The Changing Age of Scientific Creativity

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PRELIMINARY

The age at which innovators make important contributions increases with the amount and complexity of knowledge in their field. During revolutions, existing knowledge becomes less important, reducing the age at which important contributions are made. During periods of ordinary science, knowledge tends to accumulate. Data on Nobel laureates in chemistry, medicine, and physics support these hypotheses. The age at which the laureates do their prize winning research declines during revolutions. We also find that contributors to new paradigms do their prize winning research earlier than others. In periods of ordinary science, the age at which the laureates do their prize winning research tends to increase.

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I. Introduction

Since Lehman [1953] psychologists, sociologists, and economists have studied differences across disciplines in the age at which innovators do important work but, with only a few exceptions, they have not studied how these ages change over time.[1] We argue that the age at which innovators do their important work depends on the amount and complexity of knowledge in their field. Kuhn's [1962] well-known analysis of science distinguishes between revolutionary phases and phases of ordinary science. During revolutionary phases existing knowledge becomes less important (or even hinders) creativity, and the age at which important contributions are made should fall. During phases of ordinary science knowledge accumulates and the age at which important innovations are made will be constant or increasing.

We test our hypothesis using changes in the age at which Nobel laureates in chemistry, medicine, and physics do their Prize winning research.[2] We find markedly different patterns for the three fields that are directly related to the evolution of the fields.

As indicated, virtually all work on the age distribution of important work studies differences across fields. Simonton [1988] probably contains the broadest analysis since Lehman [1953]. Stephan and Levin [1993] study Nobel laureates. Weinberg and Galenson [2005] moves beyond the existing literature by looking at variations at a point in time within a discipline, but not at changes over time.

The absence of work on changes in the age at which important contributions are made is striking for, as we show, these changes are large relative to the cross-sectional

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[1] Exceptions include Galenson and Weinberg [2000, 2001]; Jones [2005]; and Weinberg [2006].
[2] Weinberg [2006] analyzes changes in the age at which Nobel laureates in economics make their contributions. As discussed in that piece, analyzing recipients of the Nobel prize in economics are complicated because the Nobel Prize in economics was instituted substantially later than the other prizes and is awarded in a different way.

differences across disciplines. Moreover the differences across disciplines are not stable, but change over time as the age at which important contributions are made changes within disciplines.

II. Theory

As indicated, we draw on Kuhn's [1962] well-known distinction between revolutionary phases and phases of ordinary science to understand changes in the age at which important contributions are made. The age at which important scholars in a discipline do important work depends on both the amount and complexity of knowledge in the field. The amount and complexity of knowledge in a field depends on whether the discipline is undergoing a revolution or in a phase of ordinary science. Indeed one might view our analysis as a quantitative method for distinguishing these phases.

To understand the effect of a revolution on the age at which scholars make their important contributions, it is easiest to think of a system in a steady state, ignoring knowledge accumulation. Galenson and Weinberg [2000, 2001] and Weinberg and Galenson [2005] show that age (or experience) can either enhance or hinder creativity – the effect depends on the nature of an individual's work. In the absence of a revolution and knowledge accumulation, the age-distribution of important contributions in a discipline will be roughly constant.

Revolutions perturb this steady-state distribution in two ways. First they make much of the existing knowledge obsolete, reducing any advantage older innovators might have had. Moreover, as Galenson and Weinberg [2000, 2001]; Weinberg and Galenson [2005]; and Weinberg [2006] show, familiarity with an existing paradigm makes it more difficult to perceive and appreciate the most radical departures from that paradigm. During a revolution, this effect disadvantages old innovators relative to young ones. For both reasons revolutions will be associated with reductions in the age of important contributions. Insofar as familiarity with the pre-revolution paradigm has the least advantage or greatest disadvantage for contributors to a revolution itself, contributors to a revolution are expected to be even younger than other contemporary contributors.

As a discipline returns to a phase of ordinary science in the wake of a revolution, newly trained scientists will increasingly be trained in the new paradigm. Unlike scientists trained before the revolution, scientists trained after the revolution will not suffer from having assimilated the pre-revolutionary paradigm and their knowledge will obsolesce at a more typical, lower rate. In the absence of knowledge accumulation, we expect the ages of important contributions to increase, converging back to their steady state level. This convergence will be complete once the generation of scientists trained under the new paradigm reaches the end of their creative years.

To this point, the discussion has assumed that disciplines are static outside of revolutionary phases. Following Jones [2005a, b], we hypothesize that knowledge accumulates and disciplines tend to become more complicated during periods of ordinary science. Consistent with Jones [2005a, b] knowledge accumulation and increased complexity will lengthen the time required to reach the research frontier and also lengthen the time required to produce important innovations after completing training (see Simonton [1988]. Thus the age at which important contributions are made should increases during periods of ordinary science. It is possible to test for knowledge accumulation by seeing whether the age at which important contributions are made increases in phases of ordinary science past the point where the discipline should have returned to a steady state.

III. Historical Context

This section discusses the evolution of the three disciplines under consideration. As is widely discussed, physics was revolutionized by quantum mechanics in the early part of the 20th century (see for instance Kuhn [1962]). Quantum mechanics impacted a wide range of fields in physics including nuclear physics, particle physics, cosmology,and solid state physics (see Pais [1986] and Kraugh [1999]). While work on quantum mechanics culminated in the mid-1920s, the earliest discoveries (anomalies) that paved the way to quantum mechanics were made at the end of the 19^{th} century. We hypothesize that the age at which important contributions in physics were made will decline before the mid-1920s. We also hypothesize that contributors to quantum mechanics itself will tend to be younger than other contributors to physics during this period. After the mid-1920s we expect the age at which important contributions are made to increase as the system converges back from its perturbation and as knowledge accumulates.

Although it has received less attention, much of modern chemistry was developed in the half century beginning in 1860 and ending at the very beginning of the 20^{th} century. Among the important contributions in these years Kekulé's work on valence and molecular structure in the early 1860s; Mendeleev's development of the periodic table in 1869; Einstein's proof of the existence of atoms in 1905; Rutherford's discovery of the atomic nucleus and Bohr's model of the atom both in 1911; and Mosely's "calling roll of the elements" in 1913 (see Pais [1986] and Brock [1993]). If the institution of the Nobel Prize in 1901 is ideal for a study of physics it is somewhat unfortunate for a study of chemistry. We expect the age at which chemists did their Nobel Prize winning work to increase over the period as the ages converge back from the revolutionary period in the first years of the Nobel Prize and as knowledge accumulates.

Two factors distinguish medicine from chemistry and physics. Medicine is larger than the other disciplines – a 1.7 trillion dollar a year industry in the United States alone – and consequently the demand for medical innovations is substantially larger than the demand for innovations in the other fields (United State Census Bureau [2006]). Of the three disciplines, medicine is the least unified, reducing the potential for discipline-wide revolutions.

While progress in medicine has been rapid, medicine has not experienced a unified, discipline-wide revolution in the period covered by this study.[3] Individual fields in medicine have been revolutionized. These include cardiology, genetics, imaging, oncology, public health, and surgery including transplants (see Porter [1997]). Unlike physics and chemistry, where revolutions affected the entire discipline, the revolutions in medicine were field-specific. They may have resulted in smaller dips and increases in individual fields, but for medicine as a whole we expect little change in the age of important contributions.

III. Data

Our data comprise all recipients of the Nobel Prizes in chemistry, physics, and medicine through 2003. As described in Jones [2005a, b], the age at which the Nobel laureates did their Nobel Prize winning research was done based historical accounts. We identify the physicists who made contributions to quantum mechanics using the Karlsson's [2001] review of the Nobel Prize in physics.

Table 1 shows descriptive statistics for our data. The mean Nobel prize winning contribution in the fields was made in 1944 or 1945. The mean age at which Nobel prize winning work is done in physics at a somewhat lower age than either medicine or chemistry, which are both quite close to each other. There are no meaningful differences in the dispersion of the ages of Nobel Prize winning work across the fields, as measured by the standard deviations.

IV. Estimation

Our main results are based on discipline-specific regressions of the age at which the Nobel laureates in made their prize winning contributions on polynomials in time. Formally our model is

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[3] The discovery of bacteria and the development of immunology, advances in public health, and anatomy in the mid-to-late 19th century are perhaps mark the beginning of modern medicine, but these are less

$$Age_i^j = \beta_0^j + \beta_1^j Year_i^j + \beta_1^j Year_i^{j\,2} + \varepsilon_i^j . \qquad (1)$$

Here Age_i^j denotes the age at which laureate *i* in field

$j \in \{Chemistry, Medicine, Physics\}$ did his Nobel Prize winning research and $Year_i^j$ denotes the year in which he did his Nobel Prize winning research. Our procedure is to begin with a linear time trend and include higher order terms until additional terms are not statistically significant. In our regressions the year is expressed as a difference from 1900 so that the intercept in our models give the age at which the laureates in each field did their Nobel Prize winning work in 1900.

V. Results

Table 2 presents estimates of equation (1) for each field. Figure 1 plots our data and predicted values for each field. Table 3 presents the mean age at which the laureates in each field did their Nobel Prize winning work and predictions from the model for 1900 and 2000.

The age pattern for physics is well captured by a quadratic model (a cubic term is insignificant). The estimates indicate a U-shaped relationship between the year and the age at which the physicists did their Nobel Prize winning work. In 1900 the physicists did their Nobel Prize winning work when they were 36.4 years old. The implied minimum point is in 1928.241 (with a standard error of 4.676 years), at which point the physicists did their Nobel Prize winning work when they were 34.0 years old. As expected the minimum coincides with when the central work on quantum mechanics was completed in the mid 1920s. From that point on, the estimated age increases until it almost reaches an age of 50 years in 2000.

A second hypothesis is that contributors to the revolution itself should do their most important work at earlier ages than other contributors. To test this hypothesis, we

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closely connected than the quantum revolution in physics (Porter [1997])..

augment our model for physicists by including a dummy variable for whether the person's work was specifically on quantum mechanics.[4] Our estimates are,

$$\underset{}{Age_i^{Physics}} = \underset{(1.580)}{38.313} + \underset{(.066)}{.204} * Year_i^{Phys} + \underset{(.0008)}{.003} * {Year_i^{Phys}}^2 - \underset{(1.531)}{3.187} * QuantMech_i^{Phys} .$$

Thus, we find that people who received their Nobel Prizes for quantum mechanics were even younger when they did their prize winning work even after controlling for age. Figure 2 plots the predicted values for this model.

In chemistry, the time pattern is well captured by a linear model. In 1900 chemists did their Nobel Prize winning work at age 35.5. The model shows that the mean age at which the chemists did their Nobel Prize winning work increased by 1 year per decade. By 2000, the chemists were on average 45.5 years old at the time that they did their Nobel Prize winning work. The increase in the age at which the chemists did their Nobel Prize winning work is consistent with knowledge accumulating in chemistry over the course of the century.

Medicine shows no time trend. In 1900 medical scientists were on average 39.0 years old when they did their Nobel Prize winning work. The age at which the medical scientists did their Nobel Prize winning work increases by .015 years per year, but this estimate is not statistically significant. The relative constancy in medicine is consistent with revolutions in individual sub-fields in medicine spaced throughout the century without a single unified revolution.

One way of quantifying our estimates of changes in the age at which Nobel Prize winning work is done within fields is to compare them to the cross-field differences. As indicated, this question has been the focus of most of the existing literature. Pooling data for the entire century, Table 3 shows that that physicists were on average 2.5 or 3 years younger when they did their Nobel Prize winning work than either chemists or medical

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[4] We also experimented with interactions between the year and the quantum mechanics dummy variable,

scientists. This finding is broadly consistent with the existing literature. These cross-field differences are quite small relative to the changes witnessed within the fields – in chemistry the mean age at which the laureates did their Prize winning work increases by 10 years over the 20th century; in physics the mean age falls 2.4 years in 28 years before rising 15.5 years during the rest of the century.

Moreover the traditional cross-field comparisons are not robust. In 1900 the Nobel Prize winning contributions to medicine are done at a later age than those in either chemistry or physics, but by 2000 this pattern is reversed. Similarly while our estimates for the full sample show that the physicists are on average younger than chemists when they do their Nobel Prize winning work, they are older in both 1900 and 2000 – the lower average age only arises because of decline in ages in physics during the quantum revolution.

V. Conclusion

We have studied changes in the age at which Nobel laureates in chemistry, medicine, and physics do their Nobel Prize winning research. We find that in revolutionary periods the age at which the laureates do their prize winning research declines and that contributors to new paradigms do their prize winning research earlier than their contemporaries. These results are consistent with an increased rate of obsolescence of knowledge and a disadvantage of familiarity with the pre-revolution paradigm during a revolution and especially for contributors to the revolution.

In periods of ordinary science, we find that the age at which the laureates do their prize winning research increases. This result is consistent with the accumulation of knowledge leading innovators to spend more time in training to reach the research frontier and also more time required to do important research once at the frontier because of the increased complexity of knowledge.

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but these interactions were not statistically significant.

One extension of our work would be to obtain direct measures of the vintage of knowledge in the disciplines, such as the age of citations, and relate these measures to changes in the age at which the people in the disciplines made their important contributions. Such an analysis would not be trivial because even when work in a discipline implicitly draws on earlier work, it may only cite relatively recent work. We hypothesize that the age of knowledge in physics would decline until the 1920s and increase afterward. In chemistry we hypothesize that the age of knowledge will increase. In medicine as a whole we expect little change in the age of knowledge, although individual fields may well experience declines during revolutions followed by increases.

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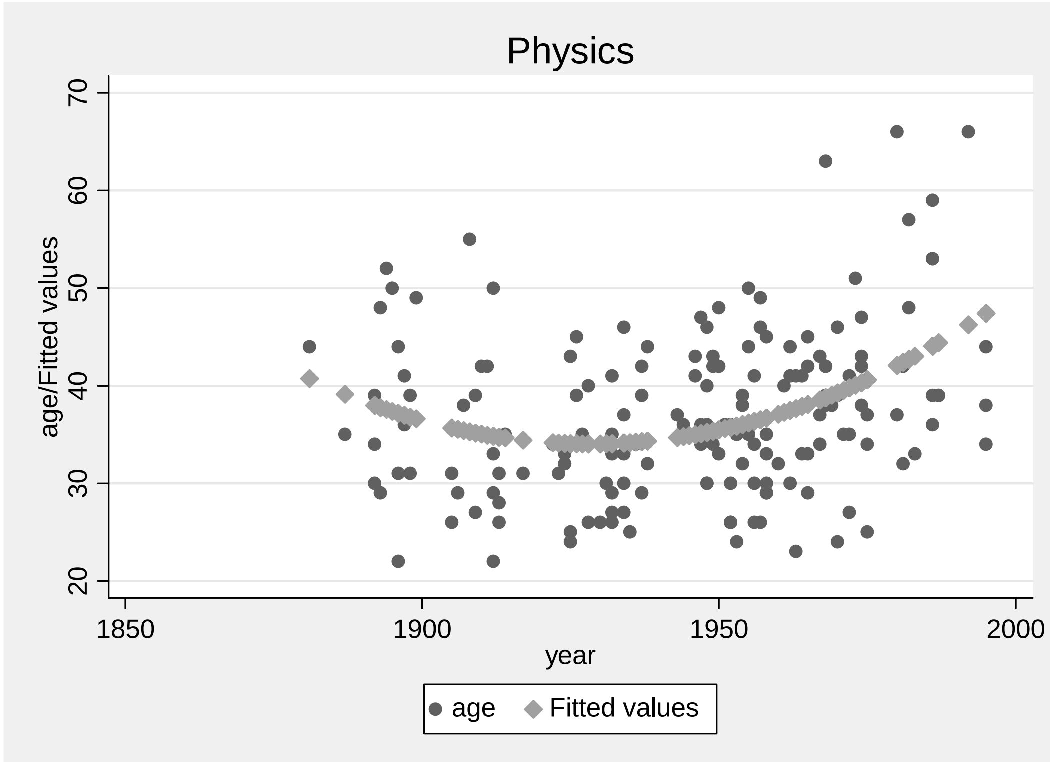
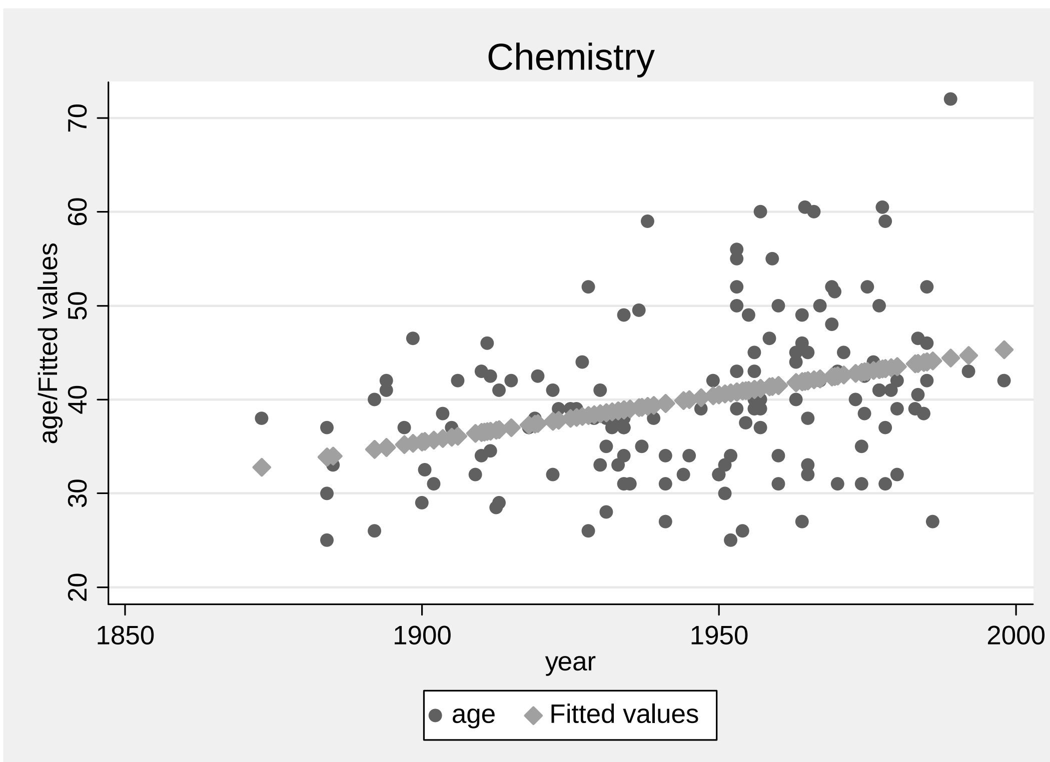
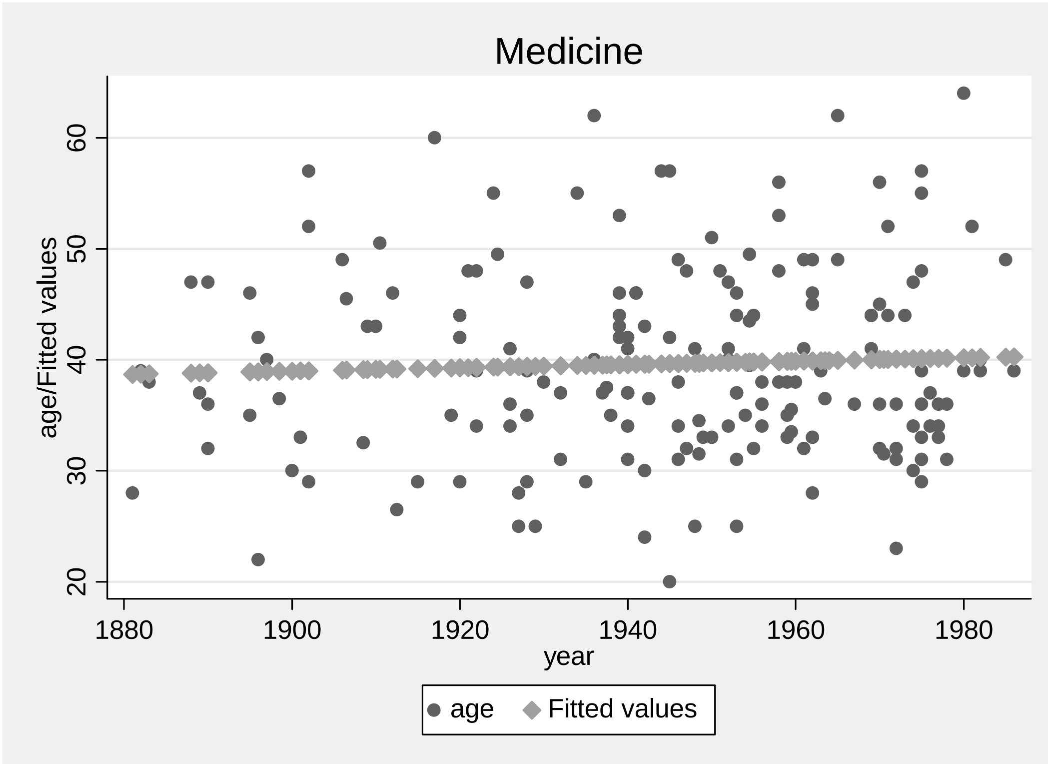
Figure 1. Trends in the age of Nobel Prize winning work.







Medicine
age/Fitted values
20
30
40
50
60
1880
1900
1920
1940
1960
1980
year
age
Fitted values

Table 2. Trends in the age of Nobel Prize winning work in physics with quantum mechanics contributions separated from other contributions.

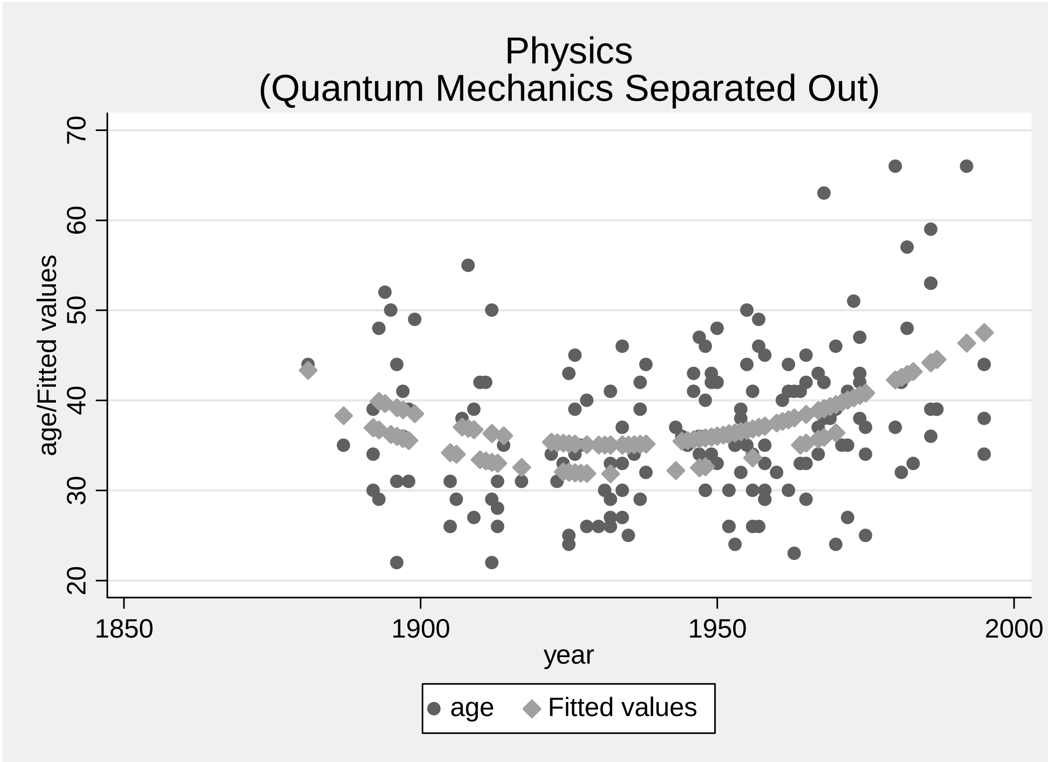


Table 1. Descriptive statistics.			
	Physics	Chemistry	Medicine
Mean year of Nobel	1944.765	1945.136	1944.261
Prize winning work	(27.586)	(28.607)	(25.810)
Mean age of Nobel	37.124	40.017	39.643
Prize winning work	(8.439)	(8.540)	(8.656)
Observations	170	143	178

Note. Standard deviations are in parentheses.

Table 2. Trends in the age of Nobel Prize winning work.

	Physics	Chemistry	Medicine
Year	-.170	.100	.015
	(.064)	(.024)	(.025)
$Year^2$	.003		
	(.0008)		
Intercept	36.426	35.487	38.983
	(1.307)	(1.264)	(1.293)
R^2	.134	.113	.002
Observations	170	143	178

Note. Standard errors are reported in parentheses. The year is measured as the difference from 1900.

Table 3. Actual mean ages and, for selected years, predicted age of Nobel Prize winning work.

	Physics	Chemistry	Medicine
Mean	37.124	40.017	39.643
	(0.647)	(0.714)	(0.649)
1900	36.426	35.487	38.983
	(1.307)	(1.264)	(1.293)
2000	49.513	45.524	40.4747
	(2.541)	(1.464)	(1.550)

Note. Standard errors are reported in parentheses.