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The Chemist's Most Creative Years

The 2500 ablest of the world's chemists attained their maximum production rate at ages 30 through 34.

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In 1835, just 123 years ago, two great chemists, J. J. Berzelius and J. A. B. Dumas, met in Paris. According to Dumas' brother (*1*, p. 117), their meeting was marked by an odd verbal exchange.

"Upon entering the room where Dumas was waiting for him, the most illustrious among illustrious chemists took Dumas by the hand, and looking him straight in the eye, said:

" 'How old are you?'

" 'Thirty-five.'

" 'That's fine! You still have 20 years of profitable research ahead of you. After 55 one does nothing important in the field of chemistry.'

"This remark gave the conversation a grave and almost an emotional turn. Upon leaving Berzelius, Dumas could not help thinking of the age of the great man who, born in 1779, was now exactly 55, and who had indicated that his present age marked the end of his important work in chemistry."

What justification did Berzelius have for making this remark? The grave turn in the conversation implies that he probably was not trying merely to make small talk. In making this remark Berzelius was perhaps expressing a mere impressionistic judgment for, in so far as is known, he made no statistical study of the problem.

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Today the record is 123 years older than it was when Berzelius and Dumas met. We have far more data available than they had, and it is now possible to give Berzelius' pronouncement a careful examination. That is what I have done in this article (*2*) by use of data obtained from 44 histories of chemistry by authors from five different countries—namely, Germany, France, England, Italy, and the United States—22 of them published since 1940 (*1*; *3–45*).

As was implied in the preceding paragraph, this study deals with the age at which the important work of the great research chemist is at an end. I have found, among other things, that although, after he has passed his thirties, the production rate for the most brilliant chemist's extremely important creative work tends to fall off both earlier and more rapidly than does the production rate for his own less brilliant output, no abrupt change occurs at any one age level (*46*). It therefore is not valid to say that the chemist's important contributions are *at an end* at any time prior to his death.

As compared with the masterworks of the less brilliant research workers, the masterworks of the most able research workers are produced by men who are of more nearly the same age. The more brilliant the chemist, the earlier the age at which he gives genuine indications of his future greatness. Although the great chemist's first research work is usually not his best, there are some conspicuous exceptions to this rule. After they started upon their professional careers, the most able chemists progressed faster than their less able colleagues. The 54 ablest chemists have attained their highest production rates and, hence, have contributed the greatest proportion of their very best work during the 15-year interval from ages 25 to 39, inclusive; the higher the caliber of the group, the larger the proportion of their masterworks contributed during this 15-year interval. When due allowance is made for the death rate, it is found that, collectively, the 2500 greatest of the world's chemists have attained their maximum production rate at ages 30 to 34, inclusive.

In what follows no attempt is made to tell what could, or should, or would have happened, under some purely hypothetical condition that conceivably might have existed but which did not actually obtain at any time or any place. Nor have I tried to extrapolate the findings. The reader can do his own speculating about what will happen in the days that lie ahead.

Sources of Information

In this study I never assume personal responsibility for identifying or judging the importance of a contribution to chemistry. I depend always upon the appraisals of recognized experts. These several specialists compiled and published their material under their own names, not for the purpose for which I have used it here, but rather for the use of professional chemists. The 44 histories were prepared by authors who had no special interest in the age factor, and it seems obvious that the compilers were concerned not with the ages of the contributors at the time they made their important contributions but rather with the actual significance of the contributions themselves. It seems unlikely, therefore, that the historians have exhibited any special bias with reference to chronological age. Indeed, most of them did not mention the contributors' ages at all, and they probably did not even give

Table 1. Data for contributions to chemistry each of which was cited and discussed in one or more of 44 histories of chemistry.

Row	Group A	B	C	D	E	F	G	H	I
1. Number of contributors	54	30	66	77	109	111	201	385	1433
2. Total No. of works	1199	552	649	813	748	749	1019	1400	2767
3. Average No. of works per chemist	22.2	18.4	9.8	10.7	6.9	6.7	5.1	3.6	1.9
4. Maximum No. of histories citing most renowned works	20 or more	15–19	10–14	7–9	5 or 6	4 only	3 only	2 only	1 only
5. Total No. of works of level of merit indicated in row 4	102	38	70	83	123	125	233	480	2767
6. No. of men whose "one best" work could be identified	53	30	66	76	98	85	178	330	838
7. Percentage of "one best" works first reported after age 55	2	0	5	3	6	6	10	10	12
8. Age prior to which 25 percent of "one best" works were reported	30.13	27.58	29.30	29.42	30.38	30.04	29.30	30.50	30.00
9. Age prior to which 50 percent of "one best" works were reported	34.31	35.50	36.33	35.83	37.25	40.83	36.20	37.22	36.55
10. Age prior to which 75 percent of "one best" works were reported	37.94	39.50	45.25	45.50	45.25	43.75	42.13	46.58	46.95
11. Age range during which middle 50 percent of "one best" works were reported	7.81	11.92	15.95	16.08	14.87	13.71	12.83	16.08	16.95

them a single thought. In preparing their histories they must have been writing as top-notch professional writers always write, and it seems safe to assume that, collectively at least, they must have exhibited good professional judgment.

From each history I copied down the name of each contributor to chemistry each time that it appeared if the historian also mentioned both a specific contribution and a specific calendar date that would enable me to know when the contribution was either first made or first reported. When the histories gave birth and death dates or the national origin of the contributor, or all of these data, that information was also noted. When birth and death dates and the country of origin could not be obtained from these histories, I obtained that information when possible from other sources.

By subtracting the date of birth of each contributor from the date on which he made or first reported his several contributions, it was possible to determine the ages of the contributors at the time they reported their contributions. Some allowance must be made, of course, for the time that may have elapsed between the inception and completion of a brilliant scientific study and between the latter date and that on which the achievement was first reported or published. Since the chemists always reported their contributions after, and never prior to, making them, the contributors must have been somewhat younger at the time they made their contributions than my data indicate.

The names of all the contributors found in each history were later typed in alphabetical order, with the aforementioned information set down after each contributor's name. This procedure yielded 44 separate lists of names. When the factual information from all 44 histories had been typed in duplicate, I used the duplicate lists to make one long master list containing, in alphabetical order, (i) the names of all contributors; (ii) their birth and death dates; (iii) the calendar dates on which they had reported their several contributions; (iv) their ages at the time they first reported each contribution; and (v) the number of different histories that cited and discussed the work reported by each contributor during any one calendar year.

This last item of information was later employed on the assumption that a group of contributions each of which was cited and discussed in, say, 15 or 20 histories of chemistry is of greater importance to chemistry than is another group of contributions each of which is cited and discussed in only one or two such histories.

In the handling of my data no count was made of the number of times a particular contribution was mentioned and discussed between the covers of any one history, but if several different contributions were made by the same individual during any one calendar year, each was counted. This means that a particular history might credit a given chemist with one specific contribution at a given chronological age level or it might credit him with several.

In making my master list I simply totaled the number of different credits (or tallies) thus obtained from the 44 histories. Therefore, in the reading of this article it should be understood that the words *contribution* and *masterwork* refer not necessarily to one specific achievement but rather to the entire output that each chemist reported during any one calendar year. In most instances we know that this output consisted of one outstanding discovery, but this is not true in all cases. The reader should keep this fact in mind constantly, for it would be awkward to incorporate it in each of the numerous statements I shall make later in which I use the words *contribution, one best contribution,* and so on.

Table 1 presents information regarding 9896 chemistry "contributions" each of which was of sufficient importance to be cited and discussed in one or more of the 44 histories. Table 1 sets forth the data for deceased chemists only, and only for those born not less than 70 years prior to publication of each history from which I obtained data. The figure of 70 years prior to the date of publication of each history from which data were obtained regarding a given chemist was set as an arbitrary dividing line in order to avoid the possible overloading of my findings with data on contributors born quite recently.

Data on living individuals are excluded from Table 1 because it obviously is not possible to study the entire lifework of chemists who are still living and achieving. In the first place, it is almost impossible to judge the actual significance of quite recent work. The importance of a chemistry contribution depends on its ultimate fruitfulness, and the ultimate fruitfulness of any scientific finding cannot be known for a good long time—if ever. Moreover, we have no sure way of knowing what the living chemist will accomplish during his later years. Table 1 includes, therefore, the data for deceased individuals only. For these the record is reasonably complete, and future events will probably change it only slightly if at all.

Sorting of Contributors and Their Contributions

The first row of Table 1 reveals the number of different contributors who attained the level of merit indicated in row 4. It shows, for example, that each of 54 chemists of group A (the most brilliant group) made one or more contributions each of which is cited and discussed in not fewer than 20 of the 44 histories, and that each of the 30 chemists of group B made one or more contributions that is mentioned and discussed in from 15 to 19 histories, and so on. Row 2 of Table 1 gives, for each group, the total number of its contributions that appear in my master list, including those of relatively minor importance. Row 3 reveals the average number of works per man within each group and indicates among other things that the average output per man (22.2 works) for group A, the most renowned group, was much greater than that (1.9 works) for group I, the least renowned group.

The fifth row of Table 1 shows the total number of works of the level of merit indicated in row 4, produced collectively by the members of each group. For example, although the 54 chemists of group A made a grand total of 1199 contributions which appear on my master list, only 102 of these contributions were cited and discussed in as many as 20 or more histories. And, although group B made a grand total of 552 contributions which appear on my list, only 38 of these contributions were cited and discussed in from 15 to 19 of the histories.

"One Best" Contribution

A chemist's one best contribution, by definition, can be made once only. Hence, if two or more of a chemist's choicest contributions were discussed in an equal number of histories, I ignored that chemist's work in preparing row 6 of Table 1 because I could not identify with certainty his one best contribution. Row 6 of Table 1 was obtained by working from this premise. It reveals the number of individuals in each group who made one contribution that was cited and discussed in more histories than was any other of their contributions. Row 7 shows the percentages of these "one best" performances that were first reported when the contributors were beyond 55 years of age. This is what interested Dumas. Notice that, of the 53 "one best" contributions made by group A, only one (or 2 percent) was first reported by a contributor over age 55. This happens to be the work of Hermann Boerhaave (1668–1738), Dutch physician and famous professor of medicine at the University of Leyden. Though he made no fundamental chemical discovery, Boerhaave's famous five-volume textbook, the *Elementa chemiae,* written we know not when but first published in 1724, when he was 56, received mention in 26 of the 44 histories.

In row 7, as one reads from left to right, the percentages grow larger. This means, of course, that the more noteworthy the chemist's one best contribution, the less likely it is that the contribution will be reported by a chemist who is over 55 years old. This statement applies not to the chemist's potential achievement at successive age levels but only to the achievement which was realized by the chemists included in the present study. One should also make a distinction between the chemist's one best contribution and his important work. Even though, if it is a highly important one, the chemist's one best contribution will probably be made before he is past 55, the work which he does beyond that age may still be very important.

Best Work of Berzelius and Dumas

On my master list, Berzelius received a grand total of 493 tallies, and in this respect he ranked first in my entire list. Dumas ranked seventh, with a grand total of 296 tallies. Although by use of this procedure one probably cannot hope to rank chemists in order of their importance with mathematical accuracy, it nevertheless seems clear that both Berzelius and Dumas are among our foremost chemists. Research that Dumas did at age 34 is cited in 37 of the 44 histories. Although Dumas lived to be 84 years old and although he made eight contributions after he was 55 which appear on my master list, he reported nothing in any one year after age 55 which is cited in more than six of the 44 histories. However, to receive mention in as many as six of 44 histories of chemistry is no mean achievement, regardless of the age at which the work is done.

As for Berzelius—my master list reveals that work reported by him at age 35 is cited and discussed in 26 of the 44 histories and that he reported nothing quite so important after he was past 55. However, he did make 13 contributions that appear in my master list when he was beyond 55, and at age 56 he reported some research that is cited in 17 of the 44 histories. This is very remarkable for a man of any age. It is obvious that both Berzelius and Dumas did more important research in chemistry when they were beyond age 55 than most other chemists have done in their palmiest days. It is also to be borne in mind that some very able chemists receive no mention at all in histories of chemistry.

If, at the time of their meeting in 1835, Dumas could have peered into the histories of chemistry that were to be published long after his death, he probably would have been amazed to discover that he, at age 34 in 1834, and Berzelius, at age 35 in 1814, had already reported their most notable research.

Ages at Which Maximum Production Rate Is Attained

The eighth row of Table 1 shows, for members of the several groups, the ages prior to which the first 25 percent of their masterworks (*47*) were produced. For example, the number for group A in row 8 (30.13) reveals that the earliest 25 percent of the 53 masterworks cited and discussed in each of 20 or more of the 44 histories were first reported when the member of the group who reported it was not beyond age 30.13. The last figure in this row (30.00) shows, for group I, that the first 25 percent of its 838 contributions were made when the individual who did the reporting was not more than 30.00 years old.

The ninth row of this table presents the ages prior to which the first 50 percent of the contributions of members of each group were made, and the 10th row reveals the ages prior to which 75 percent of their contributions were made. Although the age differences shown in row 8 are slight and those shown in row 9 are also small, row 10 highlights again the fact that the age range for produc-

Table 2. Ages at which groups of chemists first reported contributions to chemistry cited and discussed in one or more of 44 histories of chemistry.

Row	Group							
	A	B & C	D	E	F	G	H	I
1. Maximum number of histories in which most-renowned contribution to chemistry is cited	20 or more	10–19	7–9	5 or 6	4 only	3 only	2 only	1 only
2. Number of contributors	54	96	77	109	111	201	385	1433
3. Age prior to which 25 percent of initial contributions were made	21.71	22.18	24.54	25.75	24.71	26.41	27.08	28.90
4. Age prior to which 50 percent of initial contributions were made	24.71	26.28	27.90	28.42	29.00	30.30	31.42	33.71
5. Age prior to which 75 per cent of initial contributions were made	27.90	32.69	32.63	36.13	35.75	36.81	39.81	42.88
6. Five-year interval during which largest number of initial contributions were made	18–22 tied with 21–25	22–26 (B) 22–26 (C)	23–27	25–29	24–28	24–28	26–30	29–33

tion of a masterwork of very great importance is narrower than that for production of a masterwork of lesser importance. Notice in row 10 that, whereas the last 25 percent of the masterworks of group A appeared when the contributors were past age 37.94, the last 25 percent of the relatively minor masterworks of group I appeared when the contributors were beyond age 46.95.

The last row of Table 1 brings out even more clearly the fact that the most brilliant masterworks are produced by men who are of more nearly the same age than is the case when the masterworks are of less significance. Notice in row 11 that half of the 53 most brilliant masterworks in chemistry appeared during an age range of only 7.81 years but that half of the 838 masterworks of lesser merit appeared during an age range of 16.95 years. One would naturally expect half of only 53 contributions to be produced over a shorter span of years than half of 838 contributions. But why were half of the 53 most brilliant contributions (those cited by the largest number of histories) made at ages 30.13 to 37.94 rather than during some other age range of equal length—say, from ages 40.13 to 47.94, or from ages 50.13 to 57.94, for example? One can only conjecture with reference to this. At present there is no sure answer.

First Important Contributions

At what ages do the greatest chemists first show genuine indications of their future greatness? Table 2 reveals the ages at which the members of each group first published contributions important enough to be cited in one or more of the 44 histories and, therefore, important enough to appear on my master list. In this table the groups are again segregated according to the frequency with which their most renowned contribution to chemistry was cited and discussed in the 44 histories.

The first numeral in row 3 reveals that 25 percent of the members of group A *first* published a contribution important enough to be on my master list prior to age 21.71. The last numeral in this row shows that 25 percent of the members of group I did not attain this level of success until they were 28.90 years old. Row 4 indicates similarly that, whereas prior to age 24.71 half of the members of group A had done research of sufficient merit to be cited in one or more of the 44 histories, half of the members of group I did not attain this distinction until nine years later—namely, at age 33.71. The fifth row of Table 2 is even more striking. It shows that, whereas three-fourths of the most brilliant group had published research that appears on my master list by the time they were 27.90 years old, three-fourths of the least brilliant group did not reach this milestone of success until they were 15 years older—namely, at age 42.88.

The last row of Table 2 reveals the five-year interval during which the maximum number of initial contributions to chemistry were produced. Study of all the data in Table 2 reveals an unmistakable trend—namely, that the more brilliant research chemists have started their professional careers at earlier ages than have the less brilliant ones.

Table 3. Average number of contributions to chemistry made prior to age 25 which were cited and discussed in (i) one or more, (ii) two or more, and (iii) three or more histories. The largest average in each of rows 3, 4, and 5 was assigned an arbitrary value of 100 percent, and the other frequencies in the same row were then assigned proportionate percentage values.

Row	Group							
	A	B & C	D	E	F	G	H	I
1. Maximum No. of histories citing "one most renowned" contribution	20 or more	10 to 19	7 to 9	5 or 6	4 only	3 only	2 only	1 only
2. Number of contributors	54	96	77	109	111	201	385	1433
3. Average No. of contributions cited in one or more histories	1.81 (100%)	0.80 (44%)	0.43 (24%)	0.25 (14%)	0.33 (19%)	0.28 (16%)	0.21 (12%)	0.11 (6%)
4. Average No. of contributions cited in two or more histories	0.833 (100%)	0.444 (53%)	0.260 (31%)	0.101 (12%)	0.144 (17%)	0.104 (13%)	0.099 (12%)	
5. Average No. of contributions cited in three or more histories	0.667 (100%)	0.311 (47%)	0.156 (23%)	0.055 (8%)	0.081 (12%)	0.065 (10%)		

Contributions Prior to Age 25

Table 3 reveals, for the several groups, the average numbers of contributions made prior to age 25 which are cited in (i) one or more histories, (ii) two or more histories, and (iii) three or more histories. The first numeral in row 3 shows that members of group A had made an average of 1.81 contributions (each of which was important enough to place their names on my master list) before they were 25 years old. In order to facilitate comparison with the other groups in row 3, the numeral 1.81 was assigned an arbitrary value of 100 percent, and the remaining frequencies in this distribution were then assigned proportionate percentage values. As one reads along this row of percentages it will be noted that no other group did half as well prior to age 25 as did group A. And it can be seen also that, prior to age 25, the least renowned group in the list (group I) did less than 10 percent as well as did group A.

Rows 4 and 5 reveal the same general trend as does row 3. For each group in row 4, the average output per man prior to age 25 is smaller than it is in row 3, because row 4 is based upon more select contributions than is row 3. That is to say, contributions which are cited and discussed in two histories of chemistry are probably of somewhat greater average merit than are other contributions which are mentioned in one history only. Similarly, the averages in row 5 are smaller than are the averages in row 4, because contributions which are cited in three or more histories are probably of greater merit than are those which are mentioned in two histories only. From rows 3, 4, or 5 it is clear that members of the two first groups (A and B–C) got off to an earlier start than those of other groups. And, as was shown in Table 1, once they were launched upon their professional careers, they moved faster and they went further than did the members of the other groups.

More Brilliant versus Less Brilliant Contributions

Table 4 sets forth, by five-year intervals, both the number and the percentages of contributions to chemistry that were cited and discussed (i) in one only of the 44 histories and (ii) in 20 or more of the 44 histories. This table reads as follows: Of the 6347 contributions to chemistry each of which was mentioned in one only of the 44 histories, 1 percent were contributions made at ages 15 to 19, inclusive, 5 percent were made by contributors of ages 20 to 24, inclusive, and so on.

Notice in this table that, whereas 71 percent of the major contributions to chemistry were produced at ages 25 to 39, inclusive, only 43 percent of the relatively minor ones were reported during this same 15-year interval. Notice, also, that whereas only 5 percent of the major contributions were reported by contributors of age 50 or above, 26 percent, or approximately five times as large a proportion, of the relatively minor contributions were first reported by contributors who were 50 or more years of age at the time of reporting them. Table 5 reveals the relationship even more clearly than does Table 4: the greater the merit of the contribution to chemistry, the smaller the percentage of contributions of this degree of merit that have been produced at age 50 or beyond.

Greatest Chemists' Extremely Important Contributions

Although my data speak for themselves, graphs will enable me to present the picture more clearly than is possible by use of only words and numerals. Figure 1 reveals the ages at which 54 noted chemists made 155 very superior contributions to their field, each of the 155 contributions being cited and discussed in not fewer than 15 of the 44 histories of chemistry. My several tables did not take the death rate into account, but in a study of Fig. 1 it should be understood that it sets forth the average number of contributions per five-year interval. Ample allowance is thus made for the fact that time takes its toll and, therefore, that young chemists always comprise a larger group than do older ones. For example, it was found that for the five-year interval from age 30 to 34, inclusive, the 54 chemists made 43 of the contributions that are represented in Fig. 1. This was slightly more than 0.159 contributions per individual. The chemists that remained alive at age 60 to 64 made only two of these superior contributions, which was slightly more than 0.00971 contributions per living contributor. The solid line in Fig. 1 is drawn so as to be only 0.00971/0.159 as high at ages 60 to 64 as it is at ages 30 to 34. The curve is drawn in this manner in order to show graphically that the average number of contributions per living chemist—that is, their production rate—was only 0.00971/0.159 as large at age 60 to 64 as it was at age 30 to 34.

If, regardless of the number that remained alive, the older chemists had contributed at the same average rate as did the younger ones, the curve in Fig. 1 would remain as high at the higher age levels as at the lower levels. Actually, Fig. 1 exhibits a very noticeable and consistent decrement at the uppermost age levels, thus indicating that, with regard to these superior contributions, the chemists became progressively less productive at the higher age levels.

One other point should be mentioned with reference to Fig. 1. In the construction of this figure, the peak of the statistical distribution was arbitrarily assigned a value of 100 percent, and the other averages within this statistical distribu-

Table 4. Grand total of all contributions to chemistry that were made by the various age groups and that were cited and discussed in: (i) one only of 44 histories and (ii) 20 or more of the 44 histories.

Age group	Histories: One only No.	One only (%)	20 or more No.	20 or more (%)
15–19	51	1	1	1
20–24	321	5	4	4
25–29	799	13	16	17
30–34	978	15	28	27
35–39	956	15	28	27
Total 25–39		(43)		(71)
40–44	841	13	12	12
45–49	709	11	8	8
50–54	595	9	4	4
55–59	406	6	1	1
60–64	325	5		
65–69	195	3		
70–74	111	2		
75–79	44	1		
80–84	12	< 1		
85–89	4	< 1		
Totals	6347	100	102	101

Table 5. Percentages of all contributions made at age 50 or beyond that were cited and discussed in different numbers of 44 histories of chemistry.

No. of histories	Percentage
1 only	27
2 only	22
3	22
4	22
5 or 6	19
7 to 9	15
10 to 14	13
15 to 19	6
20 or more	5

Table 6. Average number of contributions to chemistry per age interval (absolute values used for the construction of Figs. 1 through 7).

Ages	Fig. 1	Fig. 2* dot-dash line	Fig. 3† dot-dash line	Fig. 4‡ broken line	Fig. 5			Fig. 6			Fig. 7§	
					Solid line	Dot-dash line	Broken line	Solid line	Dot-dash line	Broken line	Solid line	Dot-dash line
15–19	0.004	0.001	0.052	0.070		0.005	0.005		0.006	0.007	2	2
20–24	0.015	0.016	0.170	0.285	0.017	0.054	0.118	0.008	0.027	0.041	27	26
25–29	0.096	0.031	0.196	0.500	0.047	0.133	0.330	0.038	0.087	0.141	92	81
30–34	0.159	0.040	0.167	0.559	0.039	0.146	0.370	0.038	0.104	0.168	100	100
35–39	0.141	0.031	0.204	0.630	0.043	0.121	0.360	0.042	0.108	0.179	92	96
40–44	0.079	0.025	0.267	0.639	0.015	0.143	0.323	0.029	0.100	0.148	60	60
45–49	0.048	0.021	0.259	0.522	0.022	0.113	0.308	0.023	0.080	0.121	51	51
50–54	0.027	0.015	0.275	0.518	0.015	0.120	0.233	0.018	0.070	0.101	29	34
55–59	0.010	0.013	0.243	0.451	0.007	0.086	0.180	0.011	0.044	0.065	19	21
60–64	0.011	0.010	0.205	0.316	0.004	0.097	0.153	0.010	0.046	0.062	17	20
65–69		0.005	0.197	0.270		0.094	0.125	0.003	0.025	0.030	8	8
70–74		0.005	0.180	0.253		0.050	0.061	0.002	0.022	0.025	2	2
75–79		0.001	0.071	0.143		0.042	0.056	0.003	0.016	0.020		
80–84		0.001	0.097	0.097		0.015	0.015		0.007	0.007		
85–89			0.143	0.143		0.021	0.021		0.007	0.007		

* The solid line of Fig. 2 is the same as the curve in Fig. 1.
† The solid line of Fig. 3 is the same as the curve in Fig. 1.
‡ The solid line of Fig. 4 is the same as the curve in Fig. 1; the dot-dash line of Fig. 4 is the same as the dot-dash line of Fig. 3.
§ The two rows of Fig. 7 contain percentage values because each statistical distribution was converted to percentage values before the median values were ascertained.

tion were then assigned proportionate percentage values. For example, the peak of the distribution represented in Fig. 1 occurred at ages 30 to 34. This modal value was taken to be 100 percent, and the remaining frequencies were then computed and plotted as percentages of this modal value. Table 6 reveals the absolute values used for the construction of Figs. 1 through 7. It is of interest to note that these rather small decimal values yield fairly consistent and revealing age curves.

Age Range for Masterworks of Lesser Chemists

In order to reveal its similarity to certain other age curves, Fig. 1 is reproduced in Figs. 2 and 3 and drawn to a different scale in Fig. 4. Thus, the solid line of Fig. 2 is identical with that of Fig. 1. It represents, for group A, 155 contributions each of which was cited in not fewer than 15 of the 44 histories. The dot-dash line of Fig. 2 represents, on the other hand, the ages at which each of 1166 chemists produced their masterworks, each of these 1166 masterworks being cited and discussed in not more than one or two of the 44 histories of chemistry. Figure 2 thus shows that 54 of the greatest chemists reported 155 of their most important contributions during a narrower age-range than that during which 1166 lesser chemists reported their masterworks.

In the construction of the two curves of Fig. 2, the same procedure was adhered to as was employed for constructing Fig. 1. That is to say, the maximum value of each distribution used for making Fig. 2 was assigned a value of 100 percent, and the other values within each distribution were then plotted as percentages of the distribution's modal value. It should be clear that, since both modal values of Fig. 2 were arbitrarily assigned values of 100 percent, the equal heights of the two curves of Fig. 2 result from the way they were drawn and that this should not be taken to mean that the two maximum production rates were the same numerically.

Most Brilliant versus Less Brilliant Work of Greatest Chemists

Figure 3 shows that the greatest chemists have made their most noteworthy contributions during a narrower age-range than that during which they have produced their relatively minor ones. In Fig. 3, the solid line is again a reproduction of that in Fig. 1. The dot-dash line of this figure represents data for 550 of group A's relatively minor contributions each of which was cited in not more than two of the 44 histories. Obviously, these latter contributions were not the very best contributions of group A. On the contrary, it seems reasonable to assume that the solid line in Fig. 3 shows the production rate for group A's most brilliant attainments and that the dot-dash line in this figure represents the production rate for 550 of group A's less brilliant works.

It will be noticed in Fig. 3 that the curve for the less meritorious contributions rises earlier, attains its peak later—namely, at ages 40 to 44—and does not terminate until it reaches a fairly advanced age level. The slower rise of the curve for the more important contributions suggests that the chemist's first research effort is usually not his most fruitful one. Although this is generally true,

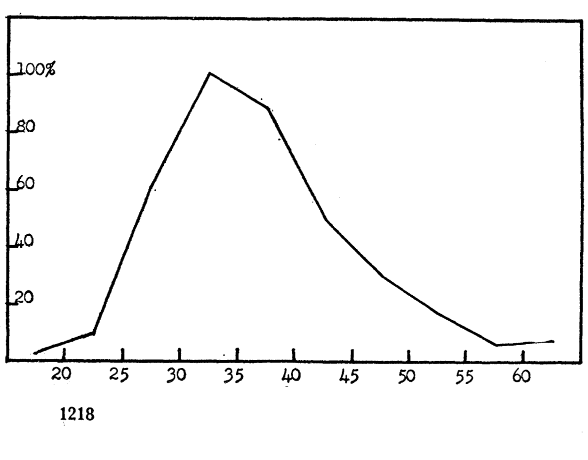

Fig. 1. Relationship of age (abscissa) to rate of production in chemistry. The curve represents average rate of production of 155 very superior contributions by 54 chemists (group A), each contribution having been cited and discussed in not fewer than 15 of 44 histories of chemistry.

there are more exceptions to this rule than might be expected.

Without such information as is revealed by Fig. 3, it might be supposed that because men may be in their best physical condition at ages 30 to 34, they are best able at this time to put in long hours of work and withstand fatigue, and that for such reasons they have worked hardest at ages 30 to 34, attaining at these ages their highest production rate for work of every caliber—their best, their good, and their least brilliant. But Fig. 3 reveals that such a conjecture is not wholly valid. Whereas group A's production rate for its best work was greatest at ages 30 to 34, for its least meritorious work (as found on my master list) it attains its highest production rate not at ages 30 to 34 but at ages 40 to 44.

Note also that, whereas the solid line is highest at ages 30 to 34, the dot-dash line dips slightly at this age level. This phenomenon probably means only that when men are producing their most notable contributions they are not likely simultaneously to be producing their least notable ones.

There probably are a great many reasons for the finding that older chemists are likely to do less important research than younger ones. Let us consider the case of Dumas once more by way of illustration. Before he was 21 years old Dumas was engaged with J. L. Prevost in original work on problems of physiological chemistry. Here we have an example of a gifted young worker who made an early start upon his professional career. From 1840 (age 40) he was one of the editors of the *Annales de chimie et de physique*. In 1849 he became a member of the French National Legislative Assembly; he acted as minister of agriculture and commerce in 1850–51, and he subsequently became a senator, president of the municipal council of Paris, and master of the French mint. It is difficult to see how, during his later years, Dumas, with all these other commitments, could possibly have given his undivided attention to research in chemistry. Obviously, he could not have done so.

Uneven Work of Greatest Chemists

It was explained earlier that in Fig. 2 the two curves are of the same maximum height because they are drawn that way and that this should not be interpreted as implying that the maximum production rates are therefore identical. Figure 4 is plotted differently. In this figure the broken line represents the production rate for all of the contributions on my master list that were made by the members of the peerless group A. It represents the production rate for 1199 works, an average of 22.02 works per man. The dot-dash line represents the same data as the dot-dash line of Fig. 3 but is drawn to a different scale. This dot-dash line represents the production rate for group A's least meritorious 550 contributions. And the solid line of Fig. 4 shows, for group A, the production rate for its 155 most brilliant achievements. The broken line of Fig. 4 covers a greater area than do the two smaller curves because this broken line is based upon a larger number of contributions—namely, the 155 most brilliant, plus the 550 least brilliant, plus 498 other contributions each of which was cited and discussed in from three to 14 of the 44 histories.

Although both curves of Fig. 3 are reproduced in Fig. 4, neither of them looks the same in Fig. 4 because in Fig. 4 the peak of the curve for *total* output was assigned a value of 100 percent and all other averages in all three distributions were then assigned proportionate percentage values. Thus, in Fig. 4, the peak of the dot-dash line is only 42 percent as high as is the peak of the broken line, because numerically the maximum production rate for the least valuable contributions of members of group A (those contributions that are cited in only one or two of the 44 histories) never exceeded 42 percent of the maximum production for the total output of members of this group.

Similarly, the peak of the solid line in Fig. 4 is only 25 percent as high as is the peak of the broken line, because the maximum production rate for the most brilliant contributions (those cited in 15 or more of the 44 histories) never exceeds 25 percent of the maximum production rate for total output. Figure 4 merits close study. For the three groups of contributions, the maximum production rates occur at the following ages: (i) for the most brilliant, at ages 30 to

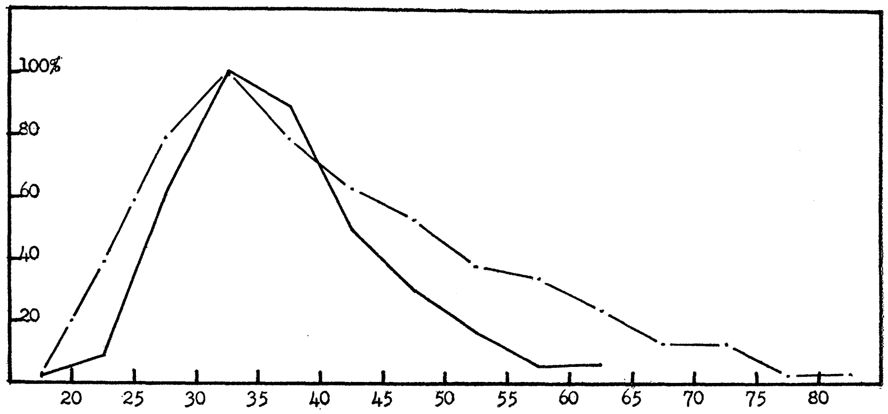

Fig. 2. Relationship of age (abscissa) to rate of production. The solid line represents the same data for the 54 chemists of group A as in Fig. 1. The dot-dash line represents average rate of production of the "one best" contribution (cited and discussed in only one or two of 44 histories of chemistry) by each of 1166 chemists.

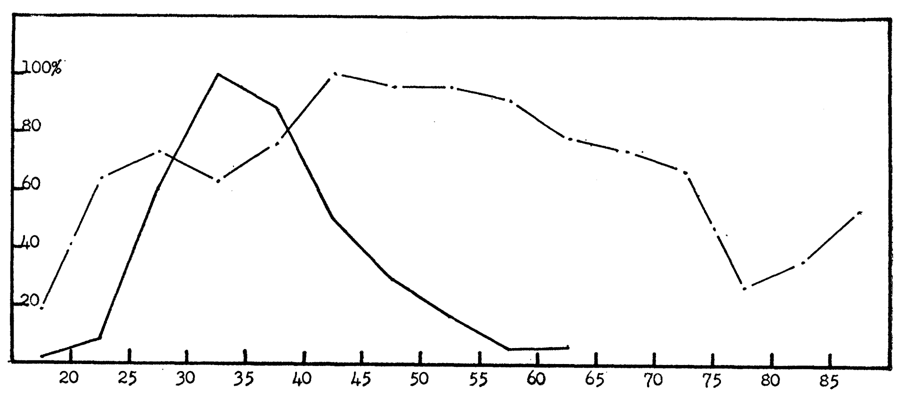

Fig. 3. Relationship of age (abscissa) to rate of production of two categories of contributions by the 54 chemists of Figs. 1 and 2. The solid line represents the same data as in Fig. 1. The dot-dash line represents average rate for 550 relatively minor contributions, each having been cited and discussed in not more than two of 44 histories of chemistry.

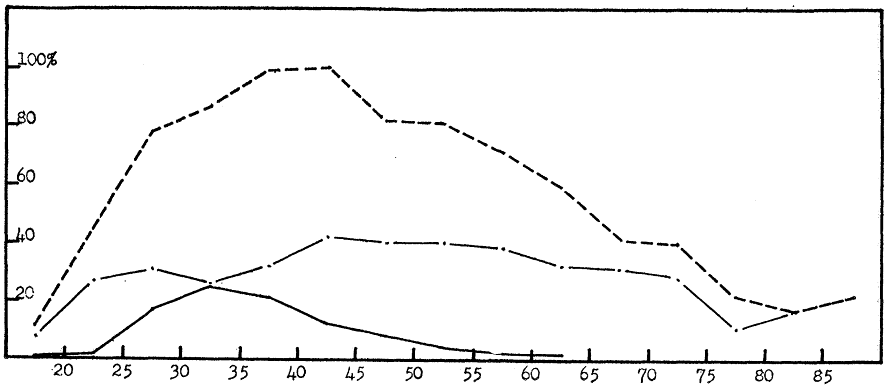

Fig. 4. Relationship of age (abscissa) to rate of production of two categories of contributions and of total contributions by the 54 chemists of Figs. 1–3. The solid line and the dot-dash line represent the same data, respectively, as the solid and dot-dash lines in Figs. 1 and 3 (drawn to a different scale). The broken line represents average rate for 1199 contributions that constitute the total output of this group, as revealed by a master list.

34, (ii) for the least brilliant, at ages 40 to 44, and (iii) for the total output, at ages 40 to 44. The fact that in this graph the curve that indicates maximum production rate for the most brilliant contributions never reaches the level of that for the least brilliant results from the way in which the two groups of contributions were chosen. One would hardly expect the maximum production rate to be as great for 151 as for 550 contributions.

Beyond age 45 the production rate for the least brilliant achievements holds up surprisingly well, but after the chemist has passed his thirties, the production rate for his creative work of highest quality tends to fall off more rapidly than does the production rate for mere quantity of output. In employing the expression "mere quantity of output" I do not mean to express scorn for what the members of group A achieved during their later years. These men were and are the most brilliant ornament of their profession, and their least important works are all masterpieces in comparison with the very best work of a host of lesser men. As here employed, the words "mere quantity of output" imply only that some of the contributions of our greatest chemists are much less important than are others.

Most striking in Fig. 4 is the very obvious tendency for the broken line and the dot-dash line to approach each other beyond about age 45. And, at the greatest age level, these two curves coincide. This means that, with increase in age beyond about 45, total output tends more and more to consist solely of relatively minor contributions. But this age change is very gradual, and no abrupt change occurs at any one age. It therefore is not valid to say that the great chemist's important work is ended at any one time prior to his death. The contributions made by the members of group A during their later years, though relatively minor as compared with their most brilliant contributions, were *in toto* important.

Uneven Work of Lesser Chemists

Some readers may think that the findings presented in Fig. 4 result largely from the small number of contributions employed for constructing the solid line. One advantage in having a large sample of contributions is the fact that the validity of this finding can be verified by use of other data. Figure 5 is based upon the contributions of an entirely different group of chemists. It presents data for 2295 contributions made by 192 chemists each of whom made at least one contribution that is cited and discussed in from 6 to 19 histories. Nevertheless, Fig. 5 reveals the same general trend as does Fig. 4. Here again the curve which shows the production rate for total output and that which shows the production rate for the least meritorious contributions tend to merge at the uppermost age level, and at the highest age level they coincide.

Figure 6 is based upon the work of chemists of less notable average accomplishment than those whose production rates are shown in Figs. 4 and 5. It sets forth data for 2453 contributions made by 528 chemists each of whom made at least one contribution that is cited in from 2 to 5 histories. Here again the two curves which represent production rates for total output and for least important contributions approach each other rapidly beyond age 39, and they coincide at the uppermost age level.

As compared with Figs. 4 and 5, the dot-dash line in Fig. 6 lies closer to the broken line at almost all ages. This results from the fact that a greater proportion of the total output of the contributors on whose work Fig. 6 is based was of relatively minor importance. This explains also why the solid line in Fig. 6 persists to a greater age level than do the solid lines in Figs. 4 and 5.

One reason why I chose to study contributions to the field of chemistry is the fact that this is a field that has been extensively worked. Therefore, large numbers of very superior contributions in this field are available for study. My master list includes all of the major chemists of whom we have any record. It includes contributors from every country that has produced any important workers in the field—that is, from far-off Australia, from Japan, China, India,

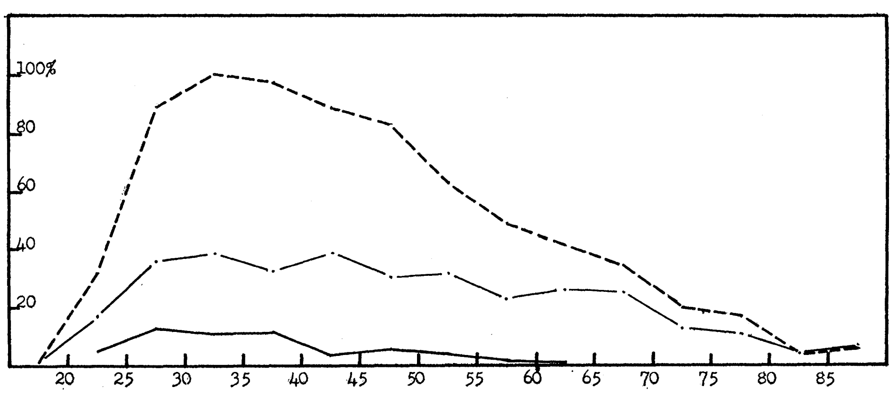

Fig. 5. Relationship of age (abscissa) to rate of production of a group of 192 chemists not covered in Figs. 1, 2, 3, and 4. The solid line represents average rate for "one best" contribution; the dot-dash line, for 1016 relatively minor contributions; the broken line, for 2295 contributions that constitute the total output of this group, as revealed by a master list.

South America, and Ceylon, and from others too numerous to list. And my findings possess internal consistency. For example, in Fig. 7 the solid line shows median percentage values that were found by study of 23 histories of chemistry and the dot-dash line presents median percentage values that were obtained by study of 31 histories. Each of these two curves presents age data for chemists, now dead, who were born after 1775 and not less than 70 years prior to publication of each book from which information was obtained. The slightness of the difference in these two curves suggests that additional data would change the picture only slightly if at all.

Some who read this article may wish to follow it up by turning to my discussion of the relation between age and achievement in many other fields of science, as well as in such other areas as practical invention, literature, music, art, politics, business, statecraft, mathematics, prize-fighting, philosophy, and so on. I refer such readers to my book, *Age and Achievement* (*48*), which sets forth, by means of tables and graphs, a considerable amount of factual information analogous to that presented here. This book also sets forth 16 possible reasons for the early decrements in production rate that occur in some fields of endeavor. (*48*, pp. 328 ff.)

Recent events evidence the fact that man is rapidly attaining control over almost everything in the universe except himself. If he is to avoid destroying himself, man must learn quickly to exploit more fully than heretofore the powers that lie within his own mind. This is only one of several reasons why we never can know too much about the conditions that give rise to creative thinking of a very high order.

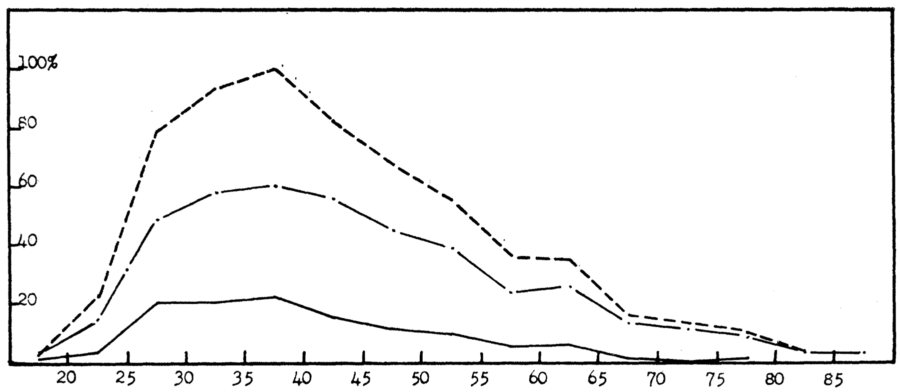

Fig. 6. Relationship of age (abscissa) to rate of production of a group of 528 chemists of less notable accomplishment than those covered in Figs. 1, 2, 3, 4, and 5. The solid line represents average rate for "one best" contribution; the dot-dash line, for 1667 relatively minor contributions; the broken line, for 2543 contributions that constitute the total output of this group, as revealed by a master list.

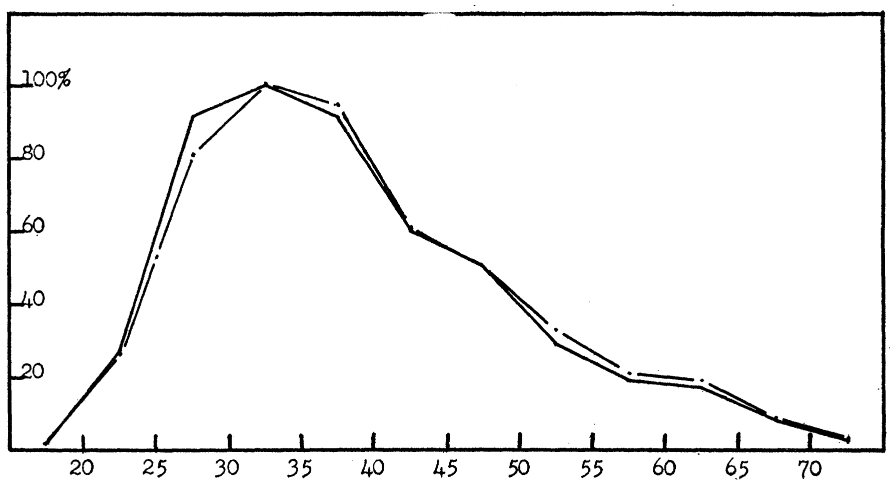

Fig. 7. Relationship of age (abscissa) to rate of production in chemistry. The solid line represents median percentage values based on data in 23 histories of chemistry; the dot-dash line, median percentage values based on data in 31 histories of chemistry.

Comment

How are the findings presented in this article to be interpreted? At present we are in no position to give an adequate explanation. Undoubtedly multiple causation operates in these complex behaviors and no condition as yet discovered is likely of itself to be a sufficient or necessary cause. Most psychologists believe, however, that few persons ever actually reach the very peak of performance of which they are capable. And, if most individuals fail to attain their potential peak performance, it is inconceivable that any entire age group has ever attained its peak. Since most individuals, and *all* age groups, are probably content to come to rest at some point below their maximum potential performance, these curves may reflect largely the relative extents to which the chemists within each of the several age groups have made an all-out effort to achieve. This is not to imply that the workers within any one age group have ever actually worked up to their full capacity but rather that the most productive group may have come closer to doing so than has any other group.

Since these curves represent only the production rates that chemists have realized at successive age levels, and not their *potential* production rates, the curves do not prove that there is a decrement in the potential ability of gifted chemists that corresponds to the decrements in the curves. Possibly the decrements result partly, even largely, from the fact that older chemists often have been less strongly motivated than have younger ones and that, as compared with members of the younger age groups, members of the older ones more often have found themselves (like Dumas) in circumstances much less favorable for eliciting their best potential effort to achieve. If the conditions under which older chemists do their creative work were made more favorable, their actual production rate for high-level contributions might well be much higher than it is and might also hold up better at the higher age levels than it has heretofore. Who knows!

Today there is much discussion about the major crisis existing in the United States because of the present and future shortage of scientific personnel. In view of this, and in view of the data presented in this article, serious consideration of the following questions is in order: (i) What are the most feasible methods for postponing the decrement in the production rate for the gifted chemist's really brilliant contributions? (ii) How can we best tap the reservoir of latent scientific talent that we know exists in our society but which we have heretofore largely ignored? (iii) For those youths who choose science as a career, what is the most practicable method for getting them launched upon their professional work at sufficiently early ages to enable them to realize their potentialities and to make the greatest possible number of important contributions?

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46. An analogous situation exists in the field of sports where, for example, the champion golfer may continue to play at an amateur level for a longer time than he will play at a championship level.
47. Like the word *contribution,* the word *masterwork* refers to the total research output reported during any one year. Often the chemist received his maximum number of credits or tallies for a single discovery, but sometimes, as in the case of Sir Humphry Davy, the chemist made several highly important discoveries during the course of a single year.
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Future Radiation Dosage from Weapon Tests

Extrapolations are offered for three possibilities—testing remains constant, it ceases, it increases.

D. R. Inglis

The world-wide radioactive fallout from H-bomb tests has raised the question whether this change in environment will have serious consequences for the healthy development of man. As has been discussed by W. F. Libby, commissioner of the Atomic Energy Commission, the main constituents which the tests add to man's radioactive environment are strontium-90 and cesium-137 (*1–3*). The former appears to be of greater importance because its chemical similarity to calcium leads to its selective deposition in bone, where in sufficient quantity it may have carcinogenic effects. In spite of the present experimental uncertainties in predicting the biological effectiveness of Sr^{90} from the better-known effects of radium, there seems to be general agreement that the Sr^{90} level now attained as a result of past tests is not a real hazard, when judged on a global scale of normal human misery.

The serious question pertains to future tests and depends, of course, on the rate at which tests may be continued in the future. Many statements, some of them of a sort to placate fears, have been made about the effects to be expected as a result of past tests.

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