procedure trial. Points on the duration function are spaced so that each will be based on roughly the same number of bar presses. Data from Figure 2 of Gharib et al. (2001).

When I became an assistant professor, I got a new lab, which allowed me to measure bar-press duration (how long the bar is held down when pressed). The lower panel of Figure 1 shows bar-press duration versus time during a peak-procedure trial. The duration-versus-time function was so different than the rate-versus-time function (upper panel) that at first I thought I would made a mistake somewhere. The rate-versus-time function was symmetrical around the time of food (about Second 45). The duration-versus-time function was highly asymmetrical around the time of food. Yet the two functions came from the same responses.

The difference between the two functions was not a complete mystery. Examples of multiplicative factors with response rate or probability support the idea that actions often come from a two-stage mechanism (Roberts, 1987). Such a mechanism could explain these results. An early process, measured by rate, decides *whether* to press the bar. A later process, measured by duration, determines *how* to press the bar. The rate and duration functions were so different because they reflected different processes.

The rate-controlling process seemed straightforward. Rats pressed the bar more often when they were closer to the time of food. That made sense.

The duration-controlling process was harder to explain. At first, the sharp rise in duration in the middle of the trial looked like a frustration effect. Amsel and Roussel (1953) found that when rats failed to get expected food in the first goal box of a double runway, they ran faster in the second runway. Similar effects have been observed many times (Amsel, 1992). With the peak procedure, bar-press duration increased exactly when a rat could realize it was not going to get food during that trial.

My colleagues and I tested the frustration explanation (Gharib et al., 2001, Experiment 2). We looked for the same effect (a sharp increase in bar-press duration after omission of expected food) in a new situation. We found the increase, but it was much smaller and briefer than the peak-procedure results had led us to expect. This implied that the frustration explanation of the peak-procedure results was wrong.

I had believed the frustration explanation (Roberts, 1998). It was hard to think of another one. I managed to think of another one only when writing up the results. The new explanation was *reducing expectation of reward increases variation of response form*. The increase in mean bar-press duration (lower panel of Figure 1) was due to an increase in the variation of bar-press duration. Because the distribution was very skewed (many short durations, few long durations), the increase in spread increased the mean. Mean bar-press duration increased exactly when expectation of reward should have decreased – when the rat could realize there would be no food that trial.

The proposed rule (reducing expectation of reward increases variation) made evolutionary sense. When the expectation of reward goes down, rats have less to lose and more to gain by pressing the bar in unusual ways. They have less to lose because their expectation of reward is lower. They have more to gain because there is more room for improvement.

The proposed rule predicted that anything that reduces reward expectation will increase duration. An experiment to test this prediction found an effect in the predicted direction (Gharib, Gade & Roberts, 2004) with $t = 6.2$. Roberts and Gharib (2006, Table 1) summed up the evidence from rats. In nine cases, treatments that lowered reward expectation increased bar-press duration. The median t value of the nine comparisons was 4.6. In no case did a treatment that lowered expectation decrease duration.

Pigeon experiments have provided more support. Stahlman, Roberts, and Blaisdell (2010) found that reducing reward expectation increased horizontal variation of peck location. Overall, their results suggested that reward expectation controlled variation in the middle of foraging – how a patch is searched. It did not control variation in patch approach (earlier) or food consumption (later). In all of these experiments, reward expectation was reduced by reducing probability of reward. Stahlman and Blaisdell (2011) found that two other ways of reducing reward expectation – reducing reward size, increasing delay of reward – also increased horizontal variation of peck location.

Similar generalizations have been found in other areas. Kramer and Weary (1991) measured the foraging of chipmunks for sunflower seeds in a forest. "As seed density was reduced, chipmunks spent progressively more time exploring before returning to the patch" (p. 443), they found. Studying how organisms evolve, Elde et al. (2012) found that when a certain virus was exposed to difficult conditions (conditions in which it did not rapidly multiply) it created multiple copies of many genes. This allowed their variation to increase. With multiple copies of a gene, a mutation is less likely to be fatal. Many other species do the same thing (Goodman, 1992; Kondrashov, 2012). Another way that stressors increase phenotypic variation, at least in fruit flies, is through a protein that usually prevents mutations from producing phenotypic changes (Queitsch, Sangster, & Lindquist, 2002; Rutherford & Lindquist, 1998). Under stressful conditions, the hidden variation becomes visible. Mustard plants show similar effects (Sangster, Lindquist, & Queitsch, 2004).

Similar observations have even been made about business. Christensen (1997) found that industry-leading companies – those with the largest expectation of reward, you could say – did not vary enough. They were "held captive by their customers" (p. 18) – that is, by their success and "expected rewards" (p. 32). Less successful companies were more adventurous. Surowiecki (2003) gave a within-company example of the same thing: When Boeing became dominant, it stopped taking risks. Battelle (2005) makes the same point about Excite, an early Web search business.

Gaps in Animal Learning Research

The duration results make sense if they reflect how animals learn how to forage – in particular, learn what to do at a food source. The lower their expectation of food, the more they explore. The rate results, in contrast, are about how animals use what they have learned. They have already learned to press a bar for food. If reward is more likely at Time X than at Time Y, they press the bar more often at Time X.

But a *get knowledge* (duration)/*use knowledge* (rate) dichotomy is too simple. A better view is that during foraging, an animal has many questions. Three are: *1. Where is food? 2. What should I do to get it? 3. When and how often should I get it?* Questions 2 and 3 are about how to use the answer to Question 1. Question 3 is about how to use the answers to Questions 1 and 2. Instrumental learning experiments usually begin after the animal has been taught where food is (Question 1) and how to get it (Question 2). They are about Question 3. They are unlikely to tell us how animals answer Questions 1 and 2. (Our research, which shed light on Question 2, was an exception.) Animals must have powerful learning mechanisms to answer Questions 1 and 2. We know little about them.

Because Questions 1, 2 and 3 are quite different, learning how animals answer Question 3 is unlikely to tell us how they answer Questions 1 and 2. Figure 1 illustrates the difference between Question 2 (bar-press duration lower panel) and Question 3 (rate, upper panel). The rate results did not help me predict the duration results. One big difference between Question 1 and Question 3 are the associated payoff matrices. When an animal goes to a known food source (Question 3), it has a relatively high chance of a small payoff (food), some chance of zero payoff (no food), and a very small chance of catastrophe (being eaten). When an animal looks for food far from known food sources (Question 1), it has a very small chance of an enormous payoff (finding a new source of food, which might supply food for years), a very high chance of zero payoff (no new source of food), and a very small chance of catastrophe (being eaten). There are two differences here between exploitation (Question 3) and location search (Question 1): 1. *Chance of success*. It is much higher for exploitation than location search. 2. *Time period over which success pays off*. In the case of location search, the reward pays off for a long time, maybe for the rest of the animal's life. In the case of exploitation, the reward is mostly immediate.

Looking for new food sources (Question 3) even when there is enough food is a kind of insurance. Insurance differs from other purchases. People buy insurance year after year even if they have never gotten a payout (e.g., their house has never burned down). In contrast, if you buy milk but never drink it you will stop buying milk. If all you know about decision making is how actions are controlled by consequences (related to Question 3), you are unlikely to understand why people buy insurance.

Peak procedure results suggest that animals also have other questions. You might think that getting knowledge (exploration) and using knowledge (exploitation) are mutually exclusive (i.e., you cannot do both at once). With physical objects get and use *are* mutually exclusive; for example, you cannot get soap and use soap at the same time. But knowledge is different. Analysis of peak-procedure durations (Gharibet al., 2001) suggested that rats time a trial with great accuracy, in contrast to what the width of the rate-versus-time function (upper panel of Figure 1) might suggest. When a rat fails to get food on a peak procedure trial, the duration of bar presses increases so sharply the rat must have been timing the signal with great accuracy. This shows that the width of the rate function does not reflect poor timing; it reflects exploration "near" (in terms of time) a food source. Animals look near a food source for other food sources. If you have had ants in your kitchen, you have seen them swarming around the food they have found. When an animal looks near a food source for other sources of food, it is exploring and exploiting at the same time.

That is another question animals ask while foraging: Question 4. *How should I look for food near a food source?* For example, how widely should I search? How long should I search? In peak procedure experiments, I found that the width of the rate function – a measure of looking near a food source -- varied without changing peak time or peak rate (Roberts, 1982). Study of what controls the width of the function may tell us something about what exploration near a food source depends on – how animals answer Question 4.

In summary, animal learning researchers (those studying instrumental learning) have spent almost all their time studying Question 3. Questions 1, 2 and 4 have rarely been studied.

One way to study Question 1 is with the peak procedure. Just as the spread of the rate function reflects looking for food "near" (in time) a known source of food, *tail rate* – the rate in the tail of the rate function (upper panel of Figure 1), long after the time of food – reflects looking for food *far* (in time) from a known source. Learning what controls spread and tail rate would be a step toward learning how rats find new food sources near and far from known sources.

Another way to study the areas of ignorance would be to build a big enclosure with 20 equally-spaced levers and a food dispenser. Reward presses of one lever, measure responding on all levers. Because animals search near a food source for food, I predict that rewarding presses on one lever will increase responding on nearby levers – what might be called *the law of near effect*. This effect will depend on distance. I also predict that rewarding presses on one lever will increase responding on distant levers in way that does not depend on distance – what might be called *the law of far effect*. An even better apparatus would allow a rat to sleep and drink near the enclosure, with access to the enclosure whenever it wants. Even the simplest experiments are likely to produce results that cannot be explained with current knowledge – because we know so little.

In natural settings, biologists have done wide-ranging experiments about foraging, which often cover the areas of ignorance I point out. The bee-dance experiments of Karl von Frisch, for example, were about how bees find food. But naturalistic experiments are no substitute for laboratory experiments. Lab experiments, especially with well-studied animals such as rats and pigeons, can be cheaper, more repeatable, study more factors, collect more data, and be better controlled.

Gaps in Human Learning

Like animal learning research, human learning research by psychologists has studied a late step in learning and not studied earlier steps. Human learning research has been about what happens when a person is exposed to new knowledge (i.e., learning trial). If there is any environmental control of desire for new knowledge – any environmental control of curiosity, *thirst* for new knowledge – it has not been studied.

The word *curiosity* barely appears in learning textbooks. In Lefrançois (2012, 464 pages), it appears only twice in the text. Here is one use: "It called attention to a completely new class of motivational systems, relating to such things as curiosity, novelty, and exploration" (p. 168). In Gluck, Mercado, and Myers (2007, 554 pages), *curiosity* appears zero times in the desire-to-learn sense. "Research and theorizing about curiosity [have] been largely moribund during the past two decades," wrote Lowenstein (1994, p. 94) in a review article. A search of *Journal of Experimental Psychology: Learning Memory and Cognition* found no uses of the word *curiosity*. Education researchers distinguish between *intrinsic* motivation (i.e., curiosity) and *extrinsic* motivation provided by grades and other rewards extrinsic to what you are studying (e.g., Ryan & Deci, 2000). But even education researchers, to my knowledge, have not studied what makes a person more or less curious.

As with animal learning and foraging, it took an accidental discovery to make me aware of the gap. For a long time I have had a treadmill, which I use daily. While using it, I always watch something, such as TV. A few years ago, I started living in China part-time. To study Chinese, I used a flashcard program called Anki. I found it hard to use for more than a few minutes. It quickly became too boring.

One day in 2010, I tried studying Anki while using my treadmill, instead of watching TV. I put my laptop on a board resting on the two armrests. To my shock, this was *more* pleasant than watching the TV show I had been watching (Roberts, 2010a). Two boring activities (studying Chinese and treadmill walking) when combined made a pleasant activity. While walking on a treadmill, I found that I could use Anki much longer (40-60 minutes) before wanting to stop. It was as if (a) walking created a thirst for dry knowledge and (b) Anki satisfied this thirst better than a TV show.

Jeremy Howard, a San Francisco entrepreneur, independently discovered the same thing. In a talk, he said:

> I can [study Chinese using Anki] for an hour. Whereas normally if I'm just sitting down I can just do it 20 minutes. . . . And at the end of that hour I was ready to do something else. Whereas at the end of 20 minutes [of study while sitting], normally I'd . . . be totally ready for a rest. (Carmichael, 2012)

After I blogged about my discovery, a reader named Adam posted on the Quantified Self forum:

> Like Jeremy Howard said in his talk, [using Anki to learn Chinese] is exhausting. After a period of about 20 minutes, I often reach a level of fatigue that makes it difficult to continue studying. I first read about the "treadmill method" on Seth Roberts's blog & found it highly effective. Like Mr. Howard, I could study for hours without becoming bored. (Adam, 2012)

Other results suggest movement may improve learning. Neuringer (1981) learned paired associates faster when active. Over nine years, a man in his sixties memorized *Paradise Lost* (about 11,000 lines) while walking on a treadmill (Seamon, Paawan, & Busch, 2010). Seamon et al. did not consider the possible effect of the treadmill. Noice and Noice (2001) tried to find out if movement improved memory. An earlier study had found that actors better remembered dialog accompanied by movement than dialog spoken while still (a correlation). In an experiment, they found that "participants who processed a script by reading the text aloud while simultaneously moving in accordance with a director's instructions retained more material than…. controls who deliberately memorized the same material" not moving (Noice & Noice, 2001, p. 820).

My discovery was an hedonic change: walking made a certain activity more pleasant, much as time without water makes drinking water more pleasant. Because of the hedonic change, I studied much longer walking than sitting. You might say I became more curious but *curiosity* is too general. Chinese characters satisfied that curiosity more than a TV show.

My guess at the general rule behind these examples is *walking makes dry knowledge pleasant*. Anki provided more new dry knowledge (the meaning of Chinese characters) per minute than the TV show I had been watching. An evolutionary explanation of this rule is that long ago, it pushed people to explore their surroundings. When they walked somewhere, it caused them to explore on the way. It caused them to take slightly longer, less efficient routes. This helped them to learn about their surroundings at low cost, without making expensive special trips. Better to blend exploration with walking done for other reasons, such as foraging.

Gaps in Economics

The gaps in economics resemble the gaps in animal and human learning research. Like animal and human learning researchers, economists focus on the last step in a process and pay little attention to earlier steps. With few exceptions, they study the use of economically-useful knowledge but not the creation and spread of that knowledge.

In animal and human learning research, the gap is at the level of data. Animal learning data come from experiments that reflect only a fraction of real-world foraging. Human learning data come from experiments in which the learner has no control over contact with the material, unlike real life. In economics, the gap is at the level of theory. Most economic data are from real life. The gap involves theory – how the data is explained. Economists almost always explain differences between X and Y (different places or times) with theories about what happens toward the end of the economic process (use of knowledge). They rarely consider that the differences they see might be due to differences in knowledge creation or spread.

A realistic view of economic life would divide it into five activities:

1. *Creation of "useless" knowledge*, that is, knowledge without obvious economic application. Nowadays, much of this happens at research universities.

2. *Creation of new products, services and production methods*. These usually come from combining "useless" knowledge (#1) and improvement of what exists (#3). For example, electricity was useless for a long time. Eventually it was used to improve/replace many existing products. Electric lamps replaced oil lamps, for example.

3. *Improvement of existing products, services and production methods*.

4. *Spread of knowledge*. Useful knowledge exists on both sides of a purchase. It includes knowing how to make X, knowing where to buy X, knowing how what to charge, what to pay, and so on. It spreads via conversation, travel, shipping of new products, apprenticeship, copying, books, classes, ads, talks, and so on.

5. *Exploitation of knowledge*. People use their economically-valuable knowledge to make and spend money.

Economic theories almost always center on Activity 5. They focus on the choices people make – to do X or Y (e.g., manufacture Product P or not, charge X or Y for P, hire someone or not, buy P or not). On the surface, this might seem reasonable because practically all (99.9% in terms of time?) economic activity consists of making such choices.

In contrast to Activity 5, which I see daily, Activity 2 (new products, etc.) is essentially invisible. I have never seen it. In terms of time, it is a vanishingly small part of economic life. Yet it is a major source of prosperity. We benefit today from countless examples of Activity 2 that happened long ago – invention of metals and pottery, for example. Examples of Activity 2 not only improve our lives, they also keep our lives from getting worse – they solve problems. Solutions to old problems eventually cause new problems (*nothing lasts forever*), so we need a constant stream of new products, services and methods – a non-zero amount of Activity 2 – just to stay in the same place. Because Activity 2 is so rare and diverse, it is very hard to study.

Neglect of Activity 2 (and associated Activities 1, 3, and 4) began with Adam Smith. Nowhere in *The Wealth of Nations* (1776) does Smith consider the possibility that nations differ in wealth because of differences in knowledge creation or spread. Modern economics textbooks continue the neglect. They say nothing interesting about knowledge creation or spread. For example, Mankiw (2009, 856 pages) spends a half page on innovation, not counting a short sidebar by someone else. The half page reveals a shallow understanding. For example, Mankiw writes, "Most technological advances come from private research by firms and individual inventors" (p. 548). Computers, the Internet and the beginning of electronics did not come from private research by firms or individual inventors. Galvani (professor), Hertz (professor), Volta (professor), and Faraday (independent scientist, professor) were not individual inventors or firm employees. A few paragraphs about *technological knowledge* (pp. 538-539) say nothing about what controls its rate of growth. In a section called "How the whole economy works," Mankiw proposes three principles, such as "a country's standard of living depends on its ability to produce goods and services" (p. 13). None of the principles says anything about knowledge creation. It is as if a biologist ignored evolution.

When economists observe a difference (e.g., a price difference), they assume it is due to a difference in Activity 5 – different purchasing decisions, for example. Their explanations assume that Activities 1-4 were equal across the conditions being compared or else had no effect.

Sometimes this is plausible. The closer in space and time the two data points (e.g., the two prices), the more plausible it is that Activities 1-4 did not matter. If, today, a cup of coffee costs more at Café A than at nearby Café B, this is unlikely to be due to differences in Activities 1-4. The further apart the two data, the less plausible it is that Activities 1-4 can be ignored. Why, today, are Europeans wealthier than Africans? Maybe differences in Activities 1-4 do not matter, maybe they do. No one knows.

Across large time spans (such as 100 years) – for example, United States per capita income in 1900 versus 2000 – Activities 1-4 surely matter. Economists who try to explain long-term growth usually posit something along these lines, some sort of difference in Activities 1-4, but they know so little about what controls those activities that their explanations are easy to criticize. An example is the book *Why Nations Fail* by Acemoglu and Robinson (2012), which is about why some countries have grown economically much faster than others. Its main point is that institutions matter: *inclusive* institutions promote innovation more than *extractive* ones. It makes a persuasive case that institutions matter. However, it makes no case at all that this dimension of institutions (inclusive versus extractive) is the only thing that matters, as the title seems to imply. (The book contains no other big ideas.) Absence of a good theory of Activities 1-4, especially Activity 2, makes the book's claim that institutional differences fully explain the growth differences it emphasizes seem over-confident.

When economists recommend policy, they almost always focus on Activity 5. They try to increase productivity in terms of Activity 5 – for example, increase employment or income. Their arguments for their recommendation, in my experience, always show that they fail to understand that productivity (in terms of Activity 5) and innovation (Activity 2) are often at odds. A policy that maximizes productivity is unlikely to maximize innovation. Yet really big improvements come from innovation, not productivity increases. If you lower the price of a TV by 10%, more people can buy one. That is a productivity increase. A few more people will be employed making TVs – another productivity increase. On the other hand, if you create a whole new appliance, anyone can buy one and whole new factories can be built to make the new product. Of course it is exceedingly hard to cause people to invent whole new appliances. But that does not mean the possibility should be ignored.

The effects of innovation take longer to be seen than productivity changes but can be much more widespread. Even small innovations can have big effects. In the 1970s, American clothing companies felt endangered by imported clothes – from South Korea, for example. They pressed government for trade protection. This led to passage of the Multi Fibre Arrangement (MFA), which regulated clothing imports. The agreement said nothing about Bangladesh, which at the time did not make clothes. When South Korea reached its MFA limit, a Bangladeshi businessman approached Daewoo, a giant South Korean clothing maker, suggesting that they duplicate their factory in Bangladesh. The head of Daewoo was open to their suggestion. Daewoo helped open the first clothing factory in Bangladesh. There are now more than 4000 clothing factories in Bangladesh. The innovation is small – it is a slightly new method of production to make clothes in Bangladesh rather than Korea – but it had an enormous effect on Bangladesh.

In some ways, productivity and innovation change together. Giving people more freedom increases both productivity and innovation; so does giving them more resources. Allowing people to benefit more from their own work improves both productivity and innovation. (This was Acemoglu and Robinson's point about innovation.) But other factors act in opposite directions on innovation and productivity – they increase one but decrease the other.

One such factor is pain/discomfort. Not debilitating or all-consuming pain, but enough to make you think hard. This increases innovation, decreases productivity. *Necessity is the mother of invention* is the aphorism, but pain/discomfort is enough. Often the source is government. The MFA pained the head of Daewoo, for example. An especially important example is the earliest European settlers of the United States. They came to find religious freedom; their religion was outlawed in England. Eventually the colonies broke free of England and started a new country, whose government embodied plenty of political innovation. Laws are one governmental source of pain/discomfort; another is war. War increases innovation partly because there is no need for the new thing to make a profit. A famous example is the greenback, which came from the Civil War. Other examples include radar, lotteries, freeze-drying, and duct tape. The pain/discomfort may be non-governmental. Poor sleep and a desire to lose weight led me to find new ways to sleep better and lose weight (Roberts, 2004).

Stability is another factor that acts in opposite ways on innovation and productivity. Extreme stability is bad for productivity (too little is at stake), but good for innovation. Innovation flourishes when you can fail at low cost. If a worker has no production quota, he will produce less but will have more opportunity to try new methods. Tenure promotes innovation for this reason. The Internet began as ARPAnet, a network that connected universities funded by the United States Department of Defense. Professors were the first users. This blended the great resources made available by war with the stability provided by tenure.

It is not easy to provide freedom, pain, and stability all at once. By and large they are corners of a triangle. The more freedom, the less pain and stability. The more pain, the less freedom and stability. The more stability, the less pain and freedom. You need all three — a point in the middle of the triangle. Where that point should be and how to put it there are far from obvious.

Here I am guessing what research will show. My overall point is that there are likely to be non-obvious generalizations about innovation. For example, too much emphasis on productivity can reduce innovation, a conclusion you will not find in any economics textbook I have seen.

A few economists study or studied innovation. Hugh Aitken, an economic historian in the Amherst College economics department, wrote two books about the development of radio (Aitken, 1976, 1985). The *Journal of Evolutionary Economics* has a fair number of articles about innovation. The journal *Economics of Innovation and New Technology* started in 1990. The biggest group of economists studying innovation may be those studying the effects of intellectual property law on patents and the like. An example is Petra Moser, an assistant professor at Stanford.

Even here there are big limitations. In the study of intellectual property law, the dependent variable (e.g., number of patents) is related to innovation but the independent variable (intellectual property law) is simply the independent variable used throughout economics (incentives). Another example is studying the effect of money spent on research and development. As I said, this is the limitation of Acemoglu and Robinson (2012). When they stop studying incentives, they often study econometric-type variables. For example, Crepona, Duguetb, and Mairessecc (1998) explained the probability of engaging in research in terms of firm size and market share. Economists have trouble not *thinking like an economist*, you might say. Because creating knowledge is so different than using it, I doubt incentive and econometric variables are the only important ones.

Much as biologists have studied foraging much more realistically than psychologists, business schools have studied innovation much more than economics departments. *The Innovator's Dilemma* (Christensen, 1997), by a Harvard Business School professor, has been very influential. McKinsey Consulting recently issued a report called *Innovation Matters* (Baily, Haskel, Hazan, Marston, & Rajah, 2013); one of the authors, Jonathan Haskel, is a professor at Imperial College Business School. *The Oxford Handbook of Innovation* (Fagerberg, Mowery, & Nelson, 2005) is part of a series (Oxford Handbooks in Business & Management) aimed at business schools.

A review of this paper by an economist called the views expressed here "an understandable point of view for an outsider". But insiders sometimes share these views, especially the view that innovation is ignored or should be studied more. A popular insider definition of economics is "the science of distributing limited means among unlimited and competing wants" (Radford, 1945, p. 201). This omits study of how the limited means came to be. A *Wikipedia* entry for "innovation economics" says, "within the last 15 years that a theory and narrative of economic growth focused on innovation" has "emerged" ("Innovation economics", 2014, "Historical origins", para. 2) citing a 2003 book (Antonelli, 2003). "In contrast to neoclassical economics, innovation economics offers differing perspectives on main focus, reasons for economic growth, and the assumptions of context between economic actors," says the entry ("Innovation economics", 2014, "Historical origins", para. 2). It names ten people, such as the economists Paul Romer and Richard Nelson, as "theorists" of innovation economics. In 2006, Robert Atkinson, an economist, founded the Information Technology and Innovation Institute in Washington, D. C., and wrote *Supply-Side Follies: Why Conservative Economics Fails, Liberal Economics Falters, and Innovation Economics is the Answer* (Atkinson, 2007). In a review on the publisher's website of *Handbook of the Economics of Innovation* (Hall & Rosenberg, 2010), Albert Link, an economics professor, wrote, "For too long the policy importance of innovation has taken a back seat to short-term stimulus initiatives. Hall and Rosenberg have assembled a scholarly collection of papers that provide a timely guide for rediscovering the role of innovation in economic growth."

Conclusions

The gaps in animal learning research, human learning research and economics are similar. In all three cases, researchers have studied what is most easily measured (the final step) and have failed to study essential earlier steps. The general problem is a failure to study how things begin.

To explain these gaps, it may help to look at similar examples. In the field of statistics, there is little understanding of how ideas *begin* (judging by articles and textbooks). At first, all ideas about this or that (e.g., how to improve sleep) have low plausibility, since there are many possibilities. Much of statistics is about testing ideas. Tests of an idea are expensive. To be worth the cost of testing, an idea has to be fairly plausible. How does an idea become plausible enough to test? Introductory statistics textbooks devote plenty of space to how to test hypotheses, but I have yet to see one that says anything about how to find ideas plausible enough to test. I have never seen a paper about the topic by a statistician.

In epidemiology there is a gap unrelated to how things begin. Although the immune system is obviously important, epidemiologists rarely acknowledge its existence. When trying to understand why Disease X varies across space or time, they almost never consider the possibility that the cause is a difference in immune function, even when this is quite plausible. For example, a review article (Fisman, 2007) about the seasonality of infectious diseases (e.g., colds are more common in winter) barely mentions the possibility that immune function is worse in winter. To support this possibility it cites only one article (Dowell, 2001), which does not use the word *immune*.

In these five areas (animal learning, human learning, economics, statistics, epidemiology), a common thread is that to study the area of ignorance, you need to make a big jump. A river, you might say, separates the area of ignorance from what is already studied. Popular animal learning research does not include methods to study how animals find new sources of food. Human learning research does not include tools that measure curiosity. If all you have measured is amount and speed of learning, to measure curiosity is conceptually difficult. In economics, innovation takes so many forms it is very hard to measure. To study how ideas begin, it is not clear what statisticians should do. Most statisticians may have never seen an idea become plausible enough to test. To measure immune function, epidemiologists cannot extend existing methods. To measure something invisible (the immune system) is conceptually difficult. They are used to measuring visible aspects of everyday life, such as diet.

I managed to *cross the river* – learn something within an area of ignorance -- because the peak procedure is an unusual scientific tool. It measures functions, not points, and thus provides a lot more information than tools that measure points. Another function-measuring tool is the spectrometer, but such tools are rare. None is used in human learning or economics. When I used the peak procedure with an unconventional measure (bar-press duration), it immediately showed a very strong effect ($t = 18$) that I could not explain. This showed that something important was missing from my understanding of animal learning. Because the effect was so large, it was easy to study – easy to do publishable follow-up experiments. I was not only studying an area of ignorance, I could do so in a career-enhancing way. That is probably one reason these areas of ignorance persist – they cannot be reached by more use of the usual tools.

Another likely reason is that science and job are not a good fit (Roberts, 2010b). Jobs are about repetition, science is the opposite – you can only make a discovery once. Jobs generally demand some sort of predictable productivity. Shirt-making and job are a good fit, trucking and job are a good fit. The less certain the science, the better it is (the more you will learn) but also the less predictable it is. Administrators and promotion committees ignore this and judge researchers by quantity (number of publications), which pushes researchers toward research with a predictable payoff, that is, something close to what they have already done. I asked an economist what he thought of the view that both productivity and creativity are important but economists study only productivity. Most economists would agree, he said, "then go back to focusing on short-term productivity. It's just easier to work with empirically. Searching for your keys under the streetlight because it's brighter there."

Another reason that science and job are a poor fit is that good science requires freedom of thought. In contrast, a job requires pleasing others, such as your customers, colleagues, and boss. These two forces (need for steady stream of publications, need to please others) push scientists to play it safe, to repeat themselves.

If the forces pushing scientists to repeat themselves are so strong, how have we made progress? At the end of *The Economy of Cities* (Jacobs, 1969), Jacobs said that if a spaceship landed on Earth her question for the visitors would be *how did you avoid stagnation?* On Earth, it seemed to Jacobs, forces favoring the status quo were stronger than forces favoring innovation. However, at least two aspects of human nature promote innovation. One is the desire for novelty that leads to fashion (shifting preferences in clothes and decoration) and "schools" of art (shifting preferences in art). A clothing designer, a decorator, and an artist cannot do the same thing over and over. If they did, their customers would leave. They must innovate to survive (Roberts, in press). Fashion, art and decoration surely helped us achieve great control over the material world, the world of things. The other aspect of human nature promoting innovation is the desire of professors to show how useless they are and the desire of others to show how much money they can waste on "useless" things such as art. Veblen (1899) emphasized this but did not appreciate its effect. There are only a few ways to be useful; there are many ways to be useless. That we attach (prestige) value to "useless" subjects (e.g., "pure" science is seen as better than "applied" science) and objects (art and decoration) allowed professors and artisans to explore much more widely.

Maybe the pro-progress forces are stronger than the anti-progress forces. Although the gaps I describe have lasted a long time, in each of the three areas (animal learning, human learning, and economics), there are recent signs of progress. In animal learning, the discovery that pushed things forward came from using the peak procedure and measuring bar-press duration. Equipment improvements and reductions in cost, including computer cost, made both things easy. The experiments I suggest (e.g., with 20 widely-spaced levers) are no longer expensive or difficult. In human learning, the effect I describe (walking makes it easier to study Chinese) was discovered independently twice, at about the same time. The discovery required both Anki and treadmill use. Anki is new and free; treadmills have come more available, if only because average income has gone up. Existence of a large new unstudied effect makes the gap area much easier for professional scientists to work on. In the case of economics, the growth of innovation economics suggests that something is changing.

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