Age and Scientific Genius

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Abstract

Great scientific output typically peaks in middle age. A classic literature has emphasized comparisons across fields in the age of peak performance. More recent work highlights large underlying variation in age and creativity patterns, where the average age of great scientific contributions has risen substantially since the early 20th Century and some scientists make pioneering contributions much earlier or later in their life-cycle than others. We review these literatures and show how the nexus between age and great scientific insight can inform the nature of creativity, the mechanisms of scientific progress, and the design of institutions that support scientists, while providing further insights about the implications of aging populations, education policies, and economic growth.

I. Introduction

What is the relationship between age and scientific genius? This question has long fascinated scientists, the institutions that support scientific research, and the public at large. Understanding the nexus between age and great scientific insight can inform the nature of creativity, the mechanisms of scientific progress, and the design of institutions that support scientists. It can also shed light on subjects that at first blush seem farther afield, such as the implications of aging populations, education policies, and economic growth. The role of age in science has attracted the interest of both scientific greats and science policy leaders. Albert Einstein once quipped that "a person who has not made his great contribution to science before the age of thirty will never do so." Meanwhile, a recent director of the National Institutes of Health declared the advancing age at which investigators receive their first NIH grant as "the greatest problem facing U.S. science".

In this chapter we review empirical evidence on the relationship between age and great scientific output, discuss mechanisms at work, and consider the implications. Studies of age and scientific output have a long pedigree, dating at least from Beard (1874), who estimated that peak performance in science and creative arts typically occurred between the ages of 35 and 40. A large research enterprise has since charted how scientific output varies over the life-cycle, often with an emphasis on cross-field comparisons. This research consistently finds that performance peaks in middle age: the life-cycle begins with a training period in which major creative output is absent, followed by a rapid rise in output to a peak, often in the late 30s or 40s, and a subsequent slow decline in output through later years. These patterns appear when looking both within individual histories and when looking at peak performance across individuals. Figure

1 considers the age distribution of signature achievements, looking across Nobel Prize winners and great technological innovators in the 20th Century. For both samples, we see that the scientific or technological breakthroughs most typically come in the late 30s. At the same time, a number of scientists make pioneering contributions before reaching 30 or in their 60s and beyond. The rapid rise and later slow decline in life-cycle output help in positing hypotheses about key ingredients to great scientific contributions, including training in the early life-cycle and institutional and/or health effects in the later life cycle that influence productivity.

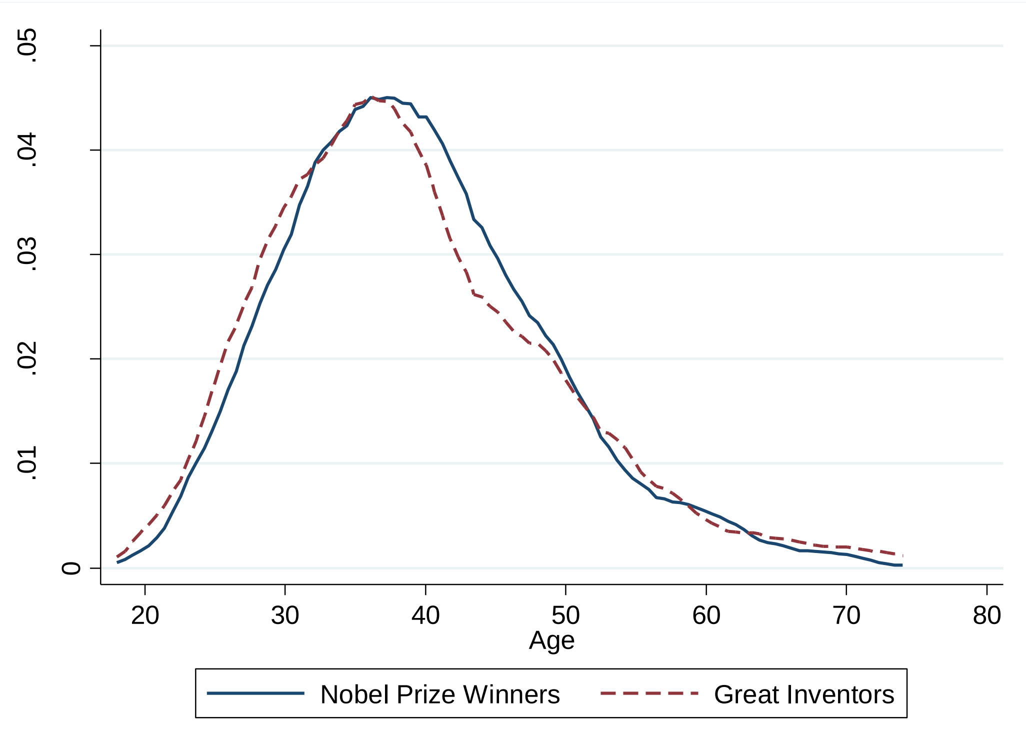

Figure 1: An Age Distribution for Scientific Genius. The Ages at which Individuals Produced Nobel-Prize Winning Insights and Great Technological Contributions over the 20th Century (Source: Jones 2010).

The literature on age and scientific genius has classically emphasized the peak age of contributions. The expansive work of Lehman (1953), like other major contributions such as Zuckerman (1977) and Simonton (1991), estimated the age of peak performance in various fields and then emphasized cross-field comparisons, where the age-output profile was considered fixed within a particular field. A classic finding is that peak performance has come earlier on average in mathematics and the physical sciences than in fields like medicine. This cross-field variation can then be used to make distinctions in the nature of creativity across fields and further inform theories relating age and genius.

A more recent literature emphasizes other variation in the data, including changes over time and variation across individuals within a field. One finding is that the age-output profile within fields is not fixed but actually changes quite dramatically over time. For example, Nobel Prize winning research is performed at an average age that is 6 years older at the end of the 20^{th} century than it was at the beginning (Jones, 2010). Figure 2 reconsiders the data from Figure 1 in three different periods and shows this effect, where the tendency for great scientific or technological contributions has been shifting toward later ages. A second type of analysis emphasizes variation across individuals within fields, where despite a broad tendency for peaking in middle age, many researchers do produce their signature contributions either early in life or at advanced ages. This new literature exploits these time dynamics and the individual level variation to further inform theories of creativity and scientific progress that emphasize both (a) training requirements in various fields and (b) cognitive theory where the nature of creativity varies across researchers. This new literature provides additional evidence about underlying mechanisms in understanding the relationship between age and great scientific output, although many other mechanisms, including institutional and sociological mechanisms, remain less explored.

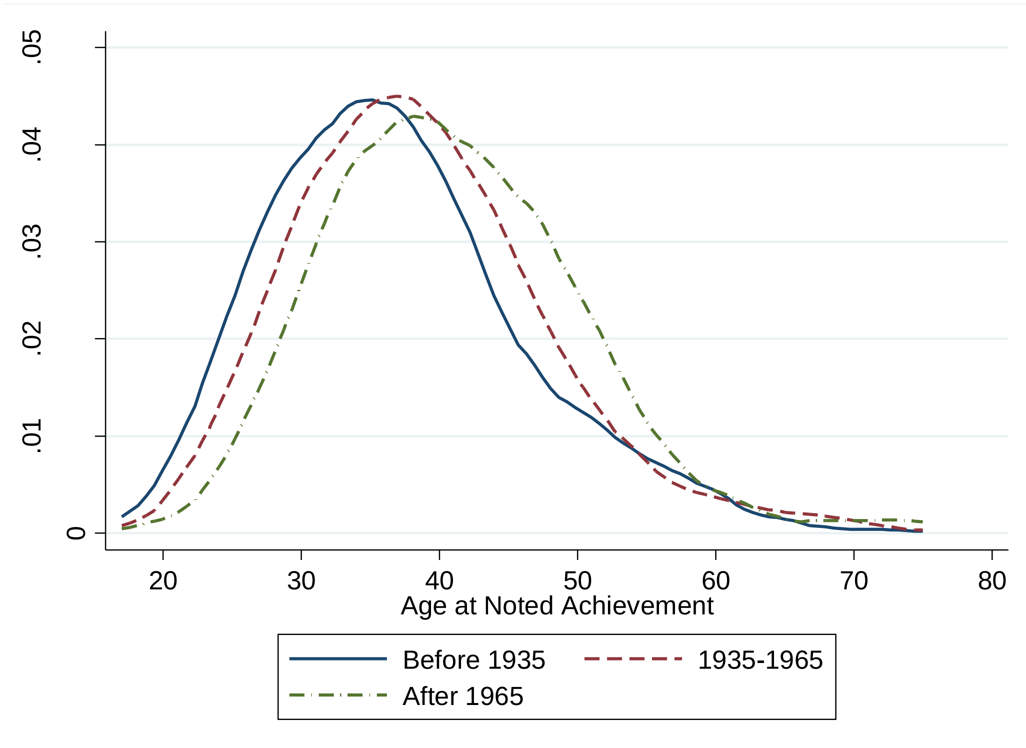

Figure 2: A Shifting Age Distribution for Scientific Genius. Nobel-Prize Winning Insights and Great Technological Contributions over the 20th Century (Source: Jones 2010).

This chapter proceeds as follows. Section II provides an overview of the classic literature, emphasizing the finding that great scientific contributions are especially likely in middle age and considering various mechanisms posited that may explain this broad life-cycle pattern. Section III reviews the more recent literature, emphasizing substantial variations across individuals and over time, which introduce new first-order facts about the link between age and scientific genius while further informing mechanisms. Section IV discusses the broader implications of the findings for understanding scientific progress, the design of science institutions, and aging populations, and also considers important outstanding research questions for further work. Section V concludes.

II. Basic Life-Cycle Patterns and Classic Views

Interest in the relationship between age and scientific genius stems partly from prominent examples of individuals who make breathtaking breakthroughs early in life. Einstein, for instance, had his *annus mirabilis* in 1905 at the tender age of 26, when he made separate contributions regarding the photoelectric effect, Brownian motion, and his special theory of relativity. Newton's *annus mirabilis* came in 1666 at the age of just 23, developing calculus and his theories of gravitation and optics. Heisenberg developed matrix mechanics and the uncertainty principle by the ages of 23 and 25 respectively. Steve Jobs co-founded Apple Computer at age 21. In music, Mozart's renown in his own lifetime was built initially on his precocity. Indeed, early contributions are sometimes taken as the hallmark of genius. Of course, defining geniuses as people who make great early contributions essentially eviscerates the question of the relationship between age and genius. Moreover, focusing on young people turns out to miss most great contributions. For example, in contrast to Einstein, 93% of Nobel Prize winning scientific breakthroughs have come from individuals beyond age 26, and even geniuses who emerge early may bloom more fully at more advanced ages. Einstein's theory of general relativity, perhaps his greatest contribution, came largely in his early to mid-30s. Copernicus completed his revolutionary theory of planetary motion around age 60. Mozart's most famous operas came in his 30s, and Steve Jobs produced by far his most commercially successful innovations in his late 40s and early 50s.

To understand the link between age and scientific genius, the literature steps away from a focus on youth per se and examines great contributions across the whole life cycle. Estimating the life cycle of scientific genius requires one to identify a sample of scientific geniuses directly and/or a sample of unusually important contributions and then determine when the research underneath these contributions began and ended in a scientist's life. As a practical matter, much of the literature identifies important contributions using prizes, frequently the Nobel Prize, which provides a sample of important scientists whose contributions can then be identified from biographies. Focusing on the Nobel Prize, for instance, tends to limit analysis to a relatively small number of fields.[1] Others have used dictionaries of scientists or membership in elite societies such as the Royal Society or the National Academies, typically identifying important works from biographies. In either case, assessments of importance are determined after the fact. The assessment of genius thus reflects judgments at a point in time, often closely contemporaneous to the scientists life (such as a prize, or membership in an elite society) or possibly in the distant future (such as dictionaries recording key breakthroughs through history).[2]

In analyzing age and scientific genius, the classic literature has typically viewed fields as the unit of analysis assuming that, for a given field, the relationship between age and scientific genius is fixed. Observations within a field are then pooled, and a life-cycle pattern (albeit across different individuals) is established for that field. Comparisons across fields may then also be made.

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[1] Some other prizes, such as the Fields Medal in mathematics, are only awarded to people who are under a given age or who make their prize-winning contribution before a given age, essentially truncating the sample. To some extent these restrictions may tell us something about the age at which important work is done in those fields, but there are fields where there are prominent prizes for people who do important work before a given age as well as at any age. In Economics, for instance, the John Bates Clark Medal is awarded to people under age 40, but the Nobel Prize is awarded to people for contributions made at any age, and there are many Nobel Laureates who did their Nobel Prize winning work after 40 and did not receive the Clark Medal despite being eligible for it.

[2] One should of course interpret results conditional on the sample used, noting that certain samples may reflect social context or temporal preferences that conflate "genius" with other selection considerations. We are not aware of work that has attempted to adjust for changes in the assessments of important research contributions over time or made strong arguments about important selection biases in the samples used, so such concerns remain theoretical. Indeed, the patterns revealed tend to show substantial similarities despite very different sampling mechanisms and populations. For example, Figure 1 shows extremely similar age distributions for both the Nobel Prize sample and the great technological contributions sample, which are produced by very different selection procedures.

Table 1 summarizes the findings of this classic literature. In constructing this table, we have focused on studies of great scientific contributions (as opposed to normal science). We have also sought to emphasize lines of research rather than each individual study. At the broadest level, the table shows that while many scientists make fundamental contributions very early or very late in their careers, such contributions are typically far less common than contributions in middle age. Most studies show age of great scientific contribution peaking in the 30s or 40s. For example, Simonton (1991) studies 2,026 notable scientists and inventors from antiquity to the 20th century and finds that contributions peak on average at age 39.

Table 1 also shows that there appear to be systematic differences across fields, with creativity tending to peak earlier in the most abstract fields and later in fields with greater context, such as history. Although the specific results vary considerably from study to study, Zuckerman's classic work (1977) is broadly representative, finding that Americans receiving the Nobel Prize before 1972 did their prize winning work at 36 in physics, 39 in chemistry, and 41 in medicine / physiology. Lehman (1953) similarly finds that physicists appear younger when looking at dictionaries of signature contributions, as opposed to the Nobel Prize.

The tendency for genius to peak, broadly, in middle age, and some noted cross-field differences, can motivate a wide class of theories for the witnessed patterns. While there is much other variation in the data to usefully explore (see Section III), an initial focus on the peak in middle age suggests several natural hypotheses for the life-cycle pattern, and the classic literature tends to focus on this peaking phenomenon as an empirical regularity. Theories may be most easily organized by asking the following questions. First, why does creativity rise so rapidly during the 20s and early 30s? Second, why does it decline, albeit much more gradually, from the 40s and beyond? We introduce here a wide variety of mechanisms proposed in the literature, based on these classic studies, but note that many of these theories are theories of scientific productivity in general rather than theories of "genius" in particular. Section III will present a different empirical perspective, emphasizing the substantial variation in the data both over time and across individuals within fields, which establishes additional empirical regularities and develops core theories governing the relationship between age and scientific genius.

The Early Life Cycle

A remarkable feature of age and scientific genius is the rarity of contributions at the beginning of life. The early life-cycle period is of course coincident with schooling, suggesting that training mechanisms may be important for understanding the life-cycle patterns. Economists have viewed the age-contribution relationship in terms of their workhorse human capital model (Becker, 1964; Ben Porath, 1967; McDowell, 1982; Levin and Stephan, 1991; Stephan and Levin, 1993; and Oster and Hamermesh, 1998). In this view, geniuses, like other researchers, invest in human capital at early ages and, in so doing, spend less time in active scientific production. Consequently skill is increasing sharply over time but is, initially, not directed toward output. Eventually, researchers transition toward active innovative careers, perhaps quite discontinuously. (One could think of people exclusively accumulating human capital through most of their education, then going through a period mixing further investment and active research after leaving fulltime coursework, especially during the Ph.D., before transitioning to a primary research orientation.) Both because human capital has accumulated during the training phase and because researchers may transition relatively quickly towards active production, productivity may naturally increase rapidly at the beginning off the career, and especially around the ages people transition from formal training to active research. In addition to active investments in human capital, researchers also surely benefit from learning-by-doing (Arrow, 1962), which provides another source of increase in output.

This mechanism appears broadly consistent with the steepness of the rise in output (see, e.g., Figure 1) and its timing during the life-cycle, so that training appears to provide a natural candidate explanation for the early life-cycle pattern, even among scientific geniuses, who form the sample. Underlying theories of creativity may provide deeper explanations along these lines. Longstanding conceptions of creativity define a cognitive process where new ideas are seen as novel combinations of existing material (Usher, 1954; Becker, 1982; Weitzman, 1998). Although training is multi-faceted, this view can be used to connect creativity to existing ideas by thinking of training as the act of acquiring existing ideas (facts, theories, tools, methods) upon which the individual genius makes novel and effective combinations. Thomas Edison's light bulb, which he called the "electric candle", is a classic example, where Edison combined an old technology, the candle, with a new technology, electricity, to make a signature technological advance. Another example is Kary Mullis's polymerase chain reaction – a Nobel Prize winning breakthrough at the heart of all modern genomics and biotechnology. Mullis's creative insight drew together knowledge of the structure of DNA with knowledge of a newly discovered "extremophile" bacterium called *thermus aquaticus*, allowing him to develop the technology of DNA replication. If creativity is seen as new combinations of extant knowledge, and extant knowledge is acquired through training (whether formal training or experience), then the relative dearth of great early-life cycle scientific contributions may naturally mirror the initial training phase. Psychologists have emphasized that a minimum of ten years is required to master training in many fields (Ericsson and Lehmann, 1996). Indeed, while Nobel Prize winning contributions before age 26 are extremely rare, they are non-existent before the age of 19.[3]

Other, albeit related, theories of the creative process can provide further inroads to understanding the early-life cycle patterns. One aspect is the rate at which ideas can be initially identified and elaborated (Simonton, 1997, 2009). Another aspect distinguishes different types of reasoning that favor young minds versus older researchers (Weinberg and Galenson, 2005). Thus, the link between creativity and extant knowledge may depend not just on the acquisition of extant knowledge via training, but may depend on the nature and difficulty of the cognitive processes involved in drawing together and extending sets of extant knowledge, including the research processes themselves. These issues will be further elaborated below.

Separate classes of mechanisms are institutional and sociological, rather than cognitive. Training itself, occurring initially through formal educational institutions, introduces institutional norms and standards around preparation that may have their own effects (Wray, 2009). Research funding can also play a role, with the early careers of researchers in fields with large equipment or personnel needs potentially less productive while they build up the necessary resources and reputations to direct their own research agendas. Sociological biases that favor established scholars, as gatekeepers of a field, may also obstruct younger scholars and possibly even geniuses in making early contributions. To the extent that the power structure of scientists privileges established scientists, or that eminence begets greater eminence as in Merton's Matthew Effect (Merton, 1968) the career process in science may further constrain the capacity for contributions among the very young. An interesting and related empirical observation is

[3] Even the creativity of youthful genius can be seen to rely on extant knowledge. For example, Heisenberg's matrix mechanics (age 22) and uncertainty principle (age 25) were a matter of combining extant mathematical tools with recently generated empirical puzzles, both of which he by necessity learned prior to creating his solution.

Zuckerman's (1977) finding that Nobel laureates whose work was done under another laureate were younger than those working outside that circle.

The Middle and Late Life-Cycle

The second major observation about age, as a starting point, is that the frequency of great scientific breakthroughs tends to wane in middle age and continues to decline thereafter. In contrast to the rapid rise in productivity in the early life cycle, this decline appears to occur slowly. The decline might be explained on various grounds, including institutional factors, health, and shifting investment-work-leisure choices as the life-cycle advances. These mechanisms are typically explanations for why scientists may spend less time on research as they age. They may also suggest lower creative capacity.

Standard human capital theories in economics may provide an explanation for a decline in important contributions towards the end the career. In this approach, both active investments in human capital and learning-by-doing drive increasing productivity, while depreciation, including the obsolescence of skill (e.g. as frontier questions and methods shift) drive declines in productivity. As the end of the career approaches, the incentive to invest in new human capital declines, leaving the forces of depreciation and obsolescence to reduce output. While this approach can generate a decline in productivity near the end of the career, it seems inconsistent, or at least incomplete, as an explanation for the much earlier declines seen in the data, with peaking frequently as early as the 30s and 40s.

A range of less-formal "institutional" or "career" explanations have less to do with the life-cycle of creativity *per se* and more to do with the realities of research lives, which may help explain peaks in early middle age. For example, family responsibilities may play an important role in shaping life-cycle creativity for geniuses and others alike and especially for women, an issue that is taking on increasing importance as more women enter the scientific enterprise. Administrative demands tend to increase as the career progresses. Thus, the genius may remain, yet the time available for research may decline. Institutional roles, from running laboratories, applying for grants, reviewing tenure cases, editing journals, et cetera, may reduce the frequency of contributions. Geniuses may especially face increasing institutional demands as leaders of their fields or, more broadly, as public intellectuals expected to weigh in on science issues.

In later life, the decline in output may also increasingly reflect preferences toward retirement or declines in health. Consistent with standard life-cycle theories in other settings, choices may shift more or less toward leisure at the end of life.[4] Meanwhile, health effects may increasingly limit productivity. Health challenges may be directly cognitive in nature or reflect broader physical health declines, especially in the late life cycle. Direct cognitive decline may reflect reduced processing capacity and/or memory associated with aging (Deary et al. 2009); laboratory experiments suggest that creative thinking in general populations becomes more difficult with age (e.g. Reese et al., 2001). General physical health declines may limit effort generally, reducing the time spent on work tasks (Currie and Madrian, 1999).

Cross-Field Comparisons

An over-arching theme of the classic literature reviewed in Table 1 is a tendency to further examine and posit explanations for cross-field differences in peak creativity (Adams, 1946; Lehman, 1953; Zuckerman, 1977; Simonton, 1991; Stephan and Levin, 1993). Positive theories for cross-field difference have traditionally taken a cognitive character. Adams (1946)

[4] Some researchers note that individual scientists can present a "second peak" just prior to retirement, which has been interpreted as a rush to get final remaining ideas and unpublished research out into the world (Pelz and Andrews, 1966; Bayer and Dutton, 1977; Blackburn et. al, 1978).

finds that peak age varies between 37 and 47, depending on the scientific discipline, and argues that disciplines that emphasize mathematical/deductive reasoning tend to display younger peak ages of great achievement. Simonton (1997, 2009) presents a model focusing on the rate at which ideas can be identified and elaborated, which varies across fields, so that fields where ideas can be identified and elaborated earlier show a tendency for research to make contributions at earlier ages.

A challenge for theories focusing on static differences across fields is that these static differences appear to be both less robust and to mask considerable systematic variations in light of new analyses. While peaks in middle age are a broadly robust phenomenon, the ordering of fields in terms of the prevalence of young peaks is not, rejecting a "static" cross-field view as the basis for understanding the link between age and scientific genius. Moreover, field-level averages mask large and instructive variation across individuals. Greater empirical purchase can be found by emphasizing variations within fields in the data.

III. The New Literature: Variation over Time and Across Individuals

Having reviewed broad classes of hypotheses surrounding training, creativity, and institutions in light of the broad tendency for great contributions to come in middle age, we now turn to other variation in the age-genius relationship. This variation presents a series of additional first-order facts that inform richer theories of the relationship between age and scientific genius while providing a range of important applications to understanding creativity, the progress of science, and other issues.

Variation over Time

Inklings of a more dynamic view of the relationship between age and great contributions appear in some of the classic literature, but without consistent evidence or clear hypotheses. Raskin (1936) finds no evidence of changes within the age and great achievement patterns for scientists during the 19th century. Adams (1946) comments that peak ages were broadly steady through the 17th through 19th centuries but may have risen early in the 20th century. Roe (1972) studies 53 scientists and finds, by contrast, that those active in the 20th century appeared to be productive earlier than those active in the 19th century. Looking at the year in which Americans received Nobel prizes Zuckerman (1977) finds a rise in age, with a U-shape for physics. Although these results are not entirely consistent, and the last only indirectly informs the age-genius relationship due to lags in the award process, these studies and those summarized in Table 2 suggest that there may be value in thinking systematically about how the age-creativity relationship varies over time.

Jones (2003, 2010) focuses on age dynamics over the 20th Century for all Nobel Prize winning research (544 individuals) and for great technological inventions as listed in scientific and technological almanacs (286 individuals). He uncovers a large shift in the mean age of great achievement, which rises 6 years over the course of the 20th century in both samples (Figure 2). Looking within fields, and controlling for country of birth, the increase in mean age is larger in both samples, rising by 8 years over the century.

A methodological contribution of this study is to address a broad demographic issue when sampling signature achievements from a population of scientists, as is the usual practice. This approach, as in the classic literature, means that the ages witnessed will depend not just on the life-cycle productivity of the individual scientists, but also on the age distribution of the underling population. For example, if scientists tend to be old, then more great achievements will tend to come from older people. This issue can be important to confront when estimating peak achievement, and especially so when looking at dynamics, because people live longer over time and populations have correspondingly gotten older on average over time.[5] When controlling for population dynamics, Jones (2010) uncovers a more precise shift in the underlying life-cycle productivity of great achievement. In particular, recall from Figure 2 that the age distribution at great achievement has become systematically older over time, with fewer contributions at young ages and more at older ages. However, the increasing rate of later life-cycle achievements shown in Figure 2appears to be a demographic effect, driven by an aging population, as opposed to reflecting increased productivity at later ages. By contrast, the decline in the frequency of great achievements among younger scientists, as shown in Figure 2, is not demographic, but reflects an especially sharp decline in early life-cycle productivity.

This empirical finding calls for further reasoning about the mechanisms at work in the early life cycle. Jones (2009, 2010, 2011) develops a "burden of knowledge" theory to explain these and other facts, linking the creative process to requisite training and the observation that the quantity of precursor scientific and technological knowledge has expanded substantially with time. As one measure of knowledge, consider that John Harvard earned the naming rights to Harvard University in 1639 largely due to his bequest of his private library, which amounted to 320 volumes. By contrast, the U.S. Library of Congress today houses 35 million books, and the Web of Science indexed 2.18 million new journal articles published in 2012 alone. To the extent that expertise over some range of existing knowledge is an essential input to the creative

[5] Populations also become younger over periods of time in the 20th century; namely, following baby booms.

process in science, the expansion of extant theories, facts, methods, et cetera, can create a rising "burden of knowledge" on successive generations of scientists who, correspondingly, may both extend their training phase and become more narrowly specialized along the knowledge frontier (Jones, 2009).

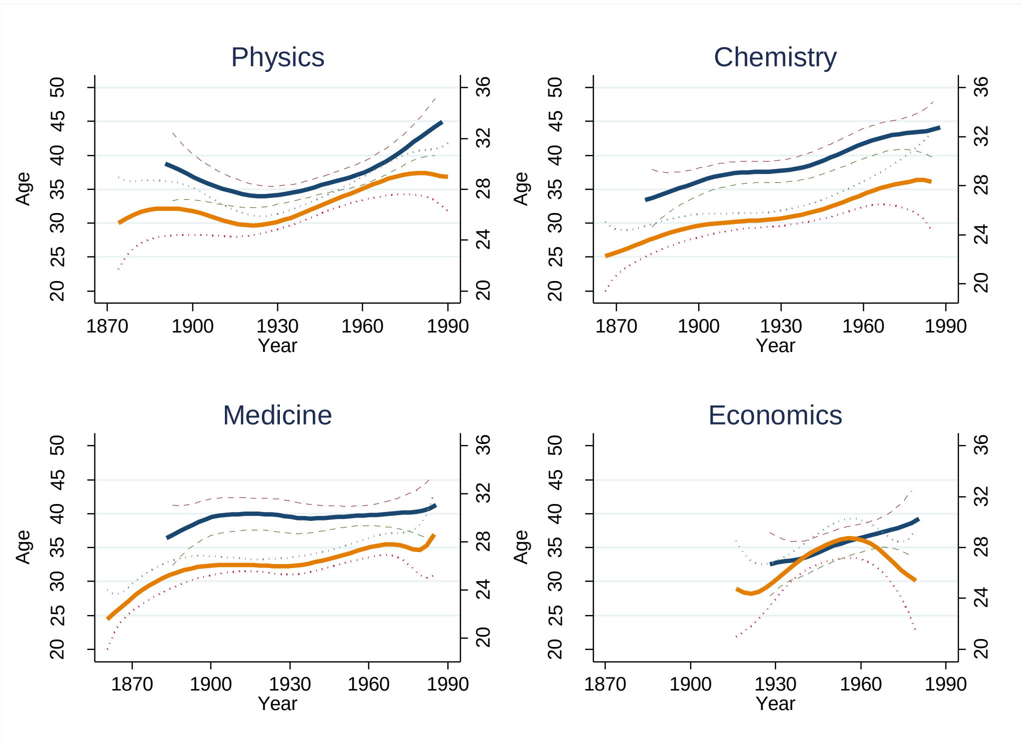

Figure 3: Mean Age at Ph.D. and Nobel Prize Winning Achievement, by Field (Source: Jones 2010).

This theory can be further explored using data directly on the educational attainment of geniuses. There is substantial evidence for rising educational duration among scientists and engineers in general (NRC, 1990, Tilghman et al., 1998), and Jones (2010) establishes an increase in the age at Ph.D. among Nobel Prize winners. This study further shows that variation in the age at Ph.D. can explain variation in the age at great achievement across fields and over time. Figure 3 provides one view of these relationships. Stepping away from the time dynamics per se, information directly on the educational attainment of geniuses can help assess the role of training more generally and suggests that time devoted to training is an important aspect in understanding why contributions early in the life-cycle are rare.

The 20th century aging phenomenon, associated with training dynamics, can be informed by a "burden of knowledge" mechanism rooted in the accumulation of scientific and technological knowledge. This accumulation has become especially rapid in the modern era, triggered in the Enlightenment and accelerating through the Industrial Revolution and beyond. Interestingly, however, the Enlightenment initially may have influenced the relationship between age and scientific genius through other mechanisms. In particular, the Enlightenment was initially associated less with a jump in knowledge than with a slow cultural, political, and institutional shift that defined "science" in modern terms, complete with the scientific method and the professionalization of science institutions. This professionalization of science may in turn have reshaped the life-cycle of scientific careers.

Wray (2009) explores age dynamics between 1600 and 1899 and interprets dynamics in this period through this lens. Noting that scholars in earlier periods worked in institutional contexts where direct routes into science were scarce – Lavoisier first trained in law, Copernicus helped manage a cathedral, and Galileo engaged in a set of secondary careers for financial support – the rise of science as a recognized profession, increasingly integrated into universities, may have allowed faster routes into the field. Studying 136 great scientists drawn from B. Dibner's Heralds of Science collection, Wray finds a statistically significant decline in age over the 1600-1899 period, from a median age of 47 in the 1600s to a median age of 38 in the 1800s, and argues that this pattern is consistent with the institutional hypothesis, where barriers to entry for the young are reduced over time.[6]

Variation across Individuals

Although genius clearly peaks in the mid-career, Figure 1 is striking for the variations around the peak. Indeed, exceptionally early work does occur and is often viewed as a hallmark of genius itself. While the classic literature has marveled over these dramatic early contributions and also commented on contributions made much later in lives, it does not provide a clear set of theories to inform the dramatic variations in the age at which innovators make important contributions within fields. More recent work has shown that age variation across individuals in the same field have systematic features (Table 3).

In the classic literature, fields have been viewed as the unit of analysis, but truly understanding variations in creativity across scientists in the same field working at a given point in time requires that we shift from fields as the unit of analysis to the innovators themselves. Work by Galenson (2001) and Galenson and Weinberg (2000, 2001) and Weinberg and Galenson (2005), initially focusing on the arts, provides a reconceptualization that has proven useful across a wide range of innovative domains. This work posits that there are two polar extremes in creativity – "conceptual" innovators who work deductively and whose work is abstract, on the one hand, and "experimental" innovators, who work inductively and whose work is concrete on the other. Deductive work derives from a priori logic and tends to be more theoretical, while inductive work derives from accumulation of knowledge and tends to be more empirical.

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[6] By contrast, Adams (1946) and others do not find a time dynamic between the 17th and 19th centuries.

This conceptual-experimental distinction has important implications for the timing of great innovations. Specifically, experimental work builds on accumulated knowledge, so it is natural that great experimental innovators would tend to do their most important work toward the end of their careers.

There are a number of reasons why great conceptual work is more likely to be done at the outset of the career. First, because conceptual innovators do not need to accumulate large amounts of experience in order to make their contributions, conceptual innovators can produce great contributions early in their careers. Second, the most important conceptual work typically involve radical departures from existing paradigms, and the ability to identify and appreciate these radical departures may be greatest shortly after initial exposure to a paradigm, before it has been fully assimilated and before the individual has produced a large body of work that either rests upon or contributes to that paradigm.

The idea that younger researchers are more willing and/or able to make radical departures from convention is widely held. Perhaps most vividly, Max Planck wrote in his *Scientific Autobiography*, "A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it." Sigmund Freud echoes this point in his *Civilization and its Discontents* saying, "the conceptions I have summarized here I first put forward only tentatively, but in the course of time they have won such a hold over me that I can no longer think in any other way."[7] Dietrich and Srinivasan (2007) provide interesting cognitive evidence along these lines; however, evidence for Planck's Principle is more generally mixed. Weinberg (2007) finds

[7] In addition to these cognitive arguments, there are also obvious institutional reasons why an older researcher whose previous work may have contributed to or rely upon a paradigm may be reluctant to its overthrow.

that the researchers who made important contributions to the development of the human capital paradigm in labor economics were more likely to have been exposed to it as graduate students, but that their contributions are not necessarily at young ages. A small literature also studies the related question of how age predicts the *adoption* of revolutionary scientific ideas. The few studies looking at this topic tend to find mixed evidence, which also may call into question Planck's Principle. Hull, Tessner, and Diamond (1978) found older scientists as fast to accept Darwin's evolutionary theory as younger scientists. Messeri (1988) in studying the adoption of plate tectonics found that first adopters were primarily older scientists. Diamond (1980) found a minor role of age in explaining the adoption of cliometrics in economics.

While the evidence on Planck's Principle is mixed, there does to appear to be a more basic and robust tendency for conceptual innovators to make their most important contributions quite early in their careers. To examine how the nature of work is related to the age of contributions, one can classify researchers based on whether their work is empirical or theoretical. This split is quite crude because conceptual innovators can do empirical work (empirical work by conceptual innovators frequently takes the form of highly-structured tests of theories) and experimental innovators can make important theoretical innovations (typically deriving from empirical work they or others have done), but can still provide some information. Figure 4A presents separate profiles for Nobel laureates whose Prize-winning work was theoretical compared to those whose Prize-winning work was empirical. The differences are considerable, with the empirical researchers doing their Prize-winning work 4.6 years later (at 39.9 years of age compared to 35.3 years). Theoretical work is more common in physics than in chemistry or in, in turn, medicine / physiology and these differences may account for some of the differences between the fields. To address this issue, Figure 4 panels B, C, and D report estimates for each of the fields. The gaps for chemistry and physics are quite large, but few medical / physiological scientists receive the Prize for theoretical work. Thus, we find substantial differences between theorists and empiricists within the same field.[8]

Weinberg and Galenson (2005) identify conceptual and experimental innovators in economics using a richer, continuous index. Economics is an attractive discipline for this sort of analysis because publications vary widely, from conceptual work involving formal statements of theorems and their proof to experimental work involving detailed analysis of industries, markets, or countries. Nobel laureate economists were classified on a continuous scale based on the presence and frequency of these (and other) elements in the text of their primary publication(s). This analysis showed that the most conceptual laureate did his most important work at 32.5 years of age compared to 53.2 for the most experimental, a difference of 20.7 years. Thus, rich classifications can generate very large differences in the age at which people make important scientific breakthroughs.

This line of work has a number of other implications, which are consistent with empirical observation. "One hit wonders" who make dramatic contributions at the outset of their careers, not reaching that level ever again are typically conceptual (Galenson, 2005). Because the most conceptual innovators do their most important work shortly after being exposed to a paradigm, they have an incentive to shift their focus across lines of work (Weinberg and Galenson, 2005). Moreover, within each line of work, their early works will tend to be more important than later works. On the other hand, experimental innovators should tend to work on related questions for

[8] Jones and Weinberg (2011) further show that these differences are robust to controls for the time that the work was done.

the extended periods of time necessary to accumulate the knowledge necessary to do important work.

While this approach places individual innovators at the forefront, it can also help inform differences in the central tendencies across fields. The earlier peaks in the average age at which work is done in abstract fields such as mathematics of physics are consistent with these fields favoring conceptual innovators, who tend to do their best work at earlier ages compared to more concrete fields such as medicine or history, which tend to favor late-peaking experimental innovators. At the same time, looking at 23 creative writers, Simonton [2007] shows that domains are an important independent determinant of age at best work even controlling for whether a writer was conceptual or experimental. This approach based on individual patterns of creativity can also illuminate the field-level dynamics discussed above. Thus, the development of a new scientific paradigm is largely theoretical while building the body of empirical work to refine and test a paradigm is more experimental. So, as knowledge accumulates in the wake of a paradigm shift, we expect ages to increase. Thus, there are reasons to believe the emphasis placed on the different types of work will vary over time and do so both systematically and in a way that is distinct from yet highly complementary to that implied by knowledge accumulation.

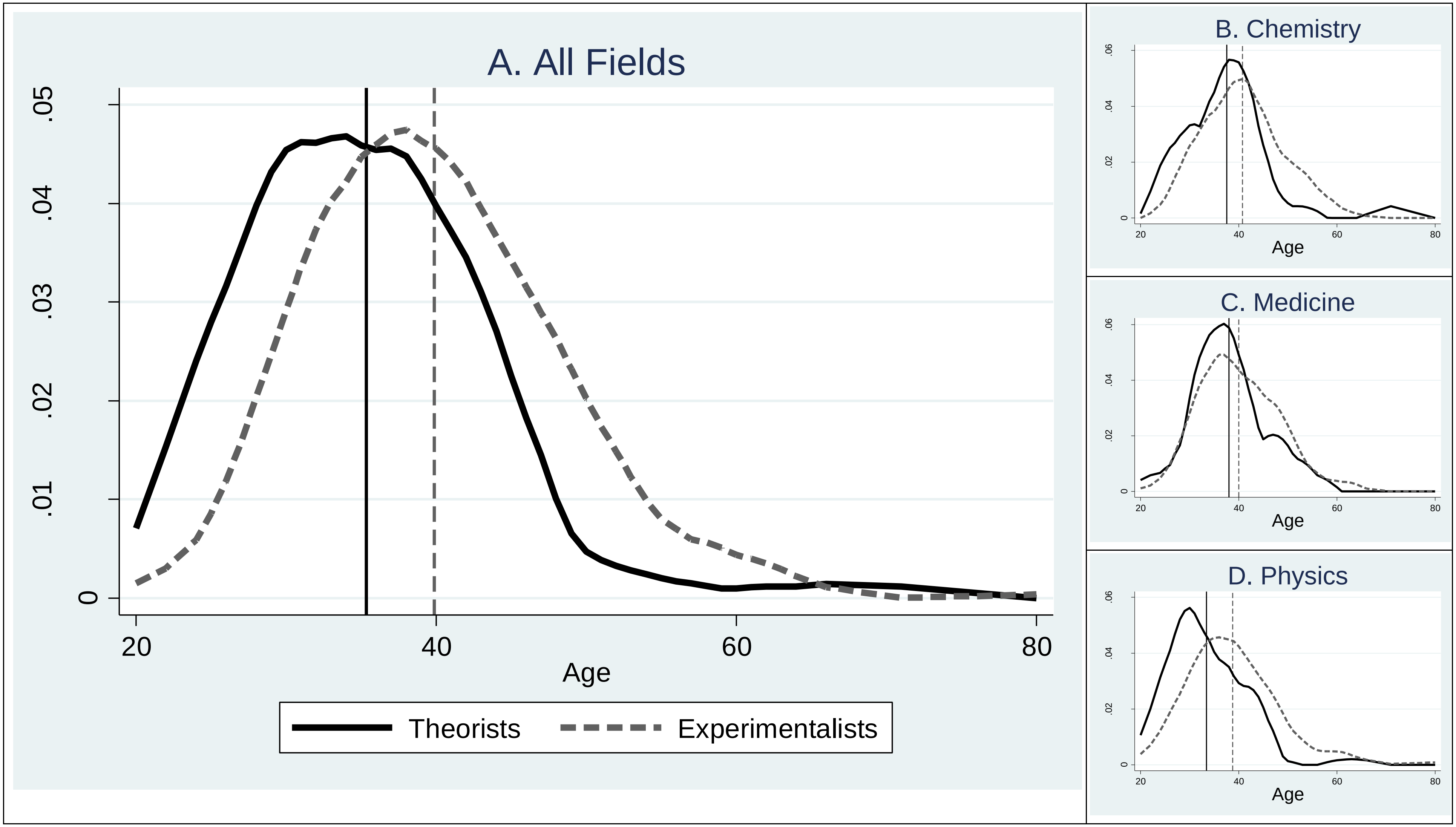


Figure 4. Differences in Lifecycle Creativity between Theorists and Experimentalists among Nobel Laureates

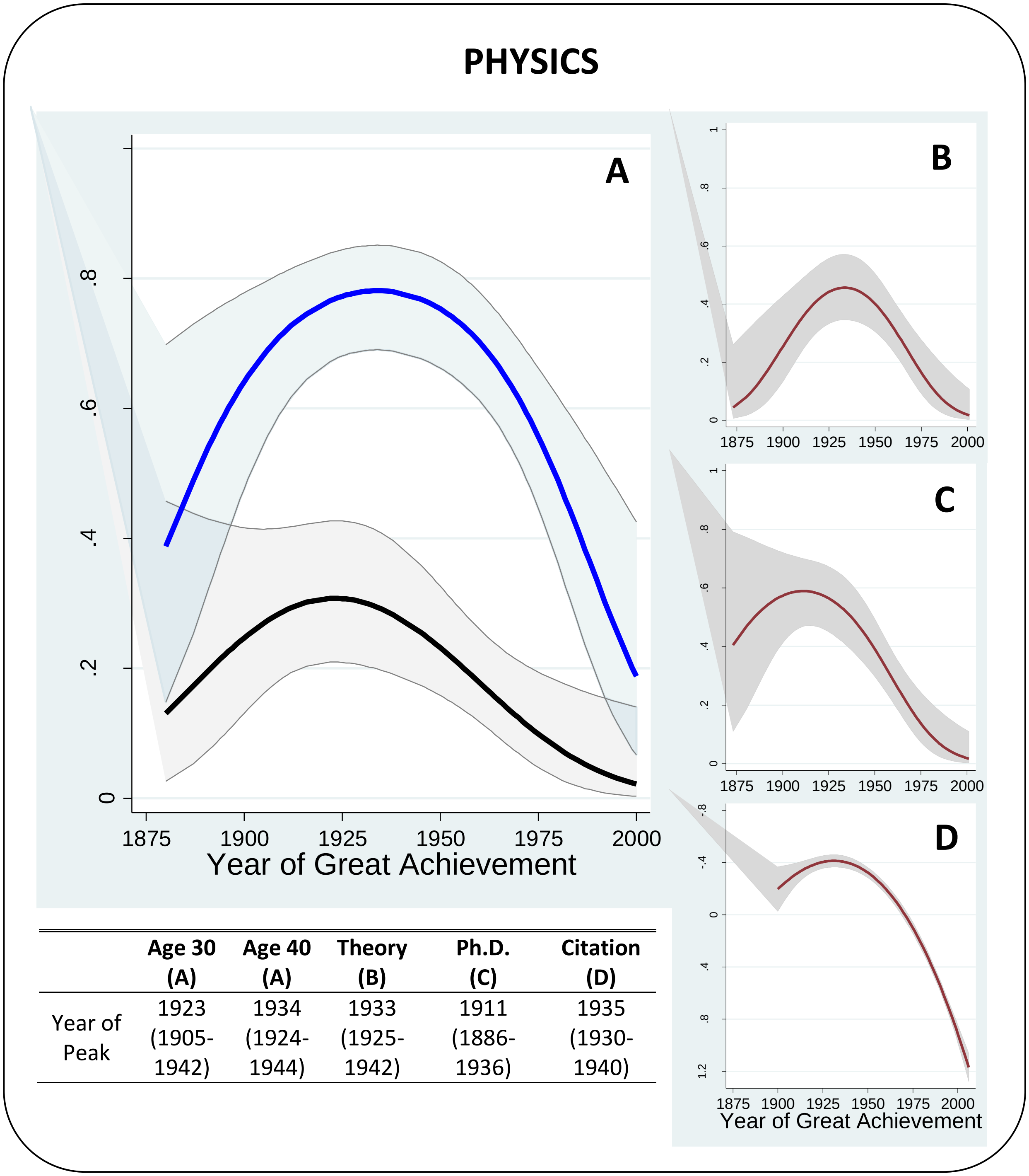
(Source: Authors' Calculations).

Field Differences, Reconsidered

Given that the relationship between age and great contributions varies substantially over time and across individuals, it is worth reconsidering whether there truly are persistently "younger" versus "older" fields, and whether field differences can be more closely mapped into underlying theories of age and creativity.

Jones and Weinberg (2011) re-examine the age-achievement relationship across fields, looking again at all Nobel Prize winning contributions. This study finds that variation in the mean age of great achievement is five times greater over time than across fields. Moreover, the dynamics within fields are so large that the "classic" ordering -- where physics laureates appear younger at the time of their breakthrough than laureates in chemistry or medicine – is unstable. Since 1985, physics laureates are actually the oldest in making contributions compared to the other fields.

Jones and Weinberg (2011) focus particularly on 20th century physics. Due to the development of quantum physics, the centerpiece of Kuhn's well-known work on revolutions, 20th century physics provides a useful laboratory for studying how innovation varies over the life-cycle. Starting with Planck's introduction of quanta in 1900, physics experienced a period where a small number of existing empirical puzzles appeared to both reject classical physics yet remain beyond any satisfying alternative theory, a tension not resolved until the formulation of consistent theoretical foundations in 1925-1927. The theories presented in Section III provide distinct but complementary lenses through which to view how a scientific revolution will affect the age-creativity relationship.



	Age 30 (A)	Age 40 (A)	Theory (B)	Ph.D. (C)	Citation (D)
Year of Peak	1923 (1905-1942)	1934 (1924-1944)	1933 (1925-1942)	1911 (1886-1936)	1935 (1930-1940)

Figure 5. Age Dynamics in Physics and Underlying Correlates
(Source: Jones and Weinberg 2011)

First, the quantum mechanics revolution rendered large portions of physics less relevant. From the perspective of “burden of knowledge” theory, this shock allowed earlier-career contributions during the revolutionary period, after which knowledge accumulated within the new paradigm and the burden of knowledge rose again (Jones, 2003, 2009, 2010). Second, Kuhn also posits a novel interplay between empirical and theoretical work during revolutions. Specifically, he sees revolutions being precipitated by a mounting body of empirical anomalies that are not explicable in the prevailing paradigm. In Kuhn’s formulation, a revolution takes place only when the theoretical work that can accommodates the accumulated anomalies is done. The revolution is then followed by empirical work elaborating the new framework. Thus, over the course of a revolution, focus shifts from relatively experimental empirical work to relatively conceptual theory and ultimately back to relatively experimental empirical work, which would imply an increase and then a decrease in the share of young contributions. Lastly, Planck’s principle would indicate that people making contributions to the revolution should be relatively young, so the share of early-career contributions should have increased and then decreased.

The case of Werner Heisenberg illustrates the interplay of these factors. His contributions of matrix mechanics and the uncertainty principle, both coming by age 25, were conceptual in nature and, further, did not build from long training in classical physics. Indeed, Heisenberg famously almost failed his Ph.D. exams because he had little knowledge of classical electromagnetism (Cassidy, 1992).

As shown in Figure 5 Panel A, Jones and Weinberg (2011) show the expected initial increase in early-career contributions and subsequent decline looking at Nobel Laureates in physics over the course of the revolution. The study further relates these dynamics within fields to measures of the “burden of knowledge” and the prevalence of conceptual versus experimental work. As suggested in Figure 5, empirical proxies for these drivers are closely coincident with changes in achievement age. Namely, there are strong relationships between achievement age dynamics within fields and field-specific dynamics in (1) whether contributions are theoretical or empirical in nature (Fig. 5B), (2) Ph.D. age (Fig. 5C), and (3) backward citation age (Fig. 5D). The first measure operationalizes the distinction between conceptual and experimental work in creative-cognitive theory, and the latter two measures can proxy for training requirements and the stock of prior knowledge, as emphasized by burden of knowledge theory.

IV. Discussion

The relationship between age and scientific genius can also inform underlying mechanisms of creativity and scientific progress, which in turn raise a number of policy-relevant issues. These issues include the design of institutions that support scientists, the implications of aging populations, and the link between models of scientific discovery and economic growth. This section considers such implications in light of the facts and theories discussed above, and closes by considering important new avenues for research.

Scientific and Technological Progress

Consider scientific progress, taking Kuhn's classic description of scientific progress that emphasizes periods of normal science, featuring the accumulation and refinement of ideas, punctuated by occasional paradigm-shifting revolutions (Kuhn 1962). Interestingly, the facts and theories about age and creativity have several implications for these perspectives on scientific progress.

First, the burden of knowledge theory appears broadly consistent with a conception of normal science, where scientific and technical knowledge expands and deepens, raising the educational burden on successive generations of scientists. Empirically, the broad tendency toward extending training phases and the commensurate decline in early life-cycle output over the 20th Century may indicate that science is mostly "normal" in the Kuhnian sense. From the perspective of Kuhn, however, perhaps more interesting is the behavior of age and creativity during the quantum mechanics revolution (Jones and Weinberg, 2011). The marked decline in age at achievement and age at Ph.D. during this revolutionary period are consistent with a "reset" to the fundamental knowledge of the field, allowing easier access to the frontier by young people. Using the age at great scientific contribution (and high degree) to quantify the burden of knowledge, a reduction in relevant, extant knowledge appears to be hallmark of revolutions. In this sense, the age at great contribution may support a Kuhnian description of science and provide a valuable marker for identifying revolutions. But, as indicated, field-level revolutions appear rare based on these metrics.

A second application of age and creativity analysis bears on the overall *rate* of scientific and technological progress. Given the increasingly delayed start to the active innovative career, spending more time in training and less time being creative over the life cycle will limit the expected contributions of the individual, other things equal. There is, in effect, less time for the genius to act like one. This tendency thus suggests a truncation in innovative capacity.[9] Other things equal, the contributions of a given set of scientists would decline.

More subtly, the link between age and creativity may also affect the *direction* of scientific progress. Linking the conceptual versus experimental analysis of the age-achievement relationship with the burden of knowledge theory may have implications for the nature of great

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[9] This early life-cycle truncation also generalizes beyond geniuses, extending to more ordinary innovators (Jones 2009).

achievements. In particular, if early life-cycle innovative capacity is increasingly truncated by training demands, then it is possible that the nature of achievements would shift from conceptual toward experimental reasoning. Thus contributions may become increasingly biased against deep, conceptual novelty. To the extent that youth, conceptual achievement, and revolutions are linked (see Section III), then the probability of revolutions may also be increasingly limited.

Demographics

Related issues involve demographics. The aging of populations in many countries, especially in countries that are traditional drivers of scientific advance, may also shift the mass of scientific effort increasingly away from conceptual contributions. This can happen naturally through the cognitive-creative mechanism of Weinberg and Galenson (2005) and also through sociological and political mechanisms that reinforce the interests of expanding numbers of older individuals at the expense of younger scientists. Thus, a similar shift in the direction of scientific progress, and the contributions of geniuses, may come from demographic change.

Significant effects may appear in the rate of scientific advance. Taking the tendency for great achievements to decline after middle age (Figure 1), a shift toward an older population may mean, most simply, fewer great contributions. Indeed, one of the salient features of Nobel Prize winners and great technological innovators over the 20th century is that, while contributions at young ages have become increasingly rare, the rate of decline in innovation potential later in life has remained steep, offering no apparent compensation for the early life-cycle effect (Figure 1).

Such demographic trends, like the truncation in the early life-cycle, auger a decline in innovative output. That said, the number of minds engaged in scientific and technological advance continues to increase. Population increases globally, and the economic development of many countries, such as China or India, bring increasing numbers of people into the collective scientific enterprise (Jones and Romer, 2010). On net, therefore, more minds may compensate for underlying challenges and actually serve to increase the rate of scientific and technological progress in the century ahead.

Lastly, a related aspect concerns centers of scientific advance around the world. Other things equal, countries with population distributions that center on middle age naturally become richer sources of active geniuses driving forward science and technology.[10] Of course, the phrase “other things equal” incorporates many things, including educational systems, population size, economic investments, political freedom, and the broader institutional support that provides the appropriate foundations for genius to appear and shine.

Science Institutions

A wide range of institutions interface with the age-creativity relationship. Given the extending training phase and delay to the start of innovative careers, one natural area of focus is education. One policy might simply encourage apparent geniuses to leave formal education behind.[11] This idea might seem well motivated if educational institutions were seen as inefficient, at least for geniuses. On the other hand, such a policy works against the mass of data showing that great innovations are rare at very young ages (even in antiquity and in environments where formal schooling was less developed), and it does not solve the underlying burden of knowledge problem, where creativity relies on combinations of extant knowledge that is increasingly profound. In this view, the appropriate response is not less education, but more

[10] See Hongzhou and Guohua (1985) for a historical analysis of national scientific leadership built on these lines.
[11] For example, the Thiel Fellows program, where promising undergraduates are given $100,000 to leave college and undertake active creative projects, rather than study, works on this margin.

efficient education – more knowledge acquisition per unit of training time -- throughout the early life cycle (Jones, 2011).

Moving beyond the full-time training phase, additional institutions come into play. If researchers spend more time reaching the research frontier even after completing their training, short tenure clocks may be less desirable. Short tenure clocks would also seem to favor fields where research can be performed more quickly and researchers whose work is more conceptual and abstract. In these ways, institutions may shape the research that is done and the researchers performing it. There has been some movement away from habilitation requirements and the chair system in the countries where they have existed. We suspect that this movement away from these institutions will allow greater creative freedom earlier in the career but note that people whose work is more experimental and those working in areas with greater knowledge burdens may derive less benefit from elimination of these institutions. Even in the US, where these institutions are not present, postdoctoral training periods are long in many fields. While we caution against attributing long postdocs exclusively to the increased knowledge burden and extended training requirements (for instance, post-doctorates may reflect the rise of big science and hierarchical research teams in some fields), slow early careers and long postdocs may not only limit early life-cycle autonomy and creativity, they may discourage potential students from entering the sciences in the first place (Jones, 2011).

New research directions

There are many open avenues in studying age and scientific genius. The shift from studies of the scientific enterprise as a whole or of entire fields to studies of individual researchers and the factors that govern their productivity marks a substantial break in approach that presents many new opportunities. Considerably more work is required to measure knowledge stocks, to identify revolutions, and to quantify the nature of individuals' research. Rapid improvements in information and computing tools may advance our understanding of the age-genius relationship and its implications. For instance, natural language processing algorithms can help quantify features of scientific publications (e.g. the vintage, novelty, and/or combinations of ideas in an article) to assess the nature of research contributions and how they vary over the life-cycle. Indeed, "big data" has great potential to greatly improve our understanding of many aspects of the careers of scientists.

More fundamentally, when one begins to think about creativity and genius as dynamic, individual processes rather than static aggregate processes, a wide range of additional topics emerge, including the implications of major life events. For instance, we know frustratingly little about how gender mediates the age-creativity relationship, nor how lifecycle events such as childbirth affect the age-creativity relationship for women or men. Nor do we understand the implications of formal retirement. A related, broader set of questions surround the socioeconomic and institutional contexts in which genius is most likely to emerge. For example, since 1965, two-thirds of all Nobel Prize winning research has been performed in the United States, yet only 5% of the world's population resides in the United States, which points strongly to context in understanding when and where genius is likely to express itself.

The decline of innovation potential in the later life-cycle remains an open question with many possible explanations (Section II) but currently no clear adjudication between them. Given the ever-growing population of older researchers, it is increasingly important to understand creativity and genius at the end of the research career.

V. Conclusion

Exploring the links between age and scientific genius is a subject of enduring fascination to scholars and the public alike. Formal studies are often surprising, both in their findings and in their broader implications. In contrast to common perceptions, most great scientific contributions are not the product of precocious youngsters but rather come disproportionately in middle age. Moreover, perceptions that some fields, such as physics, feature systematically younger contributions than others do not stand up to empirical scrutiny.

Age and scientific genius are empirically characterized by great variation across individuals and over time. This variation, increasingly emphasized in more recent scholarship, can be related to specific underlying theories of creativity and the progress of knowledge, including both the 'burden of knowledge' theory of Jones (2009) and the conceptual-experimental theory of Weinberg and Galenson (2005). Tests of additional theories, and increasingly detailed investigations of specific theories, await further scholarship. As discussed above, opportunities for new analyses abound.

The implications of these studies can step well beyond intrinsic interest in genius per se. The intersection of age and great achievements sheds light on a rich landscape, where creativity, knowledge, scientific progress, economic growth, demographics, and science institutions all intersect. As studies continue to reveal the forces at work in the age-creativity relationship, this broader landscape will continue to come into sharper focus.

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References

Adams, C. W. (1946). The age at which scientists do their best work. *Isis*, 166-169.

Arrow, K. J. (1962). The economic implications of learning by doing. *The Review of Economic Studies*, *29*(3), 155-173.

Bayer, A. E., & Dutton, J. E. (1977). Career age and research-professional activities of academic scientists: Tests of alternative nonlinear models and some implications for higher education faculty policies. *The Journal of Higher Education*, 48(3), 259-282.

Beard, G. M. (1874, 1979). Legal responsibility in old age: based on researches into the relation of age to work*;* reprinted in *The "Fixed Period" Controversy: Prelude to Ageism*, Gerald J. Gruman, Ed. New York: Arno Press.

Becker, G. S. (1964). *Human capital: a theoretical analysis with special reference to education.* National Bureau for Economic Research, Columbia University Press, New York and London.

Becker, H.S. (1982). *Art Worlds*. Univ. of California Press, California.

Ben-Porath, Y. (1967). The production of human capital and the life cycle of earnings. *The Journal of Political Economy*, *75*(4), 352-365.

Blackburn, R. T., Behymer, C. E., & Hall, D. E. (1978). Research note: Correlates of faculty publications. *Sociology of Education*, 51(2): 132-141.

Cassidy, D. C. (1992). *Uncertainty: The Life and Times of Werner Heisenberg*. Freeman, New York.

Currie, J., & Madrian, B. C. (1999). Health, health insurance and the labor market. *Handbook of Labor Economics*, *3*, 3309-3416.

Dennis, W. (1956). Age and productivity among scientists. *Science, 123*(1956): 724-725.

Diamond Jr, A. M. (1980). Age and the Acceptance of Cliometrics. *Journal of Economic History*, *40*(4), 838-841.

Diamond, A. M. (1986). The life-cycle research productivity of mathematicians and scientists. *Journal of Gerontology*, *41*(4), 520-525.

Dietrich, A., & Srinivasan, N. (2007). The optimal age to start a revolution. *The Journal of Creative Behavior, 41*(1), 54-74.

Deary, I. J., Corley, J., Gow, A. J., Harris, S. E., Houlihan, L. M., Marioni, R. E., ... & Starr, J. M. (2009). Age-associated cognitive decline. *British medical bulletin*, *92*(1), 135-152.

Ericsson, Karl A., and Andreas C. Lehmann (1996). Expert and Exceptional Performance: Evidence of Maximal Adaptation to Task Constraints. Annual Review of Psychology 47, 273–305.

Feist, G. J. (2006). The development of scientific talent in Westinghouse finalists and members of the National Academy of Sciences. *Journal of Adult Development*, *13*(1), 23-35.

Freud, S. 1929. *Civilization and its Discontents*. London: Hogarth Press.

Galenson, D. W. (2001). *Painting outside the Lines*. Cambridge: Harvard University Press.

Galenson, D. W., & Weinberg, B. A. (2000). Age and the quality of work: the case of modern American painters. *Journal of Political Economy*, *108*(4), 761-777.

Galenson, D. W., & Weinberg, B. A. (2001). Creating modern art: The changing careers of painters in France from impressionism to cubism. *The American Economic Review*, *91*(4), 1063-1071.

Galenson, D. W. (2005). One hit wonders: why some of the most important works of modern art are not by important artists. *Historical Methods*, 38(3), 101–117.

Hoisl, K. (2007). A closer look at inventive output-The role of age and career paths. *Munich School of Management Discussion Paper*, (2007-12).

Hongzhou, Z., & Guohua, J. (1985). Shifting of World's scientific center and scientists' social ages. *Scientometrics*, *8*(1), 59-80.

Hull, D. L., Tessner, P. D., & Diamond, A. M. (1978). Planck's principle. *Science*, *202*(717), 295.

Jones, B. F. (2003). Essays on Innovation, Leadership, and Growth. Ph.D. Thesis, Massachusetts Institute of Technology.

Jones, B. F. (2009). The Burden of Knowledge and the Death of the Renaissance Man: Is Innovation Getting Harder? *The Review of Economic Studies*, 76(1), 283-317.

Jones, B. F. (2010). Age and great invention. *The Review of Economics and Statistics*, *92*(1), 1-14.

Jones, B. F. (2011). As Science Evolves, How Can Science Policy? *Innovation Policy and the Economy*, *11*, 103-131.

Jones, B. F., & Weinberg, B. A. (2011). Age dynamics in scientific creativity. *Proceedings of the National Academy of Sciences*, *108*(47), 18910-18914.

Jones, C. I., & Romer, P. M. (2010). "The New Kaldor Facts: Ideas, Institutions, Population, and Human Capital." *American Economics Journal: Macroeconomics. 2*(1): 224-245.

Kanazawa, S. (2003). Why productivity fades with age: The crime–genius connection. *Journal of Research in Personality*, *37*(4), 257-272.

Kellner, D. (1940), *Redders der Meschheid, doktoren als Nobelprijswinnaars*, Amsterdam. (as referenced in Moulin 1955)

Kuhn, T. S. (1962). *The structure of scientific revolutions*. Chicago: University of Chicago Press.

Lehman, H. C. (1953). *Age and Achievement.* Princeton: Princeton University Press.

Lehman, H. C. (1966). The psychologist's most creative years. *The American Psychologist*, *21*(4), 363.

Levin, S. G., & Stephan, P. E. (1991). Research productivity over the life cycle: Evidence for academic scientists. *The American Economic Review, 81*(1), 114-132.

Lyons, J. (1968). Chronological age, professional age, and eminence in psychology. *The American Psychologist*, *23*(5), 371.

Matthews, K. R., Calhoun, K. M., Lo, N., & Ho, V. (2011). The aging of biomedical research in the United States. *PloS one*, *6*(12), e29738.

McDowell, J. M. (1982). Obsolescence of knowledge and career publication profiles: Some evidence of differences among fields in costs of interrupted careers. The American Economic Review, 72(4), 752-768.

Merton, R. K. (1968). The Matthew effect in science. *Science*, *159*(Jan. 5), 56-63.

Messeri, P. (1988). Age differences in the reception of new scientific theories: The case of plate tectonics theory. *Social Studies of Science*, *18*(1), 91-112.

Moulin, L. (1955). The Nobel Prizes for the Sciences from 1901-1950--An Essay in Sociological Analysis. *The British Journal of Sociology*, *6*(3), 246-263.

National Research Council (1990). *On Time to the Doctorate: A Study of the Lengthening Time to Completion for Doctorates in Science and Engineering*. Washington, DC: National Academy Press.

Oster, S. M., & Hamermesh, D. S. (1998). Aging and productivity among economists. *Review of Economics and Statistics*, *80*(1), 154-156.

Pelz, D., & Andrews, F. M. (1966). *Scientists in organizations Productive climates for research and development*. New York: Wiley.

Raskin, E. (1936). Comparison of scientific and literary ability: a biographical study of eminent scientists and men of letters of the nineteenth century. *The Journal of Abnormal and Social Psychology*, 31(1), 20-35.

Reese, H. W., Lee, L. J., Cohen, S. H., & Puckett Jr, J. M. (2001). Effects of intellectual variables, age, and gender on divergent thinking in adulthood. *International Journal of Behavioral Development*, *25*(6), 491-500.

Roe, A. (1972). Patterns in productivity of scientists. *Science*, *176*(4037), 940-941.

Simonton, D. K. (1988). *Scientific genius: A psychology of science*. Cambridge University Press.

Simonton, D. K. (1997). Creative Productivity: A Predictive and Explanatory Model of Career Trajectories and Landmarks. *Psychological Review 104*(1), 66-89.

Simonton, D. K. (1999). *Origins of Genius*. Oxford University Press. 308 pgs.

Simonton, D. K. (1991). Career landmarks in science: Individual differences and interdisciplinary contrasts. *Developmental Psychology*, *27*(1), 119-130.

Simonton, D. K. (2007). Creative Life Cycles in Literature; Poets versus Novelists or Conceptualists versus Experimentalists? *Psychology of Ethics, Creativity, and the Arts, 1*(3), 133-139.

Simonton, D. K. (2009). Varieties of (Scientific) Creativity A Hierarchical Model of Domain-Specific Disposition, Development, and Achievement. *Perspectives on Psychological Science, 4*(5), 441-452.

Stephan, P. E., & Levin, S. G. (1993). Age and the Nobel Prize revisited. *Scientometrics*, *28*(3), 387-399.

Tilghman, S. (chair), et al. (1998). *Trends in the Early Careers of Life Sciences*. Washington, DC: National Academy Press.

Usher, A. P. (1954). *A History of Mechanical Invention*. Cambridge, MA.

Van Dalen, H. (1999). The golden age of Nobel economists. *The American Economist*, *43*(2), 17-35.

Weinberg, B. A., & Galenson, D. W. (2005). *Creative careers: The life cycles of Nobel laureates in economics* (No. w11799). National Bureau of Economic Research.

Weinberg, B. A. (2006). *Which labor economists invested in human capital? Geography, vintage, and participation in scientific revolutions*. working paper, Ohio State University mimeo.

Weitzman, M. L. (1998). Recombinant growth, *Q. J. Econ*. 331-360.

Wray, K. B. (2003). Is science really a young man's game?. *Social Studies of Science*, *33*(1), 137-149.

Wray, K. B. (2004). An Examination of the Contributions of Young Scientists in New Fields. *Scientometrics*, 61(1), 117-128.

Wray, K. B. (2009). Did professionalization afford better opportunities for young scientists?. *Scientometrics*, *81*(3), 757-764.

Zuckerman, H. (1977). *Scientific elite: Nobel laureates in the United States*. New Jersey: Transaction Pub.

Zuckerman, H. & Merton, R. (1973). Age, aging, and age structure in science. In Robert Merton (Ed.) *The Sociology of Science* (497-559), Chicago, IL: University of Chicago Press.

Zusne, L. (1976). Age and achievement in psychology: The harmonic mean as a model. *American Psychologist*, *31*(11), 805.

Table 1: Classic Perspectives on Age and Genius

Population	Discipline(s)	Period	Sample Size	Measures
Beard, 1874 (The “Fixed Period” Controversy)				
"Great achievers"	Multiple scientific and creative arts fields	Pre-1870s	N = ~400	Age at accomplishment
Peak performance found between ages 35 and 40.				
Adams, 1946 (Isis)				
Scientists post 1600	Mathematics, Bacteriology, Chemistry, Physiology, Physics, Engineering, Pathology, Astronomy, Surgery, Psychology, Geology, Botany, Zoology, and Anthropology	1600-1944	N = 4,204	Age at big achievement
Median age of great achievement by discipline was found to be: Mathematics (37), Bacteriology (38), Chemistry (38), Physiology (40), Physics (40), Engineering (43), Pathology (44), Astronomy (45), Surgery (45), Psychology (45), Geology (46), Botany (46), Zoology (46), and Anthropology (47). Disciplines focused on deduction/intuition had great achievements younger.				

Lehman, 1953 (Age and Achievement)

Great contributors from a variety of disciplines-specific sources[12]	Chemistry, Mathematics, Physics, Astronomy, Entomology, Genetics, Agricultural Chemistry; and Psychology; Inventors	Misc.	N = 244 (Chemistry); 163 (Math); 90 (Physics); 63 (Astronomy); 402 (inventors); 86 (Entomology); 94 (Genetics); 36 (Ag. Chemistry); 50 (Psychology)	Age at big achievement

Notable inventions occurred most frequently from ages 30 to 40. Great achievement peaks differed across fields, at ages 25-30 in chemistry, 30-40 in mathematics, 40-45 in astronomy, and 30-35 in agricultural chemistry, entomology, genetics, physics, and psychology.

Moulin, 1955 (The British Journal of Sociology)

American Nobel Prize winners	Physics, Chemistry, and Medicine	1901-1950	N = 33	Age at award

The average age at receiving award ranged from 55 (Medicine) to 50 (Chemistry) and 45 (Physics).

Dennis, 1956 (Science)

"Eminent scientists" reaching age 70 with adulthoods from 1800-1900 from Webster's New International Encyclopedia	Astronomy, Chemistry, Geology, Mathematics, Naturalists, Psychology, and Physics	1800-1900	N = 156	Age at publication

[12] Chemistry – Hilditch's *A Concise History of Chemistry*; Mathematics - Cajori's *A History of Mathematics*; Physics – *A Source Book in Physics*; Astronomy – *A Source Book in Astronomy*; Inventors – *Scientific American Reference Book*, *The World Almanac and Book of Facts for 1938*, *Lincoln Library of Essential Information*, *Standard Dictionary of Facts*; Entomology, Genetics, Agricultural Chemistry, and Psychology – N/A

High productivity rate reached and maintained by 30s. Publications decreased 20 percent beginning in 60s with further decline in the 70s.

Lehman, 1966 (American Psychologist)

Superior contributors from disciplinary reviews	Psychology	1700-2000	Several hundred	Age at publication

Significant contributions in psychology came primarily from authors age 25 - 40.

Lyons, 1968 (American Psychologist)

"Eminence" and publication in top journals	Psychology	N/A	Several hundred	Age at award

Field recognized big achievements at least 16 years after occurrence, with peak in contributions similar to Lehman's (1966) findings.

Roe, 1972 (Science)

"Eminent" scientists	Biology, Physical Sciences, and Social Sciences	mid-20th century	N = 53	Age at publication

Productivity persistence was norm across disciplines; however, physicists peaked earlier and left often for administration. Attempted comparison with 19th century scientists indicates more publications in the 20th century with the age at first publication decreasing with time.

Simonton, 1991 (Developmental Psychology)

Scientists and inventors included in three selective biographical dictionaries	Mathematics, Astronomy, Physics, Chemistry, Biology, Medicine, Technology, Earth Sciences, and Other	~1500-1980	N = 2,026	Age at publication

Age-productivity curves vary across disciplines. Mathematicians were youngest in publishing first works. For best works, peak age averaged 39 across fields, with contributions in earth sciences, medicine, astronomy, and biology peaking at later ages.

Stephan and Levin, 1993 (Scientometrics)

Nobel Prize winners	Chemistry, Physics, and Medicine	1901-1992	N = 412	Age at winning research

Physics laureates were the youngest to complete prize-winning research, due largely to shorter work spans in physics. Approximately eighty percent of chemists, and two-thirds of laureates in physics and medicine began winning work before age 35. Only eight percent of laureates began prize winning work after age 45.

Van Dalen, 1999 (The American Economist)

Nobel Prize winners	Economics	1969-1998	N = 43	Age at winning research and publication

Nobel laureates in economics typically started their winning work at 29 and had their "mother lode publication" at 38. These laureates tended to have early first publications (3 years prior to PhD completion) with their last big contribution by 62.

Kanazawa, 2003 (Journal of Research in Personality)

Scientists from the Biographical Dictionary of Scientists	Mathematics, Physics, Chemists, Biologists	~1700-2000	N = 280	Age at big achievement

Approximately one quarter of scientists made discoveries during the five years around age 30.

Wray, 2004 (Scientometrics)

Significant discoveries in Hughes' The Virus	Bacteriology	1877-1898	N = 23 (scientists), 28 (discoveries)	Age at big achievement

Middle-aged scientists disproportionately contributed significant discoveries, providing more than 50% of discoveries while they were approximately a quarter of the workforce.

Feist, 2006 (Journal of Adult Development)

National Academy of Sciences-elected scientists	Cellular and Developmental Biology, Physics, Astronomy, Chemistry, Anthropology, and Psychology	early 2000s	N = 97	Age at big achievement

Peak age and plateau found at 40 followed by potential second acceleration toward end of career.

Matthews, Calhoun, Lo, and Ho, 2011 (PLoS ONE)

Nobel Prize winners; NIH principal investigators	Medicine, Physiology, and Chemistry (DNA, RNA, or proteins only)	1980-2010	N = 96	Age at award

On average prize-winning laureates in biomedical-related areas were 41 at the time they first published on their prize-winning research.

Table 2: Dynamic Perspectives on Age and Genius

Population	Discipline(s)	Period	Sample Size	Measures
Post 1900 data				
Zuckerman, 1977 (Scientific Elite)				
American Nobel Prize winners	Physics, Chemistry, Physiology/Medicine, and Economics	1901-72	N = 92	Age at winning research
Age at winning work for prize winners fluctuates in Medicine, Physics, and Chemistry when dividing U.S. laureate sample into three approximately 25 year periods.				
Jones, 2003 (Ph.D. thesis) and 2010 (Review of Economics and Statistics)				
Nobel Prize winners; Inventors from almanacs of the history of technology	Physics, Chemistry, Medicine, and Economics; Inventors	1873-1998	N = 830	Age at big achievement
Mean age of great achievement increased 6 years during the 20th century for both Nobel Prize winners and great inventors. Demographic shifts account for reductions in productivity after middle age while a productivity shift associated with longer training accounts for a sharp decline in innovation potential before age 30.				
Jones and Weinberg, 2011 (Proceedings of the National Academy of Sciences)				
Nobel prize winners (primarily)	Physics, Chemistry, and Medicine	1900-2008	N = 525	Age at winning research
Variation in the age-creativity relationship is five times larger over time than across fields. Classic cross-field comparisons of age and achievement are unstable. Age dynamics within fields closely mirror field-specific changes in (1) training patterns and (2) the frequency of theoretical contributions.				

Earlier data

Raskin, 1936 (The Journal of Abnormal and Social Psychology)

Male scientists and "literary men" listed in multiple histories	Biology, Physical Sciences, Mathematics, Poets, Novelists, and Dramatists	Produced during the Nineteenth Century	N = 120 (scientists), 123 (literary men)	Age at first/last publication and big achievement

Great contributions came at about 35 for both scientists and literary men. No evidence was found of time trends in the sample as related to age at first, greatest, or last achievement.

Zusne, 1976 (American Psychologist)

Psychologists/psychoanalysts from Annin, Boring, and Watson history	Psychology	1840-1900	N = 213	Age at publication and big achievement

Great contributions came consistently from age 35-40 consistently, while age at first publication fell from 33 to upper-20s. Age at last publication and death decreased from 75 (1840s) to 60 (1900).

Hongzhou and Guohua, 1985 (Scientometrics)

Chronological Table of Natural Scientific Events published by Shanghai Fudan University	General	1500-1960	N = 1,249 (scientists), 1,928 (achievements)	Age at big achievement

Age at outstanding achievement shifted upwards from 1500-1960, not controlling for increasing life expectancy, with peak ages occurring before age 30 prior to 1700.

Wray, 2009 (Scientometrics)

Dibner Library's 200 epochal books/pamphlets	General	1600-1899	N = 136	Age at big achievement

The median age at discovery dropped 9 years from the 1600s to the 1800s, with younger scientists making more big discoveries and older scientists making fewer.

Table 3: Intradisciplinary Perspectives on Age and Genius

Population	Discipline(s)	Period	Sample Size	Measures
Zuckerman, 1977 (Scientific Elite)				
American Nobel prize winners	Physics, Chemistry, Physiology or Medicine, and Economics	1901-1972	N = 92	Age at award
American Nobel laureates who trained with other laureates received the Nobel Prize seven years earlier than others. Prize-winning work was completed at age 38 for laureates apprenticing under another laureate (vs. age 41 for others).				
Weinberg and Galenson, 2005 (National Bureau of Economic Research)				
Nobel Prize winners	Economics	1980-1999	N = 31 (scientists), 78 (important articles)	Age at winning research; theory vs. empiricism
Experimental innovators, those economists working inductively, tended to have peak scholarly achievements in their mid-50s while conceptual innovators, economists working deductively, had their single best work at age 25.				
Dietrich and Srinivasan, 2007 (The Journal of Creative Behavior)				
Nobel Prize winners	Physics, Chemistry, and Physiology/ Medicine	1901-2003	N = 493	Age and career age at big discovery
Revolutionary discoveries, as opposed to within-paradigm discoveries, are especially likely in the 20s and early 30s. Argue for a neurological mechanism, where prefrontal cortex function declines with age and limits creative thinking.				

Jones and Weinberg, 2011 (Proceedings of the National Academy of Sciences)

Nobel prize winners; 100 most cited papers, annually	Physics, Chemistry, and Medicine	1900-2008	N = 525	Age at winning research; theory vs. empiricism

Theorists made their great achievements an average of 4 years earlier than empiricists. The quantum mechanics revolution in physics was associated with a decline in both training requirements and a shift toward conceptual contributions, both of which can statistically explain rapid decline in achievement age during this period. (See also Table 2.)