Why societies vary in their rates of innovation

The evolution of innovation-enhancing institutions

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Abstract

This chapter applies an integrated approach to decision-making and cultural evolution to explore some of the characteristics that influence population-level differences in innovativeness and to understand how such differences emerge. In laying the foundation for subsequent arguments I begin by summarizing research showing how evolutionary theory can direct and inform our understanding of decision-making, social learning and cultural evolution. Then, extending insights from existing cultural evolutionary models, I examine how a population's size and degree of 'cultural interconnectedness' can influence rates of both innovation and invention. A simple model illustrates the relative importance of cultural interconnectedness compared to individual invention. Combining ethno-historical and archaeological cases, I further explore the relative importance of "mother necessity" and "heroic genius" vs. recombination, lucky mistakes, and the accretion of small changes in driving invention. This discussion suggests that, at best, "necessity" is neither necessary nor sufficient to explain invention and that invention processes are dominated by incremental additions, recombinations, and lucky errors, not revolutionary insights. This means that inventiveness is—at least in part—a product of large populations (that generate more lucky errors) and greater interconnectedness that together with population size favors more recombinant inventions, as well as a greater likelihood of these diffusing widely. Lastly, I examine how increasing the interconnectedness in a population gives rise to an *n*-person cooperative dilemma. While some partial solutions to this dilemma have emerged across our species, only some societies have evolved the informal (and later formal) institutions—i.e., systems of reputation, signaling, and punishment—that favor the wide sharing of information, ideas and insights. Theoretical work has revealed three avenues to solving such *n*-person cooperative dilemmas, but crucially, all three generate multiple stable equilibria, meaning that while they can stabilize cooperative information sharing, they can also stabilize "information hiding and free-riding" as well as other non-group-beneficial states. In such circumstances, processes of cultural group selection, which operate through various forms of competition among groups, can favor the evolution of those institutional forms that best promote the open dissemination so crucial to innovation. This line of thinking proposes that cultural evolution has favored the emergence of institutions that increase cultural interconnectedness, thereby stimulating both greater inventiveness and more innovation at the population level.

This chapter applies an integrated approach to decision-making and cultural evolution to explore some of the characteristics that influence population-level differences in innovativeness and to understand how such differences emerge. By referring to a group's innovativeness, I aim to highlight some of the factors or processes that (1) favor the generation of more *inventions* (meaning useful or adaptive novelties) and (2) successfully spread these inventions through the population, making them in this terminology, *innovations*. My discussion has three parts. In laying the foundation for subsequent arguments I begin by summarizing research showing how evolutionary theory can direct and inform our understanding of decision-making, social learning and cultural evolution. Building on this, I examine how a population's size and its degree of *cultural interconnectedness* can influence rates of both innovation and invention. After using a simple model to illustrate the relative importance of cultural interconnectedness compared to individual invention for the spread of innovations, I then discuss a combination of ethno-historical and archaeological cases that explore the relative importance of "mother necessity" and "heroic genius" vs. recombination, lucky mistakes, and the accretion of small changes in driving invention. This discussion suggests that, at best, "necessity" is neither necessary nor sufficient to explain invention, and that invention processes are dominated by incremental additions, recombinations, and lucky errors, but not usually revolutionary insights. This means that inventiveness is—at least in part—a product of large populations (that generate more lucky errors) and greater interconnectedness. Lastly, I examine how increasing the interconnectedness in a population gives rise to an *n*-person cooperative dilemma. While some partial solutions to this dilemma have emerged across our species, only some societies have evolved the informal (and later formal) institutions—i.e., cultural systems of reputation, signaling, and punishment—that favor the wide sharing of information, ideas and insights. Theoretical work has revealed three avenues to solving such *n*-person cooperative dilemmas, but crucially, all three generate multiple stable equilibria, meaning that while they can stabilize cooperative information sharing, they can also stabilize "information hiding and free-riding" as well as other non-group-beneficial behaviors. In such circumstances, processes of cultural group selection, which operate through various forms of competition among groups, can favor the evolution of those institutional forms that best promote the open dissemination so crucial to innovation. This line of thinking proposes that cultural evolution has favored the emergence of institutions that increase cultural interconnectedness, and thereby stimulate both greater inventiveness and more innovation.

Theoretical Framework

With the physical endowments of a tropical ape, humans have successfully spread to nearly every corner of the globe in a relatively short period, from the dry savannahs and tropical forests of equatorial Africa to the frozen tundra of the Arctic and the humid swamps of New Guinea. Humans are unique in their range of environments and the nature and diversity of their behavioral adaptations. While many local genetic adaptations exist in our species, it seems certain that the same basic genetic endowment produces arctic foraging, tropical horticulture and desert pastoralism—a constellation of adaptive patterns that represents a greater range of subsistence behavior than the rest of the Primate Order combined.

The behavioral repertoires that permit such diverse adaptations to this immense range of environments are principally socially learned and represent cumulative cultural products that have been assembled and honed over generations. The tools, skills, and bodies of folkbiological knowledge relied upon by foragers from the Arctic to the Kalahari are acquired over development principally by observing and listening to older members of one’s social group. The same goes for food preparation skills, many food preferences, and medical know-how (Fiske 1998; Henrich forthcoming; Lancy 1996).

Numerous accounts of Europeans, often involving experienced explorers, stranded in places such as Australia, Amazonia or the Arctic illustrate just how ineffective our rationality, evolved modules, and fitness maximizing mechanisms are when they lack the relevant culturally-transmitted information. In these cases, individuals freeze, starve, dehydrate, or mistakenly poison themselves while seeking to escape a seemingly harsh environments that even a local adolescent, equipped with a culturally inherited body of knowledge, could have easily survived in (Henrich and McElreath 2003; Richerson and Boyd 2005). Even something as basic to human survival as making fire cannot be easily acquired without watching someone with expertise. This point is emphasized by the ethnographic evidence indicating that certain isolated human foraging societies entirely lost the knowledge of how to start of fire (Gott 2002; Holmberg 1950; Radcliffe-Brown 1964).

There seems little doubt that this emphasis on cultural learning extends to social environments. Human societies, especially small-scale groups, are obstacles courses of complex kinship relationships, overlapping status differences and systems, marriage rules and preferences, and subtle notions of proper etiquette. As any ethnographer will attest, before a would-be Machiavellian can manipulate others to his own selfish ends, he has to master the local cultural systems, values, and expectations. Only then can he effectively "work" the system. One must be an excellent "cultural learner" *before* he can be an intelligent Machiavellian.

Recognizing the importance of cumulative cultural knowledge and technological know-how for human adaptation, three decades of theoretical work applying the logic of natural selection to understanding our capacities for learning and decision-making, and in particular to our capacities for social learning, has effectively incorporated culture and cultural evolution under the Darwinian umbrella and into a larger framework for studying psychology and history (Boyd and Richerson 1985; Cavalli-Sforza 1971; Cavalli-Sforza and Feldman 1981; Henrich and Henrich 2007; Richerson, et al. 1978; Richerson and Boyd 2005; Shennan 2003). For our purposes here this approach provides a framework for (1) hypothesizing some of the micro-level psychological details of cultural learning, and (2) constructing formal models of population processes that aggregate up from theoretically and empirically grounded micro-level decision mechanisms to population-level patterns and properties.

The general potency of human cultural learning, as well as several of the specific predictions arising from this approach, are substantiated by large bodies of experimental work in both social and developmental psychology, as well as recent work in experimental economics. After more than two decades of research on cultural learning ("observational learning" or "modeling"), psychologist Albert Bandura first summarizes the spontaneous potency of cultural learning and its broad impacts on thinking and behavior:

> Observers display the same amount of observational learning regardless of whether they are informed in advance that correct imitations will be rewarded or are given no prior incentives to learn the modeled performances (Bandura et. al 1966; Rosenthal & Zimmerman 1977). After the capacity for observational learning has fully developed, one cannot keep people from learning what they have seen (p.38)

> Modeling has been shown to be a highly effective means of establishing abstract or rule-governed behavior. On the basis of observationally derived rules, people learn, among other things, judgmental orientations, linguistic styles, conceptual schemes, information-processing strategies, cognitive operations, and standards of conduct (Bandura 1971; Rosenthal & Zimmerman 1977). Evidence that generalizable rules of thought and conduct can be induced through abstract modeling reveals the broad scope of observational learning (p. 42)…

Recent work comparing chimpanzees and human children further brings home how, compared to chimpanzees, humans imitate much more and with much greater fidelity. At times this human inclination to imitate seems even slavish. In experiments in which the observable features of the task suggested that certain movements of the learner's model were probably unnecessary, human children still copied these superfluous movements while most chimpanzees immediately dropped them, to retain only the not-apparently-superfluous movements (Horner and Whiten 2005; also see Tomasello, et al. 1993).

The application of evolutionary theory to the question of from whom, and when, individuals should socially learn has generated a series of hypotheses that find support from a wide range of experiments, as well as in field data. The approach suggests that learners—in order to most efficiently acquire adaptive behavior in noisy or stochastic environments—ought to be selective in whom they paid attention to for the purposes of cultural learning, preferring those with greater skill, success, knowledge, health and prestige,[1] while also using cues of self-similarity such as gender, size, and ethnicity to help ensure that what they learn is fit for their personal attributes and current or future social roles. The approach also suggests that learners should aggregate information using conformist or blending algorithms (Boyd and Richerson 1985; Henrich and Boyd 1998; Henrich and Boyd 2002), which reduce errors in learning (by averaging them out) and facilitate the extraction of useful information. Evidence from psychology (Asch 1951; Coultas 2004; Henrich and Gil-White 2001; Insko, et al. 1985), archaeology (Mesoudi in press), and economics (Alpesteguia, et al. 2003; Kroll and Levy 1992;

[1] Prestige is this sense represents the aggregate of group members' evaluations of who is skilled, successful, and knowledgeable. In a world of imperfect information, other people's evaluations are an important source of information for refining one's own evaluations of these characteristics.

Mesoudi in press; Pingle 1995; Pingle and Day 1996) supports these predictions. See Henrich and Henrich (2007: Chapter 2) and Henrich and Gil-White (2001) reviews of the evidence.

In addition to specifying who learners should pay attention to, and how they should integrate information gleaned from different models, this approach predicts how environmental uncertainty or problem-ambiguity (problem difficulty) should impact that use of, or reliance on, social learning vs. individual learning or cost-benefit evaluation. Consistent with these models, findings from psychology, anthropology and economics indicate that as uncertainty rises, or as the difficulty/ambiguity of the problem increases, individuals' reliance on social learning increases (Davis 1984; McElreath, et al. 2005). The same experiments indicate that this increased reliance on social learning is even more pronounced when incentives are increased. That is, in contrast to the intuitions of some, adding incentive magnifies the influence and importance of social learning (Baron, et al. 1996). In these learning experiments the payoffs of overall group rise substantially when as the availability of imitative opportunities increase and social information is made increasingly available. In these experiments, the aggregate behavior of the group only approached local or global optima when imitative opportunities were presented and social information was high quality. The greater the availability of imitative opportunities the closer group profits approached to the maximum theoretical profits.

While these laboratory findings do include numerous experiments involving monetary stakes, we must also assess whether these theoretically-derived, laboratory-tested insights are consistent with findings from the spread of novel technologies and practices in the real world. The vast diffusion of innovations literature has for six decades focused on understanding why some novel techniques, technologies, and practices sometimes spread and other times do not. Underpinning many of these investigations stands the question of why some populations sometimes seem highly resistant to adopting what appears to be—in terms of economics or health—a beneficial novelty. Summarizing some of the principle findings from this extensive literature, Rogers (1995, p.18) writes:

> Diffusion investigations show that most individuals do not evaluate an innovation on the basis of scientific studies of its consequences, although such objective evaluations are not entirely irrelevant…Instead, most people depend mainly upon a subjective evaluation of an innovation that is conveyed to them from other individuals like themselves who have previously adopted the innovation. This dependence on the experience of near peers suggests that the heart of the diffusion process consists of the modeling and imitation by potential adopters of their network partners who have adopted previously.

According to Rogers, micro-level studies of diffusion processes indicate that the heart of the process does not involve each individual independently evaluating the costs and benefits of novelties. Instead, what consistently emerges as essential to such diffusion processes are the patterns of social interaction, modeling and imitation in the community. Rogers also dedicates an entire chapter to discussing how early adoptions by locally prestigious individuals can make all the difference, since people tend to emulate the successful. Sophisticated network analyses of the spread of innovations confirm these results in showing that person-to-person interactions and prestige is crucial to understanding how and why novelties diffuse through populations (Valente 1995; Valente, et al. 2003).

Consistent with the micro-level results of experiments and field observations are data on the temporal diffusion dynamics of innovations. Thousands of studies show that diffusion processes reveal an "S-shaped" diffusion curve, with time plotted on the horizontal axis and the frequency of adopters on the vertical axis (Rogers 1995). These curves rise slowly, accelerate to a maximum adoption rate in the middle, and finally slowly taper offer near the end of the adoption cycle (forming an S-like shape). Comparative analytical research using formal models that consider both evaluative cost-benefit learning and cultural transmission indicate that diffusionary processes are likely dominated by cultural learning, otherwise the "S" would not emerge (Henrich 2001; also see Young 2007). These analyses also provide explanations for the take-off points (critical frequency thresholds for diffusion) and long-tails (slow initial diffusions) that characterize much of the literature. It is, of course, possible to construct mathematical formulations involving all kinds of individual heterogeneity that can, under particular conditions, generate S-curves without cultural learning (Steele in press). However, such formulations overlook the micro-level studies of actual diffusion processes and the existing bodies of experimental data on human learning from psychology, and more recently from economics. Moreover, while S-curves are ubiquitous in diffusionary processes, these alternative formulations are only applicable to a certain subset of circumstances, and thus cannot account for the ubiquity of S-curves.

This does not mean that costs and benefits, or individual evaluations, are irrelevant. One individual in a community might, for a variety of potential reasons involving both luck and individual initiative, obtain particularly high quality information about the effectiveness of a new technology, and adopt it. The adoption might result, for a farmer, in greater success in the form of higher crop yields. Our farmer's neighbors, impressed by the high yield, might imitate several of his techniques, including the new technology. As a consequence, the new technology may diffuse through the social networks of the community until all have adopted it. In this stylized example, all of the individuals in the community save one acquired the invention by imitating high payoff individuals, thus imitation is the heart of the process, but these learners exploited the superior cost-benefit information of one person. This kind of example is crucial, since Dual Inheritance Theorists (Boyd and Richerson 1995), have long argued that one of the key adaptive advantages of culture is that it allows those with poorer information on the costs and benefits of what is locally adaptive behavior is to exploit those with superior information (and greater certainty in that information). This is one way that cultural learning, as a byproduct, can increase a group's mean fitness.

Given the debates now occurring in both anthropology and economics with regard to how to model human decision-making, I think it is important to note that the convergence of recent work in rational choice theory with the evolutionary models of learning described above. Both streams of thought predict that an individual who is seeking to maximize his payoffs in a stochastic or uncertain world will shift to relying on cultural learning mechanisms, such as imitation, under a wide range of conditions (Bowles 2004; Ellison and Fudenberg 1993; Schlag 1998; Schlag 1999; Weibull 1995). This means that rational choice theorists or behavioral ecologists who insist on assuming individual behavior results from individual cost-benefit evaluations of imperfect information are insisting that individuals behave irrationally or non-adaptively.

The take-home point of this section is that because humans often rely heavily on learning from others, especially in incentivized situations involving ambiguous costs and benefits, a general approach to understanding innovation should take seriously the cultural nature of our species. Since the invention or adoption of a novel practice or technology necessarily involves uncertain costs and benefits, owning to the lack of any direct experience from which to acquire such information, it seems plausible that social learning may be even more important for a theory of innovation than it is for other aspects of human decision-making.

Innovation is fundamentally a cultural and social process

The section examines innovation and invention as cultural and social processes. The first part presents a very simple formal model that allows us to explore the relative contributions of independent invention, cultural learning, and the diversity of learners' associations on the spread of a novelty through a population. The findings, which are consistent with other more extensive explorations, illustrate that 'cultural interconnectedness' is crucial. The second part of this section examines inventions as incremental accumulations that depend crucially on recombination, happenstance, and luck, and not so much on individual heroic genius or mother necessity.

The importance of cultural interconnectedness

Moving from the individual to the population level, we ask what kinds of characteristics make a group more innovative. This requires consideration of both *inventions*—individuals create useful, effective, adaptive novelties—and *innovations*—these novelties have to spread through the group. I first develop a simple model that combines social and individual learning in order to examine the relative contributions of invention vs. cultural transmission in the emergence of successful innovations. Consider a large population of identical individuals in which each invents a useful novelty with probability ε. If individuals do not invent it themselves, they can observe k other individuals and can acquire it culturally from each with probability λ, which captures a combination of the cultural learning abilities of the learner (vis-à-vis the thing being learned), the details of the novelty that make it more or less likely to spread, the effects of the novelty on the associates that might make them more likely to be paid attention to or learned from, and the willingness or ability of the other individual to transmit the novelty. Using this, we can write down the overall probability that each of our individuals acquires the novelty.

$$p = \varepsilon + (1-\varepsilon)(1-(1-\lambda p)^k)$$

Since our individuals are identical, *p* also represents the expected frequency of individuals in the population who adopt the useful novelty after all learning is completed. If *p* is close to one, we can say the invention has spread widely and the group has innovated. Figure 1 plots the numerical solutions to this equation for a range of values of *k* (along the horizontal axis) for three different values of ε. Note first that higher values of *k* (more associates to learn from) create a dramatic and highly non-linear increase in the probability of acquiring the novelty, that is, of generating an innovation. For low values of *k*, the probability that any one person will adopt the trait is small—which implies that the final percentage of trait adopters in the population will be small. For example, when ε is 0.10 (a 10% chance of individual invention) and $k = 2$, the probability that an individual will acquire the novel trait is 12%. This means that, on-average, if only *12% of the population* will eventually acquire the novelty. However, for values of *k* greater than about 12, over 90% of the population will adopt the novelty. The shape of these curves reveal what would empirically appear to be threshold effects, especially when the trait is difficult to figure out by experimentation or experience (low ε). Consider the curves for ε = 0.01 and 0.001: For values of *k* less than about 5 few adopt the novel trait. However, by the time *k* has reached 10 nearly 85% of the population is adopting. Between $k = 5$ and 7, *p* spikes from about 0.05 to 0.58. This indicates that small differences in the number of people from which one can learn something can make a huge different in the equilibrium percentage of the population doing something.

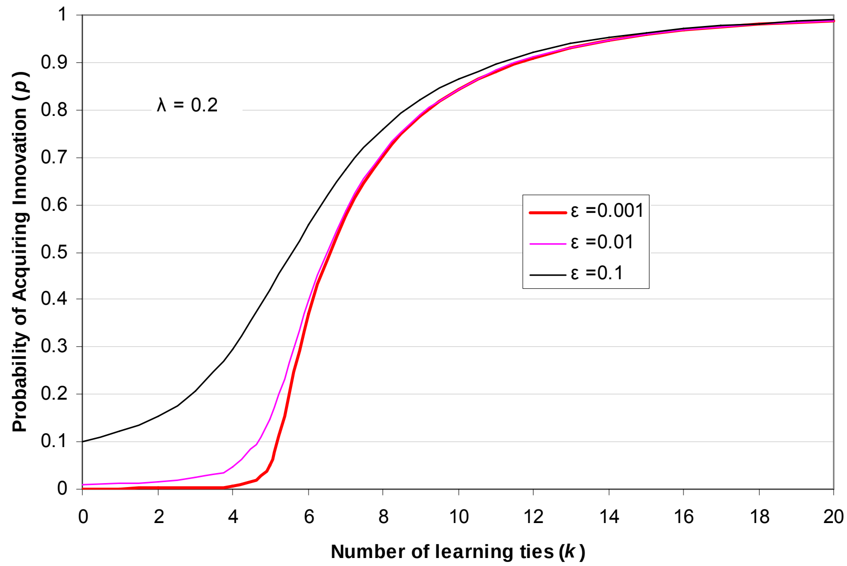

Figure 1. Plot of the relationship between *k*, the number of associates for a learner, and the frequency of adopters in the population once all individual and social learning is complete, for three value of ε, the probability of invention.

Note also the relatively small differences in the curves, especially for high values of *k*, given that the three values of ε differ by two orders of magnitude. A situation in which $\varepsilon = 0.10$ means that an individual has a 100 times greater chance of acquiring the trait by himself, via say experimentation, than when $\varepsilon = 0.001$. Interestingly, however, as *k* gets larger, ε makes less and less difference on the value of *p*, and the chances of an innovation. By the time *k* reaches 12, this 100-fold difference in ε is almost entirely wiped out by the power of cultural learning stretching out and interconnecting minds.

To probe the importance of this, imagine two different populations who, for reasons owing to geography, cultural beliefs, or cooperative institutions, have different values of *k* but are otherwise in identical situations (same λ and ε) captured by the $\varepsilon = 0.001$ curve in Figure 1. Suppose the two populations have $k = 4$ and $k = 12$, respectively. On the ground, an observer of these groups would see that essentially no one (0.4%) in population one has adopted the novelty while over 90% of individuals in population two would have adopted the innovation. If the analysts happens to think that the novelty is "smart" or "rational" then population two may seem more "inventive", "smarter" or more "rational" then population one—which of course they are not since we specified that ε is the same in both population. Population 2 is just more social.

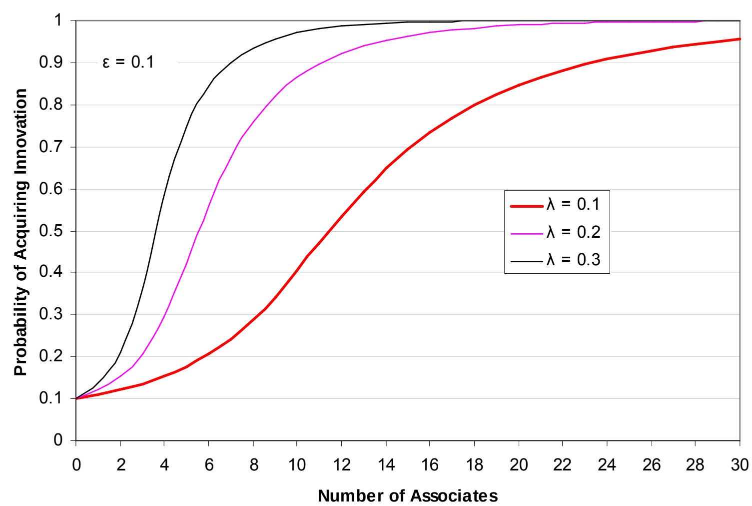

Figure 2. Plot of the relationship between *k*, the number of associates for a learner, and the frequency of adopters in the population once all individual and social learning is complete, for three value of λ, the probability of invention.

Increases in λ, our parameter measuring the effectiveness of cultural transmission between individuals, also has a larger impact than similar increases in ε. Figure 2 plots the relationship between *k* and *p* for three values of λ. While making little difference when *k* is small or large, λ shows substantial effects for intermediate values of *k*. For example, when $k = 6$ *p* goes from 20% for $\lambda = 0.1$ to 56% for $\lambda = 0.2$ and to 84% for $\lambda = 0.3$. Comparing Figures 1 and 2 for the relative effects of ε vs. λ illustrates the importance of open channels of cultural transmission in favoring innovation.

The take-home message from this analysis, which is supported by more extensively studied evolutionary models (Henrich 2004b; Shennan 2001; van Schaik and Pradhan 2003), is that a group innovativeness is more strongly determined by its cultural interconnectedness (including the effects of both k and λ) than by the individual inventiveness of its members (ε). Assuming that the probability of invention is not too small relative to the total population of potential inventors, group's that invest in cultural interconnectedness (sharing of ideas) will be substantially more innovative than groups that invest in raising the inventiveness of members.

These insights have numerous potential applications. At a continental level, larger land masses oriented on an east-west axis may favor the flow of cultural information, and farming technologies in particular, among distant populations (Diamond 1997; McNeil 1991). It may also explain the dearth of technological complexity in Australia vis-à-vis Eurasia, as well as the differences between Africa and the Americas on one hand, and Eurasia on the other. At regional levels, it may help explain the differences between populations isolated on islands vs. continental populations, and may even explain the loss of technological know-how that appears to have occurs in Tasmania, after it was separated from Victoria by rising seas (Henrich 2004b; Henrich 2006b; Rivers 1926). It may provide a cultural evolutionary explanation for the florescence of material culture during the so called human revolution (arising from population size, density, and interconnectedness), and suggest potential differences between anatomically modern humans and Neanderthals, who had similarly sized brains to us but may have varied only in their sociality (k).

On the origins of inventions: mother necessity, mistakes, and recombination

While the above suggests that individual inventiveness likely plays a smaller role in innovation than cultural interconnectedness, I want to further argue—mostly by rehearsing arguments previously made by many others—that invention is not quite what many tend to think.

I've four interrelated points on this front: (1) necessity is not the mother of invention, (2) most inventors are not heroic geniuses or intellectual revolutionaries, but add only small additions to existing accumulations, (3) these small accretions, and inventions more generally, are rarely entirely new, but usually represent only novel recombinations or cross-domain extensions of existing ideas, and (4) many of these useful additions or modifications result from lucky errors or chance interactions, not independent creations.

The idea that necessity is the mother of invention is an important assumption in much processual archaeological and anthropological theory (Johnson and Earle 1987), as well as in economics. In anthropology, the idea seems to be that when environmental circumstances shift, population increases, or external threats arise (warring groups), the innovation engine in a society and/or its members (depending on the specific paradigm) kicks into gear and soon the appropriate novel technologies, practices, or forms of social organization emerge. Often implicit in this, though not always, is the notion that the individual's own welfare is threatened, or declining, causing him to shift and invest more in invention, by taking more risks that will on-average result in more inventions (Fitzhugh and Trusler forthcoming).

The economic logic supposes that as the incentives shift sufficiently to favor alternative practices or technologies, individuals switch and invest in the alternatives. My goal in this section is not argue that "necessity" in never a factor in innovation or that incentives are irrelevant, but instead to suggest that at best necessity is only one of several progenitors of innovation, and not a necessary one at that. Below, we'll further suggest that many great inventions were initially rejected, suggesting that problems don't always find inventions but that inventions often find previously unrecognized problems.

To begin, I'd like to question the economic logic that often underlies this approach. Incentives, from the perspective of an omniscient observer, may favor an alterative technology (or practice), or a more complex version of a particular technology, but for the adaptive learner that novel technology does not yet exist, so the learner has no way to assess its relative costs and benefits. Not only does he lack any experience with which to assess the incentive differences, he has not even thought of it yet and can't have any idea of the cost associated with figuring it out (Henrich 2006b). Another theoretical issue is that if environmental shifts or population pressure have, for example, made current subsistence techniques less fruitful, an individual may have *less*, not more, time or energy to invest in invention. Invention investment may in fact decline in such circumstances. In modern economies, for example, firms invest in both their current product lines and research and development in boom times, but halt R&D in tough times (not the other way around Hargadon 2003).

Risk sensitive models of decision-making do show that if an individual's chances of survival fall below a threshold, such that on-average he dies, he should adopt a risk prone strategy, but it's far from clear that in a world with cultural learning whether a "risk prone" strategy involves investing via individual learning in invention. Rather than turning down individual risk aversion in a utility or fitness calculation, natural selection could alternatively favor recalibrating cultural learning strategies by shifting from conformist biases in transmission toward anti-conformist biases (Henrich and Boyd 1998) or reducing within-group ethnic learning biases (McElreath, et al. 2003). Such shifts in cultural learning help reduce the likelihood of sticking to locally failing strategies, make learners more sensitive to even smaller differences in perceived payoffs between themselves and others, and open up the learner up to acquiring useful novelties from other groups.

Empirically, my own reading of the ethnographic, archaeological, and historical record on these issues seems to suggest that when faced with population pressure, environmental shifts or external threats peoples do sometimes innovate, however, more often they emigrate, suffer or die. Diamond chronicles the failure to innovate and the resulting collapse of the Maya, Greenland Norse, and Easter Islanders (Diamond 2005). The Greenland case is particularly instructive because we know that while the Norse gradually starved to death and vanished in response to climate change, local Inuit populations possessed adaptive technologies that allowed them to survive and further expand at the same time. This means that the Norse could have adapted, but did not. Other provocative cases that would seem to argue against necessity as the crucial parent of invention include:

1) Foragers living in Australia for 60,000 years (Testart 1988) failed to develop (or perhaps lost) any technologies involving elastically stored energy (e.g., the bow and arrow, musical bow, bow trap or spring snare), kinetic energy (e.g., lasso and bola) or compressed air (e.g., blowpipe and dart, musical instruments).

2) New Guineans, while using bows and arrows, never adopted fletching of any kind.

3) In the New World and elsewhere, sophisticated societies facing the spread epidemic diseases, developed neither antibiotics nor even basic public health measures, like quarantines. Instead, millions died.

4) The wheel appears to have only been invented in Eurasia and nowhere else (Basalla 1988). One could argue that other places lacked large domesticated animals that made wheels particularly useful. However, wheel barrels and pulleys are still pretty useful, and

"llama carting" (see figure) is a fun-filled recreation today. Dogs, which are ubiquitous, can pull carts as well. The 19th and early 20th centuries dogs were used to pull people and milk carts in Northern Europe.

5) The Inca managed a vast empire, stretching from Columbia to Chile, without writing. It's hard to imagine there was not a need for writing.

6) Numerous human languages failed to devise linguistic systems for counting above four. One might argue that they did not need such a system, but as soon as such group encounters another group with an infinite counting system one of the first elements to transmit are often the numbers above four.

7) Zero appears to have been invented only twice in human history, once in India and once by the Maya. Most societies adopted zero soon after encountering it, although Europeans resisted zero (Seife 2000).

These are some macro-scale cases that challenge the idea that necessity is the mother of invention. As noted previously, the same argument can be made for individual's failure to innovate when faced with dire circumstances. Below, the account of Burkes and Wills ill fated expedition into the Australian outback illustrates both the futility of fitness-maximizing calculations, in the absence of culturally inherited information, and the tendency for humans, even arrogant Europeans, to rely on social learning over individual learning and experimentation for survival, when the pressure is really on.

In 1860, aiming to be the first Europeans to travel south to north across Australia, Robert Burke led an extremely well-equipped expedition of three men (King, Wills and Gray) from their base camp in Cooper's Creek in central Australia with five fully-loaded camels (specially-imported) and one horse. Figuring a maximum round trip travel time of three months, they carried 12 weeks of food and supplies. Eight weeks later they reached the tidal swamps on the northern coast and began their return. After about ten weeks their supplies ran short and they began eating their pack animals. After 12 weeks, Gray died of illness and exhaustion, and the group jettisoned most of their supplies. A month later, they arrived back in their base camp to find that their support crew had recently departed—leaving only limited supplies. Still weak, the threesome packed the available supplies and headed to the nearest outpost of "civilization" (Mt. Hopeless, 240km south). In less than a month, their clothing and boots were beyond repair, their supplies were again gone, and they ate mostly camel meat.

Faced with living off the land, they began foraging efforts and tried, unsuccessfully, to devise means to trap birds and rats. They also attempted to glean as much as they could from the aboriginals about *nardoo*, an aquatic fern whose spores they had observed the aboriginals using to make bread. Despite traveling along a creek, and receiving gifts of fish from the locals, they were unable to figure out how to catch fish. Yet, they were repeatedly impressed by the bountiful bread and fish available in the aboriginal camps, in contrast to their own wretched condition. Two months after departing from their base camp, the threesome had become entirely dependent on *nardoo* bread and occasional gifts of fish from the locals. Despite consuming what seemed to be sufficient calories, all three became increasingly fatigued, and suffered from painful bowel movements. Burke and Wills soon died, poisoned and starved from eating improperly-processed *nardoo* seeds. Unbeknownst to these intrepid explorers, *nardoo* seeds are toxic and highly indigestible if not properly processed—of course, the local aboriginals possess specialized methods for detoxifying and processing these seeds. Fatigued and delusional, King wandered off into the desert where he was rescued by an aboriginal group, the Yantruwanta. He recovered and lived with the Yantruwanta for several months until a search party found him.

The planning for this expedition could not have been more extensive, and these men were not unprepared British schoolboys out on holiday. However, despite their camels, specialized equipment, training and seven months of exposure to the desert environment before to running out of supplies, these men failed to figure out how to survive in the Australian outback. They were sustained by a combination of ideas they acquired by observing the locals, and the generosity of the locals. They did not invent any traps, snares, tools, or boomerangs, although they did unsuccessfully try to imitate those of aboriginals.

The available laboratory experimental findings, however limited, converge with the processes suggested by anecdotes like the above case, and also do not support the "mother necessity view." As discussed above, when problems get tough or the world gets uncertain, student subjects shift to social learning strategies, and rely less on their private information about the world. Adding incentives only magnifies this effect. This is, of course, why cheating is an issue. When the problems get hard, the imitation motivation gets going.

Besides the ambiguous role of necessity in yielding invention, a close look at the emergence of some well-know inventions illustrates (1) the importance small additions by many contributor, often over long time periods, with a relatively small role for singular heroic geniuses, (2) the degree to which seeming novelty really represents only new recombinations or cross-domain extensions of existing ideas or technologies, and (3) the centrality of lucky errors or chance interactions in inventions, not *sui generis* independent insights. I must leave a complete defense of these views to the existing historical works that have confronted this in detail (Basalla 1988; Diamond 1997; Hager 2007; Hargadon 2003; Meyers 2007; Sneader 2005; Williams 1987) and rely on five illustrative examples.

1. Whitney's "revolutionary" cotton gin merely modified existing long staple cotton gins, which were already widely available in the Southern U.S., to extend their processing ability to short staple cotton. These gins go back hundreds of years to Indian gins called *charka*, which used the same principles as Whitney's gin (and actually looked alike). Similar gins are seen later in 12th century Italy and 14th century China.

2. Establishing the germ theory of disease required obtaining pure cultures of bacteria. In the 19th century, dozens of researchers were trying to figure out how to do this, without success. Robert Koch solved the problem after years of pursuing it when, while cleaning up his laboratory, he ran across a half of a boiled potato that had been carelessly left for a few days. Koch noticed that the growth of discrete reddish dots at different places on the white potato, and realized that one needed a solid, not a liquid media. He went on to firmly link specific pathogens with specific diseases, and to develop his four postulates for making this link based around cultivating a pure culture (Hager 2007). None of this could have occurred without the carelessly left potato.

3. Edison's "invention" of the incandescent light bulb only improved on many other such bulbs patented between 1841 and 1878 by a wide variety of inventors. Of course, if you are from Britain, Sir Joseph W. Swan is the inventor of the incandescent light bulb, while if you are from Russia its A. N. Lodygin (Conot 1979; Diamond 1997). Edison's bulb also emerged from his Menlo Park research laboratory, meaning it was actually the product of a team effort (Hargadon 2003).

4. The Wright brother's invention of the airplane built on existing manned gliders and unmanned powered airplanes. Their contribution was a recombination of existing lines of technology (Diamond 1997), which they'd read about. The trail of the evolution of flight goes back to at least 400 B.C. with Chinese kites.
5. Darwin's discovery of descent with modification and natural selection: In the Fourth Edition of *The Origin of Species* Darwin included "An Historical Sketch of the Progress of Opinion on the Origin of Species, previous to the publication of the first edition of this work," which reviews material from 34 predecessors who had recognized "descent with modification" and denied any special creation in the origin of species. Among these, Darwin credits W.C. Wells in 1812 as the first to recognize the process of natural selection. The point is not that Darwin had read Wells (he probably had not), but rather that some combination of emerging evidence and related ideas were colliding and recombining in many minds of the time, most of whom were interacting with each other, to converge on similar conclusions. Darwin had long read and corresponded with several of the individuals on his list.
6. James Watt's "invention" of the steam engine occurred in 1769 after repairing a Newcomen steam engine constructed 57 years earlier. This engine was modified from Thomas Savery's design of 1698, the components of which trace to 17th century Europe and 13th century China. After dissecting the steam engine, famed historian Joseph Needham concluded that "No single man was the father of the steam engine'; no single civilization either." (quotation from Basalla 1988).
7. The discovery of penicillin, and the dawn of the age of antibiotics, began when Alexander Fleming returned from holiday to find that his Petri dishes had been

contaminated with mold. Seeking to clean up his chronically messy laboratory, he dumped the whole batch of dishes into a laboratory sink where they sat until he retrieved an unsubmerged disk to show a visitor. He happened to notice that while the mold was growing fine, the staph was retreating. Penicillin was discovered due to luck and messiness. Of course, Fleming published his subsequent inquiry into this lucky finding in 1929 where it was promptly ignored for a decade.

8. Lemon juice to treat or prevent scurvy: In the early days of the European expansion (1500-1800) scurvy killed more sailors than warfare, accidents, and all other causes of death combined (e.g. Vasco da Gama lost 160 men total, 100 to scurvy). After 100 years of substantial necessity, in 1601, Captain James Lancaster performed an unintended controlled experiment.[2] The lead ship of his trio was stocked with lemons, and lemon juice was provided to the crew. The crew on the other ships did not receive any citrus juice. The men on the lead ship stayed healthy while on the other ships, 110 out of 278 sailors died of scurvy. Lancaster only managed to complete the voyage by staffing the three decimated ships with men from the "lemon ship." After this was reported back in England, no one adopted or experimented further with this remarkable invention for 148 years, until a British Navy physician further confirmed the diet's efficacy (using oranges instead). Still, the British Navy failed to adopt the innovation until 1795—194 years after Lancaster's experiment and 48 years after further confirming evidence. Seventy years later the British Board of Trade finally adopted the practice and eliminated scurvy from the merchant marines. If necessity was the mother of invention, it ought not to have taken

[2] The historical record seems to provide conflicting accounts of whether the experiment was intentional, ignited by advice given in India, or accidental. The Chinese appear to have arrived at the same solution about four hundred years earlier

one-hundred years for testing. But, it really should not have taken anther 200 years for the invention to spread into an innovation.

Invention and innovation are fundamentally cultural evolutionary processes. Since nearly all inventions build on existing ideas and often involve the recombination of existing concepts, methods, or materials, often fortified or integrated with a dose of lucky mistakes or happenstance, the overall inventiveness of a social group or population depends on the number of individual minds available to create recombinations, generate insights, and get lucky, as well as on their cultural interconnectedness. This implies that the more minds in one generation, the more novel recombinations, insights, and lucky mistakes will exist for the next generation to recombine, refine, and extend across domains. The more innovations in existence, the greater the opportunities for recombinations and the more inventions are possible. Since the elements of any recombinant are acquired by learning from others, the more individuals one can potentially learn from, the greater the opportunities for creating novel recombinant inventions. Business scholars now argue that companies should design themselves specifically to bridge multiple technologically domains, especially to stimulate innovation via recombination (Hargadon 2003).

If both a population's size and its degree of cultural interconnectedness increase innovation rates, then we should expect certain kinds of practices and technologies to have an especially large impact on innovations, especially those that permit or increase the flow of information within or across groups. Anything that permits faster or easier communication should *ceteris paribus* have a impact innovation rates, such as transportation (horses, ships, roads, trains, and planes), communication (shared language, writing, mail, books, journals, literacy, telegraph, telephone, and internet) and peaceful social relationships (although in wartime, espionage seems to energize innovation) (McNeil 1982).

Increasing innovation involves solving a cooperative dilemma

The technologies, practices, institutions, and relationships mentioned above can potentially increase both the effective population size and/or the degrees of cultural interconnectedness; however, there remains a core motivational dilemma in creating innovation. Implicit in being “interconnected” lies a willingness to share what one has figured out (or stumbled upon) with others, or at least a willingness not to actively seek to prevent other from observing or learning what one knows. The overall group or population is often best served—in terms of either fitness or innovation rate—if everyone shares their ideas and inventions as openly as possible, thereby maximizing the flow of inventions, accumulation and recombinations. However, individuals or groups (in a population of other groups) have incentives to learn as much as they can from others while keeping their own ideas to themselves. These incentives turn the problem of innovation (creating and spreading inventions) into a classic cooperative dilemma with a free-rider problem.

Elsewhere Gil-White and I have examined how this natural selection acting to refine our capacities for cultural learning has begun to address this cooperative dilemma (Henrich and Gil-White 2001). We proposed that learners essentially pay those they want to learn from (e.g., highly successful and skilled models) with prestige-deference. This deference comes in many forms but includes a willingness to help, small gifts, coalitional support, and public praise (resulting in more deference from others). In exchange for this deference, the chosen model (a prestigious individual in at least the learner’s eyes) permits the learner to hang around him or her, and observe what he or she does, close up. Such models may give tips, or even perform certain actions in a manner that facilitates observational learning. We called this the information-goods theory of prestige because information, in the form of learning opportunities, is exchanged in dyadic relationship for prestige-deference. We argued that this approach explains much status related behavior, and is the only approach that makes the necessary empirical connection between the empirically observed patterns of ethological behavior, deference, and imitation. Supplementing the original evidence we presented in our paper, more recent support has emerged in studies of human emotions, including awe, respect and elevation (Algoe, et al. 2006; Tracy 2007).

This aspect of our evolved status psychology forms the foundation for the institution of apprenticeship, which appears to have emerged independently in many human societies. Apprentices seeking to learn particular skills (e.g., blacksmith, weaver, potter) work under the strict—often slavish—direction of a master. In addition to the apprentice's labor, which may be required for years, the master may also require payment, and may have other stipulations, like requiring the apprentice to promise not to setup shop in the master's own town, or swearing not to reveal the master's secrets. The apprentice's learning is usually strictly imitative, with the explicit goal being to copy the master exactly (Coy 1989).

The institution of apprenticeship, while permitting the cultural transmission of complex skills, does not maximize the flow of adaptive information among individuals in the population in a manner that will favor innovation. Since, in addressing the inherent cooperative dilemma, apprentices are usually limited in number and serve only one master, there is little chance for the diffuse interconnected, accumulation and recombination that energizes invention and drives higher rates of innovation. The society would be more innovative if masters freely distributed their knowledge, permitted as many apprentices as could be handled, and did not require a long period of servitude. Students could move among masters as they wished, comparing and recombining elements from different masters. However, the actually institution, which appears to be a direct extension of the evolved psychological mechanisms associated with the learner-model relationship, only partiality addresses the underlying cooperative dilemma.

The kind of diffuse system with high degrees of cultural interconnectedness that I've argued above will promote both innovation and invention requires solving a larger-scale *n*-person cooperative dilemma. Rather than dyadic cooperation as in the prestige and apprentice systems, cultural systems that can create higher degrees of stable *n*-person cooperation, in which individuals share widely what they know and invent, will energize both population rates of invention and innovation. Cultural evolutionary models targeting these larger-scale problems of cooperation have so far provided three classes of potential solutions, one based on an interlocking reputational system that ties together *n*-person cooperation within the group to other dyadic social interactions (e.g., Panchanathan and Boyd 2004), a second based on costly punishment of non-cooperation and on the punishment of non-punishers (e.g. Henrich and Boyd 2001), and a third that exploits cooperation as a form of signaling that distinguishes higher quality partners from lower quality partners (Gintis, et al. 2001). The first approach depends on a reputational system in which failure to cooperate results in acquiring a bad reputation such that others can withdraw their helping (or increase their hurting) during dyadic interactions that occur apart from the cooperative interaction. The second approach replies on and combines (1) the coexistence of both cultural transmitted influences on cooperation and punishment (of non-cooperators and non-punishers), (2) the reliance by learners on conformist transmission as the payoff differences between alternative strategies approaches gets smaller, and (3) the geometrical decline in payoff differences between prosocial strategies (cooperation and punishment) and selfish strategies (defection and non-punishment) as one ascends to high orders of punishment.[3] The third approach assumes that individuals vary in a non-observable quality desired by potential partners and can use signals to differentiate themselves. The signals used contribute to the benefit of the group.

All three of these solutions can solve, to varying degrees, the cooperative dilemma of information sharing laid out above. However, analyses of all three approaches also demonstrate that these mechanisms can also stabilize a wide range of individually costly behaviors (non-group beneficial), besides cooperation, and also always have a stable equilibrium at full defection. All three could stabilize, for example, practices such as female infibulations, footbinding, and taboos on nutritiously valuable foods. This means that all three require a means of equilibrium selection (Henrich 2006a): that is, some process that can pick out the group beneficial equilibrium from the myriad of non-cooperative alternatives.

The problem of equilibrium selection can be addressed by cultural group selection (Boyd and Richerson 2002; Henrich 2004a). Cultural group selection labels a class of processes that arise from the interaction and competition among social groups. The idea is that different groups will culturally evolve to different stable states involving the above mechanisms, and likely many others that theorists have not yet dreamt up. While internally stable, these different equilibrium or institutional forms will vary in their facilitation and promotion of information sharing and cultural interconnectedness. Social groups with institutions that favor innovation, due to greater

[3] Such models are structured such that strategies of cooperation and defection apply to "order-1", non-punishment and punishment of defector to "order-2", non-punishment and punishment of non-punisher at order-2 to order-3, etc. to infinity. Thus, the famed "second-order free-rider problem" focuses attention on sustaining the punishment of defectors.

interconnectedness or larger populations, will out compete, due accumulation cultural adaptation and technological evolution, those groups lacking such institutions (those at other equilibria).[4]

One line of evidence for this approach comes from ethnographic studies of the small-scale subsistence farmers whose general 'conservatism' and unwillingness to adopt novel technologies and practices has long provided a puzzle for policy makers and development economists (Hoffman 1996). My own research among the Mapuche of southern Chile shows that farmers know little of their neighbors' successes or the details of their practices. Mapuche farmers' lack of knowledge regarding others success would suppresses that the effect of our adaptive cultural learning mechanisms, which target the transmission of success-enhancing practices, techniques or technologies. Their lack of knowledge regarding the details of neighbors' practices and techniques means that, even if success differences are noticed (as in crop yields), any transmission will be error ridden and therefore less effective. This lack of knowledge no doubt results from several factors, although both interviews and observational data indicates that farmers actively hide information from others because they believe that if others know of their successes or innovations they (the successful innovator) will be envied, and such envy will physically harm them and their families, in the form illness, injuries, dramatic failures, and forms of bad luck. Similarly, individuals who seem "too interested" in other household's business face reputational damage, as they may be perceived motivated to spread gossip that will result in envy and harm to the family. While my Mapuche findings are more quantitative than most ethnographic work, the general image of how the reputation system works, and how it

[4] Since the situation we are discussing here involves competition among *stable equilibria*, the concerns often expressed about the plausibility of the genetic group selection of altruism do not apply (Henrich and Henrich 2007).

might suppress innovation and diffusion is quite consistent with economically similar populations in diverse geographic locations (Banfield 1958; Foster 1967; Redfield 1953).

The cultural beliefs connecting envy and harm, which are amazingly widespread, have also long been associated with perceptions of the world as a zero-sum game, meaning that if you are doing better, then I and everyone have to do a bit worse (Foster 1965; Foster 1974). This perception (and sometimes in reality) is accompanied by a bad reputation for deviants (innovators) that could subsequently result in possible losses in dyadic exchanges and social ostracism. Such combinations of beliefs can form a self-stabilizing cultural system because deviants, even if they reject the cultural beliefs themselves, are still incentized to avoid standing out and especially to appearing successful. These kinds of cultural beliefs can dramatically suppress innovation, and the rates of cumulative cultural evolution.

The implications of the theoretical discuss described above suggests that societies lacking cultural system that connect envy and harm via witchcraft, suppress success displays, imbued curiosity with malevolent intentions, and perceive the world as a zero-sum will be outcompeted and assimilated by societies with cultural beliefs and reputational systems that favor information sharing and open the pathways of cultural transmission.

This also implies that the relatively open cultural pathways experienced by readers of this chapter have been strongly influenced by centuries and millennia of cultural evolution, driven by cultural group selection, to create informal institution that elevate and sustain substantial cultural interconnectedness and large populations.

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